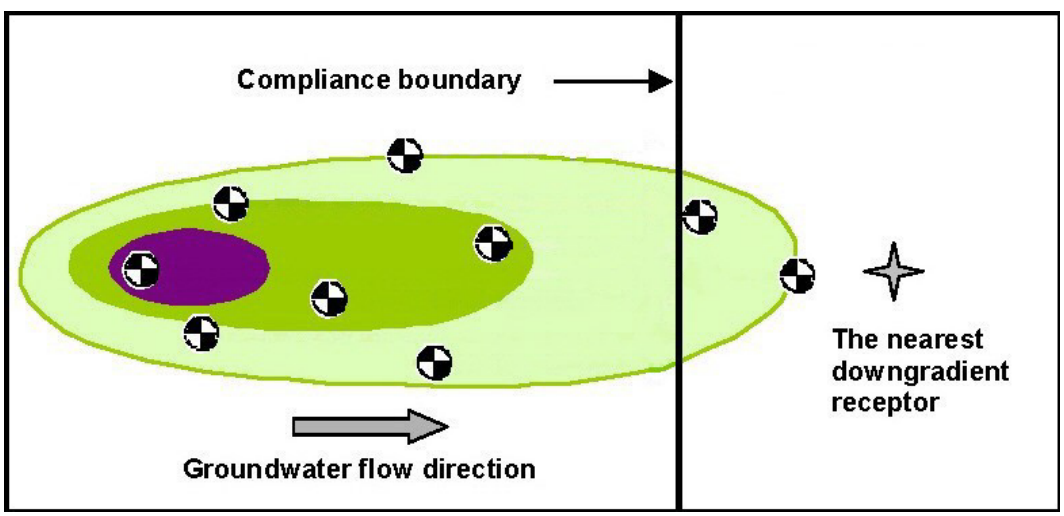
United States Environmental Protection Agency

Demonstration of Two Long-Term Groundwater Monitoring Optimization Approaches

Report with Appendices



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NOTICE

This report was prepared by Mitretek Systems (Mitretek) for the U.S. Environmental Protection Agency (U.S. EPA) under U.S. EPA Requisition #B4T024, QT-DC-04-000504, and summarizes the results of demonstration projects completed by The Parsons Corporation (Parsons) under Air Force Center for Environmental Excellence (AFCEE) contract (Contract No. F41624-00-D-8024, Task Order No. 0024), and by Groundwater Services, Inc. (GSI), also under an AFCEE contract (Contract No. F41624-98-C-8024). Reference to trade names, commercial products, process, or service does not constitute or imply endorsement, recommendation for use, or favoring by the United States Government or any agency thereof. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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PREFACE

This report summarizes the results of a demonstration in which optimization techniques were used to improve the design of long-term groundwater monitoring programs. Two different approaches to optimizing groundwater monitoring programs were used in the demonstration:

- The Monitoring and Remediation Optimization System (MAROS) software tool, developed by GSI for AFCEE (2000 and 2002), and

- A three-tiered approach applied by Parsons.

The report discusses the results of application of the two approaches to the evaluation and optimization of groundwater monitoring programs at three sites (the Fort Lewis Logistics Center, Washington, the Long Prairie Groundwater Contamination Superfund Site in Minnesota, and Operable Unit D, McClellan Air Force Base, California), and examines the overall results obtained using the two monitoring program optimization approaches. The primary goals of this demonstration were to highlight current strategies for applying optimization techniques to existing long-term monitoring programs, and to assist site managers in understanding the potential benefits associated with monitoring program optimization. The demonstration was conducted as part of an assessment of long-term monitoring optimization approaches, initiated by the U.S. Environmental Protection Agency's Office of Superfund Remediation and Technology Innovation (USEPA/OSRTI) and AFCEE.

ACKNOWLEDGEMENTS

This report summarizes the results of a demonstration of two different approaches to optimizing long-term groundwater monitoring programs. The demonstration projects summarized herein were completed by The Parsons Corporation (Parsons), Dr. Carolyn Nobel as principal investigator, and Groundwater Services, Inc. (GSI), Ms. Julia Aziz as principal investigator; the two teams are commended for the quality of their work, and the principal investigators are thanked for their helpful cooperation through the course of this project.

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EXECUTIVE SUMMARY

This report summarizes the results of a demonstration in which optimization techniques were used to improve the design of several long-term groundwater monitoring programs. Two different approaches to optimizing groundwater monitoring programs were applied in the demonstration:

- The Monitoring and Remediation Optimization System (MAROS) software tool, developed by Groundwater Services, Inc. (GSI) for AFCEE (2000 and 2002), and
- A three-tiered approach applied by The Parsons Corporation (Parsons).

The report discusses the results of application of the two approaches to the evaluation and optimization of groundwater monitoring programs at three sites (the Fort Lewis Logistics Center, Washington, the Long Prairie Groundwater Contamination Superfund Site in Minnesota, and Operable Unit D, former McClellan Air Force Base, California), and examines the overall results obtained using the two long-term monitoring optimization (LTMO) approaches. The primary goals of this demonstration were to highlight current strategies for applying optimization techniques to existing long-term monitoring (LTM) programs, and to assist site managers in understanding the potential benefits associated with monitoring program optimization. The demonstration was conducted as part of an assessment of LTMO approaches, initiated by the U.S. Environmental Protection Agency's Office of Superfund Remediation and Technology Innovation (USEPA/OSRTI) and the Air Force Center for Environmental Excellence (AFCEE).

The MAROS tool is a public-domain software package that operates in conjunction with an electronic database environment (Microsoft Access® 2000) and performs certain mathematical and/or statistical functions appropriate to completing qualitative, temporal, and spatial-statistical evaluations of a groundwater monitoring program, using data that have been loaded into the database (AFCEE, 2000 and 2002). MAROS utilizes parametric temporal analyses (using linear regression) and non-parametric trend analyses (using the Mann-Kendall test for trends) to assess the statistical significance of temporal trends in concentrations of contaminants of concern (COCs). MAROS then uses the results of the temporal-trend analyses to develop recommendations regarding optimal sampling frequency at each sampling point in a monitoring program by applying a modified Cost-Effective Sampling algorithm, to assess the feasibility of reducing the frequency of sampling at individual sampling points. Although the MAROS tool primarily is used to evaluate temporal data, it also incorporates a spatial statistical algorithm, based on a ranking system that utilizes a weighted "area-of-influence" approach (implemented using Delaunay triangulation) to assess the relative value of data generated during monitoring, and to identify the optimal locations of monitoring points. Formal decision logic and methods of incorporating user-defined secondary lines of evidence (empirical or modeling results) also are provided, and can be used to further evaluate monitoring data and make recommendations for adjustments to sampling frequency, monitoring locations, and the density of the monitoring network.

In the three-tiered LTMO approach, the monitoring-program evaluation is conducted in stages to address each of the objectives and considerations of monitoring: a qualitative evaluation first is completed, followed in succession by temporal and spatial evaluations. At the conclusion of each stage (or "tier") in the evaluation, recommendations are generated regarding potential changes in the temporal frequency of monitoring, and/or whether to retain or remove each monitoring point considered in the evaluation. After all three stages have been completed, the results of all of the analyses are combined and interpreted, using a decision algorithm, to generate final recommendations for an effective and efficient LTM program.

Application of the two approaches to the optimization of LTM programs at each of the three case-study example sites generated recommendations for reductions in sampling frequency and changes in the numbers and locations of monitoring points that are sampled. Implementation of the optimization recommendations could lead to reductions ranging from only a few percent to more than 50 percent in the numbers of samples collected and analyzed annually at particular sites (Table ES.1). The median recommended reduction in the annual number of samples collected, generated during the optimization demonstration, was 39 percent. Although available information regarding monitoring-program costs at each of the three case-study example sites is not directly comparable, it is projected that depending upon the scale of the particular LTM program, and the nature of the optimization recommendations, adoption of optimized monitoring programs at each of the case-study sites could lead to annual cost savings ranging from a few hundred dollars (using the recommendations generated by MAROS for the monitoring program at Operable Unit D [OU D], former McClellan Air Force Base [AFB]) to approximately $36,500 (using the results generated by the three-tiered approach for the monitoring program at the Fort Lewis Logistics Center Area). The results of the evaluations also demonstrate that each of the optimized monitoring programs remains adequate to address the primary objectives of monitoring at the sites. Although the general characteristics of each of the three case-study example sites are similar (chlorinated solvent contaminants in groundwater, occurring at relatively shallow depth in unconsolidated sediments), the assumptions underlying the two approaches, and the procedures that are followed in conducting the evaluations are applicable to a much broader range of conditions (e.g., dissolved metals in groundwater, or contaminants in a fractured bedrock system).

Table ES.1: Summary of Results of LTMO Demonstrations

Feature of Monitoring Program	Example Site[a/]		
	Fort Lewis	**Long Prairie**	**McClellan AFB OU D**
Total number of samples (per year) in current program	180	51	34
Range[b/] of total number of samples (per year) in refined program	107 - 113	22 – 36	17 – 32
Percent reduction in number of samples collected per year	37 - 40	29 – 51	6 – 50
Projected range of cost savings[c/] (per year)	$33,500 - $36,500	$4,200 - $8,100	$300 - $2,550

[a/] Information regarding site characteristics and the site-specific monitoring programs of the three example sites is presented in Section 3 (Fort Lewis), Section 4 (Long Prairie) and Section 5 (McClellan AFB OU D), and in Appendices C and D.

[b/] Ranges of total numbers of samples collected annually in refined programs, percentage reductions in numbers of samples collected, and associated potential annual cost savings, reflect the results of the evaluations conducted using MAROS and the three-tiered approach.

[c/] Estimates of potential annual cost savings were based on information regarding monitoring program costs provided by facility personnel. Costs associated with monitoring include cost of sample collection, sample analyses, data compilation and reporting, and management of investigation-derived waste (e.g., purge water).

Prior to initiating an LTMO evaluation, it is of critical importance that the monitoring objectives of the program to be optimized be clearly articulated, with all stakeholders agreeing to the stated objectives, so that the program can be optimized in terms of recognized (and agreed-upon) objectives, using decision rules and procedures that are acceptable to all stakeholders. The decisions regarding whether to conduct an LTMO evaluation, which approach to use, and the degree of regulatory-agency involvement in the LTMO evaluation and implementation of optimization recommendations, must be made on a site-specific basis. Factors to be considered in deciding whether to proceed with an LTMO evaluation include:

- The projected level of effort necessary to conduct the evaluation;
- The resources available for the evaluation (e.g., quality and quantity of data, staff having the appropriate technical capabilities);
- The anticipated degree of difficulty in implementing optimization recommendations; and
- The potential benefits (e.g., cost savings) that could result from an optimized monitoring program.

Optimization of a monitoring program should be considered for most sites having LTM programs that are based on sampling of characterization monitoring points, or for sites where more than about 50 samples are collected and analyzed on an annual basis. Because it is likely that monitoring programs can benefit from periodic evaluation as environmental programs evolve, monitoring program optimization also should be undertaken periodically, rather than being regarded as a one-time event. Overall site conditions should be relatively stable, with no large changes in remediation approaches occurring or anticipated. Furthermore, successful application of either approach to the site-specific evaluation of a monitoring program is directly dependent upon the amount and quality of the available data – results from a minimum of four to six separate sampling events are necessary to support a temporal analysis, and results collected at a minimum of about six (for a MAROS evaluation) to 15 (for a three-tiered evaluation) separate monitoring points are necessary to support a spatial analysis. It also is necessary to develop an adequate conceptual site model (CSM) describing site-specific conditions prior to applying either approach. In particular, the extent of contaminants in the subsurface at the site must be adequately delineated before the monitoring program can be optimized.

Although the MAROS tool is capable of being applied by an individual with little formal statistical training, interpretation of the results generated by either approach requires a relatively sophisticated understanding of hydrogeology, statistics, and the processes governing the movement and fate of contaminants in the environment. Although many of the basic assumptions and techniques underlying both optimization approaches are similar, and both optimization approaches utilize qualitative, temporal, and spatial analyses, there are several differences between the two approaches, which can cause one optimization approach (e.g., the three-tiered approach) to generate results that are not completely consistent with the results obtained using the other approach (e.g., MAROS). Nevertheless, each approach is capable of generating sound and defensible recommendations for optimizing LTM programs.

The most significant advantage conferred by both optimization approaches is the fact that both approaches apply consistent, well-documented procedures, which incorporate formal decision logic, to the process of evaluating and optimizing groundwater monitoring programs. However, the process of data preparation, screening, processing, and evaluation can be extremely time-consuming for either approach. Both approaches could benefit from further development efforts to address current limitations; and continued development of both approaches is contemplated or in progress.

Typically, a program manager should anticipate incurring costs on the order of $6,000 to $10,000 to complete an LTMO evaluation at the level of detail of the case-study examples described in this demonstration. Consequently, an LTMO evaluation may be cost-prohibitive for smaller monitoring programs. However, an LTMO evaluation that can be used to reduce the total number of samples collected at a site by about 5 to 10 samples per annum should be cost-effective.

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LIST OF ACRONYMS AND ABBREVIATIONS

α	statistical confidence level
AFB	Air Force Base
AFCEE/ERT	Air Force Center for Environmental Excellence/Technology Transfer Division
AFRPA	Air Force Real Property Agency
AR	area ratio (calculated by MAROS)
ASCE	American Society of Civil Engineering
β	statistical power
bgs	below ground surface
BRAC	Base Realignment and Closure Act
CAH	chlorinated aliphatic hydrocarbon compound
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CES	cost-effective sampling
CFR	Code of Federal Regulations
COC	contaminant of concern
COV	coefficient of variation
CR	concentration ratio (calculated by MAROS)
CSM	conceptual site model
CT	concentration trend (calculated by MAROS)
DCA	dichloroethane
DCE	dichloroethene
DNAPL	dense, non-aqueous-phase liquid
DQO	data-quality objective
EGDY	East Gate Disposal Yard
ERPIMS	(US Air Force) Environmental Restoration Program Information Management System
ESRI	Environmental Systems Research Institute, Inc.
ETD	extraction, treatment, and discharge
EW	extraction well
FS	feasibility study
ft/day	feet per day
ft/yr	feet per year
GC	gas chromatograph
GeoEAS	Geostatistical Environmental Exposure Software
GIS	geographic information system
GWMP	Groundwater Monitoring Plan
gpm	gallon(s) per minute
GSI	Groundwater Services, Inc.
GTS	Geostatistical Temporal/Spatial optimization algorithm
GWOU	Groundwater Operable Unit
ID	identifier
IDW	investigation-derived waste
IROD	Interim Record of Decision
LOGRAM	revised Logistics Center monitoring program
LTM	long-term monitoring

LIST OF ACRONYMS AND ABBREVIATIONS (continued)

LTMO	long-term monitoring optimization
LTMP	long-term monitoring program
μg/L	microgram(s) per liter
MAROS	Monitoring and Remediation Optimization System
MCL	maximum contaminant level
Mitretek	Mitretek Systems
MMR	Massachusetts Military Reservation
MPCA	Minnesota Pollution Control Agency
MS	mass spectrometer
NPL	National Priorities List
NRC	National Research Council
O&M	operations and maintenance
ORP	oxidation-reduction potential
OU	operable unit
Parsons	The Parsons Corporation
PCE	tetrachloroethene
POL	petroleum, oils, and lubricants
QA	quality assurance
QC	quality control
RAO	remedial action objective
RCRA	Resource Conservation and Recovery Act
RI	remedial investigation
ROC	rate-of-change parameter (calculated by MAROS)
ROD	record of decision
S	Mann-Kendall test statistic
SF	slope factor (calculated by MAROS)
SVE	soil-vapor extraction
TCA	trichloroethane
TCE	trichloroethene
OSRTI	U.S. EPA’s Office of Superfund Remediation and Technology Innovation
US	United States
USACE	U.S. Army Corps of Engineers
U.S. EPA	U.S. Environmental Protection Agency
VOC	volatile organic compound

1.0 INTRODUCTION

This report describes the results of a demonstration in which optimization techniques were used to improve the design of long-term groundwater monitoring programs. The primary objectives of optimizing the particular monitoring programs addressed in this study were to assess the optimal frequency of monitoring implemented in each program, and to evaluate the spatial distribution of the components of each monitoring network. Two different long-term monitoring optimization (LTMO) approaches were used in the demonstration:

1. The Monitoring and Remediation Optimization System (MAROS) software tool, developed by Groundwater Services, Inc. (GSI) for the Air Force Center for Environmental Excellence (AFCEE) (2000 and 2002); and

2. A three-tiered approach applied by The Parsons Corporation (Parsons).

The primary goals of this demonstration were to highlight current strategies for applying optimization techniques to existing long-term monitoring (LTM) programs, and to assist site managers in understanding the potential benefits associated with monitoring program optimization. The report also presents the basic concepts underlying environmental monitoring and monitoring optimization, so that the discussion of particular procedures can be understood in terms of an overall monitoring approach. The work presented in this document was commissioned by the U.S. Environmental Protection Agency's (U.S. EPA's) Office of Superfund Remediation and Technology Innovation (OSRTI).

1.1 PROJECT DESIGN

This project was conducted to demonstrate and assess two different LTMO approaches that can be used to identify opportunities for streamlining groundwater monitoring programs. The project was designed as follows:

- Three sites having existing long-term groundwater monitoring programs were selected as case-study examples for this demonstration project. The sites were required to meet minimum screening criteria to ensure that the available monitoring data were sufficient for the LTMO evaluations (refer to Sections 3, 4, and 5, and Appendix C of this report for detailed site information).

- GSI and Parsons evaluated groundwater monitoring data from each of the three sites using their respective approaches, to assess whether the monitoring programs could be streamlined without significant loss of information. GSI and Parsons then prepared reports summarizing the results of their evaluations.

- The summary reports then were provided to Mitretek Systems (Mitretek) for review. Using those summary reports, Mitretek prepared this document, which summarizes the LTMO evaluations and examines the results.

1.2 CASE-STUDY EXAMPLES

The current LTM programs at the Fort Lewis Logistics Center, Washington (Fort Lewis), the Long Prairie Groundwater Contamination Superfund Site in Minnesota (Long Prairie), and Operable Unit (OU) D, McClellan Air Force Base (AFB), California (McClellan AFB OU D), were selected as case-study example programs, because the numbers and spatial coverage of wells, and length of the monitoring history at each site, were judged to be adequate to generate meaningful results. The primary characteristics of the monitoring programs at each of the three sites are presented in Table 1.1.

Table 1.1: Characteristics of Monitoring Programs at Three Example Sites Used in Long-Term Monitoring Program Optimization Demonstrations

Monitoring-Program Characteristic	Example Site[a/]		
	Fort Lewis	**Long Prairie**	**McClellan AFB OU D**
Number of distinct water-bearing units or monitoring zones addressed by the monitoring program	2 (Upper Vashon and Lower Vashon)	3 (water table [Zone A], base of upper glacial outwash [Zone B], lower glacial outwash [Zone C])	2 (Zones A and B)
Principal contaminants[b/]	*cis*-1,2-DCE, PCE, 1,1,1-TCA, TCE, VC	*cis*-1,2-DCE, PCE, TCE	1,2-DCA, *cis*-1,2-DCE, PCE, TCE
Total number of wells included in program	21 extraction wells 40 upper Vashon monitoring wells 11 lower Vashon monitoring wells	2 municipal supply wells 6 extraction wells 12 Zone A monitoring wells 15 Zone B monitoring wells 8 Zone C monitoring wells	6 extraction wells 32 Zone A monitoring wells 13 Zone B monitoring wells
Total number of samples collected (per year)	180	51	34
Total cost[c/] of monitoring (per year)	$90,000	$14,280	Information not provided

[a/] Information regarding site characteristics and the site-specific monitoring programs of the three example sites is presented in Section 3 (Fort Lewis), Section 4 (Long Prairie) and Section 5 (McClellan AFB OU D), and in Appendices C and D.

[b/] DCA = dichloroethane; DCE = dichloroethene; PCE = tetrachloroethene;
TCA = trichloroethane; TCE = trichloroethene; VC = vinyl chloride.

[c/] Information regarding annual monitoring program costs was provided by facility personnel. Costs associated with monitoring include cost of sample collection, sample analyses, data compilation and reporting, and management of investigation-derived waste (e.g., purge water).

1.3 PURPOSES OF GROUNDWATER MONITORING

The U.S. EPA (2004) defines monitoring to be

> *"… the collection and analysis of data (chemical, physical, and/or biological) over a sufficient period of time and frequency to determine the status and/or trend in one or more environmental parameters or characteristics. Monitoring should not produce a 'snapshot in time' measurement, but rather should involve repeated sampling over time in order to define the trends in the parameters of interest relative to clearly-defined management objectives. Monitoring may collect abiotic and/or biotic data using well-defined methods and/or endpoints. These data, methods, and endpoints should be directly related to the management objectives for the site in question."*

Monitoring of groundwater systems has been practiced for decades. Monitoring activities have expanded significantly in recent years, to assess and address the problems associated with groundwater contamination and its environmental consequences, because the processes active within a groundwater system, and the interactions of a groundwater system with the rest of the environment, can be assessed only through monitoring (Zhou, 1996).

There are statutory requirements establishing the necessity for monitoring, and governing the types of monitoring that must be conducted under particular circumstances. Passage of the Resource Conservation and Recovery Act (RCRA) in 1976, and subsequent promulgation of the first regulations authorized under RCRA in 1980, resulted in significant expansion of the role of groundwater monitoring. RCRA and subsequent amendments include provisions for establishing groundwater monitoring programs at all of the hazardous-waste treatment, storage, and disposal facilities, at all of the solid-waste landfills, and at many underground storage tank facilities in the United States. In December 1980, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) was passed, in part to address potential threats posed by "uncontrolled" hazardous waste sites. CERCLA statutory authority regarding monitoring gives U.S. EPA the authority to undertake monitoring to identify threats (42 USC §9604[b]), and defines removal and remedial actions as inclusive of any monitoring reasonably required to ensure that such actions protect the public health, welfare, and the environment (42 USC §9601[23] and 42 USC §9601[24], respectively). Therefore, response actions at such sites require that monitoring programs be developed and implemented to investigate the extent of environmental contamination and to monitor the progress of cleanup activities (Makeig, 1991).

Four inherently different types of groundwater monitoring programs can be distinguished (U.S. EPA, 2004):

- Characterization monitoring;
- Detection monitoring;
- Compliance monitoring; and
- Long-term monitoring.

Characterization monitoring is initiated in an area where contaminants are known or suspected to be present in environmental media (soil, air, surface water, groundwater) as a consequence of a release of hazardous substances. Site characterization involves delineating the nature, extent, and fate of potential contaminants in the environment, identifying human populations or other biota ("receptors") that could be adversely affected by exposure to those contaminants, and assessing the possibility that the contaminants could migrate to a location where a potential receptor could come into contact with the contaminant(s) ("exposure point"). Groundwater sampling is a critical element of site characterization, as it is necessary to establish whether site-related contaminants are migrating in groundwater to potential exposure points.

Detection monitoring and compliance monitoring generally are required for facilities that are regulated under RCRA. A groundwater-quality monitoring program designed for detection monitoring consists of a network of monitoring points (wells) in an uncontaminated water-bearing unit that is at risk of contamination from an overlying waste facility. If the results of periodic sampling conducted during detection monitoring indicate that a release may have occurred, the owner or operator of the facility must implement the next phase of groundwater monitoring – compliance monitoring. During compliance monitoring, groundwater samples are collected from locations designated as compliance points, and are analyzed for constituents that are known or suspected to have been released. After it has been established that a release of the type and magnitude suspected has occurred, a corrective-action program must be implemented (Makeig, 1991).

During a corrective action, the owner or operator of a facility must remove, control, and/or treat the wastes that have caused the release, so that groundwater quality can be brought into compliance with established groundwater protection criteria. (Additional characterization monitoring may be necessary during the selection of a corrective action, so that the actual extent and fate of contaminants in the subsurface can be assessed to the extent necessary to support remedy decisions.) Groundwater cleanup criteria usually are established by the individual states, or on a site-specific basis within a state. In all cases, the cleanup criteria must be as stringent as, or more stringent than, various standards established by the federal government, unless such requirements are waived. After a remedy has been selected and put in place, groundwater monitoring also is used in evaluating the degree to which the remedial measure achieves its objectives (e.g., abatement of groundwater contaminants, restoration of groundwater quality, etc.). This type of monitoring – known as LTM – typically is initiated only after a remedy has been selected and implemented, in conjunction with some type of corrective-action program. It usually is assumed that after a site enters the LTM phase of remediation, site characterization is essentially complete, and the existing monitoring network can be adapted, as necessary, to achieve the objectives of the LTM program (Reed *et al*., 2000). Optimization techniques have been applied to the design of monitoring networks for site characterization, detection monitoring, and compliance monitoring (Loaiciga *et al.*, 1992). In practice, however, optimization techniques usually are applied only to LTM programs, as these programs typically provide well-defined spatial coverage of the area monitored, and have been implemented for a period of time sufficient to generate a relatively comprehensive monitoring history.

1.4 LONG-TERM GROUNDWATER MONITORING PROGRAM OPTIMIZATION

As of 1993, the National Research Council (NRC, 1993) estimated that groundwater had been contaminated at between 300,000 and 400,000 sites in the United States. As a consequence of the identification of certain technology limitations and recognition of the potentially significant costs for remediating all of these sites (approximately $500 billion to $1 trillion), the paradigm for groundwater remediation recently has shifted to some degree, from resource restoration to long-term risk management. This strategy change is expected to result in more contaminants being left in place for longer periods of time, thereby requiring long-term monitoring (NRC, 1999). At many sites, LTM can require decades of expensive sampling of monitoring networks, ranging in size from tens to hundreds of sampling locations, and resulting in costs of hundreds of thousands to millions of dollars per year for sampling and data management (Reed *et al*., 2000). Development of cost-effective monitoring programs, or optimization of existing programs, can produce significant cost savings over the life of particular remediation projects. As a consequence of the resources required to maintain a monitoring program for a long period of time, most monitoring optimization efforts, including the monitoring optimization evaluations described in this report, have focused on LTM.

It is critical that the objectives of monitoring be developed and clearly articulated prior to initiating a monitoring program (Bartram and Balance, 1996), or during the process of evaluating and optimizing an existing program. Monitoring program objectives are dependent upon the types of information that will be generated, and the intended uses of that information. The exact information needs of particular monitoring programs usually must be established by considering the program objectives during the planning stages or during periodic LTM program reviews. Clearly articulated program objectives will establish the end-uses of monitoring data, which in turn will clarify those data that must be collected. The connection between the data collected by monitoring and the uses to which those data are applied is an important element in the success of any water-quality monitoring program. Without carefully connecting the acquisition of data with the production and use of information contained within the data, there is a high probability that data collection will become an end in itself (Ward *et al*., 1990). Because site conditions, particularly in saturated media, can be expected to change through time, the objectives of any LTM program should be revisited and refined as necessary during the course of the program.

Monitoring objectives fall into four general categories (U.S. EPA, 1994b and 2004; Gibbons, 1994):

- Identify changes in ambient conditions;
- Detect the movement and monitor the physico-chemical fate of environmental constituents of interest (COCs, dissolved oxygen, etc.) from one location to another;
- Demonstrate compliance with regulatory requirements; and
- Demonstrate the effectiveness of a particular response activity or action.

As is clear from the discussion in Section 1.3, the two primary objectives of long-term groundwater monitoring programs are a subset of these general objectives, and can be expressed as follow:

- Evaluate the long-term temporal state of contaminant concentrations at one or more points within or outside of the remediation zone, as a means of monitoring the performance of the remedial measure (*temporal objective*); and
- Evaluate the extent to which contaminant migration is occurring, particularly if a potential exposure point for a susceptible receptor exists (*spatial objective*).

Ultimately, the relative success of any remediation system and its components (including the monitoring program) must be judged based on the degree to which they achieve their stated objectives. The most important components of a groundwater monitoring program are the network density (the number of monitoring wells and their relative locations) and the sampling frequency (the number of observations or samples per unit time) (Zhou, 1996). Designing an effective groundwater monitoring program involves locating monitoring points and developing a site-specific strategy for groundwater sampling and analysis in order to maximize the amount of relevant information (information required to effectively address the temporal and spatial objectives of monitoring) that can be obtained, while minimizing incremental costs. The efficiency of a monitoring program is considered to be optimal if it is effectively achieving its objectives at the lowest total cost, and/or with the fewest possible number of monitoring locations (Reed *et al*., 2000).

While several different LTMO methods have been developed and applied in recent years, this evaluation examines the results obtained by investigators applying two approaches in current use. The MAROS software tool, developed and applied by GSI, uses parametric and non-parametric trend analyses to assess temporal chemical concentration trends and recommend optimal sampling frequency, and also uses spatial statistical techniques to identify monitoring points that potentially are generating redundant information. The MAROS software then combines the results of the temporal trend analysis and spatial statistical analysis, and uses the combined results to generate recommendations regarding the frequency of monitoring and spatial distribution of the components of the monitoring network. Parsons has applied a three-tiered approach consisting of a qualitative evaluation, a statistical evaluation of temporal trends in contaminant concentrations, and a spatial-statistical analysis, to assess the degree to which the monitoring program addresses each of the two primary objectives of monitoring, and also to address other potentially-important considerations. The results of the three evaluations then are combined and used to assess the optimal frequency of monitoring and the spatial distribution of the various components of the monitoring network.

1.5 REPORT ORGANIZATION

The main body of this report is organized into seven sections, including this introduction:

- Concepts in groundwater monitoring and techniques for evaluating monitoring programs are discussed in Section 2; ways in which some of these techniques are implemented in the MAROS software tool and in the three-tiered approach also are described briefly.

- Background information relevant to the current groundwater monitoring programs at the Fort Lewis Logistics Center, the Long Prairie Groundwater Contamination Superfund Site, and OU D, McClellan AFB is reviewed in Sections 3, 4, and 5, respectively; and the summary results of the MAROS and three-tiered evaluations of each monitoring program are presented in those Sections.

- Section 6 examines the results of the MAROS and three-tiered evaluations of the three monitoring programs, and presents recommendations for implementing program improvements.

- References cited in this document are listed in Section 7.

Readers interested in a summary description of the demonstration project, and its results, will find this information in the main body of this report (EPA 542-R-04-001a). Readers interested in more detailed discussions can find supporting information contained in four appendices:

- Concepts and practices in groundwater monitoring, and in monitoring optimization, are discussed in detail in Appendix A.

- Features of the MAROS tool and the three-tiered LTMO approach are described in Appendix B.

- Synopses of the MAROS and three-tiered LTMO evaluations of the three monitoring programs are included in Appendix C.

- The detailed results of the MAROS and three-tiered LTMO evaluations of the three monitoring programs, as described in reports originally generated by GSI and Parsons, are presented in Appendix D.

The main body of the report, together with the appendices, comprise EPA 542-R-04-001b.

2.0 EVALUATION AND OPTIMIZATION OF LONG-TERM MONITORING PROGRAMS

2.1 CONCEPTS IN GROUNDWATER MONITORING

Designing an effective groundwater-quality monitoring program involves selecting a set of sampling sites, suite of analytes, and a sampling schedule based upon one or more monitoring-program objectives (Hudak *et al*., 1993). An effective monitoring program will provide information regarding contaminant migration and changes in chemical suites and concentrations through time at appropriate locations, thereby enabling decision-makers to verify that contaminants are not endangering potential receptors, and that remediation is occurring at rates sufficient to achieve remedial action objectives (RAOs) in a reasonable timeframe. The design of the monitoring program therefore should address existing receptor exposure pathways, as well as exposure pathways arising from potential future use of the groundwater.

The U.S. EPA (2004) defines six steps that should be followed in developing and implementing a groundwater monitoring program:

1. Identify monitoring program objectives.

2. Develop monitoring plan hypotheses (a conceptual site model, or CSM).

3. Formulate monitoring decision rules.

4. Design the monitoring plan.

5. Conduct monitoring, and evaluate and characterize the results.

6. Establish the management decision.

In this paradigm, a monitoring program is founded on the current understanding of site conditions as documented in the CSM, and monitoring is conducted to validate (or refute) the hypotheses regarding site conditions that are contained in the CSM. Thus, monitoring results are used to refine the CSM by tracking changes in site conditions through time. All monitoring-program activities are undertaken to support a management decision, established as an integral part of the monitoring program (e.g., assess whether a selected response action is/is not achieving its objectives).

Most past efforts in developing or evaluating monitoring programs have addressed only the design of the monitoring plan (Step 4 in the six-step process outlined above). The process of designing a groundwater monitoring plan involves four principal tasks (Franke, 1997):

1. Identify the volume and characteristics of the earth material targeted for sampling.

2. Select the target parameters and analytes, including field parameters/analytes and laboratory analytes.

3. Define the spatial and temporal sampling strategy, including the number of wells necessary to be sampled to meet program objectives, and the schedule for repetitive sampling of selected wells.

4. Select the wells to be sampled.

However, this procedure considers only the physical and chemical data that the monitoring plan is intended to generate, and does not completely take into account the objectives that the monitoring data are intended to address (Step 1, above), the decision(s) that the monitoring program is(are) intended to support (Step 6), or the means by which a decision will be selected (Step 3). All of the six steps outlined by the U.S. EPA (2004) should be considered during the development or evaluation of a monitoring program, if that program is to be effective and efficient, and also should be considered during optimization of existing programs.

Most monitoring programs have been designed and evaluated based on qualitative insight into the characteristics of the hydrologic system, and using professional judgment (Zhou, 1996). However, groundwater systems by nature are highly variable in space and through time, and it is difficult or impossible to account for much of the existing variability using qualitative techniques. More recently, other, more quantitative approaches have been developed, arising from the recognition that the results obtained from a monitoring program are used to make *inferences* about conditions in the subsurface on the basis of *samples*, and on the need to account for natural variability. The process of making inferences on the basis of samples, while simultaneously evaluating the associated variability, is the province of statistics; and to a large degree, the temporal and spatial variability of water-quality data currently are addressed through the application of statistical methods of evaluation, which enable large quantities of data to be managed and interpreted effectively, while the variability of the data also is quantified and managed (Ward *et al*., 1990).

All approaches to the design, evaluation, and optimization of effective groundwater monitoring programs must acknowledge and account for the dynamic nature of groundwater systems, as affected by natural phenomena and anthropogenic changes (Everett, 1980). This means that in order to assess the degree to which a particular program is achieving the temporal and spatial objectives of monitoring (Section 1.4), a monitoring-program evaluation must address the temporal and spatial characteristics of groundwater-quality data. Temporal and spatial data generally are evaluated using temporal and spatial-statistical techniques, respectively. In addition, there may be other considerations that best are addressed through qualitative evaluation.

In a qualitative evaluation, the relative performance of the monitoring program is assessed from calculations and judgments made without the use of quantitative mathematical methods (Hudak *et al*., 1993). Multiple factors may be considered qualitatively in developing recommendations for continuation or cessation of monitoring at each monitoring point. Qualitative approaches to the evaluation of a monitoring program range from relatively simple to complex, but often are highly subjective. Furthermore, the degree to which the program satisfies LTM objectives may not be readily evaluated by qualitative methods.

Temporal data (chemical concentrations measured at different points in time) provide a means of quantitatively assessing conditions in a groundwater system (Wiedemeier and Haas, 1999), and evaluating the performance of a groundwater remedy and its associated monitoring program. If attenuation or removal of contaminant mass is occurring in the subsurface as a consequence of natural processes or operation of an engineered remediation system, attenuation or mass removal will be apparent as a decrease in contaminant concentrations through time at a particular sampling location, as a decrease in contaminant concentrations with increasing distance from chemical source areas, and/or as a change in the suite of chemicals through time or with increasing migration distance. Conversely, if a persistent source is contributing to groundwater contaminant plumes or if contaminant migration is occurring, this may be apparent as an increase in contaminant concentrations through time at a particular sampling location, or as an increase in contaminant concentrations through time with increasing distance from contaminant source areas.

The temporal objective of long-term monitoring (evaluate contaminant concentrations in groundwater through time; Section 1.4) can be addressed by defining trends in contaminant concentrations, by identifying periodic fluctuations in concentrations, and by estimating long-term average ("mean") values of concentrations (Zhou, 1996). The frequency of sampling necessary to achieve the temporal objective then can be based on trend detection, accuracy of estimation of periodic fluctuations, and accuracy of estimation of long-term mean concentrations. Concentration trends, periodicity, and long-term mean concentrations typically are evaluated using statistical methods – in particular, tests for trends, including the Student's t-test (Zhou, 1996), regression analyses, Sen's (1968) non-parametric estimator of trend slope, and the Mann-Kendall test, are widely applied (Hirsch *et al.*, 1991).

Spatial techniques that can be applied to the design and evaluation of monitoring programs fall into two general categories – simulation approaches and ranking approaches (Hudak *et al*., 1993). Simulation approaches utilize computer models to simulate the evolution of contaminant plumes. The results then are incorporated into an optimization model which derives an optimal monitoring network configuration (Reed *et al*., 2000). Ranking approaches utilize weighting schemes that express the relative value to the monitoring program of candidate sampling sites distributed throughout a sampling domain (Hudak *et al*., 1993). The relative value of a potential monitoring site can be ranked by assessing its spatial position relative to areas such as contaminant sources, receptor locations, or probable zones of contaminant migration. Ranking approaches commonly use geostatistical methods to assist in the design, evaluation, or optimization of a monitoring network (American Society of Civil Engineering [ASCE], 1990a and 1990b). General concepts in groundwater monitoring, and techniques used in the design/optimization of monitoring programs, are discussed further in Appendix A.

2.2 METHODS FOR DESIGNING, EVALUATING, AND OPTIMIZING MONITORING PROGRAMS

Although monitoring network design has been studied extensively in the past, most previous studies have addressed one of two problems (Reed *et al*., 2000):

1. Application of numerical simulation and formal mathematical optimization techniques to screen monitoring plans for detection monitoring at landfills and hazardous-waste sites; or

2. Application of ranking methods, including geostatistics, to augment or design monitoring networks for site-characterization purposes.

A number of studies (Appendix A) have addressed detection monitoring by applying global approaches to the design of new monitoring networks. In contrast, few investigators have formally addressed the evaluation and optimization of LTM programs at sites having extensive monitoring networks that were installed during site characterization. The primary goal of optimization efforts at such sites is to reduce sampling costs by eliminating data redundancy to the extent possible. This type of optimization usually is not intended to identify locations for new monitoring wells, and it is assumed during optimization that the existing monitoring network sufficiently characterizes the concentrations and distribution of contaminants being monitored. It also is not intended for use in optimizing detection monitoring. Two approaches to evaluating monitoring networks – the MAROS tool and the three-tiered evaluation approach – were developed specifically for use in optimizing existing monitoring programs. (Although formal mathematical optimization techniques have been applied to the problem of optimizing monitoring programs [Appendix A], neither the MAROS tool nor the three-tiered approach incorporates mathematical optimization in the strict sense. Rather, in subsequent discussion, "optimization" refers to the application of rule-based procedures, incorporating statistical analysis and professional judgment, to identify possible improvements to a monitoring program that will continue to be effective at meeting the two objectives of monitoring while addressing qualitative constraints and minimizing the necessary incremental resources.) The principal features of these two approaches are discussed in the following sections, and are described in detail in Appendix B.

2.3 DESCRIPTION OF MAROS SOFTWARE TOOL

The MAROS software originally was developed primarily for use as a tool to assist non-technical personnel (e.g., facility environmental managers) in evaluating and optimizing long-term monitoring programs (AFCEE, 2000). As an added benefit, the MAROS tool provides a convenient platform for the organization, preliminary evaluation, and presentation of monitoring data in graphical or tabular formats. In the years since its development, the performance of the MAROS software tool has been assessed critically ("*beta* tested") by applying the tool to the evaluation and optimization of actual monitoring programs at a number of U.S. Air Force facilities (e.g., Parsons, 2000 and 2003a). In response to recommendations for modifications to the MAROS software, generated as a consequence of the *beta* testing, GSI developed MAROS Version 2, which was issued by AFCEE (2002) for additional testing in 2002. The public-domain software and accompanying documentation are available free of charge for download on the AFCEE website at http://www.afcee.brooks.af.mil/er/rpo.htm . All case-study example monitoring programs examined in the current demonstration project were evaluated and optimized using MAROS Version 2 (Sections 3.2, 4.2, and 5.2 of this report).

The MAROS tool consists of a software package that operates in conjunction with an electronic database environment (Microsoft Access® 2000) and performs certain mathematical and/or statistical functions appropriate to completing qualitative, temporal, and spatial-statistical evaluations of a monitoring program, using data that have been loaded into the database (AFCEE, 2002). MAROS utilizes parametric temporal analyses (using linear regression) and non-parametric trend analyses (using the Mann-Kendall test for trends) to assess the statistical significance of temporal trends in concentrations of contaminants of concern (COCs) (Appendix B). MAROS then uses the results of the temporal-trend analyses to develop recommendations regarding sampling frequency at each sampling point in a monitoring program by applying a modified Cost-Effective Sampling (CES) algorithm, based on the CES method developed at Lawrence Livermore National Laboratory (Ridley *et al.*, 1995). The modified CES method uses recent and historical COC measurements to determine optimal sampling frequency.

Although the MAROS tool primarily is used to evaluate temporal data, it also incorporates a spatial statistical algorithm, based on a ranking system that utilizes a weighted "area-of-influence" approach (implemented using Delaunay triangulation) to assess the relative value of data generated during monitoring, and to identify the optimal locations of monitoring points. Formal decision logic and methods of incorporating user-defined secondary lines of evidence (empirical or modeling results) also are provided, and can be used to further evaluate monitoring data and generate recommendations for adjustments to sampling frequency, monitoring locations, and the density of the monitoring network. Additional features (moment analyses) allow the user to evaluate conditions and the adequacy of the monitoring network across a contaminated site (rather than just at individual monitoring locations.)

MAROS is intended to assist users in establishing practical and cost-effective LTM goals for a specific site, by

- Identifying the COCs at the site;
- Determining whether temporal trends in groundwater COC concentration data are statistically significant;
- Using identified temporal trends to evaluate and optimize the frequency of sample collection;
- Assessing the extent to which contaminant migration is occurring, using temporal-trend and moment analyses;
- Evaluating the relative importance of each well in a monitoring network, for the purpose of identifying potentially-redundant monitoring points;
- Identifying those wells that are statistically most relevant to the current sampling program;
- Evaluating whether additional monitoring points are needed to achieve monitoring objectives;
- Providing indications of the overall performance of the site remediation approach; and
- Assessing whether the monitoring program is sufficient to achieve program objectives on local or site-wide scales.

As with any approach to LTM program optimization, successful application of the MAROS tool to the site-specific evaluation of a monitoring program is completely dependent upon the amount and quality of the available data (e.g., data requirements for a temporal trend analysis include a suggested minimum of six separate sampling events at an individual sampling point, and a spatial analysis requires sampling results from a minimum of six different sampling locations). It also is necessary to develop an adequate CSM (Section 2.1), describing site-specific conditions (e.g., direction and rate of groundwater movement, locations of contaminant sources and potential receptor exposure points) prior to applying the MAROS tool. In particular, the nature and extent of contaminants in the subsurface at the site must be adequately characterized and delineated before the monitoring program can be optimized.

MAROS is designed to accept data in any of three formats: text files in U.S. Air Force Environmental Restoration Program Information Management System (ERPIMS) format, Microsoft Access® files, or Microsoft EXCEL® files. Prior to conducting a monitoring-program evaluation, spatial and temporal data are loaded into a database, to include well identifiers (IDs), the sampling date(s) for each well, COCs, COC concentrations detected at each well sampled on each sampling date, laboratory detection limits for each COC, and any quality assurance/quality control (QA/QC) qualifiers associated with sample collection or analyses. The spatial analysis also requires that geographic coordinates (northings and eastings, referenced to some common datum) be supplied for each well.

Because MAROS can be used to evaluate the spatial and temporal characteristics of a maximum of five COCs in a single simulation, one or more COCs must be removed from data sets containing more than five COCs, or the data set must be split, so that only five COCs are included in a single simulation. MAROS is capable of evaluating a maximum of 200 monitoring points in each simulation. Prior to applying MAROS to the evaluation of a monitoring network comprising more than 200 monitoring points, those monitoring locations providing relatively little information (or information that is not compatible with the other points in the network) can be identified using qualitative methods and eliminated from the evaluation. As an alternative, a monitoring network comprising more than 200 monitoring points could be divided into subsets, each subset of the network could be evaluated using MAROS, and the results of the evaluations then could be combined to generate recommendations for the entire network.

After COCs have been identified, and the monitoring points in the network to be used in the evaluation have been selected, the MAROS evaluation and optimization of a monitoring program is completed in two stages:

- A preliminary evaluation of plume stability is completed for the monitoring network, and general recommendations for improving the monitoring program are produced; and

- More-detailed temporal and spatial evaluations then are completed for individual monitoring wells, and for the complete monitoring network.

In general, the MAROS tool is intended for use in evaluating single-layer groundwater systems having relatively simple hydrogeologic characteristics (GSI, 2003a). However, for a multi-layer groundwater system, the user could analyze those components of the monitoring network completed in individual layers, during separate evaluations.

The primary features of MAROS, and the ways in which it addresses the qualitative, temporal, and spatial aspects of environmental monitoring data, are summarized in Table 2.1. Additional details regarding the MAROS software tool, its functionality, capabilities, and methods of application, are presented in Appendix B. Details regarding specific examples of its application are presented in Appendix D.

Table 2.1: Primary Features of MAROS

Infrastructure
The MAROS tool is a public-domain software package that operates in conjunction with an electronic database environment (Microsoft™ Access® 2000) and performs certain mathematical and/or statistical functions appropriate to completing qualitative, temporal, and spatial-statistical evaluations of a monitoring program, using data that have been loaded into the database.
The MAROS software, and accompanying documentation, are available for download free of charge from the AFCEE website.
Although relatively sophisticated applications of the MAROS tool are possible, many of the steps in the evaluation are straightforward, and can be completed by a user unfamiliar with statistical concepts and practice. In such instances, the recommendations generated by application of the software should be reviewed by a more experienced individual.

Table 2.1: Primary Features of MAROS

Qualitative Evaluation
Qualitative information is used to make preliminary recommendations for the entire monitoring program rather than for individual wells. Qualitative considerations also may be applied to develop recommendations regarding sampling frequency at various stages throughout the evaluation, depending upon whether the available data are sufficient to be used reliably by the MAROS statistical tools.
Temporal Evaluation
MAROS includes a linear-regression analysis and a Mann-Kendall test to determine whether COC concentrations at a particular well display a statistically-significant temporal trend. MAROS also calculates the coefficient of variation (COV) for each statistical test, for use in evaluating whether COC concentrations displaying no trend at a particular well have a large degree of "scatter" or can be considered "Stable."
MAROS requires the results of a minimum of six sampling events to complete a temporal analysis at an individual well.
MAROS uses the results of the temporal-trend analyses to develop recommendations regarding optimal sampling frequency at each sampling location, by applying a modified CES algorithm.
MAROS uses the results of moment analyses to assess the overall stability of a plume, and can perform a data-sufficiency analysis, to assess whether RAOs have been/are being achieved at individual wells and at designated compliance points.
MAROS assigns the value of the reporting limit (or some fraction thereof) to samples having a constituent concentration below the reporting limit.
Spatial Evaluation
MAROS uses an inverse-distance weighting algorithm to estimate the concentrations of COCs at individual monitoring locations.
MAROS uses a "slope factor", calculated based on the standardized difference between the measured and estimated concentrations at a particular location, together with the average concentration ratio and area ratio, to determine the relative value of information obtained at individual monitoring points.
MAROS requires sampling results from a minimum of six different sampling locations to complete a spatial analysis.
The spatial-evaluation algorithm implemented in MAROS can be used to assess the spatial distribution of multiple COCs simultaneously.
Overall
MAROS uses the results of the temporal evaluation to generate recommendations regarding monitoring frequency, and uses the results of the spatial evaluation to identify potentially redundant monitoring points. Qualitative information is considered only during the preliminary evaluation of the monitoring program. A MAROS evaluation can be conducted using a maximum of five constituents.
A monitoring program evaluation completed using MAROS may cost in the range of $6,000 to $10,000, depending upon the size of the monitoring program.

2.4 DESCRIPTION OF THREE-TIERED APPROACH

As described by Parsons (2003b, 2003c, and 2003d), a three-tiered LTMO evaluation is conducted in stages to address each of the objectives and considerations of monitoring: a qualitative evaluation first is completed, followed in succession by temporal and spatial evaluations. At the conclusion of each stage (or "tier") in the evaluation, recommendations are generated regarding potential changes in the temporal frequency of monitoring, and/or whether to retain or remove each monitoring point considered in the evaluation. After all three stages of evaluation have been completed, the results of all of the analyses are combined and interpreted, using a decision algorithm, to generate final recommendations for an effective and efficient LTM program.

In the qualitative evaluation, the primary elements of the monitoring program (numbers and locations of wells, frequency of sample collection, analytes specified in the program) are examined, in the context of site-specific conditions, to ensure that the program is capable of generating appropriate and sufficient information regarding plume migration and changes in chemical concentrations through time. Criteria used in the qualitative evaluation are discussed in detail in Appendix B, and examples of application of these criteria are presented in the detailed case-history examples (Appendices D-1, D-2, and D-3). In the temporal evaluation, the historical monitoring data for every sampling point in the monitoring program are examined for temporal trends in COC concentrations, using the Mann-Kendall test (Appendices A and B).

After the Mann-Kendall test for trends has been completed for all COCs at all monitoring points, the spatial distribution of temporal trends in COC concentrations is used to evaluate the relative value of information obtained from periodic monitoring at each monitoring well by considering the location of the well within (or outside of) the horizontal extent of the contaminant plume, the location of the well with respect to potential receptor exposure points, and the presence or absence of temporal trends in contaminant concentrations in samples collected from the well. In the third stage of the three-tiered evaluation, spatial statistical techniques are used to assess the relative value of information (in the spatial sense) generated by sampling at each monitoring point in the network. COC concentration data collected during a single sampling event are used to identify those areas having the greatest uncertainty associated with the estimated extent and concentrations of COCs in groundwater. At the conclusion of the spatial-statistical evaluations, each well is ranked, from those providing the least information to those providing the most information, based on the amount of information the well contributed toward describing the spatial distribution of the COC being examined. Wells providing the least amount of information represent possible candidates for removal from the monitoring program, while wells providing the greatest amount of information represent sampling points that probably should be retained in any refined version of the monitoring program.

At each stage in the three-tiered evaluation, monitoring points that provide relatively greater amounts of information regarding the occurrence and distribution of COCs in groundwater are identified, and are distinguished from those monitoring points that provided relatively lesser amounts of information. After all three stages have been completed, the results of the three stages are combined to generate a refined monitoring program that potentially can provide information sufficient to address the primary objectives of monitoring at the site, at reduced cost.

The qualitative evaluation can be completed by a competent hydrogeologist. The temporal evaluation can be completed using commercially-available statistical software packages having the capability of using non-parametric methods (e.g., the Mann-Kendall test) to examine time-series data for trends. The spatial-statistical evaluation can be completed by a user familiar with geostatistical concepts, and having access to a standard geostatistical software package (e.g., the Geostatistical Environmental

Exposure Software [GeoEAS; Englund and Sparks, 1992], GSLIB [Deutsch and Journel, 1998] or similar package). In practice, data manipulation, temporal and spatial analyses, and graphical presentation of results are simplified, and the quality of the results is enhanced, if a commercially available geographic information system (GIS) software package (e.g., ArcView® GIS) (Environmental Systems Research Institute, Inc. [ESRI], 2001) with spatial-statistical capabilities (e.g., Geostatistical Analyst™, an extension to the ArcView® GIS software package) is utilized in the LTMO evaluation.

As with the MAROS tool, the site-specific evaluation of a monitoring program using the three-tiered approach is directly dependent upon the amount and quality of the available data. The primary features of the three-tiered approach, and the ways in which it addresses the qualitative, temporal, and spatial aspects of environmental monitoring data, are summarized in Table 2.2. Additional details regarding the three-tiered approach, its functionality, capabilities, and methods of application, are presented in Appendix B. Details regarding specific examples of its application are presented in Appendix D.

Table 2.2: Primary Features of Three-Tiered LTMO Approach

Infrastructure
A three-tiered LTMO evaluation is conducted in stages to address each of the objectives and considerations of monitoring: a qualitative evaluation first is completed, followed in succession by temporal and spatial evaluations. At the conclusion of each stage (or "tier") in the evaluation, recommendations are generated to retain or remove each monitoring point considered in the evaluation. After all three stages have been completed, the results of all of the analyses are combined and interpreted, using a decision algorithm, to generate final recommendations for an effective and efficient LTM program.
No software is required for the qualitative evaluation. The temporal evaluation can be completed using commercially-available statistical software packages having the capability of using non-parametric methods to examine time-series data for trends. The spatial-statistical evaluation can be completed using a standard geostatistical software package. Data manipulation, temporal and spatial analyses, and graphical presentation of results are simplified, and the quality of the results is enhanced, if a commercially-available GIS software package with spatial-statistical capabilities is used.
Completion of the qualitative evaluation requires a competent hydrogeologist and an adequate CSM. The temporal and spatial-statistical evaluations require a user familiar with non-parametric statistical and geostatistical concepts, having access to appropriate software.
Qualitative Evaluation
Qualitative information is evaluated to determine optimal sampling frequency and removal/inclusion of each well in the monitoring program based on all historical monitoring results.
Temporal Evaluation
The three-tiered temporal statistical analysis includes classifications for wells at which a particular COC has never been detected at a concentration greater than the reporting limit ("Not Detected") and for wells at which a particular COC consistently has been detected at concentrations less than the practical quantitation limit ("< PQL").
The three-tiered approach requires the results of a minimum of four sampling events (if seasonal effects are not present) to complete a temporal analysis at an individual well.

Table 2.2: Primary Features of Three-Tiered LTMO Approach

Temporal Evaluation (continued)
The three-tiered approach uses the results of the temporal evaluation to develop recommendations regarding sampling frequency, and to identify wells to be retained in or removed from the program. The approach uses a formal decision framework to develop these recommendations.
The three-tiered approach uses the results of the temporal evaluation to assess trends only at individual monitoring points.
The three-tiered approach assumes that monitoring points having historical results with "No Trend" are of limited value, while MAROS treats a monitoring point having "No Trend" in COC concentrations similar to a monitoring point having an "Increasing Trend" in concentrations.
Spatial Evaluation
The three-tiered approach applies geostatistics to estimate the spatial distribution of COCs. Application of this procedure depends upon the development of an appropriate semi-variogram.
The three-tiered approach uses changes in the median kriging error generated during different realizations to rank the relative value of information obtained at individual monitoring points. The relative ranking (from "Provides Most Information" to "Provides Least Information") is used to develop recommendations regarding which wells should be retained in or removed from the monitoring program.
The three-tiered approach requires sampling results from a minimum of 15 different sampling locations to complete a spatial analysis.
Currently, only a single "indicator COC" (typically, the COC that has been detected at the greatest number of separate monitoring locations) is used in the three-tiered spatial evaluation.
Overall
The three-tiered approach combines the results of the qualitative, temporal, and spatial evaluations to generate overall recommendations regarding optimal sampling frequency and number of monitoring points in a monitoring program. Although the spatial evaluation stage is restricted to a single constituent, the qualitative and temporal stages of the evaluation can be applied to an unlimited number of constituents.
A monitoring program evaluation completed using the three-tiered approach may cost in the range of $6,000 to $10,000, depending upon the size of the monitoring program.

2.5 CASE-STUDY EXAMPLES

The MAROS tool and the three-tiered approach each were applied to the evaluation and optimization of existing groundwater monitoring programs at three different sites – the Logistics Center at Fort Lewis, Washington, the Long Prairie Groundwater Contamination Superfund Site in Minnesota, and OU D at the former McClellan AFB, California. Pertinent features of the groundwater monitoring programs for each site, and the results of the MAROS evaluation and the three-tiered evaluation of the monitoring program at each site, are summarized in the following sections.

3.0 SUMMARY OF DEMONSTRATIONS AT LOGISTICS CENTER AREA, FORT LEWIS, WASHINGTON

An overview of features pertinent to the groundwater monitoring program at the Logistics Center area, Fort Lewis, Washington is provided in this section, together with a summary of the results of the LTMO demonstrations. The features of the site, and of the monitoring-program evaluations that were completed using the MAROS tool and the three-tiered approach, are summarized in Appendix C, and are described in detail in Appendix D-1.

3.1 FEATURES OF FORT LEWIS LOGISTICS CENTER

The Fort Lewis Military Reservation is located near the southern end of Puget Sound in Pierce County, Washington, approximately 11 miles south of Tacoma and 17 miles northeast of Olympia. The Logistics Center occupies approximately 650 acres of the Fort Lewis Military Reservation. Process wastes were disposed of at several on- and off-installation locations, including the East Gate Disposal Yard (EGDY), located southeast of the Logistics Center. Between 1946 and 1960, waste solvents (primarily trichloroethene [TCE]) and petroleum, oils, and lubricants (POL) generated during cleaning, degreasing, and maintenance operations were disposed of in trenches at the EGDY, resulting in the introduction of contaminants to soils and groundwater at and downgradient from this former landfill. The dissolved chlorinated solvent plume that originates at the EDGY extends downgradient across the entire width of the Logistics Center, and beyond the northwestern facility boundary to the southeastern shore of American Lake (Figure 3.1). The program that was developed to monitor the concentrations and extent of contaminants in groundwater in the vicinity of, and downgradient from the EDGY, and to assess the performance of remedial systems installed to address contaminants in groundwater, was the subject of the MAROS and three-tiered evaluations (Appendices C and D).

TCE has been identified as the primary COC in groundwater beneath the Logistics Center, based on its widespread detection in wells across the site. Other COCs in groundwater include *cis*-1,2-dichloroethene (DCE), tetrachloroethene (PCE), 1,1,1-trichloroethane (TCA), and vinyl chloride (VC). TCE, DCE, and TCA have been detected consistently in many wells, while PCE and VC have been detected only sporadically, in a few wells. The former waste-disposal trenches at the EGDY are the apparent source of these chlorinated aliphatic hydrocarbon compounds (CAHs) in groundwater beneath and downgradient from the Logistics Center.

Beginning in December 1995, groundwater monitoring was conducted at the Logistics Center on a quarterly basis. Under the monitoring program, 38 monitoring wells and 21 groundwater extraction wells were sampled, resulting in 236 primary samples per year (59 wells each sampled four times per year) (Appendices C and D). The primary objectives of the monitoring program, as expressed in the monitoring plan, are to confirm that the groundwater extraction systems are preventing the continued migration of contaminants in groundwater to downgradient locations, to evaluate potential reductions in contaminant concentrations through time, to assess temporal changes in the lateral and vertical extent of contaminants in groundwater, and to assess the rate of removal of contaminant mass from the subsurface.

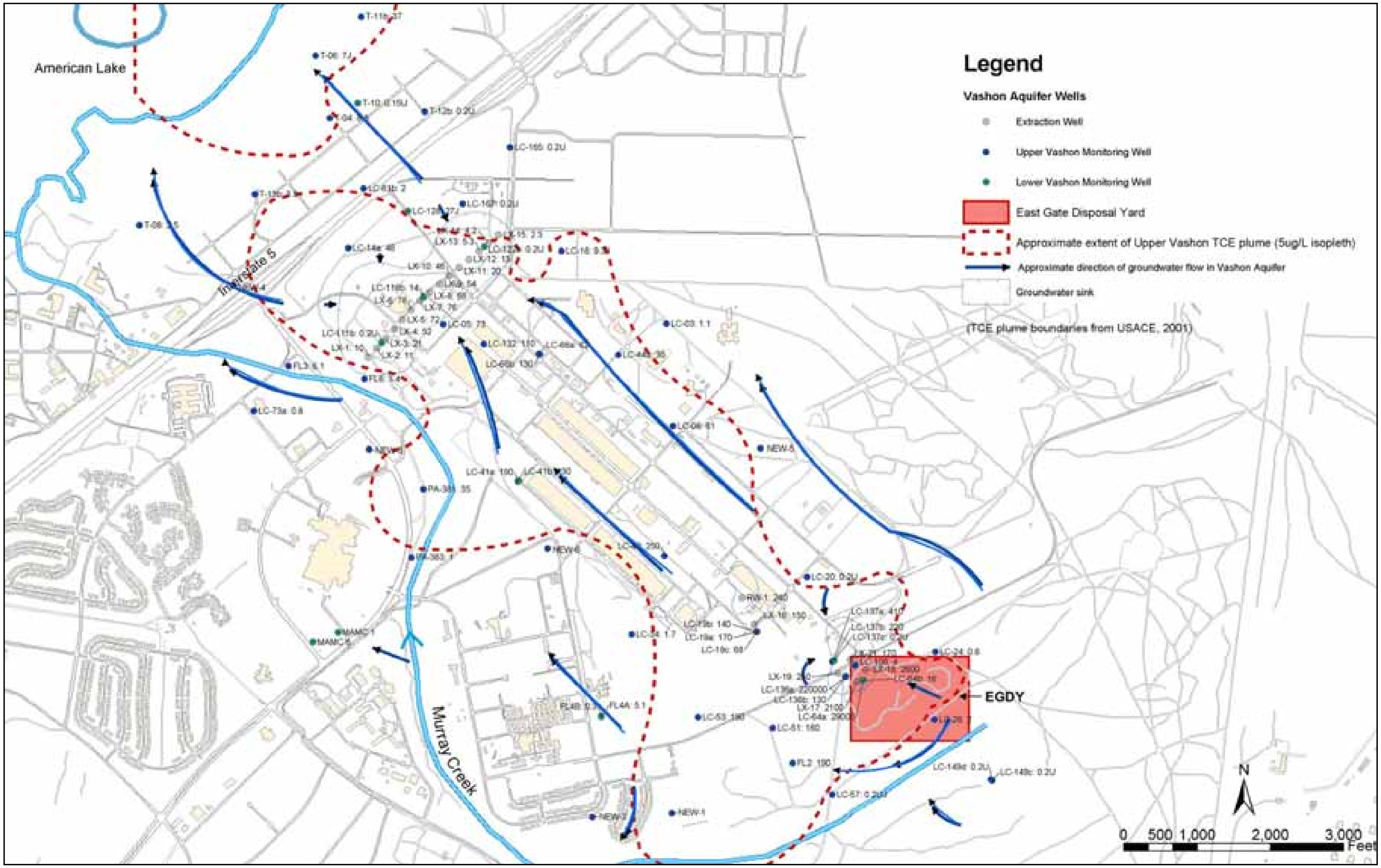

Figure 3.1: Features of Fort Lewis Logistics Center Area (after Parsons, 2003b)

Two distinct monitoring zones are recognized in the groundwater system beneath the Logistics Center area. Most groundwater monitoring wells are completed in the upper monitoring zone (the "Upper Vashon" zone); relatively few monitoring wells are completed in the lower monitoring zone (the "Lower Vashon" zone). An LTMO evaluation of the groundwater extraction system and associated monitoring network at the Logistics Center was completed by the Fort Lewis project team in May 2001 (Appendices C and D); the refined monitoring program generated as a result of this evaluation is known as the LOGRAM program. Based on the results of the LOGRAM LTMO evaluation, 24 monitoring wells were added to the Logistics Center monitoring program, and 11 previously sampled monitoring wells were removed from the program (a net increase of 13 monitoring wells); sampling frequencies generally were reduced. The revised Logistics Center monitoring program (LOGRAM), which was initiated in December 2001, includes 72 wells -- 51 monitoring wells (29 wells sampled quarterly, 3 wells sampled semi-annually, and 19 wells sampled annually), and 21 extraction wells (6 wells sampled quarterly and 15 wells sampled annually). The reduction in sampling frequency at a number of wells produced a net reduction in the total number of primary samples collected and analyzed per year, from 236 samples to 180 samples. All samples from the monitoring and extraction wells are analyzed for volatile organic compounds (VOCs) using U.S. EPA Method SW8260B.

3.2 RESULTS OF LTMO EVALUATION COMPLETED USING MAROS TOOL

Because extensive historical data were not available for the new wells installed during implementation of the current LOGRAM monitoring program, the MAROS tool was used to evaluate data from the 59 wells that remained in the monitoring program in September 2001 (21 extraction wells and 38 groundwater monitoring wells; Appendix C) included in the original monitoring program, and was not used to evaluate the LOGRAM program. The detailed results of the MAROS evaluation of the groundwater monitoring program at the Fort Lewis Logistics Center area are presented in Appendices C (Section C1.5) and D-1, and are summarized in this subsection.

Prior to the evaluation, five wells that potentially would provide "redundant" information were identified on the basis of qualitative considerations (Appendices C and D-1); these were not included in the moment analysis or in the spatial evaluation. Historic monitoring results from all monitoring and extraction wells were included in the temporal evaluation. However, results from groundwater extraction wells were not used in the spatial evaluation; and the results from two monitoring wells completed in the lower part of the Lower Vashon subunit also were excluded from the spatial evaluation, because these two wells were considered to be within a different monitoring zone than the other monitoring wells (Appendix D-1).

Application of the Mann-Kendall and linear-regression temporal trend evaluation methods (Appendices B and C) indicated that the extent and concentrations of TCE in groundwater at the Logistics Center source area (the EGDY) probably are decreasing (GSI, 2003a). TCE concentrations in groundwater at most of the extraction wells located northwest of the EGDY source area also are probably decreasing. The results of the moment analysis indicated that the location of the center of mass of the plume has remained essentially unchanged, and that the extent of TCE in groundwater has decreased over time, providing further evidence that the plume is stable under current conditions. The evaluation of overall plume stability indicated that the extent of TCE in groundwater is stable or decreasing, resulting in the recommendation that a monitoring strategy appropriate for a "*Moderate*" design category be adopted (Appendices C and D).

The results of detailed spatial analyses using the Delaunay method (Appendices C and D) indicated that 8 monitoring wells could be removed from the original monitoring program (which included 38 monitoring wells) without significant loss of information. However, the accompanying well-sufficiency analysis indicated that there is a high degree of uncertainty in predicted TCE concentrations in six areas within the network where the available historical sampling information may be inadequate; new monitoring wells were recommended for installation in these six areas (GSI, 2003a). These six locations recommended for installation of new wells correspond to six wells that had been installed and were being monitored in conjunction with the LOGRAM program (Appendix C). All groundwater extraction wells were recommended for retention in the refined monitoring program. The results of the sampling-frequency optimization analysis completed using MAROS (Appendices C and D) indicated that most wells in the monitoring network could be sampled less frequently than in the current (LOGRAM) monitoring program. The results of the data-sufficiency evaluation, completed using power-analysis methods, indicated that RAO concentrations of TCE in groundwater have nearly been achieved at the compliance boundary.

The optimized monitoring program generated using the MAROS tool includes 57 wells, with 19 sampled quarterly, 2 sampled semiannually, 30 sampled annually, and 6 sampled biennially (Appendices C and D). Adoption of the optimized program would result in collection and analysis of 113 samples per year, as compared with collection and analysis of 180 samples per year in the current LOGRAM monitoring program (Table 3.1) and 236 samples per year in the original sampling program. Implementing these recommendations could lead to a 37-percent reduction in the number of samples collected and analyzed annually, as compared with the current LOGRAM program, or a 52-percent reduction in the number of samples collected and analyzed, as compared with the original program (Table 3.1). Assuming a cost per sample of $500 for collection and chemical analyses (based on information provided by the U.S. Army Corps of Engineers [USACE, 2001]), adoption of the monitoring program as optimized using the MAROS tool is projected to result in savings of approximately $33,500 per year as compared with the LOGRAM program (Table 3.1). (The estimated cost per sample is based on information provided by facility personnel in conjunction with efforts to estimate potential cost savings resulting from optimization of the monitoring program, and includes costs associated with sample collection and analysis, data compilation and reporting, and handling of materials generated as investigation-derived waste [IDW] during sample collection [e.g., purge water].) The optimized program remains adequate to delineate the extent of TCE in groundwater, and to monitor changes in the plume over time (GSI, 2003a).

3.3 RESULTS OF LTMO EVALUATION COMPLETED USING THREE-TIERED APPROACH

The three-tiered approach was used to evaluate the original monitoring program at the Logistics Center area (which included 59 wells), and also was used to evaluate the current LOGRAM program (which includes 72 wells). Because extensive historical data were not available for the new wells included in the LOGRAM program, temporal analyses were not used in evaluating the new LOGRAM wells – only qualitative and spatial evaluations of that program were completed for these wells, and as a consequence, the results of evaluation of the two programs are not directly comparable. The detailed results of the three-tiered evaluation of the groundwater monitoring programs at the Fort Lewis Logistics Center area are presented in Appendices C (Section C1.6) and D (Appendix D-1), and are summarized in this subsection.

Table 3.1: Results of Optimization Demonstrations at Logistics Center Area Fort Lewis, Washington

Monitoring-Program Feature	Monitoring Program[a/]			
	Original (prior to December 2001)	Current (LOGRAM, after December 2001)	Original Refined using MAROS	Refined using 3-Tiered Approach
Wells sampled quarterly	59	35	19	16
Wells sampled semi-annually	--	3	2	7
Wells sampled annually	--	34	30	16
Wells sampled biennially	--	--	6	14
Wells sampled every 3 years	--	---	--	15
Total wells included in LTM program	59	72	57	69
Total number of samples (per year)	236	180	113	107
Annual cost[b/] of LTM program	$118,000	$90,000	$56,500	$53,500

[a/] Details regarding site characteristics and the site-specific monitoring programs at the Logistics Center area, Fort Lewis, Washington, are presented in Appendices C and D-1.

[b/] Information regarding annual monitoring program costs was provided by facility personnel. Costs associated with monitoring include cost of sample collection, sample analyses, data compilation and reporting, and management of investigation-derived waste (e.g., purge water).

The primary COCs (TCE, PCE, *cis*-1,2-DCE, and VC) were considered in the qualitative and temporal stages of the three-tiered evaluation; however, because TCE has been the most frequently detected COC in groundwater at the Fort Lewis Logistics Center area, the spatial-statistical stage of the three-tiered evaluation of the monitoring program used only the results of analyses for TCE in groundwater samples. Furthermore, because the Upper Vashon and Lower Vashon subunits are considered to be separate monitoring zones (Section 3.1), and the results of only a single water-bearing unit or monitoring zone can be considered in the spatial-statistical evaluation, the spatial-statistical evaluation was conducted using the sampling results from those monitoring wells completed in the Upper Vashon subunit only. Sampling results from groundwater extraction wells were not used in the spatial-statistical evaluation; however, sampling results from all wells (groundwater extraction wells, and groundwater monitoring wells completed in the Upper Vashon and Lower Vashon subunits) were used in the qualitative and temporal evaluations.

The results of the three-tiered evaluation indicated that 6 of the 72 existing wells could be removed from the LOGRAM groundwater LTM program with little loss of information (Parsons, 2003b), but also indicated that 2 existing wells that are not currently sampled should be included in the program, and that one new well should be installed and monitored. A refined monitoring program (Appendices C and D), consisting of 69 wells, with 16 wells sampled quarterly, 7 wells sampled semi-annually, 17 wells sampled annually, 14 wells sampled biennially, and 15 of the extraction wells sampled every 3 years (Table 3.1), would be adequate to address the two primary objectives of monitoring. If this refined monitoring program were adopted, 107 samples per year would be collected and analyzed, as compared with the collection and analysis of 180 samples per year in the current LOGRAM monitoring program and 236 samples per year in the original sampling program. This would represent a 40-percent reduction in the number of samples collected and analyzed annually, as compared with the LOGRAM program, or a 55-percent reduction in the number of samples collected and analyzed, as compared with the original program. Assuming a cost per sample of $500 for collection and chemical analyses, adoption of the monitoring program as optimized using the three-tiered approach is projected to result in savings of approximately $36,500 per year as compared with the LOGRAM program, or $64,500 per year as compared with the original monitoring program (Table 3.1). Additional cost savings potentially could be realized if groundwater samples collected from select wells (e.g., upgradient wells, and wells along the lateral plume margins) were analyzed for a short list of halogenated VOCs using U.S. EPA Method SW8021B instead of U.S. EPA Method SW8260B (Parsons, 2003b).

4.0 SUMMARY OF DEMONSTRATIONS AT LONG PRAIRIE GROUNDWATER CONTAMINATION SUPERFUND SITE, MINNESOTA

An overview of features pertinent to the groundwater monitoring program at the Long Prairie Groundwater Contamination Superfund Site, Minnesota (Long Prairie site) is provided in this section, together with a summary of the results of the LTMO demonstrations. The features of the site, and of the monitoring-program evaluations that were completed using the MAROS tool and the three-tiered approach, are summarized in Appendix C, and are described in detail in Appendix D-2.

4.1 FEATURES OF LONG PRAIRIE SITE

The town of Long Prairie, Minnesota is a small farming community located on the east bank of the Long Prairie River in central Minnesota. The Long Prairie site comprises a 0.16-acre source area of contaminated soil that has generated a plume of dissolved CAHs in the drinking-water aquifer underlying the north-central part of town. The source of contaminants in groundwater was a dry-cleaning establishment, which operated from 1949 through 1984 in the town's commercial district. Spent dry-cleaning solvents, primarily PCE, were discharged into the subsurface via a french drain. The subsequent migration of contaminants through the vadose zone to groundwater produced a dissolved CAH plume that has migrated to the north a distance of at least 3,600 feet from the source area, extending beneath a residential neighborhood and to within 500 feet of the Long Prairie River.

The plume of contaminated groundwater currently is being addressed by extraction of CAH-contaminated groundwater via nine extraction wells, treatment of the extracted water, and discharge of treated water to the Long Prairie River. The performance of the groundwater extraction system is monitored by means of periodic sampling of monitoring wells and water-supply wells, and routine operations and maintenance (O&M) monitoring of the extraction and treatment systems. The program that was established to monitor the concentrations and extent of contaminants in groundwater in the vicinity of, and downgradient from the PCE source area, and to assess the performance of the OU1 groundwater extraction, treatment, and discharge (ETD) system, was the subject of the MAROS and three-tiered evaluations (Appendices C and D).

PCE and its daughter products TCE and *cis*-1,2-DCE are the primary COCs at the Long Prairie site, and have been detected through a volume of groundwater about 1,000 feet wide, which extended (in October 2002) from the source area, approximately 3,200 feet downgradient to the northwest (Figure 4.1). VC also has been detected in groundwater samples, although at few locations and at lower concentrations than other CAHs.

Groundwater conditions are monitored periodically at the Long Prairie site, to evaluate whether the groundwater ETD system is effectively preventing the continued migration of CAH contaminants in groundwater to downgradient locations, and to confirm that contaminants are not migrating to the water-supply wells of the municipality of Long Prairie. Several of the monitoring locations include wells installed in clusters, with each well in a cluster completed at a different depth. Groundwater monitoring wells, extraction wells, and municipal water-supply wells are included in the monitoring program. A total of 44 wells in the Long Prairie area were sampled during the most recent

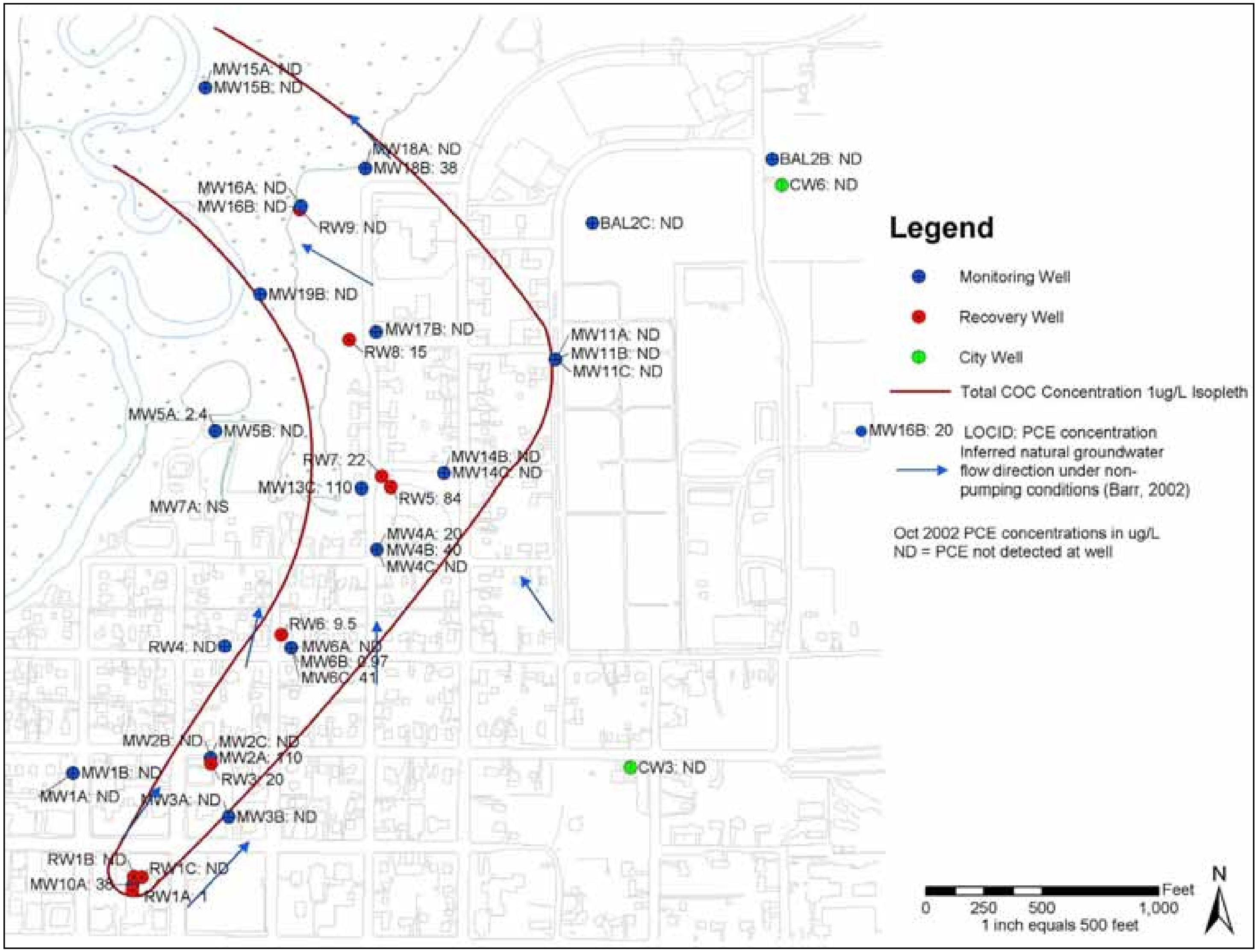

Figure 4.1: Features of Long Prairie Groundwater Contamination Superfund Site (after Parsons, 2003c)

monitoring event (October 2002) for which sampling results are available. Approximately one-half of the wells sampled during October 2002 are sampled routinely in conjunction with the groundwater monitoring program. The "current" (2002) 27-well monitoring program at the Long Prairie site includes the 18 monitoring wells, 6 active groundwater extraction wells, and one inactive extraction well sampled during scheduled monitoring events in 2000 and 2001, together with two nearby municipal-supply wells (Appendices C and D). All samples from the monitoring and extraction wells are analyzed for VOCs using U.S. EPA Method SW8021B.

4.2 RESULTS OF LTMO EVALUATION COMPLETED USING MAROS TOOL

The detailed results of the MAROS evaluation of the groundwater monitoring program at the Long Prairie site are presented in Appendix C (Section C2.6) and D (Appendix D-2), and are summarized in this subsection.

Application of the Mann-Kendall and linear-regression temporal trend evaluation methods (Appendices B and C) indicated that the extent and concentrations of PCE in groundwater at the Long Prairie source area probably are decreasing (GSI, 2003b). PCE concentrations in groundwater at 24 of 27 wells downgradient of the source area also are probably decreasing under current conditions. The results of the moment analysis indicated that the mass of PCE in groundwater is relatively stable, and that although the location of the center of mass of the plume has moved downgradient over time, the extent of PCE in groundwater has decreased through time. Overall, the results of trend analyses and moment analyses indicated that the extent of PCE in groundwater is stable or decreasing, resulting in a recommendation that a monitoring strategy appropriate for a "*Moderate"* design category be adopted (Appendices C and D).

Seventeen of the 44 wells in the existing monitoring network were included in the detailed spatial analysis (Appendices C and D); the results indicated that none of the 17 wells evaluated was redundant. Other wells in the monitoring network were examined qualitatively; and the results of qualitative considerations (GSI, 2003b) indicated that nine monitoring wells could be removed from the monitoring network without significant loss of information. Using similar qualitative analyses, three extraction wells in the source area were identified as candidates for removal from service, because concentrations of COCs in effluent from these wells historically have been below reporting limits (GSI, 2003b). However, six wells that currently are not routinely sampled were recommended for inclusion in the monitoring program. These changes in the monitoring network were projected to have a negligible effect on the degree of characterization of the extent of PCE in groundwater. The accompanying well-sufficiency analysis indicated that there is only a moderate degree of uncertainty in predicted PCE concentrations throughout the network, so that no new monitoring wells were recommended for installation (GSI, 2003b). The results of the sampling-frequency optimization analysis completed using MAROS (Appendices C and D) indicated that most wells in the monitoring network could be sampled less frequently than in the current monitoring program. The results of the data-sufficiency evaluation, completed using power-analysis methods (Appendices B and C) suggest that the monitoring program is adequate to evaluate the extent of PCE in groundwater relative to compliance points through time (GSI, 2003b).

The optimized monitoring program generated using the MAROS tool includes 32 wells, with 10 monitoring wells and 5 extraction wells sampled annually, and 13 monitoring wells, two extraction wells, and two municipal wells sampled biennially (Appendices C and D). Adoption of the optimized program would result in collection and analysis of 22 samples per year, as compared with collection and analysis of 51 samples per year in the current monitoring program (Table 4.1). Implementing these recommendations could lead to a 51-percent reduction in the number of samples collected and analyzed annually, as compared with the current program. Assuming a cost per sample in the range of $100 to $280 for collection and chemical analyses, adoption of the monitoring program as optimized using the MAROS tool is projected to result in savings ranging from approximately $2,900 to $8,120 per year. (The estimated range of costs per sample is based on information provided by facility personnel in conjunction with efforts to estimate potential cost savings resulting from optimization of the monitoring program, and includes costs associated with sample collection and analysis, data compilation and reporting, and handling of IDW [e.g., purge water].) The optimized program remains adequate to delineate the extent of COCs in groundwater, and to monitor changes in the plume over time (GSI, 2003b).

Table 4.1: Results of Optimization Demonstrations at Long Prairie Groundwater Contamination Superfund Site, Minnesota

Monitoring-Program Feature	Monitoring Program[a/]		
	Actual (October 2002)	Refined using MAROS	Refined using 3-Tiered Approach
Wells sampled quarterly	8	--	2
Wells sampled semi-annually	--	--	6
Wells sampled annually	19	16	14
Wells sampled biennially	--	16	4
Total wells included in LTM program	27	32	26
Total number of samples (per year)	51	22	36
Annual cost[b/] of LTM program	$14,280	$6,160	$10,080

[a/] Details regarding site characteristics and the site-specific monitoring programs at the Long Prairie Groundwater Contamination Superfund Site are presented in Appendices C and D-2.

[b/] Information regarding annual monitoring program costs was provided by facility personnel. The cost of monitoring is assumed to be $280 dollars per sample; costs associated with monitoring include cost of sample collection, sample analyses, data compilation and reporting, and management of investigation-derived waste (e.g., purge water).

4.3 RESULTS OF LTMO EVALUATION COMPLETED USING THREE-TIERED APPROACH

The detailed results of the three-tiered evaluation of the groundwater monitoring program at the Long Prairie site are presented in Appendices C (Section C2.6) and D (Appendix D-2), and are summarized in this subsection.

The results of the three-tiered evaluation indicated that 18 of the 44 existing wells could be removed from the groundwater monitoring network with little loss of information (Parsons, 2003c). The results further suggested that the current monitoring program (18 monitoring wells, 6 active extraction wells, one inactive extraction well, and 2 municipal water-supply wells included in the 2002 sampling program) could be further refined by removing 4 of the 27 wells now in the LTM program, and adding three wells not currently included in the program. If this refined monitoring program, consisting of 26 wells (2 wells to be sampled quarterly, 6 wells to be sampled semi-annually, 14 wells to be sampled annually, and 4 wells to be sampled biennially) were adopted, an average of 36 samples per year would be collected and analyzed, as compared with the collection and analysis of 51 samples per year in the current (2001/2002) monitoring program (Table 4.1) – a reduction of about 29 percent. Assuming a cost per sample ranging from $100 to $280 for collection and chemical analyses, adoption of the monitoring program as optimized using the three-tiered approach is projected to result in savings ranging from about $1,500 per year to about $4,200 per year (Table 4.1), as compared with the current program (Parsons, 2003c).

5.0 SUMMARY OF DEMONSTRATIONS AT McCLELLAN AFB OU D, CALIFORNIA

An overview of features pertinent to the groundwater monitoring program at OU D, McClellan AFB, California, is provided in this section, together with a summary of the results of the LTMO demonstrations. The features of the site, and of the monitoring-program evaluations that were completed using the MAROS tool and the three-tiered approach, are summarized in Appendix C, and are described in detail in Appendix D-3.

5.1 FEATURES OF McCLELLAN AFB OU D

The former McClellan AFB is located approximately 7 miles northeast of downtown Sacramento, California, and covers approximately 3,000 acres. OU D consists of contaminated groundwater beneath and downgradient from contaminant source areas in the northwestern part of McClellan AFB, and occupies approximately 192 acres. Through most of its operational history, McClellan AFB was engaged in a wide variety of military/industrial operations involving the use, storage, and disposal of hazardous materials, including industrial solvents, caustic cleaners, electroplating chemicals, metals, polychlorinated biphenyls, low-level radioactive wastes, and a variety of fuel oils and lubricants.

The COCs in groundwater targeted by the current LTM program at OU D are exclusively CAHs, including PCE, TCE, *cis*-1,2-DCE, and 1,2-dichloroethane (DCA), with 1,1-DCA, 1,1-DCE, 1,1,1-TCA, and VC also detected, but at lower concentrations and/or lower frequencies. Dissolved CAHs originating at sources near former disposal areas at OU D have migrated with regional groundwater flow to the south and southwest, and historically extended off-base, to the west of OU D. Currently, VOCs (primarily TCE) are present in groundwater primarily in the central and southwestern parts of OU D (Figure 5.1). The remediation systems currently operating to address CAH contaminants in groundwater at OU D include a groundwater ETD system, and the associated monitoring network.

In accordance with the requirements of the basewide groundwater monitoring plan, wells in the OU D area are sampled during the first quarter of each year. In the OU D area, groundwater sampling is conducted to monitor areas where dissolved VOC concentrations exceed their respective maximum contaminant levels (MCLs) in monitoring zones A and B. Groundwater monitoring data also are used to evaluate contaminant mass-removal rates. Because the extent of COCs in groundwater at OU D is relatively well defined, and COCs appear to be contained by the groundwater extraction system, the wells associated with the OU D plume are sampled relatively infrequently (annually or biennially). Currently, 22 of the 32 wells that monitor the upper part (Zone A) of the groundwater system at OU D are sampled biennially, and 10 are sampled annually. Twelve of the 13 wells that monitor a deeper part (Zone B) of the groundwater system are sampled biennially, and the remaining well is sampled annually. The six extraction wells (EWs) are sampled annually. Historically, however, the sampling schedule for wells at OU D was irregular, so that some monitoring wells at OU D have been sampled as few as five times through the historic monitoring from the monitoring and extraction wells are analyzed for VOCs by U.S. EPA Method SW8260B.

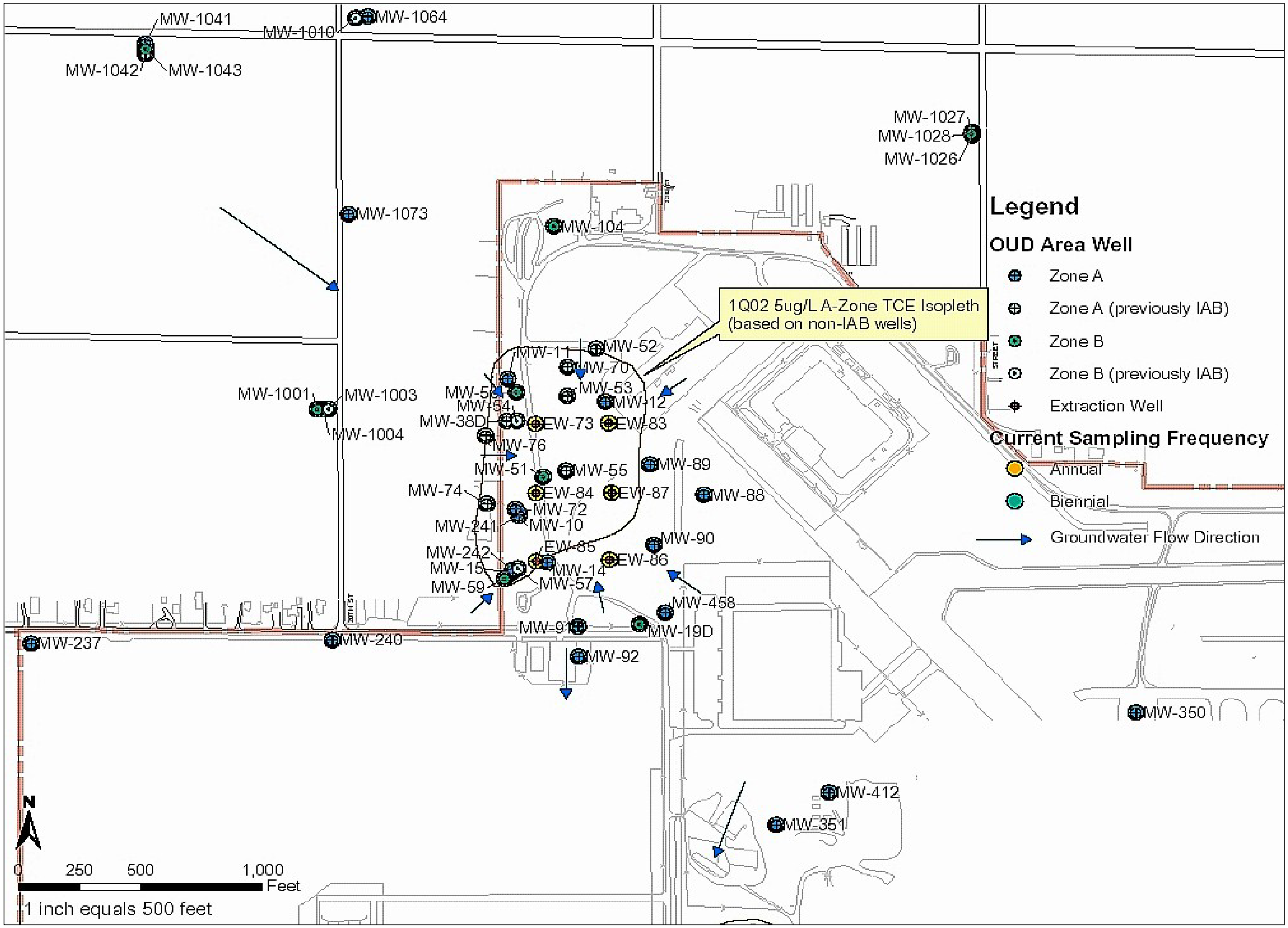

Figure 5.1: Features of McClellan AFB OU D (after Parsons, 2003d)

5.2 RESULTS OF LTMO EVALUATION COMPLETED USING MAROS TOOL

The detailed results of the MAROS evaluation of the groundwater monitoring program at McClellan AFB OU D are presented in Appendices C (Section C3.5) and D-3, and are summarized in this subsection.

Application of the Mann-Kendall and linear-regression temporal trend evaluation methods (Appendices B and C) indicated that the extent and concentrations of TCE in groundwater at the OU D source area probably are decreasing (GSI, 2003c). However, the absence of identifiable trends in TCE concentrations at many locations downgradient of the plume may be a consequence of less-frequent sampling in these areas than occurs near the OU D source area (GSI, 2003c). The results of the moment analysis indicated that the mass of TCE in groundwater is relatively stable, with occasional fluctuations suggesting increases or decreases in TCE mass. The location of the center of mass of the plume also appears to be relatively stable, with periodic temporal fluctuations in concentrations tending to cause the center of TCE mass to appear to move in the upgradient or downgradient directions. The lateral extent of TCE in groundwater has been variable, suggesting that TCE concentrations in wells used to evaluate conditions over large, off-axis areas of the plume have varied considerably through time, or that the wells have not been sampled consistently enough for a clear trend in TCE concentrations to emerge. Temporal fluctuations in the apparent mass of TCE in groundwater (calculated using the zeroth moment), the center of mass of TCE (calculated using the first moment), and the lateral extent of TCE (calculated using the second moment) likely are due to long-term variability in locations sampled, resulting from an inconsistent monitoring program through time (GSI, 2003c). The evaluation of overall plume stability indicated that the extent of TCE in groundwater at OU D is stable or slightly decreasing, resulting in a recommendation that a monitoring strategy appropriate for a "*Moderate*" design category be adopted (Appendices C and D).

The results of the detailed spatial analysis, supplemented with a qualitative evaluation (Appendices C and D), identified five monitoring wells as candidates for removal from the monitoring network. Removal of the recommended five wells would result in an 11 percent reduction in the number of wells in the monitoring network, with negligible effect on the degree of characterization of the extent of TCE in groundwater. The possibility of removing additional monitoring wells on the periphery of OU D also was examined qualitatively, and it was concluded (GSI, 2003c) that the decision to stop sampling the periphery wells should be made in accordance with non-statistical considerations, including regulatory requirements, community concerns, and/or public health issues. Non-statistical considerations may indicate that continued sampling of the periphery wells is warranted. The accompanying well-sufficiency analysis indicated that there is only a low to moderate degree of uncertainty in predicted TCE concentrations throughout the network, so that no new monitoring wells were recommended for installation (GSI, 2003c). In nearly all instances, the results of the sampling-frequency optimization analyses at McClellan AFB OU D were adversely affected by the lack of consistent temporal monitoring data (Appendices C and D). Accordingly, all recommendations generated by MAROS were examined qualitatively, after the temporal statistical evaluations had been completed, to generate recommendations regarding sampling frequency (GSI, 2003c). The results of the data-sufficiency evaluation, completed using power-analysis methods, indicate that the monitoring program is more than sufficient to evaluate the extent of TCE in groundwater relative to the compliance boundary through time, assuming continued operation of the extraction system (GSI, 2003c).

The optimized monitoring program generated using the MAROS tool includes 29 A-zone wells, 11 B-zone wells, and 6 groundwater extraction wells, with 11 monitoring wells and 6 extraction wells sampled annually, and 29 monitoring wells sampled biennially (Appendices C and D). Adoption of the optimized program would result in collection and analysis of 32 samples per year, as compared with collection and analysis of 34 samples per year in the current monitoring program (Table 5.1). Implementing these recommendations could lead to an approximately 6-percent reduction in the number of samples collected and analyzed annually, as compared with the current program. Adoption of the monitoring program as optimized using the MAROS tool is projected (GSI, 2003c) to result in savings of approximately $300 per year (Table 5.1). (Estimated annual cost savings were provided by facility personnel; however, specific information regarding the estimated annual cost of the LTM program at McClellan AFB OU D, and the total cost per sample is not available; and the means used to derive the estimated cost savings are uncertain.) The optimized program remains adequate to delineate the extent of COCs in groundwater, and to monitor changes in the condition of the plume over time (GSI, 2003c).

Table 5.1: Results of Optimization Demonstrations at McClellan AFB OU D, California

Monitoring-Program Feature	Monitoring Program[a/]		
	Actual (October 2002)	Refined using MAROS	Refined using 3-Tiered Approach
Wells sampled annually	17	17	13
Wells sampled biennially	34	29	8
Total wells in LTM program	51	46	21
Total number of samples (per year)	34	32	17
Annual cost[b/] of LTM program	--	--[c/]	--[c/]

[a/] Details regarding site characteristics and the site-specific monitoring programs at McClellan AFB OU D are presented in Appendices C and D-3.

[b/] No information regarding annual monitoring program costs was provided by facility personnel.

[c/] Total costs associated with refined monitoring programs cannot be estimated; no information available.

5.3 SUMMARY OF LTMO EVALUATION COMPLETED USING THREE-TIERED APPROACH

The detailed results of the three-tiered evaluation of the groundwater monitoring program at McClellan AFB OU D are presented in Appendices C (Section C3.6) and D (Appendix D-3), and are summarized in this subsection.

The results of the three-tiered evaluation (Parsons, 2003d) indicated that 30 of the 51 existing wells could be removed from the groundwater monitoring program with comparatively little loss of information (Parsons, 2003d). Most of the wells recommended for removal from the monitoring program are wells peripheral to the OU D plume, which also were identified as possible candidates for removal during the MAROS evaluation. If this refined monitoring program (Appendices C and D), consisting of 21 wells (13 wells to be sampled annually, and 8 wells to be sampled biennially) were adopted, an average of 17 samples per year would be collected and analyzed, as compared with the collection and analysis of 34 samples per year in the current monitoring program – a reduction of 50 percent in the number of samples collected and analyzed annually, as compared with the current program. Although information regarding the annual costs associated with the LTM program at McClellan AFB OU D including the estimated total cost per sample is not available, based on analytical costs alone, and assuming a cost per sample of $150 for chemical analyses (analyses for VOCs only), adoption of the monitoring program as optimized using the three-tiered approach is projected to result in savings of about $2,550 per year as compared with the current program

(Parsons, 2003d). Additional cost savings could be realized if groundwater samples collected from select wells (e.g., upgradient wells, and wells along the lateral plume margins) were analyzed for a short list of halogenated VOCs using U.S. EPA Method SW8021B instead of U.S. EPA Method SW8260B (Parsons, 2003d).

6.0 CONCLUSIONS AND RECOMMENDATIONS

A software tool (MAROS) developed for AFCEE, and a three-tiered approach applied by Parsons, were used to evaluate and optimize groundwater monitoring programs at the Fort Lewis Logistics Center, Washington, the Long Prairie Groundwater Contamination Superfund Site in Minnesota, and OU D, McClellan AFB, California. Although many of the basic assumptions and techniques underlying both optimization approaches are similar, and both approaches utilize qualitative, temporal, and spatial analyses, there are several differences in the details of implementation in the two approaches, which can cause one optimization approach (e.g., the three-tiered approach) to generate results that are not completely consistent with the results obtained using the other approach (e.g., MAROS). As a consequence of structural differences in approaches to the evaluation and optimization of monitoring programs, the results generated by <u>any</u> optimization approach should be expected to differ slightly from the results generated by other approaches; however, the results of any optimization approach should be defensible, if the decision logic on which the approach has been based is sound.

6.1 SUMMARY OF RESULTS OF MAROS EVALUATIONS AND THREE-TIERED APPROACH

The results of the MAROS optimization and three-tiered evaluation of the monitoring program at the Fort Lewis Logistics Center are summarized in Table 6.1. "Final" recommendations for the entire program could be developed by considering together the results of the three-tiered evaluation and of the MAROS evaluation for each well. Example composite recommendations are provided in Column 5 of Table 6.1.

Table 6.1: Summary of Optimization of Groundwater Monitoring Program at Fort Lewis Logistics Center Area[a/]

Well ID	Current[b/] Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite[c/] Recommendations
Monitoring Wells Completed in Upper Vashon Subunit				
FL2 (new[d/])	Annual	Not Considered[e/]	Annual	Annual
FL3 (new)	Quarterly	Quarterly	Remove[f/]	Quarterly
FL4B (new)	Quarterly	Not Considered	Biennial	Biennial
FL6 (new)	Quarterly	Not Considered	Biennial	Biennial
LC-03	Quarterly	Annual	Biennial	Annual
LC-05	Annual	Quarterly	Remove	Annual
LC-06	Semi-Annual	Quarterly	Annual	Semi-Annual
LC-14a	Annual	Annual	Annual	Annual
LC-16 (new)	Quarterly	Quarterly	Remove	Quarterly
LC-19a	Quarterly	Annual	Annual	Annual
LC-19b	-- [g/]	Remove	Remove	Remove
LC-19c	--	Remove	Remove	Remove
LC-20 (new)	Quarterly	Quarterly	Biennial	Quarterly
LC-24 (new)	Quarterly	Not Considered	Biennial	Biennial

Table 6.1: Summary of Optimization of Groundwater Monitoring Program at Fort Lewis Logistics Center Area

Well ID	Current Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Monitoring Wells Completed in Upper Vashon Subunit (continued)				
LC-26	Annual	Annual	Remove	Annual
LC-34 (new)	Quarterly	Not Considered	Biennial	Biennial
LC-41a	Annual	Quarterly	Annual	Annual
LC-44a	--	Remove	Remove	Remove
LC-49	Annual	Semi-Annual	Annual	Annual
LC-51	--	Remove	Remove	Remove
LC-53	Annual	Quarterly	Annual	Annual
LC-57 (new)	Quarterly	Not Considered	Biennial	Biennial
LC-61b (new)	Quarterly	Not Considered	Semi-Annual	Semi-Annual
LC-64a	Quarterly	Quarterly	Quarterly	Quarterly
LC-66a	--	Remove	Remove	Remove
LC-66b	Annual	Annual	Annual	Annual
LC-73a	--	Biennial	Remove	Remove
LC-108	--	Annual	Remove	Remove
LC-132	--	Quarterly	Annual	Annual
LC-136a	Quarterly	Quarterly	Quarterly	Quarterly
LC-136b	Annual	Remove	Annual	Annual
LC-137a	--	Remove	Remove	Remove
LC-137b	Quarterly	Quarterly	Remove	Quarterly
LC-149c	Annual	Biennial	Biennial	Biennial
LC-149d	--	Remove	Biennial	Biennial
LC-165	--	Biennial	Remove	Biennial
LC-167 (new)	Quarterly	Quarterly	Semi-Annual	Quarterly
LC-180	**Proposed for installation using 3-tiered approach**[h/]		Annual	Annual
NEW-1 (new)	Quarterly	Not Considered	Quarterly	Quarterly
NEW-2 (new)	Quarterly	Not Considered	Quarterly	Quarterly
NEW-3 (new)	Quarterly	Quarterly	Quarterly	Quarterly
NEW-4 (new)	Quarterly	Not Considered	Quarterly	Quarterly
NEW-5 (new)	Quarterly	Quarterly	Quarterly	Quarterly
NEW-6 (new)	Quarterly	Not Considered	Quarterly	Quarterly
PA-381	Annual	Annual	Biennial	Annual
PA-383	Annual	Biennial	Biennial	Biennial
T-04	Annual	Annual	Annual	Annual
T-06 (new)	Quarterly	Not Considered	Quarterly	Quarterly
T-08	Semi-Annual	Annual	Semi-Annual	Semi-Annual
T-11b (new)	Quarterly	Not Considered	Quarterly	Quarterly
T-12b	Quarterly	Annual	Biennial	Biennial
T-13b	Semi-Annual	Annual	Semi-Annual	Semi-Annual

Table 6.1: Summary of Optimization of Groundwater Monitoring Program at Fort Lewis Logistics Center Area

Well ID	Current Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Monitoring Wells Completed in Lower Vashon Subunit				
FL4a (new)	Quarterly	Not Considered	Biennial	Biennial
LC-41b (new)	Quarterly	Not Considered	Annual	Annual
LC-64b	Annual	Annual	Annual	Annual
LC-111b	Annual	Biennial	Biennial	Biennial
LC-116b	Annual	Semi-Annual	Annual	Annual
LC-122b	Annual	Biennial	Remove	Biennial
LC-128	Annual	Annual	Annual	Annual
LC-137c	Annual	Annual	Annual	Annual
MAMC 1	Quarterly	Not Considered	Quarterly	Quarterly
MAMC 6 (new)	Quarterly	Not Considered	Quarterly	Quarterly
T-10 (new)	Quarterly	Not Considered	Semi-Annual	Semi-Annual
Groundwater Extraction Wells				
LX-1	Annual	Annual	Every 3 years	Annual
LX-2	Annual	Annual	Every 3 years	Annual
LX-3	Annual	Annual	Every 3 years	Annual
LX-4	Annual	Annual	Every 3 years	Annual
LX-5	Annual	Annual	Every 3 years	Annual
LX-6	Annual	Annual	Every 3 years	Annual
LX-7	Annual	Annual	Every 3 years	Annual
LX-8	Annual	Annual	Every 3 years	Annual
LX-9	Annual	Annual	Every 3 years	Annual
LX-10	Annual	Annual	Every 3 years	Annual
LX-11	Annual	Annual	Every 3 years	Annual
LX-12	Annual	Annual	Every 3 years	Annual
LX-13	Annual	Annual	Every 3 years	Annual
LX-14	Annual	Annual	Every 3 years	Annual
LX-15	Annual	Annual	Every 3 years	Annual
LX-16	Quarterly	Quarterly	Semi-Annual	Quarterly
LX-17	Quarterly	Quarterly	Quarterly	Quarterly
LX-18	Quarterly	Quarterly	Quarterly	Quarterly
LX-19	Quarterly	Quarterly	Quarterly	Quarterly
LX-21	Quarterly	Annual	Quarterly	Quarterly
RW-1	Quarterly	Quarterly	Semi-Annual	Quarterly

a/ Information from GSI (2003a) and Parsons (2003b).

b/ "Current" monitoring program was initiated in December 2001 (Section 3.1).

c/ "Composite" recommendations generated considering the current monitoring program, and recommendations generated by MAROS tool and three-tiered approach.

d/ "new" = the well was not included in the monitoring program prior to December 2001.

e/ "Not Considered" = the well was not included in the MAROS evaluation.

f/ "Remove" indicates that the well is recommended for removal from the monitoring program.

g/ A dash (--) indicates that the well is not included in the current or refined monitoring program.

h/ "Proposed for installation" indicates that a location for an additional monitoring well was identified on the basis of the evaluation.

A well was not selected for removal from the program in the example “composite” recommendations, unless that well was recommended for removal in both the MAROS and three-tiered evaluations, or unless that well was recommended for removal in one of the evaluations, and was not included in the monitoring program that was initiated in December 2001. The frequency of sampling provided in the “composite” recommendations was the frequency of sampling specified in the recommendations generated in the MAROS and three-tiered evaluations, if those recommendations were in agreement. If the frequencies recommended in the MAROS and three-tiered evaluations did not agree, but one of the recommended frequencies was the same as the current sampling frequency, the current sampling frequency was retained in the example “composite” recommendations. If the frequency of sampling at a particular well, specified in the recommendations generated in the three-tiered evaluation, did not agree with the frequency of sampling at that well in the current monitoring program, and the MAROS evaluation did not consider that well, the frequency of sampling recommended in the three-tiered evaluation was specified in the “composite” recommendations. If none of the current, and recommended, sampling frequencies were in agreement, the intermediate sampling frequency was specified in the “composite” recommendations. This example represents a “conservative” approach to LTMO for the program at the Fort Lewis Logistics Center area, because it considers recommendations generated using two different approaches, in addition to giving weight to currently-accepted monitoring practice at the site, by also considering the current monitoring program. Adoption of the example “composite” monitoring program would result in removal of eight wells from the current monitoring program at the Fort Lewis Logistics Center area, together with adjustment of the frequency of sampling to less-frequent events at most locations. Of course, more aggressive approaches to a “composite” optimization scheme also could be applied.

The results of the MAROS optimization and the three-tiered evaluation, including recommendations for removal of wells and adjustments to sampling frequency, were fully consistent for approximately 40 percent of the wells in the Fort Lewis Logistics Center monitoring program. (Wells that MAROS did not consider are not included in this comparison.)

The results of the three-tiered evaluation and MAROS optimization of the monitoring program at the Long Prairie Groundwater Contamination Superfund Site are summarized in Table 6.2. Example composite recommendations also are provided in Column 5 of Table 6.2.

Table 6.2: Summary of Optimization of Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site[a/]

Well ID	Current[b/] Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite[c/] Recommendations
Monitoring Wells				
BAL2B	--[d/]	Biennial	Remove[e/]	Remove
BAL2C	--	Biennial	Remove	Remove
MW1A	--	Remove	Remove	Remove
MW1B	--	Biennial	Remove	Remove
MW2A	Annual	Remove	Remove	Remove
MW2B	Annual	Annual	Annual	Annual
MW2C	Annual	Annual	Remove	Annual
MW3A	--	Remove	Remove	Remove
MW3B	--	Biennial	Remove	Remove

Table 6.2: Summary of Optimization of Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site

Well ID	Current Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Monitoring Wells (continued)				
MW4A	--	Remove	Remove	Remove
MW4B	Annual	Annual	Annual	Annual
MW4C	Annual	Annual	Annual	Annual
MW5A	--	Remove	Remove	Remove
MW5B	--	Biennial	Annual	Biennial
MW6A	Annual	Remove	Remove	Remove
MW6B	Annual	Annual	Annual	Annual
MW6C	Annual	Annual	Annual	Annual
MW10A	Annual	Annual	Annual	Annual
MW11A	--	Remove	Remove	Remove
MW11B	Annual	Biennial	Biennial	Biennial
MW11C	Annual	Biennial	Biennial	Biennial
MW13C	--	Biennial	Biennial	Biennial
MW14B	Annual	Annual	Annual	Annual
MW14C	Annual	Biennial	Biennial	Biennial
MW15A	Annual	Biennial	Biennial	Biennial
MW15B	Annual	Biennial	Biennial	Biennial
MW16A	--	Remove	Remove	Remove
MW16B	Annual	Annual	Annual	Annual
MW17B	Annual	Annual	Annual	Annual
MW18A	--	Remove	Remove	Remove
MW18B	--	Biennial	Biennial	Biennial
MW19B	Annual	Biennial	Biennial	Biennial
Groundwater Extraction Wells				
RW1A	--	Remove	Remove	Remove
RW1B	--	Remove	Remove	Remove
RW1C	--	Remove	Remove	Remove
RW3	Quarterly	Annual	Annual	Annual
RW4	Annual	Biennial	Biennial	Biennial
RW5	Quarterly	Annual	Annual	Annual
RW6	Quarterly	Annual	Annual	Annual
RW7	Quarterly	Annual	Annual	Annual
RW8	Quarterly	Annual	Annual	Annual
RW9	Quarterly	Biennial	Biennial	Biennial
RW7	Quarterly	Annual	Annual	Annual
RW8	Quarterly	Annual	Annual	Annual
RW9	Quarterly	Biennial	Biennial	Biennial

Table 6.2: Summary of Optimization of Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site

Well ID	Current[b/] Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Municipal Water-Supply Wells				
CW3	Quarterly	Biennial	Biennial	Biennial
CW6	Quarterly	Biennial	Biennial	Biennial

a/ Information from GSI (2003b) and Parsons (2003c).
b/ "Current" monitoring program was in effect in 2002.
c/ "Composite" recommendations generated considering the current monitoring program, and recommendations generated by MAROS tool and three-tiered approach.
d/ A dash (--) indicates that the well is not included in the current monitoring program.
e/ "Remove" indicates that the well is recommended for removal from the monitoring program.

The results of the MAROS optimization and the three-tiered evaluation, including recommendations for removal of wells and adjustments to sampling frequency, were fully consistent for nearly 90 percent of the wells in the monitoring program at the Long Prairie site. Adoption of the example "composite" monitoring program would result in removal of 16 wells from the current monitoring network at the Long Prairie site, together with adjustment of the frequency of sampling to less-frequent events at several locations.

The results of the three-tiered evaluation and MAROS optimization of the monitoring program at McClellan AFB OU D are summarized in Table 6.3. Example composite recommendations also are provided in Column 5 of Table 6.3.

Table 6.3: Summary of Optimization of Groundwater Monitoring Program at McClellan AFB OU D[a/]

Well ID	Current[b/] Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite[c/] Recommendations
Zone A Monitoring Wells				
MW-10	Annual	Annual	Annual	Annual
MW-11	Annual	Annual	Annual	Annual
MW-12	Annual	Annual	Annual	Annual
MW-14	Biennial	Remove[d/]	Biennial	Biennial
MW-15	Annual	Annual	Annual	Annual
MW-38D	Annual	Annual	Annual	Annual
MW-52	Biennial	Biennial	Remove	Biennial
MW-53	Biennial	Biennial	Remove	Biennial
MW-55	Biennial	Biennial	Biennial	Biennial
MW-70	Biennial	Biennial	Remove	Biennial

Table 6.3: Summary of Optimization of Groundwater Monitoring Program at McClellan AFB OU D

Well ID	Current Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Zone A Monitoring Wells (continued)				
MW-72	Annual	Annual	Remove	Annual
MW-74	Biennial	Annual	Remove	Annual
MW-76	Annual	Annual	Annual	Annual
MW-88	Biennial	Biennial	Remove	Biennial
MW-89	Biennial	Biennial	Biennial	Biennial
MW-90	Biennial	Biennial	Biennial	Biennial
MW-91	Biennial	Biennial	Remove	Biennial
MW-92	Biennial	Biennial	Remove	Biennial
MW-237	Biennial	Biennial	Remove	Biennial
MW-240	Biennial	Biennial	Remove	Biennial
MW-241	Annual	Remove	Remove	Remove
MW-242	Annual	Annual	Remove	Annual
MW-350	Biennial	Biennial	Remove	Biennial
MW-351	Annual	Annual	Remove	Annual
MW-412	Biennial	Biennial	Remove	Biennial
MW-458	Biennial	Biennial	Remove	Biennial
MW-1004	Biennial	Biennial	Remove	Biennial
MW-1026	Biennial	Biennial	Remove	Biennial
MW-1041	Biennial	Remove	Remove	Remove
MW-1042	Biennial	Biennial	Remove	Biennial
MW-1064	Biennial	Biennial	Remove	Biennial
MW-1073	Biennial	Biennial	Remove	Biennial
Zone B Monitoring Wells				
MW-19D	Biennial	Biennial	Biennial	Biennial
MW-51	Biennial	Biennial	Biennial	Biennial
MW-54	Annual	Annual	Annual	Annual
MW-57	Biennial	Biennial	Remove	Biennial
MW-58	Biennial	Biennial	Biennial	Biennial
MW-59	Biennial	Biennial	Biennial	Biennial
MW-104	Biennial	Biennial	Remove	Biennial
MW-1001	Biennial	Biennial	Remove	Biennial
MW-1003	Biennial	Remove	Remove	Remove
MW-1010	Biennial	Biennial	Remove	Biennial
MW-1027	Biennial	Biennial	Biennial	Biennial
MW-1028	Biennial	Remove	Remove	Remove
MW-1043	Biennial	Biennial	Biennial	Biennial

Table 6.3: Summary of Optimization of Groundwater Monitoring Program at McClellan AFB OU D

Well ID	Current Sampling Frequency	Recommendations Generated Using MAROS Tool	Recommendations Generated Using Three-Tiered Approach	Example Composite Recommendations
Groundwater Extraction Wells				
EW-73	Annual	Annual	Annual	Annual
EW-83	Annual	Annual	Annual	Annual
EW-84	Annual	Annual	Annual	Annual
EW-85	Annual	Annual	Annual	Annual
EW-86	Annual	Annual	Annual	Annual
EW-87	Annual	Annual	Annual	Annual

a/ Information from GSI (2003c) and Parsons (2003d).

b/ "Current" monitoring program was in effect in 2002.

c/ "Composite" recommendations generated considering the current monitoring program, and recommendations generated by MAROS tool and three-tiered approach.

d/ "Remove" indicates that the well is recommended for removal from the monitoring program.

The results of the MAROS optimization and the three-tiered evaluation, including recommendations for removal of wells and adjustments to sampling frequency, were fully consistent for approximately 50 percent of the wells in the monitoring program at McClellan AFB OU D. Application of the three-tiered approach to the monitoring program generated considerably more recommendations for well-removal from the program than did the MAROS evaluation, primarily on the basis of the qualitative evaluation, which recommended the removal of wells at the periphery of OU D, that historically have had no detections (or few detections at low concentrations) of COCs in groundwater. Even though the example "composite" program represents a conservative approach to program optimization, adoption of the example "composite" monitoring program would result in removal of four wells from the current monitoring program at OU D, together with adjustment of the frequency of sampling to less-frequent events at several locations.

Application of the two approaches to the optimization of long-term monitoring programs at each of the three case-study example sites generated recommendations for reductions in sampling frequency and changes in the numbers and locations of monitoring points that are sampled. Implementation of the optimization recommendations could lead to reductions ranging from only a few percent (using MAROS at McClellan AFB OU D) to more than 50 percent (using MAROS at the Long Prairie site and the three-tiered approach at McClellan AFB OU D) in the numbers of samples collected and analyzed annually at particular sites. The median recommended reduction in the annual number of samples collected, generated during the optimization demonstration, was 39 percent. Depending upon the scale of the particular long-term monitoring program, and the nature of the optimization recommendations, adoption of an optimized monitoring program could lead to annual cost savings ranging from a few hundred dollars (using MAROS at McClellan AFB OU D) to approximately $36,500 (using the three-tiered approach at the Fort Lewis Logistics Center Area). The results of the evaluations also demonstrate that each of the optimized monitoring programs remains adequate to address the primary objectives of monitoring.

6.2 OTHER ISSUES

The procedures used in the LTMO evaluations were discussed with various stakeholders (the environmental coordinators, responsible parties, and regulatory-agency personnel) through the entire course of the project. After the evaluations had been completed, the results were presented to stakeholder groups at each facility. Presenting the results to regulators at the three facilities raised questions that had to do more with the data quality objectives (DQOs) than with the approaches themselves. It became clear that every monitoring location that was recommended for removal, or for a change in sampling frequency, had a non-quantifiable, subjective value that depended on the person making the optimization decision. Much discussion revolved around the necessity of monitoring to a degree sufficient to incontrovertibly document plume capture. Other questions were raised regarding whether changes to monitoring programs would require modifications to existing Records of Decision (RODs).

Based on those discussions, it is clear that before any optimization recommendation is accepted, there must be a careful and thorough presentation of the long-term groundwater monitoring DQOs from the viewpoint of all the stakeholders, followed by stakeholder agreement on DQOs, possibly for every groundwater monitoring location. After the objectives have been defined, and consensus has been reached, the results of the optimization analyses can be examined, and a decision made to accept or reject recommendations. Note that there may be intangible costs associated with the development and presentation of recommendations to reduce the spatial density or temporal frequency of monitoring, including resistance of stakeholders and changes in public perception.

Depending upon the degree of difficulty in arriving at stakeholder concurrence with LTMO recommendations, the tangible and intangible costs associated with conducting and implementing an LTMO evaluation may outweigh the dollar cost savings that might be realized from an optimized program. This possibility must be addressed on a site-specific basis.

6.3 CONCLUSIONS

The most significant advantage conferred by the optimization approaches is the fact that both approaches apply consistent, well-documented procedures, which incorporate formal decision logic, to the process of evaluating and optimizing monitoring programs. However, there are certain limitations to each approach to monitoring program optimization. The primary limitation of MAROS is associated with the way in which the tool deals with COC concentrations that are below the reporting limit – MAROS assigns the value of the reporting limit (or some fraction thereof) to samples having a constituent concentration below the reporting limit (Appendix B). This can lead to identification of spurious temporal trends in concentrations, or to incorrectly concluding that reported concentrations are unstable through time. Identification of spurious trends, in turn, will affect the recommendations regarding the optimal frequency of sampling. The primary limitation of the three-tiered approach is that the spatial-statistical stage of the evaluation generally is completed using sampling results for only one constituent (Appendix B). The fact that the spatial evaluation currently is conducted in two spatial dimensions (rather than three) represents a limitation of both approaches.

For either approach, the process of becoming familiar with the pertinent characteristics of a site, identifying those data appropriate for the intended application, and transferring those data to the appropriate format (even if the data are available in an electronic database), can be time-consuming and labor-intensive, and represents a significant up-front investment of time and resources. Both approaches could benefit from further development efforts to address these limitations; continued development of both approaches is contemplated or in progress.

Experience obtained during the demonstrations indicates that although the MAROS tool is capable of being applied by an individual with little formal statistical training, interpretation of the results generated by either approach requires a relatively sophisticated understanding of hydrogeology, statistics, and the processes governing the movement and fate of contaminants in the environment. The two approaches differ primarily in the procedures used to select a sampling frequency. MAROS utilizes a relatively rigorous, statistical approach based on identification of temporal trends in COC concentrations, while the three-tiered approach depends primarily upon qualitative considerations, applied using detailed knowledge of the local hydrogeologic system, with support from the results of the temporal and spatial-statistical evaluations. However, if the assumptions underlying the MAROS statistical approach are violated (e.g., the number of separate monitoring events is not sufficient to identify a trend), application of MAROS to develop recommendations regarding monitoring frequency also will depend on qualitative considerations (e.g., GSI, 2003c). Both approaches use a ranking approach to identify potentially-unnecessary monitoring locations, although the spatial-statistical procedures used to implement the ranking approach are somewhat different.

In general, the recommendations generated by MAROS regarding spatial redundancy and sampling frequency were more conservative than the recommendations generated during the three-tiered evaluation (e.g., MAROS may recommend semi-annual sampling at a particular monitoring location, while the three-tiered evaluation may recommend annual sampling at the same location). In addition, the three-tiered approach tends to generate recommendations for removing a larger proportion of wells from a monitoring program than does MAROS, because the three-tiered approach considers the results of qualitative, temporal, and spatial analyses together to determine whether a particular well should be retained or removed from the monitoring program, while MAROS will recommend a well for removal from the program only if it is classified as redundant for all COCs based on the results of the spatial evaluation alone. It is possible that the more rigorous qualitative evaluation in the three-tiered approach justifies less-conservative recommendations than are generated using the MAROS approach. For example, the three-tiered evaluation generated a recommendation for biennial sampling at well LC-149c in the optimized Fort Lewis Logistics Center monitoring program, because the qualitative review in the three-tiered evaluation identified well LC-149c as having no historical detections of COCs throughout a monitoring history comprising 24 sampling events. By contrast, the temporal-statistical evaluation algorithm in MAROS originally generated a recommendation for annual sampling at that well. (The recommendation for annual sampling later was revised by applying qualitative considerations during subsequent stages of the MAROS evaluation.)

The general characteristics of each of the three case-study example sites addressed in this demonstration project are similar, comprising chlorinated solvent contaminants in groundwater, occurring at relatively shallow depth in unconsolidated sediments. However, the assumptions underlying the two approaches, and the procedures that are followed in conducting the evaluations, are applicable to a much broader range of conditions (e.g., dissolved metals in groundwater, or contaminants in a fractured bedrock system). In summary, either the MAROS tool or the three-tiered approach can be used to generate sound and defensible recommendations for optimizing a long-term monitoring program, under a wide range of site conditions.

Prior to initiating an LTMO evaluation, it is of critical importance that the monitoring objectives of the program to be optimized and the DQOs for individual monitoring points be clearly articulated, with all stakeholders agreeing to the stated objectives, decision rules, and procedures, so that the program can be optimized in terms of recognized objectives, using decision rules and procedures that are acceptable to all stakeholders. The decisions regarding whether to conduct an LTMO evaluation, which approach to use, and the degree of regulatory-agency involvement in the LTMO evaluation and subsequent implementation of optimization recommendations, must be made on a site-specific basis. Factors to be considered in deciding whether to proceed with an LTMO evaluation include:

- The projected level of effort necessary to conduct the evaluation;
- The resources available for the evaluation (e.g., quality and quantity of data, staff having the appropriate technical capabilities);
- The anticipated degree of difficulty in implementing optimization recommendations; and
- The potential benefits (e.g., cost savings) that could result from an optimized monitoring program.

Experience suggests that optimization of a monitoring program should be considered for most sites where the LTM programs are based on monitoring points and/or sampling frequencies that were established during site characterization, or for sites where more than about 50 samples are collected and analyzed on an annual basis. Because it is likely that monitoring programs can benefit from periodic evaluation as environmental programs evolve, monitoring program optimization also should be undertaken periodically, rather than being regarded as a one-time event. Overall site conditions should be relatively stable, with no large changes in remediation approaches occurring or anticipated. For sites at which response decisions are being validated or refined (e.g., during periodic remedy-performance reviews), optimization of the LTM program should be postponed until adjustments to the response have been implemented and evaluated. Successful application of either LTMO approach to the site-specific evaluation of a monitoring program is directly dependent upon the amount and quality of the available data – results from a minimum of four to six separate sampling events are necessary to support a temporal analysis, and results collected at a minimum of about six (for a MAROS evaluation) to 15 (for a three-tiered evaluation) separate monitoring points are necessary to support a spatial analysis. It also is necessary to develop an adequate CSM, describing site-specific conditions (e.g., direction and rate of groundwater movement, locations of contaminant sources and potential receptor exposure points) prior to applying either approach; the extent of contaminants in the subsurface at the site also must be adequately delineated before the monitoring program can be optimized.

Typically, a program manager should anticipate incurring costs on the order of \$6,000 to \$10,000 to complete an LTMO evaluation using one of the two approaches presented in this demonstration, at the level of detail of the case-study examples used in the demonstration (Sections 3, 4, and 5; and Appendices C and D). Consequently, an LTMO evaluation may be cost-prohibitive for smaller monitoring programs. Assuming a payback period of three years, potential cost savings of approximately \$2,000 to \$3,300 per year must be realized if optimization of a monitoring program is to be cost-effective. Because the costs associated with collection and analysis of a groundwater sample (including prorated mobilization costs, and costs for field sampling, management of water produced during sampling, laboratory analyses, QA/QC, and reporting) using conventional sampling technologies (bailer or purge pump) can range from about \$200 per sample to more than \$500 per sample (U.S. Air Force, 2004), an LTMO evaluation that can be used to reduce the total number of samples collected at a site by about 5 to 10 samples per annum should be cost-effective.

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APPENDIX A

CONCEPTS AND PRACTICES IN MONITORING OPTIMIZATION

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CONCEPTS AND PRACTICES IN MONITORING OPTIMIZATION

A1.0 CONCEPTS IN GROUNDWATER MONITORING

The U.S. Environmental Protection Agency (U.S. EPA) (2004) defines monitoring to be

> *"... the collection and analysis of data (chemical, physical, and/or biological) over a sufficient period of time and frequency to determine the status and/or trend in one or more environmental parameters or characteristics. Monitoring should not produce a 'snapshot in time' measurement, but rather should involve repeated sampling over time in order to define the trends in the parameters of interest relative to clearly-defined management objectives. Monitoring may collect abiotic and/or biotic data using well-defined methods and/or endpoints. These data, methods, and endpoints should be directly related to the management objectives for the site in question."*

Monitoring of groundwater systems has been practiced for decades. Monitoring activities have expanded significantly in recent years to assess and address the problems associated with groundwater contamination and its environmental consequences, because the processes active within a groundwater system, and the interactions of a groundwater system with the rest of the environment, can be assessed only through monitoring (Zhou, 1996).

Designing an effective groundwater-quality monitoring program involves selecting a set of sampling sites, suite of analytes, and sampling schedule based upon one or more monitoring-program objectives (Hudak *et al.*, 1993). An effective monitoring program will provide information regarding contaminant migration and changes in chemical suites and concentrations through time at appropriate locations, thereby enabling decision-makers to verify that contaminants are not endangering potential receptors, and that remediation is occurring at rates sufficient to achieve remedial action objectives (RAOs) in a reasonable timeframe. The design of the monitoring program therefore should address existing receptor exposure pathways, as well as exposure pathways arising from potential future use of the groundwater.

The U.S. EPA (2004) defines six steps that should be followed in developing and implementing a groundwater monitoring program:

1. Identify monitoring program objectives.

2. Develop monitoring plan hypotheses (a conceptual site model, or CSM).

3. Formulate monitoring decision rules.

4. Design the monitoring plan.

5. Conduct monitoring, and evaluate and characterize the results.

6. Establish the management decision.

In this paradigm, a monitoring program is founded on the current understanding of site conditions as documented in the CSM, and monitoring is conducted to validate (or refute) the hypotheses regarding site conditions that are contained in the CSM. Thus, monitoring results are used to refine the CSM by tracking spatial and temporal changes in site conditions through time. All monitoring-program activities are undertaken to support a management decision, established as an integral part of the monitoring program (e.g., assess whether a selected response action is/is not achieving its objectives).

Most past efforts in developing or evaluating monitoring programs have addressed only the design of the monitoring plan (Step 4 in the six-step process outlined above). The process of designing a groundwater monitoring plan involves four principal tasks (Franke, 1997):

1. Identify the volume and characteristics of the earth material targeted for sampling.

2. Select the target parameters and analytes, including field parameters/analytes and laboratory analytes.

3. Define the spatial and temporal sampling strategy, including the number of wells necessary to be sampled to meet program objectives, and the schedule for repetitive sampling of selected wells.

4. Select the wells to be sampled.

However, this procedure considers only the physical and chemical data that the monitoring plan is intended to generate, and does not completely take into account the objectives that the monitoring data are intended to address (Step 1, above), the decision(s) that the monitoring program is(are) intended to support (Step 6), or the means by which a decision will be selected (Step 3). All of the six steps outlined by the U.S. EPA (2004) should be considered during the development or evaluation of a monitoring program, if that program is to be effective and efficient, and also should be considered during optimization of existing programs.

Hydrogeologic units are part of the basic framework of a CSM; thus, it is convenient to identify the volume of earth material targeted for groundwater sampling in terms of hydrogeologic units. Target parameters and analytes typically will include those constituents that are known or suspected to be potential contaminants, or contaminants of concern (COCs) at a particular site. Target analytes also may include constituents or parameters that are not necessarily related to the occurrence of contaminants, but which provide information regarding hydrogeologic or geochemical conditions affecting the fate of identified COCs (e.g., oxidation/reduction potential as an indicator of *in-situ* degradation of organic chemicals) or the performance of a selected remedy (Makeig, 1991). The number of wells sampled depends primarily on the known or anticipated spatial variability in groundwater conditions and quality, because if spatial variability is great, a greater number of wells must be sampled to capture that variability (Franke, 1997). Sampling frequency also is an extremely important consideration in the design of a monitoring program – if samples are not collected frequently enough, some of the temporal variability in groundwater quality and conditions may be missed, and potentially important information will be lost. On the other hand, if samples are collected more frequently than necessary, some of the information obtained is redundant (Zhou, 1996).

Criteria used to identify wells that are suitable for sampling are program-specific (Franke, 1997). The most fundamental criterion is that a well must produce water from, and only from, the particular hydrogeologic unit that is targeted for sampling. A second criterion, which considers the primary purpose for which the well was constructed, relates to existing wells and is an important consideration in judging the suitability of a particular well in meeting program objectives (Lapham *et al.*, 1996). In particular, large-capacity wells (groundwater extraction or production wells) may not be suitable for particular sampling purposes; these must be distinguished from small-capacity wells (groundwater monitoring wells). A third criterion involves the construction features of the well, including the length and placement of the completion interval (well screen), types of materials used in well construction, and methods used during well installation. Wells meeting the criteria established for a particular groundwater monitoring program can be considered for inclusion in the program, depending upon the suitability of their locations with respect to achieving the spatial objectives of the program.

In the past, most monitoring programs have been designed and evaluated based on qualitative insight into the characteristics of the hydrologic system, and using professional judgment (Loaiciga *et al.*, 1992; Zhou, 1996). However, groundwater systems by nature are highly variable in space and through time, and it is difficult or impossible to account for much of the existing variability using qualitative techniques. More recently, other, more quantitative approaches have been developed, arising from the recognition that the results obtained from a monitoring program are used to make inferences about conditions in the subsurface on the basis of samples, and on the need to account for natural variability. The process of making inferences on the basis of samples, while simultaneously evaluating the associated variability, is the province of statistics; and to a large degree, the temporal and spatial variability of water-quality data currently are addressed through the application of statistical methods of evaluation, which enable large quantities of data to be managed and interpreted effectively, while the variability of the data also is quantified and managed (Ward *et al.*, 1990).

All approaches to the design, evaluation, and optimization of effective groundwater monitoring programs must acknowledge and account for the dynamic nature of groundwater systems, as affected by natural phenomena and anthropogenic changes (Everett, 1980). This means that in order to assess the degree to which a particular program is achieving the temporal and spatial objectives of monitoring (Section 1.4 of the report), a monitoring-program evaluation must address the temporal and spatial characteristics of groundwater-quality data. Temporal and spatial data generally are evaluated using temporal and spatial-statistical techniques, respectively. In addition, there may be other considerations that best are addressed through qualitative evaluation.

A1.1 CONSIDERATIONS AND APPROACHES IN QUALITATIVE EVALUATION OF MONITORING PROGRAMS

In a qualitative evaluation, the relative performance of the monitoring program is assessed from calculations and judgments made without the use of quantitative mathematical methods (Hudak *et al.*, 1993). Multiple factors may be considered qualitatively in developing recommendations for continuation or cessation of monitoring at each monitoring point. Sampling locations are determined by hydrogeologic and other conditions within, and at locations distal from the source(s) of contaminants (e.g., Schock *et al.*, 1989). The ultimate configuration of the monitoring program, including the location of wells, analytes included in the evaluation, and frequency of monitoring, is subject to the investigator's understanding of:

- The properties and configuration of the groundwater system;

- The ways in which these properties (and configuration) influence the movement and fate of contaminants, and the resultant contaminant distributions, and

- What constitutes an "optimal" monitoring program, given probable contaminant migration pathways and travel times.

Qualitative approaches to the evaluation of a monitoring program range from relatively simple to complex, but often are highly subjective. Furthermore, the degree to which the program satisfies long-term monitoring (LTM) objectives may not be readily evaluated by qualitative methods.

A1.2 CONSIDERATIONS AND APPROACHES IN EVALUATION OF TEMPORAL DATA

Temporal data (chemical concentrations measured at different points in time) provide a means of quantitatively assessing conditions in a groundwater system (Wiedemeier and Haas, 1999), and evaluating the performance of a groundwater remedy and its associated monitoring program. If attenuation or removal of contaminant mass is occurring in the subsurface as a consequence of natural processes or operation of an engineered remediation system, attenuation or mass removal will be apparent as a decrease in contaminant concentrations through time at a particular sampling location, as a decrease in contaminant concentrations with increasing distance from chemical source areas, and/or as a change in the suite of chemicals through time or with increasing migration distance. Conversely, if a persistent source is contributing contaminants to groundwater, or if contaminant migration is occurring, this may be apparent as an increase in contaminant concentrations through time at a particular sampling location, or as an increase in contaminant concentrations through time with increasing distance from contaminant source areas.

The temporal objective of LTM (evaluate contaminant concentrations in groundwater through time; Section 1.4 of the report) can be addressed by identifying trends in contaminant concentrations, by identifying periodic fluctuations in concentrations, or by estimating long-term average ("mean") values of concentrations (Zhou, 1996). Decisions regarding the frequency of sampling necessary to achieve the temporal objective of monitoring then can be based on trend detection, accuracy of estimation of periodic fluctuations, or accuracy of estimation of long-term mean concentrations.

Trends in contaminant concentrations can be identified by plotting temporal concentration data (Wiedemeier and Haas, 1999); however, visual identification of trends in plotted data may be a subjective process, particularly if the concentration data do not have a uniform trend, but are variable through time. It is preferable to examine temporal trends in chemical concentrations using various statistical procedures, including the Student's t-test (Zhou, 1996), regression analyses, Sen's (1968) non-parametric test for the slope of a trend, and the Mann-Kendall test for trends. The Mann-Kendall non-parametric test (Gibbons, 1994) is well-suited for evaluation of environmental data because the sample size can be small (as few as four data points), no assumptions are made regarding the underlying statistical distribution of the data, and the test can be adapted to account for seasonal variations in the data (Hirsch *et al.*, 1991). The Mann-Kendall test statistic can be calculated at a specified level of confidence to evaluate whether a temporal trend is present in contaminant concentrations detected through time in samples from an individual well. Sampling should be conducted at a frequency sufficient to detect temporal trends in concentrations at a specified level of statistical power (Zhou, 1996). If a trend is determined to be present, a non-parametric slope of the trend line (change in concentrations per unit time) also can be estimated using the test procedure, or using Sen's (1968) test. A negative slope (indicating decreasing contaminant concentrations through time) or a positive slope (increasing concentrations through time) provides statistical confirmation of temporal trends that may have been identified visually (Figure A.1).

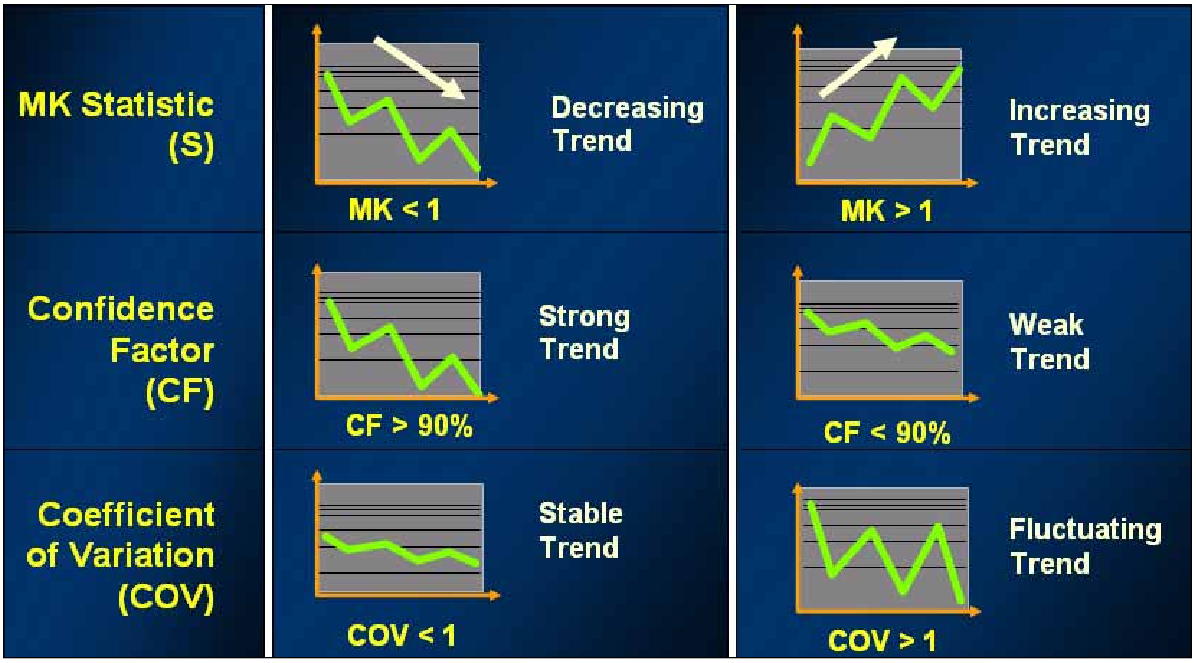

Figure A.1: Interpretation of Mann-Kendall Test for Trends (after AFCEE, 2000)

Periodic fluctuations in temporal concentration data can be evaluated using harmonic decomposition, Fourier-series analysis, by evaluating the correlation structure of the time series, or using other time-series statistical techniques (Davis, 1986). The half-width of the confidence interval of the mean can be used to estimate the mean value of a time series. The characteristics of any identified periodicity, or the confidence interval of the mean, then can be used to adjust the frequency of sampling (Zhou, 1996).

A1.3 CONSIDERATIONS AND APPROACHES IN EVALUATION OF SPATIAL DATA

Spatial techniques that can be applied to the design and evaluation of monitoring programs fall into two general categories – simulation approaches and ranking approaches (Hudak *et al*., 1993). Simulation approaches utilize computer models to simulate the evolution of contaminant plumes. The results then are incorporated into an optimization model which derives an optimal monitoring network configuration. (Note that the "optimal" configurations identified using this approach generally are not unique [Reed *et al*., 2000].) In addition to a stochastic simulator for generating multiple realizations of the spatial distribution of hydraulic properties, it is necessary to apply a mass-transport model to derive numerous realizations of dissolved contaminant plumes. Because transport modeling in two dimensions can fail to identify optimal vertical locations of sampling horizons, and also can result in monitoring points being placed too far from a contaminant source and at non-optimal spacings, three-dimensional transport modeling is preferable (Hudak, 2000). Numerical modeling of contaminant transport in moving groundwater, especially in three dimensions, is considerably more difficult than is simulation of groundwater movement alone. In addition, transport modeling is vulnerable to numerical errors (numerical dispersion and oscillation), and can require considerable computational resources and execution time, making simulation approaches impractical for many applications.

Ranking approaches utilize weighting schemes that express the relative values to the monitoring program of candidate sampling sites distributed throughout a sampling domain (Hudak *et al*., 1993).

The relative value of a potential monitoring site can be ranked by assessing its spatial position relative to areas such as contaminant sources, receptor locations, or probable zones of contaminant migration.

Alternative weighting schemes also can be used to express the relative value of candidate monitoring locations. For example, ranking approaches commonly use geostatistical methods to assist in the design, evaluation, or optimization of a monitoring network (American Society of Civil Engineering [ASCE], 1990a and 1990b). Approaches using geostatistical methods can be classified further as local or global in nature. The local approach to monitoring network evaluation uses geostatistics to assess monitoring networks by iteratively analyzing the effectiveness of adding sampling points to the network, or removing sampling points from the network (Reed *et al.*, 2000). Additional sampling points are added to the network based on an analysis of which locations will generate the maximum decrease in the estimation variance attained in geostatistical interpolation. Sampling points are removed from the network based on an analysis of which locations will generate the minimum increase in the estimation variance during geostatistical interpolation. The global approach to monitoring network design uses geostatistical methods to evaluate the likely performance of potential monitoring networks still in the planning stage (ASCE, 1990a and 1990b). In the global approach, several spatial configurations and densities of sampling points are considered, each of which is evaluated using the global estimation variance for each potential monitoring network. The global estimation variance then is minimized to optimize the performance of potential network designs.

A2.0 EXAMPLE APPLICATIONS OF METHODS FOR DESIGNING, EVALUATING AND OPTIMIZING MONITORING PROGRAMS

Although monitoring network design has been studied extensively in the past, most previous studies have addressed one of two problems (Reed *et al*., 2000):

1. Application of numerical simulation and formal mathematical optimization techniques for screening monitoring plans for detection monitoring at landfills and hazardous-waste sites, or

2. Application of ranking methods, including geostatistics, to augment or design monitoring networks for site-characterization purposes.

Loaiciga *et al.* (1992) examined several methods of designing and optimizing monitoring networks, including qualitative techniques based primarily on hydrogeologic interpretations, and statistical methods, including simulation methods, variance-reduction methods, and probabilistic methods. They found that most of the existing methods used in designing groundwater monitoring networks make several important simplifications:

- In the majority of the methods, monitoring design decisions are made only once, at the beginning of program development, with no opportunity to modify the program as additional information is compiled and evaluated;

- Most monitoring design methods use surrogate objectives for cost and risk-based criteria; and

- In many instances, the methods oversimplify the hydrogeologic environment, and the applicability in more complex and realistic settings remains unproven.

If not recognized, these shortcomings can lead to the development and implementation of a flawed monitoring program.

Storck *et al*. (1995) used a simulation approach (Section A1.3) to examine ways to design and evaluate groundwater monitoring networks for leaking disposal facilities. A Monte Carlo simulator was used to generate a large number of equally likely realizations of a random hydraulic conductivity field and a contaminant source location. A numerical model simulating groundwater flow and dissolved contaminant transport was used to generate a contaminant plume for each realization of the hydraulic-conductivity field. The results of the transport simulations then were used as input to an optimization model, which generated optimal trade-off curves among three conflicting objectives:

1. Maximize probability of contaminant detection,

2. Minimize cost of monitoring network (i.e., minimum number of monitoring wells), and

3. Minimize volume of contaminated groundwater.

The model was applied to a hypothetical scenario in order to examine the sensitivity of the trade-off curves to various model parameters.

Kelly (1996) applied a numerical model of groundwater flow and dissolved contaminant migration, together with knowledge of locations of potential contaminant sources, to determine screened-interval elevations and locations for 75 monitoring wells in 35 clusters, for a network designed to assure protection of the municipal well field for Independence, Missouri.

Dresel and Murray (1998) used a ranking approach (Section A1.3) to assist in the design of a groundwater monitoring network at the US Department of Energy's Hanford site in Washington. A geostatistical model of existing plumes was used to generate a large number of realizations of contaminant distribution in groundwater at the facility. Analysis of the realizations provided a quantitative measure of the uncertainties in contaminant concentrations, and a measure of the probability that a cutoff value (e.g., a target remedial concentration) would be exceeded at any point. A metric based on uncertainty measures and declustering weights was developed to rank the relative value of each monitoring well in the network design. The metric was used, together with hydrogeologic and regulatory considerations, in identifying candidate locations for inclusion in or removal from the network.

Hudak *et al*. (1993) applied a ranking methodology to the design of a detection-monitoring network for the Butler County Municipal Landfill in southwest Ohio. A geographic information system (GIS) was used to assign relative weights to candidate monitoring locations on the basis of distance from possible contaminant sources, location relative to probable contaminant migration pathways, and distance to a potential receptor exposure point. The GIS application was found to be relatively straightforward to implement, was capable of addressing established regulatory policy, and could be used to address several monitoring objectives.

Chieniawski *et al*. (1995) used a simulation approach combined with a ranking approach to examine the problem of optimizing detection monitoring at a waste facility under conditions of uncertainty. A numerical model was used, together with stochastic realizations of contaminant transport, to generate numerous realizations of contaminant movement for use as input into a multi-objective optimization model. The optimization model was solved using a genetic algorithm and generated trade-off curves comparing the relative cost of a particular monitoring network design with the probability that the network could detect a leak.

The studies described above dealt primarily with detection (i.e., sentinel-well) monitoring and global approaches to the design of new monitoring networks. By contrast, few investigators have formally addressed the evaluation and optimization of LTM programs at sites having extensive monitoring networks that were installed during site characterization. The primary goal of optimization efforts at such sites is to reduce sampling costs by eliminating data redundancy to the extent possible. This type of optimization usually is not intended to identify locations for new monitoring wells, and it is assumed that the existing monitoring network is sufficient to characterize the concentrations and spatial distribution of contaminants being monitored. It also is not intended for use in optimizing detection monitoring.

Ridley *et al.* (1995) developed a method (the "Cost-Effective Sampling [CES] Method") for estimating the lowest-frequency (and, as a result, lowest- cost) sampling schedule for a particular sampling location which will still provide information at the level needed for making regulatory and remedial decisions. The determination of optimal sampling frequency is based on the magnitude and variability of concentrations, and on concentration trends at the sampling location. The underlying principle is that the sampling schedule at a particular location should be determined primarily by the rate of change in contaminant concentrations that have been detected at that location in the recent past -- the faster the rate of change, the more frequently sampling should be conducted.

Reed *et al*. (2000) developed and applied a simulation approach for optimizing existing monitoring programs using a numerical model of groundwater flow and contaminant transport, several statistically-based plume-interpolation techniques, and a formal mathematical optimization model based on a genetic algorithm. The optimization approach was used to identify cost-effective sampling plans that were based on the assumption that the total mass of dissolved contaminant in groundwater could be accurately quantified. Application of the approach to the monitoring program at Hill AFB indicated that monitoring costs could be reduced by as much as 60 percent without significant changes in the resulting estimates of dissolved contaminant mass. Reed and Minsker (2004) and Reed *et al.* (2001 and 2003) extended this work using several different mathematical optimization algorithms to address multi-objective monitoring optimization problems.

Tuckfield *et al.* (2001) reviewed the operational efficiency of groundwater monitoring networks at the U.S. Department of Energy's Savannah River Site. The purpose of the evaluation was to optimize the number of groundwater wells requisite for monitoring the plumes of the principal constituent of concern, trichloroethene (TCE). A multidisciplinary approach, combining geochemistry, geohydrology, geostatistics, and regulatory knowledge was used to evaluate whether or not a well should remain on the current sampling schedule. The wells within each of three aquifer zones were evaluated with respect to relevancy, reliability, and regulatory importance. These evaluations identified sets of wells that were considered to be candidates for deletion from the sampling schedule. The effects of a reduced amount of data due to well deletion were then evaluated using geostatistical redundancy analysis. In addition, historical trends in the contaminant concentration data were examined to determine those analytes that should remain on the sampling schedule for each well. At the conclusion of the evaluation, approximately 20 percent of the currently-sampled wells were recommended for removal from the monitoring program; and the list of analytes to be sampled and analyzed was reduced considerably.

Cameron and Hunter (2002) applied a spatial and temporal optimization algorithm known as the Geostatistical Temporal/Spatial (GTS) Optimization Algorithm to the evaluation and optimization of two existing monitoring programs at the Massachusetts Military Reservation (MMR), Cape Cod, Massachusetts. The GTS algorithm is intended for use in optimizing LTM networks using geostatistical methods, and was developed to ensure that only those monitoring data sufficient and necessary to support decisions crucial to addressing monitoring program objectives are collected and analyzed. The algorithm uses geostatistical methods to optimize sampling frequency and to define a network of essential sampling locations. The algorithm incorporates a decision-pathway analysis that is separated into temporal and spatial (i.e., frequency and location) components, which are used to identify temporal and spatial redundancies in existing monitoring networks. The results of the temporal analysis applied to the monitoring programs at MMR indicated that sampling frequency could be reduced at most locations by 40 to 70 percent. The results of the spatial analysis indicated that 109 of the 536 wells included in the two monitoring programs at MMR were spatially redundant, and could be removed from the programs. More recently, Cameron and Hunter (2004) applied the GTS algorithm to monitoring programs at three other sites, and confirmed that use of this optimization approach could generate savings ranging from 30 percent to 63 percent of monitoring costs.

Ling *et al.* (2003) developed an innovative methodology for improving existing groundwater monitoring plans at small-scale sites. The methodology consists of three stand-alone procedures: a procedure for reducing spatial redundancy, a well-siting procedure for adding new sampling locations, and a procedure for determining optimal sampling frequency. The spatial redundancy reduction procedure was used to eliminate redundant wells through an optimization process that minimizes the errors in plume delineation and the estimation of average plume concentration. The well-siting procedure was used to locate possible new sampling points for an inadequately delineated plume *via* regression analysis of plume centerline concentrations and estimation of plume dispersivity values. The sampling frequency determination procedure was used to generate recommendations regarding the future frequency of sampling for each sampling location based on the direction, magnitude, and uncertainty of the concentration trend derived from representative historical concentration data. Although the methodology was designed for small-scale sites, it is adaptable for large-scale site applications. The methodology was applied to a small petroleum hydrocarbon-contaminated site with a network of 12 monitoring wells to demonstrate its effectiveness and validity.

APPENDIX B

DESCRIPTION OF MAROS TOOL AND THREE-TIERED OPTIMIZATION APPROACH

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DESCRIPTION OF MAROS TOOL AND THREE-TIERED OPTIMIZATION APPROACH

B1.0 OPTIMIZATION OF LONG-TERM MONITORING PROGRAMS

"Optimization" is defined (American Heritage Dictionary of the English Language, 2000) to be

> *"The procedure or procedures used to make a system or design as effective or functional as possible ..."*

and when a particular system has been "optimized", its operation occurs under "optimal" conditions, defined (WordNet 2.0 at http://www.cogsci.princeton.edu/~wn/) to be those conditions

> *"... most desirable possible under a restriction expressed or implied"*.

Long-term monitoring (LTM) programs typically are implemented at sites having extensive monitoring networks that were installed during site characterization. The primary goal of optimization efforts at such sites is to reduce sampling costs by eliminating data redundancy to the extent possible. This type of optimization usually is not intended to identify locations for new monitoring wells, and it is assumed during optimization that the existing monitoring network sufficiently characterizes the concentrations and distribution of contaminants being monitored. Two approaches to evaluating monitoring networks – the MAROS tool and the three-tiered evaluation approach – were developed specifically for use in optimizing existing LTM programs. (Although formal mathematical optimization techniques have been applied to the problem of optimizing monitoring programs [Appendix A], neither the MAROS tool nor the three-tiered approach incorporates mathematical optimization in the strict sense. Rather, in keeping with the definitions provided above, "optimization" in subsequent discussion refers to the application of rule-based procedures, incorporating statistical analysis and professional judgment, to identify possible improvements to a monitoring program that will continue to be effective at meeting the objectives of monitoring while addressing qualitative constraints and minimizing the necessary incremental resources.) The principal features of these two approaches are discussed in the following sections, and are described in the following subsections.

B2.0 DESCRIPTION OF MAROS TOOL

B2.1 GENERAL CHARACTERISTICS OF MAROS SOFTWARE TOOL

The *M*onitoring *a*nd *R*emediation *O*ptimization *S*ystem (MAROS) software originally was developed primarily for use as a tool to assist non-technical personnel (e.g., facility environmental managers) with the organization, preliminary evaluation, and presentation of monitoring data (Air Force Center for Environmental Excellence [AFCEE], 2000). In the years since its development, the performance of the MAROS software tool has been assessed critically ("beta tested") by applying the tool to the evaluation and optimization of actual monitoring programs at a number of U.S. Air Force facilities (e.g., Parsons, 2000 and 2003a). In response to recommendations for modifications to the MAROS software, generated as a consequence of the beta testing, Groundwater Services, Inc. (GSI) has refined MAROS and expanded its capabilities; the new version of MAROS was issued by AFCEE (2002) for additional testing in 2002. The public-domain software, and accompanying documentation, are available for free download on the AFCEE website at http://www.afcee.brooks.af.mil/er/rpo.htm . All subsequent discussion refers to features of the most-current version of MAROS (Version 2); and all case-study example monitoring programs examined in the current demonstration project were evaluated and optimized using this version of MAROS (Appendices C and D of this report).

The MAROS tool consists of a software package that operates in conjunction with an electronic database environment (Microsoft Access 2000®) and performs certain mathematical and/or statistical functions appropriate to completing qualitative, temporal, and spatial-statistical evaluations of a monitoring program, using data that have been loaded into the database (AFCEE, 2000 and 2002). MAROS utilizes parametric temporal analyses (using linear regression) and non-parametric trend analyses (using the Mann-Kendall test for trends) to assess the statistical significance of temporal trends in concentrations of contaminants of concern (COCs). MAROS then uses the results of the temporal-trend analyses to develop recommendations regarding sampling frequency at each sampling point in a monitoring program by applying a modified CES algorithm, based on the CES method developed at Lawrence Livermore National Laboratory (Ridley *et al.*, 1995). MAROS utilizes parametric temporal analyses (using linear regression) and non-parametric trend analyses (using the Mann-Kendall test for trends) to assess the statistical significance of temporal trends in concentrations of COCs (Table B.1).

Although the MAROS tool primarily is used to evaluate temporal data, it also incorporates a spatial statistical algorithm, based on a ranking system (Appendix A) that utilizes a weighted "area-of-influence" approach (implemented using Delaunay triangulation) to assess the relative value of data generated during monitoring, and to identify the optimal locations of monitoring points (Table B.1). Formal decision logic structures and methods of incorporating user-defined secondary lines of evidence (empirical or modeling results) also are provided, and can be used to further evaluate monitoring data and make recommendations for adjustments to sampling frequency, monitoring locations, and the density of the monitoring network. Additional features (moment analyses) allow the user to evaluate conditions and the adequacy of the monitoring network across a contaminated site (rather than just at individual monitoring locations.)

Table B.1: Features of MAROS

Feature	MAROS
Maximum Number of Wells/Points Examined	200
Maximum Number of COCs Examined	5
COC Identification	✓
Temporal Trend Analysis	✓
Sampling Frequency Optimization	✓
Well Significance Spatial Analysis	✓
Plume Moment Analysis	✓
Power Analysis at Individual Wells	✓
Risk-Based Power Analysis of Site	✓

MAROS is intended to assist users in establishing practical and cost-effective long-term monitoring LTM goals for a specific site, by

- Identifying the COCs at the site,
- Determining whether temporal trends in groundwater COC concentration data are statistically significant,
- Using identified temporal trends to evaluate and optimize the frequency of sample collection,
- Assessing the extent to which contaminant migration is occurring, using temporal-trend and moment analyses,
- Evaluating the relative importance of each well in a monitoring network, for the purpose of identifying potentially-redundant monitoring points,
- Identifying those wells that are statistically most relevant to the current sampling program,
- Evaluating whether additional monitoring points are needed to achieve monitoring objectives,
- Providing indications of the overall performance of the site remediation approach, and
- Assessing whether the monitoring program is sufficient to achieve program objectives on local or site-wide scales.

Successful application of the MAROS tool to the site-specific evaluation of a monitoring program is completely dependent upon the amount and quality of the available data (e.g., data requirements for a temporal trend analysis include a suggested minimum of six separate sampling events at an individual sampling point, and a spatial analysis requires sampling results from a minimum of six different sampling locations). It also is necessary to develop an adequate conceptual site model (CSM), describing site-specific conditions (e.g., direction and rate of groundwater movement, locations of contaminant sources and potential receptor exposure points) prior to applying the MAROS tool. Furthermore, the extent of contaminants in the subsurface at the site must be adequately delineated before the monitoring program can be optimized.

MAROS is designed to accept data in any of three formats: text files in US Air Force Environmental Restoration Program Information System (ERPIMS) format, Microsoft Access® files, or Microsoft EXCEL® files. Prior to conducting a monitoring-program evaluation, spatial and temporal data are loaded into a database, to include well identifiers (IDs), the sampling date(s) for each well, COCs, COC concentrations detected at each well sampled on each sampling date, laboratory detection limits for each COC, and any quality assurance/quality control (QA/QC) qualifiers associated with sample collection or analyses. The spatial analysis also requires that geographic coordinates (northings and eastings, referenced to some common datum) be supplied for each well.

MAROS can be used to identify site-specific COCs by comparing COC concentrations in the chemical database with applicable regulatory standards (e.g., maximum contaminant levels [MCLs]). Because MAROS can be used to evaluate the spatial and temporal characteristics of a maximum of five COCs in a single simulation, one or more COCs must be removed from data sets containing more than five COCs, or the data set must be split, so that only five COCs are included in a single simulation.

MAROS is capable of evaluating a maximum of 200 monitoring points in each simulation. Prior to applying MAROS to the evaluation of a monitoring network comprising more than 200 monitoring points, those monitoring locations providing relatively little information (or information that is not compatible with the other points in the network) can be identified using qualitative methods and eliminated from the evaluation. As an alternative, a monitoring network comprising more than 200 monitoring points could be divided into subsets, each subset of the network could be evaluated using MAROS, and the results of the evaluations then could be combined to generate recommendations for the entire network.

After COCs have been identified, and the monitoring points in the network to be used in the evaluation have been selected, the MAROS evaluation and optimization of a monitoring program is completed in two stages:

- A preliminary evaluation of plume stability is completed for the monitoring network, and general recommendations for improving the monitoring program are produced; and
- More-detailed temporal and spatial evaluations then are completed for individual monitoring wells, and for the complete monitoring network.

In general, the MAROS tool is intended for use in evaluating single-layer groundwater systems having relatively simple hydrogeologic characteristics (GSI, 2003a). However, for a multi-layer groundwater system, the user could use MAROS to analyze those components of the monitoring network completed in individual layers, during separate evaluations. The primary features and capabilities of the MAROS software are briefly described in the following subsections; additional details are available in the user's manuals (AFCEE, 2000 and 2002).

B2.2 PRELIMINARY EVALUATION OF PLUME STABILITY

In the preliminary MAROS evaluation, the entire historical groundwater COC database for the monitoring program is examined to assess overall plume stability; and the results of the plume-stability evaluation then are used to estimate the frequency and duration of sampling, and the density of the monitoring-well network that would be appropriate to address plume conditions. The preliminary evaluation incorporates several of the elements of a qualitative evaluation of the monitoring program (Appendix A). As a database to be used with the MAROS tool is constructed, each monitoring point is designated as occupying some relative location within, or downgradient from, the plume. Designations for the locations of monitoring points allowed by MAROS include "source," "tail," and "not used." Each monitoring point is assigned to one of these categories on the basis of the direction of groundwater movement, location of the monitoring point relative to the plume(s), and COC concentrations measured at the monitoring point. MAROS then uses these designations in the preliminary evaluation, together with the local velocity of groundwater movement (supplied by the user), a description of plume characteristics and other local conditions (Table B.2), and the results of concentration trend analyses, to assess overall plume stability, and to generate recommendations regarding sampling frequency and duration, and the spatial density of sampling points in the network for the monitoring program. A schematic of the procedures followed in the preliminary evaluation is presented in Figure B.1.

Table B.2: Simulation Parameters Used in Basic MAROS Evaluations

Simulation Parameter
Current Plume Width
Current Plume Length
Groundwater Seepage Velocity
Distance from Source to Nearest Downgradient Receptor
Distance from Source to Facility Boundary or Point of Compliance
Distance from "Tail" of Plume to Nearest Downgradient Receptor
Distance from "Tail" of Plume to Facility Boundary or Point of Compliance
Non-Aqueous-Phase Liquids (NAPLs) Present? (Y/N)
Temporal Fluctuations in Groundwater Elevations? (Y/N)
Remediation System Currently Active? (Y/N)

B2.2.1 System Design Category

In the preliminary evaluation, MAROS assigns the COC plume to one of three system design categories ("*Moderate*" [M], "*Extensive*" [E], or "*Limited*" [L]), based on the degree of stability in COC concentrations through time at monitoring locations near the source and tail of the plume. The assigned system design category then is used in conjunction with the results of analyses of temporal trends in COC concentrations in groundwater to develop preliminary recommendations regarding the duration of monitoring, sampling frequency, and the density of sampling points in the monitoring network.

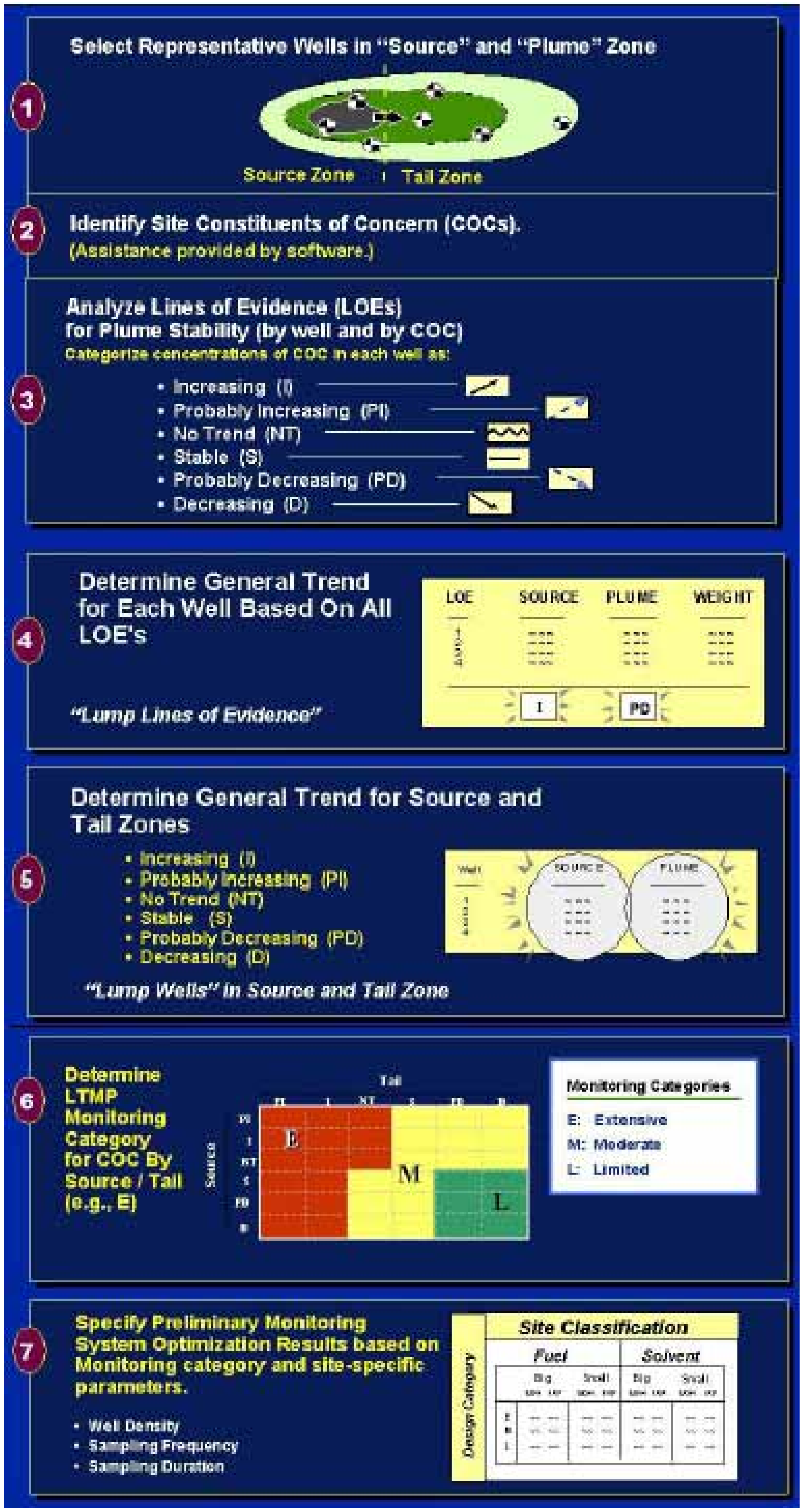


Figure B.1: Overview of Preliminary Evaluation Methodology (after GSI, 2003a)

B2.2.2 Sampling Frequency

Recommendations regarding the sampling frequency at a site are generated by MAROS during the preliminary evaluation based on the monitoring system design category to which the site is assigned (i.e., M, E, or L), and the required length of time calculated for a “conservative” COC (i.e., a constituent that moves advectively with groundwater at the groundwater seepage velocity, and is not slowed by sorption reactions) to move in groundwater to the designated receptor exposure point.

B2.2.3 Duration of Monitoring

Recommendations regarding the duration of continued monitoring at a site are generated by MAROS during the preliminary evaluation based on the length of the historical monitoring record (sites having longer historical records require continued future sampling through periods of shorter duration) and on temporal trends that are identified in the historical monitoring records of monitoring points in the source and tail areas of the plume (monitoring at points having decreasing trends in COC concentrations is continued through periods of shorter duration than is monitoring at points having “no trend”).

B2.2.4 Density of Monitoring Network

Recommendations regarding the relative density of sampling points in a monitoring network are derived during the preliminary evaluation using a simple “rule of thumb,” as expressed in the following equation (AFCEE, 2000):

$$\textit{\textbf{Sampling density (number of wells/acre)}} = \textbf{\textit{1.5 x (plume length)}}^{\textbf{\textit{0.4}}} \qquad \text{Equation B-1}$$

B2.2.5 “Spurious” Trends

Recommendations generated by MAROS regarding the duration and frequency of sampling are based in large part on the system design category selected by MAROS using the results from evaluation of temporal trends in COC concentrations at monitoring locations in the source area and tail areas of a plume. However, the presence or absence of concentration trends identified by MAROS may be misleading, because of the way in which MAROS deals with concentration values below the analytical detection limit (or reporting limit) for a particular COC. MAROS assigns a surrogate value (selected by the user to be the reporting limit, or some fraction of the reporting limit) to sample results having a constituent concentration below the reporting limit. This practice can lead to identification of spurious temporal trends in concentrations, or to incorrectly concluding that reported concentrations are unstable through time, as a consequence of misinterpreting temporal changes in COC reporting limits as representing actual changes in COC concentrations. This possibility suggests that the results of temporal-trend analyses completed by MAROS should be examined critically before conclusions are made regarding temporal trends in COC concentrations.

B2.3 TEMPORAL EVALUATION

After the preliminary evaluation of a monitoring program has been completed (Section B1.2), the MAROS analysis can be extended to provide detailed results for individual monitoring points, using temporal and spatial techniques. The MAROS tool can be used to examine the concentration history of the specified COCs at each sampling point in the monitoring network for the presence of temporal trends in concentrations, using parametric linear regression techniques and the Mann-Kendall test. MAROS uses the results of the temporal-trend analyses to classify trends in COC concentrations at each monitoring point into one of six categories: "*Increasing*" (I), "*Probably Increasing*" (PI), "*Stable*" (S), "*Probably Decreasing*" (PD), "*Decreasing*" (D), or "*No Trend*" (NT), based on the decision logic presented in Tables B.3 and B.4. Identified trends in COC concentrations then are applied in conjunction with the results of the preliminary evaluation of plume stability to generate preliminary recommendations regarding appropriate sampling frequencies for each COC on a location-specific basis. ***Note that the same considerations regarding the possible identification of spurious trends that can occur during the preliminary evaluation of plume stability (Section B1.2.5) also apply to the evaluation of temporal trends in COC concentrations at individual monitoring wells.***

Table B.3: Decision Matrix Used in Linear Regression Analysis as Implemented in MAROS

Confidence in Trend	Logarithmic Slope	
	Positive	**Negative**
< 90%	No Trend	COV[a/] < 1 Stable COV ≥ 1 No Trend
90% - 95%	Probably Increasing	Probably Decreasing
> 95%	Increasing	Decreasing

[a/] COV = coefficient of variation.

Table B.4: Decision Matrix Used In Mann-Kendall Trend Analysis as Implemented in MAROS

Mann-Kendal Test Statistic[a/]	Confidence in Trend	Concentration Trend
S > 0	> 95%	Increasing
S > 0	90% - 95 %	Probably Increasing
S > 0	< 90%	No Trend
S ≤ 0	< 90% and COV[b/] ≥ 1	No Trend
S ≤ 0	< 90% and COV < 1	Stable
S < 0	90% - 95%	Probably Decreasing
S < 0	95%	Decreasing

[a/] Mann-Kendall test statistic (S) is used to evaluate whether a trend is present in temporal data, and the degree of statistical confidence regarding the presence of a trend. The numerical sign of the test statistic indicates whether the trend is increasing or decreasing.

[b/] COV = coefficient of variation.

MAROS uses the results of the temporal-trend analyses to develop recommendations regarding sampling frequency at each sampling point in a monitoring program by applying a modified CES algorithm, which uses recent and historical COC measurements to determine optimal sampling frequency, based on the six categories of concentration trends (CT) used in the Mann-Kendall analysis, the rate-of-change (ROC) parameter (derived from the slope of the line fitted to COC concentration data in the linear-regression analysis), and the MCL for each constituent. Recommendations regarding sampling frequencies at individual wells are developed in three stages:

1. **Determine Sampling Frequency using Recent Concentration Trends.** Sampling frequency initially is determined using the ROC and CT, applied using the decision matrix presented in Table B.5.

2. **Adjust Sampling Frequency Based on Recent/Overall Ratio.** Next, the frequency of recent sampling events is compared with the overall frequency of sampling through the entire history of monitoring at a particular location. If recent sampling events have been completed at greater frequency than the overall frequency (e.g., recent events have been completed quarterly, while the frequency of sampling events through much of the prior history of monitoring at that location has been semi-annual), continuation of the frequency of recent monitoring events is recommended. If recent sampling events have been completed at lesser frequency than the overall frequency (e.g., recent events have been completed annually, while the frequency of sampling events through much of the prior history of monitoring at that location has been semi-annual) and the concentrations of one or more COCs are "*Increasing*", "*Probably Increasing*", or display "*No Trend*", then MAROS generates a recommendation that the more conservative overall frequency of sampling (more frequent sampling) be adopted for future monitoring events.

3. **Adjust Sampling Frequency Based on MCL.** If the maximum concentration of a particular COC detected at a monitoring point historically has been less than one-half the MCL concentration for that constituent, and constituent concentrations have not increased through time, then the sampling frequency can be reduced (e.g., from semi-annual monitoring to annual monitoring).

Table B.5: Decision Matrix Used to Develop Recommendations for Monitoring Frequency as Implemented in MAROS

Mann-Kendall Trend Results	Rate of Change (ROC)				
	High	Moderately High	Medium	Moderately Low	Low
	Recommended Sampling Frequency[a/]				
Increasing	Q	Q	S	S	A
Probably Increasing	Q	Q	S	S	A
No Trend	Q	Q	S	S	A
Stable	Q	S	A	A	A
Probably Decreasing	Q	S	A	A	A
Decreasing	Q	S	A	A	A

[a/] Sampling frequencies are as follow: Q = quarterly, S = semi-annual, A = annual.

The documentation for MAROS (AFCEE, 2000 and 2002) also recommends that sampling can be terminated at monitoring points that are not critical to the monitoring program, and at which cleanup standards have been attained; however, monitoring points meeting these criteria are not identified in the program output.

B2.4 SPATIAL EVALUATION

A spatial evaluation also is completed for each sampling location in the monitoring program during the second stage of the MAROS assessment. In the spatial evaluation of a monitoring network, MAROS applies an algorithm based on Delaunay triangulation to assign a relative importance to each sampling point in the network, for use in identifying redundant sampling locations that could potentially be removed from the monitoring program, with relatively little impact on the statistical characterization of the contaminant plume (AFCEE, 2000 and 2002). (Although Delaunay triangulation is not, strictly speaking, a "spatial-statistical" procedure, triangulated irregular networking, of which Delaunay triangulation is a subset, is regarded by many investigators [e.g., Griffith, 1996] as forming the basis of spatial statistics. Consequently, the algorithms used to conduct the spatial evaluations in MAROS may be referred to as "spatial-statistical procedures".) In conducting the spatial evaluation, MAROS uses an inverse-distance weighting algorithm to estimate a COC concentration at each sampling location, based on the measured concentrations at the "natural neighbor" locations defined by the Delaunay triangles surrounding the location for which the estimated concentration is generated (Figure B.2). MAROS then calculates a slope factor (SF) based on the standardized difference between the measured and estimated concentrations at the location for which the concentration is being estimated. The value of the SF can range from 0.0 to 1.0, with a SF of 0.0 indicating that the concentration at a particular location can be estimated exactly using the concentration values at surrounding monitoring points. Values of the SF greater than 0.0 indicate that some degree of error is present in the estimate, with increasing values of SF indicating progressively greater differences between estimated and measured values. Significant differences between COC concentrations measured at a particular monitoring point, and the COC concentrations estimated for that monitoring point using the inverse-distance weighting algorithm (as indicated by values of SF near 1.0), suggest that actual sampling results from the monitoring point provide a significant amount of information, which might not be obtainable by other means.

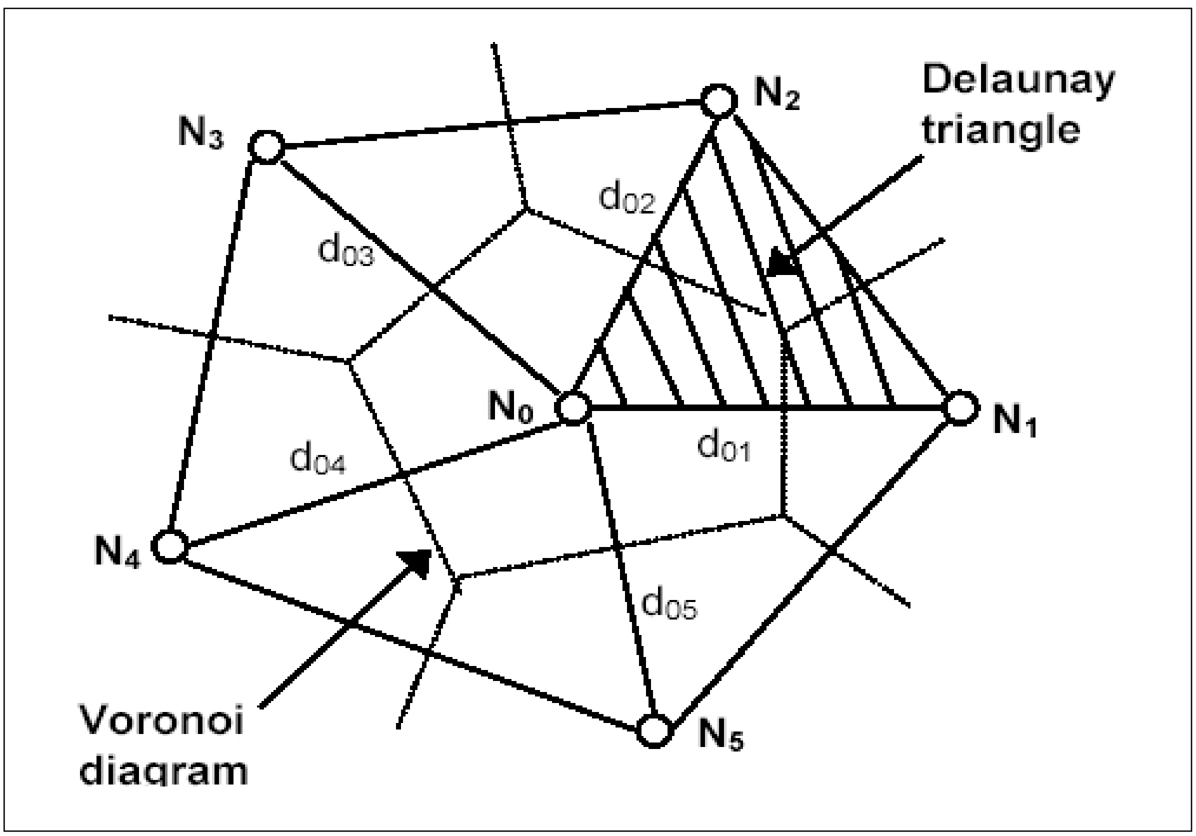


Figure B.2: Natural Neighbors of a Monitoring Point (N_0) as Defined Using Delaunay Triangles
(after AFCEE, 2000)

If the SF for an individual monitoring point is below a specified threshold value (currently established at 0.01 for sampling points on the periphery of the monitoring network, and at 0.10 for sampling points in the interior of the network), MAROS computes two other parameters for that monitoring point. The average concentration ratio (CR) is the ratio of the plume-wide average COC concentration calculated based on the plume-wide average concentration, which is calculated using an area-weighted averaging method and excluding the actual COC concentration result from the monitoring point in question, to the plume-wide average COC concentration calculated using the area-weighted averaging method, including the actual COC concentration result from that point. The area ratio (AR) is the ratio of the total area covered by all the Delaunay triangles within the simulation domain with the monitoring point in question excluded from the network, to the area covered by all the Delaunay triangles within the simulation domain with the monitoring point in question included in the network. If the CR and AR are above a specified threshold value (currently established at 0.95 for both parameters), the monitoring location is classified as "redundant" for that COC. Monitoring points (wells) are removed iteratively from the network -- the well having the smallest value of SF is removed, and the CR and AR then are calculated. If the values of the CR and AR are below the specified threshold, the well having the next lowest SF value is removed, the CR and AR values are checked, and so on. This process is repeated for all COCs. If removal of any monitoring point from the network does not result in significant loss of information (as indicated by a SF having a value below the specified threshold, with corresponding values of CR and AR above the specified threshold) for ***all*** COCs, that monitoring point is considered "redundant", and can be removed from the monitoring program.

The results of the spatial evaluation also can be used in a "well sufficiency analysis", to evaluate whether new sampling locations are needed in areas within the existing monitoring network where there is a high degree of uncertainty in COC concentrations. The MAROS software identifies potential new sampling locations in unsampled (or undersampled) regions by examining the SF values derived for those regions using SF values obtained using the Delaunay triangulation algorithm applied to existing sampling locations. Areas having large values of SF (near 1.0) are candidate regions for new sampling locations.

B2.5 MOMENT ANALYSES

Other features of the MAROS software also enable the user to evaluate whether:

- Temporal trends in the overall concentrations and movement of COCs throughout a plume (rather than at individual monitoring points) are statistically significant,
- Cleanup criteria have been met for each COC at each well, to some pre-determined statistically-significant level, and
- Non-exceedance criteria for each COC were met at defined compliance boundaries during each sampling event.

These features are implemented by means of two additional statistical analyses: a moment analysis of COC conditions throughout the plume, and a data-sufficiency analysis, consisting of an analysis of statistical power of the COC data available for individual wells, and a risk-based power analysis of the entire plume (Table B.1).

The Moment Analysis consists of an assessment of the characteristics and overall stability of a plume, based on spatial and temporal COC concentration data. MAROS uses these data, together with additional site-specific information (supplied by the user) (Table B.6), to generate three statistical moments:

- The zeroth moment, which represents the total mass of a COC dissolved in the plume;
- The first moment, representing the coordinates of the center of mass of the plume and the distance from the center of mass to the contaminant source; and
- The second moment, which is a measure of the overall spread of the plume about the center of mass in the longitudinal and transverse directions of the horizontal plane.

Table B.6: Simulation Parameters Used in MAROS Evaluations of Moments and Risk-Based Power

Simulation Parameter
Effective Porosity of Saturated Earth Material (used in Moment Analysis)
Saturated Thickness of Water-Bearing Unit (used in Moment Analysis)
General Direction of Groundwater Movement (used in Moment Analysis)
Identification of Wells Along Plume Centerline (used in Risk-Based Power Analysis)
Distance from "Tail" of Plume to Nearest Downgradient Receptor (used in Risk-Based Power Analysis)

The effective porosity of the saturated earth material ("soil") at the site is used, together with the saturated thickness of the water-bearing unit and site-specific COC concentration data, to estimate the total mass of a particular COC within a plume (used in calculating the zeroth moment). The general direction of groundwater movement is necessary to establish the overall configuration of the plume (defined in MAROS by the directions of the longitudinal and transverse plume axes), which then is used to calculate the first and second moments. Each moment is calculated by numerically integrating contaminant concentration data over spatial regions defined during the spatial evaluation. Because the value of each of the moments is COC-dependent, MAROS calculates moments for each COC during each monitoring event. (In order to conduct the moment analysis for COC concentrations detected during a particular monitoring event, the spatial configuration of the plume must be relatively well defined for that event. Therefore, the moment analysis cannot be completed by MAROS for monitoring events having fewer than six locations sampled for a particular COC.) MAROS then applies a non-parametric temporal analysis (using the Mann-Kendall test for trends) to identify overall trends in each moment for each COC. These trends can provide the user an indication of the overall magnitude and stability of a plume, and also can be used to evaluate the relative importance of information generated at each monitoring point during a particular sampling event.

B2.6 DATA-SUFFICIENCY ANALYSES

During implementation of groundwater remedies involving LTM, cleanup levels specified for particular COCs in groundwater may be achieved only gradually at certain monitoring locations. Therefore, MAROS also incorporates a two-part Data-Sufficiency Analysis (Table B.1). The results of the power-analysis component can be used as an indication of whether remedial action objectives

(RAOs) for each COC have been, or are being, achieved at individual monitoring locations. If the long-term average concentration of a particular COC at some monitoring location can be demonstrated to be below some specified target-level concentration (e.g., the RAO concentration) with a specified degree of statistical confidence, that monitoring point can be removed from the monitoring program, or the frequency of sampling at that location may be reduced. If the long-term average concentration at some monitoring location appears to be below the specified target-level concentration, but this cannot be demonstrated at the specified level of statistical confidence, then the power analysis can be used to establish the number of additional samples that must be collected from the monitoring point in order to confirm that target-level concentrations have been achieved at that location. The algorithm for power analysis for individual monitoring points uses the number of samples collected at a monitoring point through its complete sampling history, and the temporal variability among COC concentration data at that monitoring point, to evaluate whether there is statistically-significant evidence that the concentrations of a particular COC at that location have decreased to levels below a specified threshold concentration (currently established at 80 percent of the RAO concentration of a particular COC) (AFCEE, 2002). MAROS then uses the results of the power analyses to classify each monitoring point into one of three categories: "*RAOs Attained*", "*RAOs Not Attained*", or "*Continue Sampling*", based on the decision logic presented in Table B.7.

Table B.7: Decision Matrix Used in Power Analysis as Implemented in MAROS

Decision Criteria[a/] for COC	**Inference**	**Cleanup Status**
$LR < \beta/(1-\alpha)$	Mean concentration is above RAO[b/]	Not Attained
$\beta/(1-\alpha) < LR < (1-\beta)/\alpha$	Mean concentration may be below RAO (but the difference is not statistically significant)	Continue Sampling
$(1-\beta)/\alpha < LR$	Mean concentration is below RAO (at a high level of confidence)	Attained

[a/] Decision criteria are as follow:
LR = likelihood ratio estimator.
α = pre-specified statistical confidence level.
β = pre-specified statistical power.

[b/] RAO = remedial action objective (COC cleanup concentration).

If the specified threshold concentration for a particular COC has been "*Attained*" at a particular monitoring point, MAROS then uses the results of the power analysis to calculate the minimum number of samples that would have been required to obtain the degree of statistical power specified for the analysis. This information may be used to estimate the numbers of samples required to be collected at adjacent monitoring points to achieve a similar level of confidence in the monitoring results.

The algorithm used in the power analysis is *parametric*, in that the underlying statistical distribution of the concentration data for a particular COC is assumed to follow some known form (Rock, 1988). MAROS conducts the power analysis in accordance with the assumption that the concentration data for a particular COC are normally distributed, and repeats the analysis using the same data, in accordance with the assumption that the concentration data are lognormally distributed. The assumption of lognormally distributed data is recommended for concentration data having a high degree of temporal variability, or for data sets containing fewer than about 20 results (AFCEE, 2002). If the concentration data are neither normally nor lognormally distributed, the results of the power analysis should be regarded with skepticism. Furthermore, the assumption that the concentrations of a particular COC are "*Stable*" at the monitoring point under consideration is implicit in the algorithm used to implement the power analysis. If COC concentrations display some temporal trend, rather than being "*Stable*", the results of the power analysis will be misleading. This possibility should be assessed during the evaluation using the results of the Mann-Kendall analysis of temporal trends (Section B1.3).

The data-quality objectives (DQO) process of the U.S. Environmental Protection Agency (U.S. EPA) (1994a and 1996) requires that the number of samples collected during monitoring activities be sufficient to support remediation decisions, with a pre-specified probability of making Type I (α) and Type II (β) errors. A Type I error occurs if the hypothesis under consideration (e.g., "the target-level concentration of trichloroethene [TCE] in groundwater at monitoring well MW-XX has not been achieved") is rejected when it actually is true. A statistical "confidence level" (α) is selected for a test of the hypothesis to reduce the likelihood of a Type I error to some acceptable degree. A Type II error occurs if the hypothesis under consideration is accepted when it actually is false. Statistical "power" (β) is established for a test of the hypothesis at a level sufficient to reduce the likelihood of a Type II error to some acceptable degree. The confidence of a compliance-monitoring test is given by $1-\alpha$, and the power of the test is given by $1-\beta$. Any statistical confidence level may be selected by the individual conducting a particular statistical test; however, the power of a test depends not only on the intrinsic characteristics of the test itself, but also on the characteristics of the data the test is used to evaluate (in particular, the variability of the data, and the number of individual measurements) (Rock, 1988). The power of any statistical test increases as the data conform more closely to any assumptions (e.g., normality of the statistical distribution) on which the test depends, and also as the number of individual measurements increases.

It is not possible to completely eliminate Type I or Type II errors from any statistical test (Sheskin, 2000); and in most circumstances it is only possible to increase statistical confidence (small α) by reducing statistical power (larger β). In the context of LTM, the consequences of committing a Type I error (e.g., cessation of monitoring at a location where target-level concentrations of COCs have not, in fact, been achieved) are regarded as much greater than are the consequences of committing a Type II error (e.g., continued monitoring at a location where target-level concentrations of COCs actually have been achieved). Accordingly, standard environmental statistical practice seeks to minimize the likelihood of committing a Type I error, at the expense of possibly committing a Type II error (Gibbons, 1994). Following the U.S. EPA's (1994a) convention, 95 percent confidence ($1-\alpha$) and 80 percent power ($1-\beta$) currently are established as DQO decision criteria in MAROS (AFCEE, 2002), for tests used to assess whether the concentrations of COCs in groundwater at particular locations are below specified target-level concentrations.

The other component of the Data-Sufficiency Analysis is a risk-based power analysis of the plume, which uses the historic concentrations of COCs at a minimum of three user-specified monitoring points along the "centerline" of a plume, together with historic concentrations of COCs measured at all other site-related wells, to predict COC concentrations at user-defined "compliance points" downgradient from the plume. The algorithm for the risk-based power analysis examines COC concentrations at specified monitoring points, fits a first-order exponential decay model to observed concentrations detected at those locations, and then uses the fitted exponential model to calculate the corresponding COC concentrations that might occur as a result of COC migration to a compliance point located a specified distance downgradient from the monitoring location nearest the compliance point. MAROS uses this algorithm to predict COC concentrations arriving at the compliance point (at a distance specified by the user downgradient from the tail of the plume) from each of the specified centerline locations (Table B.6) and from all other sampling locations for which a result is available for a particular monitoring event, computes the mean and variance of predicted COC concentrations, and compares these values with RAO concentrations to determine whether RAOs were achieved at the specified compliance point for particular COCs during each historical monitoring event.

Results generated by this component of the data-sufficiency analysis fall into one of three categories:

1. The predicted mean concentration at the compliance boundary is significantly higher than the RAO, indicating that RAOs at the specified boundary have been exceeded. In this case, no risk-based power analysis is performed.

2. The predicted mean concentration at the compliance boundary is significantly lower than the RAO, indicating that RAOs have been attained at the specified boundary. This type of result usually is produced only when a sufficiently large number of sample results is available (resulting in high statistical power).

3. The predicted mean concentration at the compliance boundary apparently is below the RAO, but the statistical significance associated with this result is low (low statistical power). In this case, more samples must be collected (to increase the level of statistical power) or additional time must elapse for the effects of a remedy to become apparent (resulting in lower COC concentrations and lower associated statistical variance). MAROS then estimates the number of additional samples that must be collected to achieve the necessary statistical power.

Additional details regarding site-specific applications of the MAROS software tool are presented in Appendix D.

B3.0 DESCRIPTION OF THREE-TIERED APPROACH

B3.1 GENERAL CHARACTERISTICS OF THREE-TIERED APPROACH

As described by Parsons (2003b, 2003c, and 2003d), a three-tiered long-term monitoring optimization (LTMO) evaluation is conducted in stages to address each of the objectives and considerations of monitoring: a qualitative evaluation first is completed, followed in succession by temporal and spatial evaluations. At the conclusion of each stage (or "tier") in the evaluation, recommendations are generated regarding potential changes in the temporal frequency of monitoring, and/or whether to retain or remove each monitoring point considered in the evaluation. After all three stages have been completed, the results of all of the analyses are combined and interpreted, using a decision algorithm, to generate final recommendations for an effective and efficient LTM program.

The qualitative evaluation can be completed by a competent hydrogeologist. The temporal evaluation can be completed using commercially-available statistical software packages having the capability of using non-parametric methods (e.g., the Mann-Kendall test) to examine time-series data for trends; and the spatial-statistical evaluation can be completed by a user familiar with geostatistical concepts, with access to a standard geostatistical software package (e.g., Geostatistical Environmental Exposure Software [GeoEAS; Englund and Sparks, 1992], GSLIB [Deutsch and Journel, 1998] or similar package). In practice, data manipulation, temporal and spatial analyses, and graphical presentation of results are simplified, and the quality of the results is enhanced, if a commercially-available geographical information system (GIS) software package (e.g., ArcView® GIS) (Environmental Systems Research Institute, Inc. [ESRI], 2001) with spatial-statistical capabilities (e.g., Geostatistical Analyst™, an extension to the ArcView® GIS software package) is utilized in the LTMO evaluation.

As with the MAROS tool, the site-specific evaluation of a monitoring program is completely dependent upon the amount and quality of the available data. Typical data requirements for completing a three-tiered LTMO evaluation are presented in Table B.8.

Table B.8: Typical Information Required to Complete Three-Tiered LTMO Evaluation

General Types of Information Needed
Site features (roads, buildings, surface-water bodies, property boundaries)
Hydrogeologic conditions
Well locations (coordinates)
Well completion information
Configuration of groundwater potentiometric surface (used to derive directions of groundwater movement and horizontal hydraulic gradients)
Groundwater levels through time
Identification of COCs
All historical COC analyses/results
Cleanup goals and monitoring objectives
Locations of potential exposure points and receptors
Description of current monitoring program

B3.2 QUALITATIVE EVALUATION

In the qualitative evaluation, the primary elements of the monitoring program (numbers and locations of wells, frequency of sample collection, analytes specified in the program) are examined, in the context of site-specific conditions, to ensure that the program is capable of generating appropriate and sufficient information regarding contaminant migration and changes in chemical concentrations through time, so that decision-makers can verify that contaminants are not endangering potential receptors, and that remediation is occurring at rates sufficient to achieve RAOs within a reasonable timeframe. The evaluation of the monitoring program therefore must consider existing receptor exposure pathways, as well as exposure pathways arising from potential future use of the groundwater. Potential redundancies in sampling location, and inappropriate sampling frequencies, also are examined in the qualitative evaluation. Typical factors that are considered in the qualitative evaluation include (Parsons, 2003b, 2003c, and 2003d):

- Heterogeneity of water-bearing unit(s),
- Type(s) of contaminant(s),
- Distance and direction to potential receptor exposure point(s),
- Direction of groundwater movement and groundwater seepage velocity,
- Potential impacts to surface water, and
- Effects associated with implemented remedy(ies).

These factors will influence the locations and spacing of monitoring points, and the sampling frequency. Typically, the greater the seepage velocity and the lesser the distance to receptor exposure points, the more frequently groundwater sampling should be conducted. Examples of application of qualitative considerations are described in detail in Appendix D.

All monitoring points that are sampled periodically in conjunction with the LTM program under consideration are included in the qualitative evaluation. Multiple factors are considered in developing recommendations for continued monitoring or cessation of monitoring at each monitoring point or well. In some cases, a recommendation is made to continue monitoring a particular well, but at less frequent intervals than at present. Factors considered in developing recommendations to retain a well in, or to remove a well from the monitoring program, are summarized in Table B.9. Typical factors considered in developing recommendations for monitoring frequency are summarized in Table B.10.

The analytes and methods used for chemical analyses also are examined in the qualitative evaluation. Typically, LTM programs are initiated only after site characterization has been completed (Reed *et al*., 2000), and site-related COCs have been identified. Because the COCs have been identified, it may be possible in some cases to conduct the required chemical analyses using a different analytical method than was used during site characterization activities. If the alternate method has a shorter list of analytes or if the analyte list is restricted only to the identified site-related COCs, it may be possible to reduce the unit cost of chemical analysis of samples. For example, analyses for volatile organic compounds (VOCs) often are conducted during the site- characterization phase of investigations using U.S. EPA Method SW8260B (a gas-chromatographic/mass-spectrometric [GC/MS] method). If the analytes to be determined in samples are known, Method SW8260B can be replaced by U.S. EPA Method SW8021B (a GC method), with potentially-significant cost savings realized on a unit-cost basis.

The qualitative stage of the three-tiered evaluation is complete when recommendations regarding retention in, or removal from the program, the frequency of sample collection, and the analytes and analytical methods to be used, have been generated for every sampling location (well) in the monitoring program.

Table B.9: Qualitative Monitoring Network Optimization Decision Logic

Reasons for Retaining a Well in a Monitoring Network	Reasons for Removing a Well From a Monitoring Network
Well is needed to further characterize the site or monitor changes in contaminant concentrations through time	Well provides spatially redundant information with a neighboring well (e.g., same constituents, and/or short distance between wells
Well is important for defining the lateral or vertical extent of contaminants	Well has been dry for more than two years
Well is needed to monitor water quality at compliance point or receptor exposure point (e.g., municipal wells)	Contaminant concentrations are consistently below laboratory detection limits or cleanup goals
Well is important for defining background water quality	Well is completed in same water-bearing zone as nearby well(s)

Table B.10: Qualitative Monitoring Frequency Decision Logic

Reasons for Increasing Sampling Frequency	Reasons for Decreasing Sampling Frequency
Groundwater velocity is high	Groundwater velocity is low
Change in concentration would significantly alter a decision or course of action	Change in concentration would not significantly alter a decision or course of action
Well is close to source area or operating remedy	Well is farther from source area or operating remedy
Cannot predict if concentrations will change significantly over time	Concentrations are not expected to change significantly over time, or contaminant levels have been below cleanup objectives for some period of time

B3.3 TEMPORAL STATISTICAL EVALUATION

In the temporal evaluation, the historical monitoring data for every sampling point in the monitoring program are examined for temporal trends in COC concentrations, using the Mann-Kendall test (Appendix A). The Mann-Kendall test statistic is calculated at a specified level of confidence to evaluate whether a temporal trend is present in contaminant concentrations detected through time in samples from an individual well. As implemented, the algorithm used to evaluate trends assigns a value of "Not Detected" to those wells with sampling results that are consistently below analytical detection limits (or reporting limits) through time, rather than assigning a surrogate value corresponding to the detection limit – a procedure that could generate potentially-misleading and spurious "trends" in concentration (e.g., the procedure used by MAROS [Section B1.2.5]). In addition, a value of "Below PQL" is assigned to those constituents for which no values are measured at levels above the practical quantitation limit (PQL). In the absence of the "Below PQL" classification category, the results of the trend analysis applied to a sampling point having consistent detections of trace concentrations of a particular COC could indicate an increasing or decreasing trend in concentrations, which would be primarily an artifact of the analytical methods, rather than representing actual increases or decreases in COC concentrations in groundwater.

After the Mann-Kendall test for trends has been completed for all COCs at all monitoring points, the spatial distribution of temporal trends in COC concentrations is used to evaluate the relative value of information obtained from periodic monitoring at each monitoring well by considering the location of the well within (or outside of) the contaminant plume, the location of the well with respect to potential receptor exposure points, and the presence or absence of temporal trends in contaminant concentrations in samples collected from the well. The degree to which the amount and quality of information that can be obtained at a particular monitoring point serves the two primary objectives of monitoring (temporal and spatial objectives) is considered in this evaluation, in accordance with the decision logic structure presented in Figure B.3. The temporal evaluation stage of the three-tiered evaluation is complete when recommendations regarding retention in, or removal from the program have been generated for every sampling location (well) in the monitoring program, using the temporal-trend decision logic (Figure B.3).

B3.4 SPATIAL STATISTICAL EVALUATION

In the third stage of the three-tiered evaluation, spatial statistical techniques are used to assess the relative value of information generated by sampling at each monitoring point in the network, by using COC concentrations to identify those areas having the greatest uncertainty associated with the estimated extent and concentrations of COCs in groundwater. In order to ensure that the spatial evaluation is as representative of actual conditions in the groundwater system as possible, the sampling event during which the greatest number of discrete points were sampled is identified, and the results of that event are used in the spatial statistical evaluation. As with the MAROS tool (Section B1.1), geostatistical methods generally are used in evaluating groundwater systems having only a single layer. However, for a multi-groundwater system, the user could complete a sequential layer-by-layer examination of the groundwater system during separate evaluations. A further limitation is that geostatistical methods can be used to examine the spatial characteristics of only a single COC during an evaluation. One approach is to identify the most widespread COC for use as an "indicator contaminant", and complete the spatial statistical evaluation using monitoring results only for that COC. If this is judged to be unsatisfactory, the spatial statistical evaluation should be completed for several or all of the COCs.

After the COC of interest has been identified, and the monitoring event for which COC concentration results are to be used has been selected, the COC concentrations are used to generate a semivariogram, which depicts the range of distances over which, and the degree to which, sample values at a given point are related to sample values at adjacent, or nearby, points (Clark, 1987), and which also indicates how close together sample points must be for a value determined at one point to be useful in predicting unknown values at other points. When a semivariogram is calculated for a variable over an area (e.g., concentrations of TCE in groundwater within a water-bearing unit), an irregular spread of points across the semivariogram plot is the usual result (Rock, 1988). One of the most subjective tasks of geostatistical analysis is to identify a continuous, theoretical semivariogram model that closely honors the actual data. Fitting a theoretical model to calculated semivariance points usually is accomplished by trial-and-error, rather than by a formal statistical procedure (Davis, 1986; Clark, 1987; Rock, 1988), and requires the expertise of an experienced geostatistical analyst.

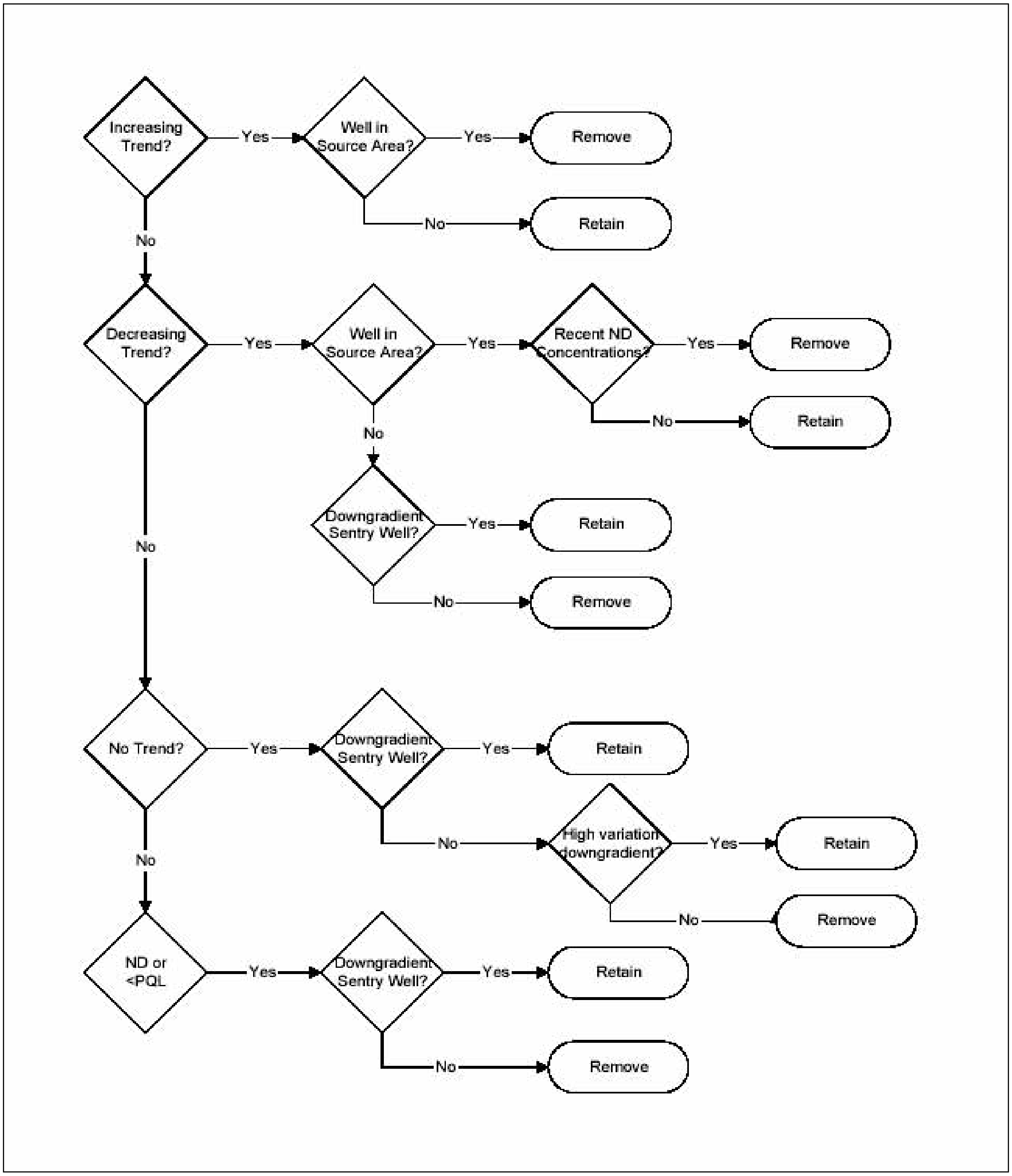


Figure B.3: Temporal COC Concentration Trend Decision Logic Structure
(after Parsons, 2003b)

After a semivariogram model has been developed to describe the spatial distribution of a particular COC, it can be used to estimate the concentrations of that COC at every point in the spatial domain (the area of covered by the monitoring network), and simultaneously to calculate prediction standard errors for the COC concentrations that have been estimated, using the spatial-statistical procedure known as *kriging* (Clark, 1987). First, the median kriging standard deviation is obtained from the kriging standard errors calculated using the complete monitoring network sampled in the current program. Next, each of the monitoring wells is removed sequentially from the network; and for each resulting network configuration having one well less than the current program, a kriging realization is completed using the concentrations of the COC of interest detected in samples from the remaining wells. The "missing well" monitoring network realizations are used to calculate prediction standard errors; and the median kriging standard deviations are obtained for each "missing well" realization and compared with the median kriging standard deviation for the "base-case" realization obtained using the current complete monitoring network, as a means of evaluating the amount of information loss (as represented by increases in kriging error) resulting from the use of fewer monitoring points.

If removal of a particular well from the monitoring network causes very little change in the resulting median kriging standard deviation (currently established at less than about 1 percent), that well is regarded as contributing only a limited amount of information to the monitoring program. Likewise, if removal of a well from the monitoring network produces larger increases in kriging standard deviation, this is regarded as an indication that the well contributes a relatively greater amount of information, and is relatively more important to the monitoring network. At the conclusion of the kriging realizations, each well is ranked, from those providing the least information to those providing the most information, based on the amount of information (as measured by changes in median kriging standard deviation) the well contributed toward describing the spatial distribution of the COC being examined. Wells providing the least amount of information represent possible candidates for removal from the monitoring program, while wells providing the greatest amount of information represent sampling points that probably should be retained in any refined version of the monitoring program. In general, no conclusions regarding removal from or retention in the monitoring network can be made about the wells providing information intermediate between the greatest and least relative amounts of spatial information.

B3.5 SUMMARY OF THREE-TIERED EVALUATION

At each stage in the three-tiered evaluation, monitoring points that provide relatively greater amounts of information regarding the occurrence and distribution of COCs in groundwater are identified, and are distinguished from those monitoring points that provided relatively lesser amounts of information. After all three stages have been completed, the results of the evaluations are combined to generate a refined monitoring program that potentially can provide information sufficient to address the primary objectives of monitoring at the site, at reduced cost. The results of the three tiers of the evaluation are combined and summarized in accordance with the following algorithm:

1. Wells designated as point-of-compliance or remedy-performance monitoring points in decision documents are retained in the monitoring program under all circumstances, regardless of possible rationale for removing such wells from the program.

2. Each well retained in the monitoring program on the basis of the qualitative hydrogeologic evaluation is recommended to be retained in the refined monitoring program.

3. Each well retained in the monitoring program on the basis of the temporal hydrogeologic evaluation is recommended to be retained in the refined monitoring program.

4. Those wells identified during the spatial evaluation of the monitoring network as contributing the most information regarding the occurrence and distribution of COCs in groundwater are recommended to be retained in any subset of the network that will be used for monitoring.

5. Any well recommended for removal from the monitoring program on the basis of one evaluation (e.g., qualitative hydrogeologic) and for retention on the basis of another evaluation (e.g., temporal statistical) is recommended for retention in the refined monitoring program, and is further examined to determine if a less-frequent monitoring schedule is appropriate.

6. Only those wells recommended for removal on the basis of all three evaluations, or on the basis of the qualitative and temporal evaluations (with no recommendation resulting from the spatial evaluation) should be removed from the monitoring program.

Additional details regarding site-specific applications of the three-tiered approach are presented in Appendix D.

APPENDIX C

SYNOPSES OF CASE-STUDY EXAMPLES

APPENDIX C

SYNOPSES OF CASE-STUDY EXAMPLES

The *M*onitoring *a*nd *R*emediation *O*ptimization *S*ystem (MAROS) tool and the three-tiered approach each were applied to the evaluation and optimization of existing groundwater monitoring networks at three different sites – the Logistics Center area at Fort Lewis, Washington, the Long Prairie Groundwater Contamination Superfund Site in Minnesota, and Operable Unit (OU) D at McClellan AFB, California. Features of each site, and a summary of the results of the MAROS evaluation and the three-tiered evaluation of the groundwater monitoring program at each site, are described in the following subsections. The detailed results of the MAROS and three-tiered LTMO evaluations of the three monitoring programs, as described in reports originally generated by GSI and Parsons, are presented in Appendix D.

C1.0 LOGISTICS CENTER AREA, FORT LEWIS, WASHINGTON

The following summary of information regarding the location, operational history, geology, and hydrogeology of Fort Lewis, Washington, the current monitoring program at the Logistics Center area, available hydrologic and chemical data that were used in the monitoring-program evaluations, and the results of the long-term monitoring optimization (LTMO) evaluations, has been excerpted from Parsons (2003b) and Groundwater Services, Inc. (GSI) (2003a). Copies of both documents are included in Appendix D-1; the reader is referred to the Appendix for additional details.

C1.1 SITE DESCRIPTION AND OPERATIONAL HISTORY

The Fort Lewis Military Reservation is located near the southern end of Puget Sound in Pierce County, approximately 11 miles south of Tacoma and 17 miles northeast of Olympia, Washington. The installation is bounded on the northwest by Interstate 5 and on the south and southwest by Murray Creek. Murray Creek discharges into American Lake, approximately 2 miles northwest of the East Gate Disposal Yard (EGDY). The Logistics Center occupies approximately 650 acres of the Fort Lewis Military Reservation.

Process wastes were disposed of at several on- and off-installation locations, including the EGDY), located southeast of the Logistics Center (Figure C.1). Between 1946 and 1960, waste solvents (primarily trichloroethene [TCE]) and petroleum, oils, and lubricants (POL) generated during cleaning, degreasing, and maintenance operations were disposed of in trenches at the EGDY, resulting in the introduction of contaminants to soils and groundwater at, and downgradient from this former landfill. The dissolved chlorinated solvent plume that originates at the EDGY extends downgradient across the entire width of the Logistics Center, and beyond the northwestern facility boundary to the southeastern shore of American Lake. The program that was developed to monitor the concentrations and extent of contaminants in groundwater in the vicinity of, and downgradient from the EDGY, and to assess the performance of remedial systems installed to address contaminants in groundwater (Section C1.3), was the subject of the MAROS and three-tiered evaluations.

C1.2 GEOLOGY AND HYDROGEOLOGY

Fort Lewis is underlain by a complex sequence of glacial and non-glacial Quaternary sediments, ranging up to 2,000 feet in thickness. Most of the dissolved contaminants originating at the EGDY source area occur within the uppermost water-bearing zone (the "Vashon Aquifer") at the Fort Lewis Logistics Center, and the groundwater monitoring wells within the Logistics Center monitoring network all are completed in the Vashon Aquifer. The stratigraphic units that comprise the Vashon Aquifer include (from uppermost to lowermost) the Vashon Drift, Olympia beds, and Pre-Olympia Drift.

Vashon Drift deposits typically extend from ground surface to depths of approximately 60 to 95 feet below ground surface (bgs), but may extend to approximately 230 feet bgs in some areas. The Vashon Drift consists primarily of sands and gravels, which occasionally are silty. The Olympia beds, which underlie the Vashon Drift in some areas beneath the northern part of the EGDY, consist of alluvial sands and gravels with silt, silty gravel, scattered wood, and peat, and may be up to 40 feet thick. The Pre-Olympia Drift ranges from 10 to 70 feet in thickness, and consists of very fine to

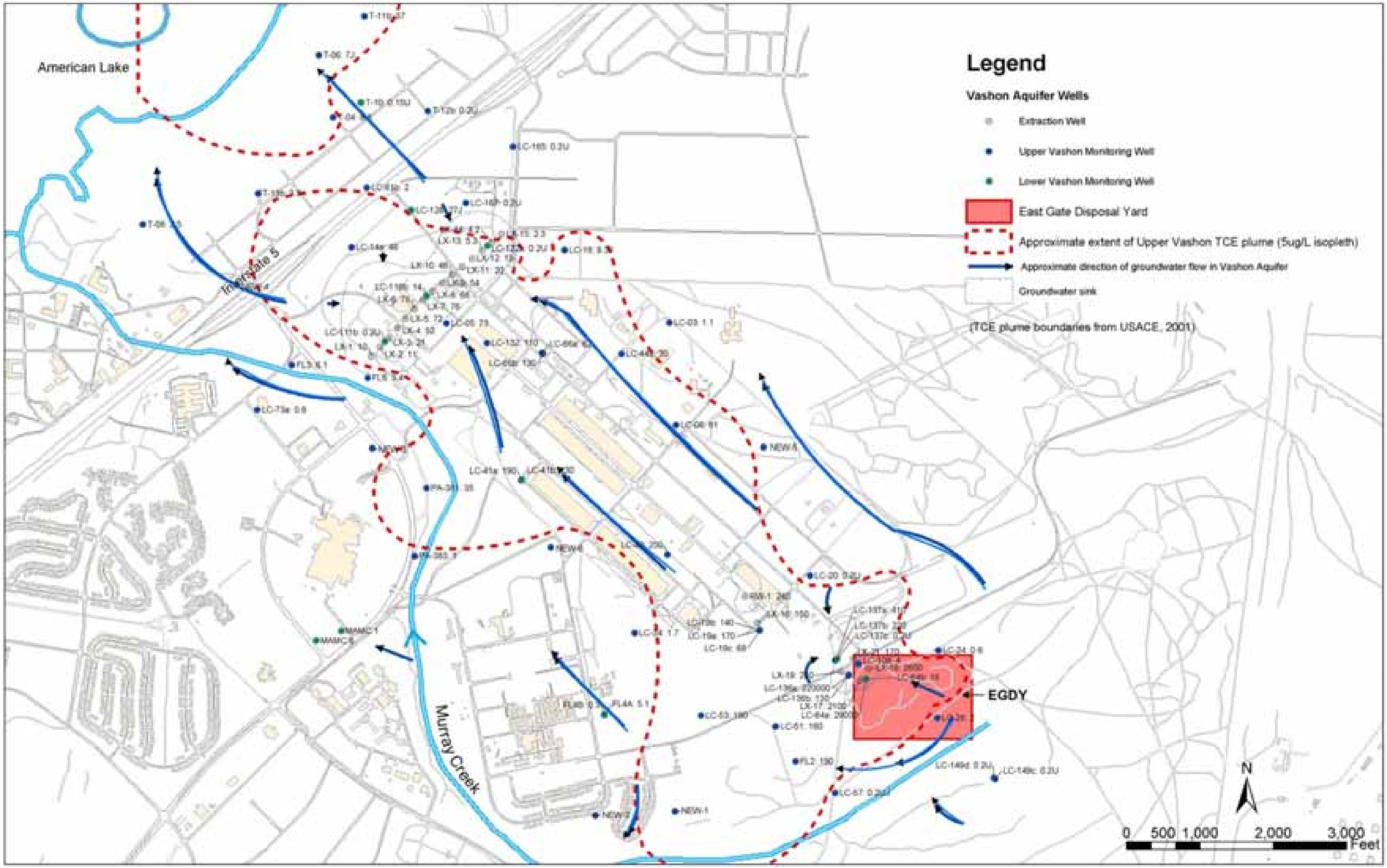


Figure C.1: **Features of Fort Lewis Logistics Center Area** (after Parsons, 2003b) coarse sand with lenses of gravelly sand and sandy silt, sandy gravel with cobbles, and silty gravel with sand and clay seams.

Groundwater within the Vashon Aquifer (also termed the "Upper Aquifer") is unconfined. The aquifer occurs within Vashon Drift deposits and Pre-Olympia Drift deposits, and is subdivided into Upper and Lower Vashon subunits, although regionally these subunits are considered to comprise a single unconfined aquifer. Silty or clayey units within the Vashon deposits and Olympia beds may act locally as discontinuous confining layers, hydraulically separating the Upper and Lower Vashon subunits within the Vashon Aquifer. The stratigraphic units comprising the Lower Vashon Aquifer are laterally discontinuous, and are present beneath the EGDY and in the area north and east of well LC-41 (Figure C.1), but are absent between the EGDY and well LC-41.

The depth to groundwater beneath Fort Lewis is spatially variable, but generally ranges from 5 to 25 feet bgs throughout most of the Logistics Center area. The elevation of the water table fluctuates approximately 5 to 6 feet seasonally, and can change by nearly 15 feet over periods of several years. Regionally, the direction of groundwater movement within the Vashon Aquifer is to the northwest; however, flow directions are locally and seasonally variable. Murray Creek, a northwesterly-flowing stream that discharges into American Lake (Figure C.1), probably affects local groundwater gradients in the upper part of the Vashon Aquifer. The calculated horizontal velocity of groundwater movement in the more-permeable strata within the Vashon Aquifer, which are the primary pathways for groundwater movement and contaminant migration at the Logistics Center area, ranges up to about 15 feet per day (ft/day), or more than 5,000 feet per year (ft/year).

C1.3 NATURE AND EXTENT OF CONTAMINANTS IN GROUNDWATER

TCE has been identified as the primary contaminant in groundwater beneath the Logistics Center, based on its widespread detection in wells across the site. Other contaminants of concern (COCs) in groundwater include *cis*-1,2-dichloroethene (*cis*-1,2-DCE), tetrachloroethene (PCE), 1,1,1-trichloroethane (1,1,1-TCA), and vinyl chloride (VC). TCE, DCE, and TCA have been detected consistently in many wells, while PCE and VC have been detected only sporadically, in a few wells. The former waste-disposal trenches at the EGDY are the apparent source of these chlorinated aliphatic hydrocarbon compounds (CAHs) in groundwater beneath, and downgradient from the Logistics Center.

Within the Vashon Aquifer, TCE is present in groundwater at concentrations exceeding the federal drinking-water maximum contaminant level (MCL) of 5 micrograms per liter (µg/L) (U.S. Environmental Protection Agency [U.S. EPA], 2000), at distances extending more than 2 miles downgradient from the EGDY to American Lake, where contaminants originating at the EGDY are presumed to discharge. CAH constituents have migrated in groundwater to the west-southwest from the EDGY source area toward Murray Creek, probably as a consequence of a local westerly hydraulic gradient; and CAHs also apparently have migrated in groundwater to a gaining reach of Murray Creek, where contaminated groundwater discharges to the stream (Figure C.1).

In most locations at the Logistics Center area, the extent of TCE in groundwater, as defined by the 5-µg/L isopleth for TCE, has remained relatively stable since it was assessed during the remedial investigation (completed in 1990). The westernmost extent of COCs in groundwater was poorly defined until recently; therefore, as a consequence of the lack of historic contaminant-concentration data in this area, it is not known whether the western edge of the plume is stable, expanding, or contracting. The concentrations of TCE and *cis*-1,2-DCE in groundwater samples from most wells in the Logistics Center area have remained relatively constant since the late 1980s. COC concentrations at some wells (primarily extraction wells and monitoring wells near extraction wells) have exhibited slight decreasing trends, while other wells within the interior of the plume have exhibited slight increasing trends over time.

Two groundwater extraction and treatment systems have been in operation at the Fort Lewis Logistics Center since 1995, to address contaminated groundwater in the Vashon Aquifer. The "I-5 system", which consists of 15 extraction wells and 4 infiltration galleries installed near the northwest installation boundary (Figure C.1), is operated to prevent the continued migration of contaminated groundwater in the Vashon Aquifer across the installation boundary. The "East Gate system", consisting of a 4-well primary extraction system and a 2-well secondary system, was installed to remove and treat contaminated groundwater from the Vashon Aquifer directly downgradient from the source area in the former EGDY.

C1.4 CURRENT GROUNDWATER MONITORING PROGRAM IN LOGISTICS CENTER AREA

Beginning in December 1995, groundwater monitoring was conducted at the Logistics Center on a quarterly basis. In conjunction with the monitoring program, 38 monitoring wells and 21 groundwater extraction wells were sampled, resulting in 236 primary samples per year (59 wells each sampled four times per year) (Table C.1). (Note that Table C.1 is based upon information provided in Parsons [2003b].) The primary objectives of the monitoring program, as expressed in the monitoring plan, are to confirm that the groundwater extraction systems are preventing the continued migration of contaminants in groundwater to downgradient locations, to evaluate potential reductions in contaminant concentrations through time, to assess temporal changes in the lateral and vertical extent of contaminants in groundwater within the Vashon Aquifer, and to assess the rate of removal of contaminant mass from the subsurface.

The Upper and Lower Vashon subunits are regarded as two distinct monitoring zones in the groundwater system beneath the Logistics Center area. Most groundwater monitoring wells are completed in the upper monitoring zone (the "Upper Vashon" zone); relatively few monitoring wells are completed in the lower monitoring zone (the "Lower Vashon" zone). As part of an LTMO evaluation of the groundwater extraction system and associated monitoring network at the Logistics Center, completed in May 2001 by the Fort Lewis project team using MAROS Version 1, all available TCE concentration data were examined to determine whether sampling frequencies could be reduced, and concurrently to identify those wells that were most suited for continued monitoring of the performance of the groundwater-extraction remedy. No extraction wells were considered for removal from the network. Based on the results of the May 2001 LTMO evaluation, 24 monitoring wells were added to the Logistics Center monitoring program, and 11 previously-sampled monitoring wells were removed from the program (a net increase of 13 monitoring wells), and sampling frequencies generally were reduced (Table C.1). The revised Logistics Center monitoring program (LOGRAM), which was initiated in December 2001, includes 72 wells -- 51 Vashon Aquifer monitoring wells (29 wells sampled quarterly, 3 wells sampled semi-annually, and 19 wells sampled annually), and all 21 extraction wells (6 wells sampled quarterly and 15 wells sampled annually). The reduction in sampling frequency at a number of wells (Table C.1) produced a net reduction in the total number of primary samples collected and analyzed per year, from 236 samples to 180 samples. All samples from the monitoring and extraction wells are analyzed for volatile organic compounds (VOCs) using U.S. EPA Method SW8260B.

Table C.1: Groundwater Monitoring Program at Fort Lewis Logistics Center Area[a/]

Well ID	Sampling Frequency[b/] (prior to December 2001)	Sampling Frequency[b/] (after December 2001)
Monitoring Wells Completed in Upper Vashon Subunit		
FL2 (new[c/])	NA[d/]	Annual
FL3 (new)	NA	Quarterly
FL4B (new)	NA	Quarterly
FL6 (new)	NA	Quarterly
LC-03	Quarterly	Quarterly
LC-05	Quarterly	Annual
LC-06	Quarterly	Semi-Annual
LC-14a	Quarterly	Annual
LC-16 (new)	NA	Quarterly
LC-19a	Quarterly	Quarterly
LC-19b	Quarterly	-- [e/]
LC-19c	Quarterly	--
LC-20 (new)	NA	Quarterly
LC-24 (new)	NA	Quarterly
LC-26	Quarterly	Annual
LC-34 (new)	NA	Quarterly
LC-41a	Quarterly	Annual
LC-44a	Quarterly	--
LC-49	Quarterly	Annual
LC-51	Quarterly	--
LC-53	Quarterly	Annual
LC-57 (new)	NA	Quarterly
LC-61b (new)	NA	Quarterly
LC-64a	Quarterly	Quarterly
LC-66a	Quarterly	--
LC-66b	Quarterly	Annual
LC-73a	Quarterly	--
LC-108	Quarterly	--
LC-132	Quarterly	--
LC-136a	Quarterly	Quarterly
LC-136b	Quarterly	Annual
LC-137a	Quarterly	--
LC-137b	Quarterly	Quarterly
LC-149c	Quarterly	Annual
LC-149d	Quarterly	--
LC-165	Quarterly	--
LC-167 (new)	NA	Quarterly
NEW-1 (new)	NA	Quarterly

Table C.1: Groundwater Monitoring Program at Fort Lewis Logistics Center Area

Well ID	Sampling Frequency (prior to December 2001)	Sampling Frequency (after December 2001)
Monitoring Wells Completed in Upper Vashon Subunit (continued)		
NEW-2 (new)	NA	Quarterly
NEW-3 (new)	NA	Quarterly
NEW-4 (new)	NA	Quarterly
NEW-5 (new)	NA	Quarterly
NEW-6 (new)	NA	Quarterly
PA-381	Quarterly	Annual
PA-383	Quarterly	Annual
T-04	Quarterly	Annual
T-06 (new)	NA	Quarterly
T-08	Quarterly	Semi-Annual
T-11b (new)	NA	Quarterly
T-12b	Quarterly	Quarterly
T-13b	Quarterly	Semi-Annual
Monitoring Wells Completed in Lower Vashon Subunit		
FL4A (new)	NA	Quarterly
LC-41b (new)	NA	Quarterly
LC-64b	Quarterly	Annual
LC-111b	Quarterly	Annual
LC-116b	Quarterly	Annual
LC-122b	Quarterly	Annual
LC-128	Quarterly	Annual
LC-137c	Quarterly	Annual
MAMC 1 (new)	NA	Quarterly
MAMC 6 (new)	NA	Quarterly
T-10 (new)	NA	Quarterly
Groundwater Extraction Wells		
LX-1	Quarterly	Annual
LX-2	Quarterly	Annual
LX-3	Quarterly	Annual
LX-4	Quarterly	Annual
LX-5	Quarterly	Annual
LX-6	Quarterly	Annual
LX-7	Quarterly	Annual
LX-8	Quarterly	Annual
LX-9	Quarterly	Annual
LX-10	Quarterly	Annual
LX-11	Quarterly	Annual
LX-12	Quarterly	Annual
LX-13	Quarterly	Annual
LX-14	Quarterly	Annual
LX-15	Quarterly	Annual
LX-16	Quarterly	Quarterly

Table C.1: Groundwater Monitoring Program at Fort Lewis Logistics Center Area

Well ID	Sampling Frequency (prior to December 2001)	Sampling Frequency (after December 2001)
Groundwater Extraction Wells (continued)		
LX-17	Quarterly	Quarterly
LX-18	Quarterly	Quarterly
LX-19	Quarterly	Quarterly
LX-21	Quarterly	Quarterly
RW-1	Quarterly	Quarterly

a/ Information from Parsons (2003b).
b/ Sampling frequencies were adjusted in conjunction with other revisions to the groundwater monitoring program in December 2001.
c/ "new" indicates that the well was not included in the monitoring program prior to December 2001.
d/ NA = well was not sampled prior to December 2001.
e/ A dash (--) indicates that the well is not included in the current monitoring program.

C1.5 SUMMARY OF LTMO EVALUATION COMPLETED USING MAROS TOOL

C1.5.1 Summary of Groundwater Analytical Data for Logistics Center Area Used in MAROS Evaluation

Because extensive historical data were not available for the new wells installed during implementation of the current LOGRAM monitoring program, the MAROS tool was used to evaluate data from the 59 monitoring wells included in the original monitoring program (the program that was in effect prior to December 2001), and was not used to evaluate the LOGRAM program. Rather, the groundwater monitoring program at the Logistics Center area was evaluated using the MAROS tool, applied to the results of quarterly sampling events completed during the period November 1995 through September 2001, prior to development and implementation of the LOGRAM program (GSI, 2003a). By September 2001, 24 separate monitoring events had been completed at the Logistics Center area. The historic sampling results for the 59 wells that remained in the monitoring program in September 2001 (21 extraction wells and 38 monitoring wells; Column 2 of Table C.1) were examined in the MAROS evaluation. The locations of these wells, and their status in the current monitoring program, are presented on Figure C.2.

Prior to the evaluation, wells that potentially would provide "redundant" information were identified on the basis of qualitative considerations; the following monitoring wells were identified as redundant with other, existing wells:

- Wells LC-19b and LC-19c were redundant with existing well LC-19a;
- Well LC-66a was redundant with well LC-66b;
- Well LC-137a was redundant with well LC-137b; and
- Well LC-149d was redundant with well LC-149c.

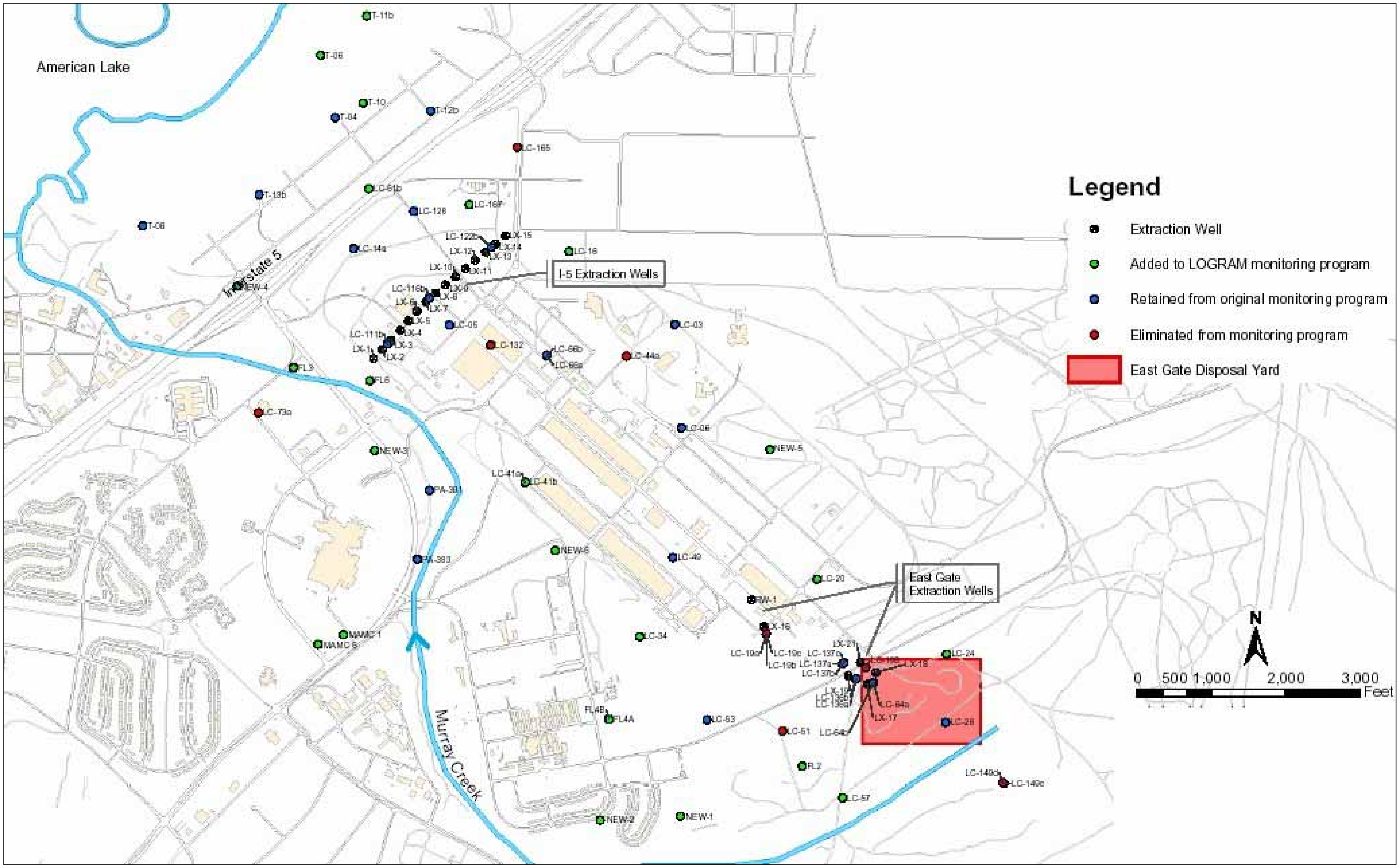


Figure C.2 Groundwater Monitoring Network at Fort Lewis Logistics Center Area (after Parsons, 2003b)

Wells considered to be "redundant" with other wells were not included in the moment analysis or in the spatial evaluation (using the Delaunay method; Appendix B). Historic monitoring results from all monitoring and extraction wells were included in the temporal evaluation (using the modified cost-effective sampling [CES] approach; Appendix B). However, results from groundwater extraction wells were not used in the spatial evaluation; and the results from two monitoring wells completed in the lower part of the Lower Vashon subunit (wells LC-64b and LC-137c) also were excluded from the spatial evaluation, because these two wells were considered to be within a different monitoring zone than the other monitoring wells (Appendix D-1).

At the beginning of the MAROS evaluation, the sampling-results database provided by the US Army Corps of Engineers (USACE) was processed to remove duplicate data measurements, by averaging the primary and duplicate analytical results and using this average to represent a single value detected at that sampling point, during that sampling event. Concentration values that were below reporting limits were replaced with surrogate values, selected to be the minimum reporting limit for that particular constituent, a procedure that assumes that reporting limits remained uniform through time. Trace-level results were represented by their actual values. The processed database contained analytical data for the 38 monitoring wells and 21 extraction wells in service in September 2001.

Although five COCs (PCE, TCE, *cis*-1,2-DCE, VC, and 1,1,1-TCA) historically have been detected in groundwater at the site (Section C1.3), TCE was used as an indicator compound, based on its widespread detection at relatively elevated concentrations in wells across the site; and the MAROS evaluation of the monitoring program at the Fort Lewis Logistics Center area used only the results of analyses for TCE in groundwater samples.

C1.5.2 Results of Evaluation Completed Using MAROS Tool

Application of the Mann-Kendall and linear regression temporal trend evaluation methods (Appendices A and B) indicated that the trends in TCE concentrations at about 60 percent of the monitoring wells designated as "source area" wells were "Probably Decreasing", "Decreasing", or "Stable", while TCE concentrations at extraction wells in the source area all were "Probably Decreasing", or "Decreasing". This indicated that the extent and concentrations of TCE in groundwater at the Logistics Center source area (the EGDY) probably are decreasing (GSI, 2003a). TCE concentrations in groundwater at most of the extraction wells located northwest of the EGDY source area were "Probably Decreasing", "Decreasing", or "Stable"; and about one-half of the wells in the "tail" and off-axis parts of the plume displayed similar TCE concentration trends. The results of the moment analysis (Appendix B) indicated that the location of the center of mass of the plume has remained essentially unchanged, and the extent of TCE in groundwater has decreased over time, providing further evidence that the plume is stable. The evaluation of overall plume stability (Appendix B) indicated that the extent of TCE in groundwater of the upper Vashon Aquifer is stable or decreasing, resulting in the recommendation that a monitoring strategy appropriate for a "*Moderate"* design category (Appendix B) be adopted.

The results of detailed spatial analyses using the Delaunay method (Appendix B) indicated that 8 monitoring wells could be removed from the original monitoring program (which included 38 monitoring wells) without significant loss of information (Table C.2; compare the results of the MAROS evaluation with the original and LOGRAM monitoring programs). However, the accompanying well sufficiency analysis indicated that there is a high degree of uncertainty in predicted TCE concentrations in six areas within the network where the available historic sampling information may be inadequate; new monitoring wells were recommended for installation in these six areas (GSI, 2003a). These six locations recommended for installation of new wells correspond to six wells that had been installed and were being monitored in conjunction with the LOGRAM program (wells FL3, LC-16, LC-20, LC-167, NEW-3, and NEW-5; Table C.2). All groundwater extraction wells were recommended for retention in the refined monitoring program.

Table C.2: Refined Groundwater Monitoring Program at Fort Lewis Logistics Center Area Generated Using the MAROS Tool[a]

Well ID	Historic Sampling Frequency[b] (prior to December 2001)	Historic Sampling Frequency[b] (after December 2001)	Results of MAROS Evaluation: Remove/Retain[c]	Results of MAROS Evaluation: Recommended Sampling Frequency
Monitoring Wells Completed in Upper Vashon Subunit				
FL2 (new[d])	NA[e]	Annual	Not Considered[f]	--[g]
FL3 (new)	NA	Quarterly	Add[h]	Quarterly
FL4B (new)	NA	Quarterly	Not Considered	--
FL6 (new)	NA	Quarterly	Not Considered	--
LC-03	Quarterly	Quarterly	Retain	Annual
LC-05	Quarterly	Annual	Retain	Quarterly
LC-06	Quarterly	Semi-Annual	Retain	Quarterly
LC-14a	Quarterly	Annual	Retain	Annual
LC-16 (new)*	NA	Quarterly	Add	Quarterly
LC-19a	Quarterly	Quarterly	Retain	Annual
LC-19b	Quarterly	--	Remove	--
LC-19c	Quarterly	--	Remove	--
LC-20 (new)*	NA	Quarterly	Add	Quarterly
LC-24 (new)	NA	Quarterly	Not Considered	--
LC-26	Quarterly	Annual	Retain	Annual
LC-34 (new)	NA	Quarterly	Not Considered	--
LC-41a	Quarterly	Annual	Retain	Quarterly
LC-44a	Quarterly	--	Remove	--
LC-49	Quarterly	Annual	Retain	Semi-Annual
LC-51	Quarterly	--	Remove	--
LC-53	Quarterly	Annual	Retain	Quarterly
LC-57 (new)	NA	Quarterly	Not Considered	--
LC-61b (new)	NA	Quarterly	Not Considered	--
LC-64a	Quarterly	Quarterly	Retain	Quarterly
LC-66a	Quarterly	--	Remove	--
LC-66b	Quarterly	Annual	Retain	Annual
LC-73a	Quarterly	--	Retain	Biennial
LC-108	Quarterly	--	Retain	Annual
LC-132	Quarterly	--	Retain	Quarterly
LC-136a	Quarterly	Quarterly	Retain	Quarterly
LC-136b	Quarterly	Annual	Remove	--
LC-137a	Quarterly	--	Remove	--
LC-137b	Quarterly	Quarterly	Retain	Quarterly
LC-149c	Quarterly	Annual	Retain	Biennial
LC-149d	Quarterly	--	Remove	--
LC-165	Quarterly	--	Retain	Biennial

Table C.2: Refined Groundwater Monitoring Program at Fort Lewis Logistics Center Area Generated Using the MAROS Tool

Well ID	Historic Sampling Frequency (prior to December 2001)	Historic Sampling Frequency (after December 2001)	Results of MAROS Evaluation: Remove/Retain	Results of MAROS Evaluation: Recommended Sampling Frequency
Monitoring Wells Completed in Upper Vashon Subunit (continued)				
LC-167 (new)*	NA	Quarterly	Add	Quarterly
NEW-1 (new)	NA	Quarterly	Not Considered	--
NEW-2 (new)	NA	Quarterly	Not Considered	--
NEW-3 (new)*	NA	Quarterly	Add	Quarterly
NEW-4 (new)	NA	Quarterly	Not Considered	--
NEW-5 (new)*	NA	Quarterly	Add	Quarterly
NEW-6 (new)	NA	Quarterly	Not Considered	--
PA-381	Quarterly	Annual	Retain	Annual
PA-383	Quarterly	Annual	Retain	Biennial
T-04	Quarterly	Annual	Retain	Annual
T-06 (new)	NA	Quarterly	Not Considered	--
T-08	Quarterly	Semi-Annual	Retain	Annual
T-11b (new)	NA	Quarterly	Not Considered	--
T-12b	Quarterly	Quarterly	Retain	Annual
T-13b	Quarterly	Semi-Annual	Retain	Annual
Monitoring Wells Completed in Lower Vashon Subunit				
FL4a (new)	NA	Quarterly	Not Considered	--
LC-41b (new)	NA	Quarterly	Not Considered	--
LC-64b	Quarterly	Annual	Retain	Annual
LC-111b	Quarterly	Annual	Retain	Biennial
LC-116b	Quarterly	Annual	Retain	Semi-Annual
LC-122b	Quarterly	Annual	Retain	Biennial
LC-128	Quarterly	Annual	Retain	Annual
LC-137c	Quarterly	Annual	Retain	Annual
MAMC 1	NA	Quarterly	Not Considered	--
MAMC 6 (new)	NA	Quarterly	Not Considered	--
T-10 (new)	NA	Quarterly	Not Considered	--
Groundwater Extraction Wells				
LX-1	Quarterly	Annual	Retain	Annual
LX-2	Quarterly	Annual	Retain	Annual
LX-3	Quarterly	Annual	Retain	Annual
LX-4	Quarterly	Annual	Retain	Annual
LX-5	Quarterly	Annual	Retain	Annual
LX-6	Quarterly	Annual	Retain	Annual
LX-7	Quarterly	Annual	Retain	Annual
LX-8	Quarterly	Annual	Retain	Annual
LX-9	Quarterly	Annual	Retain	Annual
LX-10	Quarterly	Annual	Retain	Annual
LX-11	Quarterly	Annual	Retain	Annual
LX-12	Quarterly	Annual	Retain	Annual
LX-13	Quarterly	Annual	Retain	Annual
LX-14	Quarterly	Annual	Retain	Annual
LX-15	Quarterly	Annual	Retain	Annual
LX-16	Quarterly	Quarterly	Retain	Quarterly
LX-17	Quarterly	Quarterly	Retain	Quarterly

Table C.2: Refined Groundwater Monitoring Program at Fort Lewis Logistics Center Area Generated Using the MAROS Tool

Well ID	Historic Sampling Frequency		Results of MAROS Evaluation	
	(prior to December 2001)	(after December 2001)	Remove/Retain	Recommended Sampling Frequency
Groundwater Extraction Wells (continued)				
LX-18	Quarterly	Quarterly	Retain	Quarterly
LX-19	Quarterly	Quarterly	Retain	Quarterly
LX-21	Quarterly	Quarterly	Retain	Annual
RW-1	Quarterly	Quarterly	Retain	Quarterly

[a/] Information from GSI (2003a).
[b/] Sampling frequencies were adjusted in conjunction with other revisions to the groundwater monitoring program in December 2001.
[c/] "Remove" = MAROS recommended that the well be removed from the monitoring program.
"Retain" = MAROS recommended that the well continue to be sampled at the indicated frequency.
[d/] "new" = the well was not included in the monitoring program prior to December 2001.
[e/] NA = well was not sampled prior to December 2001.
[f/] "Not Considered" = the well was not included in the MAROS evaluation.
[g/] A dash (--) indicates that the well is not included in the current or refined monitoring program.
[h/] Add = current LOGRAM well identified by MAROS for inclusion in the refined monitoring program.

Using a modified CES method, MAROS applies the results of the temporal-trend analysis to develop recommendations regarding sampling frequency for each well in a monitoring program (Appendix B). However, because MAROS substitutes a surrogate value (typically, the laboratory reporting limit) for measurements that are below the reporting limit (Appendix B), the algorithm cannot distinguish between a well at which detectable concentrations of COCs never have occurred (i.e., "Not Detected" classification in the three-tiered approach; Appendix B) and a well which historically has contained very low (but detectable) concentrations of COCs in samples. Logically, a well having no detectable concentrations of COCs throughout its monitoring history should be assigned a "Stable" classification by MAROS, based on the criteria presented in Table B.4 (i.e., a Mann-Kendall test statistic of zero and a covariance less than 1). However, because reporting limits can vary through time or among samples, it is possible for MAROS to identify spurious trends in COC concentrations for such wells. To partially rectify this shortcoming, the minimum reporting limit for TCE was assigned to all sampling results for TCE which were below reporting limits (Section C1.5.1). Although this substitutional procedure assumes that reporting limits remained uniform through time, and potentially introduces bias into the result, its application resulted in assignment of a "Stable" classification by MAROS to TCE concentrations in the only well at the Fort Lewis Logistics Center area having no detectable concentrations of TCE in groundwater samples collected throughout its monitoring history (well LC-149c) (GSI, 2003a, Appendix B, "Statistical Trend Analysis Summary").

MAROS also may identify spurious temporal trends in COC concentrations at wells where COCs historically have been detected, particularly if measured concentrations have been below practical quantitation limits (this situation corresponds to the "below PQL" classification in the three-tiered LTMO approach; Appendix B). Wells at which TCE was been detected historically at low frequencies and low concentrations, but for which MAROS identified a trend that differed from a "Stable" trend, using either linear regression or the Mann-Kendall test, are shaded in Table C.2, together with the sampling frequencies developed using TCE concentration trends, even though the "trends" identified for those wells by MAROS may be spurious. For example, even though TCE has been measured at concentrations greater than the reporting limit in only one of eight samples collected and analyzed through the entire period of monitoring at well T-12b, MAROS identified "No Trend" in concentrations of TCE in samples from this well using the Mann-Kendall test (GSI, 2003a, Appendix B, "Statistical Trend Analysis Summary"). In this instance, assigning a classification of a "Stable" trend probably would be more appropriate. Such a classification should be inserted by the practitioner, following examination and evaluation of output generated by MAROS.

The results of the sampling frequency optimization analysis completed by MAROS indicated that most wells in the monitoring network could be sampled less frequently than once per quarter. The results of the data sufficiency evaluation, completed using power analysis methods (Appendix B), indicated that remedial action objective (RAO) concentrations of TCE in groundwater have nearly been achieved at the compliance boundary 2,000 feet downgradient from well LC-19a (the well furthest downgradient from the EGDY source area). This suggests that the monitoring program is adequate to evaluate the extent of TCE in groundwater relative to the compliance boundary through time (GSI, 2003a).

The optimized monitoring program generated using the MAROS tool includes 57 wells, with 19 sampled quarterly, 2 sampled semiannually, 30 sampled annually, and 6 sampled biennially (Table C.2). Adoption of the optimized program would result in collection and analysis of 113 samples per year, as compared with collection and analysis of 180 samples per year in the current LOGRAM monitoring program and 236 samples per year in the original sampling program. Implementing these recommendations could lead to a 37-percent reduction in the number of samples collected and analyzed annually, as compared with the current LOGRAM program, or a 52-percent reduction in the number of samples collected and analyzed, as compared with the original (pre-December 2001) program. Assuming a cost per sample of $500 for collection and chemical analyses, adoption of the monitoring program as optimized using the MAROS tool is projected to result in savings of approximately $33,500 per year as compared with the LOGRAM program. (The estimated cost per sample is based on information provided by facility personnel in conjunction with efforts to estimate potential cost savings resulting from optimization of the monitoring program, and includes costs associated with sample collection and analysis, data compilation and reporting, and handling of materials generated as investigation-derived waste [IDW] during sample collection [e.g., purge water].) The optimized program remains adequate to delineate the extent of TCE in groundwater, and to monitor changes in the plume over time (GSI, 2003a).

C1.6 SUMMARY OF LTMO EVALUATION COMPLETED USING THREE-TIERED APPROACH

C1.6.1 Summary of Groundwater Analytical Data for Logistics Center Area Used in Three-Tiered Approach

The groundwater monitoring program at the Logistics Center area also was evaluated using the three-tiered approach, applied to the results of quarterly sampling events completed during the period February 1995 through December 2001 (Parsons, 2003b). During that period, a total of 83 wells (21 extraction wells and 62 monitoring wells) have been sampled, in conjunction with the original monitoring program, the LOGRAM monitoring program, or both (Table C.1). Prior to the evaluation, the sampling-results database provided by the USACE was processed to remove duplicate data measurements by retaining the greater of the primary and duplicate analytical results, and discarding the lower value. The database that was utilized in the three-tiered evaluation of the groundwater monitoring program for the Logistics Center area differed slightly from the database that was utilized in the corresponding MAROS evaluation in the following respects:

- The three-tiered approach was applied using a database having a slightly longer historical period of record, extending from February 1995 through December 2001, versus a historical period of record extending from November 1995 through September 2001 that was utilized in the MAROS evaluation (Section C1.5.1).

- The method used in the three-tiered approach to deal with analytical results from duplicate samples (retaining the greater of the primary and duplicate analytical results, and discarding the lower value) differed from the method used in the MAROS evaluation (averaging the primary and duplicate analytical results, and using this average to represent a single value; Section C1.5.1).

- The method used in the three-tiered approach to deal with concentration values that were below reporting limits (value reported as "Not Detected"; Appendix B) differed from the method adopted in the MAROS evaluation (assigning a surrogate value corresponding to the minimum reporting limit for a particular constituent; Appendix B).

The processed database used in the three-tiered evaluation contained analytical data for 74 of the 83 wells included in the original and/or the LOGRAM monitoring program, and contained the results of more than 20 sampling events for each of the 21 extraction wells and the 38 monitoring wells included in the original monitoring program (1995 to December 2001). However, the results of fewer than four sampling events were available for 18 of the wells that were added to the monitoring program in December 2001; and no results were available for 9 of the wells (the six NEW wells, and wells MAMC 1, MAMC 6, and T-11b), which were added to the program in 2001.

TCE is the COC that historically has been detected most frequently (in 90 percent of samples) and at the highest concentrations in groundwater at the Logistics Center area, with TCE concentrations exceeding the MCL for TCE (5 μg/L) in approximately 74 percent of samples (Table C.3). (Note that Table C.3 is based upon information provided in Parsons [2003b].) TCE has been detected in groundwater samples from 71 of the 74 wells for which sampling results are available, and has exceeded its MCL in samples from 56 of these wells. The other primary COCs (*cis*-1,2-DCE, PCE, and VC) have been detected less frequently, at lower concentrations, and in samples from fewer wells than has TCE (Table C.3). Accordingly, TCE was selected as an indicator compound, based on its widespread detection at relatively elevated concentrations in wells across the site. Although the other primary COCs (PCE, *cis*-1,2-DCE, and VC) were considered, together with TCE, in the qualitative and temporal stages of the three-tiered evaluation, the spatial-statistical stage of the three-tiered evaluation of the monitoring program at the Fort Lewis Logistics Center area used only the results of analyses for TCE in groundwater samples. Furthermore, because the Upper Vashon and Lower Vashon subunits are considered to be separate monitoring zones (Section C1.4), and the results of only a single water-bearing unit or monitoring zone can be considered in the spatial-statistical evaluation, the spatial-statistical evaluation was conducted using the sampling results from those monitoring wells completed in the Upper Vashon subunit only. Sampling results from groundwater extraction wells were not used in the spatial-statistical evaluation; however, sampling results from all wells (groundwater extraction wells, and groundwater monitoring wells completed in the Upper Vashon and Lower Vashon subunits) were used in the qualitative and temporal evaluations.

Table C.3: Summary of Occurrence of COCs[a/] in Groundwater at Fort Lewis Logistics Center[b/]

Constituent[c/]	Total Number of Samples Analyzed for Constituent[d/]	Percentage of Samples Having Detected Concentrations	Range of Detected Concentrations (μg/L)[e/]	Number of Wells Having Samples Analyzed for Constituent	Number of Wells at Which Constituent was Detected	MCL[f/] (μg/L)	Percentage of Samples with MCL Exceedances	Number of Wells with MCL Exceedances
cis-1,2-DCE	1,402	80.5%	0.1 - 18,000	73	61	70	5.5%	6
PCE	1,399	15.8%	0.1 - 420	73	43	5	0.50%	3
TCE	1,402	89.9%	0.2 - 250,000	74	71	5	73.8%	56
VC	1,396	1.3%	0.023 - 3,600	73	10	2	0.50%	3

a/ COCs = contaminants of concern.

b/ Information from Parsons (2003b).

c/ Constituents are as follow:
DCE = dichloroethene; PCE = tetrachloroethene; TCE = trichloroethene; VC = vinyl chloride.

d/ Analytical data include sampling results from February 1995 through December 2001.

e/ μg/L = micrograms per liter.

f/ MCL = maximum contaminant level.

C1.6.2 Results of Evaluation Completed Using Three-Tiered Approach

The three-tiered approach was used to evaluate the original monitoring program at the Logistics Center area (which included 59 wells), and also was used to evaluate the current LOGRAM program (which includes 72 wells). In the three-tiered evaluation, sampling results for 74 of the 83 wells included in the original and/or the LOGRAM groundwater monitoring programs at the Fort Lewis Logistics Center were evaluated using qualitative hydrogeologic knowledge, temporal statistical techniques, and spatial statistics. (Because extensive historical data were not available for the new wells included in the LOGRAM program, temporal analyses were not used in evaluating the LOGRAM – only qualitative and spatial evaluations of that program were completed for these wells, and as a consequence, the results of evaluation of the two programs are not directly comparable.) At each tier of the evaluation, monitoring points that provide relatively greater amounts of information regarding the occurrence and distribution of COCs in groundwater were identified, and were distinguished from those monitoring points that provide relatively lesser amounts of information. The results of the tiered evaluations were combined and summarized to provide recommendations regarding optimization of the monitoring network, and the frequency of sample collection (Parsons, 2003b).

The results of the three-tiered evaluation indicated that 15 of the 83 existing wells (including 6 of the wells currently monitored in the LOGRAM program) could be removed from the groundwater long-term monitoring (LTM) program with little loss of information (Parsons, 2003b), but also indicated that 2 existing wells that are not currently sampled should be included in the program, and that one new well should be installed and monitored. A refined monitoring program (Table C.4; compare the results of the three-tiered evaluation with the original and LOGRAM monitoring programs), consisting of 69 wells, with 16 wells sampled quarterly, 7 wells sampled semi-annually, 17 wells sampled annually, 14 wells sampled biennially, and the 15 I-5 extraction wells sampled every 3 years, would be adequate to address the two primary objectives of monitoring. If this refined monitoring program were adopted, 107 samples per year would be collected and analyzed, as compared with the collection and analysis of 180 samples per year in the current LOGRAM monitoring program and 236 samples per year in the original sampling program. This would represent a 40-percent reduction in the number of samples collected and analyzed annually, as compared with the LOGRAM program, or a 55-percent reduction in the number of samples collected and analyzed, as compared with the original program. Assuming a cost per sample of $500 for collection and chemical analyses, adoption of the monitoring program as optimized using the three-tiered approach is projected to result in savings of approximately $36,500 per year as compared with the LOGRAM program, or $64,500 per year as compared with the original monitoring program. Additional cost savings could be realized if groundwater samples collected from select wells (e.g., upgradient wells, and wells along the lateral plume margins) were analyzed for a short list of halogenated VOCs using U.S. EPA Method SW8021B instead of U.S. EPA Method SW8260B (Parsons, 2003b).

Table C.4: Refined Groundwater Monitoring Program at Fort Lewis Logistics Center Area Generated Using the Three-Tiered Approach[a/]

	Historic Sampling Frequency[b/]		Results of Three-Tiered Evaluation	
Well ID	(prior to December 2001)	(after December 2001)	Remove/Retain[c/]	Recommended Sampling Frequency
Monitoring Wells Completed in Upper Vashon Subunit				
FL2 (new[d/])	NA[e/]	Annual	Retain	Annual
FL3 (new)	NA	Quarterly	Remove	--[f/]
FL4B (new)	NA	Quarterly	Retain	Biennial
FL6 (new)	NA	Quarterly	Retain	Biennial
LC-03	Quarterly	Quarterly	Retain	Biennial
LC-05	Quarterly	Annual	Remove	--
LC-06	Quarterly	Semi-Annual	Retain	Annual
LC-14a	Quarterly	Annual	Retain	Annual
LC-16 (new)	NA	Quarterly	Remove	--
LC-19a	Quarterly	Quarterly	Retain	Annual
LC-19b	Quarterly	--	Remove	--
LC-19c	Quarterly	--	Remove	--
LC-20 (new)	NA	Quarterly	Retain	Biennial
LC-24 (new)	NA	Quarterly	Retain	Biennial
LC-26	Quarterly	Annual	Remove	--
LC-34 (new)	NA	Quarterly	Retain	Biennial
LC-41a	Quarterly	Annual	Retain	Annual
LC-44a	Quarterly	--	Remove	--
LC-49	Quarterly	Annual	Retain	Annual
LC-51	Quarterly	--	Remove	--
LC-53	Quarterly	Annual	Retain	Annual
LC-57 (new)	NA	Quarterly	Retain	Biennial
LC-61b (new)	NA	Quarterly	Retain	Semi-Annual
LC-64a	Quarterly	Quarterly	Retain	Quarterly
LC-66a	Quarterly	--	Remove	--
LC-66b	Quarterly	Annual	Retain	Annual
LC-73a	Quarterly	--	Remove	--
LC-108	Quarterly	--	Remove	--
LC-132	Quarterly	--	Retain	Annual
LC-136a	Quarterly	Quarterly	Retain	Quarterly
LC-136b	Quarterly	Annual	Retain	Annual
LC-137a	Quarterly	--	Remove	--
LC-137b	Quarterly	Quarterly	Remove	--
LC-149c	Quarterly	Annual	Retain	Biennial
LC-149d	Quarterly	--	Retain	Biennial
LC-165	Quarterly	--	Remove	--
LC-167 (new)	NA	Quarterly	Retain	Semi-Annual
LC-180	**Proposed for installation[g/]**			Annual
NEW-1 (new)	NA	Quarterly	Retain	Quarterly
NEW-2 (new)	NA	Quarterly	Retain	Quarterly

Table C.4: Refined Groundwater Monitoring Program at Fort Lewis Logistics Center Area Generated Using the Three-Tiered Approach

Well ID	Historic Sampling Frequency (prior to December 2001)	Historic Sampling Frequency (after December 2001)	Results of Three-Tiered Evaluation: Remove/Retain	Results of Three-Tiered Evaluation: Recommended Sampling Frequency
Monitoring Wells Completed in Upper Vashon Subunit (continued)				
NEW-3 (new)	NA	Quarterly	Retain	Quarterly
NEW-4 (new)	NA	Quarterly	Retain	Quarterly
NEW-5 (new)	NA	Quarterly	Retain	Quarterly
NEW-6 (new)	NA	Quarterly	Retain	Quarterly
PA-381	Quarterly	Annual	Retain	Biennial
PA-383	Quarterly	Annual	Retain	Biennial
T-04	Quarterly	Annual	Retain	Annual
T-06 (new)	NA	Quarterly	Retain	Quarterly
T-08	Quarterly	Semi-Annual	Retain	Semi-Annual
T-11b (new)	NA	Quarterly	Retain	Quarterly
T-12b	Quarterly	Quarterly	Retain	Biennial
T-13b	Quarterly	Semi-Annual	Retain	Semi-Annual
Monitoring Wells Completed in Lower Vashon Subunit				
FL4a (new)	NA	Quarterly	Retain	Biennial
LC-41b (new)	NA	Quarterly	Retain	Annual
LC-64b	Quarterly	Annual	Retain	Annual
LC-111b	Quarterly	Annual	Retain	Biennial
LC-116b	Quarterly	Annual	Retain	Annual
LC-122b	Quarterly	Annual	Remove	--
LC-128	Quarterly	Annual	Retain	Annual
LC-137c	Quarterly	Annual	Retain	Annual
MAMC 1 (new)	NA	Quarterly	Retain	Quarterly
MAMC 6 (new)	NA	Quarterly	Retain	Quarterly
T-10 (new)	NA	Quarterly	Retain	Semi-Annual
Groundwater Extraction Wells				
LX-1	Quarterly	Annual	Retain	Every 3 years
LX-2	Quarterly	Annual	Retain	Every 3 years
LX-3	Quarterly	Annual	Retain	Every 3 years
LX-4	Quarterly	Annual	Retain	Every 3 years
LX-5	Quarterly	Annual	Retain	Every 3 years
LX-6	Quarterly	Annual	Retain	Every 3 years
LX-7	Quarterly	Annual	Retain	Every 3 years
LX-8	Quarterly	Annual	Retain	Every 3 years
LX-9	Quarterly	Annual	Retain	Every 3 years
LX-10	Quarterly	Annual	Retain	Every 3 years
LX-11	Quarterly	Annual	Retain	Every 3 years
LX-12	Quarterly	Annual	Retain	Every 3 years
LX-13	Quarterly	Annual	Retain	Every 3 years
LX-14	Quarterly	Annual	Retain	Every 3 years
LX-15	Quarterly	Annual	Retain	Every 3 years

Table C.4: Refined Groundwater Monitoring Program at Fort Lewis Logistics Center Area Generated Using the Three-Tiered Approach

Well ID	Historic Sampling Frequency (prior to December 2001)	Historic Sampling Frequency (after December 2001)	Results of Three-Tiered Evaluation: Remove/Retain	Results of Three-Tiered Evaluation: Recommended Sampling Frequency
Groundwater Extraction Wells (continued)				
LX-16	Quarterly	Quarterly	Retain	Semi-Annual
LX-17	Quarterly	Quarterly	Retain	Quarterly
LX-18	Quarterly	Quarterly	Retain	Quarterly
LX-19	Quarterly	Quarterly	Retain	Quarterly
LX-21	Quarterly	Quarterly	Retain	Quarterly
RW-1	Quarterly	Quarterly	Retain	Semi-Annual

[a/] Information from Parsons (2003b).

[b/] Sampling frequencies were adjusted in conjunction with other revisions to the groundwater monitoring program in December 2001.

[c/] "Remove" = Three-tiered evaluation recommended that the well be removed from the monitoring program.
"Retain" = Three-tiered evaluation recommended that the well continue to be sampled at the indicated frequency.

[d/] "new" = the well was not included in the monitoring program prior to December 2001.

[e/] NA = well was not sampled prior to December 2001.

[f/] A dash (--) indicates that the well is not included in the current or refined monitoring program.

[g/] "Proposed for installation" indicates that a location for an additional monitoring well was identified on the basis of the evaluation.

C2.0 LONG PRAIRIE GROUNDWATER CONTAMINATION SUPERFUND SITE, MINNESOTA

The following summary of information regarding the location, operational history, geology, and hydrogeology of the Groundwater Contamination Superfund Site at Long Prairie, Minnesota (Long Prairie site), the current monitoring program, available chemical data that were used in the monitoring-program evaluations, and the results of the LTMO evaluations, has been excerpted from Parsons (2003c) and GSI (2003b). Copies of both documents are included in Appendix D-2; the reader is referred to the Appendix for additional details.

C2.1 SITE DESCRIPTION AND HISTORY

The town of Long Prairie, Minnesota is a small farming community located on the east bank of the Long Prairie River, in Todd County, central Minnesota, about 120 miles northwest of the Minneapolis/St. Paul metroplex. The Long Prairie site comprises a 0.16-acre source area of contaminated soil that has generated a plume of dissolved CAH contaminants in the drinking-water aquifer underlying the north-central part of town. The source of contaminants in groundwater was a dry-cleaning establishment, which operated from 1949 through 1984 in the town's commercial district. Spent dry-cleaning solvents, primarily PCE, were discharged into the subsurface via a french drain. The subsequent migration of contaminants through the vadose zone to groundwater produced a dissolved CAH plume that has migrated to the north a distance of at least 3,600 feet from the source area, extending beneath a residential neighborhood and to within 500 feet of the Long Prairie River.

Contaminants first were identified in groundwater in 1983, during a survey of municipal drinking-water-supply wells for synthetic organic contaminants. PCE and other CAHs, including TCE and *cis*-1,2-DCE, were detected in samples from two wells (wells CW4 and CW5) of the five Long Prairie municipal water-supply wells, which are completed in the lower unit of the Long Prairie Sand Plain aquifer. CAH contaminants also were detected in samples from eight of 21 residential wells that were sampled. Subsequently, a remedial investigation and feasibility study (RI/FS) was completed in accordance with the terms of a Multi-Site Cooperative Agreement signed in 1984 between the Minnesota Pollution Control Agency (MPCA) and the U.S. EPA. Based on the results of the RI/FS, the Long Prairie Groundwater Contamination Site was promulgated to the National Priorities List (NPL) in 1985, and a Record of Decision (ROD) was signed in 1988.

The ROD established three OUs at the Long Prairie site. The plume of contaminated groundwater was identified as OU1; the response action at OU1 consists of extraction of CAH-contaminated groundwater via nine extraction wells, treatment of the extracted water, and discharge of treated water to the Long Prairie River. Operation of the groundwater extraction, treatment, and discharge (ETD) system is intended to restore aquifer quality to MCLs, and to prevent further migration and discharge of the CAH plume to the Long Prairie River. The source-area soils were designated as OU2, and were addressed by means of a soil-vapor extraction (SVE) system. OU3 comprises an alternative water supply system, which provided municipal water hookups to local residents with private wells affected by CAH contaminants.

The performance of the OU1 groundwater extraction and treatment system is monitored by means of periodic sampling of monitoring wells and water-supply wells, and routine operations and maintenance (O&M) monitoring of the extraction and treatment systems. The program that was established to monitor the concentrations and extent of contaminants in groundwater in the vicinity of, and downgradient from the PCE source area, and to assess the performance of the OU1 groundwater ETD system (Section C2.3), was the subject of the MAROS and three-tiered evaluations.

C2.2 GEOLOGY AND HYDROGEOLOGY

The earth materials underlying the town of Long Prairie consist of a series of glacial till and outwash deposits nearly 700 feet thick, that were deposited in a large valley along the Long Prairie River. Outwash sediments within the valley comprise coarse sands and gravels deposited during two separate periods of glaciation; the outwash deposits are separated by finer-grained tills. The uppermost distinct geologic unit is called the surficial, upper outwash unit, and is present only within the glacial valley. The upper outwash unit is underlain by a till deposit (the upper Wadena till), which is not present everywhere in the vicinity. Beneath the upper Wadena till is the lower outwash unit, which in turn is underlain by a lower till deposit. The upper Wadena till is absent immediately east of the Long Prairie River, and in this area the upper and lower outwash deposits are in physical and hydraulic contact, and form a single hydrogeologic unit. However, the upper Wadena till is intact along the eastern side of the outwash valley, and where present, functions as a confining unit lying between the upper and lower outwash units. In these areas, groundwater within the lower outwash unit is present under confined to semi-confined conditions. Where the upper Wadena till is absent, groundwater in the outwash aquifer occurs under water-table (unconfined) conditions. Groundwater at all locations within the surficial, upper outwash unit is under water-table (unconfined) conditions. The vertical hydraulic gradients between the upper and lower outwash deposits generally are negligible, but may be slightly downward near the northern end of the CAH plume.

The solvent release at the Long Prairie site occurred in an area where the upper Wadena till is present between the upper and lower outwash units. However, the till is not present immediately north of the source area, and CAH contaminants are present in groundwater in both the upper and lower parts of the outwash deposits west of the western edge of the upper Wadena till. Because the upper and lower outwash units are in direct hydraulic communication where the confining till is absent, it is possible for contaminants originating at the solvent-release source area to move from the upper outwash unit into the lower outwash unit, and then to be drawn into the city wells (wells CW3 and CW6) which are completed in the lower outwash unit to the east of the source area (Figure C.3). The directions of groundwater movement in the upper and lower outwash deposits generally are parallel to the channel of the Long Prairie River, suggesting that the river is not in direct hydraulic communication with the groundwater system, and that the influence of the river on the configuration of the groundwater potentiometric surface (and on the directions of groundwater movement) in the area is limited. Groundwater moves to the northeast beneath the PCE source area, to the vicinity of extraction wells RW5 and RW7, and from there moves west-northwest toward the Long Prairie River (Figure C.3). The directions of groundwater movement also are influenced locally by pumping of the city water-supply wells, and by operation of the OU1 extraction wells. The calculated horizontal velocity of groundwater movement in the upper outwash unit ranges up to about 1.7 ft/day, or more than 600 ft/year. The hydraulic properties of the lower outwash unit are inferred to be comparable to those of the upper outwash unit, and the corresponding rates of groundwater movement probably also are comparable.

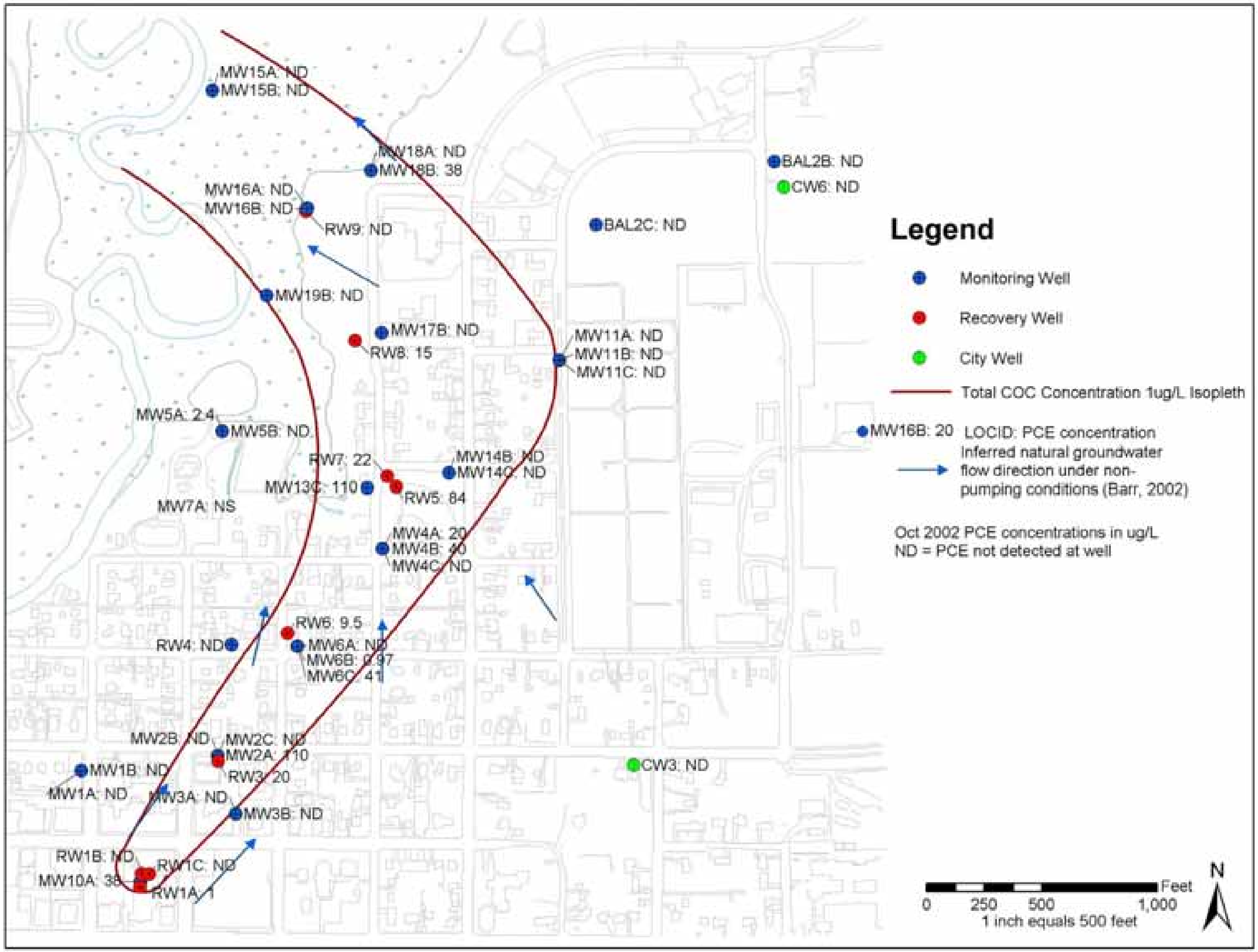


Figure C.3 Features of Long Prairie Groundwater Contamination Superfund Site (after Parsons, 2003c)

C2.3 NATURE AND EXTENT OF CONTAMINANTS IN GROUNDWATER

Contaminants were introduced to the subsurface at the Long Prairie site by discharge of dry-cleaning solvents directly into glacial outwash deposits at the site of the former dry-cleaning establishment. The waste solvents then percolated through the coarse outwash soils at the source area to the water table in the Long Prairie Sand Plain aquifer, and subsequently migrated as dissolved constituents in groundwater. PCE and its daughter products TCE and *cis*-1,2-DCE have been detected through a volume of groundwater about 1,000 feet wide, which extended (in October 2002) from the source area, near the inactive RW1A/1B/1C extraction well cluster, approximately 3,200 feet downgradient to the northwest, to the vicinity of nested monitoring well pair MW18A/B (Figure C.3). VC also has been detected in groundwater samples, although at few locations and at lower concentrations than other CAHs. CAH contaminants have been detected in groundwater through the full saturated thickness of the upper glacial outwash deposits, and also historically have been detected in the lower outwash deposits beneath the upper till at city well CW3.

The maximum concentrations of PCE historically detected in groundwater have been as high as 150,000 µg/L. Recently, the maximum detected concentrations of PCE have decreased to approximately 100 µg/L, and PCE no longer is present at detectable concentrations in the lower outwash deposits east of the glacial channel. However, CAH contaminants persist throughout the saturated upper outwash deposits within the glacial channel (along the centerline of the plume), and the overall extent of CAHs in groundwater, as defined by the 5-µg/L isopleth for PCE, has not changed significantly since operation of the groundwater ETD system was initiated, in 1996. In October 2002, PCE concentrations in the plume ranged from 2.4 µg/L at the northern end of the plume (well MW18B) to 110 µg/L near the center of the plume, at well MW14B (Figure C.3).

The OU1 groundwater ETD system was installed to prevent continued migration of CAH contaminants to Long Prairie River, and to remove sufficient contaminant mass that contaminant concentrations in groundwater at the site would be reduced to levels below their respective MCLs. The groundwater extraction system includes 10 groundwater extraction wells located along the axis of the plume, four of which (wells RW1A, RW1B, RW1C, and RW4) have been removed permanently from service. The system is designed to extract and treat up to 250 gallons per minute (gpm) of groundwater; treated groundwater is discharged to the Long Prairie River.

C2.4 CURRENT GROUNDWATER MONITORING PROGRAM AT LONG PRAIRIE SITE

Groundwater conditions are monitored periodically at the Long Prairie site, to evaluate whether the groundwater ETD system is effectively preventing the continued migration of CAH contaminants in groundwater to downgradient locations, and to confirm that contaminants are not migrating to the water-supply wells of the municipality of Long Prairie. Groundwater monitoring wells, extraction wells, and municipal water-supply wells are included in the monitoring program. A total of 44 wells in the Long Prairie area were sampled during the most recent monitoring event (October 2002) for which sampling results are available.

Several of the monitoring locations include wells installed in clusters, with each well in a cluster completed at a different depth. The screens of monitoring wells having an "A" designation (e.g., MW6A) extend across the water table; wells having a "B" designation (e.g., MW6B) are completed at the base of the upper glacial outwash unit; and wells having a "C" designation (e.g., MW6C) are completed within the lower outwash unit. Approximately one-half of the wells sampled during

October 2002 are sampled routinely in conjunction with the groundwater monitoring program. For example, in 2000 and 2001, 26 of the 44 wells were sampled (Table C.5), with the six active groundwater extraction wells (wells RW3, RW5, RW6, RW7, RW8, and RW9) and municipal water-supply well CW3 sampled quarterly, and 18 monitoring wells sampled annually. Inactive extraction well RW4 also was included in the monitoring program, and was sampled annually. In 2002, municipal water-supply well CW6 was added to the monitoring program, and was sampled quarterly.

In the second quarter of 2000, the suite of VOCs for which groundwater samples were analyzed was reduced to the identified COCs (PCE, TCE, *cis*-1,2-DCE, and VC). In addition, a gas-chromatographic (GC) analytical method (assumed to be U.S. EPA Method SW8021B) now is used instead of the gas-chromatographic/mass spectrometric (GC/MS) method (assumed to be U.S. EPA Method SW8260B) that formerly was required.

The "current" (2002) 27-well monitoring program at the Long Prairie site includes the 18 monitoring wells, 6 active and one inactive groundwater extraction wells sampled during scheduled monitoring events in 2000 and 2001, together with municipal-supply wells CW3 and CW6. The locations of these wells, and their status in the current monitoring program, are presented on Figure C.3.

Table C.5: Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site[a/]

Well ID	Sampling Frequency			
	2000	2001	2002	October 2002
Monitoring Wells				
BAL2B	-- [b/]	--	--	✓ [c/]
BAL2C	--	--	--	✓
MW1A	--	--	--	✓
MW1B	--	--	--	✓
MW2A	Annual	Annual	Annual	✓
MW2B	Annual	Annual	Annual	✓
MW2C	Annual	Annual	Annual	✓
MW3A	--	--	--	✓
MW3B	--	--	--	✓
MW4A	--	--	--	✓
MW4B	Annual	Annual	Annual	✓
MW4C	Annual	Annual	Annual	✓
MW5A	--	--	--	✓
MW5B	--	--	--	✓
MW6A	Annual	Annual	Annual	✓
MW6B	Annual	Annual	Annual	✓
MW6C	Annual	Annual	Annual	✓
MW10A	Annual	Annual	Annual	✓
MW11A	--	--	--	✓
MW11B	Annual	Annual	Annual	✓
MW11C	Annual	Annual	Annual	✓
MW13C	--	--	--	✓
MW14B	Annual	Annual	Annual	✓
MW14C	Annual	Annual	Annual	✓

Table C.5: Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site

Well ID	Sampling Frequency			
	2000	2001	Well ID	2000
Monitoring Wells (continued)				
MW15A	Annual	Annual	Annual	✓
MW15B	Annual	Annual	Annual	✓
MW16A	--	--	--	✓
MW16B	Annual	Annual	Annual	✓
MW17B	Annual	Annual	Annual	✓
MW18A	--	--	--	✓
MW18B	--	--	--	✓
MW19B	Annual	Annual	Annual	✓
Groundwater Extraction Wells				
RW1A	--	--	--	✓
RW1B	--	--	--	✓
RW1C	--	--	--	✓
RW3	Quarterly	Quarterly	Quarterly	✓
RW4	Annual	Annual	Annual	✓
RW5	Quarterly	Quarterly	Quarterly	✓
RW6	Quarterly	Quarterly	Quarterly	✓
RW7	Quarterly	Quarterly	Quarterly	✓
RW8	Quarterly	Quarterly	Quarterly	✓
RW9	Quarterly	Quarterly	Quarterly	✓
Municipal Water-Supply Wells				
CW3	Quarterly	Quarterly	Quarterly	✓
CW6	--	--	Quarterly	✓

[a/] Information from Parsons (2003c).
[b/] A dash (--) indicates that the well was not included in the monitoring program for that year.
[c/] A check mark (✓) indicates that the well was sampled during the October 2002 monitoring event.

C2.5 SUMMARY OF LTMO EVALUATION COMPLETED USING MAROS TOOL

C2.5.1 Summary of Groundwater Analytical Data for Long Prairie Site Used in MAROS Evaluation

The groundwater monitoring program at the Long Prairie site was evaluated using the MAROS tool, applied to the results of sampling events completed during the period May 1996 through October 2002 (GSI, 2003b). The available monitoring network consists of 44 wells (31 monitoring wells, 3 municipal-supply wells, and 10 extraction wells) (Table C.5). The frequency of sampling the wells in the network has varied through time -- extraction wells generally have been sampled quarterly, while monitoring wells generally have been sampled on a semi-annual or annual basis since the LTM plan was adopted in 1996. Sampling at some wells was terminated for a period of several years before they were sampled again in October 2002. As a consequence of the irregular sampling schedule, some monitoring wells have been sampled on as few as five occasions during the seven-year period from 1996 to 2002. Sampling data from 1996 to 2002 were used for the detailed optimization analysis, with a subset of these data used in some of the analyses.

Prior to beginning the MAROS evaluation, the sampling-results database provided by the MPCA's environmental contractor was processed to remove duplicate data measurements by averaging the primary and duplicate analytical results, and using this average to represent a single value detected at that sampling point, during that sampling event. Concentration values that were below reporting limits were replaced with surrogate values, selected to be the minimum reporting limit for that particular constituent. Trace-level results were represented by their actual values. The processed database contained results for each constituent measured in groundwater samples from each of the 44 wells in the vicinity of the Long Prairie site.

Although four COCs (PCE, TCE, *cis*-1,2-DCE, and VC; Section 3.2.3) historically have been detected in groundwater at the site, PCE was used as an indicator compound, based on its widespread detection at relatively elevated concentrations in wells across the site; and the MAROS evaluation of the monitoring program at the Long Prairie site used only the results of analyses for PCE in groundwater samples.

C2.5.2 Results of Evaluation Completed Using MAROS Tool

Sufficient data (the results of at least six sampling events) were available for 31 monitoring wells and 9 groundwater extraction wells within the time period 1996 to 2002 to assess temporal trends in PCE concentrations. Application of the Mann-Kendall and linear regression temporal trend evaluation methods (Appendix B) indicated that the trends in PCE concentrations at two of four of the monitoring wells designated as "source area" wells were "Probably Decreasing", "Decreasing", or "Stable", while PCE concentrations at seven of 10 extraction wells in the source area were "Probably Decreasing", "Decreasing" or "Stable". This indicated that the extent and concentrations of PCE in groundwater at the Long Prairie source area probably are decreasing (GSI, 2003b). PCE concentrations in groundwater at 24 of 27 wells in the "tail" part of the plume also were "Probably Decreasing", "Decreasing" or "Stable". The results of the moment analysis (Appendix B) indicated that the mass of PCE in groundwater is relatively stable, and that although the location of the center of mass of the plume has moved downgradient over time, the extent of PCE in groundwater has decreased through time. Overall, the results of trend analyses and moment analyses (Appendix B) indicated that the extent of PCE in groundwater of the upper outwash unit is stable or decreasing, resulting in a recommendation that a monitoring strategy appropriate to a "*Moderate"* design category (Appendix B) be adopted.

The sampling results available for 17 of the wells in the 44-well monitoring network were sufficient to conduct a detailed spatial analysis using the Delaunay method (Appendix B). The results of the spatial analysis indicated that none of the 17 wells was redundant. Other wells in the 44-well monitoring network were examined qualitatively; and the results of evaluation using qualitative considerations (GSI, 2003b) indicated that nine monitoring wells could be removed from the monitoring network without significant loss of information (Table C.6; compare with the 2001 and 2002 monitoring programs). Using similar qualitative analyses, three extraction wells in the source area were identified as candidates for removal from service, because concentrations of COCs in effluent from these wells historically have been below reporting limits (GSI, 2003b). However, six existing wells that currently are not routinely sampled were recommended for inclusion in the monitoring program. These changes in the monitoring network were projected to have a negligible effect on the degree of characterization of the extent of PCE in groundwater. The accompanying well sufficiency analysis indicated that there is only a moderate degree of uncertainty in predicted PCE concentrations throughout the network, so that no new monitoring wells were recommended for installation (GSI, 2003b).

In some instances, the results of the sampling frequency optimization analysis, completed using the modified CES method (Appendix B), were affected by the lack of consistent monitoring. The sampling frequency analysis requires sampling results from a minimum of six separate monitoring events at a particular sampling location. In instances when fewer than six separate results were available for a particular monitoring well, the algorithm implemented in MAROS selected a "conservative" sampling frequency (i.e., MAROS specified that samples should be collected from that well more frequently than would otherwise have been the case). In some instances, the recommendations generated by MAROS were examined qualitatively, by inspecting the historic and recent PCE concentrations in samples from those wells, and occasionally the MAROS recommendations were not adopted (GSI, 2003b). For example, PCE has not been measured at concentrations above reporting limits in any of 14 samples historically collected from well CW6. However, MAROS identified a spurious "Increasing" trend in PCE concentrations at well CW6 using linear regression, which would have resulted in assignment of quarterly or semi-annual sampling frequency for this well (Appendix B). The MAROS-assigned frequency was changed to biennial sampling (Table C.6). Wells at which PCE has been detected at low frequencies (or not detected) and low concentrations, but for which MAROS identified a trend that differed from a "Stable" trend, using either linear regression or the Mann-Kendall test, are shaded in Table C.6, together with the final recommended sampling frequencies.

Table C.6: Refined Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site Generated Using the MAROS Tool[a/]

Well ID	Historic Sampling Frequency		Results of MAROS Evaluation	
	2001	2002	Remove/Retain[b/]	Recommended Sampling Frequency
Monitoring Wells				
BAL2B	--[c/]	--	Retain	Biennial
BAL2C	--	--	Retain	Biennial
MW1A	--	--	Remove	--
MW1B	--	--	Retain	Biennial
MW2A	Annual	Annual	Remove	--
MW2B	Annual	Annual	Retain	Annual
MW2C	Annual	Annual	Retain	Annual
MW3A	--	--	Remove	--
MW3B	--	--	Retain	Biennial
MW4A	--	--	Remove	--
MW4B	Annual	Annual	Retain	Annual
MW4C	Annual	Annual	Retain	Annual
MW5A	--	--	Remove	--
MW5B	--	--	Retain	Biennial
MW6A	Annual	Annual	Remove	--
MW6B	Annual	Annual	Retain	Annual
MW6C	Annual	Annual	Retain	Annual
MW10A	Annual	Annual	Retain	Annual

Table C.6: Refined Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site Generated Using the MAROS Tool

Well ID	Historic Sampling Frequency		Results of MAROS Evaluation	
	2001	2002	Remove/Retain	Recommended Sampling Frequency
Monitoring Wells (continued)				
MW11A	--	--	Remove	--
MW11B	Annual	Annual	Retain	Biennial
MW11C	Annual	Annual	Retain	Biennial
MW13C	--	--	Retain	Biennial
MW14B	Annual	Annual	Retain	Annual
MW14C	Annual	Annual	Retain	Biennial
MW15A	Annual	Annual	Retain	Biennial
MW15B	Annual	Annual	Retain	Biennial
MW16A	--	--	Remove	--
MW16B	Annual	Annual	Retain	Annual
MW17B	Annual	Annual	Retain	Annual
MW18A	--	--	Remove	--
MW18B	--	--	Retain	Biennial
MW19B	Annual	Annual	Retain	Biennial
Groundwater Extraction Wells				
RW1A	--	--	Remove	--
RW1B	--	--	Remove	--
RW1C	--	--	Remove	--
RW3	Quarterly	Quarterly	Retain	Annual
RW4	Annual	Annual	Retain	Biennial
RW5	Quarterly	Quarterly	Retain	Annual
RW6	Quarterly	Quarterly	Retain	Annual
RW7	Quarterly	Quarterly	Retain	Annual
RW8	Quarterly	Quarterly	Retain	Annual
RW9	Quarterly	Quarterly	Retain	Biennial
Municipal Water-Supply Wells				
CW3	Quarterly	Quarterly	Retain	Biennial
CW6	--	Quarterly	Retain	Biennial

[a/] Information from GSI (2003b).
[b/] "Remove" = MAROS recommended that the well be removed from the monitoring program.
"Retain" = MAROS recommended that the well continue to be sampled at the indicated frequency.
[c/] A dash (--) indicates that the well is not included in the current or refined monitoring program.

The results of the data sufficiency evaluation, completed using power analysis methods (Appendix B) suggest that the monitoring program is adequate to evaluate the extent of PCE in groundwater relative to the compliance boundary through time (GSI, 2003b).

The optimized monitoring program generated using the MAROS tool includes 32 wells, with 10 monitoring wells and 5 extraction wells sampled annually, and 13 monitoring wells, two extraction wells, and two municipal wells sampled biennially (Table C.6). Adoption of the optimized program would result in collection and analysis of 22 samples per year, as compared with collection and analysis of 51 samples per year in the current monitoring program. Implementing these recommendations could lead to a 51-percent reduction in the number of samples collected and analyzed annually, as compared with the current program. Assuming a cost per sample in the range of $100 to $280 for collection and chemical analyses, adoption of the monitoring program as optimized using the MAROS tool is projected to result in savings ranging from approximately $2,900 to $8,120 per year. (The estimated range of costs per sample is based on information provided by facility personnel in conjunction with efforts to estimate potential cost savings resulting from optimization of the monitoring program, and includes costs associated with sample collection and analysis, data compilation and reporting, and handling of materials generated during sample collection [e.g., purge water] as IDW.) The optimized program remains adequate to delineate the extent of COCs in groundwater, and to monitor changes in the plume over time (GSI, 2003b).

C2.6 SUMMARY OF LTMO EVALUATION COMPLETED USING THREE-TIERED APPROACH

C2.6.1 Summary of Groundwater Analytical Data for Long Prairie Site Used in Three-Tiered Approach

The groundwater monitoring program at the Long Prairie site also was evaluated using the three-tiered approach, applied to the results of sampling events completed during the period May 1996 through October 2002 (Parsons, 2003c). Prior to the evaluation, the sampling-results database provided by MPCA's environmental contractor was processed to remove duplicate data measurements by retaining the greater of the primary and duplicate analytical results, and discarding the lower value. The database that was utilized in the three-tiered evaluation of the groundwater monitoring program for the Long Prairie site differed slightly from the database that was utilized in the corresponding MAROS evaluation in the following respects:

- The method used in the three-tiered approach to deal with analytical results from duplicate samples (retaining the greater of the primary and duplicate analytical results, and discarding the lower value) differed from the method used in the MAROS evaluation (averaging the primary and duplicate analytical results, and using this average to represent a single value; Section C2.5.1).

- The method used in the three-tiered approach for dealing with concentration values that were below reporting limits (value reported as "Not Detected"; Appendix B) differed from the method used in the MAROS evaluation (assigning a surrogate value corresponding to the reporting limit; Appendix B).

The processed database contained results for each constituent measured in groundwater samples from each of the 44 wells in the vicinity of the Long Prairie site. Depending upon the number of times a particular well was sampled, from 1 (well sampled once) to 29 (well sampled 29 times) records were available for each constituent at a particular well.

The primary COCs in groundwater at the Long Prairie site are PCE, TCE, and *cis*-1,2-DCE (Section C2.3). The occurrence of these three COCs in groundwater at the Long Prairie site, based on data collected from 33 monitoring wells during the period May 1996 through October 2002, is summarized in Table C.7. The data summarized in Table C.7 exclude results for the extraction wells (with the exception of inactive extraction well RW4, which is sampled annually as a monitoring well) and municipal water-supply wells CW3 and CW6.

Table C.7: Summary of Occurrence of COCs[a/] in Groundwater at Long Prairie Groundwater Contamination Superfund Site[b/]

Constituent[c/]	Total Number of Samples Analyzed for Constituent[d/]	Percentage of Samples Having Detected Concentrations	Range of Detected Concentrations (µg/L)[e/]	Number of Wells Having Samples Analyzed for Constituent	Number of Wells at Which Constituent was Detected	MCL[f/] (µg/L)	Percentage of Samples with MCL Exceedances	Number of Wells with MCL Exceedances
cis-1,2-DCE	248	44.0%	0.34 - 570	33	22	70	1.2%	2
PCE	248	39.1%	0.97 - 150,000	33	20	5	32.7%	14
TCE	248	34.7%	0.57 - 85	33	17	5	21.4%	11

[a/] COCs = contaminants of concern.
[b/] Information from Parsons (2003c).
[c/] Constituents are as follow:
DCE = dichloroethene; PCE = tetrachloroethene; TCE = trichloroethene.
[d/] Analytical data include sampling results from May 1996 through October 2002.
[e/] µg/L = micrograms per liter.
[f/] MCL = maximum contaminant level.

PCE is the COC that historically has been detected at the highest concentrations in groundwater at the Long Prairie site, with PCE concentrations exceeding the MCL for PCE (5 µg/L) (USEPA, 2000) in approximately 33 percent of samples. PCE has been detected frequently (in 39 percent of samples), has been measured in groundwater samples from 20 of the 33 wells included in this summary, and has exceeded its MCL in samples from 14 of these wells. *cis*-1,2-DCE (a product of the reductive dechlorination of PCE) also is widespread in groundwater at the site, and has been detected in 44 percent of samples. However, detected concentrations of *cis*-1,2-DCE have exceeded its MCL (70 µg/L) in only about 1 percent of samples. The other primary COC (TCE) has been detected less frequently, at lower concentrations, and in samples from fewer wells than have PCE and *cis*-1,2-DCE (Table C.7). As a consequence of the widespread detection of PCE, at relatively elevated concentrations in groundwater across the site, PCE was selected to be an indicator compound. Although the other primary COCs (TCE and *cis*-1,2-DCE) were considered, together with PCE, in the qualitative and temporal stages of the three-tiered evaluation, the spatial-statistical stage of the three-tiered evaluation of the monitoring program at the Long Prairie site used only the results of analyses for PCE in groundwater samples.

Sixteen of the 44 wells sampled in October 2002 were included in the spatial-statistical evaluation. Although samples from the OU1 extraction wells have been used historically to define the extent of contaminants in groundwater, data from extraction wells are not appropriate for use in a kriging analysis because they represent COC concentrations averaged over the volume within the well's capture zone, and thus are not point-specific, nor temporally discrete; the recovery wells also typically are screened across a longer interval than are the site monitoring wells. Similarly, city wells CW3 and CW6 were excluded from the spatial analysis because they also are active extraction wells.

Kriging was used to predict concentrations over a two-dimensional surface, and thus including data from multiple co-located wells screened at different depths is not appropriate. In this application, the well within each cluster of well having the highest concentration of PCE was retained for use in the geostatistical evaluation. Of the clustered wells, the "B" zone wells usually displayed the highest PCE concentrations in October 2002 and were included in the spatial analysis; however, the "C" zone well MW6C from the MW6 cluster also was included in the spatial analysis.

C2.6.2 Results of Evaluation Completed Using Three-Tiered Approach

The results of the three-tiered evaluation (Parsons, 2003c) indicated that 18 of the 44 existing wells could be removed from the groundwater monitoring network with little loss of information (Parsons, 2003c). The results further suggest that the current monitoring program (18 monitoring wells, 6 active extraction wells, one inactive extraction well, and municipal water-supply wells CW3 and CW6 included in the 2002 sampling schedule) could be further refined by removing four of the 27 wells now in the LTM program, and adding three existing wells that currently are not included in the program (Table C.8; compare with the 2001 and 2002 monitoring programs). If this refined monitoring program, consisting of 26 wells (2 wells to be sampled quarterly, 6 wells to be sampled semi-annually, 14 wells to be sampled annually, and 4 wells to be sampled biennially) were adopted, an average of 36 samples per year would be collected and analyzed, as compared with the collection and analysis of 51 samples per year in the current (2001/2002) monitoring program. This would represent a 29-percent reduction in the number of samples collected and analyzed annually, as compared with the current program. Assuming a cost per sample ranging from $100 to $280 for collection and chemical analyses, adoption of the monitoring program as optimized using the three-tiered approach is projected to result in savings ranging from about $1,500 per year to about $4,200 per year, as compared with the current program (Parsons, 2003c).

Table C.8: Refined Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site Generated Using the Three-Tiered Approach[a/]

Well ID	Historic Sampling Frequency		Results of Three-Tiered Evaluation	
	2001	2002	Remove/Retain[b/]	Recommended Sampling Frequency
Monitoring Wells				
BAL2B	--[c/]	--	Remove	--
BAL2C	--	--	Remove	--
MW1A	--	--	Remove	--
MW1B	--	--	Remove	--
MW2A	Annual	Annual	Remove	--
MW2B	Annual	Annual	Retain	Annual
MW2C	Annual	Annual	Remove	--
MW3A	--	--	Remove	--
MW3B	--	--	Remove	--
MW4A	--	--	Remove	--
MW4B	Annual	Annual	Retain	Annual
MW4C	Annual	Annual	Retain	Annual
MW5A	--	--	Remove	--
MW5B	--	--	Retain	Annual
MW6A	Annual	Annual	Remove	--
MW6B	Annual	Annual	Retain	Annual
MW6C	Annual	Annual	Retain	Annual
MW10A	Annual	Annual	Retain	Annual
MW11A	--	--	Remove	--
MW11B	Annual	Annual	Retain	Biennial
MW11C	Annual	Annual	Retain	Biennial
MW13C	--	--	Retain	Biennial
MW14B	Annual	Annual	Retain	Annual
MW14C	Annual	Annual	Retain	Biennial
MW15A	Annual	Annual	Retain	Biennial
MW15B	Annual	Annual	Retain	Biennial
MW16A	--	--	Remove	--
MW16B	Annual	Annual	Retain	Annual
MW17B	Annual	Annual	Retain	Annual
MW18A	--	--	Remove	--
MW18B	--	--	Retain	Biennial
MW19B	Annual	Annual	Retain	Biennial
Groundwater Extraction Wells				
RW1A	--	--	Remove	--
RW1B	--	--	Remove	--
RW1C	--	--	Remove	--
RW3	Quarterly	Quarterly	Retain	Annual
RW4	Annual	Annual	Retain	Biennial

Table C.8: Refined Groundwater Monitoring Program at Long Prairie Groundwater Contamination Superfund Site Generated Using the Three-Tiered Approach

	Historic Sampling Frequency		Results of Three-Tiered Evaluation	
Well ID	2001	2002	Remove/Retain	Recommended Sampling Frequency
Groundwater Extraction Wells (continued)				
RW5	Quarterly	Quarterly	Retain	Annual
RW6	Quarterly	Quarterly	Retain	Annual
RW7	Quarterly	Quarterly	Retain	Annual
RW8	Quarterly	Quarterly	Retain	Annual
RW9	Quarterly	Quarterly	Retain	Biennial
Municipal Water-Supply Wells				
CW3	Quarterly	Quarterly	Retain	Biennial
CW6	--	Quarterly	Retain	Biennial

[a/] Information from Parsons (2003c).

[b/] "Remove" = Three-tiered evaluation recommended that the well be removed from the monitoring program.
"Retain" = Three-tiered evaluation recommended that the well continue to be sampled at the indicated frequency.

[c/] A dash (--) indicates that the well is not included in the current or refined monitoring program.

C3.0 MCCLELLAN AFB OU D, CALIFORNIA

The following summary of information regarding the location, operational history, geology, and hydrogeology of OU D at McClellan AFB, the current monitoring program at OU D, available chemical data that were used in the monitoring-program evaluations, and the results of the LTMO evaluations, has been excerpted from Parsons (2003d) and GSI (2003c). Copies of both documents are included in Appendix D-3; the reader is referred to the Appendix for additional details.

C3.1 SITE DESCRIPTION AND OPERATIONAL HISTORY

McClellan AFB is located approximately 7 miles northeast of downtown Sacramento, California. The installation covers approximately 3,000 acres and is bounded by the city of Sacramento on the west and southwest, the unincorporated areas of Antelope on the north, Rio Linda on the northwest, and North Highlands on the east. OU D is located in the northwestern part of McClellan AFB, and occupies approximately 192 acres. Through most of its operational history, McClellan AFB was engaged in a wide variety of military/industrial operations involving the use, storage, and disposal of hazardous materials, including industrial solvents, caustic cleaners, electroplating chemicals, metals, polychlorinated biphenyls, low-level radioactive wastes, and a variety of fuel oils and lubricants. Historic waste-disposal practices included the use of burial pits for the disposal and/or burning of these materials. Fifteen sites that were used as waste pits from the mid-1950s through the 1970s are located at OU D. In 1985, the “Area D” cap was constructed over several waste pits, to reduce the infiltration of precipitation through the waste pits, thereby also reducing the migration of contaminants from the vadose zone to groundwater at the site. Prior to 1985, three waste pits were excavated to remove the sludge waste.

McClellan AFB was included on the Superfund NPL in 1987. A single OU was designated for groundwater at the Base, and an Interim Record of Decision (IROD), which specifies groundwater extraction and treatment as the interim remedy for groundwater, was signed for the Base-wide Groundwater OU (GWOU) in 1995. In 1995, McClellan AFB was recommended for closure under the Base Realignment and Closure Act (BRAC); and the installation was closed in July 2001. Ongoing environmental restoration activities are being directed by the Air Force Real Property Agency (AFRPA) (formerly the Air Force Base Conversion Agency).

C3.2 GEOLOGY AND HYDROGEOLOGY

The sediments in the upper few hundred feet of the subsurface beneath the Base consist of coalescing deposits laid down by fluvial systems of various sizes and competence that flowed generally from northeast to southwest or west. Geologic materials are primarily sand, silt, and clay, generally poorly sorted, with localized occurrences of gravel in the southern part of the Base. The sediments were deposited by streams, producing morphologically irregular lenses and strata that are laterally and vertically discontinuous. Distinguishing among units, or correlating stratigraphy over distances greater than a few tens of feet, is difficult, as a consequence of the coalescing and intercalating nature of the sediments.

Although the stratigraphy of the sediments beneath McClellan AFB is complex, the juxtaposed and intercalated strata of sand, silt, clay, and gravel comprise a single water-bearing unit (the “upper” water-bearing unit). The geologic and hydraulic properties of the upper water-bearing unit vary over short distances, and the more permeable intervals are hydraulically-interconnected laterally and vertically, so that in general, groundwater movement (and associated advective migration of contaminants) may occur throughout the water-bearing unit. The upper unit beneath McClellan AFB has been divided into the vadose (unsaturated) zone and five monitoring zones (Zones A through E, from shallowest to deepest) below the water table, distinguished on the basis of general hydraulic characteristics. Generally, the strata associated with the various zones dip to the west, and increase in thickness from east to west. As a consequence of the heterogeneity of the sediments beneath the Base, and the relative capacities of different deposits to transmit water, it is entirely possible for two adjacent wells screened at different depth intervals to be completed within the same monitoring zone, or for two wells screened at similar depths to be completed in different monitoring zones.

The thickness of monitoring zone A ranges from 9 to 50 feet, and groundwater occurs in the A zone under unconfined conditions. The thickness of monitoring zone B ranges from 40 to 75 feet, and groundwater in this zone appears to occur under partially confined conditions. Monitoring wells at OU D have been constructed only in the A and B monitoring zones; therefore, no information is available regarding the deeper monitoring zones at OU D.

The depth to the water table beneath McClellan AFB ranges between about 90 and 110 feet bgs. At OU D, the depth to groundwater within the upper unit varies from approximately 99 to 102 feet bgs. As a consequence of the relatively great depth to the water table, surface streams are not in direct hydraulic communication with the groundwater system beneath the Base. Water-table elevations have declined at rates ranging from 1 to 2 feet per year during the past 50 years, and are expected to continue to decline at a rate of about 2 feet per year as a consequence of large-scale groundwater production for industrial, irrigation, and municipal uses in the Sacramento area.

Under natural conditions, prior to installation and operation of the OU D groundwater extraction system, groundwater typically moved from northeast to south or southwest in the A monitoring zone, and from north to south in the B monitoring zone. The local directions of groundwater movement beneath OU D currently are strongly influenced by the groundwater extraction system operating at the site. Groundwater movement generally is directed radially inward toward the extraction wells (EWs). The largest horizontal hydraulic gradients in the groundwater system at OU D occur near active EWs. Vertical gradients within that part of the groundwater system influenced by active groundwater extraction at OU D generally are downward, similar to vertical gradients that exist between the A and B monitoring zones in other parts of the Base. At distances greater than about 1,000 feet from the extraction system, vertical gradients may be directed upward or downward, depending on local potentiometric conditions. The calculated horizontal advective velocity of groundwater movement in the A and B monitoring zones at OU D ranges between about 14 and 30 ft/year; and the bulk value of horizontal hydraulic conductivity of the saturated materials within the upper water-bearing unit is about 5 to 15 times greater than the vertical hydraulic conductivity, indicating that advective groundwater movement beneath OU D occurs primarily in the horizontal plane.

C3.3 NATURE AND EXTENT OF CONTAMINANTS IN GROUNDWATER

The COCs in groundwater targeted by the current LTM program at OU D are exclusively CAHs, including PCE, TCE, *cis*-1,2-DCE, and 1,2-dichloroethane (1,2-DCA), with 1,1-DCA, 1,1-DCE, 1,1,1-TCA, and vinyl chloride also detected, but at lower concentrations and/or lower frequencies. Some evidence suggests that one or more of these CAHs may remain in vadose-zone soils near the former waste pits at OU D as dense, non-aqueous-phase liquids (DNAPLs); and that a free or residual DNAPL remains in the subsurface near or below the water table in some locations at OU D. Residual

DNAPL near or below the water table at OU D may persist as a continuing source of dissolved contaminants for an extended period of time. Dissolved CAHs originating from sources near the OU D waste pits have migrated with regional groundwater flow to the south and southwest, and historically extended off-Base, to the west of OU D. Currently, VOCs (primarily TCE) are present in groundwater primarily in the central and southwestern parts of OU D (Figure C.4).

The remediation systems currently operating at OU D include an SVE system, a groundwater extraction and treatment system, and associated monitoring networks. The current groundwater extraction system in OU D consists of six EWs (EW-73, and EW-83 through EW-87), five of which are operational. (Well EW-84 was removed from service in August 1997.) All EWs were installed to a depth of about 160 feet bgs, and are fully screened across both the A and B monitoring zones (and consequently extract groundwater from both zones). Although low concentrations of VOCs were detected historically in groundwater samples collected from off-Base wells located northwest of OU D, no contaminants have been detected in groundwater samples from off-Base monitoring wells to the west or northwest of OU D since 1995, possibly because dissolved contaminants have been hydraulically captured by the OU D groundwater extraction system. In general, the concentrations of CAHs dissolved in groundwater have declined during the period of system operation. However, low concentrations of VOCs continue to be detected sporadically at locations distal from potential source areas, in the west and southwestern parts of OU D.

C3.4 CURRENT GROUNDWATER MONITORING PROGRAM AT MCCLELLAN AFB OU D

In 1996, the Groundwater Monitoring Plan (GWMP) for all on- and off-Base wells was established under the Long-Term Monitoring Program (LTMP) to update the GSAP and to support GWOU IROD activities. In accordance with the requirements of the GWMP, wells in the OU D area are sampled during the first quarter of each year. In the OU D area, groundwater sampling is conducted to monitor areas where dissolved VOC concentrations exceed their respective MCLs in monitoring zones A and B. Groundwater monitoring data also are used to evaluate contaminant mass-removal rates. The field sampling plan identifies the wells to be sampled in OU D based on the rationale and decision logic presented in the GWMP; the monitoring frequency and sampling rationale for each well are continually evaluated, and can change as new sampling data are obtained. Based on groundwater-quality data collected through the first quarter of 2002, 6 EWs and 45 monitoring wells (Figure C.4) have been identified as sampling points for OU D groundwater.

Because the extent of COCs in groundwater at OU D is relatively well defined, and COCs appear to be contained by the groundwater extraction system, the wells associated with the OU D plume are sampled relatively infrequently (annually or biennially). The six EWs are sampled annually (Table C.9). Currently, 22 of the 32 wells that monitor Zone A groundwater at OU D are sampled biennially, and 10 are sampled annually. Twelve of the 13 Zone B wells are sampled biennially, and the remaining well is sampled annually. (Note that Table C.9 is based upon information provided in Parsons [2003d].) Historically, however, the sampling schedule for wells at OU D was irregular, so that some monitoring wells at OU D have been sampled as few as five times through the historic monitoring period. All samples from the monitoring and extraction wells are analyzed for VOCs by U.S. EPA Method SW8260B.

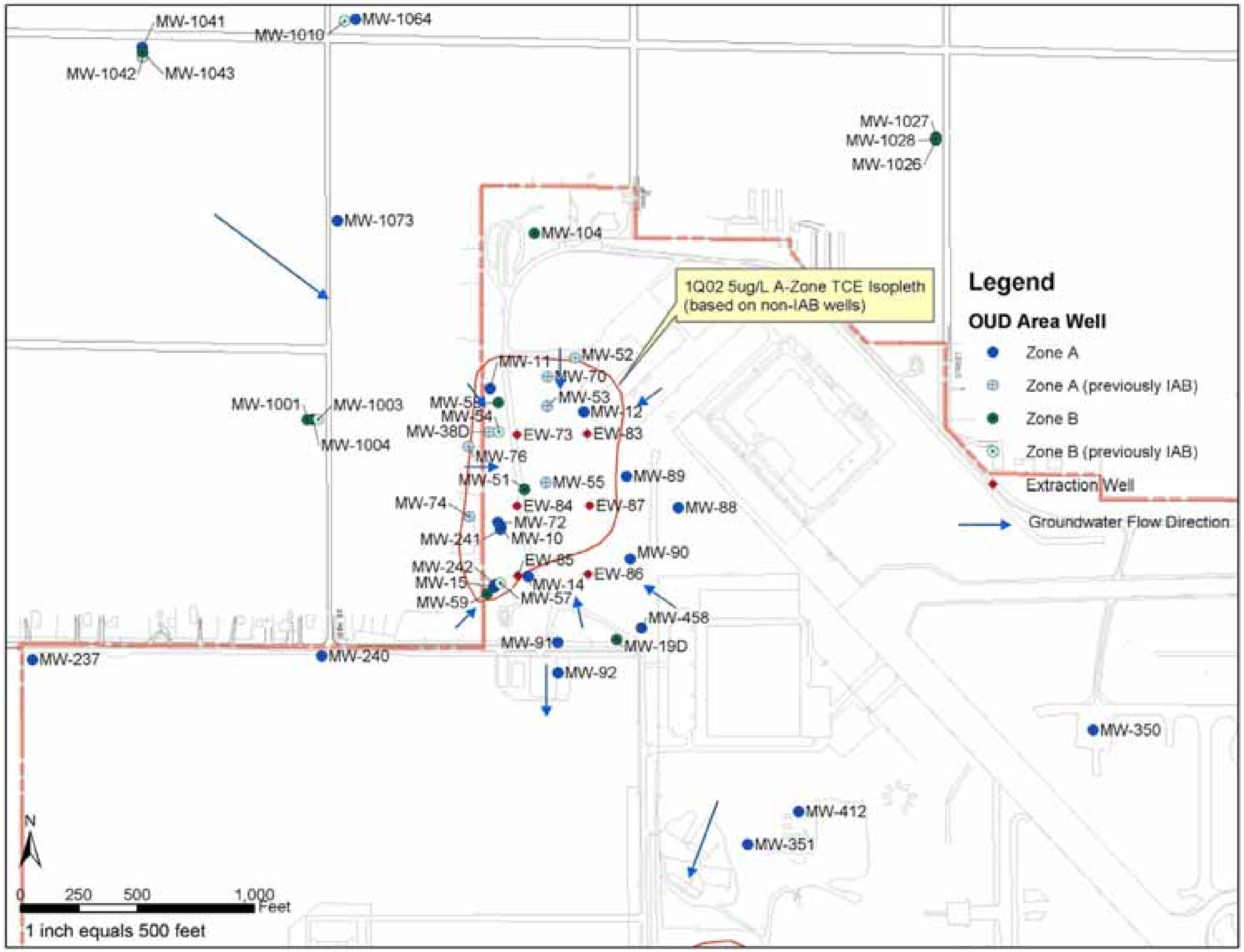


Figure C.4: Groundwater Monitoring Network at McClellan AFB OU D (after Parsons, 2003d)

Table C.9: Current Groundwater Monitoring Program at McClellan AFB OU D[a/]

Well ID	Completion Zone Assumed for Evaluation	Sampling Frequency
Zone A Monitoring Wells		
MW-10	A	Annual
MW-11	A	Annual
MW-12	A	Annual
MW-14	A	Biennial
MW-15	A	Annual
MW-38D	A* [b/]	Annual
MW-52	A*	Biennial
MW-53	A*	Biennial
MW-55	A*	Biennial
MW-70	A*	Biennial
MW-72	A	Annual
MW-74	A*	Biennial
MW-76	A*	Annual
MW-88	A	Biennial
MW-89	A	Biennial
MW-90	A	Biennial
MW-91	A	Biennial
MW-92	A	Biennial
MW-237	A	Biennial
MW-240	A	Biennial
MW-241	A	Annual
MW-242	A	Annual
MW-350	A	Biennial
MW-351	A	Annual
MW-412	A	Biennial
MW-458	A	Biennial
MW-1004	A	Biennial
MW-1026	A	Biennial
MW-1041	A	Biennial
MW-1042	A*	Biennial
MW-1064	A	Biennial
MW-1073	A	Biennial
Zone B Monitoring Wells		
MW-19D	B	Biennial
MW-51	B	Biennial
MW-54	B*	Annual
MW-57	B*	Biennial
MW-58	B	Biennial
MW-59	B	Biennial
MW-104	B	Biennial
MW-1001	B	Biennial
MW-1003	B*	Biennial
MW-1010	B*	Biennial

Table C.9: Current Groundwater Monitoring Program at McClellan AFB OU D

Well ID	Completion Zone Assumed for Evaluation	Sampling Frequency
Zone B Monitoring Wells (continued)		
MW-1027	B	Biennial
MW-1028	B	Biennial
MW-1043	B	Biennial
Groundwater Extraction Wells		
EW-73	A/B	Annual
EW-83	A/B	Annual
EW-84	A/B	Annual
EW-85	A/B	Annual
EW-86	A/B	Annual
EW-87	A/B	Annual

[a/] Information from Parsons (2003d).

[b/] * = Assumed monitoring zone assigned based on criteria presented by Parsons (2003d).

C3.5 SUMMARY OF LTMO EVALUATION COMPLETED USING MAROS TOOL

C3.5.1 Summary of Groundwater Analytical Data for McClellan AFB OU D Used in MAROS Evaluation

The groundwater database for McClellan AFB OU D contains the results of sampling events completed during the period April 1990 through August 2001 (GSI, 2003c). Sampling results for 2001 were excluded from the database used for the MAROS evaluation, because a different sampling technique (passive diffusion sampling) was being tested during that period, and the comparability of the 2001 analytical data with historic data (collected using other techniques) was regarded as uncertain. The available monitoring network consists of 32 monitoring wells completed in Zone A, 13 monitoring wells completed in Zone B, and six extraction wells completed in both Zone A and Zone B.

Prior to beginning the MAROS evaluation, the sampling-results database provided by the Base was processed to remove analytical data collected during 2001, and to remove duplicate data measurements by averaging the primary and duplicate analytical results, and using this average to represent a single value detected at that sampling point, during that sampling event. Concentration values that were below reporting limits were replaced with surrogate values, selected to be the minimum reporting limit for that particular constituent. Trace-level results were represented by their actual values. The processed database contained results for each constituent measured in groundwater samples from each of the 51 wells at OU D.

Although four primary COCs (PCE, TCE, *cis*-1,2-DCE, and 1,2-DCA; Section C3.3) are present in groundwater at the site, with other CAHs occasionally present at low concentrations, TCE was used as an indicator compound, based on its widespread detection at relatively elevated concentrations in wells across the site; and the MAROS evaluation of the monitoring program at McClellan AFB OU D used only the results of analyses for TCE in groundwater samples.

C3.5.2 Results of Evaluation Completed Using MAROS Tool

Sufficient data (the results of at least six sampling events) were available for all 32 monitoring wells completed in Zone A, all 13 monitoring wells completed in Zone B, and all 6 groundwater extraction wells, for the time period April 1990 through 2000, to assess temporal trends in TCE concentrations. Application of the Mann-Kendall and linear regression temporal trend evaluation methods (Appendix B) indicated that the trends in TCE concentrations at nine of ten of the A-zone monitoring wells designated as "source area" wells were "Probably Decreasing", "Decreasing", or "Stable", while TCE concentrations at five of six extraction wells in the source area were "Probably Decreasing", "Decreasing" or "Stable". This indicated that the extent and concentrations of TCE in groundwater at the OU D source area probably are decreasing (GSI, 2003c).

The trends in TCE concentrations at nine of 22 A-zone monitoring wells and at six of 12 B-zone monitoring wells in the "tail" part of the plume also were "Probably Decreasing", "Decreasing", or "Stable", although there appear to be no trends in TCE concentrations at most B-zone monitoring wells. The absence of identifiable trends in TCE concentrations at many locations in the "tail" and off-axis parts of the plume may be a consequence of less-frequent sampling in these areas than occurs near the OU D source area (GSI, 2003c).

The results of the moment analysis (Appendix B) indicated that the mass of TCE in groundwater is relatively stable, with occasional fluctuations suggesting increases or decreases in TCE mass. The location of the center of mass of the plume also is relatively stable, with periodic temporal fluctuations in concentrations tending to cause the center of TCE mass to appear to move in the upgradient or downgradient directions. The lateral extent of TCE in groundwater has been variable, suggesting that TCE concentrations in wells used to evaluate conditions over large, off-axis areas of the plume have varied considerably through time, or that the wells have not been sampled consistently enough for a clear trend in TCE concentrations to emerge. Temporal fluctuations in the apparent mass of TCE in groundwater (calculated using the zeroth moment), the center of mass of TCE (calculated using the first moment), and the lateral extent of TCE (calculated using the second moment) likely are due to long-term variability in sampling locations, resulting from an inconsistent monitoring program through time (GSI, 2003c). The evaluation of overall plume stability (Section 2.3.2) indicated that the extent of TCE in groundwater at OU D is stable or slightly decreasing, resulting in a recommendation that a monitoring strategy appropriate for a "*Moderate"* design category be adopted (Appendix B).

The sampling results available for 31 A-zone monitoring wells and for 12 B-zone monitoring wells were used to conduct a detailed spatial analysis based on the Delaunay method (Appendix B). The results of the spatial analysis indicated that 3 of the 31 A-zone wells were candidates for removal from the monitoring network, and that 2 of the B-zone wells were candidates for removal. These recommendations were examined qualitatively, considering historic detections of COCs in the wells, and the possible need for continued characterization of the extent of COCs in groundwater at OU D; and a total of 5 monitoring wells (3 A-zone wells and 2 B-zone wells) were recommended for removal from the monitoring program (Table C.10; compare the current monitoring program with the MAROS recommendations). Removal of the recommended 5 wells would result in an 11-percent reduction in the number of wells in the monitoring network, with negligible effect on the degree of characterization of the extent of TCE in groundwater. The accompanying well sufficiency analysis indicated that there is only a low to moderate degree of uncertainty in predicted TCE concentrations throughout the network, so that no new monitoring wells were recommended for installation (GSI, 2003c).

Table C.10: Refined Groundwater Monitoring Program at McClellan AFB OU D Generated Using the MAROS Tool[a/]

Well ID	Current Sampling Frequency	Results of MAROS Evaluation	
		Remove/Retain[b/]	Recommended Sampling Frequency
Zone A Monitoring Wells			
MW-10	Annual	Retain	Annual
MW-11	Annual	Retain	Annual
MW-12	Annual	Retain	Annual
MW-14	Biennial	Remove	-- [c/]
MW-15	Annual	Retain	Annual
MW-38D	Annual	Retain	Annual
MW-52	Biennial	Retain	Biennial
MW-53	Biennial	Retain	Biennial
MW-55	Biennial	Retain	Biennial
MW-70	Biennial	Retain	Biennial
MW-72	Annual	Retain	Annual
MW-74	Biennial	Retain	Annual
MW-76	Annual	Retain	Annual
MW-88	Biennial	Retain	Biennial
MW-89	Biennial	Retain	Biennial
MW-90	Biennial	Retain	Biennial
MW-91	Biennial	Retain	Biennial
MW-92	Biennial	Retain	Biennial
MW-237	Biennial	Retain	Biennial
MW-240	Biennial	Retain	Biennial
MW-241	Annual	Remove	--
MW-242	Annual	Retain	Annual
MW-350	Biennial	Retain	Biennial
MW-351	Annual	Retain	Annual
MW-412	Biennial	Retain	Biennial
MW-458	Biennial	Retain	Biennial
MW-1004	Biennial	Retain	Biennial
MW-1026	Biennial	Retain	Biennial
MW-1041	Biennial	Remove	--
MW-1042	Biennial	Retain	Biennial
MW-1064	Biennial	Retain	Biennial
MW-1073	Biennial	Retain	Biennial
Zone B Monitoring Wells			
MW-19D	Biennial	Retain	Biennial
MW-51	Biennial	Retain	Biennial
MW-54	Annual	Retain	Annual
MW-57	Biennial	Retain	Biennial
MW-58	Biennial	Retain	Biennial
MW-59	Biennial	Retain	Biennial
MW-104	Biennial	Retain	Biennial
MW-1001	Biennial	Retain	Biennial

Table C.10: Refined Groundwater Monitoring Program at McClellan AFB OU D Generated Using the MAROS Tool

Well ID	Current Sampling Frequency	Results of MAROS Evaluation	
		Remove/Retain	Recommended Sampling Frequency
Zone B Monitoring Wells (continued)			
MW-1003	Biennial	Remove	--
MW-1010	Biennial	Retain	Biennial
MW-1027	Biennial	Retain	Biennial
MW-1028	Biennial	Remove	--
MW-1043	Biennial	Retain	Biennial
Groundwater Extraction Wells			
EW-73	Annual	Retain	Annual
EW-83	Annual	Retain	Annual
EW-84	Annual	Retain	Annual
EW-85	Annual	Retain	Annual
EW-86	Annual	Retain	Annual
EW-87	Annual	Retain	Annual

[a/] Information from GSI (2003c).
[b/] "Remove" = MAROS recommended that the well be removed from the monitoring program.
"Retain" = MAROS recommended that the well continue to be sampled at the indicated frequency.
[c/] A dash (--) indicates that the well is not included in the refined monitoring program.

Not all of the wells identified by MAROS as candidates for removal were eliminated from the refined monitoring program. The results of application of the MAROS algorithm indicated that well MW-72 was a candidate for removal; however, qualitative considerations suggested that MW-72 should be retained in the monitoring program. The concentrations of TCE in samples from well MW-72 have been greater than the MCL concentration for TCE (as of the 2000 sampling event), and the well is located on the centerline of the CAH plume and was used as the basis for the risk-based power analysis for containment at the compliance boundary. Well MW-1041 was not recommended by MAROS as a candidate for removal; however, well MW-1041 is located near the maximum upgradient extent of CAHs in groundwater at OU D, together with wells MW-1042, MW-1064, MW-1043 and MW-1010, far cross-gradient wells MW-237, MW-1026, MW-1027, and MW-1028, and far down-gradient well MW-350 (Figure C.4). Well MW-1041 was judged to be redundant with well MW-1042 on qualitative grounds, and was recommended for removal from the monitoring program (Table C.10). The possibility of removing other periphery monitoring wells also was examined, and it was concluded (GSI, 2003c) that although the MAROS analysis indicated that new wells could be used to replace the periphery wells, the decision to stop sampling the periphery wells should be made in accordance with non-statistical considerations, including regulatory requirements, community concerns, and/or public health issues. Non-statistical considerations may indicate that continued sampling of the periphery wells is warranted.

In nearly all instances, the results of the sampling frequency optimization analysis at McClellan AFB OU D, completed using the modified CES method (Appendix B), were adversely affected by the lack of consistent monitoring. The sampling frequency analysis requires sampling results from a minimum of six separate monitoring events at a particular sampling point. Historically, sampling frequencies for all wells at OU D have been irregular, so that no more than 5 to 7 records are available for numerous monitoring wells throughout the entire period from 1990 to 2000. In instances when fewer than six separate results were available for a particular monitoring well, or when a temporal trend in TCE concentrations could not be identified, the algorithm implemented in MAROS selected a "conservative" sampling frequency (i.e., MAROS specified that samples should be collected from that well more frequently than would otherwise have been the case). Accordingly, all recommendations generated by MAROS were examined qualitatively, by inspecting the historic and recent TCE concentrations in samples from those wells, and as a result, very few of the MAROS recommendations regarding sampling frequency were adopted. Rather, the subsequent qualitative evaluation that was conducted using the COC concentrations detected historically in samples from OU D monitoring wells was felt to generate more reasonable recommendations regarding sampling frequency (GSI, 2003c).

The results of the data-sufficiency evaluation, completed using power analysis methods (Appendix B) indicate that the monitoring program is more than sufficient to evaluate the extent of TCE in groundwater relative to the compliance boundary through time, assuming continued operation of the extraction system (GSI, 2003c).

The optimized monitoring program generated using the MAROS tool includes 29 A-zone wells, 11 B-zone wells, and 6 groundwater extraction wells, with 11 monitoring wells and 6 extraction wells sampled annually, and 29 monitoring wells sampled biennially (Table C.10). Adoption of the optimized program would result in collection and analysis of 32 samples per year, as compared with collection and analysis of 34 samples per year in the current monitoring program. Implementing these recommendations could lead to an approximately 6-percent reduction in the number of samples collected and analyzed annually, as compared with the current program. Adoption of the monitoring program as optimized using the MAROS tool is projected, based on information provided by facility personnel (GSI, 2003c), to result in savings of approximately $300 per year. (Estimated annual cost savings were provided by facility personnel; however, specific information regarding the estimated annual cost of the LTM program at McClellan AFB OU D, and the total cost per sample, is not available, and the means used to derive the estimated cost savings are uncertain.) Although projected annual cost savings are small, optimization of the monitoring program in accordance with the recommendations generated by MAROS could result in moderate cost savings over the life of the LTM program. The optimized program remains adequate to delineate the extent of COCs in groundwater, and to monitor changes in the condition of the plume over time (GSI, 2003c).

C3.6 SUMMARY OF LTMO EVALUATION COMPLETED USING THREE-TIERED APPROACH

C3.6.1 Summary of Groundwater Analytical Data for McClellan AFB OU D Used in Three-Tiered Approach

The OU D groundwater monitoring program also was evaluated using the three-tiered approach, applied to the results of sampling events completed during the period April 1990 through August 2001 (Parsons, 2003d), including the period of time during which passive diffusion sampling was conducted. Prior to the evaluation, the sampling-results database provided by the Base was processed to remove duplicate data measurements by retaining the greater of the primary and duplicate analytical results, and discarding the lower value. The processed analytical database contained from 5 to 18 sampling results for each constituent, at each of the 51 wells in the current OU D monitoring program. The database that was utilized in the three-tiered evaluation of the groundwater monitoring program for McClellan AFB OU D differed slightly from the database that was utilized in the corresponding MAROS evaluation in the following respects:

- The three-tiered approach was applied to a database having a slightly longer historical period of record, extending from April 1990 through August 2001, versus a historical period of record extending from April 1990 through the end of 2000 utilized in the MAROS evaluation (Section C3.5.1). The database utilized in the three-tiered evaluation included the analytical results for samples that were collected using passive diffusion sampling methods.

- The method used in the three-tiered approach to deal with analytical results from duplicate samples (retaining the greater of the primary and duplicate analytical results, and discarding the lower value) differed from the method used in the MAROS evaluation (averaging the primary and duplicate analytical results, and using this average to represent a single value; Section C3.5.1).

- The method used in the three-tiered approach for dealing with concentration values that were below reporting limits (reporting the value as "Not Detected"; Appendix B) differed from the method used in the MAROS evaluation (assigning a surrogate value corresponding to the reporting limit; Appendix B).

The occurrence of the four primary COCs identified in the GWOU IROD for groundwater at OU D (TCE, 1,2-DCA, *cis*-1,2-DCE, and PCE) is summarized in Table C.11. TCE historically has been detected most frequently (in 63 percent of samples) and at the highest concentrations of any COC in groundwater at McClellan AFB OU D, with TCE concentrations exceeding the MCL for TCE (5 μg/L) in approximately 38 percent of samples. TCE has been detected in groundwater samples from 46 of the 51 wells in the monitoring program, and has exceeded its MCL in samples from 26 of these wells. The other primary COCs (1,2-DCA, *cis*-1,2-DCE, and PCE) have been detected less frequently, at lower concentrations, and in samples from fewer wells than has TCE (Table C.11); therefore, TCE was selected as an indicator compound, based on its widespread detection at relatively elevated concentrations in wells across the site. Although the other primary COCs (1,2-DCA, *cis*-1,2-DCE, and PCE) were considered, together with TCE, in the qualitative and temporal stages of the three-tiered evaluation, the spatial-statistical evaluation of the monitoring program at McClellan AFB OU D used only the results of analyses for TCE in groundwater samples.

The A-zone wells were considered separately from the B-zone wells in the spatial analysis because even though the A and B zones are hydraulically connected, the A- and B-zone wells generally are completed in shallower and deeper zones, respectively, of the water-bearing unit. The number of wells completed in the B zone (13) was considered to be too few for use in a spatial-statistical analysis; and active extraction wells also were excluded from the spatial analysis.

C3.6.2 Results of Evaluation Completed Using Three-Tiered Approach

The spatial-statistical stage of the three-tiered evaluation was limited to monitoring wells completed in the A zone, because the number of wells completed in the B zone was not sufficient to complete a separate spatial evaluation for that zone (Parsons, 2003d). The most recent validated analytical data available (sampling results from the February 2000 or March 2001 monitoring events) were used in spatial-statistical evaluation, because an "instantaneous" representation of the spatial distribution of the variable of interest (TCE in groundwater) is required for the geostatistical analysis. As semivariogram models were calculated for TCE (a pre-requisite for the spatial evaluation), considerable scatter of the data was apparent during fitting of the models. Several data transformations (including a log transformation) were applied in attempts to obtain a reasonable semivariogram model. Ultimately, the concentration data were transformed to rank statistics, and nonparametric techniques were utilized to develop a semivariogram model. The inability to fit a

Table C.11: Summary of Occurrence of COCs[a/] in Groundwater at McClellan AFB OU D[b/]

Constituent[c/]	Total Number of Samples Analyzed for Constituent[d/]	Percentage of Samples Having Detected Concentrations	Range of Detected Concentrations (µg/L)[e/]	Number of Wells Having Samples Analyzed for Constituent	Number of Wells at Which Constituent was Detected	MCL[f/] (µg/L)	Percentage of Samples with MCL Exceedances	Number of Wells with MCL Exceedances
1,2-DCA	568	32.2%	0.0265 - 210	51	38	5	13.7%	13
cis-1,2-DCE	428	36.2%	0.0387 - 87.4	51	27	70	0.47%	2
PCE	569	23.6%	0.0294 - 770	51	34	5	5.4%	5
TCE	569	62.9%	0.0519 - 5,000	51	46	5	38.3%	26

a/ COCs = contaminants of concern.
b/ Information from Parsons (2003d).
c/ Constituents are as follow:
DCA = dichloroethane; DCE = dichloroethene; PCE = tetrachloroethene; TCE = trichloroethene.
d/ Analytical data include sampling results from April 1990 through August 2001.
e/ mg/L = micrograms per liter.
f/ MCL = maximum contaminant level.

parametric semivariogram model is a further illustration of the high degree of spatial variability in TCE concentrations, which also was noted during the MAROS evaluation of the monitoring program at McClellan AFB OU D (Section C3.5.2).

The results of the three-tiered evaluation (Parsons, 2003d) indicated that 30 of the 51 existing wells could be removed from the groundwater monitoring program with comparatively little loss of information (Table C.12; compare the current monitoring program with the recommendations generated during the three-tiered evaluation). Most of the wells recommended for removal from the monitoring program are wells peripheral to the OU D plume, which also were identified as possible candidates for removal during the MAROS evaluation (Section C3.5.2). However, the conclusion of the MAROS evaluation was that the decision to stop sampling the periphery wells should be made "in accordance with non-statistical considerations, including regulatory requirements, community concerns, and/or public health issues" (GSI, 2003c).

If this refined monitoring program, consisting of 21 wells (13 wells to be sampled annually, and 8 wells to be sampled biennially) were adopted, an average of 17 samples per year would be collected and analyzed, as compared with the collection and analysis of 34 samples per year in the current monitoring program – a reduction of 50 percent in the number of samples collected and analyzed annually, as compared with the current program. Although information regarding the annual costs associated with the LTM program at McClellan AFB OU D including the estimated total cost per sample is not available, based on analytical costs alone, and assuming a cost per sample of $150 for chemical analyses (analyses for VOCs only), adoption of the monitoring program as optimized using the three-tiered approach is projected to result in savings of about $2,550 per year, as compared with the current program (Parsons, 2003d). Additional cost savings could be realized if groundwater samples collected from select wells (e.g., upgradient wells, and wells along the lateral plume margins) were analyzed for a short list of halogenated VOCs using U.S. EPA Method SW8021B instead of U.S. EPA Method SW8260B (Parsons, 2003d).

Table C.12: Refined Groundwater Monitoring Program at McClellan AFB OU D Generated Using the Three-Tiered Approach[a/]

Well ID	Current Sampling Frequency	Results of Three-Tiered Evaluation	
		Remove/Retain[b/]	Recommended Sampling Frequency
Zone A Monitoring Wells			
MW-10	Annual	Retain	Annual
MW-11	Annual	Retain	Annual
MW-12	Annual	Retain	Annual
MW-14	Biennial	Retain	Biennial
MW-15	Annual	Retain	Annual
MW-38D	Annual	Retain	Annual
MW-52	Biennial	Remove	--[c/]
MW-53	Biennial	Remove	--
MW-55	Biennial	Retain	Biennial
MW-70	Biennial	Remove	--
MW-72	Annual	Remove	--
MW-74	Biennial	Remove	--

Table C.12: Refined Groundwater Monitoring Program at McClellan AFB OU D Generated Using the Three-Tiered Approach

Well ID	Current Sampling Frequency	Results of Three-Tiered Evaluation	
		Remove/Retain	Recommended Sampling Frequency
Zone A Monitoring Wells (continued)			
MW-76	Annual	Retain	Annual
MW-88	Biennial	Remove	--
MW-89	Biennial	Retain	Biennial
MW-90	Biennial	Retain	Biennial
MW-91	Biennial	Remove	--
MW-92	Biennial	Remove	--
MW-237	Biennial	Remove	--
MW-240	Biennial	Remove	--
MW-241	Annual	Remove	--
MW-242	Annual	Remove	--
MW-350	Biennial	Remove	--
MW-351	Annual	Remove	--
MW-412	Biennial	Remove	--
MW-458	Biennial	Remove	--
MW-1004	Biennial	Remove	--
MW-1026	Biennial	Remove	--
MW-1041	Biennial	Remove	--
MW-1042	Biennial	Remove	--
MW-1064	Biennial	Remove	--
MW-1073	Biennial	Remove	--
Zone B Monitoring Wells			
MW-19D	Biennial	Retain	Biennial
MW-51	Biennial	Retain	Biennial
MW-54	Annual	Retain	Annual
MW-57	Biennial	Remove	--
MW-58	Biennial	Retain	Biennial
MW-59	Biennial	Retain	Biennial
MW-104	Biennial	Remove	--
MW-1001	Biennial	Remove	--
MW-1003	Biennial	Remove	--
MW-1010	Biennial	Remove	--
MW-1027	Biennial	Retain	Biennial
MW-1028	Biennial	Remove	--
MW-1043	Biennial	Retain	Biennial
Groundwater Extraction Wells			
EW-73	Annual	Retain	Annual
EW-83	Annual	Retain	Annual

Table C.12: Refined Groundwater Monitoring Program at McClellan AFB OU D Generated Using the Three-Tiered Approach

Well ID	Current Sampling Frequency	Results of Three-Tiered Evaluation	
		Remove/Retain	Recommended Sampling Frequency
Groundwater Extraction Wells (continued)			
EW-84	Annual	Retain	Annual
EW-85	Annual	Retain	Annual
EW-86	Annual	Retain	Annual
EW-87	Annual	Retain	Annual

[a/] Information from Parsons (2003d).
[b/] "Remove" = Three-tiered evaluation recommended that the well be removed from the monitoring program.
"Retain" = Three-tiered evaluation recommended that the well continue to be sampled at the indicated frequency.
[c/] A dash (--) indicates that the well is not included in the refined monitoring program.

APPENDIX D

ORIGINAL MONITORING PROGRAM OPTIMIZATION REPORTS BY GROUNDWATER SERVICES, INC. AND PARSONS

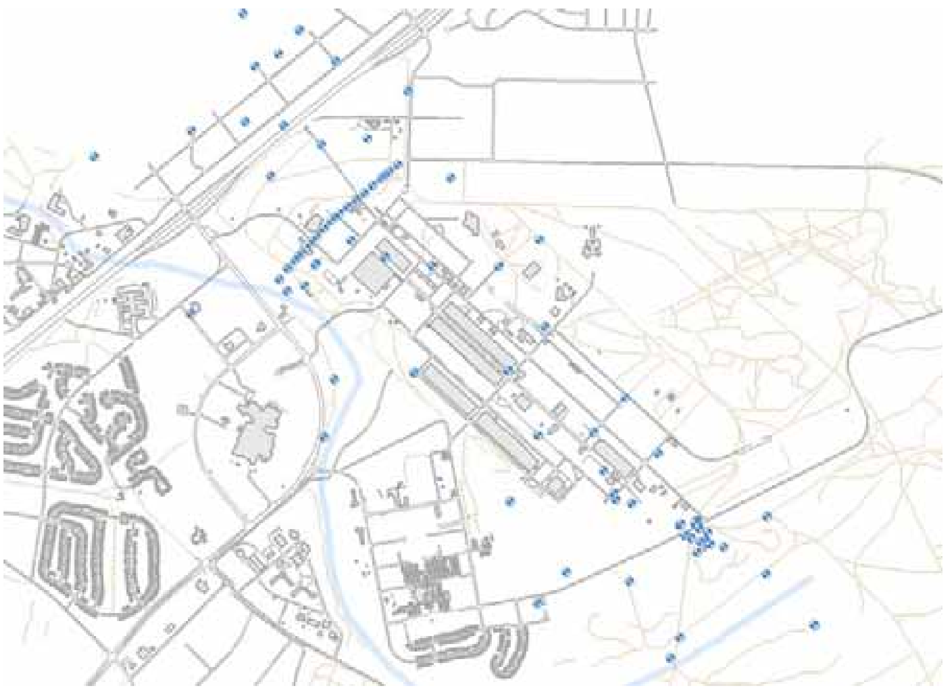
APPENDIX D-1

OPTIMIZATION OF MONITORING PROGRAM
AT
FORT LEWIS LOGISTICS CENTER, WASHINGTON

G-2236-15

MAROS 2.0 Application: Upper Aquifer Monitoring Network Optimization Fort Lewis Logistics Center

Pierce County, Washington



Submitted to
Air Force Center for Environmental Excellence

April 7, 2003

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GROUNDWATER
SERVICES, INC.

MAROS 2.0 APPLICATION
UPPER AQUIFER MONITORING NETWORK OPTIMIZATION
FORT LEWIS LOGISTICS CENTER

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MAROS 2.0 APPLICATION UPPER AQUIFER MONITORING NETWORK OPTIMIZATION, FORT LEWIS LOGISTICS CENTER

Pierce County, Washington

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EXECUTIVE SUMMARY

Long-term monitoring programs, whether applied for process control, performance measurement, or compliance purposes, require large scale data collection effort and time commitment, making their cumulative costs very high. With the increasing use of risk-based goals and natural attenuation in recent years as well as the move toward long-term closure upon completion of cleanup activities, the need for better-designed long-term monitoring plans that are cost-effective, efficient, and protective of human and ecological health has greatly increased. The Monitoring and Remediation Optimization System (MAROS) methodology provides an optimal monitoring network solution, given the parameters within a complicated groundwater system which will increase its effectiveness. By applying statistical techniques to existing historical and current site analytical data, as well as considering hydrogeologic factors and the location of potential receptors, the software suggests an optimal plan along with an analysis of individual monitoring wells for the current monitoring system. This report summarizes the findings of an application of the MAROS 2.0 software to the Upper Aquifer long-term monitoring well network at the Fort Lewis Logistics Center in Pierce County, Washington.

The primary constituent of concern at the site is trichloroethylene (TCE) which is analyzed at 43 monitoring wells in the Upper Aquifer original well network, as of 2001 (Figure 1). All monitoring wells, unless abandoned, have been sampled quarterly in the Upper Aquifer for TCE since the implementation of the original long-term monitoring plan. By September 2001, 24 sampling events had been carried out at the site. The historical TCE data for all or in some cases a subset of wells were analyzed using the MAROS 2.0 software in order to : 1) gain an overall understanding of the plume stability, and 2) recommend changes in sampling frequency and sampling locations without compromising the effectiveness of the long-term monitoring network.

Project Objectives

The general objective of the project was to optimize the original Fort Lewis Upper Aquifer long-term monitoring network and sampling plan applying the MAROS 2.0 statistical and decision support methodology. The key objectives of the project included:

- Determining the overall plume stability through trend analysis and moment analysis
- Evaluating individual well TCE concentration trends over time
- Addressing adequate and effective sampling through reduction of redundant wells without information loss and addition of new wells for future sampling
- Assessing future sampling frequency recommendations while maintaining sufficient plume stability information

- Evaluating risk-based site cleanup status using data sufficiency analysis
- Comparing the MAROS 2.0 original (2001) monitoring plan optimization with the 2002 LOGRAM plan implemented in 2002

Results

The MAROS 2.0 sampling optimization software/methodology has been applied to the Fort Lewis Upper Aquifer's original RAM program as of September, 2001. Results from the temporal trend analysis, moment analysis, sampling location determination, sampling frequency determination, and data sufficiency analysis indicate that:

- Site monitoring wells were divided into source wells and tail wells where source wells are in the vicinity of NAPL or have historically elevated concentrations of TCE.

- 6 out of 10 source wells and 15 out of 33 tail wells have a Probably Decreasing, Decreasing, or Stable trend. Both of the statistical methods used to evaluate trends (Mann-Kendall and Linear Regression) gave similar trend estimates for each well.

- 6 out of 6 source area extraction wells have a Probably Decreasing, or Decreasing trend. Both the Mann-Kendall and Linear Regression methods gave similar trend estimates for each well.

- 12 out of 15 plume containment extraction wells have Probably Decreasing, Decreasing, or Stable trend. Both the Mann-Kendall and Linear Regression methods gave similar trend estimates for each well.

- The dissolved mass shows an increase over time, whereas the center of mass has stayed stable and the plume spread shows a decrease over time. The increase in dissolved mass maybe due to either 1) the extraction system moving high concentration groundwater from source zones to nearby monitoring wells; or 2) the change in the wells sampled over the sampling period analyzed.

- Overall plume stability results indicate that a monitoring system of "Moderate" intensity is appropriate for this plume compared to "Limited" or "Extensive" systems due to a stable Upper Aquifer plume.

- The well redundancy optimization tool, using the Delaunay method, indicates that 8 existing monitoring wells may not be needed for plume monitoring and can be eliminated from the original monitoring network of 38 wells without compromising the accuracy of the monitoring network.

- The well sufficiency optimization tool, using the Delaunay method, indicates that 6 new monitoring wells may help reduce uncertainty in selected areas within the original monitoring network.

- The well sampling frequency tool, the Modified CES method, indicates the number of samples collected over time sampling can potentially be reduced by 56% by sampling at a less-than-quarterly frequency for most of the monitoring wells. A 57% reduction in sampling can potentially be achieved for the monitoring extraction wells using the sampling frequency recommended by the MAROS analysis.

- The MAROS Data Sufficiency (Power Analysis) application indicates that the monitoring record has sufficient statistical power at this time to say that the plume will not cross a "hypothetical statistical compliance boundary" located 2000 feet downgradient of the most downgradient well at the site. As more sampling records accumulate, this hypothetical statistical compliance boundary will get closer and closer to the downgradient wells of the monitoring system.

- Comparison of the original Upper Aquifer monitoring plan with the 2002 LOGRAM sampling plan, indicates that similar sampling frequency and well redundancy results were obtained. However, well adequacy results differed due to the constraints of assessing only the existing well network within the MAROS software.

The MAROS optimized plan consists of 56 wells: 19 sampled quarterly, 2 sampled semiannually, 30 sampled annually, and 5 sampled biennially. The MAROS optimized plan would result in 113 (112.5) samples per year, compared to 180 samples per year in the current LOGRAM monitoring program and 236 samples per year in the original sampling program. Implementing these recommendations could lead to a 37% reduction from the LOGRAM plan and 52% reduction from the original plan in terms of the samples to be collected per year. Based on a per sample cost of $500, the MAROS optimized plan could reduce the site monitoring cost by $33,500 and $61,500 from the LOGRAM plan and the original plan, respectively.

The recommended long-term monitoring strategy, based on the analysis of the original monitoring plan, results in considerable reduction in sampling costs and allows site personnel to develop a better understanding of plume behavior over time. A reduction in the number of redundant wells, an increase in the number of wells in areas with inadequate information, as well as reduction in sampling frequency is expected to results in a significant cost savings over the long-term at Fort Lewis. An approximate cost savings estimate of $33,500 per year is projected while still maintaining adequate delineation of the plume as well as knowledge of the plume state over time.

1.0 INTRODUCTION

Long-term monitoring programs, whether applied for process control, performance measurement, or compliance purposes, require large scale data collection effort and time commitment, making their cumulative costs very high. With the increasing use of risk-based goals and natural attenuation in recent years as well as the move toward long-term closure upon completion of cleanup activities, the need for better-designed long-term monitoring plans that are cost-effective, efficient, and protective of human and ecological health has greatly increased. AFCEE's Monitoring and Remediation Optimization System (MAROS) methodology provides an optimal monitoring network solution, given the parameters within a complicated groundwater system which will increase its effectiveness. By applying statistical techniques to existing historical and current site analytical data, as well as considering hydrogeologic factors and the location of potential receptors, the software suggests an optimal plan along with an analysis of individual monitoring wells for the current monitoring system. This report summarizes the findings of an application of the MAROS 2.0 software to the original Upper Aquifer long-term monitoring well network at the Fort Lewis Logistics Center in Pierce County, Washington.

1.1 Geology/Hydrogeology

The Fort Lewis Logistics Center is located in Pierce County, Washington. The shallow geologic units under the Logistics Center (known as the Upper Aquifer) consists primarily of outwash sand and outwash gravel. The geologic units that comprise the Upper Aquifer are the Upper Vashon Recessional Outwash and the Lower Vashon Advance Outwash. The depth to groundwater is typically 10 to 30 feet below ground surface (bgs), with the Upper Aquifer having an approximate saturated thickness of 60 feet. The groundwater flow direction is predominantly toward the west-northwest and the groundwater seepage velocity is approximately 550 ft/yr. For a detailed description of site geology and hydrogeology refer to USACE (2002).

1.2 Remedial Action and Long-Term Monitoring

The Fort Lewis Logistics Center was activated in April 1942. Trichloroethene (TCE) was used as a degreasing agent at this facility until the mid-1970s when it was replaced with 1,1,1-trichloroethane. Waste TCE was disposed of in several locations. In 1985, the Army identified traces of TCE in several monitoring wells installed in the Upper Aquifer. A limited site investigation was performed in 1986 and a CERCLA remedial investigation (RI) began in 1987. The results of the RI showed that the ground water plume in the shallow Upper Aquifer principally contains TCE and is over 2 miles long, between 3,000 to 4,000 feet wide and 60 to 80 feet thick (USACE 2000). The plume also contains 1,2-dichloroethene (1,2-DCE) at concentrations of approximately 10 percent of the TCE level. According to the results of the RI, the East Gate Disposal Yard (EGDY) is the most significant source of TCE. Nonaqueous-phase liquid (NAPL) was found in the "source area" consisting primarily of TPH (diesel-, gasoline-, motor-oil- and total) and TCE. The

Logistics Center area that extends from the west boundary of EGDY toward Interstate 5 is designated as the “down-gradient area”.

A pump-and-treat system installed at the site began operation in August 1995. The remedial action applied at the site includes groundwater extraction and treatment and recharge of treated groundwater back into the Upper Aquifer (USACE 2000). The objective of the remediation is to restore the Upper Aquifer to drinking water standards by reducing the TCE concentration to less than 5 ppb within 30~40 years at down-gradient compliance points.

The original groundwater long-term monitoring plan was completed in August 1995 (USACE, 2000). It consisted of performance monitoring and compliance monitoring with the following goals: 1) plume containment monitoring to confirm that the plume remains hydraulically controlled; and 2) plume reduction monitoring to verify progress toward achieving cleanup goals. The number of monitoring wells that were sampled in the original Upper Aquifer monitoring network is 43 (Figure 1). There are also 21 extraction wells in the monitoring plan. All monitoring wells, unless abandoned, have been sampled quarterly in the Upper Aquifer for TCE since the implementation of the original long-term monitoring plan. Between November 1995 and September 2001, 24 sampling events had been carried out at the site.

In 2001, USACE used the MAROS 1.0 software to optimize the sampling frequency at the Fort Lewis site and used a qualitative evaluation to assess the well redundancy and well adequacy in the well network (USACE 2001). The resulting LOGRAM revised monitoring plan was approved by the EPA and implemented in 2002. The revised monitoring network consists of 51 monitoring wells and 21 extraction wells, with a reduction of some of the wells to be sampled semiannually and annually that had previously been sampled quarterly. The well redundancy analysis resulted in 11 monitoring wells being removed from the network, while the well adequacy analysis resulted in 24 monitoring wells added to the monitoring plan. The LOGRAM plan was implemented in December, 2001. However, at the time of this study there were inadequate sampling results (less than 4 quarters of data) to include the new well’s data in the LOGRAM monitoring plan in the current MAROS 2.0 analysis.

The MAROS 2.0 analysis performed for this study utilizes the data from the original Fort Lewis long-term monitoring plan (November 1995 to September 2001). The monitoring data from the optimized LOGRAM plan was not utilized in this study, but a comparison of the MAROS 2.0 results with the USACE will be provided.

2.0 MAROS METHODOLOGY

The MAROS 2.0 software used to optimize the LTM network at the Fort Lewis Logistics Center is explained in general terms in this section. MAROS is a collection of tools in one software package that is used in an explanatory, non-linear fashion. The tool includes models, statistics, heuristic rules, and empirical relationships to assist the user in optimizing a groundwater monitoring network system while maintaining adequate delineation of the plume as well as knowledge of the plume state over time. Different users utilize the tool in different ways and interpret the results from a different viewpoint. For a detailed description of the structure of the software and further utilities, refer to the MAROS 2.0 Manual (Aziz et al. 2002).

2.1 MAROS Conceptual Model

In MAROS 2.0, two levels of analysis are used for optimizing long-term monitoring plans: 1) an overview statistical evaluation with interpretive trend analysis based on temporal trend analysis and plume stability information; and 2) a more detailed statistical optimization based on spatial and temporal redundancy reduction methods (see Figure 2 for further details). In general, the MAROS method applies to 2-D aquifers that have relatively simple site hydrogeology. However, for a multi-aquifer (3-D) system, the user could apply the statistical analysis layer-by-layer.

The overview statistics or interpretive trend analysis assesses the general monitoring system category by considering individual well concentration trends, overall plume stability, hydrogeologic factors (e.g., seepage velocity, and current plume length), and the location of potential receptors (e.g., property boundaries or drinking water wells). The analysis relies on temporal trend analysis to assess plume stability, which is then used to determine the general monitoring system category. Since the temporal trend analysis focuses on where the monitoring well is located, the site wells are divided into two different zones: the source zone or the tail zone. The source zone includes areas with non-aqueous phase liquids (NAPLs), contaminated vadose zone soils, and areas where aqueous-phase releases have been introduced into ground water. The source zone generally contains locations with historical high ground water concentrations of the COCs. The tail zone is usually the area downgradient of the contaminant source zone. Although this classification is a simplification of the well location, this broadness makes the user aware on an individual well basis that the concentration trend results can have a different interpretation depending on the well location in and around the plume. The location and type of the individual wells allows further interpretation of the trend results, depending on what type of well is being analyzed (e.g., remediation well, leading plume edge well, or monitoring well). General recommendations for the monitoring network frequency and density are suggested based on heuristic rules applied to the source and tail trend results.

The detailed statistics level of analysis or sampling optimization, on the other hand, consists of a well redundancy analysis and well sufficiency analysis using the Delaunay method, a sampling frequency analysis using the Modified Cost Effective Sampling

(CES) method and a data sufficiency analysis using power analysis. The well redundancy analysis is designed to minimize monitoring locations and the Modified CES method is designed to minimize the frequency of sampling. The data sufficiency analysis uses power analysis to assess the sampling record to determine if the current monitoring network and record is sufficient in terms of evaluating risk-based site target level status.

2.2 Data Management

In MAROS, ground water monitoring data can be imported from simple database-format Microsoft® Excel spreadsheets, Microsoft Access tables, previously created MAROS database archive files, or entered manually. Compliance monitoring data interpretation in MAROS is based on historical ground water monitoring data from a consistent set of wells over a series of sampling events. Statistical validity of the concentration trend analysis requires constraints on the minimum data input of at least four wells (ASTM 1998) in which COCs have been detected. Individual sampling locations need to include data from at least six most-recent sampling events. To ensure a meaningful comparison of COC concentrations over time and space, both data quality and data quantity need to be considered. Prior to statistical analysis, the user can consolidate irregularly sampled data or smooth data that might result from seasonal fluctuations or a change in site conditions.

Imported ground water monitoring data and the site-specific information entered in Site Details can be archived and exported as MAROS archive files. These archive files can be appended as new monitoring data becomes available, resulting in a dynamic long-term monitoring database that reflects the changing conditions at the site (i.e. biodegradation, compliance attainment, completion of remediation phase, etc.).

2.3 Site Details

Information needed for the MAROS analysis includes site-specific parameters such as seepage velocity and current plume length. Part of the trend analysis methodology applied in MAROS focuses on where the monitoring well is located, therefore the user needs to divide site wells into two different zones: the source zone or the tail zone. The source zone includes areas with non-aqueous phase liquids (NAPLs), contaminated vadose zone soils, and areas where aqueous-phase releases have been introduced into ground water. The source zone generally contains locations with historical high ground water concentrations of the COCs. The tail zone is usually the area downgradient of the contaminant source zone. Although this classification is a simplification of the well location, this broadness makes the user aware on an individual well basis that the concentration trend results can have a different interpretation depending on the well location in and around the plume. It is up to the user to make further interpretation of the trend results, depending on what type of well is being analyzed (e.g., remediation well, leading plume edge well, or monitoring well).

MAROS allows the analysis of up to 5 COCs concurrently and users can pick COCs from a list of compounds existing in the monitoring data, or select COCs based on recommendations provided in MAROS based on toxicity, prevalence, and mobility of compounds.

2.4 Data Consolidation

Typically long-term monitoring raw data have been measured irregularly in time or contain many non-detects, trace level results, and duplicates. Therefore, before the data can be further analyzed, raw data are filtered, consolidated, transformed, and possibly smoothed to allow for a consistent dataset meeting the minimum data requirements for statistical analysis mentioned previously.

MAROS allows users to specify the period of interest in which data will be consolidated (i.e., monthly, bi-monthly, quarterly, semi-annual, yearly, or a biennial basis). In computing the representative value when consolidating, one of four statistics can be used: median, geometric mean, mean, and maximum. Non-detects can be transformed to one half the reporting or method detection limit (DL), the DL, or a fraction of the DL. Trace level results can be represented by their actual values, one half of the DL, the DL, or a fraction of their actual values. Duplicates are reduced in MAROS by one of three ways: assigning the average, maximum, or first value. The reduced data for each COC and each well can be viewed as a time series in a graphical form on a linear or semi-log plot generated by the software.

2.5 Overview Statistics: Plume Trend Analysis

Within the MAROS software there are historical data analyses that support a conclusion about plume stability (e.g., increasing plume, etc.) through statistical trend analysis of historical monitoring data. Plume stability results are assessed from time-series concentration data with the application of three statistical tools: Mann-Kendall Trend analysis, linear regression trend analysis and moment analysis. The two trend methods are used to estimate the concentration trend for each well and each COC based on a statistical trend analysis of concentrations versus time at each well. These trend analyses are then consolidated to give the user a general plume stability and general monitoring frequency and density recommendations (see Figure 3 for further step-by-step details). Both qualitative and quantitative plume information can be gained by these evaluations of monitoring network historical data trends both spatially and temporally. The MAROS Overview Statistics are the foundation the user needs to make informed optimization decisions at the site. The Overview Statistics are designed to allow site personnel to develop a better understanding of the plume behavior over time and understand how the individual well concentration trends are spatially distributed within the plume. This step allows the user to gain information that will support a more informed decision to be made in the next level or detailed statistics optimization analysis (Figure 2).

2.5.1 Mann-Kendall Analysis

The Mann-Kendall test is a non-parametric statistical procedure that is well suited for analyzing trends in data over time. The Mann-Kendall test can be viewed as a nonparametric test for zero slope of the first-order regression of time-ordered concentration data versus time. The Mann-Kendall test does not require any assumptions as to the statistical distribution of the data (e.g. normal, lognormal, etc.) and can be used with data sets which include irregular sampling intervals and missing data. The Mann-Kendall test is designed for analyzing a single groundwater constituent, multiple constituents are analyzed separately. The Mann-Kendall S statistic measures the trend in the data: positive values indicate an increase in concentrations over time and negative values indicate a decrease in concentrations over time. The strength of the trend is proportional to the magnitude of the Mann-Kendall statistic (i.e., a large value indicates a strong trend). The confidence in the trend is determined by consulting the S statistic and the sample size n in a Kendall probability table such as the one reported in Hollander and Wolfe (1973).

The concentration trend is determined for each well and each COC based on results of the S statistic, the confidence in the trend, and the Coefficient of Variation (COV). The decision matrix for this evaluation is shown in Table 1. A Mann-Kendall S statistic that is greater than 0 combined with a confidence of greater than 95% is categorized as an Increasing trend while a Mann-Kendall S statistic of greater than 0 with a confidence between 90% and 95% is defined as a Probably Increasing trend, and so on.

Depending on statistical indicators, the concentration trend is classified into six categories:

- Decreasing (D),
- Probably Decreasing (PD),
- Stable (S),
- No Trend (NT),
- Probably Increasing (PI)
- Increasing (I).

These trend estimates are then analyzed to identify the source and tail region overall stability category (see Figure 3 for further details).

2.5.2 Linear Regression Analysis

Linear Regression is a parametric statistical procedure that is typically used for analyzing trends in data over time. Using this type of analysis, a higher degree of scatter simply corresponds to a wider confidence interval about the average log-slope. Assuming the sign (i.e., positive or negative) of the estimated log-slope is correct, a level of confidence that the slope is not zero can be easily determined. Thus, despite a poor goodness of fit, the overall trend in the data may still be ascertained, where low levels of confidence correspond to “Stable” or “No Trend” conditions (depending on the degree of scatter) and higher levels of confidence indicate the stronger likelihood of a trend. The linear regression analysis is based on the first-order linear regression of the log-transformed concentration data versus time. The slope obtained from this log-transformed regression, the confidence level for this log-slope, and the COV of the untransformed data are used to determine the concentration trend. The decision matrix for this evaluation is shown in Table 2. To estimate the confidence in the log-slope, the standard error of the log-slope is calculated. The coefficient of variation, defined as the standard deviation divided by the average, is used as a secondary measure of scatter to distinguish between "Stable" or "No Trend" conditions for negative slopes. The Linear Regression Analysis is designed for analyzing a single groundwater constituent; multiple constituents are analyzed separately, (up to five COCs simultaneously). For this evaluation, a decision matrix developed by Groundwater Services, Inc. is also used to determine the "Concentration Trend" category (plume stability) for each well.

Depending on statistical indicators, the concentration trend is classified into six categories:

- Decreasing (D),
- Probably Decreasing (PD),
- Stable (S),
- No Trend (NT),
- Probably Increasing (PI)
- Increasing (I).

The resulting confidence in the trend, together with the log-slope and the COV of the untransformed data, are used in the linear regression analysis decision matrix to determine the concentration trend. For example, a positive log-slope with a confidence of less than 90% is categorized as having No Trend whereas a negative log-slope is considered Stable if the COV is less than 1 and categorized as No Trend if the COV is greater than 1.

2.5.3 Overall Plume Analysis

General recommendations for the monitoring network frequency and density are suggested based on heuristic rules applied to the source and tail trend results. Individual well trend results are consolidated and weighted by the MAROS according to user input, and the direction and strength of contaminant concentration trends in the source zone and tail zone for each COC are determined. Based on

i) the consolidated trend analysis,
ii) hydrogeologic factors (e.g., seepage velocity), and
iii) location of potential receptors (e.g., wells, discharge points, or property boundaries),

the software suggests an general optimization plan for the current monitoring system in order to efficiently effectively monitor in the future. A flow chart of the utilizing the trend analysis results and other site-specific parameters to form a general sampling frequency and well density recommendation is outlined in Figure 2. For example, a generic plan for a shrinking petroleum hydrocarbon plume (BTEX) in a slow hydrogeologic environment (silt) with no nearby receptors would entail minimal, low frequency sampling of just a few indicators. On the other hand, the generic plan for a chlorinated solvent plume in a fast hydrogeologic environment that is expanding but has very erratic concentrations over time would entail more extensive, higher frequency sampling. The generic plan is based on a heuristically derived algorithm for assessing future sampling duration, location and density that takes into consideration plume stability. For a detailed description of the heuristic rules used in the MAROS software, refer to the MAROS 2.0 Manual (Aziz et al. 2002).

2.5.3 Moment Analysis

An analysis of moments can help resolve plume trends, where the zeroth moment shows change in dissolved mass vs. time, the first moment shows the center of mass location vs. time, and the second moment shows the spread of the plume vs. time. Moment calculations can predict how the plume will change in the future if further statistical analysis is applied to the moments to identify a trend (in this case, Mann Kendall Trend Analysis is applied). The trend analysis of moments can be summarized as:

- Zeroth Moment: Change in dissolved mass over time
- First Moment: Change in the center of mass location over time
- Second Moment: Spread of the plume over time

The role of moment analysis in MAROS is to provide a relative measure of plume stability and condition. Plume stability may vary by constituent, therefore the MAROS Moment analysis can be used to evaluate multiple COCs simultaneously which can be used to provide a quick way of comparing individual plume parameters to determine the size and movement of constituents relative to one another. Moment analysis in the MAROS software can also be used to assist the user in evaluating the impact on plume delineation in future sampling events by removing identified “redundant” wells from a long-term monitoring program (this analysis was not performed as part of this study, for more details on this application of moment analysis refer to the MAROS 2.0 Manual (Aziz et al. 2002)).

The **zeroth moment** is a dissolved mass estimate. The zeroth moment calculation can show high variability over time, largely due to the fluctuating concentrations at the most contaminated wells as well as varying monitoring well network. Plume analysis and delineation based exclusively on concentration can exhibit a fluctuating degree of temporal and spatial variability. The mass estimate is also sensitive to the extent of the site monitoring well network over time. The zeroth moment trend over time is determined by using the Mann-Kendall Trend Methodology. The zeroth Moment trend test allows the user to understand how the plume mass has changed over time. Results for the trend include: Increasing, Probably Increasing, No Trend, Stable, Probably Decreasing, Decreasing or Not Applicable (Insufficient Data). When considering the results of the Zeroth moment trend, the following factors should be considered which could effect the calculation and interpretation of the plume mass over time: 1) Change in the spatial distribution of the wells sampled historically 2) Different wells sampled within the well network over time (addition and subtraction of well within the network). 3) Adequate versus inadequate delineation of the plume over time

The **first moment** estimates the center of mass, coordinates (Xc and Yc) for each sample event and COC. The changing center of mass locations indicate the movement of the center of mass over time. Whereas, the distance from the original source location to the center of mass locations indicate the movement of the center of mass over time relative to the original source. Calculation of the first moment normalizes the spread by the concentration indicating the center of mass. The first moment trend of the distance to the center of mass over time shows movement of the plume in relation to the original source location over time. Analysis of the movement of mass should be viewed as it relates to 1) the original source location of contamination 2) the direction of groundwater flow and/or 3) source removal or remediation. Spatial and temporal trends in the center of mass can indicate spreading or shrinking or transient movement based on season variation in rainfall or other hydraulic considerations. No appreciable movement or a neutral trend in the center of mass would indicate plume stability. However, changes in the first moment over time do not necessarily completely characterize the changes in the concentration distribution (and the mass) over time. Therefore, in order to fully characterize the plume the First Moment trend should be compared to the Zeroth moment trend (mass change over time).

The **second moment** indicates the spread of the contaminant about the center of mass (Sxx and Syy), or the distance of contamination from the center of mass for a particular COC and sample event. The Second Moment represents the spread of the plume over time in both the x and y directions. The Second Moment trend indicates the spread of the plume about the center of mass. Analysis of the spread of the plume should be viewed as it relates to the direction of groundwater flow. An increasing trend in the second moment indicates an expanding plume, whereas a declining trend in the plume indicates a shrinking plume. No appreciable movement or a neutral trend in the center of mass would indicate plume stability. The second moment provides a measure of the spread of the concentration distribution about the plume's center of mass. However, changes in the second moment over time do not necessarily completely characterize the changes in the concentration distribution (and the mass) over time. Therefore, in order to fully characterize the plume the Second Moment trend should be compared to the zeroth moment trend (mass change over time).

2.6 Detailed Statistics: Optimization Analysis

Although the overall plume analysis shows a general recommendation regarding sampling frequency reduction and a general sampling density, a more detailed analysis is also available with the MAROS 2.0 software in order to allow for further reductions on a well-by-well basis for frequency, well redundancy, well sufficiency and sampling sufficiency. The MAROS Detailed Statistics allows for a quantitative analysis for spatial and temporal optimization of the well network on a well-by-well basis. The results from the Overview Statistics should be considered along with the MAROS optimization recommendations gained from the Detailed Statistical Analysis described previously. The MAROS Detailed Statistics results should be reassessed in view of site knowledge and regulatory requirements as well as in consideration of the Overview Statistics (Figure 2).

The Detailed Statistics or Sampling Optimization MAROS module can be used to determine the minimal number of sampling locations and the lowest frequency of sampling that can still meet the requirements of sampling spatially and temporally for an existing monitoring program. It also provides an analysis of the sufficiency of data for the monitoring program.

Sampling optimization in MAROS consists of four parts:

- Well redundancy analysis using the Delaunay method
- Well sufficiency analysis using the Delaunay method
- Sampling frequency determination using the Modified CES method
- Data sufficiency analysis using statistical power analysis.

The well redundancy analysis using the Delaunay method identifies and eliminates redundant locations from the monitoring network. The well sufficiency analysis can determine the areas where new sampling locations might be needed. The Modified CES method determines the optimal sampling frequency for a sampling location based on the direction, magnitude, and uncertainty in its concentration trend. The data sufficiency analysis examines the risk-based site cleanup status and power and expected sample size associated with the cleanup status evaluation.

2.6.1 Well Redundancy Analysis – Delaunay Method

The well redundancy analysis using the Delaunay method is designed to select the minimum number of sampling locations based on the spatial analysis of the relative importance of each sampling location in the monitoring network. The approach allows elimination of sampling locations that have little impact on the historical characterization of a contaminant plume. An extended method or wells sufficiency analysis, based on the Delaunay method, can also be used for recommending new sampling locations. Details about the Delaunay method can be found in Appendix A.2 of the MAROS Manual (AFCEE 2002).

Well redundancy analysis uses the Delaunay triangulation method to determine the significance of the current sampling locations relative to the overall monitoring network. The Delaunay method calculates the network Area and Average concentration of the plume using data from multiple monitoring wells. A slope factor (SF) is calculated for each well to indicate the significance of this well in the system (i.e. how removing a well changes the average concentration.)

The well redundancy optimization process is performed in a stepwise fashion. Step one involves assessing the significance of the well in the system, if a well has a small SF (little significance to the network), the well may be removed from the monitoring network. Step two involves evaluating the information loss of removing a well from the network. If one well has a small SF, it may or may not be eliminated depending on whether the information loss is significant. If the information loss is not significant, the well can be eliminated from the monitoring network and the process of optimization continues with fewer wells. However if the well information loss is significant then the optimization terminates. This sampling optimization process allows the user to assess "redundant" wells that will not incur significant information loss on a constituent-by-constituent basis for individual sampling events.

2.6.2 Well Sufficiency Analysis – Delaunay Method

The well sufficiency analysis, using the Delaunay method, is designed to recommend new sampling locations in areas within the existing monitoring network where there is a high level uncertainty in plume concentration. Details about the well sufficiency analysis can be found in Appendix A.2 of the MAROS Manual (AFCEE 2002).

In many cases, new sampling locations need to be added to the existing network to enhance the spatial plume characterization. In MAROS, the method for determining new sampling locations recommends the area for a possible new sampling location where there is a high level of uncertainty in concentration estimation. The Slope Factor (SF) values obtained from the redundancy reduction described above are used to calculate the concentration estimation error at each triangle area formed in the Delaunay triangulation. The estimated SF value at each triangle area is then classified into four levels: Small, Moderate, Large, or Extremely large because the larger the estimated SF value, the higher the estimation error at this area. Therefore, the triangle areas with the estimated SF value at the Extremely large or Large level are candidate regions for new sampling locations.

The results from the Delaunay method and the method for determining new sampling locations are derived solely from the spatial configuration of the monitoring network and the spatial pattern of the contaminant plume. No parameters such as the hydrogeologic conditions are considered in the analysis. Therefore, professional judgement and regulatory considerations must be used to make final decisions.

2.6.3 Sampling Frequency Determination - Modified CES Method

The Modified CES method optimizes sampling frequency for each sampling location based on the magnitude, direction, and uncertainty of its concentration trend derived from its recent and historical monitoring records. The Modified Cost Effective Sampling estimates the lowest-frequency sampling schedule for a given groundwater monitoring location yet still provide needed information for regulatory and remedial decision-making. The Modified CES method was developed on the basis of the Cost Effective Sampling (Ridley et al. 1995). Details about the Modified CES method can be found in Appendix A.3 of the MAROS Manual (AFCEE 2002).

In order to estimate the least frequent sampling schedule for a monitoring location that still provides enough information for regulatory and remedial decision-making, MCES employs three steps to determine the sampling frequency. The first step involves analyzing frequency based on recent trends. A preliminary location sampling frequency

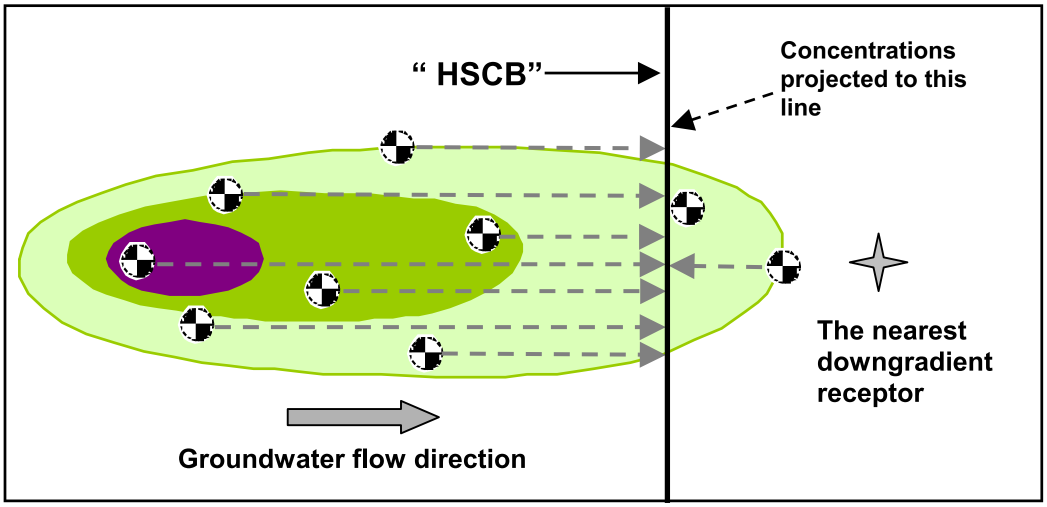
(PLSF) is determined based on the trends determined by rates of change from linear regression and Mann-Kendall analysis of the most recent monitoring data (Figure 4). The variability of the sequential sampling data is accounted for by the Mann-Kendall analysis. The PLSF is then adjusted based on overall trends. If the long-term history of change is significantly greater than the recent trend, the frequency may be reduced by one level. Otherwise, no change could be made. The final step in the analysis involves reducing frequency based on risk. Since not all compounds in the target being assessed are equally harmful, frequency is reduced by one level if recent maximum concentration for compound of high risk is less than 1/2 of the Maximum Concentration Limit (MCL). The result of applying this method is a suggested sampling frequency based on recent sampling data trends and overall sampling data trends.

The finally determined sampling frequency from the Modified CES method can be Quarterly, Semiannual, Annual, and Biennial. Users can further reduce the sampling frequency to, for example, once every three years, if the trend estimated from Biennial data (i.e., data drawn once every two years from the original data) is the same as that estimated from the original data.

2.6.4 Data Sufficiency Analysis – Power Analysis

Statistical power analysis is a technique for interpreting the results of statistical tests. It provides additional information about a statistical test: 1) the power of the statistical test, i.e., the probability of finding a difference in the variable of interest when a difference truly exists; and 2) the expected sample size of a future sampling plan given the minimum detectable difference it is supposed to detect. For example, if the mean concentration is lower than the cleanup goal but a statistical test cannot prove this, the power and expected sample size can tell the reason and how many more samples are needed to result in a significant test. The additional samples can be obtained by a longer period of sampling or an increased sampling frequency. Details about the data sufficiency analysis can be found in Appendix A.6 of the MAROS Manual (AFCEE 2002).

When applying the MAROS power analysis method, a hypothetical statistical compliance boundary (HSCB) is assigned to be a line perpendicular to the groundwater flow direction (see figure below). Monitoring well concentrations are projected onto the HSCB using the distance from each well to the compliance boundary along with a decay coefficient. The projected concentrations from each well and each sampling event are then used in the risk-based power analysis. Since there may be more than one sampling event selected by the user, the risk-based power analysis results are given on an event-by-event basis. This power analysis can then indicate if target are statistically achieved at the HSCB. For instance, at a site where the historical monitoring record is short with few wells, the HSCB would be distant; whereas, at a site with longer duration of sampling with many wells, the HSCB would be close. Ultimately, at a site the goal would be to have the HSCB coincide with or be within the actual compliance boundary (typically the site property line).



In order to perform a risk-based cleanup status evaluation for the whole site, a strategy was developed as follows.

- Estimate concentration versus distance decay coefficient from plume centerline wells.
- Extrapolate concentration versus distance for each well using this decay coefficient.
- Comparing the extrapolated concentrations with the compliance concentration using power analysis.

Results from this analysis can be *Attained* or *Not Attained*, providing a statistical interpretation of whether the cleanup goal has been met on the site-scale from the risk-based point of view. The results as a function of time can be used to evaluate if the monitoring system has enough power at each step in the sampling record to indicate certainty of compliance by the plume location and condition relative to the compliance boundary. For example, if results are *Not Attained* at early sampling events but are *Attained* in recent sampling events, it indicates that the recent sampling record provides a powerful enough result to indicate compliance of the plume relative to the location of the receptor or compliance boundary.

3.0 SITE RESULTS

The original groundwater long-term monitoring plan for the Fort Lewis Logistics Center was completed in August 1995 (USACE 2000). The monitoring plan consisted of performance monitoring and compliance monitoring with the following goals:

1) plume containment monitoring to confirm that the TCE plume remains hydraulically controlled; and
2) plume reduction monitoring to verify progress toward achieving cleanup goals.

43 monitoring wells and 21 extraction wells in the Upper Aquifer were included in the long-term monitoring network as of 2001 (Figure 1). All monitoring wells, unless abandoned, have been sampled quarterly in the Upper Aquifer for TCE since the implementation of the long-term monitoring plan. By September 2001, 24 sampling events had been carried out at the site.

In applying the MAROS methodology to develop a revised monitoring strategy for the Fort Lewis Upper Aquifer, many site and dataset parameters were applied. General site assumptions include:

- Only wells included in the long-term groundwater monitoring plan as of September, 2001 were considered in the temporal concentration trend analysis (Table 3).
- Five chemicals of concern (COCs) that have been historically present at the site: tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cis-1,2-DCE), and vinyl chloride (VC), and 1,1,1-trichloroethane (1,1,1-TCA), however, TCE was used as a indicator compound due to its presence throughout the site at elevated concentrations.
- All source/tail assignments were made based on the TCE Plume. Source wells were selected based on historically elevated concentrations of TCE and proximity to the East Gate Disposal Yard.
- Site-specific hydrogeologic parameters related to the Upper Aquifer including groundwater flow direction, seepage velocity, saturated thickness, porosity, receptor locations, and can be found in the Table 4.
- Monitoring Data from November, 1995 to September, 2001 were used in the MAROS analysis. Monitoring data obtained from the LOGRAM monitoring plan implementation was insufficient (less than 4 quarters of monitoring data) to be used in the MAROS optimization analysis.

3.1 Data Consolidation

In MAROS, ground water monitoring data can be imported from simple database-format Microsoft® Excel spreadsheets, Microsoft® Access tables, previously created MAROS database archive files, or entered manually. The historical monitoring data from Fort Lewis were received in Excel format. The constituent name for TCE was then changed to the MAROS input parameter nomenclature, the columns in the file where formatted to the MAROS Access file import format and then imported into the MAROS software using the import tool. The long-term monitoring raw data contained many non-detects, trace level results, and duplicates. Therefore, in the MAROS software the raw data are filtered, consolidated, and the period of interest was specified (i.e. monitoring data from November 1995 to September 2001). For statistical evaluation of the data, a representative value for each sample point in time is needed. MAROS has many automated options to choose how these values are assigned. For the Fort Lewis data, non-detects values were chosen to be set to the minimum detection limit, allowing for uniform detection limits over time. Trace level results were chosen to be represented by their actual values and duplicates samples were chosen to be assigned the average of the two samples. The reduced data for each well were viewed as a time series in a graphical form on a linear or semi-log plot generated by the software.

3.2 Overview Statistics: Plume Trend Analysis

3.2.1 Mann-Kendall/Linear Regression Analysis

All 43 monitoring wells and 21 extraction wells had sufficient data within the time period of November 1995 to September 2001 (greater than 2 years of quarterly data) to assess the trends in the wells. Trend results from the Mann-Kendall and Linear Regression temporal trend analysis for both Upper Aquifer monitoring wells and extraction wells are given in Table 5. The monitoring well trend results show that 6 out of 10 source wells and 15 out of 33 tail wells have a Probably Decreasing, Decreasing, or Stable trend. Both methods gave similar trend estimates for each well. The extraction well trend results show that 18 out of 21 wells have a Probably Decreasing, Decreasing, or Stable trend. Both methods gave similar trend estimates for each well. When considering the spatial distribution of the trend results (Figures 5 and 6 – maps created in ArcGIS from MAROS results), the majority of the decreasing or stable trend results are located near the East Gate Storage Yard, indicating a decreasing source. Another area of decreasing trends is in the vicinity of the line of extraction or plume containment wells. However, there are some extraction wells within the line of plume containment that show increasing trends over time (Figures 7 and 8 – maps created in ArcGIS from MAROS results). Whereas, the extraction wells in the source all show decreasing or probably decreasing trends.

Well Type	**MAROS Trend Analysis**	
	PD, D, S	**I, PI**
Source	6 of 10 (60%)	4 of 10 (40%)
Tail	15 of 33 (45%)	11 of 33 (33%)
Extraction	18 of 21 (85%)	2 of 21 (9%)

Note: Decreasing (D), Probably Decreasing (PD), Stable (S), Probably Increasing (PI), and Increasing (I)

Although monitoring wells and extraction wells are present in the well network, these well trend results need to be treated differently for the purpose of individual trend analysis interpretation primarily due to the different course of action possible for the two types of wells. For monitoring wells, strongly decreasing concentration trends may lead the site manager to decrease their monitoring frequency, as well look at the well as possibly attaining its remediation goal. Conversely, strongly decreasing concentration trends in extraction wells may indicate ineffective or near-asymptotic contamination extraction, which may in turn lead to either the shutting down of the well or a drastic change in the extraction scheme. Other reasons favoring the separation of these two types of wells in the trend analysis interpretation is the fact that they produce very different types of samples. On average, the extraction wells at Fort Lewis possess screens that are twice as large and extraction wells pull water from a much wider area than the average monitoring well. Therefore, the potential for the dilution of extraction well samples is far greater than monitoring well samples.

3.2.2 Moment Analysis

Moment Trend results from the Zeroth, First, and Second Moment analyses for the Upper Aquifer monitoring well network were varied. Moment Trend results from a selected Upper Aquifer monitoring well dataset are given in the Moment Analysis Report, Appendix B. Approximately 35 wells were used in the moment analysis. Wells with redundant spatial concentration information were not utilized in the moment analysis (i.e. LC-137b, LC149d, LC-19c, etc.).

Moment Type	Mann-Kendall Trend Analysis	
	Trend	Comment
Zeroth	Increasing	The increase in dissolved mass maybe due to the extraction system moving high concentration groundwater from source zones to nearby monitoring wells or the change in monitoring wells sampled over the sampling period analyzed.
First	Stable	The center of mass remained in relatively the same location through time, with slight movement forward or backward along the direction of groundwater flow.
Second	Decreasing	Shrinking to stable plume, indicating that wells representing very large areas both on the tip and the sides of the plume show decreasing concentrations.

The zeroth moment analysis showed an increasing trend (increase in dissolved mass) over time (Appendix B). The zeroth moment or mass estimate can show high variability over time, largely due to the fluctuating concentrations at the most contaminated wells as well as a varying monitoring well network. In order to consider the fluctuating factors that could influence a mass increase, the data were consolidated to annual sampling and the zeroth moment trend re-evaulated, however the trend in the mass remained the same. Another factor to consider when interpreting the mass increase over time is the change in the spatial distribution of the wells sampled historically. At the Fort Lewis site there were changes in the well distribution over time, due to addition and subtraction of wells from the well network. The observed mass increase could also stem from more mass being dissolved from the NAPL while the remediation system is operating.

The first moment, or center of mass, for each sample event remained relatively stable to slightly decreasing in distance relative to the approximate source location (LC-108), see Figure 9, as well as the MAROS First Moment Report in Appendix B. The center of mass remained in relatively the same location through time, with slight movement forward or backward along the direction of groundwater flow. These spatial and temporal trends in the center of mass distance from the source location can indicate transient movement based on season variation in rainfall or other hydraulic considerations. With no appreciable movement or a neutral trend in center of mass as is the case at Fort Lewis, there is additional confirmation separate from the individual well trend analysis, that the plume is relatively stable to decreasing. This stable center of the mass indicates that although the mass has been increasing over time, the plume itself is stable.

The second moment, or spread of the plume over time in both the x and y directions for each sample event, showed a decreasing trend over time, Appendix B. The second moment provides a measure of the spread of the concentration distribution about the plume's center of mass. Analysis of the spread of the plume indicates a shrinking to stable plume, indicating that wells representing very large areas both on the tip and the sides of the plume show decreasing concentrations. This decreasing trend in the spread of the plume strengthens the individual well Mann-Kendall and Linear Regression trend analysis spatially, where most of the tail wells showed a decreasing or probably decreasing TCE concentration trend.

3.2.3 Overview Statistics: Plume Analysis

In evaluating overall plume stability, the trend analysis results and all monitoring wells were assigned “Medium” weights within the MAROS software (as described in Figure 3), assuming equal importance for each well and each trend result in the overall analysis.

Overview Statistics Results:

- Overall trend for Source region: Stable,
- Overall trend for Tail region: near Stable (No Trend),
- Overall results from moment analysis indicate a stable to decreasing plume,
- Overall monitoring intensity needed: Moderate.

These results matched with the judgment based on the visual comparison of TCE plumes over time, as well as the Moment Analysis. The TCE concentrations observed in 2001 are plotted in Figure B.10. The TCE plume concentrations observed in 1998 was very similar to that of 2001, indicating that the TCE plume is relatively stable over time.

For a generic plume, the MAROS software indicates to:

- Change from quarterly sampling frequency to biannual sampling
- May need > 50 wells

These MAROS results are for a generic site, and are based on knowledge gained from applying the MAROS Overview Statistics. The frequency reduction is a only site-wide reduction recommendation for whole monitoring network and the number of wells seems high. Therefore, it was decided to do a detailed analysis for both the well redundancy and sampling frequency utilizing the detailed statistics analysis in the MAROS 2.0 software in order to allow for reductions and recommendations on a well-by-well basis. These overview statistics were also used when evaluating a final recommendation for each well after the detailed statistical analysis was applied.

3.3 Detailed Statistics: Optimization Analysis

From December 1995 to September 2001, a total of 24 rounds of quarterly sampling have been performed. More than 40 Upper Aquifer monitoring wells were sampled throughout this time period, but in the interim a number of wells were abandoned. The number of Upper Aquifer monitoring wells that are sampled as of September 2001 is 38. These 38 wells, as well as the Upper Aquifer's 21 extraction wells, were used in the MAROS sampling optimization analysis (see Table 3 for a list of the wells used in the analysis). In both the well redundancy analysis and well sufficiency analysis, only the monitoring wells were used. In the sampling frequency analysis and data sufficiency analysis, both the monitoring wells and the extraction wells were analyzed. Results for well redundancy, well sufficiency, sampling frequency, and data sufficiency analyses are detailed in the following sub-sections.

3.3.1 Well Redundancy Analysis – Delaunay Method

The goal of the well redundancy analysis is to identify wells that are redundant within monitoring network as candidates for removal from the sampling plan. The approach allows elimination of sampling locations that have little impact on the historical characterization of a contaminant plume.

A monitoring network of 30 monitoring wells was used for the Delaunay Analysis. Clustered wells that had equivalent duplicates were excluded from the analysis (Table 3 lists the wells excluded and the 30 wells used in the analysis). The Delaunay analysis was conducted with the 8 latest sampling events (December 1999 to September 2001). The results show that 8 monitoring wells are candidates for elimination from the original 2001 long-term monitoring network. These wells are overall most redundant in the past two years (December 1999 to September 2001), from the standpoint of their contribution to the spatial definition of the plume.

After consideration of the MAROS recommendations and the need for plume and site characterization, 8 wells can be eliminated from the existing 38-well network, resulting in a reduction of 21%. Well removal candidates include:

- LC-136b
- LC-137a
- LC-149d
- LC-19b
- LC-19c
- LC-44a
- LC-51
- LC-66a

There were some wells that the MAROS software suggested eliminating from the monitoring network, however, there were site-specific reasons to keep the wells within the monitoring network (Table 6 and Table 11). For example, well LC-06 was suggested for elimination, but the well shows an increasing trend in the TCE concentration data over time and the well defines the middle-lateral boundary of the plume. Also, well LC-19a was suggested for elimination, however, the well is located on the plume centerline and is the basis for risk-based power analysis for attainment at the compliance boundary. Similarly, there were wells that were not used in the Delaunay analysis that were clustered wells with equivalent duplicates very close to a well that had similar concentrations and concentration trends over time (see Table 3 lists the wells excluded and the 30 wells used in the analysis, see Table 11 for results). These clustered wells with similar screen intervals, concentration trends, and concentration ranges to a nearby well were suggested for elimination without having used them in the MAROS well redundancy analysis. However, information gained from the MAROS trend analysis and a qualitative assessment of the concentration history of the well, indicated these wells could be eliminated without significant loss of information.

The TCE plumes shown in Figure 10 generated based on the existing and optimized networks using September 2001 data agree with each other quite well, indicating that eliminating these wells from the monitoring network does not show any significant loss of information.

3.3.2 Well Sufficiency Analysis – Delaunay Method

The well sufficiency analysis, an extended application of analysis of the monitoring network, also based on the Delaunay method, can be used for recommending new sampling locations in areas where additional plume information is needed. It is designed to recommend new sampling locations in areas within the existing monitoring network where there is a high level uncertainty in plume concentration. In many cases, new sampling locations need to be added to the existing network to enhance the spatial plume characterization. The results for determining new sampling locations are derived solely from the spatial configuration of the monitoring network and the spatial pattern of the contaminant plume. Therefore, new well locations needed outside the existing monitoring well network (i.e. a new sentinel well outside the existing plume network) are not able to be assessed.

The well sufficiency analysis for recommending new sampling locations was performed using the same wells as in the well redundancy analysis. With this analysis, areas within the monitoring well network where there is high uncertainty for predicting concentrations are recommended for additional sample locations within the existing well network. The SF values obtained from the analysis shown in Table 6 were used to generate Figure 11, which recommends the triangular regions for placing new sampling locations. The estimated SF value at each triangle area is classified into four levels: Small, Moderate, Large, or Extremely large because the larger the estimated SF value, the higher the estimation error at this area. Therefore, the triangle areas with the estimated SF value at the Extremely large or Large level are candidate regions for new sampling locations.

5 new sampling locations (New #2 to #6) are recommended at regions with large estimation errors and 1 new location (New #1) in the center of the three regions with moderate estimation errors. Proposed well New #1 and well New #5 correspond to New-3 and New-5 in the new series wells, respectively. Well New #2 corresponds to FL-3 proposed in the LOGRAM plan, New #2 corresponds to LC-167, New #4 corresponds to LC-16, and New #6 corresponds to LC-20. Because these 6 wells are new proposed wells, their sampling frequencies are all set to quarterly, at least until 6 samples are available for trend estimation. Because the MAROS analysis for well sufficiency (new sampling locations) can only calculate SF values inside the triangulation domain, new wells that are used to better characterize the plume extent outside the triangulation domain need to be decided based on the plume and site hydrogeologic conditions and were not considered at this site.

3.3.3 Sampling Frequency Analysis– Modified CES Method

The sampling frequency analysis, using the Modified CES method, was applied to optimize the sampling frequency for each sampling location based on the magnitude, direction, and uncertainty of its concentration trend of its recent and historical TCE data. The Modified Cost Effective Sampling method estimates the lowest-frequency sampling schedule for a given groundwater monitoring location yet still provide needed information for regulatory and remedial decision-making. In sampling frequency analysis with the Modified CES method, both the 38 monitoring wells and the 21 extraction wells were analyzed (Table 7). Results from the analysis show that the sampling frequency can be significantly reduced in the future, for both monitoring wells and extraction wells (Table 7).

For the original monitoring well plan as of 2001, considering all the wells prior to the well redundancy analysis, 7 wells can be sampled biennially, 18 annually, 3 semiannually, and 12 quarterly. The reduction in sampling for the monitoring wells is about 52% (152 quarterly samples with the original plan versus 79 samples with the MAROS optimized plan). For the extraction well system, 16 wells are recommended to be sampled annually and 5 wells still need to be sampled quarterly, resulting in a reduction of approximately 57% (84 quarterly samples with the original plan versus 36 samples with the optimized plan).

Monitoring Wells	Frequency Analysis		
	Current Sampling Frequency	Recommended Sampling Frequency	Number of Wells (See Table 7 for List)
Group 1	Quarterly	Annual	16
Group 2	Quarterly	Semiannual	3
Group 3	Quarterly	Quarterly	12 (No Change)
Group 4	Quarterly	Biennial	7

In all cases, the MAROS suggested sampling frequency seemed reasonable when considering the location of the wells, sampling history, site conditions, well type, and concentration levels. The Fort Lewis site data used for the MAROS analysis was uniform and sufficient (24 quarterly monitoring records available for each well), Therefore, concentration trend estimation and the resulting frequency results, either based on recent data or overall data, accurately reflect the site conditions in recent and long-term data trends. Furthermore, all wells with a MAROS annual or biennial sampling recommendation have the same recent and overall frequency (Table 7). This indicates that concentration trends in these wells are consistent over the time period being analyzed (1995 to 2001), therefore, a reduced sampling frequency will continue to reflect changes in the concentration over time. For the biennial recommendations, recent maximum concentrations in those wells are below half of the MCL and show no signs of increasing/probably increasing trend, making the biennial recommendation a conservative estimate of future sampling frequency. Third, because the TCE plume is quite stable spatially over past several years and is contained by the extraction wells, it is unlikely that the plume will show rapid changes over the long-term. Therefore, reducing the frequency of most wells to annual, and in a few cases biennially, will allow the monitoring network to continue adequately delineating the plume over time.

If the cost of each sample, including collection and analysis, is $500 then the total cost savings each year with the sample frequency reduction alone would be $39,500 and $24,000 for the monitoring well system and extraction well system, respectively.

3.3.4 Data Sufficiency – Power Analysis

In the MAROS data sufficiency analysis, statistical power analysis was used to assess the sufficiency of monitoring plans for detecting difference between the mean concentration and cleanup goal. Results from the analysis indicate remediation progress from the risk-based standpoint at a hypothetical statistical compliance boundary (HSCB). The power and expected sample size associated with the target level evaluation may indicate the need for expansion or redundancy reduction of future sampling plans.

In the risk-based site cleanup evaluation, two analyses were performed (see Appendix B for all related MAROS reports). In the first analysis, the distance from the most downgradient well to the nearest downgradient receptor (HSCB) was assumed to be

1000 ft. The general groundwater flow angle is 140 degrees counterclockwise from East. Selected plume centerline wells are LC-137b, LC-19a, LC-49, LC-66b, LC-14a, and T-13b (Table 8). A total of 14 sampling events (June 1998 to September 2001) were used in the analysis. The second analysis used the same parameters except that the distance from the HSCB was assumed to be 2000 ft. Table 9 shows plume centerline concentration regression results for each selected sampling event, which range from 6×10^{-5} to 3×10^{-4} per ft (see Appendix B for individual well projected concentration values).

Table 10 shows the risk-based site target level status at selected sampling events for both analyses (i.e., HSCB at 1000 ft and HSCB at 2000 ft downgradient of the monitoring system). A general trend observed from the results is that the site changed from fully “not attained” (i.e., “S/E”, the mean concentration significantly exceeds the target level) to partly “not attained” (i.e., the mean concentration is lower than the target level but statistically significant, as indicated by the lower power) or “attained.” This is especially true for the second analysis where the HSCB distance is assumed 2000 ft.

Therefore, at this site the HSCB is now at 2000 feet (3 straight “attains”) but will likely move to 1000 feet as soon as monitoring record becomes larger. For example, the 1000 feet HSBC has one “attain” in the second to last sampling event. The HSCB is getting tighter and tighter as the monitoring record increases. In general, monitoring networks become more powerful over time. This analysis indicates that the monitoring system is working because it is powerful enough to accurately reflect the location of the plume relative to the compliance point. Therefore, the current monitoring network is sufficient in terms of evaluating risk-based site target level status, if the pump-and-treat remedial system contains the plume and keeps reducing the contaminant concentration in the Upper Aquifer.

4.0 SUMMARY AND RECOMMENDATIONS

In recent years, the high cost of long-term monitoring as part of active or passive remediation of affected ground water has made the design of efficient and effective ground water monitoring plans a pressing concern. Periodically updating and revising long-term monitoring programs with changing conditions at the site can mean considerable savings in site monitoring costs. The MAROS decision-support software presented in this report assists in revising existing long-term monitoring plans based on the historical and current monitoring data and plume behavior over time.

The MAROS 2.0 sampling optimization software/methodology has been applied to the Fort Lewis Upper Aquifer's original RAM program as of September 2001. The optimization results and subsequent recommendations allow for optimization of the spatial and temporal groundwater monitoring system at the Fort Lewis Logistics Center. The original long-term monitoring network could be optimized through reduction in sampling frequency and sampling locations, as well as improving the understanding of the plume through additional optimally placed sampling locations (Results are summarized in Table 11 and all MAROS Reports are in Appendix B).

Overview Statistics

Both the Mann-Kendall and Linear Regression temporal trend methods gave similar trend estimates for each well. Results from the temporal trend analysis indicate that 60% of the plume source area monitoring wells indicate a Probably Decreasing, Decreasing, or Stable TCE concentration trend, whereas only about half of the wells in the tail and edges of the plume have similar trends. The trend results for the extraction wells in the source area indicate all wells have Probably Decreasing, or Decreasing concentrations over time, indicating a decreasing source area. The majority of the extraction/plume containment wells located northwest of the source area show Probably Decreasing, Decreasing, or Stable trends.

Results from the moment trend analysis give further evidence of a stable plume, with the center of mass location has stayed stable and the plume spread shows a decrease over time. Overall plume stability results recommend a ***moderate monitoring strategy*** due to a stable to decreasing Upper Aquifer plume. The overview results are relatively generic and not well specific, therefore, a detailed statistical analysis with a well-by-well analysis was assessed.

Detailed Statistics

Further analysis from the well redundancy analysis using the Delaunay method optimization indicate that 8 monitoring wells could be eliminated from the original monitoring network of 38 wells without any significant loss of plume information (Table 11). However, the well sufficiency analysis indicates there are 6 areas within the network where there are high uncertainties in the predicted TCE concentration that seem to lack adequate sampling and are recommended for new monitoring well placement.

The sampling frequency optimization analysis using the modified CES method, indicated that most of the wells in the monitoring network could be sampled at a less-than-quarterly frequency.

Data sufficiency analysis using power analysis methods, shows that the site is close to target levels at the compliance boundary 2000 ft downgradient from the most downgradient well. This analysis indicates that the monitoring system is working because it is powerful enough to accurately reflect the location of the plume relative to the compliance boundary. This shows the sufficiency of the monitoring system in terms of evaluating risk-based site target level status if the pump-and-treat remedial system continues to contain the plume and keeps reducing the contaminant concentration in the Upper Aquifer.

Comparison of the original Upper Aquifer monitoring plan as of 2001 with the 2002 LOGRAM sampling plan (Table 11), indicates that similar sampling frequency and well redundancy results were recommended at Fort Lewis. However, well adequacy results (analysis of addition of wells to the monitoring network) differed due to the constraints of assessing only the existing well network within the MAROS software.

The MAROS optimized plan consists of 56 wells: 19 sampled quarterly, 2 sampled semiannually, 30 sampled annually, and 5 sampled biennially. The MAROS optimized plan would result in 113 (112.5) samples per year, compared to 180 samples per year in the current LOGRAM monitoring program and 236 samples per year in the original sampling program. Implementing these recommendations could lead to a 37% reduction from the LOGRAM plan and 52% reduction from the original plan in terms of the samples to be collected per year. Based on a per sample cost of $500, the MAROS optimized plan could reduce the site monitoring cost by $33,500 and $61,500 from the LOGRAM plan and the original plan, respectively.

The recommended long-term monitoring strategy results in considerable reduction in sampling costs and allows site personnel to develop a better understanding of plume behavior over time. A reduction in the number of redundant wells, an increase in the number of wells in areas with inadequate information, as well as reduction in sampling frequency is expected to results in a significant cost savings over the long-term at Fort Lewis. An approximate cost savings estimate of $33,500 per year is projected while still maintaining adequate delineation of the plume as well as knowledge of the plume state over time.

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GROUNDWATER SERVICES, INC.

MAROS 2.0 APPLICATION
UPPER AQUIFER MONITORING NETWORK OPTIMIZATION

Fort Lewis Logistics Center
Pierce County, Washington

TABLES

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Table 1
Mann-Kendall Analysis Decision Matrix (Aziz, et. al., 2002)

Mann-Kendall Statistic	Confidence in the Trend	Concentration Trend
S > 0	> 95%	Increasing
S > 0	90 - 95%	Probably Increasing
S > 0	< 90%	No Trend
S ≤ 0	< 90% and COV ≥ 1	No Trend
S ≤ 0	< 90% and COV < 1	Stable
S < 0	90 - 95%	Probably Decreasing
S < 0	> 95%	Decreasing

Table 2
Linear Regression Analysis Decision Matrix (Aziz, et. al., 2002)

Confidence in the Trend	Log-slope	
	Positive	Negative
< 90%	No Trend	COV < 1 Stable COV > 1 No Trend
90 - 95%	Probably Increasing	Probably Decreasing
> 95%	Increasing	Decreasing

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Table 3
Sampling Locations Used in the MAROS Analysis

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	Hydrologic Unit	Used in Delaunay Analysis?	Used in Modified CES Analysis?	Summary of Sampling History
LC-03	UV	Yes	Yes	Sampled quarterly since 95
LC-05	UV	Yes	Yes	Sampled quarterly since 95
LC-06	UV	Yes	Yes	Sampled quarterly since 95
LC-14a	UV	Yes	Yes	Sampled quarterly since 95
LC-19a	UV	Yes	Yes	Sampled quarterly since June 98
LC-19b	UV	No: duplicates LC-19a	Yes	Sampled quarterly since June 98
LC-19c	UV	No: duplicates LC-19a	Yes	Sampled quarterly since June 98
LC-26	UV	Yes	Yes	Sampled quarterly since 95
LC-41a	UV	Yes	Yes	Sampled quarterly since 95
LC-44a	UV	Yes	Yes	Sampled quarterly since 95
LC-49	UV	Yes	Yes	Sampled quarterly since 95
LC-51	UV	Yes	Yes	Sampled quarterly since 95
LC-53	UV	Yes	Yes	Sampled quarterly since 95
LC-64a	UV	Yes	Yes	Sampled quarterly since 95
LC-66a	UV	No: duplicates LC-66b	Yes	Sampled quarterly since 95
LC-66b	UV	Yes	Yes	Sampled quarterly since 95
LC-73a	UV	Yes	Yes	Sampled quarterly since 95
LC-108	UV	Yes	Yes	Sampled quarterly since 95
LC-132	UV	Yes	Yes	Sampled quarterly since 95
LC-136a	UV	No	Yes	Sampled quarterly since 95
LC-136b	UV	Yes	Yes	Sampled quarterly since 95
LC-137a	UV	No: duplicates LC-137b	Yes	Sampled quarterly since 95
LC-137b	UV	Yes	Yes	Sampled quarterly since 95
LC-149c	UV	Yes	Yes	Sampled quarterly since 95
LC-149d	UV	No: duplicates LC-149c	Yes	Sampled quarterly since 95
LC-165	UV	Yes	Yes	Sampled quarterly since 95
PA-381	UV	Yes	Yes	Sampled quarterly since 95
PA-383	UV	Yes	Yes	Sampled quarterly since 95
T-04	UV	Yes	Yes	Sampled quarterly since 95
T-08	UV	Yes	Yes	Sampled quarterly since 95

Notes: 1) UV=Upper Vashon (the upper layer of the Upper Aquifer), LV=Lower Vashon (the lower layer of the Upper Aquifer), EW=Upper Aquifer extraction well

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Table 3
Sampling Locations Used in the MAROS Analysis

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	Hydrologic Unit	Used in Delaunay Analysis?	Used in Modified CES Analysis?	Summary of Sampling History
T-12b	UV	Yes	Yes	Sampled quarterly since December 99
T-13b	UV	Yes	Yes	Sampled quarterly since 95
LC-64b	LV	No: screened in the lower part of the Upper Aquifer	Yes	Sampled quarterly since 95
LC-111b	LV	Yes	Yes	Sampled quarterly since 95
LC-116b	LV	Yes	Yes	Sampled quarterly since 95
LC-122b	LV	Yes	Yes	Sampled quarterly since 95
LC-128	LV	Yes	Yes	Sampled quarterly since 95
LC-137c	LV	No: screened in the lower part of the Upper Aquifer	Yes	Sampled quarterly since 95
LX-1	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-2	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-3	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-4	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-5	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-6	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-7	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96

Notes: 1) UV=Upper Vashon (the upper layer of the Upper Aquifer), LV=Lower Vashon (the lower layer of the Upper Aquifer), EW=Upper Aquifer extraction well

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Table 3
Sampling Locations Used in the MAROS Analysis

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	Hydrologic Unit	Used in Delaunay Analysis?	Used in Modified CES Analysis?	Summary of Sampling History
LX-8	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-9	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-10	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-11	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-12	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-13	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-14	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-15	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-16	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-17	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-18	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-19	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
LX-21	EW	No, extraction well	Yes	Sampled for the last two quarters of 95, then quarterly since December 96
RW-1	EW	No, extraction well	Yes	Sampled for four quarters between 97 and 98, then quarterly since March 01

Notes: 1) UV=Upper Vashon (the upper layer of the Upper Aquifer), LV=Lower Vashon (the lower layer of the Upper Aquifer), EW=Upper Aquifer extraction well

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TABLE 4
Upper Aquifer Site-Specific Parameters

Fort Lewis Logistics Center
Pierce County, Washington

Parameter	Value
Seepage Velocity	548 ft/yr [1]
Porosity	25% [1]
Approximate Source Location	Well LC-108 [2]
Approximate Saturated Thickness	60 ft [3]
Direction	NW [4]

Notes:

1. U.S. ACE, 1998, Two Year Performance Evaluation Report for the Groundwater Treatment System, Logistics Center, Fort Lewis, Washington.
2. Location of source area obtained from highest TCE concentrations within the East Gate Disposal Yard.
3. U.S. ACE, 2002, EDGY Phase II RI FIR, Fort Lewis Logistics Center, Figure 5-4.
4. U.S. ACE, 1994, Fort Lewis Logistics Center Lower Aquifer Study, Final Addendum to Final Technical Memorandum.

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TABLE 5
Results of Upper Aquifer Trend Analysis

Fort Lewis Logistics Center
Pierce County, Washington

Well	Well Type [3]	Well Category [5]	Mann-Kendall Trend [4]	Linear Regression Trend [4]	Overall Trend [6]	Number of Samples	Number of Detects
LC-03	MW	T	I	I	I	23	22
LC-05	MW	T	I	I	I	24	24
LC-06	MW	T	I	I	I	24	24
LC-14a	MW	T	PD	S	S	24	24
LC-19a	MW	T	S	S	S	14	14
LC-19b	MW	T	S	S	S	14	14
LC-19c	MW	T	S	S	S	14	14
LC-26	MW	T	NT	PI	PI	23	11
LC-41a	MW	T	NT	NT	NT	24	24
LC-44a	MW	T	NT	NT	NT	24	24
LC-49	MW	T	PI	PI	PI	24	24
LC-49a	MW	T	NT	NT	NT	12	12
LC-51	MW	T	I	PI	PI	24	24
LC-53	MW	T	I	I	I	24	24
LC-64a	MW	S	NT	PI	PI	24	24
LC-64b	MW	S	D	D	D	24	24
LC-66a	MW	T	S	NT	S	24	24
LC-66b	MW	T	S	NT	S	24	24
LC-73a	MW	T	I	I	I	23	23
LC-108	MW	S	PD	D	D	24	24
LC-111b	MW	T	PD	PD	PD	23	8
LC-116b	MW	T	I	I	I	24	20
LC-122b	MW	T	S	S	S	23	2
LC-128	MW	T	PI	NT	PI	24	24
LC-132	MW	T	I	I	I	24	24
LC-134	MW	S	D	D	D	20	20
LC-136a	MW	S	I	I	I	24	24
LC-136b	MW	S	NT	S	S	23	23
LC-137a	MW	S	I	I	I	24	24
LC-137b	MW	S	PI	PI	PI	24	24
LC-137c	MW	S	D	D	D	24	19
LC-144a	MW	T	S	S	S	11	11
LC-149c	MW	T	S	S	S	24	0
LC-149d	MW	T	S	D	PD	24	2
LC-162	MW	S	D	D	D	20	20
LC-165	MW	T	S	PD	S	23	4
PA-381	MW	T	PI	NT	PI	24	24
PA-383	MW	T	S	S	S	24	24
T-01	MW	T	S	PD	S	16	16

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TABLE 5
Results of Upper Aquifer Trend Analysis

Fort Lewis Logistics Center
Pierce County, Washington

Well	Well Type [3]	Well Category [5]	Mann-Kendall Trend [4]	Linear Regression Trend [4]	Overall Trend [6]	Number of Samples	Number of Detects
LX-5	EW	T	D	D	D	19	19
LX-6	EW	T	D	D	D	20	20
LX-7	EW	T	S	S	S	20	20
LX-8	EW	T	NT	NT	NT	18	18
LX-9	EW	T	D	PD	D	19	19
LX-10	EW	T	S	D	PD	20	20
LX-11	EW	T	D	D	D	20	20
LX-12	EW	T	D	D	D	20	20
LX-13	EW	T	PI	I	PI	15	15
LX-14	EW	T	S	S	S	20	20
LX-15	EW	T	NT	NT	NT	20	20
LX-16	EW	T	D	D	D	8	8
LX-17	EW	S	S	S	S	19	19
LX-18	EW	S	D	D	D	20	20
LX-19	EW	S	S	S	S	18	18
LX-21	EW	S	D	S	PD	20	20
RW-1	EW	T	S	S	S	8	8

Notes:
1. Consolidation of data included non-detect values set to the minium detection limit (0.001 mg/L) and duplicate data for the quarter were averaged.
2. Only wells that were part of the network in 2001 were analyzed.
3. EW = Extraction Well; MW = Monitoring Well
4. Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)

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Table 6
Well Redundancy Analysis Results – Delaunay Method

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	Well Used in Analysis?	MAROS Well Redundancy Analysis Result	MAROS Interpreted Well Redundancy	Comments
LC-03	Yes	Keep	Keep	
LC-05	Yes	Keep	Keep	
LC-06	Yes	**Eliminate**	**Keep**	Defines the middle-lateral boundary of plume
LC-14a	Yes	Keep	Keep	
LC-19a	Yes	**Eliminate**	**Keep**	On plume centerline and used in MAROS data sufficiency analysis
LC-19b	No: duplicates LC-19a	-	**Eliminate**	Duplicates LC-19a
LC-19c	No: duplicates LC-19a	-	**Eliminate**	Duplicates LC-19a
LC-26	Yes	Keep	Keep	
LC-41a	Yes	**Eliminate**	**Keep**	Monitors leak to the Lower Aquifer
LC-44a	Yes	**Eliminate**	**Eliminate**	Spatially redundant
LC-49	Yes	**Eliminate**	**Keep**	On plume centerline and used in MAROS data sufficiency analysis
LC-51	Yes	**Eliminate**	**Eliminate**	Spatially Redundant
LC-53	Yes	Keep	Keep	
LC-64a	Yes	Keep	Keep	
LC-64b	No: screened in the lower part of the Upper Aquifer	-	**Keep**	Monitors source area in the lower part of the Upper Aquifer
LC-66a	No: duplicates LC-66b	-	**Eliminate**	Duplicates LC-66b
LC-66b	Yes	Keep	Keep	
LC-73a	Yes	Keep	Keep	
LC-108	Yes	Keep	Keep	
LC-111b	Yes	Keep	Keep	

Notes: 1) The latest 8 sampling events (December 1999 to September 2001) were used in the above analysis
2) InsideSF = 0.15, HullSF = 0.01, AR = CR = 0.95
3) “-“ = Not Applicable.

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Table 6
Well Redundancy Analysis Results – Delaunay Method

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	Well Used in Analysis?	MAROS Analysis Result	Keep or Eliminate?	Comments
LC-116b	Yes	Keep	Keep	
LC-122b	Yes	Keep	Keep	
LC-128	Yes	Keep	Keep	
LC-132	Yes	Keep	Keep	
LC-136a	No	-	Keep	Monitors the hot spot in the source area
LC-136b	Yes	**Eliminate**	**Eliminate**	Spatially redundant
LC-137a	No: duplicates LC-137b	-	**Eliminate**	Duplicates LC-137b
LC-137b	Yes	Keep	Keep	
LC-137c	No: screened in the lower part of the Upper Aquifer	-	Keep	Monitors the lower part of the Upper Aquifer
LC-149c	Yes	Keep	Keep	
LC-149d	No: duplicates LC-149c	-	**Eliminate**	Duplicates LC-149c
LC-165	Yes	Keep	Keep	
PA-381	Yes	Keep	Keep	
PA-383	Yes	Keep	Keep	
T-04	Yes	Keep	Keep	
T-08	Yes	Keep	Keep	
T-12b	Yes	Keep	Keep	
T-13b	Yes	**Eliminate**	**Keep**	On plume centerline and used in MAROS data sufficiency analysis

Notes: 1) The latest 8 sampling events (December 1999 to September 2001) were used in the above analysis
2) InsideSF = 0.15, HullSF = 0.01, AR = CR = 0.95
3) "-" = Not Applicable.

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Table 7
Sampling Frequency Analysis Results – Modified CES

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	MAROS Frequency Based on Recent Trend(1)	MAROS Frequency Based on Overall Trend(2)	MAROS Recommended Frequency(3)
LC-03	Annual	Annual	Annual
LC-05	Quarterly	Semiannual	Quarterly
LC-06	Annual	Quarterly	Quarterly
LC-14a	Annual	Annual	Annual
LC-19a	Annual	Annual	Annual
LC-19b	Quarterly	Annual	Quarterly
LC-19c	Semiannual	Annual	Semiannual
LC-26	Annual	Annual	Annual
LC-41a	Quarterly	Annual	Quarterly
LC-44a	Annual	Annual	Annual
LC-49	Semiannual	Semiannual	Semiannual
LC-51	Quarterly	Semiannual	Quarterly
LC-53	Semiannual	Quarterly	Quarterly
LC-64a	Quarterly	Quarterly	Quarterly
LC-64b	Annual	Annual	Annual
LC-66a	Annual	Annual	Annual
LC-66b	Annual	Annual	Annual
LC-73a	Annual	Annual	Biennial
LC-108	Annual	Annual	Annual
LC-111b	Annual	Annual	Biennial
LC-116b	Semiannual	Annual	Semiannual
LC-122b	Annual	Annual	Biennial
LC-128	Annual	Annual	Annual
LC-132	Annual	Quarterly	Quarterly
LC-136a	Quarterly	Quarterly	Quarterly
LC-136b	Quarterly	Annual	Quarterly
LC-137a	Quarterly	Quarterly	Quarterly
LC-137b	Quarterly	Quarterly	Quarterly
LC-137c	Annual	Annual	Annual
LC-149c	Annual	Annual	Biennial

Notes: (1) The frequency determined by MAROS based on the analysis of the latest 8 sampling events, i.e., December 1999 to September 2001
(2) The frequency determined by MAROS based on the analysis of all sampling events, i.e., December 1995 to September 2001
(3) The frequency finally recommended by MAROS after considering recent and overall frequency results as well as the rates of change in these trends. Rate parameters used are 1MCL/year, 2MCL/year, and 4MCL/year for Low, Medium, and High rates, respectively; the MCL of TCE is 0.005 mg/L

GROUNDWATER SERVICES, INC.

Table 7
Sampling Frequency Determination Results – Modified CES

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	MAROS Frequency Based on Recent Trend(1)	MAROS Frequency Based on Overall Trend(2)	MAROS Recommended Frequency(3)
LC-149d	Annual	Annual	Biennial
LC-165	Annual	Annual	Biennial
PA-381	Annual	Annual	Annual
PA-383	Annual	Annual	Biennial
T-04	Annual	Annual	Annual
T-08	Annual	Annual	Annual
T-12b	Annual	Annual	Annual
T-13b	Annual	Annual	Annual
Extraction Wells			
LX-1	Annual	Annual	Annual
LX-10	Annual	Annual	Annual
LX-11	Annual	Annual	Annual
LX-12	Annual	Annual	Annual
LX-13	Annual	Annual	Annual
LX-14	Annual	Annual	Annual
LX-15	Annual	Annual	Annual
LX-16	Quarterly	Quarterly	Quarterly
LX-17	Quarterly	Annual	Quarterly
LX-18	Quarterly	Annual	Quarterly
LX-19	Quarterly	Annual	Quarterly
LX-2	Annual	Annual	Annual
LX-21	Annual	Annual	Annual
LX-3	Annual	Annual	Annual
LX-4	Annual	Annual	Annual
LX-5	Annual	Annual	Annual
LX-6	Annual	Annual	Annual
LX-7	Annual	Annual	Annual
LX-8	Annual	Annual	Annual
LX-9	Annual	Annual	Annual
RW-1	Quarterly	Quarterly	Quarterly

Notes: (1) The frequency determined by MAROS based on the analysis of the latest 8 sampling events, i.e., December 1999 to September 2001
(2) The frequency determined by MAROS based on the analysis of all sampling events, i.e., December 1995 to September 2001
(3) The frequency finally recommended by MAROS after considering recent and overall frequency results.
Rate parameters used are 1MCL/year, 2MCL/year, and 4MCL/year for Low, Medium, and High rates, respectively; the MCL of TCE is 0.005 mg/L

GROUNDWATER SERVICES, INC.

Table 8
Selected Plume Centerline Wells
Risk-Based Site Cleanup Evaluation – Power Analysis

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	Distance from Well to Receptor (feet)
T-13b	1931.0
LC-14a	3382.6
LC-66b	6318.1
LC-49	9390.6
LC-19a	11025.9
LC-137b	12082.4

Note: Groundwater flow angle is 140 degrees counterclockwise from East; the distance from the most downgradient well to the nearest downgradient receptor is assumed 1000 feet.

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Table 9
Plume Centerline Concentration
Regression Results – Power Analysis

Fort Lewis Logistics Center
Pierce County, Washington

Sampling Event	Number of Centerline Wells	Regression Coefficient (1/ft)	Confidence in Coefficient
2nd Quarter 1998	6	-2.88E-04	97.4%
3rd Quarter 1998	6	-2.59E-04	93.3%
4th Quarter 1998	5	-5.62E-05	64.3%
1st Quarter 1999	6	-2.44E-04	93.7%
2nd Quarter 1999	6	-1.95E-04	95.2%
3rd Quarter 1999	6	-2.80E-04	98.1%
4th Quarter 1999	6	-2.71E-04	97.1%
1st Quarter 2000	6	-2.73E-04	97.0%
2nd Quarter 2000	6	-2.55E-04	96.0%
3rd Quarter 2000	6	-3.21E-04	98.4%
4th Quarter 2000	6	-3.03E-04	97.6%
1st Quarter 2001	6	-3.13E-04	98.3%
2nd Quarter 2001	6	-3.54E-04	99.3%
3rd Quarter 2001	6	-3.43E-04	98.8%

Note: Regression is on natural log concentration of TCE versus distance from source centerline wells shown in Table 8.

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Table 10
Risk-Based Site Cleanup Evaluation Results – Power Analysis

Fort Lewis Logistics Center
Pierce County, Washington

		Distance to HSCB = 1000 ft		Distance to HSCB = 2000 ft	
Sampling Event	**Sample Size**	**Cleanup Status**	**Power**	**Cleanup Status**	**Power**
2nd Quarter 1998	35	Not Attained	S/E	Not Attained	0.436
3rd Quarter 1998	35	Not Attained	S/E	Not Attained	S/E
4th Quarter 1998	28	Not Attained	S/E	Not Attained	S/E
1st Quarter 1999	35	Not Attained	S/E	Not Attained	S/E
2nd Quarter 1999	35	Not Attained	S/E	Not Attained	S/E
3rd Quarter 1999	35	Not Attained	S/E	Not Attained	0.102
4th Quarter 1999	36	Not Attained	S/E	Not Attained	0.091
1st Quarter 2000	36	Not Attained	S/E	Not Attained	0.211
2nd Quarter 2000	36	Not Attained	S/E	Not Attained	S/E
3rd Quarter 2000	36	Not Attained	0.075	Attained	0.690
4th Quarter 2000	36	Not Attained	S/E	Not Attained	0.475
1st Quarter 2001	36	Not Attained	0.059	Attained	0.594
2nd Quarter 2001	36	Attained	0.739	Attained	1.000
3rd Quarter 2001	36	Not Attained	0.304	Attained	0.972

Note: The power analysis used for this application assumes normality of data. Distance to the Hypothetical Statistical Compliance Boundary (HSCB) is the distance from the most downgradient well to the HSCB; S/E = extrapolated result significantly exceeds the target level (0.005 mg/L).

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Table 11
Summary of MAROS Sampling Optimization Results

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	Hydro-logic Unit	MAROS Well Category S = Source T= Tail	LOGRAM Well?(1)	LOGRAM Sampling Frequency(2)	MAROS Trend Result(3)	MAROS Interpreted Well Redundancy/Well Sufficiency Results	MAROS Interpreted Sampling Frequency Results	Comments
LC-03	UV	T	Yes	Quarterly	I	***Keep***	***Annual***	Increasing trend & downgradient well
LC-05	UV	T	Yes	Annual	I	***Keep***	***Quarterly***	Increasing trend & downgradient of source area
LC-06	UV	T	Yes	Semiannual	I	***Keep***	***Quarterly***	Increasing trend & defines the middle-lateral boundary of plume
LC-14a	UV	T	Yes	Annual	S	***Keep***	***Annual***	Stable trend & downgradient well
LC-16	UV	-	Yes, New	Quarterly	-	***New (New #4)***	***Quarterly***	New well & delineates north of extraction system
LC-19a	UV	T	Yes	Quarterly	S	***Keep***	***Annual***	Stable trend & downgradient of source area and on plume centerline
LC-19b	UV	T	No, eliminated	-	S	***Eliminate***	***Quarterly***	Stable trend & duplicates LC-19a
LC-19c	UV	T	No, eliminated	-	S	***Eliminate***	***Semiannual***	Stable trend & duplicates LC-19a
LC-20	UV	-	Yes, New	Quarterly	-	***New (New #6)***	***Quarterly***	New well & delineates north of source area
LC-24	UV	-	Yes, New	Quarterly	-	-	-	-
LC-26	UV	T	Yes	Annual	PI	***Keep***	***Annual***	Probably increasing trend & slightly upgradient of source area
LC-34	UV	-	Yes, New	Quarterly	-	-	-	-
LC-41a	UV	T	Yes	Annual	NT	***Keep***	***Quarterly***	No trend & monitors leak to the Lower Aquifer
LC-44a	UV	T	No, eliminated	-	NT	***Eliminate***	***Annual***	No trend & spatially redundant
LC-49	UV	T	Yes	Annual	PI	***Keep***	***Semiannual***	Probably increasing trend & downgradient of source area and on plume centerline
LC-51	UV	T	No, eliminated	-	PI	***Eliminate***	***Quarterly***	Spatially redundant
LC-53	UV	T	Yes	Annual	I	***Keep***	***Quarterly***	Increasing trend & downgradient of source
LC-57	UV	-	Yes, New	Quarterly	-	-	-	-
LC-61b	UV	-	Yes, New	Quarterly	-	-	-	-
LC-64a	UV	S	Yes	Quarterly	PI	***Keep***	***Quarterly***	Probably increasing trend & source well

Notes:
(1) Wells to be sampled or eliminated based on the USEPA approved LOGRAM monitoring plan (December 2001)
(2) Sampling frequency based on the USEPA approved LOGRAM monitoring plan (December 2001)
(3) Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)
(4) "-" = Not Applicable, UV=Upper Vashon (the upper layer of the Upper Aquifer), LV=Lower Vashon (the lower layer of the Upper Aquifer), EW=Upper Aquifer extraction well

GROUNDWATER SERVICES, INC.

Table 11
Summary of MAROS Sampling Optimization Results

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	Hydro-logic Unit	MAROS Well Category S = Source T= Tail	LOGRAM Well?(1)	LOGRAM Sampling Frequency(2)	MAROS Trend Result(3)	MAROS Interpreted Well Redundancy/Well Sufficiency Results	MAROS Interpreted Sampling Frequency Results	Comments
LC-66a	UV	T	No, eliminated	-	S	***Eliminate***	***Annual***	Stable trend & duplicates LC-66b
LC-66b	UV	T	Yes	Annual	S	***Keep***	***Annual***	Stable trend &upgradient of extraction system
LC-73a	UV	T	No, eliminated	-	I	***Keep***	***Biennial***	Concentration < 0.5MCL & cross gradient of plume
LC-108	UV	S	No, eliminated	-	D	***Keep***	***Annual***	Decreasing trend & source well
LC-132	UV	T	No, eliminated	-	I	***Keep***	***Quarterly***	Increasing trend & downgradient of source area
LC-136a	UV	S	Yes	Quarterly	I	***Keep***	***Quarterly***	Increasing trend & monitors the hot spot in the source area
LC-136b	UV	S	Yes	Annual	S	***Eliminate***	***Quarterly***	Stable trend & spatially redundant
LC-137a	UV	S	No, eliminated	-	I	***Eliminate***	***Quarterly***	Duplicates LC-137b
LC-137b	UV	S	Yes	Quarterly	PI	***Keep***	***Quarterly***	Probably increasing trend & source well
LC-149c	UV	T	Yes	Annual	S	***Keep***	***Biennial***	Stable trend & upgradient well
LC-149d	UV	T	No, eliminated	-	PD	***Eliminate***	***Biennial***	Upgradient well & duplicates LC-149c
LC-165	UV	T	No, eliminated	-	S	***Keep***	***Biennial***	Stable trend & down/cross gradient sentry well
LC-167	UV	-	Yes, New	Quarterly	-	***New (New #3)***	***Quarterly***	New well & delineates downgradient of extraction system
PA-381	UV	T	Yes	Annual	PI	***Keep***	***Annual***	Probably increasing trend & delineates the lower middle boundary of plume
PA-383	UV	T	Yes	Annual	S	***Keep***	***Biennial***	Stable trend & down/cross gradient sentry well
T-04	UV	T	Yes	Annual	NT	***Keep***	***Annual***	No trend & downgradient well
T-06	UV	-	Yes, New	Quarterly	-	-	-	-
T-08	UV	T	Yes	Semiannual	PI	***Keep***	***Annual***	Probably increasing trend & downgradient sentry well
T-11b	UV	-	Yes, New	Quarterly	-	-	-	-
T-12b	UV	T	Yes	Quarterly	S	***Keep***	***Annual***	Stable trend & downgradient sentry well

Notes:
(1) Wells to be sampled or eliminated based on the USEPA approved LOGRAM monitoring plan (December 2001)
(2) Sampling frequency based on the USEPA approved LOGRAM monitoring plan (December 2001)
(3) Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)
(4) “-“ = Not Applicable, UV=Upper Vashon (the upper layer of the Upper Aquifer), LV=Lower Vashon (the lower layer of the Upper Aquifer), EW=Upper Aquifer extraction well

GROUNDWATER SERVICES, INC.

Table 11
Summary of MAROS Sampling Optimization Results

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	Hydro-logic Unit	MAROS Well Category S = Source T= Tail	LOGRAM Well?(1)	LOGRAM Sampling Frequency(2)	MAROS Trend Result(3)	MAROS Interpreted Well Redundancy/Well Sufficiency Results	MAROS Interpreted Sampling Frequency Results	Comments
T-13b	UV	T	Yes	Semiannual	NT	***Keep***	***Annual***	No trend & downgradient sentry well
FL2	UV	-	Yes, New	Quarterly	-	-	-	-
FL3	UV	-	Yes, New	Quarterly	-	***New (New #2)***	***Quarterly***	New well & delineates downgradient of extraction system
FL4b	UV	-	Yes, New	Quarterly	-	-	-	-
FL6	UV	-	Yes, New	Quarterly	-	-	-	-
"New-1"	UV	-	Yes, proposed	Quarterly	-	-	-	-
"New-2"	UV	-	Yes, proposed	Quarterly	-	-	-	-
"New-3"	UV	-	Yes, proposed	Quarterly	-	***New (New #1)***	***Quarterly***	New well & delineates down/cross gradient of plume
"New-4"	UV	-	Yes, proposed	Quarterly	-	-	-	-
"New-5"	UV	-	Yes, proposed	Quarterly	-	***New (New #5)***	***Quarterly***	New well & delineates down/cross gradient of source area
"New-6"	UV	-	Yes, proposed	Quarterly	-	-	-	-
LC-41b	LV	-	Yes, New	Quarterly	-	-	-	-
LC-64b	LV	S	Yes	Annual	D	***Keep***	***Annual***	Decreasing trend & monitors source area in the lower part of the Upper Aquifer
LC-111b	LV	T	Yes	Annual	PD	***Keep***	***Biennial***	Probably decreasing trend & under extraction system in LV
LC-116b	LV	T	Yes	Annual	I	***Keep***	***Semiannual***	Increasing trend & under extraction system in LV
LC-122b	LV	T	Yes	Annual	D	***Keep***	***Biennial***	Decreasing trend & under extraction system in LV
LC-128	LV	T	Yes	Annual	PI	***Keep***	***Annual***	Probably increasing trend & downgradient of extraction system in LV
LC-137c	LV	S	Yes	Annual	D	***Keep***	***Annual***	Decreasing trend & monitors the source in LV
T-10	LV	-	Yes, newly added	Quarterly	-	-	-	-
FL4a	LV	-	Yes, newly added	Quarterly	-	-	-	-

Notes:
(1) Wells to be sampled or eliminated based on the USEPA approved LOGRAM monitoring plan (December 2001)
(2) Sampling frequency based on the USEPA approved LOGRAM monitoring plan (December 2001)
(3) Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)
(4) "-" = Not Applicable, UV=Upper Vashon (the upper layer of the Upper Aquifer), LV=Lower Vashon (the lower layer of the Upper Aquifer), EW=Upper Aquifer extraction well

GROUNDWATER SERVICES, INC.

Table 11
Summary of MAROS Sampling Optimization Results

Fort Lewis Logistics Center
Pierce County, Washington

Well Name	Hydro-logic Unit	MAROS Well Category S = Source T= Tail	LOGRAM Well(1)	LOGRAM Sampling Frequency(2)	MAROS Trend Result(3)	MAROS Interpreted Well Redundancy/Well Sufficiency Results	MAROS Interpreted Sampling Frequency Results	Comments
MAMC1	LV	-	Yes, New	Quarterly	-	**-**	**-**	-
MAMC6	LV	-	Yes, New	Quarterly	-	**-**	**-**	-
LX-1	EW	T	Yes	Annual	S	***Keep***	***Annual***	Stable trend & performance monitoring
LX-2	EW	T	Yes	Annual	D	***Keep***	***Annual***	Decreasing trend & performance monitoring
LX-3	EW	T	Yes	Annual	D	***Keep***	***Annual***	Decreasing trend & performance monitoring
LX-4	EW	T	Yes	Annual	D	***Keep***	***Annual***	Decreasing trend & performance monitoring
LX-5	EW	T	Yes	Annual	D	***Keep***	***Annual***	Decreasing trend & performance monitoring
LX-6	EW	T	Yes	Annual	D	***Keep***	***Annual***	Decreasing trend & performance monitoring
LX-7	EW	T	Yes	Annual	S	***Keep***	***Annual***	Stable trend & performance monitoring
LX-8	EW	T	Yes	Annual	NT	***Keep***	***Annual***	No trend & performance monitoring
LX-9	EW	T	Yes	Annual	PD	***Keep***	***Annual***	Probably increasing trend & performance monitoring
LX-10	EW	T	Yes	Annual	D	***Keep***	***Annual***	Decreasing trend & performance monitoring
LX-11	EW	T	Yes	Annual	D	***Keep***	***Annual***	Decreasing trend & performance monitoring
LX-12	EW	T	Yes	Annual	D	***Keep***	***Annual***	Decreasing trend & performance monitoring
LX-13	EW	T	Yes	Annual	I	***Keep***	***Annual***	Increasing trend but low concentration & performance monitoring
LX-14	EW	T	Yes	Annual	S	***Keep***	***Annual***	Stable trend & performance monitoring
LX-15	EW	T	Yes	Annual	NT	***Keep***	***Annual***	No trend & performance monitoring
LX-16	EW	T	Yes	Quarterly	D	***Keep***	***Quarterly***	Decreasing trend but high concentration & performance monitoring
LX-17	EW	S	Yes	Quarterly	S	***Keep***	***Quarterly***	Stable trend but high concentration & performance monitoring
LX-18	EW	S	Yes	Quarterly	D	***Keep***	***Quarterly***	Decreasing trend but high concentration & performance monitoring
LX-19	EW	S	Yes	Quarterly	S	***Keep***	***Quarterly***	Stable trend but high concentration & performance monitoring
LX-21	EW	S	Yes	Quarterly	S	***Keep***	***Annual***	Stable trend but high concentration & performance monitoring
RW-1	EW	T	Yes	Quarterly	S	***Keep***	***Quarterly***	Stable trend but high concentration & performance monitoring

Notes:
(1) Wells to be sampled or eliminated based on the USEPA approved LOGRAM monitoring plan (December 2001)
(2) Sampling frequency based on the USEPA approved LOGRAM monitoring plan (December 2001)
(3) Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)
(4) "-" = Not Applicable, UV=Upper Vashon (the upper layer of the Upper Aquifer), LV=Lower Vashon (the lower layer of the Upper Aquifer), EW=Upper Aquifer extraction well

January 15, 2003
GSI Job No. G-2236-15

GROUNDWATER SERVICES, INC.

MAROS 2.0 APPLICATION
UPPER AQUIFER MONITORING NETWORK OPTIMIZATION

Fort Lewis Logistics Center
Pierce County, Washington

FIGURES

GSI Job No. G-2236
Date Issued: 1/15/03

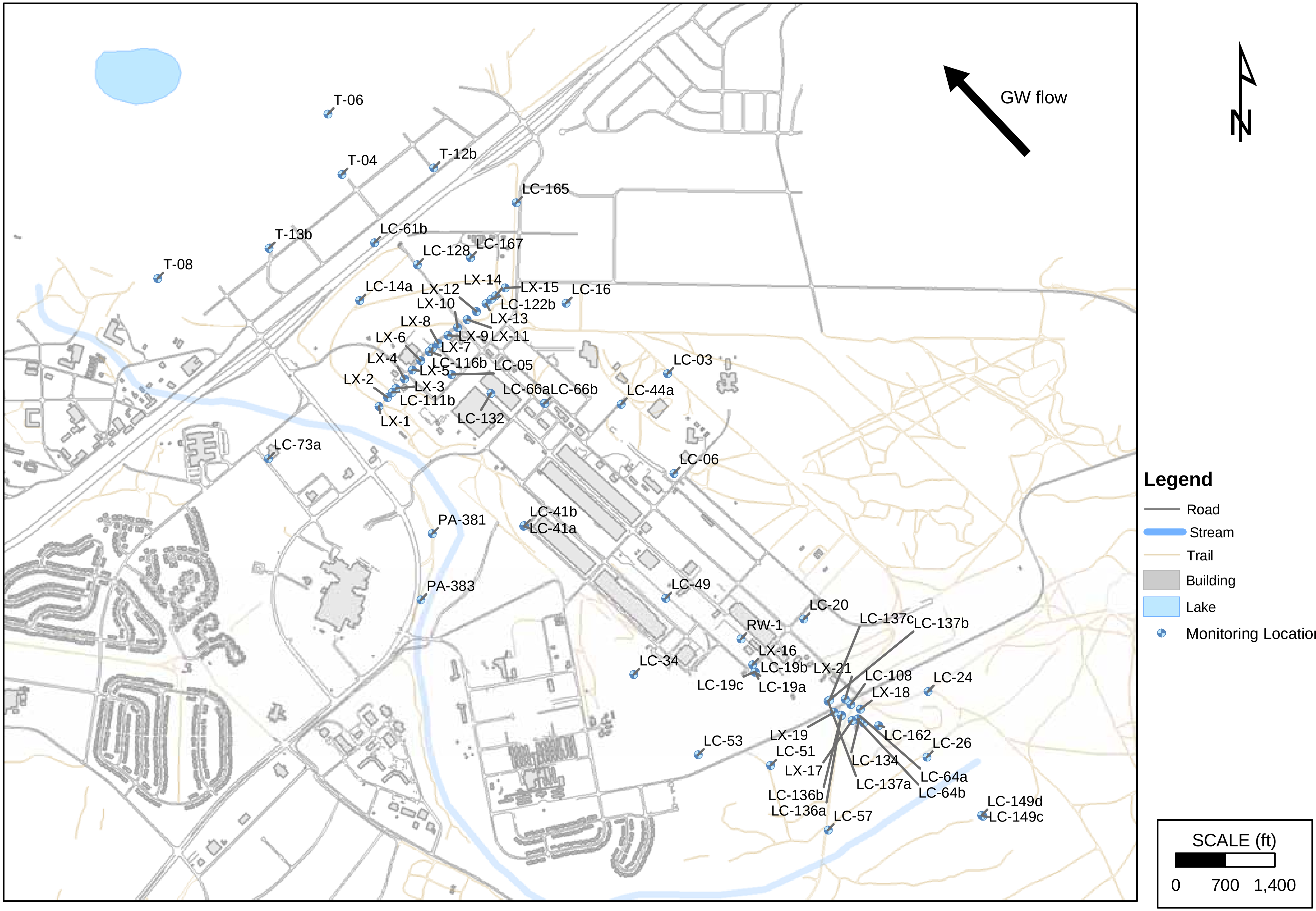

Figure 1 Upper Aquifer Groundwater Monitoring Network
Fort Lewis Logistics Center, Pierce County, Washington

GROUNDWATER SERVICES, INC.

MAROS: Decision Support Tool

MAROS is a collection of tools in one software package that is used in an explanatory, non-linear fashion. The tool includes models, geostatistics, heuristic rules, and empirical relationships to assist the user in optimizing a groundwater monitoring network system while maintaining adequate delineation of the plume as well as knowledge of the plume state over time. Different users utilize the tool in different ways and interpret the results from a different viewpoint.

↓

Overview Statistics

What it is: Simple, qualitative and quantitative plume information can be gained through evaluation of monitoring network historical data trends both spatially and temporally. The MAROS Overview Statistics are the foundation the user needs to make informed optimization decisions at the site.

What it does: The Overview Statistics are designed to allow site personnel to develop a better understanding of the plume behavior over time and understand how the individual well concentration trends are spatially distributed within the plume. This step allows the user to gain information that will support a more informed decision to be made in the next level of optimization analysis.

What are the tools: Overview Statistics includes two analytical tools:

1) **Trend Analysis:** includes Mann-Kendall and Linear Regression statistics for individual wells and results in general heuristically-derived monitoring categories with a suggested sampling density and monitoring frequency.

2) **Moment Analysis:** includes dissolved mass estimation (0^{th} Moment), center of mass (1^{st} Moment), and plume spread (2^{nd} Moment) over time. Trends of these moments show the user another piece of information about the plume stability over time.

What is the product: A first-cut blueprint for a future long-term monitoring program that is intended to be a foundation for more detailed statistical analysis.

↓

Detailed Statistics

What it is: The MAROS Detailed Statistics allows for a quantitative analysis for spatial and temporal optimization of the well network on a well-by-well basis.

What it does: The results from the Overview Statistics should be considered along side the MAROS optimization recommendations gained from the Detailed Statistical Analysis. The MAROS Detailed Statistics results should be reassessed in view of site knowledge and regulatory requirements as well as the Overview Statistics.

What are the tools: Detailed Statistics includes four analytical tools:

1) **Sampling Frequency Optimization:** uses the Modified CES method to establish a recommended future sampling frequency.

2) **Well Redundancy Analysis:** uses the Delaunay Method to evaluate if any wells within the monitoring network are redundant and can be eliminated without any significant loss of plume information.

3) **Well Sufficiency Analysis:** uses the Delaunay Method to evaluate areas where new wells are recommended within the monitoring network due to high levels of concentration uncertainty.

4) **Data Sufficiency Analysis:** uses Power Analysis to assess if the historical monitoring data record has sufficient power to accurately reflect the location of the plume relative to the nearest receptor or compliance point.

What is the product: List of wells to remove from the monitoring program, locations where monitoring wells may need to be added, recommended frequency of sampling for each well, analysis if the overall system is statistically powerful to monitor the plume.

Figure 2. MAROS Decision Support Tool Flow Chart

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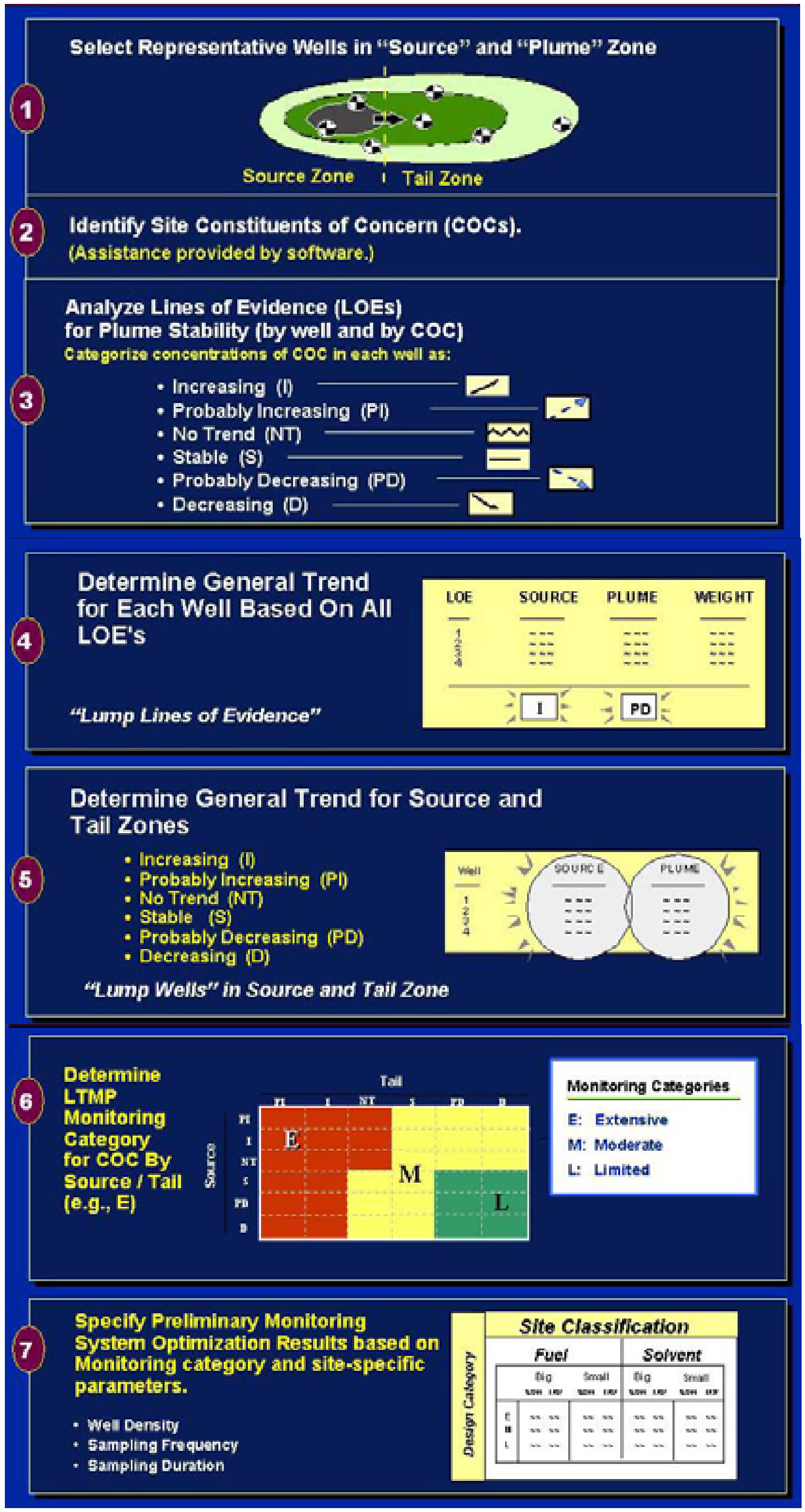

Figure 3:
MAROS Overview Statistics Trend Analysis Methodology

GROUNDWATER SERVICES, INC.

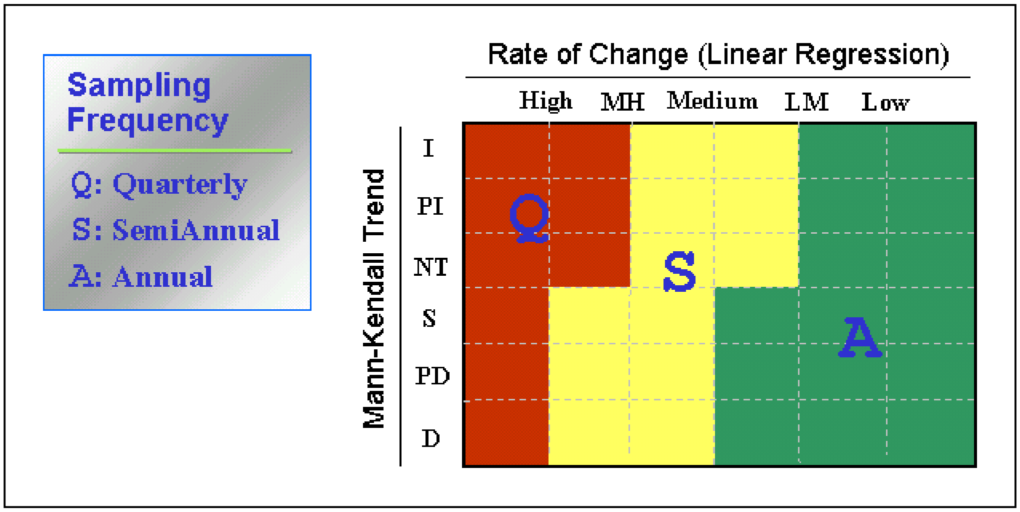

Figure 4. Decision Matrix for Determining Provisional Frequency (*Figure A.3.1 of the MAROS Manual (AFCEE 2001)*)

GSI Job No. G-2236
Date Issued: 1/15/03

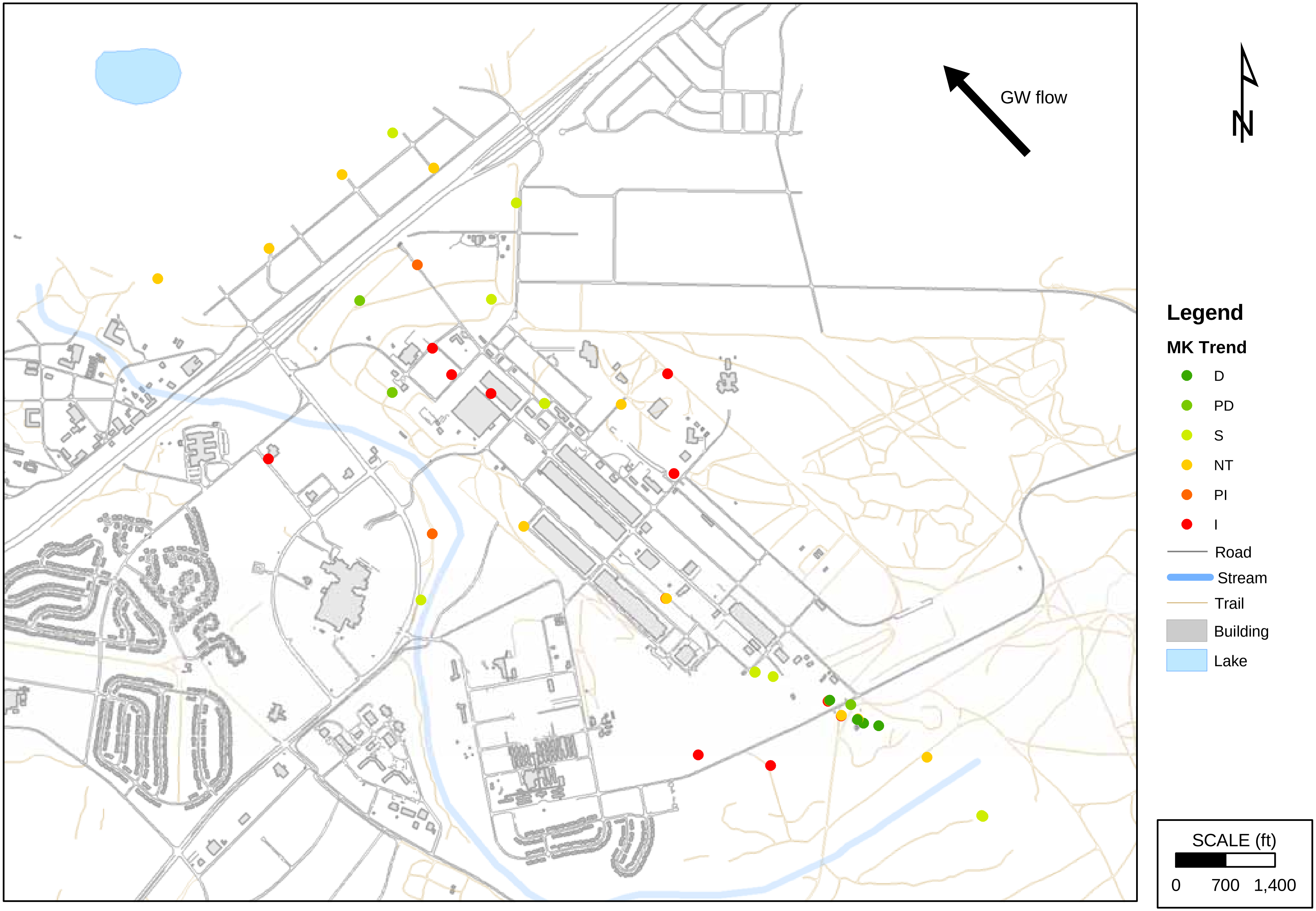

Figure 5 Upper Aquifer TCE Mann-Kendall Trend Results
Fort Lewis Logistics Center, Pierce County, Washington

GSI Job No. G-2236
Date Issued: 1/15/03

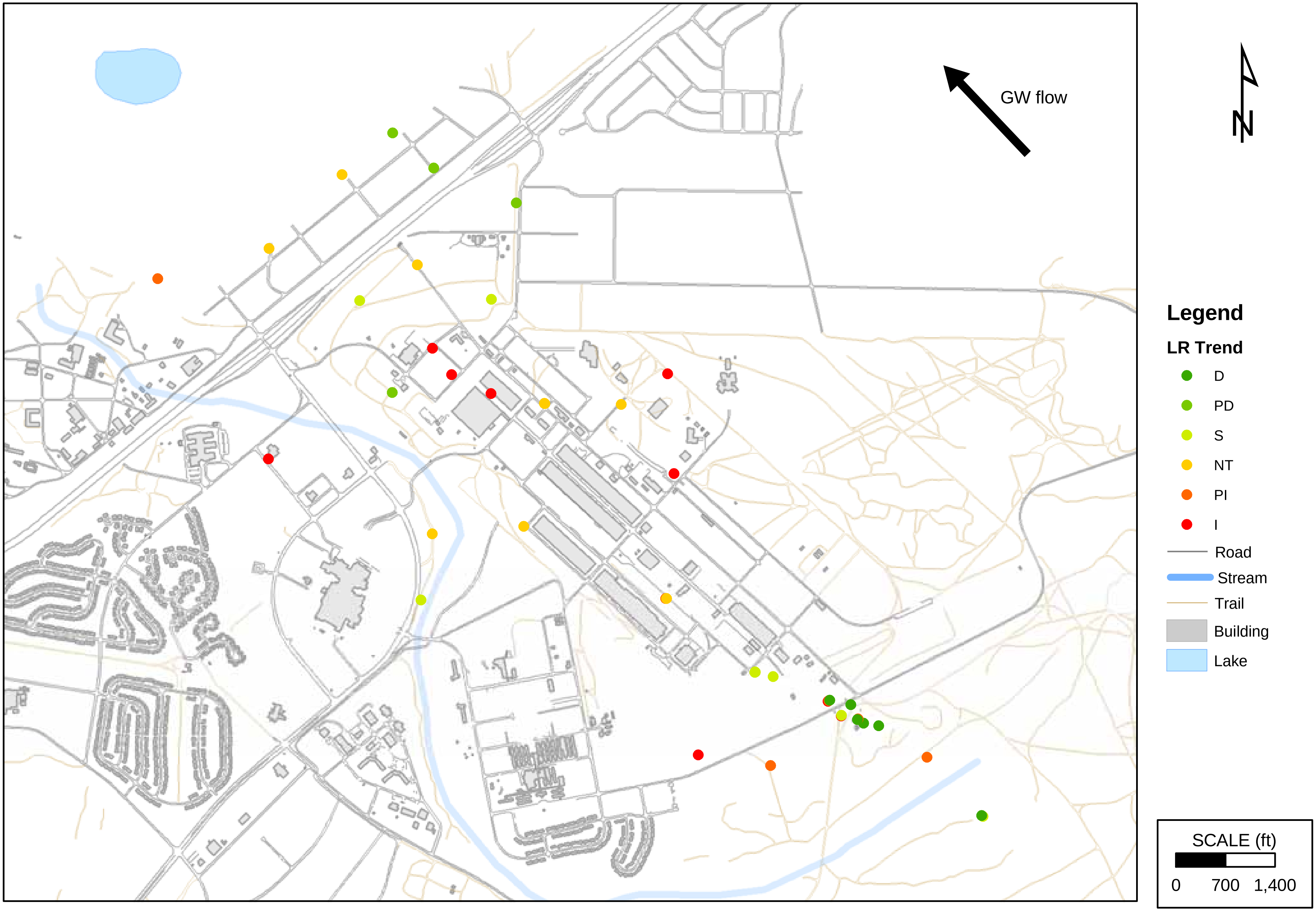

Figure 6 Upper Aquifer TCE Linear Regression Trend Results
Fort Lewis Logistics Center, Pierce County, Washington

GSI Job No. G-2236
Date Issued: 1/15/03

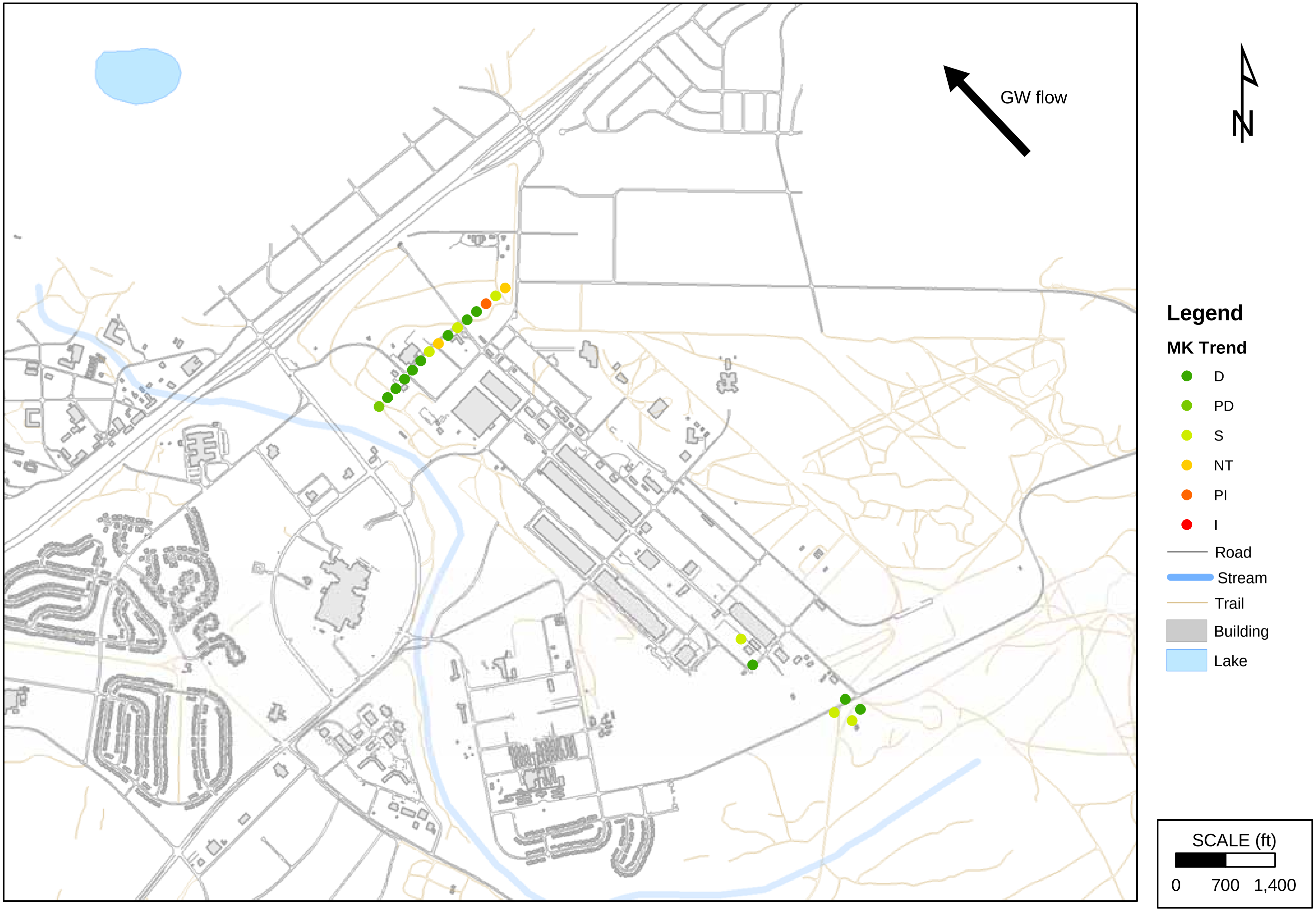

Figure 7 Upper Aquifer TCE Mann-Kendall Trend Results, Extraction Wells
Fort Lewis Logistics Center, Pierce County, Washington

GSI Job No. G-2236
Date Issued: 1/15/03

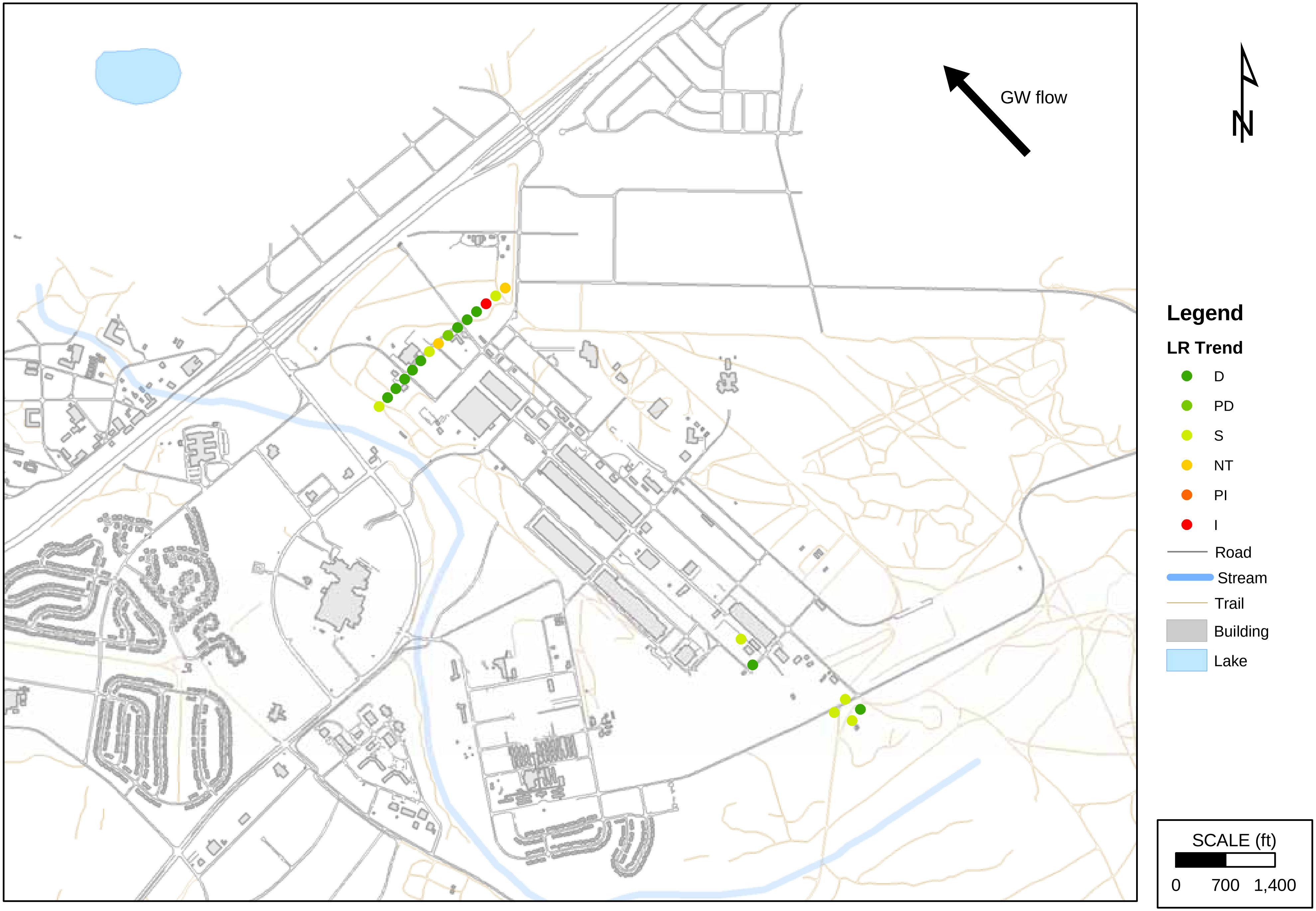

Figure 8 Upper Aquifer TCE Linear Regression Trend Results, Extraction Wells
Fort Lewis Logistics Center, Pierce County, Washington

GSI Job No. G-2236
Date Issued: 1/15/03

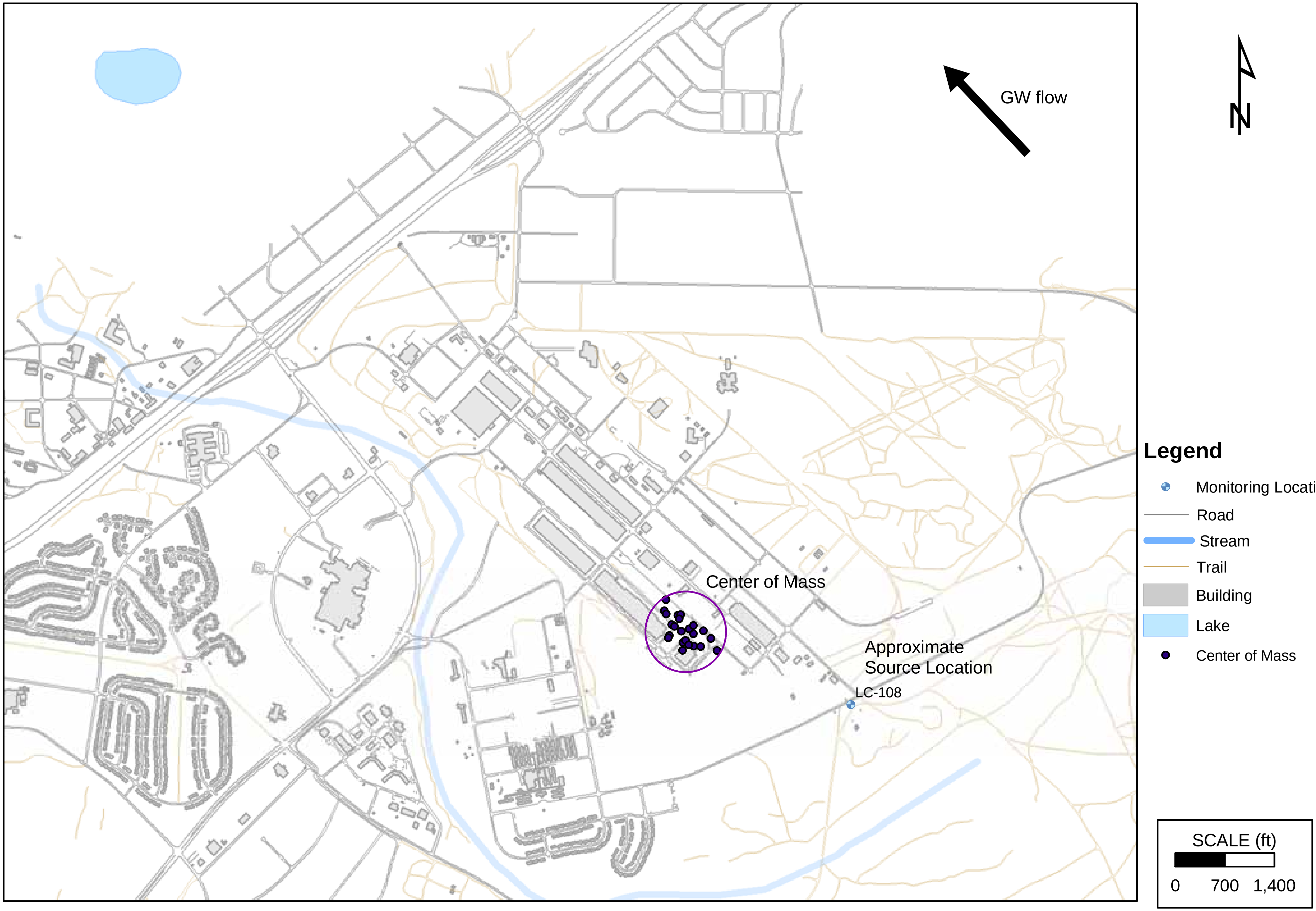

Figure 9 Upper Aquifer: TCE First Moment (Center of Mass) Over Time
Fort Lewis Logistics Center, Pierce County, Washington

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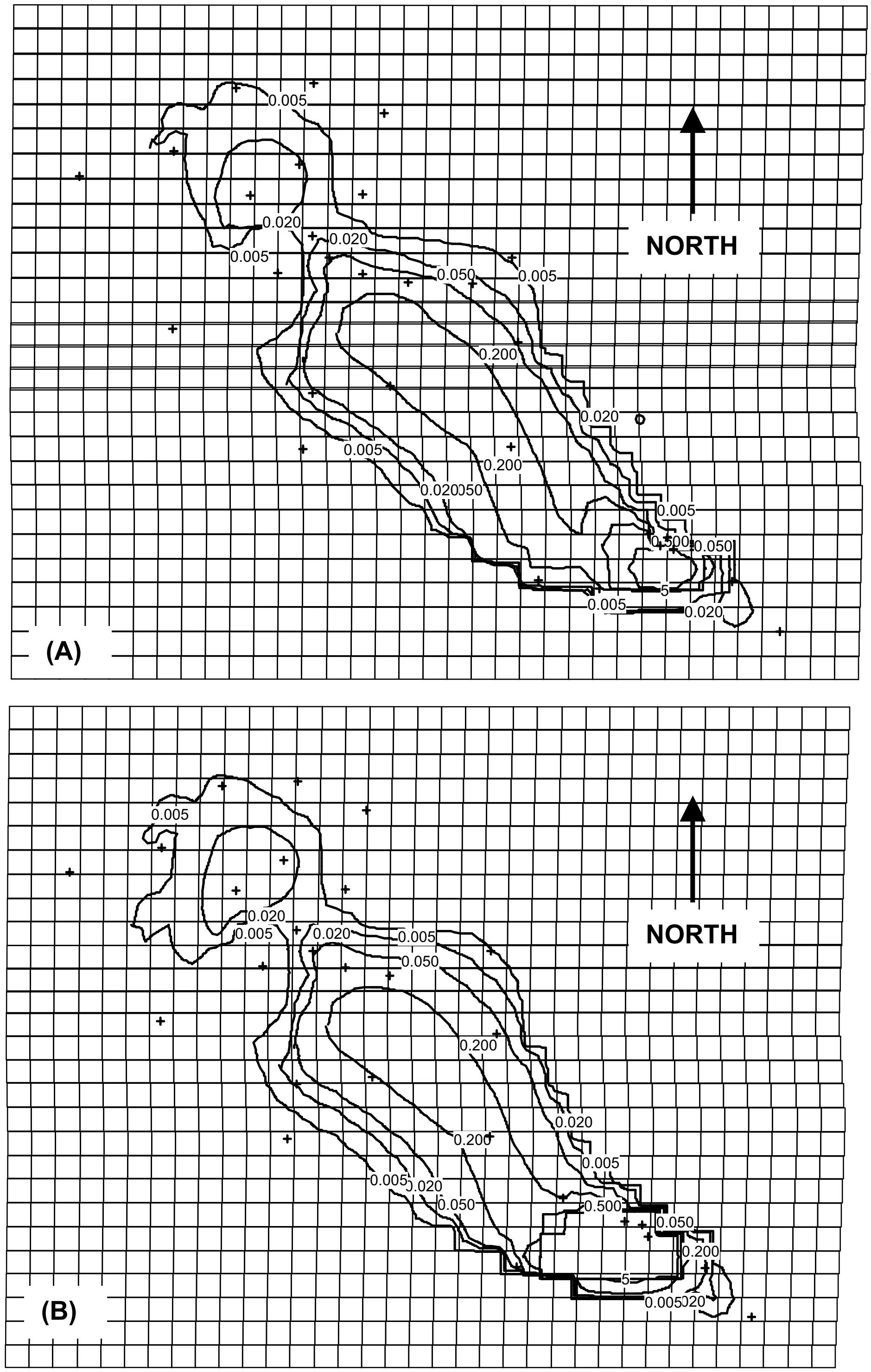

Figure 10. The TCE plume drawn with September 2001 data: (A) before optimization and (B) after optimization

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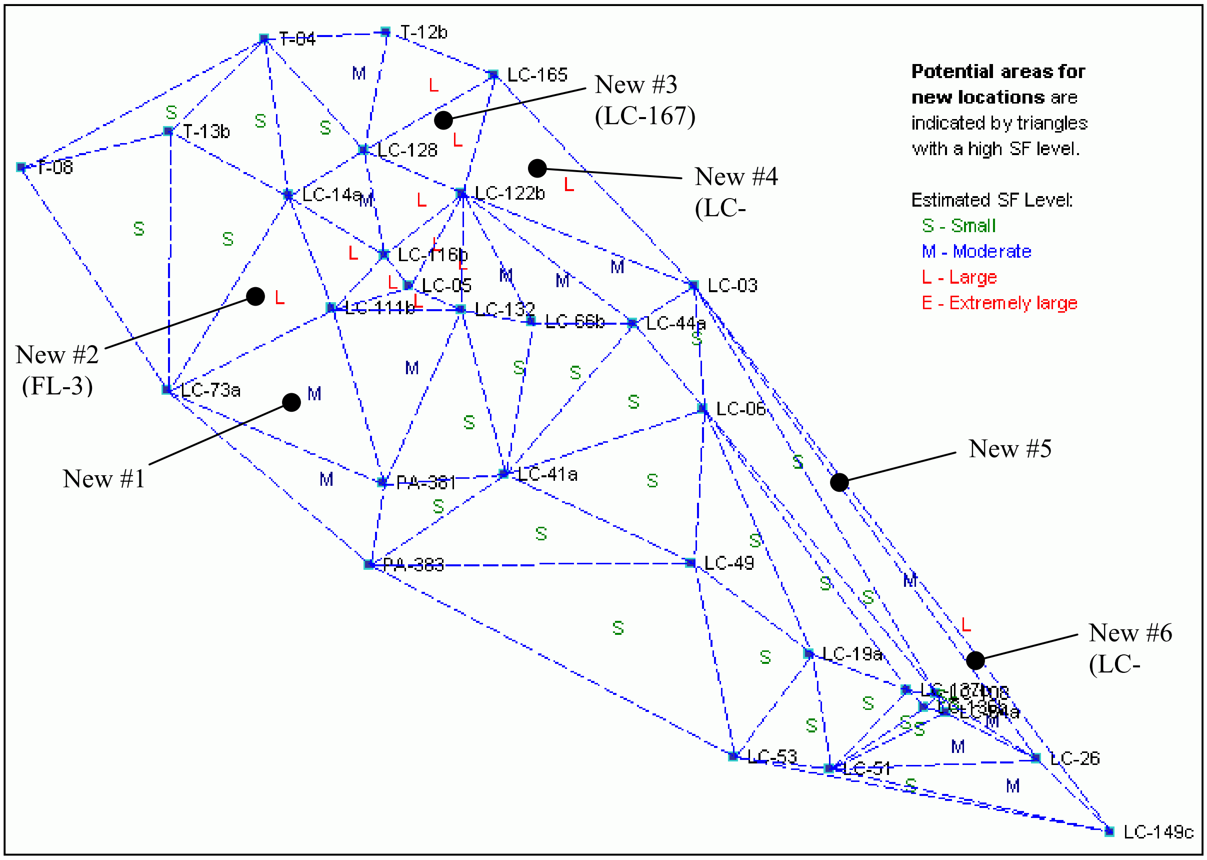

Figure 11. Well Sufficiency Results: Recommendation for New Sampling Locations.

Notes: **L**: SF values > 0.4; **M**: SF values between 0.3 ~ 0.4; **S**: SF values < 0.3. Areas with **L** or **M** symbols are candidate regions for placing new wells. Six new wells are recommended (existing or proposed wells around these locations according to 2002 LOGRAM plan are shown in parentheses).

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APPENDICES

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GROUNDWATER SERVICES, INC.

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APPENDIX A: Upper Aquifer Fort Lewis Historical TCE Maps

Upper Aquifer Fort Lewis Historical TCE Maps (1985 – 2001)

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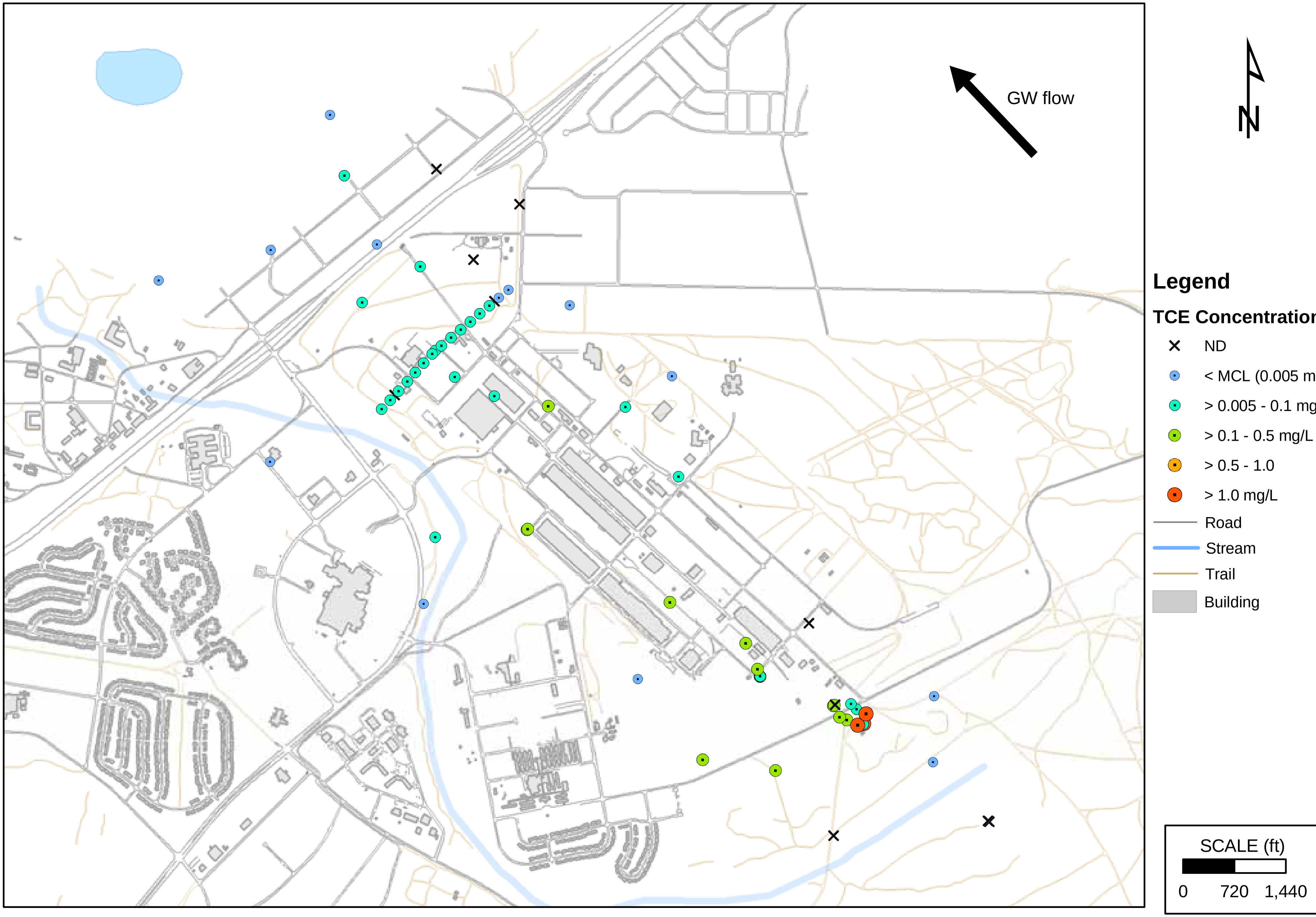
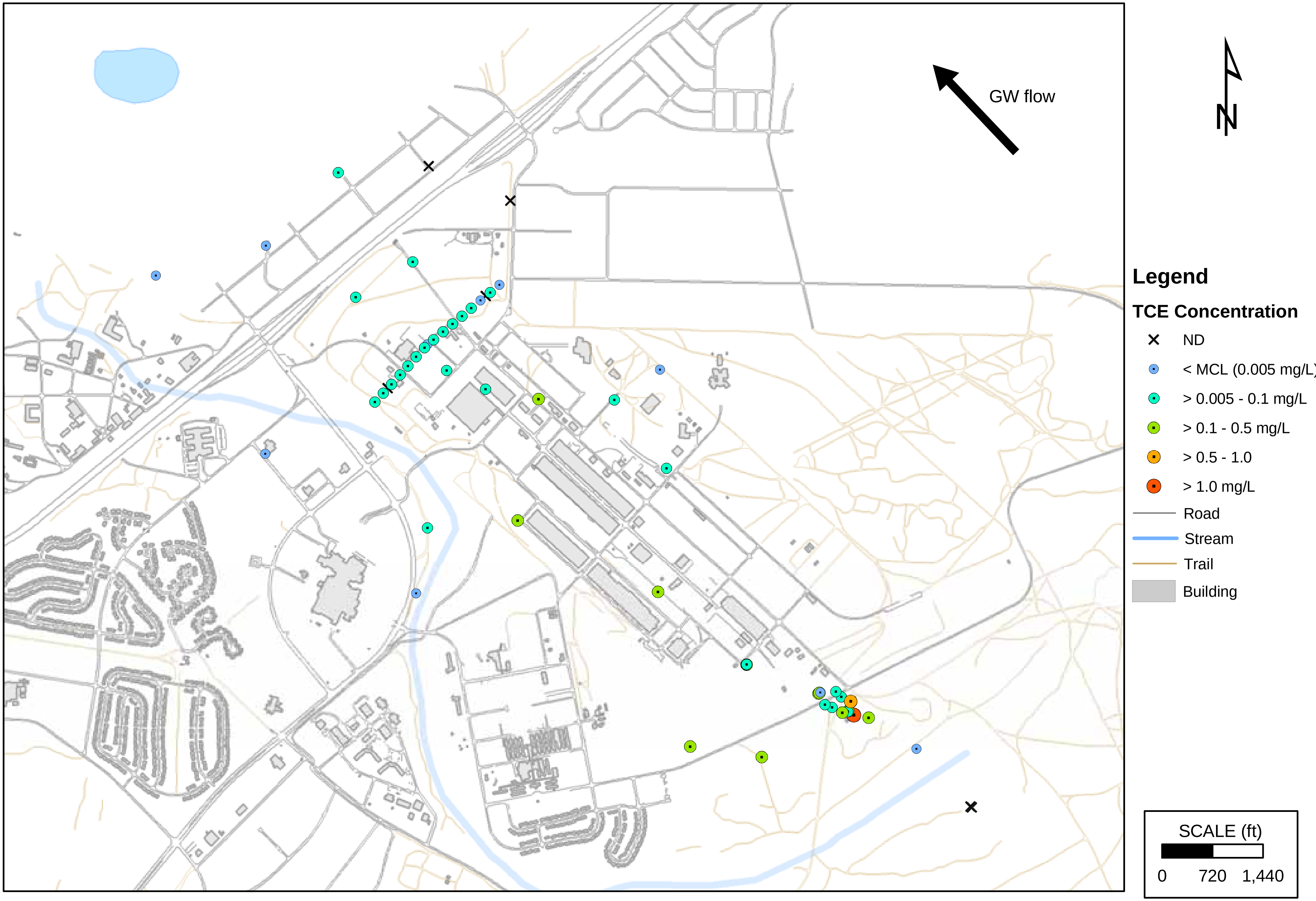
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

2001 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

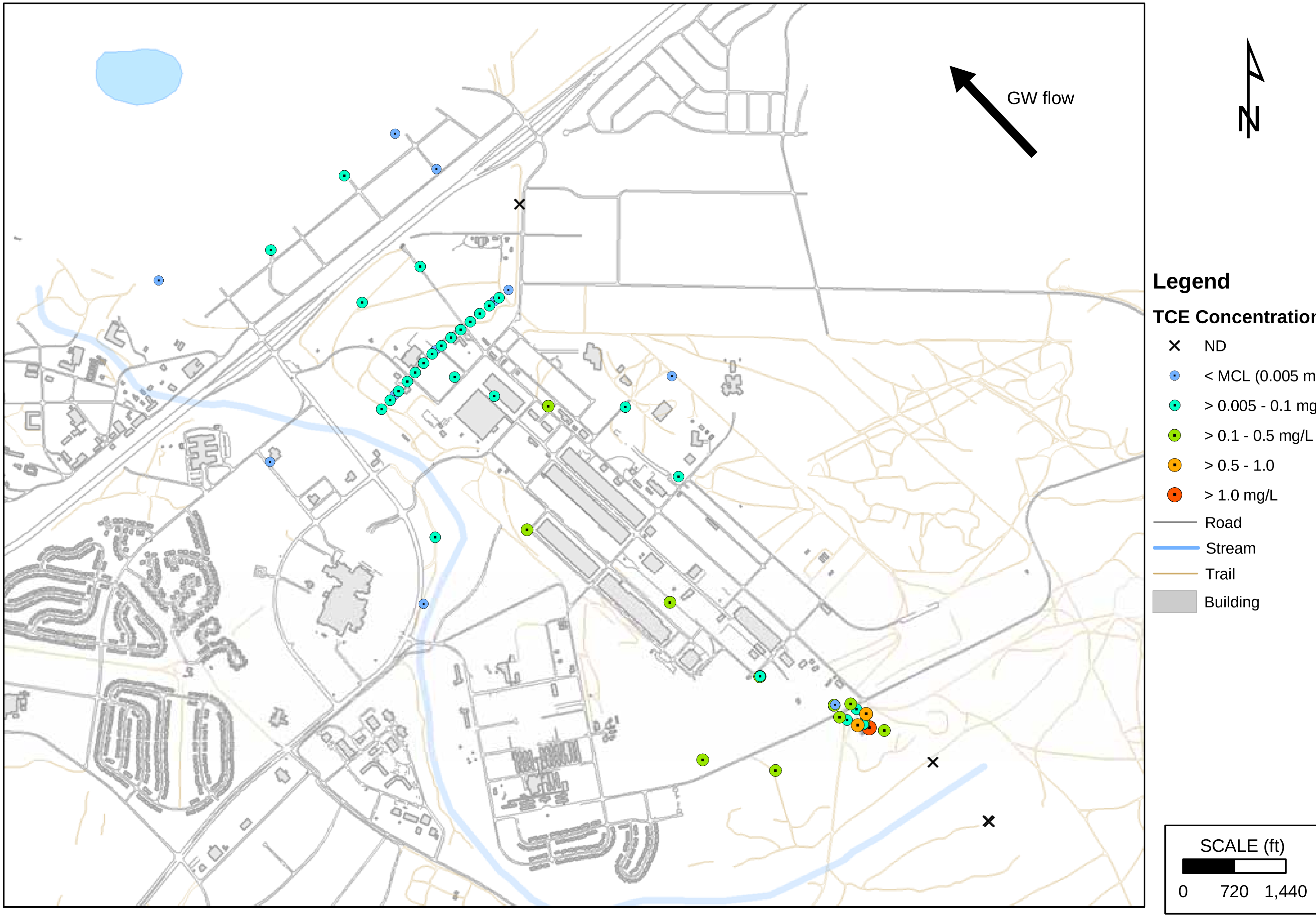
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

2000 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

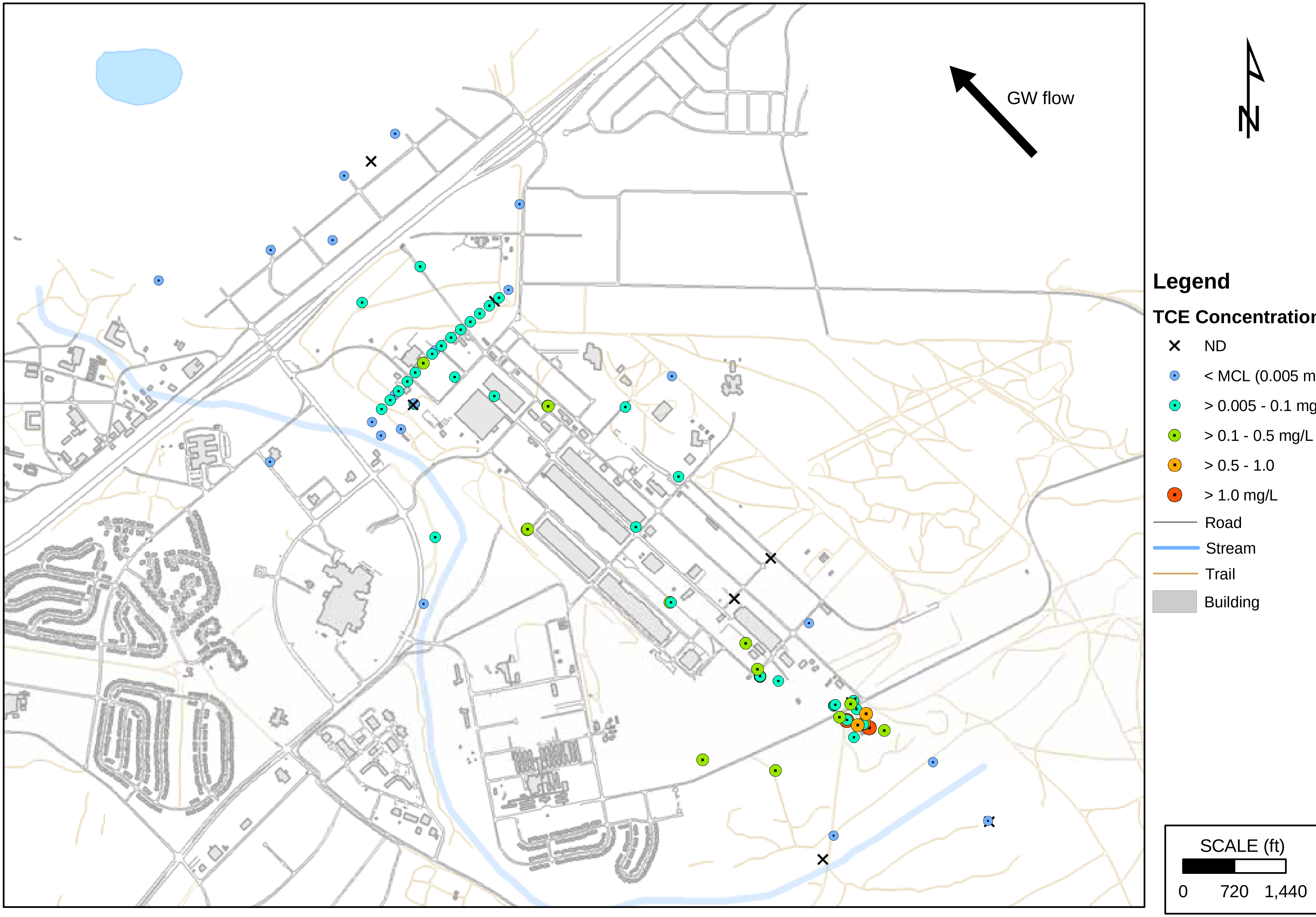
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1999 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

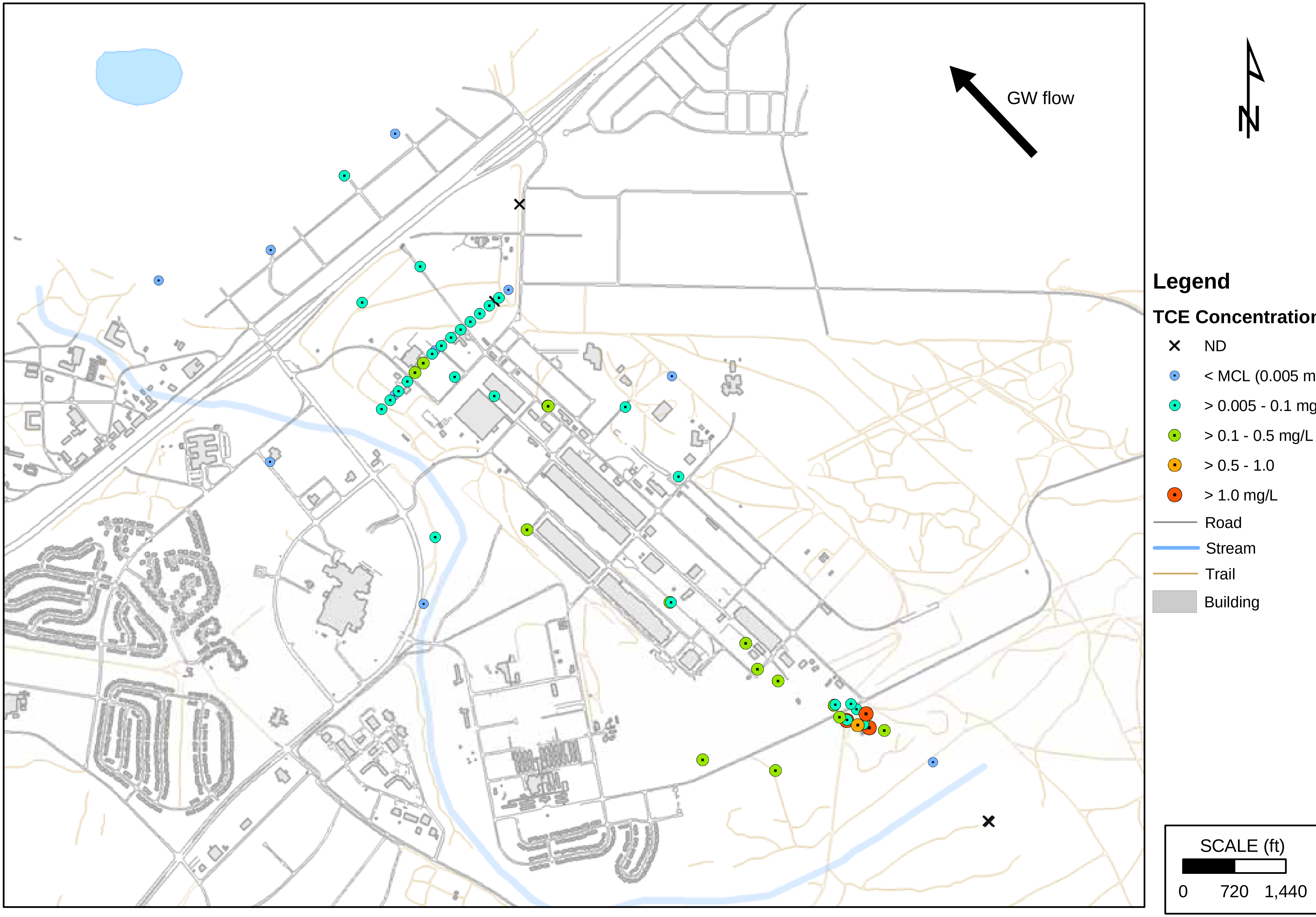
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1998 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

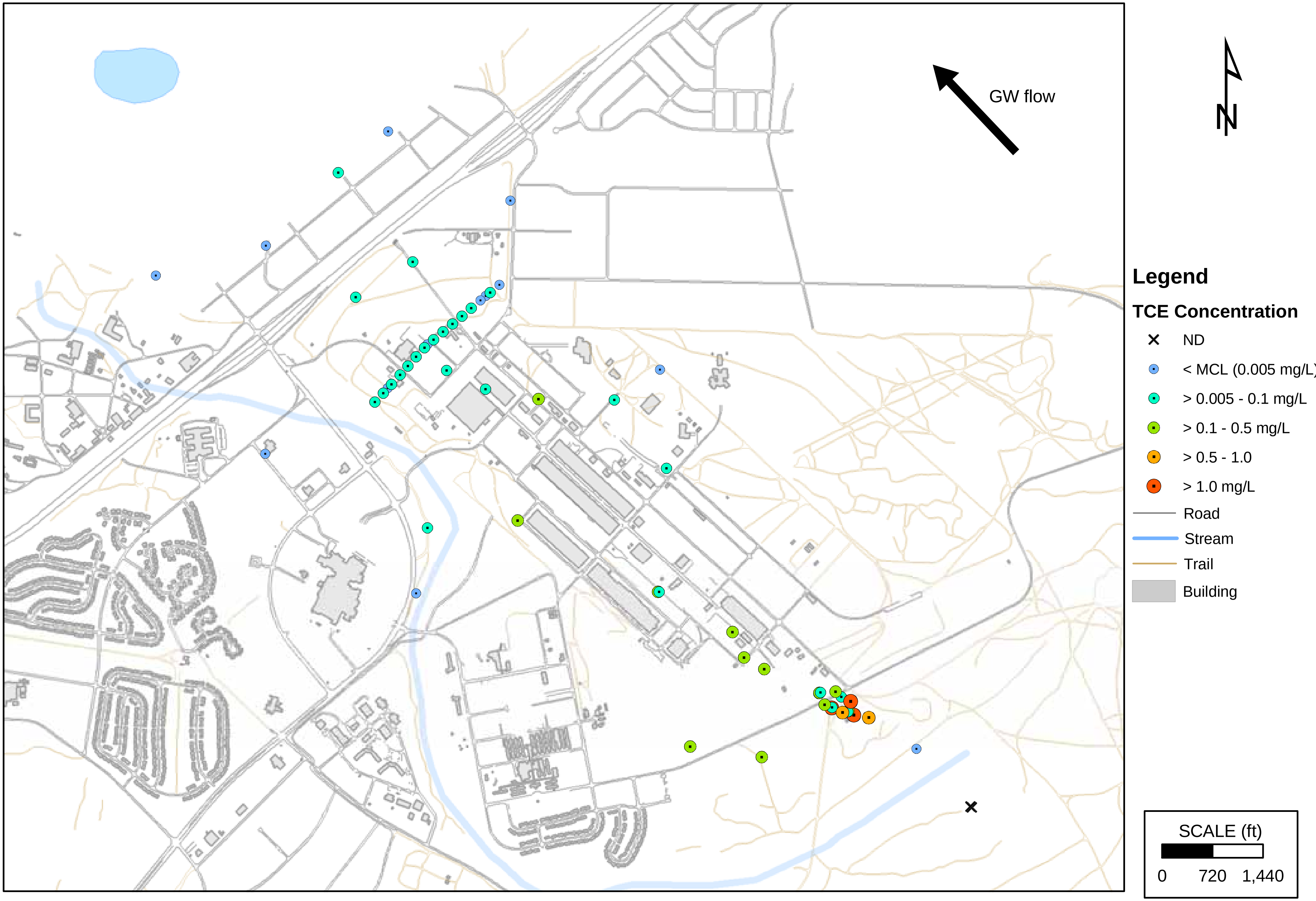
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1997 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

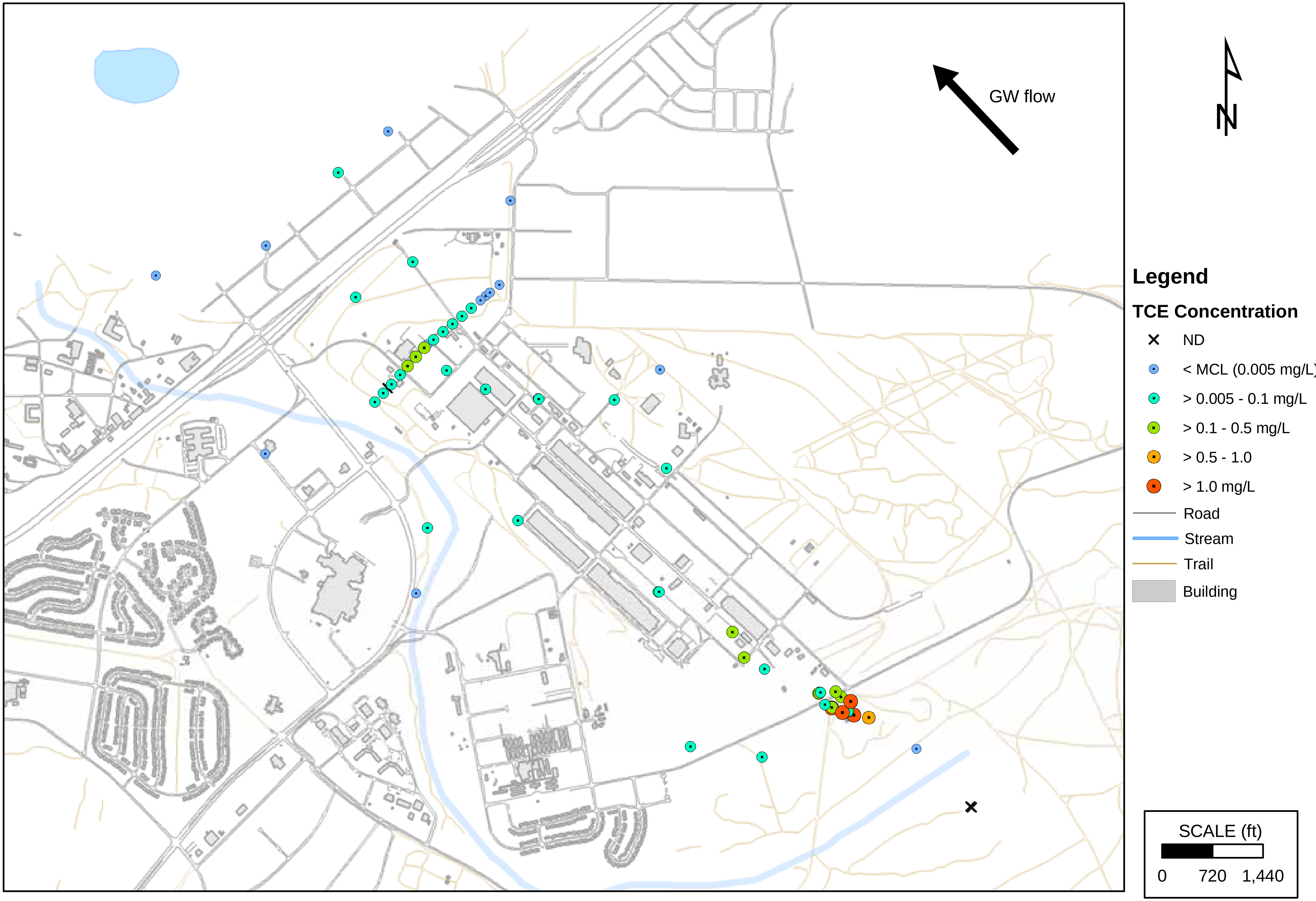
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1996 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

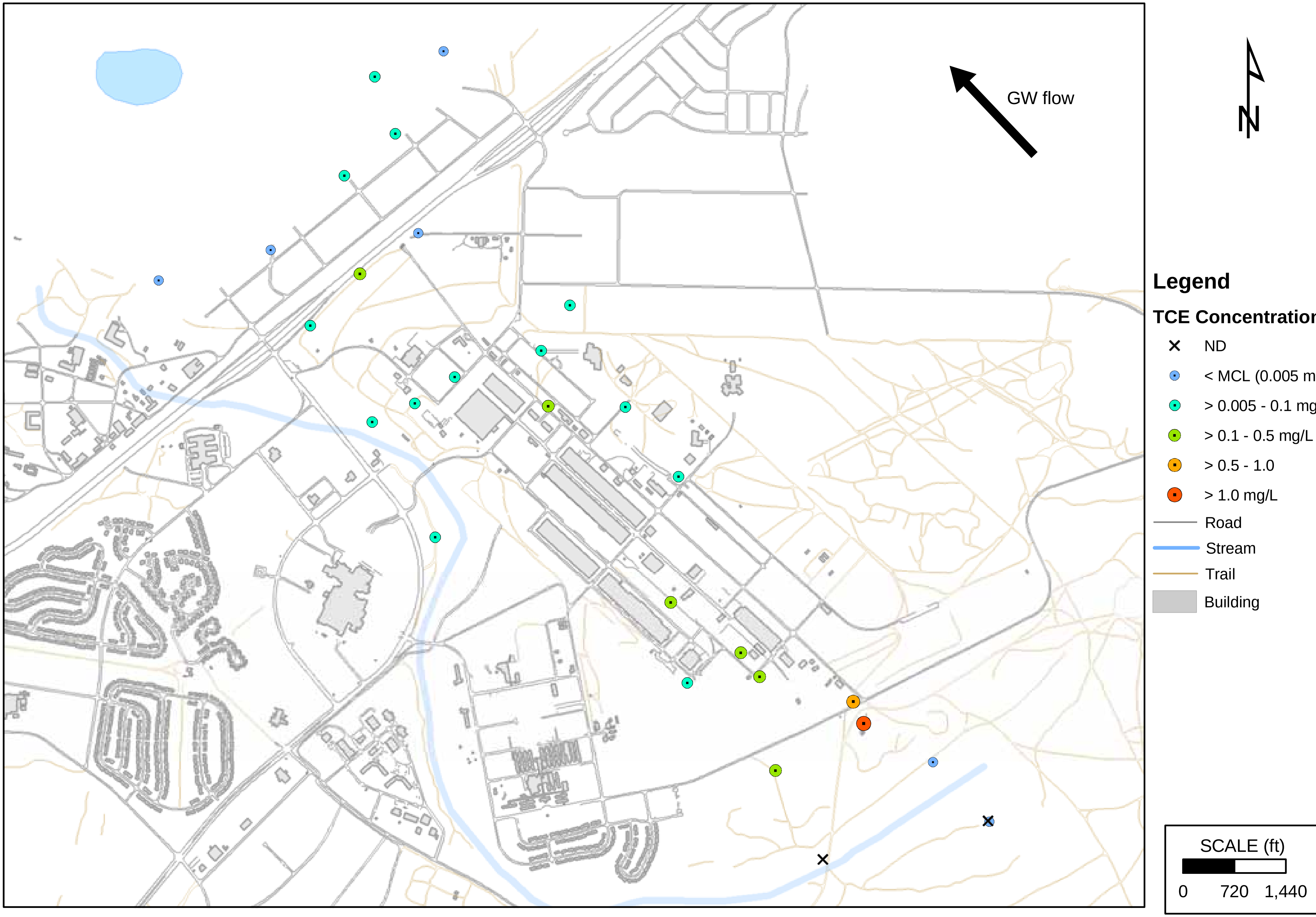
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1995 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

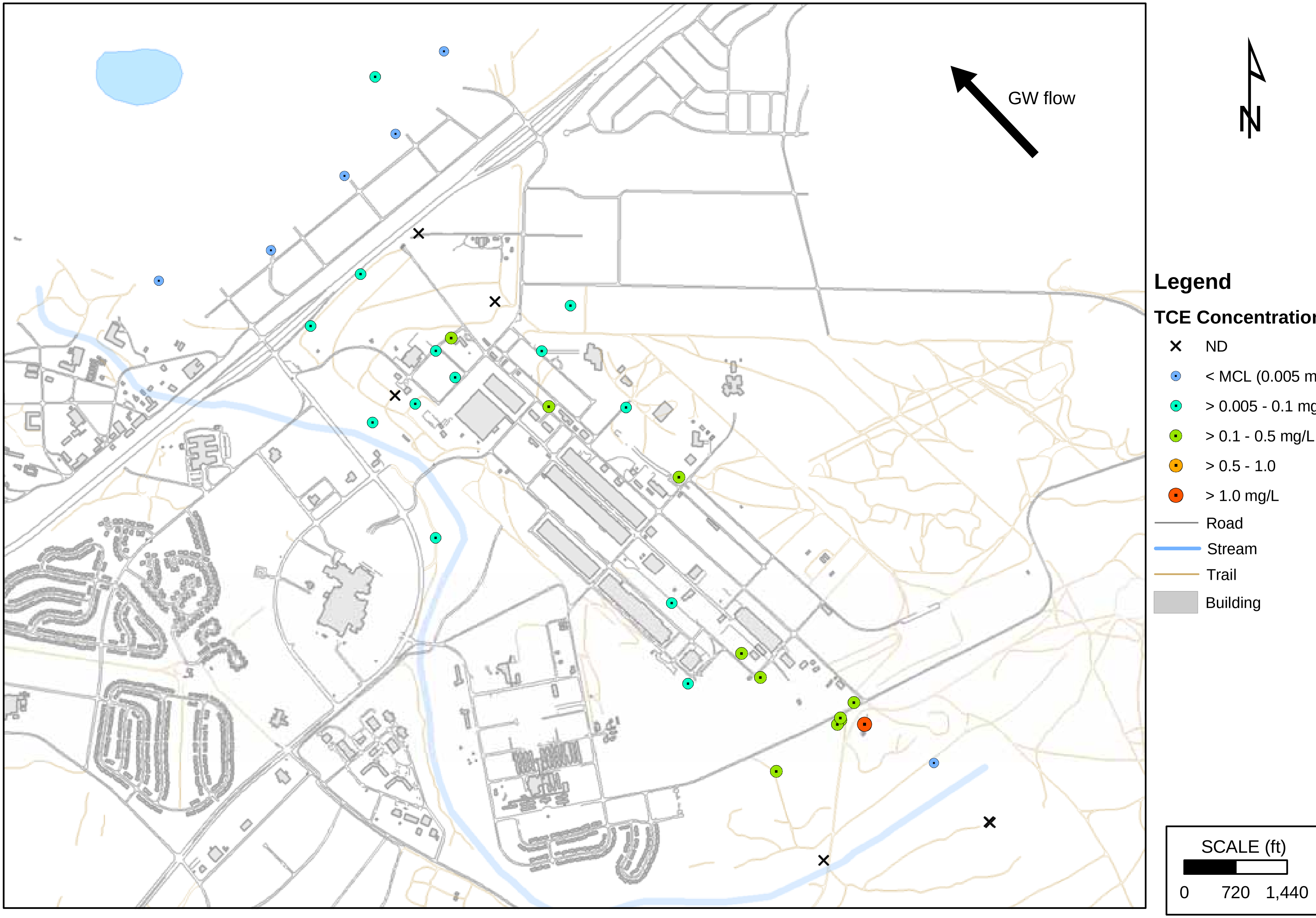
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1994 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

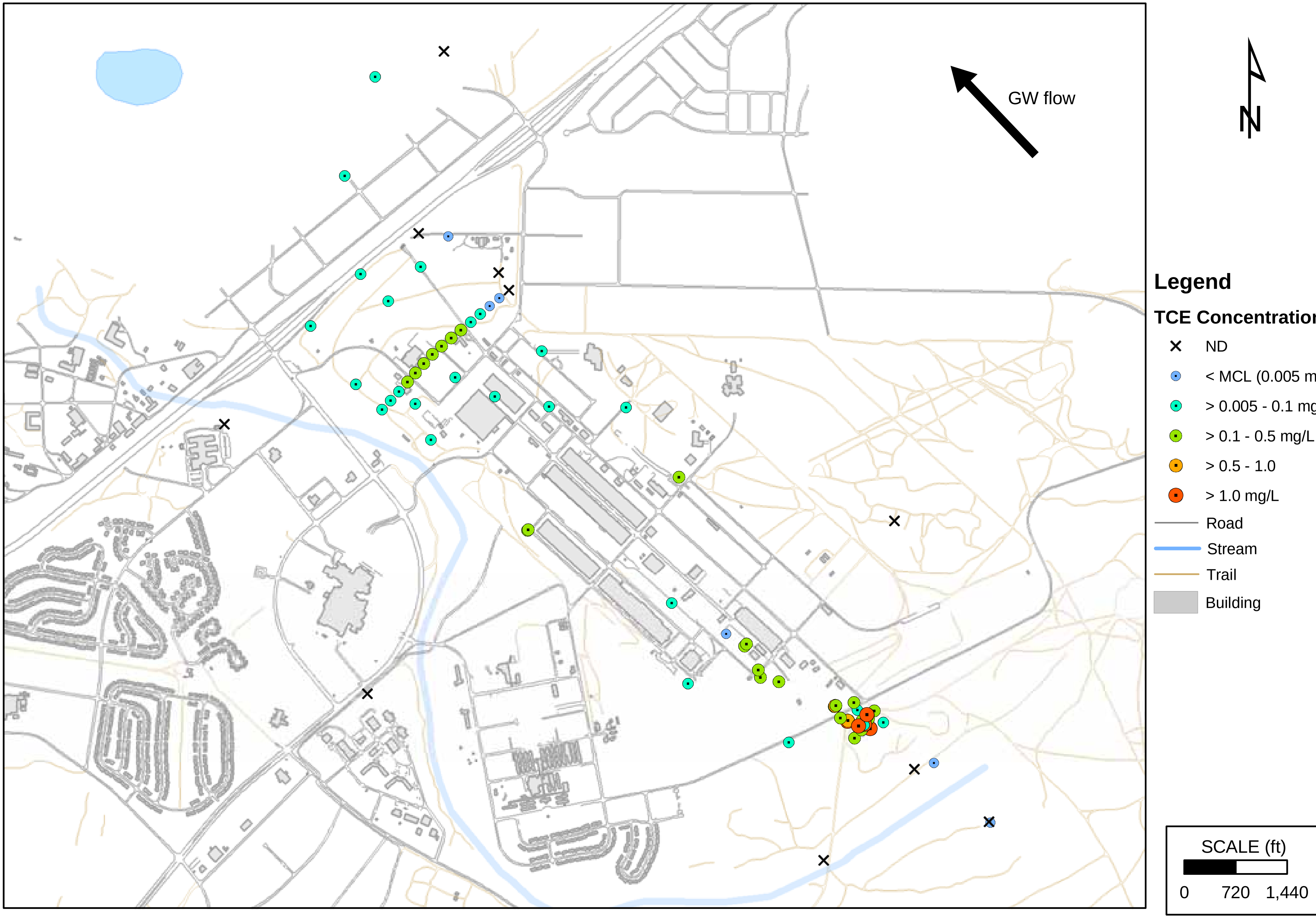
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1993 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

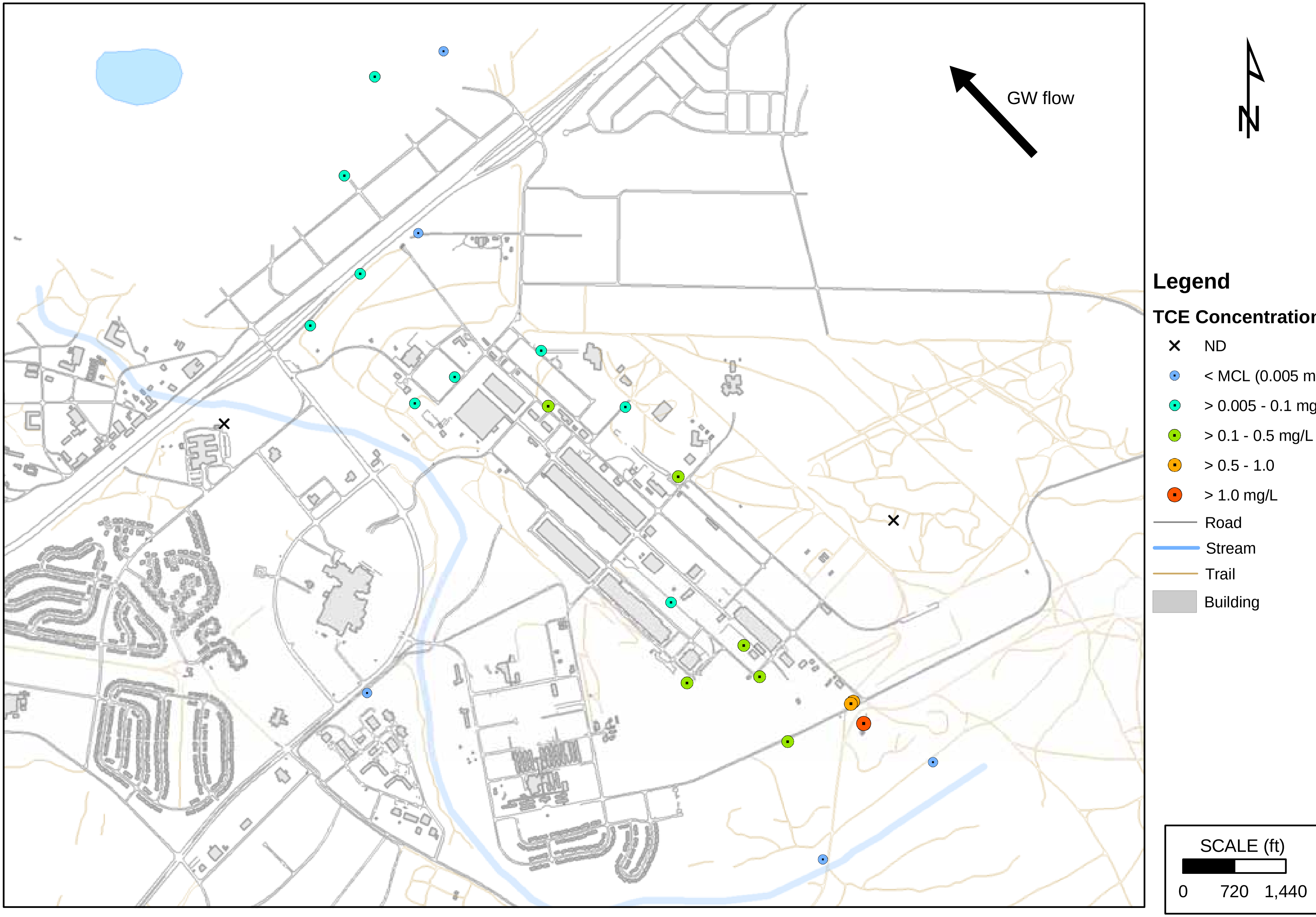
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1992 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

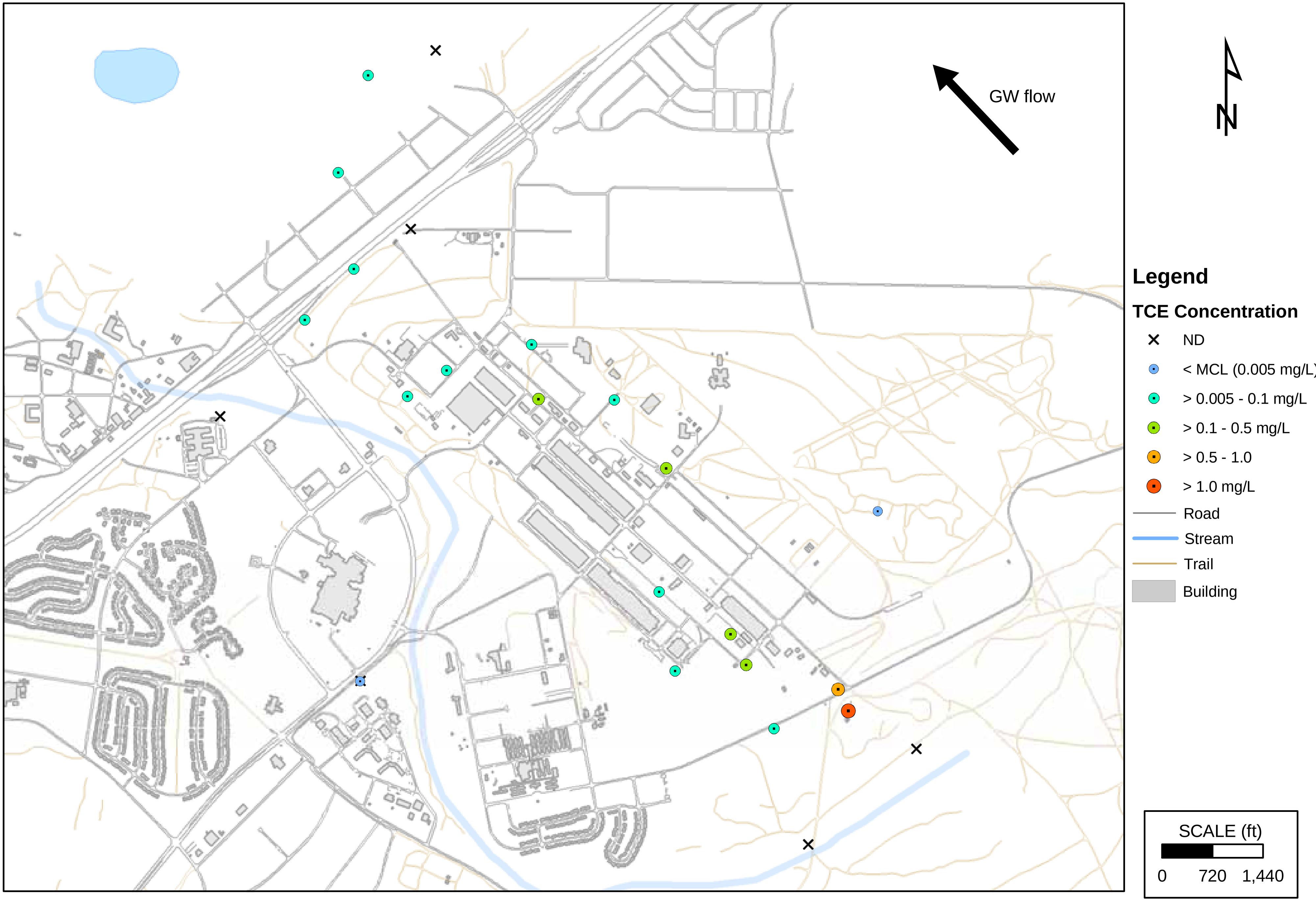
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1991 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

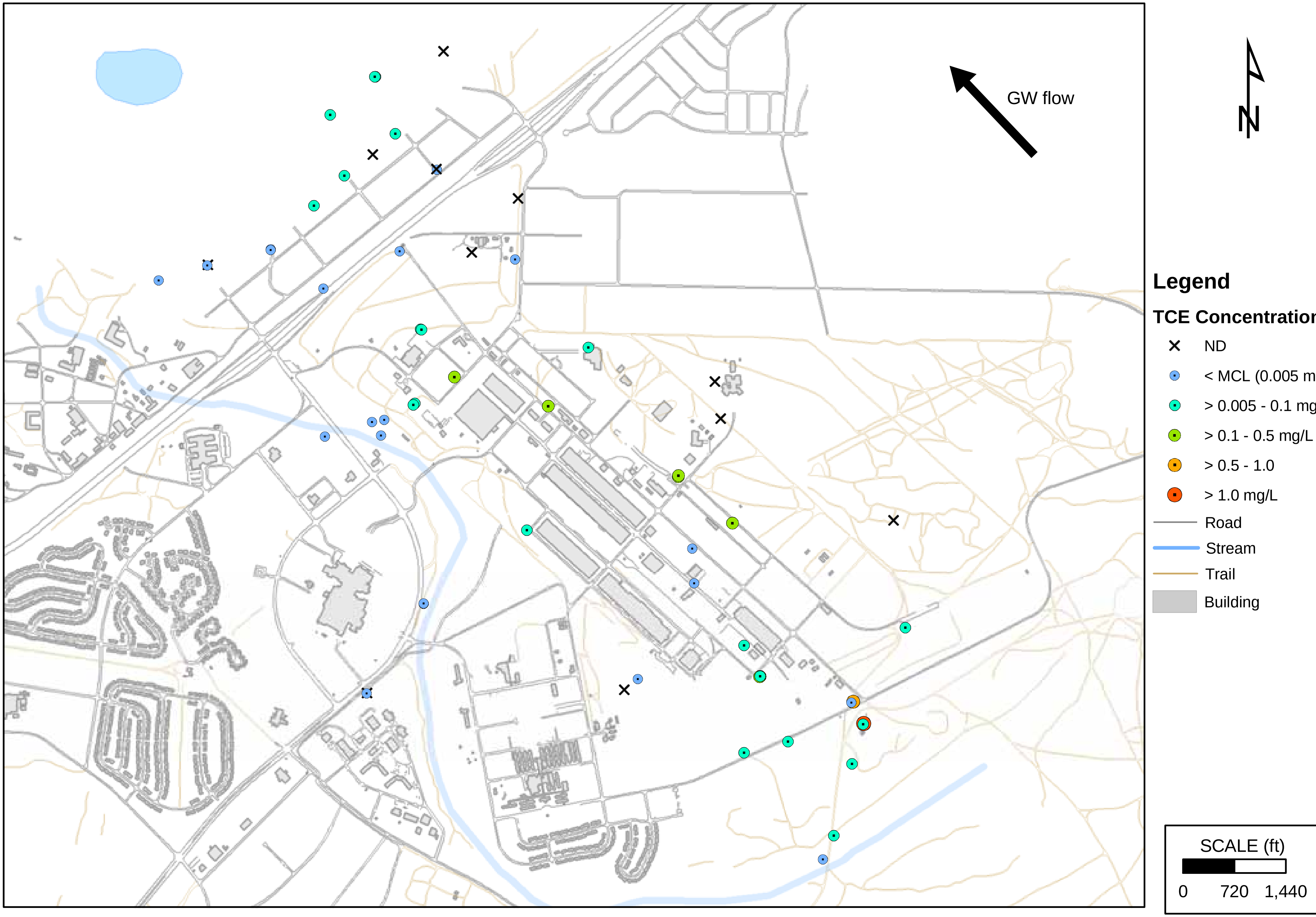
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1990 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

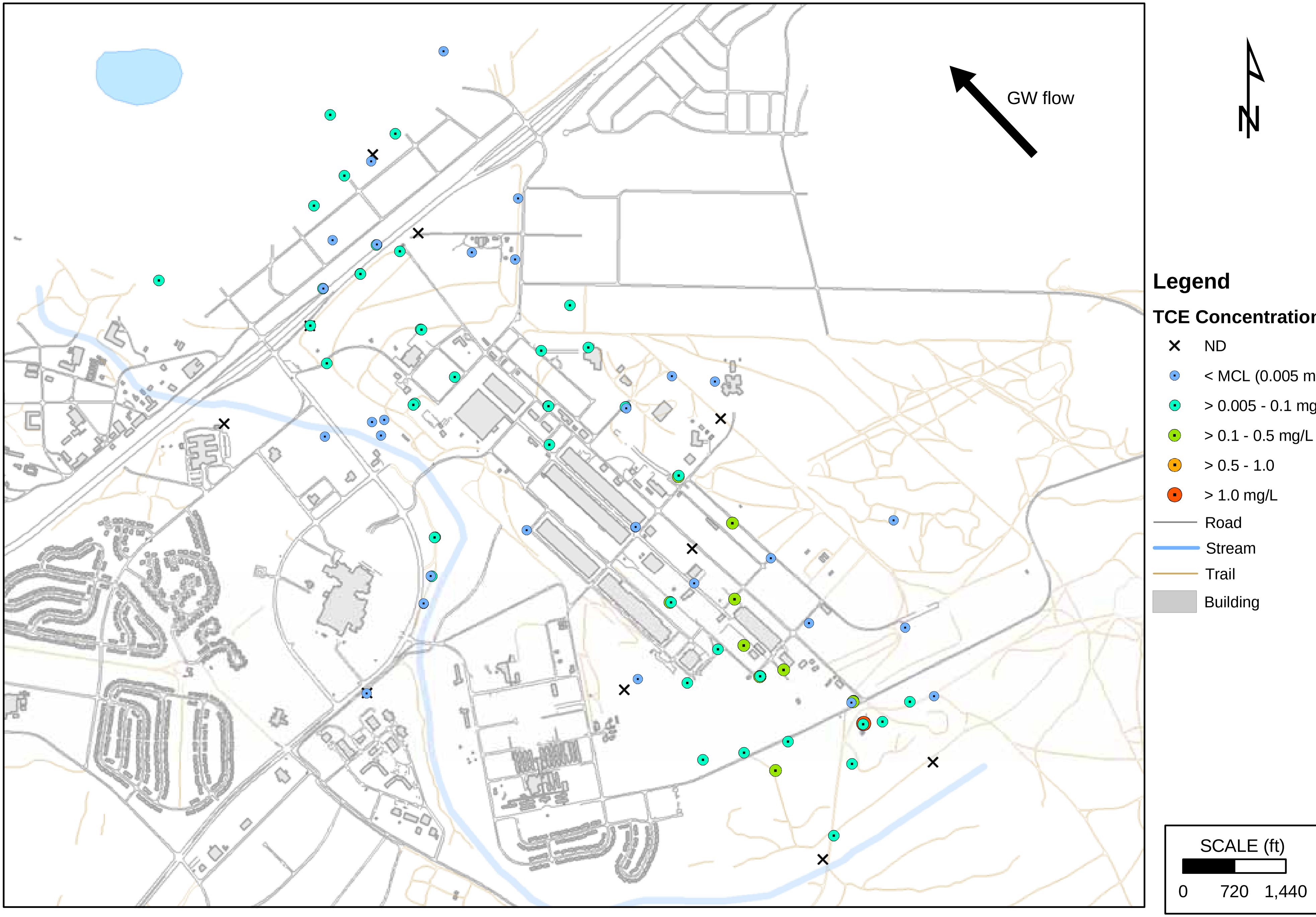
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1988 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

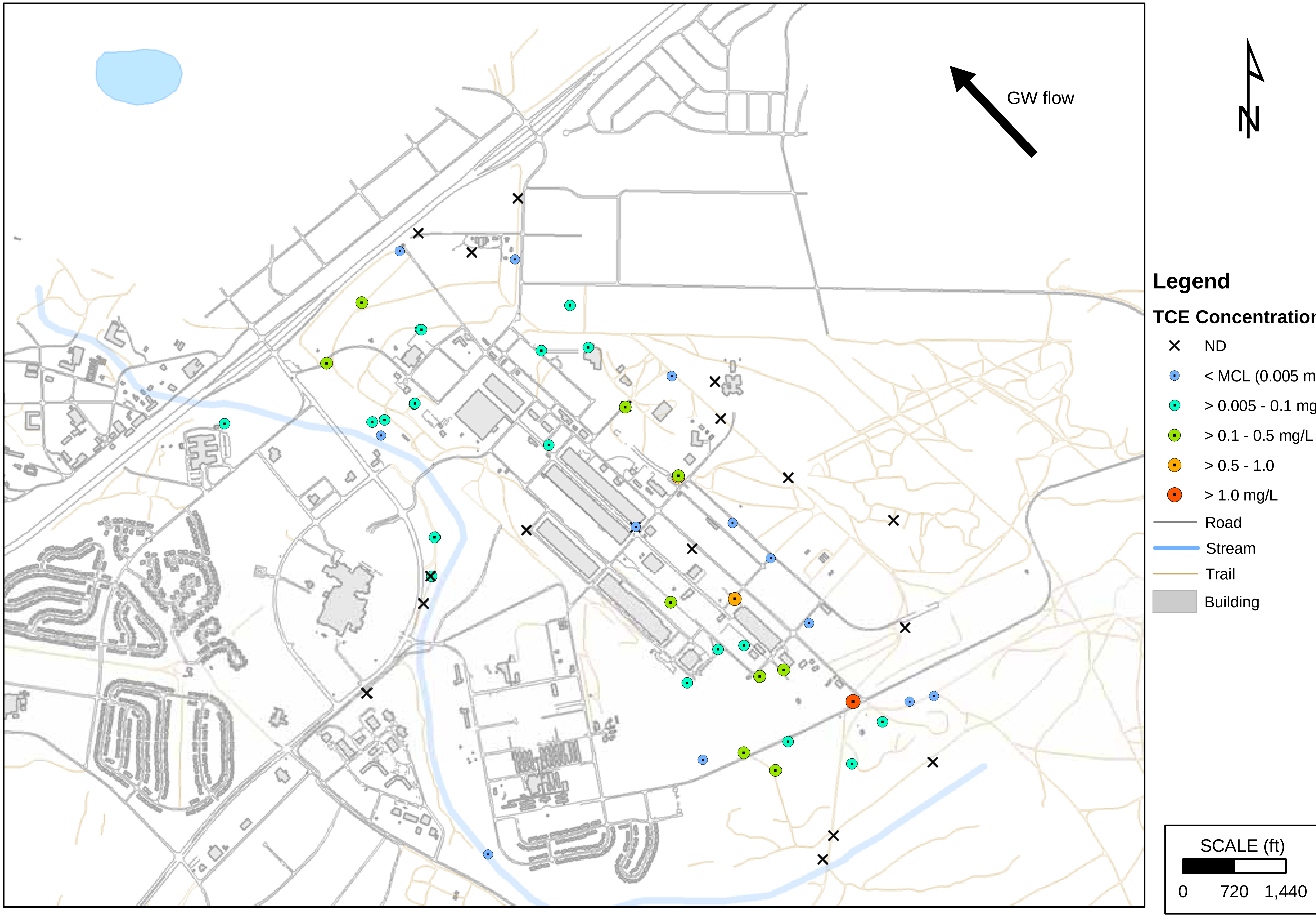
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1987 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

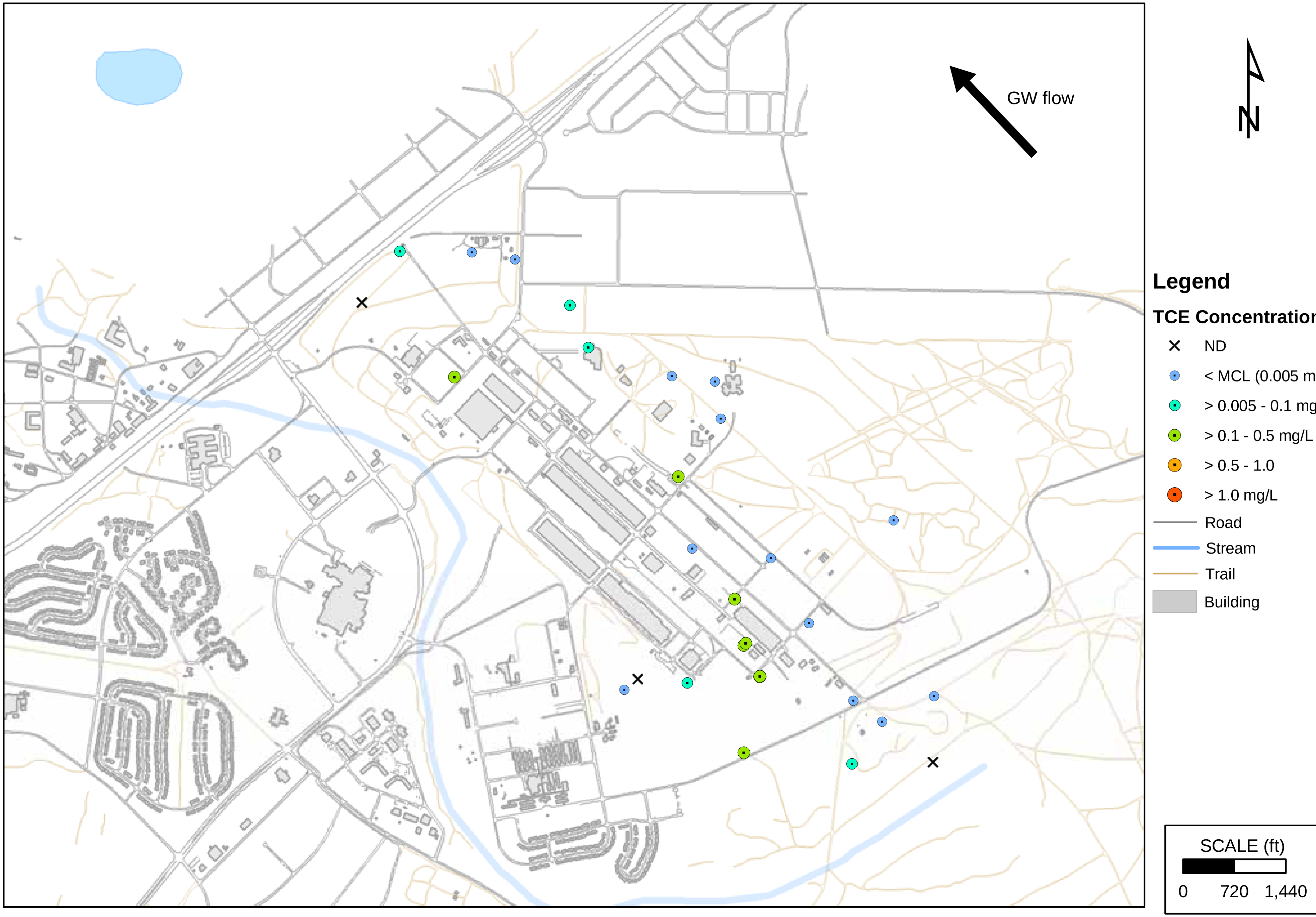
GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1986 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

GSI Job No. G-2236
Date Issued: 11/27/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1985 Upper Aquifer TCE
Fort Lewis Logistics Center, Pierce County, Washington

January 15, 2003
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MAROS 2.0 APPLICATION
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APPENDIX B: Upper Aquifer Fort Lewis MAROS 2.0 Reports

Linear Regression Statistics Summary
Mann-Kendall Statistics Summary
Spatial Moment Analysis Summary
Zeroth, First, and Second Moment Reports
Plume Analysis Summary
Site Results Summary
Sampling Location Optimization Results
Sampling Frequency Optimization Results
Risk-Based Power Analysis – Plume Centerline Concentrations
Risk-Based Power Analysis – Site Cleanup Status

MAROS Mann-Kendall Statistics Summary

Project: Fort Lewis Upper Aquifer **User Name:** Julia Aziz

Location: Pierce County **State:** Washington

Time Period: 11/1/1995 **to** 10/1/2001
Consolidation Period: No Time Consolidation
Consolidation Type: Median
Duplicate Consolidation: Average
ND Values: Specified Detection Limit
J Flag Values : Actual Value

Well	Source/ Tail	Number of Samples	Number of Detects	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	All Samples "ND" ?	Concentration Trend
TRICHLOROETHYLENE (TCE)								
LC-64b	S	24	24	0.51	-159	100.0%	No	D
LC-108	S	24	24	1.81	-61	93.1%	No	PD
LC-134	S	20	20	0.74	-57	96.6%	No	D
LC-136a	S	24	24	0.57	198	100.0%	No	I
LC-136b	S	23	23	0.28	21	69.9%	No	NT
LC-137a	S	24	24	0.92	92	98.9%	No	I
LC-137b	S	24	24	0.56	67	94.9%	No	PI
LC-137c	S	24	19	1.12	-189	100.0%	No	D
LC-162	S	20	20	0.62	-122	100.0%	No	D
LC-64a	S	24	24	2.24	50	88.7%	No	NT
LX-17	S	19	19	0.37	-34	87.4%	No	S
LX-18	S	20	20	0.46	-65	98.2%	No	D
LX-19	S	18	18	0.26	-13	67.3%	No	S
LX-21	S	20	20	0.32	-53	95.4%	No	D
T-01	T	16	16	0.31	-16	74.7%	No	S
LC-53	T	24	24	0.25	86	98.3%	No	I
LC-19b	T	14	14	0.62	-12	72.3%	No	S
LC-19a	T	14	14	0.21	-21	86.0%	No	S
LC-165	T	23	4	0.82	-27	75.2%	No	S
LX-9	T	19	19	0.19	-57	97.5%	No	D
LC-14a	T	24	24	0.30	-55	90.9%	No	PD
LC-149d	T	24	2	0.60	-1	50.0%	No	S
LC-149c	T	24	0	0.00	0	49.0%	Yes	S
LC-144a	T	11	11	0.49	-13	82.1%	No	S
PA-381	T	24	24	0.31	59	92.5%	No	PI
LC-26	T	23	11	4.26	23	71.7%	No	NT
RW-1	T	8	8	0.14	-7	76.4%	No	S
LC-41a	T	24	24	0.21	40	83.1%	No	NT
T-04	T	24	24	0.47	48	87.7%	No	NT
T-08	T	24	24	0.21	50	88.7%	No	NT
LC-132	T	24	24	0.34	188	100.0%	No	I
LC-128	T	24	24	0.45	64	94.1%	No	PI
LC-122b	T	23	2	0.70	-11	60.3%	No	S
LC-116b	T	24	20	1.99	118	99.9%	No	I
LC-111b	T	23	8	1.36	-59	93.7%	No	PD
T-12b	T	8	1	2.38	-7	76.4%	No	NT
LC-06	T	24	24	0.69	103	99.5%	No	I
LC-05	T	24	24	0.67	106	99.6%	No	I

Project: Fort Lewis Upper Aquifer **User Name:** Julia Aziz

Location: Pierce County **State:** Washington

Well	Source/ Tail	Number of Samples	Number of Detects	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	All Samples "ND" ?	Concentration Trend
TRICHLOROETHYLENE (TCE)								
PA-383	T	24	24	0.38	-33	78.4%	No	S
LX-1	T	20	20	0.27	-44	91.8%	No	PD
LX-4	T	18	18	0.23	-75	99.8%	No	D
LX-2	T	20	20	0.28	-106	100.0%	No	D
LX-5	T	19	19	0.22	-79	99.7%	No	D
LX-6	T	20	20	0.21	-108	100.0%	No	D
LX-7	T	20	20	0.21	-39	89.0%	No	S
LX-16	T	8	8	0.15	-17	97.7%	No	D
LX-15	T	20	20	0.29	2	51.3%	No	NT
LX-14	T	20	20	0.25	-3	52.6%	No	S
LX-13	T	15	15	0.27	33	94.3%	No	PI
LX-12	T	20	20	0.29	-73	99.1%	No	D
LC-19c	T	14	14	0.22	-8	64.6%	No	S
LX-10	T	20	20	0.27	-37	87.7%	No	S
LX-3	T	20	20	0.24	-112	100.0%	No	D
LC-73a	T	23	23	0.42	67	95.9%	No	I
LC-66b	T	24	24	0.59	-8	56.8%	No	S
LC-66a	T	24	24	0.29	-35	79.8%	No	S
T-13b	T	23	23	0.14	15	64.3%	No	NT
LX-8	T	18	18	0.12	21	77.3%	No	NT
LC-03	T	23	22	2.39	140	100.0%	No	I
LC-51	T	24	24	0.20	96	99.1%	No	I
LC-49a	T	12	12	0.33	7	65.6%	No	NT
LC-49	T	24	24	0.25	67	94.9%	No	PI
LC-44a	T	24	24	0.41	41	83.8%	No	NT
LX-11	T	20	20	0.34	-92	99.9%	No	D

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)-Due to insufficient Data (< 4 sampling events); Source/Tail (S/T)

The Number of Samples and Number of Detects shown above are post-consolidation values.

MAROS Linear Regression Statistics Summary

Project: Fort Lewis Upper Aquifer

User Name: Julia Aziz

Location: Pierce County

State: Washington

Time Period: 11/1/1995 **to** 10/1/2001

Consolidation Period: No Time Consolidation

Consolidation Type: Median

Duplicate Consolidation: Average

ND Values: Specified Detection Limit

J Flag Values : Actual Value

Well	Source/ Tail	Average Conc (mg/L)	Median Conc (mg/L)	Standard Deviation	All Samples "ND" ?	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
TRICHLOROETHYLENE (TCE)									
LX-17	S	6.0E-01	5.5E-01	2.2E-01	No	-1.1E-04	0.37	79.3%	S
LC-108	S	3.2E-02	1.4E-02	5.8E-02	No	-6.7E-04	1.81	95.3%	D
LX-21	S	1.1E-01	1.1E-01	3.4E-02	No	-1.4E-04	0.32	87.1%	S
LX-18	S	9.4E-01	8.4E-01	4.3E-01	No	-3.8E-04	0.46	99.6%	D
LC-64b	S	4.3E-02	4.5E-02	2.2E-02	No	-7.5E-04	0.51	100.0%	D
LC-64a	S	2.1E+00	4.2E-01	4.8E+00	No	7.6E-04	2.24	94.1%	PI
LC-162	S	4.7E-01	4.3E-01	2.9E-01	No	-8.3E-04	0.62	100.0%	D
LC-137c	S	1.2E-02	9.0E-03	1.4E-02	No	-3.2E-03	1.12	100.0%	D
LC-137b	S	1.6E-01	1.3E-01	9.0E-02	No	3.3E-04	0.56	94.5%	PI
LC-137a	S	1.6E-01	8.6E-02	1.5E-01	No	7.3E-04	0.92	99.5%	I
LC-136b	S	9.0E-02	8.8E-02	2.5E-02	No	-3.5E-05	0.28	64.6%	S
LC-136a	S	1.1E+02	8.3E+01	6.1E+01	No	8.2E-04	0.57	100.0%	I
LC-134	S	2.3E+00	2.0E+00	1.7E+00	No	-5.1E-04	0.74	97.8%	D
LX-19	S	1.2E-01	1.1E-01	3.1E-02	No	-6.7E-05	0.26	70.9%	S
LC-05	T	3.2E-02	3.0E-02	2.2E-02	No	6.6E-04	0.67	99.7%	I
LC-149c	T	1.0E-04	1.0E-04	2.1E-12	Yes	0.0E+00	0.00	100.0%	S
LC-19c	T	5.1E-02	4.9E-02	1.1E-02	No	-5.8E-05	0.22	64.4%	S
LC-19b	T	1.1E-01	9.4E-02	6.8E-02	No	-3.3E-04	0.62	83.9%	S
LC-19a	T	1.7E-01	1.7E-01	3.4E-02	No	-1.3E-04	0.21	75.8%	S
LC-165	T	1.3E-04	1.0E-04	1.1E-04	No	-2.1E-04	0.82	94.7%	PD
LC-14a	T	5.7E-02	5.8E-02	1.7E-02	No	-4.2E-05	0.30	66.3%	S
LC-149d	T	1.2E-04	1.0E-04	7.2E-05	No	-1.3E-06	0.60	100.0%	D
LC-144a	T	9.4E-02	9.4E-02	4.6E-02	No	-4.6E-04	0.49	77.7%	S
LC-132	T	7.3E-02	7.8E-02	2.5E-02	No	5.7E-04	0.34	100.0%	I
LC-128	T	2.2E-02	2.1E-02	9.6E-03	No	1.3E-04	0.45	87.7%	NT
LC-122b	T	1.2E-04	1.0E-04	8.5E-05	No	-2.4E-05	0.70	58.1%	S
LC-116b	T	2.2E-03	2.7E-04	4.4E-03	No	1.8E-03	1.99	100.0%	I
LC-41a	T	1.7E-01	1.7E-01	3.5E-02	No	5.6E-05	0.21	74.2%	NT
LC-06	T	5.9E-02	4.9E-02	4.1E-02	No	7.0E-04	0.69	99.7%	I
LC-44a	T	2.3E-02	2.0E-02	9.5E-03	No	1.6E-04	0.41	89.7%	NT
LC-03	T	1.5E-03	8.0E-04	3.6E-03	No	1.3E-03	2.39	100.0%	I
LC-111b	T	2.2E-04	1.0E-04	2.9E-04	No	-3.7E-04	1.36	94.2%	PD
PA-381	T	3.8E-02	3.6E-02	1.2E-02	No	1.2E-04	0.31	88.5%	NT
LC-26	T	2.3E-03	1.0E-04	9.8E-03	No	6.7E-04	4.26	93.0%	PI
LX-4	T	6.2E-02	5.8E-02	1.4E-02	No	-2.1E-04	0.23	99.6%	D
LX-5	T	9.6E-02	9.8E-02	2.1E-02	No	-2.4E-04	0.22	99.9%	D
LX-6	T	1.0E-01	9.5E-02	2.1E-02	No	-2.3E-04	0.21	99.9%	D
LX-7	T	8.0E-02	8.3E-02	1.7E-02	No	-9.3E-05	0.21	85.4%	S
LX-2	T	1.4E-02	1.4E-02	3.9E-03	No	-2.9E-04	0.28	99.8%	D

Project: Fort Lewis Upper Aquifer **User Name:** Julia Aziz

Location: Pierce County **State:** Washington

Well	Source/ Tail	Average Conc (mg/L)	Median Conc (mg/L)	Standard Deviation	All Samples "ND" ?	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
TRICHLOROETHYLENE (TCE)									
LX-9	T	6.6E-02	6.8E-02	1.2E-02	No	-1.2E-04	0.19	90.6%	PD
LX-16	T	1.6E-01	1.6E-01	2.4E-02	No	-1.5E-04	0.15	98.7%	D
PA-383	T	1.2E-03	1.3E-03	4.8E-04	No	-9.0E-05	0.38	72.3%	S
RW-1	T	1.7E-01	1.6E-01	2.3E-02	No	-6.8E-05	0.14	83.1%	S
T-01	T	1.9E-03	1.8E-03	6.1E-04	No	-1.9E-04	0.31	90.3%	PD
T-04	T	8.2E-03	8.3E-03	3.8E-03	No	2.2E-04	0.47	87.1%	NT
T-08	T	2.5E-03	2.4E-03	5.4E-04	No	9.1E-05	0.21	91.6%	PI
T-12b	T	6.4E-04	1.0E-04	1.5E-03	No	-3.5E-03	2.38	93.3%	PD
LX-8	T	7.5E-02	7.4E-02	9.2E-03	No	4.5E-05	0.12	80.8%	NT
LX-1	T	1.0E-02	1.0E-02	2.7E-03	No	-1.4E-04	0.27	89.5%	S
LC-49	T	2.2E-01	2.4E-01	5.7E-02	No	1.6E-04	0.25	93.6%	PI
LC-49a	T	8.5E-02	8.6E-02	2.8E-02	No	3.1E-04	0.33	80.7%	NT
LC-51	T	1.4E-01	1.5E-01	2.9E-02	No	1.1E-04	0.20	93.7%	PI
LC-53	T	1.7E-01	1.7E-01	4.2E-02	No	1.5E-04	0.25	96.7%	I
LC-66a	T	9.1E-02	9.6E-02	2.6E-02	No	2.3E-05	0.29	57.6%	NT
LX-3	T	2.8E-02	2.8E-02	6.8E-03	No	-3.2E-04	0.24	100.0%	D
LC-73a	T	7.0E-04	7.0E-04	3.0E-04	No	3.0E-04	0.42	98.4%	I
T-13b	T	4.6E-03	4.5E-03	6.6E-04	No	1.8E-05	0.14	64.9%	NT
LX-10	T	6.3E-02	6.3E-02	1.7E-02	No	-1.7E-04	0.27	95.4%	D
LX-11	T	3.8E-02	4.0E-02	1.3E-02	No	-3.8E-04	0.34	99.6%	D
LX-12	T	2.4E-02	2.4E-02	7.0E-03	No	-2.8E-04	0.29	99.1%	D
LX-13	T	5.0E-03	5.3E-03	1.3E-03	No	2.1E-04	0.27	95.3%	I
LX-14	T	5.8E-03	5.8E-03	1.5E-03	No	-2.9E-05	0.25	60.3%	S
LX-15	T	3.1E-03	3.0E-03	8.8E-04	No	9.3E-05	0.29	77.8%	NT
LC-66b	T	1.3E-01	1.2E-01	7.8E-02	No	6.0E-05	0.59	68.4%	NT

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); COV = Coefficient of Variation

MAROS Statistical Trend Analysis Summary

Project: Fort Lewis Upper Aquifer

User Name: Julia Aziz

Location: Pierce County

State: Washington

Time Period: 11/1/1995 **to** 10/1/2001

Consolidation Period: No Time Consolidation

Consolidation Type: Median

Duplicate Consolidation: Average

ND Values: Specified Detection Limit

J Flag Values : Actual Value

Well	Source/ Tail	Number of Samples	Number of Detects	Average Conc. (mg/L)	Median Conc. (mg/L)	All Samples "ND" ?	Mann-Kendall Trend	Linear Regression Trend
TRICHLOROETHYLENE (TCE)								
LC-03	T	23	22	1.5E-03	8.0E-04	No	I	I
LC-05	T	24	24	3.2E-02	3.0E-02	No	I	I
LC-06	T	24	24	5.9E-02	4.9E-02	No	I	I
LC-108	S	24	24	3.2E-02	1.4E-02	No	PD	D
LC-111b	T	23	8	2.2E-04	1.0E-04	No	PD	PD
LC-116b	T	24	20	2.2E-03	2.7E-04	No	I	I
LC-122b	T	23	2	1.2E-04	1.0E-04	No	S	S
LC-128	T	24	24	2.2E-02	2.1E-02	No	PI	NT
LC-132	T	24	24	7.3E-02	7.8E-02	No	I	I
LC-134	S	20	20	2.3E+00	2.0E+00	No	D	D
LC-136a	S	24	24	1.1E+02	8.3E+01	No	I	I
LC-136b	S	23	23	9.0E-02	8.8E-02	No	NT	S
LC-137a	S	24	24	1.6E-01	8.6E-02	No	I	I
LC-137b	S	24	24	1.6E-01	1.3E-01	No	PI	PI
LC-137c	S	24	19	1.2E-02	9.0E-03	No	D	D
LC-144a	T	11	11	9.4E-02	9.4E-02	No	S	S
LC-149c	T	24	0	1.0E-04	1.0E-04	Yes	S	S
LC-149d	T	24	2	1.2E-04	1.0E-04	No	S	D
LC-14a	T	24	24	5.7E-02	5.8E-02	No	PD	S
LC-162	S	20	20	4.7E-01	4.3E-01	No	D	D
LC-165	T	23	4	1.3E-04	1.0E-04	No	S	PD
LC-19a	T	14	14	1.7E-01	1.7E-01	No	S	S
LC-19b	T	14	14	1.1E-01	9.4E-02	No	S	S
LC-19c	T	14	14	5.1E-02	4.9E-02	No	S	S
LC-26	T	23	11	2.3E-03	1.0E-04	No	NT	PI
LC-41a	T	24	24	1.7E-01	1.7E-01	No	NT	NT
LC-44a	T	24	24	2.3E-02	2.0E-02	No	NT	NT
LC-49	T	24	24	2.2E-01	2.4E-01	No	PI	PI
LC-49a	T	12	12	8.5E-02	8.6E-02	No	NT	NT
LC-51	T	24	24	1.4E-01	1.5E-01	No	I	PI
LC-53	T	24	24	1.7E-01	1.7E-01	No	I	I
LC-64a	S	24	24	2.1E+00	4.2E-01	No	NT	PI
LC-64b	S	24	24	4.3E-02	4.5E-02	No	D	D
LC-66a	T	24	24	9.1E-02	9.6E-02	No	S	NT
LC-66b	T	24	24	1.3E-01	1.2E-01	No	S	NT

MAROS Statistical Trend Analysis Summary

Well	Source/ Tail	Number of Samples	Number of Detects	Average Conc. (mg/L)	Median Conc. (mg/L)	All Samples "ND" ?	Mann-Kendall Trend	Linear Regression Trend
TRICHLOROETHYLENE (TCE)								
LC-73a	T	23	23	7.0E-04	7.0E-04	No	I	I
LX-1	T	20	20	1.0E-02	1.0E-02	No	PD	S
LX-10	T	20	20	6.3E-02	6.3E-02	No	S	D
LX-11	T	20	20	3.8E-02	4.0E-02	No	D	D
LX-12	T	20	20	2.4E-02	2.4E-02	No	D	D
LX-13	T	15	15	5.0E-03	5.3E-03	No	PI	I
LX-14	T	20	20	5.8E-03	5.8E-03	No	S	S
LX-15	T	20	20	3.1E-03	3.0E-03	No	NT	NT
LX-16	T	8	8	1.6E-01	1.6E-01	No	D	D
LX-17	S	19	19	6.0E-01	5.5E-01	No	S	S
LX-18	S	20	20	9.4E-01	8.4E-01	No	D	D
LX-19	S	18	18	1.2E-01	1.1E-01	No	S	S
LX-2	T	20	20	1.4E-02	1.4E-02	No	D	D
LX-21	S	20	20	1.1E-01	1.1E-01	No	D	S
LX-3	T	20	20	2.8E-02	2.8E-02	No	D	D
LX-4	T	18	18	6.2E-02	5.8E-02	No	D	D
LX-5	T	19	19	9.6E-02	9.8E-02	No	D	D
LX-6	T	20	20	1.0E-01	9.5E-02	No	D	D
LX-7	T	20	20	8.0E-02	8.3E-02	No	S	S
LX-8	T	18	18	7.5E-02	7.4E-02	No	NT	NT
LX-9	T	19	19	6.6E-02	6.8E-02	No	D	PD
PA-381	T	24	24	3.8E-02	3.6E-02	No	PI	NT
PA-383	T	24	24	1.2E-03	1.3E-03	No	S	S
RW-1	T	8	8	1.7E-01	1.6E-01	No	S	S
T-01	T	16	16	1.9E-03	1.8E-03	No	S	PD
T-04	T	24	24	8.2E-03	8.3E-03	No	NT	NT
T-08	T	24	24	2.5E-03	2.4E-03	No	NT	PI
T-12b	T	8	1	6.4E-04	1.0E-04	No	NT	PD
T-13b	T	23	23	4.6E-03	4.5E-03	No	NT	NT

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); No Detectable Concentration (NDC)

The Number of Samples and Number of Detects shown above are post-consolidation values.

MAROS Zeroth Moment Analysis

Project: Fort Lewis Upper Aquifer

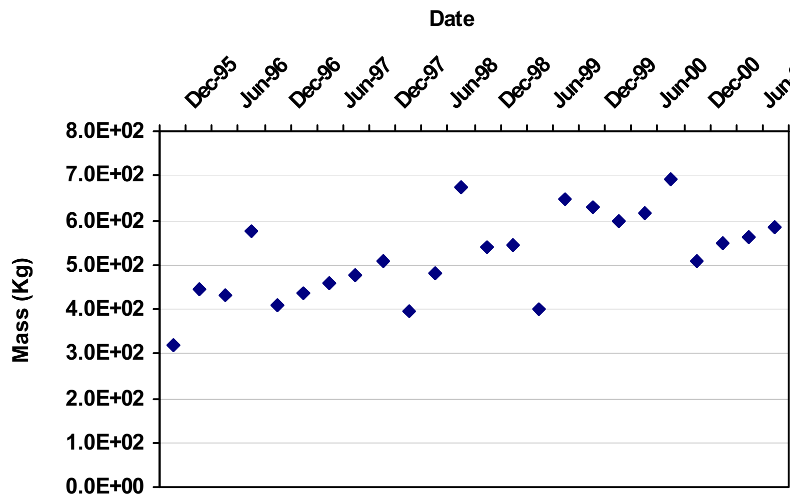
User Name: Julia Aziz

Location: Pierce County

State: Washington

COC: TRICHLOROETHYLENE (TCE)

Change in Dissolved Mass Over Time



Porosity: 0.25

Saturated Thickness:

Uniform: 60 ft

Mann Kendall S Statistic:

128

Confidence in Trend:

99.9%

Coefficient of Variation:

0.19

Zeroth Moment Trend:

I

Data Table:

Effective Date	Constituent	Estimated Mass (Kg)	Number of Wells
12/1/1995	TRICHLOROETHYLENE (TCE)	3.2E+02	35
3/1/1996	TRICHLOROETHYLENE (TCE)	4.4E+02	35
6/1/1996	TRICHLOROETHYLENE (TCE)	4.3E+02	35
9/1/1996	TRICHLOROETHYLENE (TCE)	5.7E+02	35
12/1/1996	TRICHLOROETHYLENE (TCE)	4.1E+02	34
3/1/1997	TRICHLOROETHYLENE (TCE)	4.4E+02	35
6/1/1997	TRICHLOROETHYLENE (TCE)	4.6E+02	35
9/1/1997	TRICHLOROETHYLENE (TCE)	4.8E+02	35
12/1/1997	TRICHLOROETHYLENE (TCE)	5.1E+02	35
3/1/1998	TRICHLOROETHYLENE (TCE)	4.0E+02	35
6/1/1998	TRICHLOROETHYLENE (TCE)	4.8E+02	36
9/1/1998	TRICHLOROETHYLENE (TCE)	6.8E+02	35
12/1/1998	TRICHLOROETHYLENE (TCE)	5.4E+02	27
3/1/1999	TRICHLOROETHYLENE (TCE)	5.4E+02	34
6/1/1999	TRICHLOROETHYLENE (TCE)	4.0E+02	34
9/1/1999	TRICHLOROETHYLENE (TCE)	6.5E+02	34
12/1/1999	TRICHLOROETHYLENE (TCE)	6.3E+02	34
3/1/2000	TRICHLOROETHYLENE (TCE)	6.0E+02	34
6/1/2000	TRICHLOROETHYLENE (TCE)	6.1E+02	34
9/1/2000	TRICHLOROETHYLENE (TCE)	6.9E+02	34
12/1/2000	TRICHLOROETHYLENE (TCE)	5.1E+02	32
3/1/2001	TRICHLOROETHYLENE (TCE)	5.5E+02	32

MAROS Zeroth Moment Analysis

Effective Date	Constituent	Estimated Mass (Kg)	Number of Wells
6/1/2001	TRICHLOROETHYLENE (TCE)	5.6E+02	32
9/1/2001	TRICHLOROETHYLENE (TCE)	5.8E+02	32

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); ND = Non-detect. Moments are not calculated for sample events with less than 6 wells.

MAROS First Moment Analysis

Project: Fort Lewis Upper Aquifer

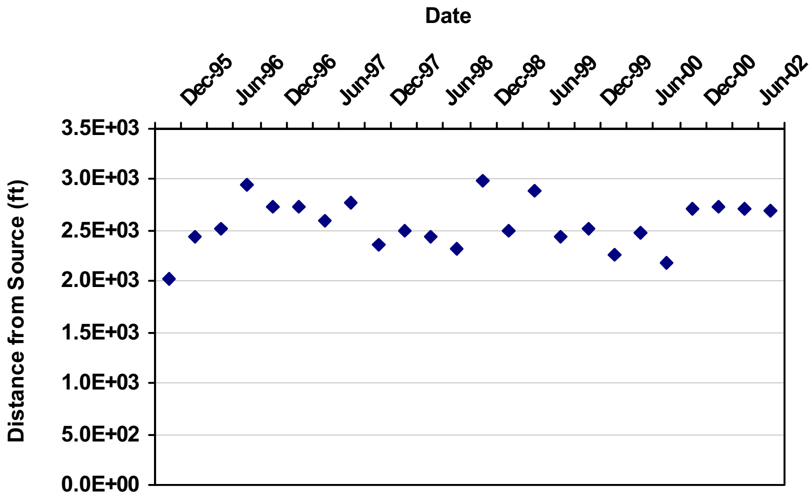
User Name: Julia Aziz

Location: Pierce County

State: Washington

COC: TRICHLOROETHYLENE (TCE)

Distance from Source to Center of Mass



Mann Kendall S Statistic: -2

Confidence in Trend: 51.0%

Coefficient of Variation: 0.09

First Moment Trend: S

Data Table:

Effective Date	Constituent	Xc (ft)	Yc (ft)	Distance from Source (ft)	Number of Wells
12/1/1995	TRICHLOROETHYLENE (TCE)	1,494,603	653,396	2,031	35
3/1/1996	TRICHLOROETHYLENE (TCE)	1,494,202	653,479	2,436	35
6/1/1996	TRICHLOROETHYLENE (TCE)	1,494,121	653,510	2,522	35
9/1/1996	TRICHLOROETHYLENE (TCE)	1,493,859	653,957	2,941	35
12/1/1996	TRICHLOROETHYLENE (TCE)	1,493,930	653,609	2,736	34
3/1/1997	TRICHLOROETHYLENE (TCE)	1,493,916	653,576	2,737	35
6/1/1997	TRICHLOROETHYLENE (TCE)	1,494,099	653,667	2,601	35
9/1/1997	TRICHLOROETHYLENE (TCE)	1,493,962	653,760	2,764	35
12/1/1997	TRICHLOROETHYLENE (TCE)	1,494,275	653,457	2,359	35
3/1/1998	TRICHLOROETHYLENE (TCE)	1,494,159	653,539	2,496	35
6/1/1998	TRICHLOROETHYLENE (TCE)	1,494,203	653,477	2,434	36
9/1/1998	TRICHLOROETHYLENE (TCE)	1,494,410	653,674	2,322	35
12/1/1998	TRICHLOROETHYLENE (TCE)	1,493,883	654,112	2,993	27
3/1/1999	TRICHLOROETHYLENE (TCE)	1,494,115	653,399	2,492	34
6/1/1999	TRICHLOROETHYLENE (TCE)	1,493,885	653,910	2,897	34
9/1/1999	TRICHLOROETHYLENE (TCE)	1,494,269	653,633	2,432	34
12/1/1999	TRICHLOROETHYLENE (TCE)	1,494,208	653,700	2,515	34
3/1/2000	TRICHLOROETHYLENE (TCE)	1,494,370	653,452	2,269	34
6/1/2000	TRICHLOROETHYLENE (TCE)	1,494,268	653,750	2,482	34
9/1/2000	TRICHLOROETHYLENE (TCE)	1,494,517	653,565	2,178	34
12/1/2000	TRICHLOROETHYLENE (TCE)	1,494,002	653,738	2,719	32
3/1/2001	TRICHLOROETHYLENE (TCE)	1,494,049	653,892	2,742	32
6/1/2001	TRICHLOROETHYLENE (TCE)	1,494,089	653,903	2,712	32

MAROS First Moment Analysis

Effective Date	Constituent	Xc (ft)	Yc (ft)	Distance from Source (ft)	Number of Wells
9/1/2001	TRICHLOROETHYLENE (TCE)	1,494,069	653,844	2,703	32

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events). Moments are not calculated for sample events with less than 6 wells.

MAROS First Moment Analysis

Project: Fort Lewis Upper Aquifer

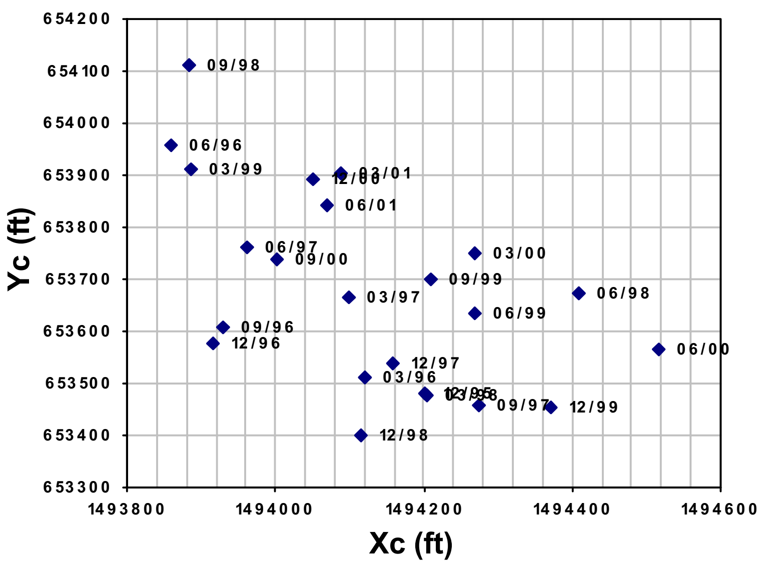
User Name: Julia Aziz

Location: Pierce County

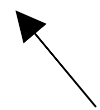
State: Washington

COC: TRICHLOROETHYLENE (TCE)

Change in Location of Center of Mass Over Time



Groundwater Flow Direction:



Source Coordinate:

X: 1,496,486

Y: 652,634

Effective Date	Constituent	Xc (ft)	Yc (ft)	Distance from Source (ft)	Number of Wells
12/1/1995	TRICHLOROETHYLENE (TCE)	1,494,603	653,396	2,031	35
3/1/1996	TRICHLOROETHYLENE (TCE)	1,494,202	653,479	2,436	35
6/1/1996	TRICHLOROETHYLENE (TCE)	1,494,121	653,510	2,522	35
9/1/1996	TRICHLOROETHYLENE (TCE)	1,493,859	653,957	2,941	35
12/1/1996	TRICHLOROETHYLENE (TCE)	1,493,930	653,609	2,736	34
3/1/1997	TRICHLOROETHYLENE (TCE)	1,493,916	653,576	2,737	35
6/1/1997	TRICHLOROETHYLENE (TCE)	1,494,099	653,667	2,601	35
9/1/1997	TRICHLOROETHYLENE (TCE)	1,493,962	653,760	2,764	35
12/1/1997	TRICHLOROETHYLENE (TCE)	1,494,275	653,457	2,359	35
3/1/1998	TRICHLOROETHYLENE (TCE)	1,494,159	653,539	2,496	35
6/1/1998	TRICHLOROETHYLENE (TCE)	1,494,203	653,477	2,434	36
9/1/1998	TRICHLOROETHYLENE (TCE)	1,494,410	653,674	2,322	35
12/1/1998	TRICHLOROETHYLENE (TCE)	1,493,883	654,112	2,993	27
3/1/1999	TRICHLOROETHYLENE (TCE)	1,494,115	653,399	2,492	34
6/1/1999	TRICHLOROETHYLENE (TCE)	1,493,885	653,910	2,897	34
9/1/1999	TRICHLOROETHYLENE (TCE)	1,494,269	653,633	2,432	34
12/1/1999	TRICHLOROETHYLENE (TCE)	1,494,208	653,700	2,515	34
3/1/2000	TRICHLOROETHYLENE (TCE)	1,494,370	653,452	2,269	34
6/1/2000	TRICHLOROETHYLENE (TCE)	1,494,268	653,750	2,482	34
9/1/2000	TRICHLOROETHYLENE (TCE)	1,494,517	653,565	2,178	34
12/1/2000	TRICHLOROETHYLENE (TCE)	1,494,002	653,738	2,719	32
3/1/2001	TRICHLOROETHYLENE (TCE)	1,494,049	653,892	2,742	32
6/1/2001	TRICHLOROETHYLENE (TCE)	1,494,089	653,903	2,712	32
9/1/2001	TRICHLOROETHYLENE (TCE)	1,494,069	653,844	2,703	32

MAROS First Moment Analysis

Effective Date	Constituent	Xc (ft)	Yc (ft)	Distance from Source (ft)	Number of Wells

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events). Moments are not calculated for sample events with less than 6 wells.

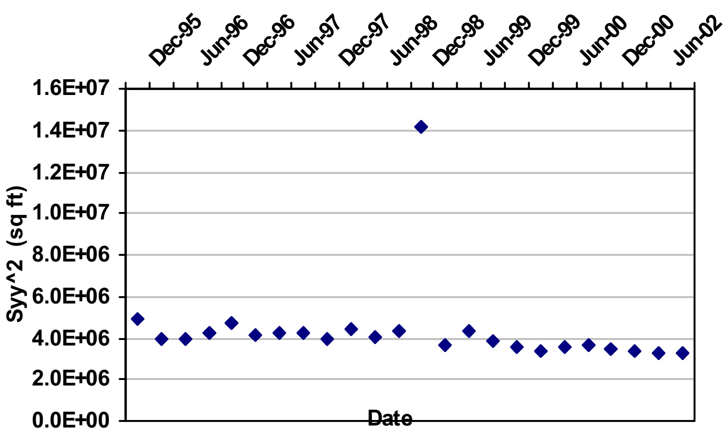
MAROS Second Moment Analysis

Project: Fort Lewis Upper Aquifer **User Name:** Julia Aziz

Location: Pierce County **State:** Washington

COC: TRICHLOROETHYLENE (TCE)

Change in Plume Spread Over Time

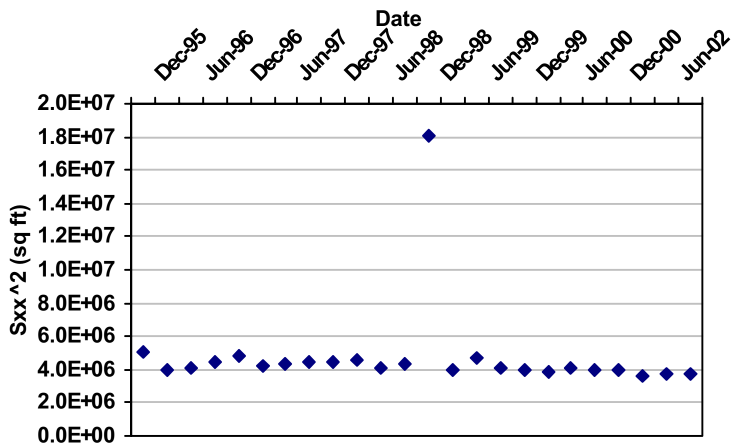


Mann Kendall S Statistic: -146

Confidence in Trend: 100.0%

Coefficient of Variation: 0.49

Second Moment Trend: D



Mann Kendall S Statistic: -134

Confidence in Trend: 100.0%

Coefficient of Variation: 0.60

Second Moment Trend: D

Data Table:

Effective Date	Constituent	Sigma XX (sq ft)	Sigma YY (sq ft)	Number of Wells
12/1/1995	TRICHLOROETHYLENE (TCE)	5,012,168	4,898,123	35
3/1/1996	TRICHLOROETHYLENE (TCE)	3,998,297	3,918,813	35
6/1/1996	TRICHLOROETHYLENE (TCE)	4,143,839	3,999,799	35
9/1/1996	TRICHLOROETHYLENE (TCE)	4,433,515	4,219,867	35
12/1/1996	TRICHLOROETHYLENE (TCE)	4,802,967	4,688,850	34
3/1/1997	TRICHLOROETHYLENE (TCE)	4,252,709	4,187,670	35
6/1/1997	TRICHLOROETHYLENE (TCE)	4,299,841	4,196,466	35
9/1/1997	TRICHLOROETHYLENE (TCE)	4,496,534	4,271,155	35
12/1/1997	TRICHLOROETHYLENE (TCE)	4,423,644	3,966,113	35
3/1/1998	TRICHLOROETHYLENE (TCE)	4,635,910	4,388,878	35
6/1/1998	TRICHLOROETHYLENE (TCE)	4,125,427	4,095,919	36
9/1/1998	TRICHLOROETHYLENE (TCE)	4,360,842	4,323,315	35

MAROS Second Moment Analysis

Effective Date	Constituent	Sigma XX (sq ft)	Sigma YY (sq ft)	Number of Wells
12/1/1998	TRICHLOROETHYLENE (TCE)	18,123,344	14,198,215	27
3/1/1999	TRICHLOROETHYLENE (TCE)	3,944,965	3,637,538	34
6/1/1999	TRICHLOROETHYLENE (TCE)	4,691,727	4,316,807	34
9/1/1999	TRICHLOROETHYLENE (TCE)	4,143,586	3,888,306	34
12/1/1999	TRICHLOROETHYLENE (TCE)	3,920,347	3,548,080	34
3/1/2000	TRICHLOROETHYLENE (TCE)	3,837,803	3,394,424	34
6/1/2000	TRICHLOROETHYLENE (TCE)	4,118,134	3,606,414	34
9/1/2000	TRICHLOROETHYLENE (TCE)	4,031,575	3,675,232	34
12/1/2000	TRICHLOROETHYLENE (TCE)	3,930,191	3,512,792	32
3/1/2001	TRICHLOROETHYLENE (TCE)	3,655,290	3,356,920	32
6/1/2001	TRICHLOROETHYLENE (TCE)	3,740,729	3,297,856	32
9/1/2001	TRICHLOROETHYLENE (TCE)	3,739,485	3,318,478	32

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events)

The Sigma XX and Sigma YY components are estimated using the given field coordinate system and then rotated to align with the estimated groundwater flow direction. Moments are not calculated for sample events with less than 6 wells.

MAROS Spatial Moment Analysis Summary

Project: Fort Lewis Upper Aquifer

Location: Pierce County

User Name: Julia Aziz

State: Washington

	0th Moment	1st Moment (Center of Mass)			2nd Moment (Spread)		
Effective Date	**Estimated Mass (Kg)**	**Xc (ft)**	**Yc (ft)**	**Source Distance (ft)**	**Sigma XX (sq ft)**	**Sigma YY (sq ft)**	**Number of Wells**
TRICHLOROETHYLENE (TCE)							
12/1/1995	3.2E+02	1,494,603	653,396	2,031	5,012,168	4,898,123	35
3/1/1996	4.4E+02	1,494,202	653,479	2,436	3,998,297	3,918,813	35
6/1/1996	4.3E+02	1,494,121	653,510	2,522	4,143,839	3,999,799	35
9/1/1996	5.7E+02	1,493,859	653,957	2,941	4,433,515	4,219,867	35
12/1/1996	4.1E+02	1,493,930	653,609	2,736	4,802,967	4,688,850	34
3/1/1997	4.4E+02	1,493,916	653,576	2,737	4,252,709	4,187,670	35
6/1/1997	4.6E+02	1,494,099	653,667	2,601	4,299,841	4,196,466	35
9/1/1997	4.8E+02	1,493,962	653,760	2,764	4,496,534	4,271,155	35
12/1/1997	5.1E+02	1,494,275	653,457	2,359	4,423,644	3,966,113	35
3/1/1998	4.0E+02	1,494,159	653,539	2,496	4,635,910	4,388,878	35
6/1/1998	4.8E+02	1,494,203	653,477	2,434	4,125,427	4,095,919	36
9/1/1998	6.8E+02	1,494,410	653,674	2,322	4,360,842	4,323,315	35
12/1/1998	5.4E+02	1,493,883	654,112	2,993	18,123,344	14,198,215	27
3/1/1999	5.4E+02	1,494,115	653,399	2,492	3,944,965	3,637,538	34
6/1/1999	4.0E+02	1,493,885	653,910	2,897	4,691,727	4,316,807	34
9/1/1999	6.5E+02	1,494,269	653,633	2,432	4,143,586	3,888,306	34
12/1/1999	6.3E+02	1,494,208	653,700	2,515	3,920,347	3,548,080	34
3/1/2000	6.0E+02	1,494,370	653,452	2,269	3,837,803	3,394,424	34
6/1/2000	6.1E+02	1,494,268	653,750	2,482	4,118,134	3,606,414	34
9/1/2000	6.9E+02	1,494,517	653,565	2,178	4,031,575	3,675,232	34
12/1/2000	5.1E+02	1,494,002	653,738	2,719	3,930,191	3,512,792	32
3/1/2001	5.5E+02	1,494,049	653,892	2,742	3,655,290	3,356,920	32
6/1/2001	5.6E+02	1,494,089	653,903	2,712	3,740,729	3,297,856	32
9/1/2001	5.8E+02	1,494,069	653,844	2,703	3,739,485	3,318,478	32

Project: Fort Lewis Upper Aquifer

Location: Pierce County

User Name: Julia Aziz

State: Washington

Moment Type	Consituent	Coefficient of Variation	Mann-Kendall S Statistic	Confidence in Trend	Moment Trend
Zeroth Moment: Mass					
	TRICHLOROETHYLENE (TCE)	0.19	128	99.9%	I
1st Moment: Distance to Source					
	TRICHLOROETHYLENE (TCE)	0.09	-2	51.0%	S
2nd Moment: Sigma XX					
	TRICHLOROETHYLENE (TCE)	0.60	-134	100.0%	D
2nd Moment: Sigma YY					
	TRICHLOROETHYLENE (TCE)	0.49	-146	100.0%	D

Note: The following assumptions were applied for the calculation of the Zeroth Moment:

Porosity: 0.25 **Saturated Thickness:** Uniform: 60 ft

Mann-Kendall Trend test performed on all sample events for each constituent. Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)-Due to insufficient Data (< 4 sampling events).

Note: The Sigma XX and Sigma YY components are estimated using the given field coordinate system and then rotated to align with the estimated groundwater flow direction. Moments are not calculated for sample events with less than 6 wells.

MAROS Site Results

Project: Fort Lewis Upper Aquifer
User Name: Julia Aziz
Location: Pierce County
State: Washington

User Defined Site and Data Assumptions:

Hydrogeology and Plume Information:

Groundwater Seepage Velocity: 547.5 ft/yr
Current Plume Length: 10000 ft
Current Plume Width 4000 ft
Number of Tail Wells: 108
Number of Source Wells: 8

Source Information:

Source Treatment: No Current Site Treatment

NAPL is not observed at this site.

Down-gradient Information:

Distance from Edge of Tail to Nearest:
Down-gradient receptor: 1000 ft
Down-gradient property: 200 ft

Distance from Source to Nearest:
Down-gradient receptor: 10000 ft
Down-gradient property: 1000 ft

Data Consolidation Assumptions:

Time Period: 11/1/1995 **to** 10/1/2001
Consolidation Period: No Time Consolidation
Consolidation Type: Geometric Mean
Duplicate Consolidation: Average
ND Values: Specified Detection Limit
J Flag Values : Actual Value

Plume Information Weighting Assumptions:

Consolidation Step 1. Weight Plume Information by Chemical
Summary Weighting: Weighting Applied to All Chemicals Equally

Consolidation Step 2. Weight Well Information by Chemical
Well Weighting: No Weighting of Wells was Applied.
Chemical Weighting: No Weighting of Chemicals was Applied.

Note: These assumptions were made when consolidating the historical montoring data and lumping the Wells and COCs.

1. Compliance Monitoring/Remediation Optimization Results:

Preliminary Monitoring System Optimization Results: Based on site classification, source treatment and Monitoring System Category the following suggestions are made for site Sampling Frequency, Duration of Sampling, and Well Density. These criteria take into consideration: Plume Stability, Type of Plume, and Groundwater Velocity.

COC	Tail Stability	Source Stability	Level of Effort	Sampling Duration	Sampling Frequency	Sampling Density
TRICHLOROETHYLENE (TCE)	NT	S	M	Sample 4 more years	Biannually (6 months)	> 50

Note:

Plume Status: (I) Increasing; (PI)Probably Increasing; (S) Stable; (NT) No Trend; (PD) Probably Decreasing; (D) Decreasing

Design Categories: (E) Extensive; (M) Moderate; (L) Limited (N/A) Not Applicable, Insufficient Data Available

Level of Monitoring Effort Indicated by Analysi Moderate

2. Spatial Moment Analysis Results:

Moment Type	Consituent	Coefficient of Variation	Mann-Kendall S Statistic	Confidence in Trend	Moment Trend
Zeroth Moment: Mass					
	TRICHLOROETHYLENE (TCE)	0.19	128	99.9%	I
1st Moment: Distance to Source					
	TRICHLOROETHYLENE (TCE)	0.09	-2	51.0%	S
2nd Moment: Sigma XX					
	TRICHLOROETHYLENE (TCE)	0.60	-134	100.0%	D
2nd Moment: Sigma YY					
	TRICHLOROETHYLENE (TCE)	0.49	-146	100.0%	D

Note: The following assumptions were applied for the calculation of the Zeroth Moment:

Porosity: 0.25 **Saturated Thickness:** Uniform: 60 ft

Mann-Kendall Trend test performed on all sample events for each constituent. Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)-Due to insufficient Data (< 4 sampling events).

MAROS Sampling Frequency Optimization Results

Project: Fort Lewis **User Name:** Meng

Location: Seattle **State:** Washington

The Overall Number of Sampling Events: 24

"Recent Period" defined by evetns: **From** 4th Quarter 1999 12/1/1999 **To** 3rd Quarter 2001 9/1/2001

Well	Recommended Sampling Frequency	Frequency Based on Recent Data	Frequency Based on Overall Data
TRICHLOROETHYLENE (TCE)			
LC-03	Annual	Annual	Annual
LC-05	Quarterly	Quarterly	SemiAnnual
LC-06	Quarterly	Annual	Quarterly
LC-108	Annual	Annual	Annual
LC-111b	Biennial	Annual	Annual
LC-116b	SemiAnnual	SemiAnnual	Annual
LC-122b	Biennial	Annual	Annual
LC-128	Annual	Annual	Annual
LC-132	Quarterly	Annual	Quarterly
LC-134	Quarterly	Quarterly	Annual
LC-136a	Quarterly	Quarterly	Quarterly
LC-136b	Quarterly	Quarterly	Annual
LC-137a	Quarterly	Quarterly	Quarterly
LC-137b	Quarterly	Quarterly	Quarterly
LC-137c	Annual	Annual	Annual
LC-149c	Biennial	Annual	Annual
LC-149d	Biennial	Annual	Annual
LC-14a	Annual	Annual	Annual
LC-162	Quarterly	Quarterly	Annual
LC-165	Biennial	Annual	Annual
LC-19a	Annual	Annual	Annual
LC-19b	Quarterly	Quarterly	Annual
LC-19c	SemiAnnual	SemiAnnual	Annual
LC-26	Annual	Annual	Annual
LC-41a	Quarterly	Quarterly	Annual
LC-44a	Annual	Annual	Annual
LC-49	SemiAnnual	SemiAnnual	SemiAnnual
LC-51	Quarterly	Quarterly	SemiAnnual
LC-53	Quarterly	SemiAnnual	Quarterly
LC-64a	Quarterly	Quarterly	Quarterly

Project: Fort Lewis **User Name:** Meng

Location: Seattle **State:** Washington

Well	Recommended Sampling Frequency	Frequency Based on Recent Data	Frequency Based on Overall Data
LC-64b	Annual	Annual	Annual
LC-66a	Annual	Annual	Annual
LC-66b	Annual	Annual	Annual
LC-73a	Biennial	Annual	Annual
LX-1	Annual	Annual	Annual
LX-10	Annual	Annual	Annual
LX-11	Annual	Annual	Annual
LX-12	Annual	Annual	Annual
LX-13	Annual	Annual	Annual
LX-14	Annual	Annual	Annual
LX-15	Annual	Annual	Annual
LX-16	Quarterly	Quarterly	Quarterly
LX-17	Quarterly	Quarterly	Annual
LX-18	Quarterly	Quarterly	Annual
LX-19	Quarterly	Quarterly	Annual
LX-2	Annual	Annual	Annual
LX-21	Annual	Annual	Annual
LX-3	Annual	Annual	Annual
LX-4	Annual	Annual	Annual
LX-5	Annual	Annual	Annual
LX-6	Annual	Annual	Annual
LX-7	Annual	Annual	Annual
LX-8	Annual	Annual	Annual
LX-9	Annual	Annual	Annual
PA-381	Annual	Annual	Annual
PA-383	Biennial	Annual	Annual
RW-1	Quarterly	Quarterly	Quarterly
T-04	Annual	Annual	Annual
T-08	Annual	Annual	Annual
T-12b	Annual	Annual	Annual
T-13b	Annual	Annual	Annual

Note: Sampling frequency is determined considering both recent and overall concentration trends. Sampling Frequency is the final recommendation; Frequency Based on Recent Data is the frequency determined using recent (short) period of monitoring data; Frequency Based on Overall Data is the frequency determined using overall (long) period of monitoring data. If the "recent period" is defined using a different series of sampling events, the results could be different.

MAROS Sampling Location Optimization Results

Project: Fort Lewis

User Name: Meng

Location: Seattle

State: Washington

Sampling Events Analyzed: **From** 4th Quarter 1999 12/1/1999 **to** 3rd Quarter 2001 9/1/2001

Well	X (feet)	Y (feet)	Removable?	Average Slope Factor*	Minimum Slope Factor*	Maximum Slope Factor*	Eliminated?
TRICHLOROETHYLENE (TCE)							
LC-03	1493904.00	657303.00	☑	0.255	0.113	0.365	☐
LC-05	1490857.00	657293.00	☑	0.357	0.277	0.463	☐
LC-06	1493994.00	655896.00	☑	0.083	0.038	0.148	☑
LC-108	1496486.63	652634.44	☑	0.263	0.101	0.453	☐
LC-111b	1490017.75	657038.50	☑	0.682	0.634	0.709	☐
LC-116b	1490585.63	657662.75	☑	0.254	0.000	0.617	☐
LC-122b	1491418.00	658353.44	☑	0.666	0.623	0.688	☐
LC-128	1490373.75	658841.19	☑	0.372	0.288	0.451	☐
LC-132	1491411.00	657023.69	☑	0.233	0.213	0.259	☐
LC-136b	1496354.88	652485.88	☑	0.073	0.000	0.169	☑
LC-137b	1496179.63	652691.44	☑	0.144	0.060	0.210	☐
LC-149c	1498352.88	651059.25	☑	0.539	0.440	0.728	☐
LC-14a	1489560.00	658337.00	☑	0.338	0.277	0.412	☐
LC-165	1491769.63	659713.06	☑	0.426	0.380	0.569	☐
LC-19a	1495139.00	653095.00	☑	0.024	0.004	0.076	☑
LC-26	1497563.00	651895.00	☑	0.567	0.320	0.717	☐
LC-41a	1491874.50	655151.06	☑	0.142	0.075	0.175	☑
LC-44a	1493248.00	656872.00	☑	0.102	0.011	0.158	☑
LC-49	1493877.00	654135.00	☑	0.116	0.099	0.172	☑
LC-51	1495357.00	651777.00	☑	0.076	0.009	0.134	☑
LC-53	1494335.00	651926.00	☑	0.090	0.021	0.129	☐
LC-64a	1496588.25	652433.13	☑	0.310	0.115	0.475	☐
LC-66b	1492172.00	656883.00	☑	0.179	0.160	0.215	☐
LC-73a	1488270.38	656103.75	☑	0.235	0.177	0.273	☐
PA-381	1490584.00	655045.00	☑	0.248	0.203	0.282	☐
PA-383	1490422.00	654112.00	☑	0.478	0.439	0.517	☐
T-04	1489309.00	660114.00	☑	0.033	0.002	0.079	☐
T-08	1486709.00	658646.00	☑	0.014	0.010	0.022	☐
T-12b	1490605.00	660206.38	☑	0.622	0.189	0.701	☐
T-13b	1488281.00	659071.00	☑	0.084	0.062	0.098	☑

Project: Fort Lewis

User Name: Meng

Location: Seattle

State: Washington

Well	X (feet)	Y (feet)	Removable?	Average Slope Factor*	Minimum Slope Factor*	Maximum Slope Factor*	Eliminated?

Note: The Slope Factor indicates the relative importance of a well in the monitoring network at a given sampling event; the larger the SF value of a well, the more important the well is and vice versa; the Average Slope Factor measures the overall well importance in the selected time period; the state coordinates system (i.e., X and Y refer to Easting and Northing respectively) or local coordinates systems may be used; wells that are NOT selected for analysis are not shown above.
* When the report is generated after running the Excel module, SF values will NOT be shown above.

MAROS Risk-Based Power Analysis for Site Cleanup

Project: Fort Lewis Upper Aquifer

User Name Meng

Location: Seattle

State: Washington

Parameters:

Groundwater Flow Direction: 140 degrees

Distance to Receptor: 1000 feet

From Period: 2nd Quarter 1998 **to** 3rd Quarter 2001

6/1/1998 9/1/2001

Selected Plume Centerline Wells:

Well	Distance to Receptor (feet)
T-13b	1931.0
LC-14a	3382.6
LC-66b	6318.1
LC-49	9390.6
LC-19a	11025.9
LC-137b	12082.4

The distance is measured in the Groundwater Flow Angle from the well to the compliance boundary.

				Normal Distribution Assumption			Lognormal Distribution Assumption				
Sample Event	Sample Szie	Sample Mean	Sample Stdev.	Cleanup Status	Power	Expected Sample Size	Celanup Status	Power	Expected Sample Size	Alpha Level	Expected Power
TRICHLOROETHYLENE (TCE)				Cleanup Goal = 0.005							
2nd Quarter 1998	35	5.04E-03	6.42E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
3rd Quarter 1998	35	1.07E-02	1.75E-02	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
4th Quarter 1998	28	4.27E-02	4.36E-02	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
1st Quarter 1999	35	7.03E-03	9.55E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
2nd Quarter 1999	35	8.21E-03	9.30E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
3rd Quarter 1999	35	6.16E-03	7.16E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
4th Quarter 1999	36	6.16E-03	7.66E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
1st Quarter 2000	36	5.55E-03	7.21E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
2nd Quarter 2000	36	6.86E-03	8.53E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
3rd Quarter 2000	36	4.80E-03	5.80E-03	Not Attained	0.075	>100	Not Attained	S/E	S/E	0.05	0.8
4th Quarter 2000	36	5.13E-03	6.17E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
1st Quarter 2001	36	4.92E-03	6.05E-03	Not Attained	0.059	>100	Not Attained	S/E	S/E	0.05	0.8
2nd Quarter 2001	36	3.40E-03	4.16E-03	Attained	0.739	43	Not Attained	S/E	S/E	0.05	0.8
3rd Quarter 2001	36	4.05E-03	5.00E-03	Not Attained	0.304	>100	Not Attained	S/E	S/E	0.05	0.8

Note: #N/C means "not conducted" due to a small sample size (N<4) or that the mean concentration is much greater than the cleanup level; Sample Size is the number of sampling locations used in the power analysis; Expected Sample Size is the number of concentration data needed to reach the Expected Power under current sample variability.

Risk-Based Power Analysis -- Projected Concentrations

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

From Period 6/1/1998 **to** 9/1/2001 **Distance from the most downgradient well to recep** 1000 feet

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
2nd Quarter 1998	6/1/1998	LC-03	6.000E-04	7375.0	-2.88E-04	7.158E-05	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-05	3.200E-02	5047.2	-2.88E-04	7.468E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-06	3.400E-02	8348.3	-2.88E-04	3.064E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-108	1.700E-02	12354.3	-2.88E-04	4.827E-04	No	Yes
2nd Quarter 1998	6/1/1998	LC-111b	6.000E-04	4567.9	-2.88E-04	1.608E-04	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-116b	2.450E-04	4601.7	-2.88E-04	6.502E-05	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-122b	6.000E-04	4795.4	-2.88E-04	1.506E-04	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-128	1.900E-02	3681.9	-2.88E-04	6.573E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-132	7.300E-02	5644.7	-2.88E-04	1.434E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-134	2.800E+00	12661.3	-2.88E-04	7.276E-02	No	No
2nd Quarter 1998	6/1/1998	LC-136a	7.800E+01	12352.7	-2.88E-04	2.216E+00	No	No
2nd Quarter 1998	6/1/1998	LC-136b	7.000E-02	12348.8	-2.88E-04	1.991E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-137a	1.000E-01	12077.8	-2.88E-04	3.075E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-137b	1.200E-01	12082.4	-2.88E-04	3.685E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-137c	4.300E-03	12086.6	-2.88E-04	1.319E-04	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-144a	3.400E-02	11261.0	-2.88E-04	1.323E-03	No	No
2nd Quarter 1998	6/1/1998	LC-149c	6.000E-04	14796.4	-2.88E-04	8.425E-06	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-149d	6.000E-04	14773.9	-2.88E-04	8.480E-06	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-14a	4.700E-02	3382.6	-2.88E-04	1.772E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-162	4.500E-01	12847.7	-2.88E-04	1.108E-02	No	No
2nd Quarter 1998	6/1/1998	LC-165	6.000E-04	4190.8	-2.88E-04	1.792E-04	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-19a	2.000E-01	11025.9	-2.88E-04	8.328E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-19b	9.700E-02	11024.1	-2.88E-04	4.041E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-19c	7.600E-02	11022.5	-2.88E-04	3.168E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-26	1.400E-04	13654.1	-2.88E-04	2.733E-06	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-41a	1.800E-01	7203.5	-2.88E-04	2.256E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-44a	1.400E-02	7149.5	-2.88E-04	1.782E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-49	2.600E-01	9390.6	-2.88E-04	1.735E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-49a	8.900E-02	9398.3	-2.88E-04	5.925E-03	No	No
2nd Quarter 1998	6/1/1998	LC-51	1.500E-01	12040.1	-2.88E-04	4.663E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-53	1.500E-01	11161.4	-2.88E-04	6.007E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-64a	7.500E-01	12561.5	-2.88E-04	2.006E-02	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
2nd Quarter 1998	6/1/1998	LC-64b	5.900E-02	12560.8	-2.88E-04	1.578E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-66a	9.600E-02	6311.6	-2.88E-04	1.556E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-66b	1.200E-01	6318.1	-2.88E-04	1.941E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-73a	4.800E-04	3830.2	-2.88E-04	1.591E-04	Yes	Yes
2nd Quarter 1998	6/1/1998	LX-1	1.100E-02	4553.1	-2.88E-04	2.960E-03	No	No
2nd Quarter 1998	6/1/1998	LX-10	5.500E-02	4684.8	-2.88E-04	1.425E-02	No	No
2nd Quarter 1998	6/1/1998	LX-11	3.700E-02	4715.9	-2.88E-04	9.501E-03	No	No
2nd Quarter 1998	6/1/1998	LX-12	2.000E-02	4746.4	-2.88E-04	5.091E-03	No	No
2nd Quarter 1998	6/1/1998	LX-13	4.500E-03	4777.3	-2.88E-04	1.135E-03	No	No
2nd Quarter 1998	6/1/1998	LX-14	5.300E-03	4809.2	-2.88E-04	1.325E-03	No	No
2nd Quarter 1998	6/1/1998	LX-15	2.700E-03	4840.1	-2.88E-04	6.689E-04	No	No
2nd Quarter 1998	6/1/1998	LX-16	1.500E-01	10934.0	-2.88E-04	6.414E-03	No	No
2nd Quarter 1998	6/1/1998	LX-17	4.500E-01	12512.4	-2.88E-04	1.221E-02	No	No
2nd Quarter 1998	6/1/1998	LX-18	7.000E-01	12499.3	-2.88E-04	1.906E-02	No	No
2nd Quarter 1998	6/1/1998	LX-19	1.100E-01	12245.1	-2.88E-04	3.223E-03	No	No
2nd Quarter 1998	6/1/1998	LX-2	1.500E-02	4563.1	-2.88E-04	4.025E-03	No	No
2nd Quarter 1998	6/1/1998	LX-21	1.100E-01	12247.8	-2.88E-04	3.221E-03	No	No
2nd Quarter 1998	6/1/1998	LX-3	3.000E-02	4571.9	-2.88E-04	8.030E-03	No	No
2nd Quarter 1998	6/1/1998	LX-4	6.700E-02	4580.3	-2.88E-04	1.789E-02	No	No
2nd Quarter 1998	6/1/1998	LX-5	8.800E-02	4583.3	-2.88E-04	2.348E-02	No	No
2nd Quarter 1998	6/1/1998	LX-6	9.600E-02	4587.7	-2.88E-04	2.558E-02	No	No
2nd Quarter 1998	6/1/1998	LX-7	7.500E-02	4597.5	-2.88E-04	1.993E-02	No	No
2nd Quarter 1998	6/1/1998	LX-8	6.800E-02	4623.3	-2.88E-04	1.793E-02	No	No
2nd Quarter 1998	6/1/1998	LX-9	6.700E-02	4653.9	-2.88E-04	1.751E-02	No	No
2nd Quarter 1998	6/1/1998	PA-381	3.300E-02	6283.1	-2.88E-04	5.393E-03	No	Yes
2nd Quarter 1998	6/1/1998	PA-383	5.000E-04	6758.7	-2.88E-04	7.125E-05	Yes	Yes
2nd Quarter 1998	6/1/1998	RW-1	1.600E-01	10572.4	-2.88E-04	7.593E-03	No	No
2nd Quarter 1998	6/1/1998	T-01	1.900E-03	2217.7	-2.88E-04	1.003E-03	No	No
2nd Quarter 1998	6/1/1998	T-04	5.200E-03	2048.1	-2.88E-04	2.881E-03	No	Yes
2nd Quarter 1998	6/1/1998	T-08	2.300E-03	1000.0	-2.88E-04	1.724E-03	No	Yes
2nd Quarter 1998	6/1/1998	T-13b	4.600E-03	1931.0	-2.88E-04	2.636E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-03	1.500E-03	7375.0	-2.59E-04	2.225E-04	No	Yes
3rd Quarter 1998	9/1/1998	LC-05	4.400E-02	5047.2	-2.59E-04	1.192E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-06	1.200E-01	8348.3	-2.59E-04	1.384E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-108	1.100E-02	12354.3	-2.59E-04	4.500E-04	No	Yes
3rd Quarter 1998	9/1/1998	LC-111b	6.000E-04	4567.9	-2.59E-04	1.840E-04	Yes	Yes

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Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 1998	9/1/1998	LC-116b	3.000E-04	4601.7	-2.59E-04	9.121E-05	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-122b	1.000E-04	4795.4	-2.59E-04	2.892E-05	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-128	2.400E-02	3681.9	-2.59E-04	9.257E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-132	5.400E-02	5644.7	-2.59E-04	1.253E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-134	2.800E+00	12661.3	-2.59E-04	1.058E-01	No	No
3rd Quarter 1998	9/1/1998	LC-136a	1.100E+02	12352.7	-2.59E-04	4.501E+00	No	No
3rd Quarter 1998	9/1/1998	LC-136b	9.800E-02	12348.8	-2.59E-04	4.014E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-137a	5.500E-01	12077.8	-2.59E-04	2.417E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-137b	3.300E-01	12082.4	-2.59E-04	1.448E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-137c	1.580E-02	12086.6	-2.59E-04	6.926E-04	No	Yes
3rd Quarter 1998	9/1/1998	LC-149c	1.000E-04	14796.4	-2.59E-04	2.174E-06	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-149d	4.000E-04	14773.9	-2.59E-04	8.749E-06	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-14a	1.100E-01	3382.6	-2.59E-04	4.585E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-162	2.900E-01	12847.7	-2.59E-04	1.044E-02	No	No
3rd Quarter 1998	9/1/1998	LC-165	2.000E-04	4190.8	-2.59E-04	6.763E-05	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-19a	1.567E-01	11025.9	-2.59E-04	9.037E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-19b	1.200E-01	11024.1	-2.59E-04	6.925E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-19c	4.515E-02	11022.5	-2.59E-04	2.607E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-26	1.000E-04	13654.1	-2.59E-04	2.922E-06	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-41a	1.450E-01	7203.5	-2.59E-04	2.249E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-44a	2.000E-02	7149.5	-2.59E-04	3.145E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-49	2.600E-01	9390.6	-2.59E-04	2.290E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-49a	9.200E-02	9398.3	-2.59E-04	8.086E-03	No	No
3rd Quarter 1998	9/1/1998	LC-51	2.000E-01	12040.1	-2.59E-04	8.874E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-53	2.100E-01	11161.4	-2.59E-04	1.170E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-64a	5.800E-01	12561.5	-2.59E-04	2.249E-02	No	No
3rd Quarter 1998	9/1/1998	LC-64b	8.000E-02	12560.8	-2.59E-04	3.102E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-66a	1.200E-01	6311.6	-2.59E-04	2.344E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-66b	4.800E-01	6318.1	-2.59E-04	9.360E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-73a	8.000E-04	3830.2	-2.59E-04	2.970E-04	No	Yes
3rd Quarter 1998	9/1/1998	LX-1	9.700E-03	4553.1	-2.59E-04	2.986E-03	No	No
3rd Quarter 1998	9/1/1998	LX-10	5.600E-02	4684.8	-2.59E-04	1.666E-02	No	No
3rd Quarter 1998	9/1/1998	LX-11	3.500E-02	4715.9	-2.59E-04	1.033E-02	No	No
3rd Quarter 1998	9/1/1998	LX-12	2.000E-02	4746.4	-2.59E-04	5.857E-03	No	No
3rd Quarter 1998	9/1/1998	LX-13	5.900E-03	4777.3	-2.59E-04	1.714E-03	No	No
3rd Quarter 1998	9/1/1998	LX-14	5.600E-03	4809.2	-2.59E-04	1.614E-03	No	No
3rd Quarter 1998	9/1/1998	LX-15	3.100E-03	4840.1	-2.59E-04	8.861E-04	No	No

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Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 1998	9/1/1998	LX-17	6.900E-01	12512.4	-2.59E-04	2.709E-02	No	No
3rd Quarter 1998	9/1/1998	LX-18	1.000E+00	12499.3	-2.59E-04	3.940E-02	No	No
3rd Quarter 1998	9/1/1998	LX-19	1.200E-01	12245.1	-2.59E-04	5.049E-03	No	No
3rd Quarter 1998	9/1/1998	LX-2	1.600E-02	4563.1	-2.59E-04	4.913E-03	No	No
3rd Quarter 1998	9/1/1998	LX-21	1.500E-01	12247.8	-2.59E-04	6.307E-03	No	No
3rd Quarter 1998	9/1/1998	LX-3	3.500E-02	4571.9	-2.59E-04	1.072E-02	No	No
3rd Quarter 1998	9/1/1998	LX-5	9.600E-02	4583.3	-2.59E-04	2.933E-02	No	No
3rd Quarter 1998	9/1/1998	LX-6	1.200E-01	4587.7	-2.59E-04	3.662E-02	No	No
3rd Quarter 1998	9/1/1998	LX-7	1.000E-01	4597.5	-2.59E-04	3.044E-02	No	No
3rd Quarter 1998	9/1/1998	LX-8	7.500E-02	4623.3	-2.59E-04	2.268E-02	No	No
3rd Quarter 1998	9/1/1998	LX-9	7.400E-02	4653.9	-2.59E-04	2.220E-02	No	No
3rd Quarter 1998	9/1/1998	PA-381	5.800E-02	6283.1	-2.59E-04	1.141E-02	No	Yes
3rd Quarter 1998	9/1/1998	PA-383	4.000E-04	6758.7	-2.59E-04	6.960E-05	Yes	Yes
3rd Quarter 1998	9/1/1998	T-01	1.700E-03	2217.7	-2.59E-04	9.577E-04	No	No
3rd Quarter 1998	9/1/1998	T-04	1.500E-02	2048.1	-2.59E-04	8.830E-03	No	Yes
3rd Quarter 1998	9/1/1998	T-08	3.700E-03	1000.0	-2.59E-04	2.856E-03	No	Yes
3rd Quarter 1998	9/1/1998	T-13b	6.200E-03	1931.0	-2.59E-04	3.762E-03	No	Yes
4th Quarter 1998	12/1/1998	LC-05	1.800E-02	5047.2	-5.62E-05	1.356E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-06	6.700E-02	8348.3	-5.62E-05	4.192E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-108	1.500E-01	12354.3	-5.62E-05	7.494E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-116b	3.000E-04	4601.7	-5.62E-05	2.317E-04	No	Yes
4th Quarter 1998	12/1/1998	LC-128	1.800E-02	3681.9	-5.62E-05	1.464E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-132	7.700E-02	5644.7	-5.62E-05	5.608E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-134	1.000E+00	12661.3	-5.62E-05	4.911E-01	No	No
4th Quarter 1998	12/1/1998	LC-136a	4.550E+01	12352.7	-5.62E-05	2.273E+01	No	No
4th Quarter 1998	12/1/1998	LC-136b	8.000E-02	12348.8	-5.62E-05	3.998E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-137a	4.800E-02	12077.8	-5.62E-05	2.436E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-137b	3.950E-02	12082.4	-5.62E-05	2.004E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-137c	2.300E-02	12086.6	-5.62E-05	1.167E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-149c	1.000E-04	14796.4	-5.62E-05	4.356E-05	Yes	Yes
4th Quarter 1998	12/1/1998	LC-149d	3.000E-04	14773.9	-5.62E-05	1.308E-04	Yes	Yes
4th Quarter 1998	12/1/1998	LC-14a	4.600E-02	3382.6	-5.62E-05	3.804E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-162	1.100E-01	12847.7	-5.62E-05	5.345E-02	No	No
4th Quarter 1998	12/1/1998	LC-19a	1.900E-01	11025.9	-5.62E-05	1.023E-01	No	Yes
4th Quarter 1998	12/1/1998	LC-19b	7.800E-02	11024.1	-5.62E-05	4.199E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-19c	5.300E-02	11022.5	-5.62E-05	2.854E-02	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

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TRICHLOROETHYLENE (TCE)								
4th Quarter 1998	12/1/1998	LC-41a	1.700E-01	7203.5	-5.62E-05	1.134E-01	No	Yes
4th Quarter 1998	12/1/1998	LC-44a	1.800E-02	7149.5	-5.62E-05	1.205E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-49	3.000E-01	9390.6	-5.62E-05	1.770E-01	No	Yes
4th Quarter 1998	12/1/1998	LC-51	1.400E-01	12040.1	-5.62E-05	7.119E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-53	1.600E-01	11161.4	-5.62E-05	8.548E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-64a	1.200E+00	12561.5	-5.62E-05	5.926E-01	No	No
4th Quarter 1998	12/1/1998	LC-64b	4.100E-02	12560.8	-5.62E-05	2.025E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-66a	1.400E-01	6311.6	-5.62E-05	9.821E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-66b	1.200E-01	6318.1	-5.62E-05	8.415E-02	No	Yes
4th Quarter 1998	12/1/1998	LX-1	5.500E-03	4553.1	-5.62E-05	4.259E-03	No	No
4th Quarter 1998	12/1/1998	LX-10	6.700E-02	4684.8	-5.62E-05	5.150E-02	No	No
4th Quarter 1998	12/1/1998	LX-11	1.400E-02	4715.9	-5.62E-05	1.074E-02	No	No
4th Quarter 1998	12/1/1998	LX-12	1.700E-02	4746.4	-5.62E-05	1.302E-02	No	No
4th Quarter 1998	12/1/1998	LX-13	5.100E-03	4777.3	-5.62E-05	3.900E-03	No	No
4th Quarter 1998	12/1/1998	LX-14	5.000E-03	4809.2	-5.62E-05	3.816E-03	No	No
4th Quarter 1998	12/1/1998	LX-15	2.500E-03	4840.1	-5.62E-05	1.905E-03	No	No
4th Quarter 1998	12/1/1998	LX-17	8.700E-01	12512.4	-5.62E-05	4.308E-01	No	No
4th Quarter 1998	12/1/1998	LX-18	1.000E+00	12499.3	-5.62E-05	4.956E-01	No	No
4th Quarter 1998	12/1/1998	LX-19	2.000E-01	12245.1	-5.62E-05	1.005E-01	No	No
4th Quarter 1998	12/1/1998	LX-2	1.400E-02	4563.1	-5.62E-05	1.083E-02	No	No
4th Quarter 1998	12/1/1998	LX-21	1.300E-01	12247.8	-5.62E-05	6.534E-02	No	No
4th Quarter 1998	12/1/1998	LX-3	3.500E-02	4571.9	-5.62E-05	2.707E-02	No	No
4th Quarter 1998	12/1/1998	LX-5	9.800E-02	4583.3	-5.62E-05	7.576E-02	No	No
4th Quarter 1998	12/1/1998	LX-6	1.200E-01	4587.7	-5.62E-05	9.274E-02	No	No
4th Quarter 1998	12/1/1998	LX-7	5.500E-02	4597.5	-5.62E-05	4.248E-02	No	No
4th Quarter 1998	12/1/1998	LX-8	8.300E-02	4623.3	-5.62E-05	6.402E-02	No	No
4th Quarter 1998	12/1/1998	LX-9	3.950E-02	4653.9	-5.62E-05	3.041E-02	No	No
4th Quarter 1998	12/1/1998	PA-381	2.600E-02	6283.1	-5.62E-05	1.827E-02	No	Yes
4th Quarter 1998	12/1/1998	PA-383	9.000E-04	6758.7	-5.62E-05	6.157E-04	No	Yes
4th Quarter 1998	12/1/1998	T-01	2.000E-03	2217.7	-5.62E-05	1.766E-03	No	No
4th Quarter 1998	12/1/1998	T-04	3.200E-03	2048.1	-5.62E-05	2.852E-03	No	Yes
4th Quarter 1998	12/1/1998	T-08	2.700E-03	1000.0	-5.62E-05	2.553E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-03	8.000E-04	7375.0	-2.44E-04	1.326E-04	Yes	Yes
1st Quarter 1999	3/1/1999	LC-05	6.000E-03	5047.2	-2.44E-04	1.754E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-06	9.800E-03	8348.3	-2.44E-04	1.281E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-108	6.400E-03	12354.3	-2.44E-04	3.152E-04	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1st Quarter 1999	3/1/1999	LC-111b	2.000E-04	4567.9	-2.44E-04	6.570E-05	Yes	Yes
1st Quarter 1999	3/1/1999	LC-116b	3.000E-04	4601.7	-2.44E-04	9.774E-05	Yes	Yes
1st Quarter 1999	3/1/1999	LC-122b	5.000E-04	4795.4	-2.44E-04	1.554E-04	Yes	Yes
1st Quarter 1999	3/1/1999	LC-128	9.500E-03	3681.9	-2.44E-04	3.873E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-132	4.500E-02	5644.7	-2.44E-04	1.137E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-134	1.400E+00	12661.3	-2.44E-04	6.397E-02	No	No
1st Quarter 1999	3/1/1999	LC-136a	1.200E+02	12352.7	-2.44E-04	5.911E+00	No	No
1st Quarter 1999	3/1/1999	LC-136b	1.100E-01	12348.8	-2.44E-04	5.424E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-137a	3.700E-02	12077.8	-2.44E-04	1.949E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-137b	5.500E-02	12082.4	-2.44E-04	2.894E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-137c	1.600E-02	12086.6	-2.44E-04	8.410E-04	No	Yes
1st Quarter 1999	3/1/1999	LC-149c	1.000E-04	14796.4	-2.44E-04	2.716E-06	Yes	Yes
1st Quarter 1999	3/1/1999	LC-149d	1.000E-04	14773.9	-2.44E-04	2.731E-06	Yes	Yes
1st Quarter 1999	3/1/1999	LC-14a	4.000E-02	3382.6	-2.44E-04	1.754E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-162	5.000E-01	12847.7	-2.44E-04	2.183E-02	No	No
1st Quarter 1999	3/1/1999	LC-165	1.000E-04	4190.8	-2.44E-04	3.601E-05	Yes	Yes
1st Quarter 1999	3/1/1999	LC-19a	2.200E-01	11025.9	-2.44E-04	1.498E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-19b	3.300E-01	11024.1	-2.44E-04	2.247E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-19c	5.100E-02	11022.5	-2.44E-04	3.474E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-26	3.000E-04	13654.1	-2.44E-04	1.076E-05	Yes	Yes
1st Quarter 1999	3/1/1999	LC-41a	1.700E-01	7203.5	-2.44E-04	2.938E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-44a	1.300E-02	7149.5	-2.44E-04	2.276E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-49	2.500E-01	9390.6	-2.44E-04	2.535E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-51	1.800E-01	12040.1	-2.44E-04	9.569E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-53	1.800E-01	11161.4	-2.44E-04	1.185E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-64a	1.100E+00	12561.5	-2.44E-04	5.150E-02	No	No
1st Quarter 1999	3/1/1999	LC-64b	5.600E-02	12560.8	-2.44E-04	2.622E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-66a	1.100E-01	6311.6	-2.44E-04	2.362E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-66b	1.600E-01	6318.1	-2.44E-04	3.431E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-73a	1.350E-03	3830.2	-2.44E-04	5.308E-04	No	Yes
1st Quarter 1999	3/1/1999	LX-1	1.300E-02	4553.1	-2.44E-04	4.286E-03	No	No
1st Quarter 1999	3/1/1999	LX-10	7.800E-02	4684.8	-2.44E-04	2.490E-02	No	No
1st Quarter 1999	3/1/1999	LX-11	5.000E-02	4715.9	-2.44E-04	1.584E-02	No	No
1st Quarter 1999	3/1/1999	LX-12	3.300E-02	4746.4	-2.44E-04	1.038E-02	No	No
1st Quarter 1999	3/1/1999	LX-13	5.400E-03	4777.3	-2.44E-04	1.686E-03	No	No
1st Quarter 1999	3/1/1999	LX-14	6.000E-03	4809.2	-2.44E-04	1.858E-03	No	No
1st Quarter 1999	3/1/1999	LX-15	3.500E-03	4840.1	-2.44E-04	1.076E-03	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1st Quarter 1999	3/1/1999	LX-17	5.800E-01	12512.4	-2.44E-04	2.748E-02	No	No
1st Quarter 1999	3/1/1999	LX-18	9.600E-01	12499.3	-2.44E-04	4.563E-02	No	No
1st Quarter 1999	3/1/1999	LX-19	1.400E-01	12245.1	-2.44E-04	7.080E-03	No	No
1st Quarter 1999	3/1/1999	LX-2	1.400E-02	4563.1	-2.44E-04	4.604E-03	No	No
1st Quarter 1999	3/1/1999	LX-21	1.100E-01	12247.8	-2.44E-04	5.559E-03	No	No
1st Quarter 1999	3/1/1999	LX-3	3.200E-02	4571.9	-2.44E-04	1.050E-02	No	No
1st Quarter 1999	3/1/1999	LX-4	9.200E-02	4580.3	-2.44E-04	3.013E-02	No	No
1st Quarter 1999	3/1/1999	LX-6	1.300E-01	4587.7	-2.44E-04	4.250E-02	No	No
1st Quarter 1999	3/1/1999	LX-7	4.500E-02	4597.5	-2.44E-04	1.468E-02	No	No
1st Quarter 1999	3/1/1999	LX-8	8.600E-02	4623.3	-2.44E-04	2.787E-02	No	No
1st Quarter 1999	3/1/1999	LX-9	8.300E-02	4653.9	-2.44E-04	2.670E-02	No	No
1st Quarter 1999	3/1/1999	PA-381	4.200E-02	6283.1	-2.44E-04	9.083E-03	No	Yes
1st Quarter 1999	3/1/1999	PA-383	1.800E-03	6758.7	-2.44E-04	3.466E-04	No	Yes
1st Quarter 1999	3/1/1999	T-01	1.600E-03	2217.7	-2.44E-04	9.319E-04	No	No
1st Quarter 1999	3/1/1999	T-04	5.300E-03	2048.1	-2.44E-04	3.217E-03	No	Yes
1st Quarter 1999	3/1/1999	T-08	2.500E-03	1000.0	-2.44E-04	1.959E-03	No	Yes
1st Quarter 1999	3/1/1999	T-13b	5.300E-03	1931.0	-2.44E-04	3.310E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-03	4.500E-04	7375.0	-1.95E-04	1.068E-04	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-05	2.200E-02	5047.2	-1.95E-04	8.219E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-06	5.000E-02	8348.3	-1.95E-04	9.810E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-108	2.000E-02	12354.3	-1.95E-04	1.796E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-111b	1.000E-04	4567.9	-1.95E-04	4.102E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-116b	1.000E-04	4601.7	-1.95E-04	4.075E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-122b	1.000E-04	4795.4	-1.95E-04	3.924E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-128	2.100E-02	3681.9	-1.95E-04	1.024E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-132	8.000E-02	5644.7	-1.95E-04	2.660E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-134	5.600E-01	12661.3	-1.95E-04	4.737E-02	No	No
2nd Quarter 1999	6/1/1999	LC-136a	1.000E+02	12352.7	-1.95E-04	8.983E+00	No	No
2nd Quarter 1999	6/1/1999	LC-136b	5.000E-02	12348.8	-1.95E-04	4.495E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-137a	9.500E-02	12077.8	-1.95E-04	9.004E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-137b	8.000E-02	12082.4	-1.95E-04	7.576E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-137c	4.000E-04	12086.6	-1.95E-04	3.785E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-149c	1.000E-04	14796.4	-1.95E-04	5.577E-06	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-149d	1.000E-04	14773.9	-1.95E-04	5.602E-06	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-14a	5.800E-02	3382.6	-1.95E-04	2.998E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-162	1.850E-01	12847.7	-1.95E-04	1.509E-02	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

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TRICHLOROETHYLENE (TCE)								
2nd Quarter 1999	6/1/1999	LC-165	1.000E-04	4190.8	-1.95E-04	4.415E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-19a	9.000E-02	11025.9	-1.95E-04	1.047E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-19b	9.000E-02	11024.1	-1.95E-04	1.048E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-19c	5.400E-02	11022.5	-1.95E-04	6.288E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-26	1.000E-04	13654.1	-1.95E-04	6.969E-06	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-41a	1.500E-01	7203.5	-1.95E-04	3.679E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-44a	1.750E-02	7149.5	-1.95E-04	4.338E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-49	1.000E-01	9390.6	-1.95E-04	1.601E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-51	9.000E-02	12040.1	-1.95E-04	8.593E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-53	1.000E-01	11161.4	-1.95E-04	1.133E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-64a	5.100E-01	12561.5	-1.95E-04	4.399E-02	No	No
2nd Quarter 1999	6/1/1999	LC-64b	6.400E-02	12560.8	-1.95E-04	5.521E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-66a	7.150E-02	6311.6	-1.95E-04	2.087E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-66b	7.000E-02	6318.1	-1.95E-04	2.041E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-73a	4.500E-04	3830.2	-1.95E-04	2.132E-04	No	Yes
2nd Quarter 1999	6/1/1999	LX-1	9.800E-03	4553.1	-1.95E-04	4.032E-03	No	No
2nd Quarter 1999	6/1/1999	LX-10	6.300E-02	4684.8	-1.95E-04	2.526E-02	No	No
2nd Quarter 1999	6/1/1999	LX-11	4.500E-02	4715.9	-1.95E-04	1.793E-02	No	No
2nd Quarter 1999	6/1/1999	LX-12	2.700E-02	4746.4	-1.95E-04	1.070E-02	No	No
2nd Quarter 1999	6/1/1999	LX-13	6.800E-03	4777.3	-1.95E-04	2.678E-03	No	No
2nd Quarter 1999	6/1/1999	LX-14	7.500E-03	4809.2	-1.95E-04	2.935E-03	No	No
2nd Quarter 1999	6/1/1999	LX-15	4.400E-03	4840.1	-1.95E-04	1.712E-03	No	No
2nd Quarter 1999	6/1/1999	LX-17	3.900E-01	12512.4	-1.95E-04	3.396E-02	No	No
2nd Quarter 1999	6/1/1999	LX-18	5.400E-01	12499.3	-1.95E-04	4.714E-02	No	No
2nd Quarter 1999	6/1/1999	LX-19	1.200E-01	12245.1	-1.95E-04	1.101E-02	No	No
2nd Quarter 1999	6/1/1999	LX-2	1.200E-02	4563.1	-1.95E-04	4.927E-03	No	No
2nd Quarter 1999	6/1/1999	LX-21	9.300E-02	12247.8	-1.95E-04	8.527E-03	No	No
2nd Quarter 1999	6/1/1999	LX-3	2.500E-02	4571.9	-1.95E-04	1.025E-02	No	No
2nd Quarter 1999	6/1/1999	LX-4	5.700E-02	4580.3	-1.95E-04	2.332E-02	No	No
2nd Quarter 1999	6/1/1999	LX-5	9.950E-02	4583.3	-1.95E-04	4.069E-02	No	No
2nd Quarter 1999	6/1/1999	LX-6	9.400E-02	4587.7	-1.95E-04	3.841E-02	No	No
2nd Quarter 1999	6/1/1999	LX-7	8.300E-02	4597.5	-1.95E-04	3.385E-02	No	No
2nd Quarter 1999	6/1/1999	LX-8	7.400E-02	4623.3	-1.95E-04	3.003E-02	No	No
2nd Quarter 1999	6/1/1999	LX-9	6.900E-02	4653.9	-1.95E-04	2.783E-02	No	No
2nd Quarter 1999	6/1/1999	PA-381	5.200E-02	6283.1	-1.95E-04	1.526E-02	No	Yes
2nd Quarter 1999	6/1/1999	PA-383	2.000E-03	6758.7	-1.95E-04	5.351E-04	No	Yes
2nd Quarter 1999	6/1/1999	T-01	1.650E-03	2217.7	-1.95E-04	1.071E-03	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

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TRICHLOROETHYLENE (TCE)								
2nd Quarter 1999	6/1/1999	T-04	8.800E-03	2048.1	-1.95E-04	5.901E-03	No	Yes
2nd Quarter 1999	6/1/1999	T-08	3.100E-03	1000.0	-1.95E-04	2.551E-03	No	Yes
2nd Quarter 1999	6/1/1999	T-13b	5.500E-03	1931.0	-1.95E-04	3.774E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-03	1.200E-03	7375.0	-2.80E-04	1.518E-04	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-05	4.400E-02	5047.2	-2.80E-04	1.069E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-06	1.200E-01	8348.3	-2.80E-04	1.155E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-108	4.000E-04	12354.3	-2.80E-04	1.253E-05	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-111b	1.000E-04	4567.9	-2.80E-04	2.779E-05	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-116b	3.000E-04	4601.7	-2.80E-04	8.257E-05	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-122b	1.000E-04	4795.4	-2.80E-04	2.607E-05	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-128	2.200E-02	3681.9	-2.80E-04	7.837E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-132	9.100E-02	5644.7	-2.80E-04	1.870E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-134	2.000E+00	12661.3	-2.80E-04	5.747E-02	No	No
3rd Quarter 1999	9/1/1999	LC-136a	1.300E+02	12352.7	-2.80E-04	4.073E+00	No	No
3rd Quarter 1999	9/1/1999	LC-136b	8.100E-02	12348.8	-2.80E-04	2.541E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-137a	2.700E-01	12077.8	-2.80E-04	9.137E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-137b	2.100E-01	12082.4	-2.80E-04	7.098E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-137c	8.100E-03	12086.6	-2.80E-04	2.734E-04	No	Yes
3rd Quarter 1999	9/1/1999	LC-149c	1.000E-04	14796.4	-2.80E-04	1.579E-06	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-149d	1.000E-04	14773.9	-2.80E-04	1.589E-06	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-14a	6.200E-02	3382.6	-2.80E-04	2.402E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-162	2.800E-01	12847.7	-2.80E-04	7.636E-03	No	No
3rd Quarter 1999	9/1/1999	LC-165	1.000E-04	4190.8	-2.80E-04	3.089E-05	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-19a	1.700E-01	11025.9	-2.80E-04	7.727E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-19b	1.200E-01	11024.1	-2.80E-04	5.457E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-19c	4.600E-02	11022.5	-2.80E-04	2.093E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-26	1.000E-04	13654.1	-2.80E-04	2.175E-06	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-41a	1.900E-01	7203.5	-2.80E-04	2.522E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-44a	1.800E-02	7149.5	-2.80E-04	2.425E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-49	1.700E-01	9390.6	-2.80E-04	1.222E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-51	1.600E-01	12040.1	-2.80E-04	5.472E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-53	1.700E-01	11161.4	-2.80E-04	7.438E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-64a	3.700E-01	12561.5	-2.80E-04	1.093E-02	No	No
3rd Quarter 1999	9/1/1999	LC-64b	3.600E-02	12560.8	-2.80E-04	1.064E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-66a	8.250E-02	6311.6	-2.80E-04	1.406E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-66b	1.200E-01	6318.1	-2.80E-04	2.041E-02	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

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TRICHLOROETHYLENE (TCE)								
3rd Quarter 1999	9/1/1999	LC-73a	8.000E-04	3830.2	-2.80E-04	2.734E-04	No	Yes
3rd Quarter 1999	9/1/1999	LX-1	1.400E-02	4553.1	-2.80E-04	3.906E-03	No	No
3rd Quarter 1999	9/1/1999	LX-10	6.100E-02	4684.8	-2.80E-04	1.640E-02	No	No
3rd Quarter 1999	9/1/1999	LX-11	4.000E-02	4715.9	-2.80E-04	1.066E-02	No	No
3rd Quarter 1999	9/1/1999	LX-12	2.300E-02	4746.4	-2.80E-04	6.079E-03	No	No
3rd Quarter 1999	9/1/1999	LX-14	7.300E-03	4809.2	-2.80E-04	1.896E-03	No	No
3rd Quarter 1999	9/1/1999	LX-15	4.000E-03	4840.1	-2.80E-04	1.030E-03	No	No
3rd Quarter 1999	9/1/1999	LX-17	4.800E-01	12512.4	-2.80E-04	1.438E-02	No	No
3rd Quarter 1999	9/1/1999	LX-18	5.350E-01	12499.3	-2.80E-04	1.609E-02	No	No
3rd Quarter 1999	9/1/1999	LX-19	1.000E-01	12245.1	-2.80E-04	3.229E-03	No	No
3rd Quarter 1999	9/1/1999	LX-2	1.100E-02	4563.1	-2.80E-04	3.061E-03	No	No
3rd Quarter 1999	9/1/1999	LX-21	1.100E-01	12247.8	-2.80E-04	3.549E-03	No	No
3rd Quarter 1999	9/1/1999	LX-3	2.400E-02	4571.9	-2.80E-04	6.661E-03	No	No
3rd Quarter 1999	9/1/1999	LX-4	5.900E-02	4580.3	-2.80E-04	1.634E-02	No	No
3rd Quarter 1999	9/1/1999	LX-5	1.000E-01	4583.3	-2.80E-04	2.767E-02	No	No
3rd Quarter 1999	9/1/1999	LX-6	9.200E-02	4587.7	-2.80E-04	2.542E-02	No	No
3rd Quarter 1999	9/1/1999	LX-7	8.300E-02	4597.5	-2.80E-04	2.287E-02	No	No
3rd Quarter 1999	9/1/1999	LX-8	7.200E-02	4623.3	-2.80E-04	1.970E-02	No	No
3rd Quarter 1999	9/1/1999	LX-9	6.900E-02	4653.9	-2.80E-04	1.872E-02	No	No
3rd Quarter 1999	9/1/1999	PA-381	4.400E-02	6283.1	-2.80E-04	7.559E-03	No	Yes
3rd Quarter 1999	9/1/1999	PA-383	2.100E-03	6758.7	-2.80E-04	3.157E-04	No	Yes
3rd Quarter 1999	9/1/1999	T-01	2.400E-03	2217.7	-2.80E-04	1.289E-03	No	No
3rd Quarter 1999	9/1/1999	T-04	1.000E-02	2048.1	-2.80E-04	5.632E-03	No	Yes
3rd Quarter 1999	9/1/1999	T-08	3.800E-03	1000.0	-2.80E-04	2.871E-03	No	Yes
3rd Quarter 1999	9/1/1999	T-13b	5.300E-03	1931.0	-2.80E-04	3.084E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-03	8.500E-04	7375.0	-2.71E-04	1.152E-04	Yes	Yes
4th Quarter 1999	12/1/1999	LC-05	2.700E-02	5047.2	-2.71E-04	6.878E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-06	1.100E-01	8348.3	-2.71E-04	1.146E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-108	3.400E-02	12354.3	-2.71E-04	1.196E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-111b	1.000E-04	4567.9	-2.71E-04	2.901E-05	Yes	Yes
4th Quarter 1999	12/1/1999	LC-116b	1.000E-04	4601.7	-2.71E-04	2.874E-05	Yes	Yes
4th Quarter 1999	12/1/1999	LC-122b	1.000E-04	4795.4	-2.71E-04	2.727E-05	Yes	Yes
4th Quarter 1999	12/1/1999	LC-128	2.850E-02	3681.9	-2.71E-04	1.051E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-132	1.000E-01	5644.7	-2.71E-04	2.167E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-134	1.975E+00	12661.3	-2.71E-04	6.393E-02	No	No
4th Quarter 1999	12/1/1999	LC-136a	1.800E+02	12352.7	-2.71E-04	6.334E+00	No	No

Project: Fort Lewis Upper Aquifer   **User Name:** Meng

Location: Seattle   **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
4th Quarter 1999	12/1/1999	LC-136b	5.000E-02	12348.8	-2.71E-04	1.761E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-137a	5.700E-02	12077.8	-2.71E-04	2.161E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-137b	1.300E-01	12082.4	-2.71E-04	4.922E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-137c	3.000E-04	12086.6	-2.71E-04	1.135E-05	Yes	Yes
4th Quarter 1999	12/1/1999	LC-149c	1.000E-04	14796.4	-2.71E-04	1.815E-06	Yes	Yes
4th Quarter 1999	12/1/1999	LC-149d	1.000E-04	14773.9	-2.71E-04	1.826E-06	Yes	Yes
4th Quarter 1999	12/1/1999	LC-14a	5.200E-02	3382.6	-2.71E-04	2.080E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-162	1.700E-01	12847.7	-2.71E-04	5.232E-03	No	No
4th Quarter 1999	12/1/1999	LC-165	1.000E-04	4190.8	-2.71E-04	3.213E-05	Yes	Yes
4th Quarter 1999	12/1/1999	LC-19a	1.700E-01	11025.9	-2.71E-04	8.571E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-19b	7.300E-02	11024.1	-2.71E-04	3.682E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-19c	4.700E-02	11022.5	-2.71E-04	2.372E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-26	1.000E-04	13654.1	-2.71E-04	2.473E-06	Yes	Yes
4th Quarter 1999	12/1/1999	LC-41a	1.600E-01	7203.5	-2.71E-04	2.272E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-44a	3.700E-02	7149.5	-2.71E-04	5.332E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-49	2.700E-01	9390.6	-2.71E-04	2.120E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-51	8.000E-02	12040.1	-2.71E-04	3.064E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-53	2.300E-01	11161.4	-2.71E-04	1.118E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-64a	4.300E-01	12561.5	-2.71E-04	1.430E-02	No	No
4th Quarter 1999	12/1/1999	LC-64b	9.000E-03	12560.8	-2.71E-04	2.994E-04	No	Yes
4th Quarter 1999	12/1/1999	LC-66a	1.000E-01	6311.6	-2.71E-04	1.808E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-66b	1.300E-01	6318.1	-2.71E-04	2.347E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-73a	1.200E-03	3830.2	-2.71E-04	4.251E-04	No	Yes
4th Quarter 1999	12/1/1999	LX-1	1.100E-02	4553.1	-2.71E-04	3.203E-03	No	No
4th Quarter 1999	12/1/1999	LX-10	6.300E-02	4684.8	-2.71E-04	1.770E-02	No	No
4th Quarter 1999	12/1/1999	LX-11	3.600E-02	4715.9	-2.71E-04	1.003E-02	No	No
4th Quarter 1999	12/1/1999	LX-12	2.200E-02	4746.4	-2.71E-04	6.080E-03	No	No
4th Quarter 1999	12/1/1999	LX-14	6.800E-03	4809.2	-2.71E-04	1.848E-03	No	No
4th Quarter 1999	12/1/1999	LX-15	3.400E-03	4840.1	-2.71E-04	9.161E-04	No	No
4th Quarter 1999	12/1/1999	LX-17	5.500E-01	12512.4	-2.71E-04	1.854E-02	No	No
4th Quarter 1999	12/1/1999	LX-18	7.900E-01	12499.3	-2.71E-04	2.672E-02	No	No
4th Quarter 1999	12/1/1999	LX-19	1.100E-01	12245.1	-2.71E-04	3.986E-03	No	No
4th Quarter 1999	12/1/1999	LX-2	1.500E-02	4563.1	-2.71E-04	4.357E-03	No	No
4th Quarter 1999	12/1/1999	LX-21	1.100E-01	12247.8	-2.71E-04	3.983E-03	No	No
4th Quarter 1999	12/1/1999	LX-3	2.400E-02	4571.9	-2.71E-04	6.954E-03	No	No
4th Quarter 1999	12/1/1999	LX-4	6.000E-02	4580.3	-2.71E-04	1.735E-02	No	No
4th Quarter 1999	12/1/1999	LX-5	1.000E-01	4583.3	-2.71E-04	2.889E-02	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
4th Quarter 1999	12/1/1999	LX-6	9.300E-02	4587.7	-2.71E-04	2.683E-02	No	No
4th Quarter 1999	12/1/1999	LX-7	8.800E-02	4597.5	-2.71E-04	2.532E-02	No	No
4th Quarter 1999	12/1/1999	LX-8	7.700E-02	4623.3	-2.71E-04	2.200E-02	No	No
4th Quarter 1999	12/1/1999	LX-9	6.800E-02	4653.9	-2.71E-04	1.927E-02	No	No
4th Quarter 1999	12/1/1999	PA-381	2.800E-02	6283.1	-2.71E-04	5.103E-03	No	Yes
4th Quarter 1999	12/1/1999	PA-383	1.500E-03	6758.7	-2.71E-04	2.403E-04	No	Yes
4th Quarter 1999	12/1/1999	T-04	1.200E-02	2048.1	-2.71E-04	6.889E-03	No	Yes
4th Quarter 1999	12/1/1999	T-08	3.000E-03	1000.0	-2.71E-04	2.288E-03	No	Yes
4th Quarter 1999	12/1/1999	T-12b	4.400E-03	2981.5	-2.71E-04	1.962E-03	No	Yes
4th Quarter 1999	12/1/1999	T-13b	5.400E-03	1931.0	-2.71E-04	3.200E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-03	6.500E-04	7375.0	-2.73E-04	8.653E-05	Yes	Yes
1st Quarter 2000	3/1/2000	LC-05	1.100E-02	5047.2	-2.73E-04	2.767E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-06	6.800E-02	8348.3	-2.73E-04	6.937E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-108	5.100E-03	12354.3	-2.73E-04	1.740E-04	Yes	Yes
1st Quarter 2000	3/1/2000	LC-111b	1.000E-04	4567.9	-2.73E-04	2.868E-05	Yes	Yes
1st Quarter 2000	3/1/2000	LC-116b	1.000E-04	4601.7	-2.73E-04	2.842E-05	Yes	Yes
1st Quarter 2000	3/1/2000	LC-122b	1.000E-04	4795.4	-2.73E-04	2.695E-05	Yes	Yes
1st Quarter 2000	3/1/2000	LC-128	2.500E-02	3681.9	-2.73E-04	9.135E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-132	8.300E-02	5644.7	-2.73E-04	1.773E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-134	1.250E+00	12661.3	-2.73E-04	3.921E-02	No	No
1st Quarter 2000	3/1/2000	LC-136a	1.900E+02	12352.7	-2.73E-04	6.485E+00	No	No
1st Quarter 2000	3/1/2000	LC-136b	9.800E-02	12348.8	-2.73E-04	3.349E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-137a	6.100E-02	12077.8	-2.73E-04	2.245E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-137b	1.350E-01	12082.4	-2.73E-04	4.961E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-137c	2.000E-04	12086.6	-2.73E-04	7.342E-06	Yes	Yes
1st Quarter 2000	3/1/2000	LC-149c	1.000E-04	14796.4	-2.73E-04	1.750E-06	Yes	Yes
1st Quarter 2000	3/1/2000	LC-149d	1.000E-04	14773.9	-2.73E-04	1.761E-06	Yes	Yes
1st Quarter 2000	3/1/2000	LC-14a	5.800E-02	3382.6	-2.73E-04	2.300E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-162	3.800E-01	12847.7	-2.73E-04	1.133E-02	No	No
1st Quarter 2000	3/1/2000	LC-165	1.000E-04	4190.8	-2.73E-04	3.180E-05	Yes	Yes
1st Quarter 2000	3/1/2000	LC-19a	1.800E-01	11025.9	-2.73E-04	8.831E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-19b	8.300E-02	11024.1	-2.73E-04	4.074E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-19c	3.900E-02	11022.5	-2.73E-04	1.915E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-26	1.000E-04	13654.1	-2.73E-04	2.391E-06	Yes	Yes
1st Quarter 2000	3/1/2000	LC-41a	1.500E-01	7203.5	-2.73E-04	2.093E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-44a	1.400E-02	7149.5	-2.73E-04	1.982E-03	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1st Quarter 2000	3/1/2000	LC-49	2.000E-01	9390.6	-2.73E-04	1.534E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-51	1.700E-01	12040.1	-2.73E-04	6.320E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-53	1.700E-01	11161.4	-2.73E-04	8.037E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-64a	3.900E-01	12561.5	-2.73E-04	1.257E-02	No	No
1st Quarter 2000	3/1/2000	LC-64b	1.800E-02	12560.8	-2.73E-04	5.804E-04	No	Yes
1st Quarter 2000	3/1/2000	LC-66a	1.100E-01	6311.6	-2.73E-04	1.958E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-66b	1.300E-01	6318.1	-2.73E-04	2.310E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-73a	1.100E-03	3830.2	-2.73E-04	3.860E-04	No	Yes
1st Quarter 2000	3/1/2000	LX-1	1.100E-02	4553.1	-2.73E-04	3.168E-03	No	No
1st Quarter 2000	3/1/2000	LX-10	1.100E-01	4684.8	-2.73E-04	3.056E-02	No	No
1st Quarter 2000	3/1/2000	LX-11	4.300E-02	4715.9	-2.73E-04	1.184E-02	No	No
1st Quarter 2000	3/1/2000	LX-12	3.000E-02	4746.4	-2.73E-04	8.194E-03	No	No
1st Quarter 2000	3/1/2000	LX-14	8.200E-03	4809.2	-2.73E-04	2.202E-03	No	No
1st Quarter 2000	3/1/2000	LX-15	4.300E-03	4840.1	-2.73E-04	1.145E-03	No	No
1st Quarter 2000	3/1/2000	LX-17	4.600E-01	12512.4	-2.73E-04	1.503E-02	No	No
1st Quarter 2000	3/1/2000	LX-18	7.700E-01	12499.3	-2.73E-04	2.525E-02	No	No
1st Quarter 2000	3/1/2000	LX-19	1.000E-01	12245.1	-2.73E-04	3.515E-03	No	No
1st Quarter 2000	3/1/2000	LX-2	1.300E-02	4563.1	-2.73E-04	3.733E-03	No	No
1st Quarter 2000	3/1/2000	LX-21	9.700E-02	12247.8	-2.73E-04	3.407E-03	No	No
1st Quarter 2000	3/1/2000	LX-3	2.200E-02	4571.9	-2.73E-04	6.303E-03	No	No
1st Quarter 2000	3/1/2000	LX-4	5.100E-02	4580.3	-2.73E-04	1.458E-02	No	No
1st Quarter 2000	3/1/2000	LX-5	9.000E-02	4583.3	-2.73E-04	2.570E-02	No	No
1st Quarter 2000	3/1/2000	LX-6	8.800E-02	4587.7	-2.73E-04	2.510E-02	No	No
1st Quarter 2000	3/1/2000	LX-7	8.400E-02	4597.5	-2.73E-04	2.390E-02	No	No
1st Quarter 2000	3/1/2000	LX-8	7.600E-02	4623.3	-2.73E-04	2.147E-02	No	No
1st Quarter 2000	3/1/2000	LX-9	6.800E-02	4653.9	-2.73E-04	1.905E-02	No	No
1st Quarter 2000	3/1/2000	PA-381	4.700E-02	6283.1	-2.73E-04	8.433E-03	No	Yes
1st Quarter 2000	3/1/2000	PA-383	1.400E-03	6758.7	-2.73E-04	2.206E-04	No	Yes
1st Quarter 2000	3/1/2000	T-04	8.500E-03	2048.1	-2.73E-04	4.855E-03	No	Yes
1st Quarter 2000	3/1/2000	T-08	2.600E-03	1000.0	-2.73E-04	1.978E-03	No	Yes
1st Quarter 2000	3/1/2000	T-12b	1.000E-04	2981.5	-2.73E-04	4.425E-05	Yes	Yes
1st Quarter 2000	3/1/2000	T-13b	4.600E-03	1931.0	-2.73E-04	2.713E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-03	8.000E-04	7375.0	-2.55E-04	1.223E-04	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-05	2.400E-02	5047.2	-2.55E-04	6.636E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-06	1.400E-01	8348.3	-2.55E-04	1.670E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-108	2.400E-02	12354.3	-2.55E-04	1.032E-03	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

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TRICHLOROETHYLENE (TCE)								
2nd Quarter 2000	6/1/2000	LC-111b	1.000E-04	4567.9	-2.55E-04	3.124E-05	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-116b	4.000E-04	4601.7	-2.55E-04	1.239E-04	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-122b	1.000E-04	4795.4	-2.55E-04	2.948E-05	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-128	2.100E-02	3681.9	-2.55E-04	8.221E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-132	1.000E-01	5644.7	-2.55E-04	2.375E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-134	1.450E+00	12661.3	-2.55E-04	5.766E-02	No	No
2nd Quarter 2000	6/1/2000	LC-136a	1.600E+02	12352.7	-2.55E-04	6.882E+00	No	No
2nd Quarter 2000	6/1/2000	LC-136b	9.000E-02	12348.8	-2.55E-04	3.875E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-137a	5.400E-02	12077.8	-2.55E-04	2.491E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-137b	1.100E-01	12082.4	-2.55E-04	5.069E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-137c	1.000E-04	12086.6	-2.55E-04	4.603E-06	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-149c	1.000E-04	14796.4	-2.55E-04	2.308E-06	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-149d	1.000E-04	14773.9	-2.55E-04	2.322E-06	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-14a	6.700E-02	3382.6	-2.55E-04	2.831E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-162	2.800E-01	12847.7	-2.55E-04	1.062E-02	No	No
2nd Quarter 2000	6/1/2000	LC-165	1.000E-04	4190.8	-2.55E-04	3.439E-05	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-19a	1.700E-01	11025.9	-2.55E-04	1.025E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-19b	7.000E-02	11024.1	-2.55E-04	4.223E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-19c	4.200E-02	11022.5	-2.55E-04	2.535E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-26	7.500E-05	13654.1	-2.55E-04	2.316E-06	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-41a	1.600E-01	7203.5	-2.55E-04	2.554E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-44a	4.200E-02	7149.5	-2.55E-04	6.798E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-49	2.200E-01	9390.6	-2.55E-04	2.012E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-51	1.500E-01	12040.1	-2.55E-04	6.987E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-53	9.500E-02	11161.4	-2.55E-04	5.535E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-64a	3.400E-01	12561.5	-2.55E-04	1.387E-02	No	No
2nd Quarter 2000	6/1/2000	LC-64b	1.800E-02	12560.8	-2.55E-04	7.343E-04	No	Yes
2nd Quarter 2000	6/1/2000	LC-66a	1.000E-01	6311.6	-2.55E-04	2.004E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-66b	1.100E-01	6318.1	-2.55E-04	2.200E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-73a	9.000E-04	3830.2	-2.55E-04	3.393E-04	No	Yes
2nd Quarter 2000	6/1/2000	LX-1	9.200E-03	4553.1	-2.55E-04	2.885E-03	No	No
2nd Quarter 2000	6/1/2000	LX-10	7.700E-02	4684.8	-2.55E-04	2.335E-02	No	No
2nd Quarter 2000	6/1/2000	LX-11	5.100E-02	4715.9	-2.55E-04	1.534E-02	No	No
2nd Quarter 2000	6/1/2000	LX-12	3.600E-02	4746.4	-2.55E-04	1.075E-02	No	No
2nd Quarter 2000	6/1/2000	LX-14	7.600E-03	4809.2	-2.55E-04	2.233E-03	No	No
2nd Quarter 2000	6/1/2000	LX-15	4.500E-03	4840.1	-2.55E-04	1.312E-03	No	No
2nd Quarter 2000	6/1/2000	LX-17	4.000E-01	12512.4	-2.55E-04	1.652E-02	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
2nd Quarter 2000	6/1/2000	LX-18	5.800E-01	12499.3	-2.55E-04	2.403E-02	No	No
2nd Quarter 2000	6/1/2000	LX-19	9.200E-02	12245.1	-2.55E-04	4.067E-03	No	No
2nd Quarter 2000	6/1/2000	LX-2	1.300E-02	4563.1	-2.55E-04	4.066E-03	No	No
2nd Quarter 2000	6/1/2000	LX-21	9.600E-02	12247.8	-2.55E-04	4.241E-03	No	No
2nd Quarter 2000	6/1/2000	LX-3	2.000E-02	4571.9	-2.55E-04	6.242E-03	No	No
2nd Quarter 2000	6/1/2000	LX-4	5.000E-02	4580.3	-2.55E-04	1.557E-02	No	No
2nd Quarter 2000	6/1/2000	LX-5	1.000E-01	4583.3	-2.55E-04	3.112E-02	No	No
2nd Quarter 2000	6/1/2000	LX-6	1.000E-01	4587.7	-2.55E-04	3.108E-02	No	No
2nd Quarter 2000	6/1/2000	LX-7	9.600E-02	4597.5	-2.55E-04	2.977E-02	No	No
2nd Quarter 2000	6/1/2000	LX-8	8.900E-02	4623.3	-2.55E-04	2.741E-02	No	No
2nd Quarter 2000	6/1/2000	LX-9	8.000E-02	4653.9	-2.55E-04	2.445E-02	No	No
2nd Quarter 2000	6/1/2000	PA-381	6.600E-02	6283.1	-2.55E-04	1.332E-02	No	Yes
2nd Quarter 2000	6/1/2000	PA-383	1.600E-03	6758.7	-2.55E-04	2.861E-04	No	Yes
2nd Quarter 2000	6/1/2000	T-04	1.200E-02	2048.1	-2.55E-04	7.122E-03	No	Yes
2nd Quarter 2000	6/1/2000	T-08	2.400E-03	1000.0	-2.55E-04	1.860E-03	No	Yes
2nd Quarter 2000	6/1/2000	T-12b	1.000E-04	2981.5	-2.55E-04	4.680E-05	Yes	Yes
2nd Quarter 2000	6/1/2000	T-13b	4.800E-03	1931.0	-2.55E-04	2.935E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-03	1.800E-02	7375.0	-3.21E-04	1.689E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-05	4.800E-02	5047.2	-3.21E-04	9.506E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-06	1.000E-01	8348.3	-3.21E-04	6.868E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-108	2.400E-02	12354.3	-3.21E-04	4.559E-04	No	Yes
3rd Quarter 2000	9/1/2000	LC-111b	1.000E-04	4567.9	-3.21E-04	2.310E-05	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-116b	4.100E-03	4601.7	-3.21E-04	9.367E-04	No	Yes
3rd Quarter 2000	9/1/2000	LC-122b	1.000E-04	4795.4	-3.21E-04	2.147E-05	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-128	6.200E-02	3681.9	-3.21E-04	1.903E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-132	9.100E-02	5644.7	-3.21E-04	1.488E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-134	2.050E+00	12661.3	-3.21E-04	3.529E-02	No	No
3rd Quarter 2000	9/1/2000	LC-136a	1.900E+02	12352.7	-3.21E-04	3.611E+00	No	No
3rd Quarter 2000	9/1/2000	LC-136b	8.300E-02	12348.8	-3.21E-04	1.579E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-137a	3.300E-01	12077.8	-3.21E-04	6.850E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-137b	2.100E-01	12082.4	-3.21E-04	4.352E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-137c	3.000E-04	12086.6	-3.21E-04	6.210E-06	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-149c	1.000E-04	14796.4	-3.21E-04	8.677E-07	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-149d	1.000E-04	14773.9	-3.21E-04	8.740E-07	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-14a	5.200E-02	3382.6	-3.21E-04	1.757E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-162	2.300E-01	12847.7	-3.21E-04	3.729E-03	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 2000	9/1/2000	LC-165	1.000E-04	4190.8	-3.21E-04	2.607E-05	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-19a	1.800E-01	11025.9	-3.21E-04	5.236E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-19b	9.800E-02	11024.1	-3.21E-04	2.852E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-19c	5.300E-02	11022.5	-3.21E-04	1.543E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-26	1.000E-04	13654.1	-3.21E-04	1.252E-06	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-41a	1.800E-01	7203.5	-3.21E-04	1.785E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-44a	2.700E-02	7149.5	-3.21E-04	2.724E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-49	2.300E-01	9390.6	-3.21E-04	1.131E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-51	1.600E-01	12040.1	-3.21E-04	3.362E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-53	2.100E-01	11161.4	-3.21E-04	5.849E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-64a	2.500E-01	12561.5	-3.21E-04	4.443E-03	No	No
3rd Quarter 2000	9/1/2000	LC-64b	2.100E-02	12560.8	-3.21E-04	3.733E-04	No	Yes
3rd Quarter 2000	9/1/2000	LC-66a	8.000E-02	6311.6	-3.21E-04	1.056E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-66b	1.100E-01	6318.1	-3.21E-04	1.449E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-73a	7.000E-04	3830.2	-3.21E-04	2.048E-04	No	Yes
3rd Quarter 2000	9/1/2000	LX-1	7.600E-03	4553.1	-3.21E-04	1.764E-03	No	No
3rd Quarter 2000	9/1/2000	LX-10	6.400E-02	4684.8	-3.21E-04	1.424E-02	No	No
3rd Quarter 2000	9/1/2000	LX-11	3.500E-02	4715.9	-3.21E-04	7.709E-03	No	No
3rd Quarter 2000	9/1/2000	LX-12	2.300E-02	4746.4	-3.21E-04	5.016E-03	No	No
3rd Quarter 2000	9/1/2000	LX-13	5.300E-03	4777.3	-3.21E-04	1.145E-03	No	No
3rd Quarter 2000	9/1/2000	LX-14	5.800E-03	4809.2	-3.21E-04	1.240E-03	No	No
3rd Quarter 2000	9/1/2000	LX-15	2.900E-03	4840.1	-3.21E-04	6.138E-04	No	No
3rd Quarter 2000	9/1/2000	LX-17	4.700E-01	12512.4	-3.21E-04	8.486E-03	No	No
3rd Quarter 2000	9/1/2000	LX-18	6.550E-01	12499.3	-3.21E-04	1.188E-02	No	No
3rd Quarter 2000	9/1/2000	LX-19	8.800E-02	12245.1	-3.21E-04	1.731E-03	No	No
3rd Quarter 2000	9/1/2000	LX-2	9.800E-03	4563.1	-3.21E-04	2.267E-03	No	No
3rd Quarter 2000	9/1/2000	LX-21	1.000E-01	12247.8	-3.21E-04	1.965E-03	No	No
3rd Quarter 2000	9/1/2000	LX-3	2.000E-02	4571.9	-3.21E-04	4.613E-03	No	No
3rd Quarter 2000	9/1/2000	LX-4	5.600E-02	4580.3	-3.21E-04	1.288E-02	No	No
3rd Quarter 2000	9/1/2000	LX-5	6.300E-02	4583.3	-3.21E-04	1.448E-02	No	No
3rd Quarter 2000	9/1/2000	LX-6	8.900E-02	4587.7	-3.21E-04	2.043E-02	No	No
3rd Quarter 2000	9/1/2000	LX-7	8.300E-02	4597.5	-3.21E-04	1.899E-02	No	No
3rd Quarter 2000	9/1/2000	LX-9	6.700E-02	4653.9	-3.21E-04	1.505E-02	No	No
3rd Quarter 2000	9/1/2000	PA-381	3.500E-02	6283.1	-3.21E-04	4.663E-03	No	Yes
3rd Quarter 2000	9/1/2000	PA-383	1.000E-03	6758.7	-3.21E-04	1.144E-04	Yes	Yes
3rd Quarter 2000	9/1/2000	T-04	8.300E-03	2048.1	-3.21E-04	4.302E-03	No	Yes
3rd Quarter 2000	9/1/2000	T-08	2.200E-03	1000.0	-3.21E-04	1.596E-03	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 2000	9/1/2000	T-12b	1.000E-04	2981.5	-3.21E-04	3.842E-05	Yes	Yes
3rd Quarter 2000	9/1/2000	T-13b	3.750E-03	1931.0	-3.21E-04	2.018E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-03	2.000E-03	7375.0	-3.03E-04	2.140E-04	No	Yes
4th Quarter 2000	12/1/2000	LC-05	7.600E-02	5047.2	-3.03E-04	1.646E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-06	4.600E-02	8348.3	-3.03E-04	3.664E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-108	4.200E-03	12354.3	-3.03E-04	9.934E-05	Yes	Yes
4th Quarter 2000	12/1/2000	LC-111b	1.000E-04	4567.9	-3.03E-04	2.505E-05	Yes	Yes
4th Quarter 2000	12/1/2000	LC-116b	5.700E-03	4601.7	-3.03E-04	1.413E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-122b	1.000E-04	4795.4	-3.03E-04	2.338E-05	Yes	Yes
4th Quarter 2000	12/1/2000	LC-128	2.200E-02	3681.9	-3.03E-04	7.208E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-132	1.000E-01	5644.7	-3.03E-04	1.807E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-136a	7.500E+01	12352.7	-3.03E-04	1.775E+00	No	No
4th Quarter 2000	12/1/2000	LC-136b	1.000E-01	12348.8	-3.03E-04	2.369E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-137a	2.800E-01	12077.8	-3.03E-04	7.202E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-137b	2.800E-01	12082.4	-3.03E-04	7.192E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-137c	1.000E-04	12086.6	-3.03E-04	2.565E-06	Yes	Yes
4th Quarter 2000	12/1/2000	LC-149c	1.000E-04	14796.4	-3.03E-04	1.128E-06	Yes	Yes
4th Quarter 2000	12/1/2000	LC-149d	1.000E-04	14773.9	-3.03E-04	1.136E-06	Yes	Yes
4th Quarter 2000	12/1/2000	LC-14a	5.000E-02	3382.6	-3.03E-04	1.794E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-165	1.000E-04	4190.8	-3.03E-04	2.808E-05	Yes	Yes
4th Quarter 2000	12/1/2000	LC-19a	1.000E-01	11025.9	-3.03E-04	3.538E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-19b	1.100E-01	11024.1	-3.03E-04	3.894E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-19c	3.700E-02	11022.5	-3.03E-04	1.310E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-26	4.700E-02	13654.1	-3.03E-04	7.497E-04	No	Yes
4th Quarter 2000	12/1/2000	LC-41a	8.000E-02	7203.5	-3.03E-04	9.014E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-44a	3.000E-02	7149.5	-3.03E-04	3.436E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-49	3.300E-01	9390.6	-3.03E-04	1.916E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-51	1.700E-01	12040.1	-3.03E-04	4.423E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-53	2.700E-01	11161.4	-3.03E-04	9.168E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-64a	1.000E-02	12561.5	-3.03E-04	2.221E-04	No	No
4th Quarter 2000	12/1/2000	LC-64b	2.350E-02	12560.8	-3.03E-04	5.221E-04	No	Yes
4th Quarter 2000	12/1/2000	LC-66a	8.300E-02	6311.6	-3.03E-04	1.226E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-66b	1.300E-01	6318.1	-3.03E-04	1.916E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-73a	9.000E-04	3830.2	-3.03E-04	2.819E-04	No	Yes
4th Quarter 2000	12/1/2000	LX-1	4.900E-03	4553.1	-3.03E-04	1.233E-03	No	No
4th Quarter 2000	12/1/2000	LX-10	3.550E-02	4684.8	-3.03E-04	8.582E-03	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
4th Quarter 2000	12/1/2000	LX-11	1.600E-02	4715.9	-3.03E-04	3.832E-03	No	No
4th Quarter 2000	12/1/2000	LX-12	1.000E-02	4746.4	-3.03E-04	2.373E-03	No	No
4th Quarter 2000	12/1/2000	LX-13	2.900E-03	4777.3	-3.03E-04	6.817E-04	No	No
4th Quarter 2000	12/1/2000	LX-14	2.700E-03	4809.2	-3.03E-04	6.286E-04	No	No
4th Quarter 2000	12/1/2000	LX-15	1.550E-03	4840.1	-3.03E-04	3.575E-04	No	No
4th Quarter 2000	12/1/2000	LX-17	2.900E-01	12512.4	-3.03E-04	6.538E-03	No	No
4th Quarter 2000	12/1/2000	LX-18	3.825E-01	12499.3	-3.03E-04	8.658E-03	No	No
4th Quarter 2000	12/1/2000	LX-19	5.500E-02	12245.1	-3.03E-04	1.345E-03	No	No
4th Quarter 2000	12/1/2000	LX-2	6.000E-03	4563.1	-3.03E-04	1.505E-03	No	No
4th Quarter 2000	12/1/2000	LX-21	5.000E-02	12247.8	-3.03E-04	1.221E-03	No	No
4th Quarter 2000	12/1/2000	LX-3	1.350E-02	4571.9	-3.03E-04	3.377E-03	No	No
4th Quarter 2000	12/1/2000	LX-4	3.600E-02	4580.3	-3.03E-04	8.983E-03	No	No
4th Quarter 2000	12/1/2000	LX-5	5.250E-02	4583.3	-3.03E-04	1.309E-02	No	No
4th Quarter 2000	12/1/2000	LX-6	5.500E-02	4587.7	-3.03E-04	1.369E-02	No	No
4th Quarter 2000	12/1/2000	LX-7	5.000E-02	4597.5	-3.03E-04	1.241E-02	No	No
4th Quarter 2000	12/1/2000	LX-9	3.900E-02	4653.9	-3.03E-04	9.517E-03	No	No
4th Quarter 2000	12/1/2000	PA-381	4.300E-02	6283.1	-3.03E-04	6.404E-03	No	Yes
4th Quarter 2000	12/1/2000	PA-383	1.100E-03	6758.7	-3.03E-04	1.418E-04	Yes	Yes
4th Quarter 2000	12/1/2000	T-04	8.000E-03	2048.1	-3.03E-04	4.300E-03	No	Yes
4th Quarter 2000	12/1/2000	T-08	2.900E-03	1000.0	-3.03E-04	2.142E-03	No	Yes
4th Quarter 2000	12/1/2000	T-12b	1.000E-04	2981.5	-3.03E-04	4.051E-05	Yes	Yes
4th Quarter 2000	12/1/2000	T-13b	4.900E-03	1931.0	-3.03E-04	2.729E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-03	1.500E-03	7375.0	-3.13E-04	1.486E-04	Yes	Yes
1st Quarter 2001	3/1/2001	LC-05	8.300E-02	5047.2	-3.13E-04	1.706E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-06	6.700E-02	8348.3	-3.13E-04	4.893E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-108	1.300E-02	12354.3	-3.13E-04	2.704E-04	No	Yes
1st Quarter 2001	3/1/2001	LC-111b	1.000E-04	4567.9	-3.13E-04	2.388E-05	Yes	Yes
1st Quarter 2001	3/1/2001	LC-116b	1.400E-02	4601.7	-3.13E-04	3.309E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-122b	1.000E-04	4795.4	-3.13E-04	2.224E-05	Yes	Yes
1st Quarter 2001	3/1/2001	LC-128	2.100E-02	3681.9	-3.13E-04	6.622E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-132	9.700E-02	5644.7	-3.13E-04	1.653E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-136a	1.900E+02	12352.7	-3.13E-04	3.954E+00	No	No
1st Quarter 2001	3/1/2001	LC-136b	1.100E-01	12348.8	-3.13E-04	2.292E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-137a	2.700E-01	12077.8	-3.13E-04	6.125E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-137b	2.500E-01	12082.4	-3.13E-04	5.663E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-137c	1.000E-04	12086.6	-3.13E-04	2.262E-06	Yes	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1st Quarter 2001	3/1/2001	LC-149c	1.000E-04	14796.4	-3.13E-04	9.674E-07	Yes	Yes
1st Quarter 2001	3/1/2001	LC-149d	1.000E-04	14773.9	-3.13E-04	9.743E-07	Yes	Yes
1st Quarter 2001	3/1/2001	LC-14a	5.800E-02	3382.6	-3.13E-04	2.009E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-165	1.000E-04	4190.8	-3.13E-04	2.688E-05	Yes	Yes
1st Quarter 2001	3/1/2001	LC-19a	1.600E-01	11025.9	-3.13E-04	5.047E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-19b	8.600E-02	11024.1	-3.13E-04	2.714E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-19c	4.400E-02	11022.5	-3.13E-04	1.389E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-26	3.000E-04	13654.1	-3.13E-04	4.152E-06	Yes	Yes
1st Quarter 2001	3/1/2001	LC-41a	1.900E-01	7203.5	-3.13E-04	1.986E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-44a	3.400E-02	7149.5	-3.13E-04	3.615E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-49	2.400E-01	9390.6	-3.13E-04	1.264E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-51	1.500E-01	12040.1	-3.13E-04	3.443E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-53	2.200E-01	11161.4	-3.13E-04	6.651E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-64a	8.600E+00	12561.5	-3.13E-04	1.676E-01	No	No
1st Quarter 2001	3/1/2001	LC-64b	1.600E-02	12560.8	-3.13E-04	3.120E-04	No	Yes
1st Quarter 2001	3/1/2001	LC-66a	6.700E-02	6311.6	-3.13E-04	9.264E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-66b	1.100E-01	6318.1	-3.13E-04	1.518E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-73a	7.000E-04	3830.2	-3.13E-04	2.107E-04	No	Yes
1st Quarter 2001	3/1/2001	LX-1	1.100E-02	4553.1	-3.13E-04	2.640E-03	No	No
1st Quarter 2001	3/1/2001	LX-10	4.300E-02	4684.8	-3.13E-04	9.901E-03	No	No
1st Quarter 2001	3/1/2001	LX-11	2.600E-02	4715.9	-3.13E-04	5.929E-03	No	No
1st Quarter 2001	3/1/2001	LX-12	2.000E-02	4746.4	-3.13E-04	4.517E-03	No	No
1st Quarter 2001	3/1/2001	LX-13	6.500E-03	4777.3	-3.13E-04	1.454E-03	No	No
1st Quarter 2001	3/1/2001	LX-14	5.900E-03	4809.2	-3.13E-04	1.307E-03	No	No
1st Quarter 2001	3/1/2001	LX-15	3.000E-03	4840.1	-3.13E-04	6.579E-04	No	No
1st Quarter 2001	3/1/2001	LX-18	8.000E-01	12499.3	-3.13E-04	1.590E-02	No	No
1st Quarter 2001	3/1/2001	LX-19	1.200E-01	12245.1	-3.13E-04	2.583E-03	No	No
1st Quarter 2001	3/1/2001	LX-2	1.400E-02	4563.1	-3.13E-04	3.349E-03	No	No
1st Quarter 2001	3/1/2001	LX-21	9.200E-02	12247.8	-3.13E-04	1.979E-03	No	No
1st Quarter 2001	3/1/2001	LX-3	2.300E-02	4571.9	-3.13E-04	5.487E-03	No	No
1st Quarter 2001	3/1/2001	LX-4	5.800E-02	4580.3	-3.13E-04	1.380E-02	No	No
1st Quarter 2001	3/1/2001	LX-5	9.100E-02	4583.3	-3.13E-04	2.163E-02	No	No
1st Quarter 2001	3/1/2001	LX-6	8.200E-02	4587.7	-3.13E-04	1.946E-02	No	No
1st Quarter 2001	3/1/2001	LX-7	7.900E-02	4597.5	-3.13E-04	1.869E-02	No	No
1st Quarter 2001	3/1/2001	LX-8	7.300E-02	4623.3	-3.13E-04	1.714E-02	No	No
1st Quarter 2001	3/1/2001	LX-9	6.100E-02	4653.9	-3.13E-04	1.418E-02	No	No
1st Quarter 2001	3/1/2001	PA-381	2.300E-02	6283.1	-3.13E-04	3.209E-03	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1st Quarter 2001	3/1/2001	PA-383	8.000E-04	6758.7	-3.13E-04	9.615E-05	Yes	Yes
1st Quarter 2001	3/1/2001	T-04	1.200E-02	2048.1	-3.13E-04	6.315E-03	No	Yes
1st Quarter 2001	3/1/2001	T-08	2.400E-03	1000.0	-3.13E-04	1.754E-03	No	Yes
1st Quarter 2001	3/1/2001	T-12b	1.000E-04	2981.5	-3.13E-04	3.927E-05	Yes	Yes
1st Quarter 2001	3/1/2001	T-13b	4.250E-03	1931.0	-3.13E-04	2.320E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-03	1.500E-03	7375.0	-3.54E-04	1.102E-04	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-05	4.100E-02	5047.2	-3.54E-04	6.865E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-06	7.400E-02	8348.3	-3.54E-04	3.850E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-108	1.600E-02	12354.3	-3.54E-04	2.015E-04	No	Yes
2nd Quarter 2001	6/1/2001	LC-111b	1.000E-04	4567.9	-3.54E-04	1.984E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-116b	1.100E-02	4601.7	-3.54E-04	2.157E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-122b	1.000E-04	4795.4	-3.54E-04	1.831E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-128	2.200E-02	3681.9	-3.54E-04	5.974E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-132	9.900E-02	5644.7	-3.54E-04	1.342E-02	No	Yes
2nd Quarter 2001	6/1/2001	LC-136a	1.800E+02	12352.7	-3.54E-04	2.268E+00	No	No
2nd Quarter 2001	6/1/2001	LC-136b	9.200E-02	12348.8	-3.54E-04	1.161E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-137a	3.500E-01	12077.8	-3.54E-04	4.862E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-137b	3.200E-01	12082.4	-3.54E-04	4.438E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-137c	1.000E-04	12086.6	-3.54E-04	1.385E-06	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-149c	1.000E-04	14796.4	-3.54E-04	5.305E-07	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-149d	1.000E-04	14773.9	-3.54E-04	5.347E-07	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-14a	3.500E-02	3382.6	-3.54E-04	1.057E-02	No	Yes
2nd Quarter 2001	6/1/2001	LC-165	1.000E-04	4190.8	-3.54E-04	2.268E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-19a	1.600E-01	11025.9	-3.54E-04	3.226E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-19b	4.500E-02	11024.1	-3.54E-04	9.077E-04	No	Yes
2nd Quarter 2001	6/1/2001	LC-19c	6.200E-02	11022.5	-3.54E-04	1.251E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-26	3.000E-04	13654.1	-3.54E-04	2.385E-06	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-41a	2.000E-01	7203.5	-3.54E-04	1.561E-02	No	Yes
2nd Quarter 2001	6/1/2001	LC-44a	2.800E-02	7149.5	-3.54E-04	2.227E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-49	2.400E-01	9390.6	-3.54E-04	8.633E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-51	1.500E-01	12040.1	-3.54E-04	2.112E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-53	1.900E-01	11161.4	-3.54E-04	3.651E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-64a	1.400E+01	12561.5	-3.54E-04	1.639E-01	No	No
2nd Quarter 2001	6/1/2001	LC-64b	2.200E-02	12560.8	-3.54E-04	2.576E-04	No	Yes
2nd Quarter 2001	6/1/2001	LC-66a	6.800E-02	6311.6	-3.54E-04	7.277E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-66b	1.100E-01	6318.1	-3.54E-04	1.174E-02	No	Yes

Project: Fort Lewis Upper Aquifer　　**User Name:** Meng

Location: Seattle　　**State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
2nd Quarter 2001	6/1/2001	LC-73a	6.000E-04	3830.2	-3.54E-04	1.546E-04	Yes	Yes
2nd Quarter 2001	6/1/2001	LX-1	1.000E-02	4553.1	-3.54E-04	1.995E-03	No	No
2nd Quarter 2001	6/1/2001	LX-10	3.900E-02	4684.8	-3.54E-04	7.424E-03	No	No
2nd Quarter 2001	6/1/2001	LX-11	2.100E-02	4715.9	-3.54E-04	3.954E-03	No	No
2nd Quarter 2001	6/1/2001	LX-12	1.600E-02	4746.4	-3.54E-04	2.980E-03	No	No
2nd Quarter 2001	6/1/2001	LX-13	5.600E-03	4777.3	-3.54E-04	1.032E-03	No	No
2nd Quarter 2001	6/1/2001	LX-14	4.700E-03	4809.2	-3.54E-04	8.562E-04	No	No
2nd Quarter 2001	6/1/2001	LX-15	2.400E-03	4840.1	-3.54E-04	4.324E-04	No	No
2nd Quarter 2001	6/1/2001	LX-16	1.200E-01	10934.0	-3.54E-04	2.499E-03	No	No
2nd Quarter 2001	6/1/2001	LX-17	1.100E+00	12512.4	-3.54E-04	1.310E-02	No	No
2nd Quarter 2001	6/1/2001	LX-18	1.050E+00	12499.3	-3.54E-04	1.256E-02	No	No
2nd Quarter 2001	6/1/2001	LX-19	1.300E-01	12245.1	-3.54E-04	1.702E-03	No	No
2nd Quarter 2001	6/1/2001	LX-2	1.300E-02	4563.1	-3.54E-04	2.584E-03	No	No
2nd Quarter 2001	6/1/2001	LX-21	9.600E-02	12247.8	-3.54E-04	1.256E-03	No	No
2nd Quarter 2001	6/1/2001	LX-3	2.700E-02	4571.9	-3.54E-04	5.350E-03	No	No
2nd Quarter 2001	6/1/2001	LX-4	5.400E-02	4580.3	-3.54E-04	1.067E-02	No	No
2nd Quarter 2001	6/1/2001	LX-5	8.550E-02	4583.3	-3.54E-04	1.687E-02	No	No
2nd Quarter 2001	6/1/2001	LX-6	7.900E-02	4587.7	-3.54E-04	1.557E-02	No	No
2nd Quarter 2001	6/1/2001	LX-7	7.200E-02	4597.5	-3.54E-04	1.414E-02	No	No
2nd Quarter 2001	6/1/2001	LX-8	8.200E-02	4623.3	-3.54E-04	1.595E-02	No	No
2nd Quarter 2001	6/1/2001	LX-9	5.500E-02	4653.9	-3.54E-04	1.059E-02	No	No
2nd Quarter 2001	6/1/2001	PA-381	3.600E-02	6283.1	-3.54E-04	3.891E-03	No	Yes
2nd Quarter 2001	6/1/2001	PA-383	8.000E-04	6758.7	-3.54E-04	7.307E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	RW-1	1.500E-01	10572.4	-3.54E-04	3.551E-03	No	No
2nd Quarter 2001	6/1/2001	T-04	8.800E-03	2048.1	-3.54E-04	4.261E-03	No	Yes
2nd Quarter 2001	6/1/2001	T-08	1.900E-03	1000.0	-3.54E-04	1.333E-03	No	Yes
2nd Quarter 2001	6/1/2001	T-12b	1.000E-04	2981.5	-3.54E-04	3.479E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	T-13b	4.000E-03	1931.0	-3.54E-04	2.019E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-03	2.200E-03	7375.0	-3.43E-04	1.756E-04	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-05	7.300E-02	5047.2	-3.43E-04	1.294E-02	No	Yes
3rd Quarter 2001	9/1/2001	LC-06	6.100E-02	8348.3	-3.43E-04	3.487E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-108	4.000E-03	12354.3	-3.43E-04	5.792E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-111b	1.000E-04	4567.9	-3.43E-04	2.089E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-116b	1.400E-02	4601.7	-3.43E-04	2.891E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-122b	1.000E-04	4795.4	-3.43E-04	1.932E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-128	1.350E-02	3681.9	-3.43E-04	3.821E-03	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 2001	9/1/2001	LC-132	1.100E-01	5644.7	-3.43E-04	1.589E-02	No	Yes
3rd Quarter 2001	9/1/2001	LC-136a	2.500E+02	12352.7	-3.43E-04	3.622E+00	No	No
3rd Quarter 2001	9/1/2001	LC-136b	1.250E-01	12348.8	-3.43E-04	1.813E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-137a	4.100E-01	12077.8	-3.43E-04	6.526E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-137b	3.050E-01	12082.4	-3.43E-04	4.847E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-137c	1.000E-04	12086.6	-3.43E-04	1.587E-06	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-149c	1.000E-04	14796.4	-3.43E-04	6.268E-07	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-149d	1.000E-04	14773.9	-3.43E-04	6.317E-07	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-14a	4.600E-02	3382.6	-3.43E-04	1.443E-02	No	Yes
3rd Quarter 2001	9/1/2001	LC-165	1.000E-04	4190.8	-3.43E-04	2.377E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-19a	1.700E-01	11025.9	-3.43E-04	3.881E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-19b	1.400E-01	11024.1	-3.43E-04	3.198E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-19c	6.800E-02	11022.5	-3.43E-04	1.554E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-26	2.000E-03	13654.1	-3.43E-04	1.855E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-41a	1.900E-01	7203.5	-3.43E-04	1.608E-02	No	Yes
3rd Quarter 2001	9/1/2001	LC-44a	3.000E-02	7149.5	-3.43E-04	2.587E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-49	2.500E-01	9390.6	-3.43E-04	9.997E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-51	1.600E-01	12040.1	-3.43E-04	2.580E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-53	1.900E-01	11161.4	-3.43E-04	4.141E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-64a	1.900E+01	12561.5	-3.43E-04	2.562E-01	No	No
3rd Quarter 2001	9/1/2001	LC-64b	1.550E-02	12560.8	-3.43E-04	2.091E-04	No	Yes
3rd Quarter 2001	9/1/2001	LC-66a	6.200E-02	6311.6	-3.43E-04	7.124E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-66b	1.300E-01	6318.1	-3.43E-04	1.490E-02	No	Yes
3rd Quarter 2001	9/1/2001	LC-73a	8.000E-04	3830.2	-3.43E-04	2.152E-04	No	Yes
3rd Quarter 2001	9/1/2001	LX-1	1.000E-02	4553.1	-3.43E-04	2.100E-03	No	No
3rd Quarter 2001	9/1/2001	LX-10	4.600E-02	4684.8	-3.43E-04	9.232E-03	No	No
3rd Quarter 2001	9/1/2001	LX-11	2.000E-02	4715.9	-3.43E-04	3.971E-03	No	No
3rd Quarter 2001	9/1/2001	LX-12	1.300E-02	4746.4	-3.43E-04	2.555E-03	No	No
3rd Quarter 2001	9/1/2001	LX-13	5.300E-03	4777.3	-3.43E-04	1.030E-03	No	No
3rd Quarter 2001	9/1/2001	LX-14	4.200E-03	4809.2	-3.43E-04	8.077E-04	No	No
3rd Quarter 2001	9/1/2001	LX-15	2.300E-03	4840.1	-3.43E-04	4.377E-04	No	No
3rd Quarter 2001	9/1/2001	LX-16	1.400E-01	10934.0	-3.43E-04	3.298E-03	No	No
3rd Quarter 2001	9/1/2001	LX-17	7.800E-01	12512.4	-3.43E-04	1.070E-02	No	No
3rd Quarter 2001	9/1/2001	LX-18	1.200E+00	12499.3	-3.43E-04	1.653E-02	No	No
3rd Quarter 2001	9/1/2001	LX-19	1.600E-01	12245.1	-3.43E-04	2.405E-03	No	No
3rd Quarter 2001	9/1/2001	LX-2	1.100E-02	4563.1	-3.43E-04	2.302E-03	No	No
3rd Quarter 2001	9/1/2001	LX-21	1.000E-01	12247.8	-3.43E-04	1.502E-03	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 2001	9/1/2001	LX-3	2.100E-02	4571.9	-3.43E-04	4.381E-03	No	No
3rd Quarter 2001	9/1/2001	LX-4	5.200E-02	4580.3	-3.43E-04	1.082E-02	No	No
3rd Quarter 2001	9/1/2001	LX-5	7.200E-02	4583.3	-3.43E-04	1.496E-02	No	No
3rd Quarter 2001	9/1/2001	LX-6	7.800E-02	4587.7	-3.43E-04	1.618E-02	No	No
3rd Quarter 2001	9/1/2001	LX-7	7.600E-02	4597.5	-3.43E-04	1.572E-02	No	No
3rd Quarter 2001	9/1/2001	LX-8	6.800E-02	4623.3	-3.43E-04	1.394E-02	No	No
3rd Quarter 2001	9/1/2001	LX-9	5.400E-02	4653.9	-3.43E-04	1.095E-02	No	No
3rd Quarter 2001	9/1/2001	PA-381	3.500E-02	6283.1	-3.43E-04	4.061E-03	No	Yes
3rd Quarter 2001	9/1/2001	PA-383	1.000E-03	6758.7	-3.43E-04	9.858E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	RW-1	1.500E-01	10572.4	-3.43E-04	4.000E-03	No	No
3rd Quarter 2001	9/1/2001	T-04	8.800E-03	2048.1	-3.43E-04	4.361E-03	No	Yes
3rd Quarter 2001	9/1/2001	T-08	2.500E-03	1000.0	-3.43E-04	1.774E-03	No	Yes
3rd Quarter 2001	9/1/2001	T-12b	1.000E-04	2981.5	-3.43E-04	3.598E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	T-13b	3.850E-03	1931.0	-3.43E-04	1.986E-03	No	Yes

Note: Projected Concentrations that are below the user-specified detection limit are indicated by a check mark to its right; for sampling events with less than 3 selected plume centerline wells, NO projected concentrations are calculated because no regression coefficient is available.

MAROS Risk-Based Power Analysis for Site Cleanup

Project: Fort Lewis Upper Aquifer

User Name Meng

Location: Seattle

State: Washington

Parameters:

Groundwater Flow Direction: 140 degrees

Distance to Receptor: 2000 feet

From Period: 2nd Quarter 1998 **to** 3rd Quarter 2001

6/1/1998 9/1/2001

Selected Plume Centerline Wells:

Well	Distance to Receptor (feet)
T-13b	2931.0
LC-14a	4382.6
LC-66b	7318.1
LC-49	10390.6
LC-19a	12025.9
LC-137b	13082.4

The distance is measured in the Groundwater Flow Angle from the well to the compliance boundary.

				Normal Distribution Assumption			Lognormal Distribution Assumption				
Sample Event	Sample Szie	Sample Mean	Sample Stdev.	Cleanup Status	Power	Expected Sample Size	Celanup Status	Power	Expected Sample Size	Alpha Level	Expected Power
TRICHLOROETHYLENE (TCE)				Cleanup Goal = 0.005							
2nd Quarter 1998	35	3.78E-03	4.81E-03	Not Attained	0.436	97	Not Attained	S/E	S/E	0.05	0.8
3rd Quarter 1998	35	8.22E-03	1.35E-02	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
4th Quarter 1998	28	4.03E-02	4.12E-02	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
1st Quarter 1999	35	5.51E-03	7.49E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
2nd Quarter 1999	35	6.76E-03	7.65E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
3rd Quarter 1999	35	4.65E-03	5.41E-03	Not Attained	0.102	>100	Not Attained	S/E	S/E	0.05	0.8
4th Quarter 1999	36	4.70E-03	5.84E-03	Not Attained	0.091	>100	Not Attained	S/E	S/E	0.05	0.8
1st Quarter 2000	36	4.22E-03	5.48E-03	Not Attained	0.211	>100	Not Attained	S/E	S/E	0.05	0.8
2nd Quarter 2000	36	5.32E-03	6.61E-03	Not Attained	S/E	S/E	Not Attained	S/E	S/E	0.05	0.8
3rd Quarter 2000	36	3.48E-03	4.21E-03	Attained	0.690	49	Not Attained	S/E	S/E	0.05	0.8
4th Quarter 2000	36	3.79E-03	4.56E-03	Not Attained	0.475	88	Not Attained	S/E	S/E	0.05	0.8
1st Quarter 2001	36	3.60E-03	4.43E-03	Attained	0.594	63	Not Attained	S/E	S/E	0.05	0.8
2nd Quarter 2001	36	2.38E-03	2.92E-03	Attained	1.000	9	Not Attained	S/E	S/E	0.05	0.8
3rd Quarter 2001	36	2.87E-03	3.55E-03	Attained	0.972	18	Not Attained	S/E	S/E	0.05	0.8

Note: #N/C means "not conducted" due to a small sample size (N<4) or that the mean concentration is much greater than the cleanup level; Sample Size is the number of sampling locations used in the power analysis; Expected Sample Size is the number of concentration data needed to reach the Expected Power under current sample variability.

Risk-Based Power Analysis -- Projected Concentrations

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

From Period 6/1/1998 **to** 9/1/2001 **Distance from the most downgradient well to recep** 2000 feet

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
2nd Quarter 1998	6/1/1998	LC-03	6.000E-04	8375.0	-2.88E-04	5.365E-05	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-05	3.200E-02	6047.2	-2.88E-04	5.598E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-06	3.400E-02	9348.3	-2.88E-04	2.296E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-108	1.700E-02	13354.3	-2.88E-04	3.618E-04	No	Yes
2nd Quarter 1998	6/1/1998	LC-111b	6.000E-04	5567.9	-2.88E-04	1.205E-04	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-116b	2.450E-04	5601.7	-2.88E-04	4.873E-05	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-122b	6.000E-04	5795.4	-2.88E-04	1.129E-04	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-128	1.900E-02	4681.9	-2.88E-04	4.927E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-132	7.300E-02	6644.7	-2.88E-04	1.075E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-134	2.800E+00	13661.3	-2.88E-04	5.454E-02	No	No
2nd Quarter 1998	6/1/1998	LC-136a	7.800E+01	13352.7	-2.88E-04	1.661E+00	No	No
2nd Quarter 1998	6/1/1998	LC-136b	7.000E-02	13348.8	-2.88E-04	1.492E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-137a	1.000E-01	13077.8	-2.88E-04	2.305E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-137b	1.200E-01	13082.4	-2.88E-04	2.762E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-137c	4.300E-03	13086.6	-2.88E-04	9.885E-05	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-144a	3.400E-02	12261.0	-2.88E-04	9.917E-04	No	No
2nd Quarter 1998	6/1/1998	LC-149c	6.000E-04	15796.4	-2.88E-04	6.315E-06	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-149d	6.000E-04	15773.9	-2.88E-04	6.356E-06	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-14a	4.700E-02	4382.6	-2.88E-04	1.329E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-162	4.500E-01	13847.7	-2.88E-04	8.307E-03	No	No
2nd Quarter 1998	6/1/1998	LC-165	6.000E-04	5190.8	-2.88E-04	1.344E-04	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-19a	2.000E-01	12025.9	-2.88E-04	6.242E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-19b	9.700E-02	12024.1	-2.88E-04	3.029E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-19c	7.600E-02	12022.5	-2.88E-04	2.374E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-26	1.400E-04	14654.1	-2.88E-04	2.048E-06	Yes	Yes
2nd Quarter 1998	6/1/1998	LC-41a	1.800E-01	8203.5	-2.88E-04	1.691E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-44a	1.400E-02	8149.5	-2.88E-04	1.336E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-49	2.600E-01	10390.6	-2.88E-04	1.300E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-49a	8.900E-02	10398.3	-2.88E-04	4.441E-03	No	No
2nd Quarter 1998	6/1/1998	LC-51	1.500E-01	13040.1	-2.88E-04	3.495E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-53	1.500E-01	12161.4	-2.88E-04	4.502E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-64a	7.500E-01	13561.5	-2.88E-04	1.504E-02	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
2nd Quarter 1998	6/1/1998	LC-64b	5.900E-02	13560.8	-2.88E-04	1.183E-03	No	Yes
2nd Quarter 1998	6/1/1998	LC-66a	9.600E-02	7311.6	-2.88E-04	1.166E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-66b	1.200E-01	7318.1	-2.88E-04	1.455E-02	No	Yes
2nd Quarter 1998	6/1/1998	LC-73a	4.800E-04	4830.2	-2.88E-04	1.193E-04	Yes	Yes
2nd Quarter 1998	6/1/1998	LX-1	1.100E-02	5553.1	-2.88E-04	2.219E-03	No	No
2nd Quarter 1998	6/1/1998	LX-10	5.500E-02	5684.8	-2.88E-04	1.068E-02	No	No
2nd Quarter 1998	6/1/1998	LX-11	3.700E-02	5715.9	-2.88E-04	7.121E-03	No	No
2nd Quarter 1998	6/1/1998	LX-12	2.000E-02	5746.4	-2.88E-04	3.816E-03	No	No
2nd Quarter 1998	6/1/1998	LX-13	4.500E-03	5777.3	-2.88E-04	8.509E-04	No	No
2nd Quarter 1998	6/1/1998	LX-14	5.300E-03	5809.2	-2.88E-04	9.930E-04	No	No
2nd Quarter 1998	6/1/1998	LX-15	2.700E-03	5840.1	-2.88E-04	5.014E-04	No	No
2nd Quarter 1998	6/1/1998	LX-16	1.500E-01	11934.0	-2.88E-04	4.807E-03	No	No
2nd Quarter 1998	6/1/1998	LX-17	4.500E-01	13512.4	-2.88E-04	9.150E-03	No	No
2nd Quarter 1998	6/1/1998	LX-18	7.000E-01	13499.3	-2.88E-04	1.429E-02	No	No
2nd Quarter 1998	6/1/1998	LX-19	1.100E-01	13245.1	-2.88E-04	2.416E-03	No	No
2nd Quarter 1998	6/1/1998	LX-2	1.500E-02	5563.1	-2.88E-04	3.017E-03	No	No
2nd Quarter 1998	6/1/1998	LX-21	1.100E-01	13247.8	-2.88E-04	2.414E-03	No	No
2nd Quarter 1998	6/1/1998	LX-3	3.000E-02	5571.9	-2.88E-04	6.019E-03	No	No
2nd Quarter 1998	6/1/1998	LX-4	6.700E-02	5580.3	-2.88E-04	1.341E-02	No	No
2nd Quarter 1998	6/1/1998	LX-5	8.800E-02	5583.3	-2.88E-04	1.760E-02	No	No
2nd Quarter 1998	6/1/1998	LX-6	9.600E-02	5587.7	-2.88E-04	1.917E-02	No	No
2nd Quarter 1998	6/1/1998	LX-7	7.500E-02	5597.5	-2.88E-04	1.494E-02	No	No
2nd Quarter 1998	6/1/1998	LX-8	6.800E-02	5623.3	-2.88E-04	1.344E-02	No	No
2nd Quarter 1998	6/1/1998	LX-9	6.700E-02	5653.9	-2.88E-04	1.313E-02	No	No
2nd Quarter 1998	6/1/1998	PA-381	3.300E-02	7283.1	-2.88E-04	4.042E-03	No	Yes
2nd Quarter 1998	6/1/1998	PA-383	5.000E-04	7758.7	-2.88E-04	5.340E-05	Yes	Yes
2nd Quarter 1998	6/1/1998	RW-1	1.600E-01	11572.4	-2.88E-04	5.691E-03	No	No
2nd Quarter 1998	6/1/1998	T-01	1.900E-03	3217.7	-2.88E-04	7.514E-04	No	No
2nd Quarter 1998	6/1/1998	T-04	5.200E-03	3048.1	-2.88E-04	2.160E-03	No	Yes
2nd Quarter 1998	6/1/1998	T-08	2.300E-03	2000.0	-2.88E-04	1.292E-03	No	Yes
2nd Quarter 1998	6/1/1998	T-13b	4.600E-03	2931.0	-2.88E-04	1.976E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-03	1.500E-03	8375.0	-2.59E-04	1.718E-04	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-05	4.400E-02	6047.2	-2.59E-04	9.203E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-06	1.200E-01	9348.3	-2.59E-04	1.068E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-108	1.100E-02	13354.3	-2.59E-04	3.474E-04	No	Yes
3rd Quarter 1998	9/1/1998	LC-111b	6.000E-04	5567.9	-2.59E-04	1.421E-04	Yes	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 1998	9/1/1998	LC-116b	3.000E-04	5601.7	-2.59E-04	7.042E-05	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-122b	1.000E-04	5795.4	-2.59E-04	2.232E-05	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-128	2.400E-02	4681.9	-2.59E-04	7.147E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-132	5.400E-02	6644.7	-2.59E-04	9.677E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-134	2.800E+00	13661.3	-2.59E-04	8.167E-02	No	No
3rd Quarter 1998	9/1/1998	LC-136a	1.100E+02	13352.7	-2.59E-04	3.475E+00	No	No
3rd Quarter 1998	9/1/1998	LC-136b	9.800E-02	13348.8	-2.59E-04	3.099E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-137a	5.500E-01	13077.8	-2.59E-04	1.866E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-137b	3.300E-01	13082.4	-2.59E-04	1.118E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-137c	1.580E-02	13086.6	-2.59E-04	5.347E-04	No	Yes
3rd Quarter 1998	9/1/1998	LC-149c	1.000E-04	15796.4	-2.59E-04	1.679E-06	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-149d	4.000E-04	15773.9	-2.59E-04	6.754E-06	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-14a	1.100E-01	4382.6	-2.59E-04	3.539E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-162	2.900E-01	13847.7	-2.59E-04	8.060E-03	No	No
3rd Quarter 1998	9/1/1998	LC-165	2.000E-04	5190.8	-2.59E-04	5.221E-05	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-19a	1.567E-01	12025.9	-2.59E-04	6.977E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-19b	1.200E-01	12024.1	-2.59E-04	5.346E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-19c	4.515E-02	12022.5	-2.59E-04	2.012E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-26	1.000E-04	14654.1	-2.59E-04	2.256E-06	Yes	Yes
3rd Quarter 1998	9/1/1998	LC-41a	1.450E-01	8203.5	-2.59E-04	1.736E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-44a	2.000E-02	8149.5	-2.59E-04	2.428E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-49	2.600E-01	10390.6	-2.59E-04	1.768E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-49a	9.200E-02	10398.3	-2.59E-04	6.242E-03	No	No
3rd Quarter 1998	9/1/1998	LC-51	2.000E-01	13040.1	-2.59E-04	6.851E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-53	2.100E-01	12161.4	-2.59E-04	9.030E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-64a	5.800E-01	13561.5	-2.59E-04	1.736E-02	No	No
3rd Quarter 1998	9/1/1998	LC-64b	8.000E-02	13560.8	-2.59E-04	2.395E-03	No	Yes
3rd Quarter 1998	9/1/1998	LC-66a	1.200E-01	7311.6	-2.59E-04	1.810E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-66b	4.800E-01	7318.1	-2.59E-04	7.226E-02	No	Yes
3rd Quarter 1998	9/1/1998	LC-73a	8.000E-04	4830.2	-2.59E-04	2.293E-04	No	Yes
3rd Quarter 1998	9/1/1998	LX-1	9.700E-03	5553.1	-2.59E-04	2.306E-03	No	No
3rd Quarter 1998	9/1/1998	LX-10	5.600E-02	5684.8	-2.59E-04	1.286E-02	No	No
3rd Quarter 1998	9/1/1998	LX-11	3.500E-02	5715.9	-2.59E-04	7.976E-03	No	No
3rd Quarter 1998	9/1/1998	LX-12	2.000E-02	5746.4	-2.59E-04	4.522E-03	No	No
3rd Quarter 1998	9/1/1998	LX-13	5.900E-03	5777.3	-2.59E-04	1.323E-03	No	No
3rd Quarter 1998	9/1/1998	LX-14	5.600E-03	5809.2	-2.59E-04	1.246E-03	No	No
3rd Quarter 1998	9/1/1998	LX-15	3.100E-03	5840.1	-2.59E-04	6.841E-04	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 1998	9/1/1998	LX-17	6.900E-01	13512.4	-2.59E-04	2.092E-02	No	No
3rd Quarter 1998	9/1/1998	LX-18	1.000E+00	13499.3	-2.59E-04	3.042E-02	No	No
3rd Quarter 1998	9/1/1998	LX-19	1.200E-01	13245.1	-2.59E-04	3.898E-03	No	No
3rd Quarter 1998	9/1/1998	LX-2	1.600E-02	5563.1	-2.59E-04	3.793E-03	No	No
3rd Quarter 1998	9/1/1998	LX-21	1.500E-01	13247.8	-2.59E-04	4.869E-03	No	No
3rd Quarter 1998	9/1/1998	LX-3	3.500E-02	5571.9	-2.59E-04	8.279E-03	No	No
3rd Quarter 1998	9/1/1998	LX-5	9.600E-02	5583.3	-2.59E-04	2.264E-02	No	No
3rd Quarter 1998	9/1/1998	LX-6	1.200E-01	5587.7	-2.59E-04	2.827E-02	No	No
3rd Quarter 1998	9/1/1998	LX-7	1.000E-01	5597.5	-2.59E-04	2.350E-02	No	No
3rd Quarter 1998	9/1/1998	LX-8	7.500E-02	5623.3	-2.59E-04	1.751E-02	No	No
3rd Quarter 1998	9/1/1998	LX-9	7.400E-02	5653.9	-2.59E-04	1.714E-02	No	No
3rd Quarter 1998	9/1/1998	PA-381	5.800E-02	7283.1	-2.59E-04	8.811E-03	No	Yes
3rd Quarter 1998	9/1/1998	PA-383	4.000E-04	7758.7	-2.59E-04	5.373E-05	Yes	Yes
3rd Quarter 1998	9/1/1998	T-01	1.700E-03	3217.7	-2.59E-04	7.394E-04	No	No
3rd Quarter 1998	9/1/1998	T-04	1.500E-02	3048.1	-2.59E-04	6.817E-03	No	Yes
3rd Quarter 1998	9/1/1998	T-08	3.700E-03	2000.0	-2.59E-04	2.205E-03	No	Yes
3rd Quarter 1998	9/1/1998	T-13b	6.200E-03	2931.0	-2.59E-04	2.904E-03	No	Yes
4th Quarter 1998	12/1/1998	LC-05	1.800E-02	6047.2	-5.62E-05	1.282E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-06	6.700E-02	9348.3	-5.62E-05	3.963E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-108	1.500E-01	13354.3	-5.62E-05	7.085E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-116b	3.000E-04	5601.7	-5.62E-05	2.190E-04	No	Yes
4th Quarter 1998	12/1/1998	LC-128	1.800E-02	4681.9	-5.62E-05	1.384E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-132	7.700E-02	6644.7	-5.62E-05	5.301E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-134	1.000E+00	13661.3	-5.62E-05	4.642E-01	No	No
4th Quarter 1998	12/1/1998	LC-136a	4.550E+01	13352.7	-5.62E-05	2.149E+01	No	No
4th Quarter 1998	12/1/1998	LC-136b	8.000E-02	13348.8	-5.62E-05	3.780E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-137a	4.800E-02	13077.8	-5.62E-05	2.303E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-137b	3.950E-02	13082.4	-5.62E-05	1.894E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-137c	2.300E-02	13086.6	-5.62E-05	1.103E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-149c	1.000E-04	15796.4	-5.62E-05	4.118E-05	Yes	Yes
4th Quarter 1998	12/1/1998	LC-149d	3.000E-04	15773.9	-5.62E-05	1.237E-04	Yes	Yes
4th Quarter 1998	12/1/1998	LC-14a	4.600E-02	4382.6	-5.62E-05	3.596E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-162	1.100E-01	13847.7	-5.62E-05	5.053E-02	No	No
4th Quarter 1998	12/1/1998	LC-19a	1.900E-01	12025.9	-5.62E-05	9.669E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-19b	7.800E-02	12024.1	-5.62E-05	3.970E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-19c	5.300E-02	12022.5	-5.62E-05	2.698E-02	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
4th Quarter 1998	12/1/1998	LC-41a	1.700E-01	8203.5	-5.62E-05	1.072E-01	No	Yes
4th Quarter 1998	12/1/1998	LC-44a	1.800E-02	8149.5	-5.62E-05	1.139E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-49	3.000E-01	10390.6	-5.62E-05	1.674E-01	No	Yes
4th Quarter 1998	12/1/1998	LC-51	1.400E-01	13040.1	-5.62E-05	6.730E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-53	1.600E-01	12161.4	-5.62E-05	8.081E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-64a	1.200E+00	13561.5	-5.62E-05	5.602E-01	No	No
4th Quarter 1998	12/1/1998	LC-64b	4.100E-02	13560.8	-5.62E-05	1.914E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-66a	1.400E-01	7311.6	-5.62E-05	9.285E-02	No	Yes
4th Quarter 1998	12/1/1998	LC-66b	1.200E-01	7318.1	-5.62E-05	7.955E-02	No	Yes
4th Quarter 1998	12/1/1998	LX-1	5.500E-03	5553.1	-5.62E-05	4.026E-03	No	No
4th Quarter 1998	12/1/1998	LX-10	6.700E-02	5684.8	-5.62E-05	4.869E-02	No	No
4th Quarter 1998	12/1/1998	LX-11	1.400E-02	5715.9	-5.62E-05	1.016E-02	No	No
4th Quarter 1998	12/1/1998	LX-12	1.700E-02	5746.4	-5.62E-05	1.231E-02	No	No
4th Quarter 1998	12/1/1998	LX-13	5.100E-03	5777.3	-5.62E-05	3.687E-03	No	No
4th Quarter 1998	12/1/1998	LX-14	5.000E-03	5809.2	-5.62E-05	3.608E-03	No	No
4th Quarter 1998	12/1/1998	LX-15	2.500E-03	5840.1	-5.62E-05	1.801E-03	No	No
4th Quarter 1998	12/1/1998	LX-17	8.700E-01	13512.4	-5.62E-05	4.073E-01	No	No
4th Quarter 1998	12/1/1998	LX-18	1.000E+00	13499.3	-5.62E-05	4.685E-01	No	No
4th Quarter 1998	12/1/1998	LX-19	2.000E-01	13245.1	-5.62E-05	9.504E-02	No	No
4th Quarter 1998	12/1/1998	LX-2	1.400E-02	5563.1	-5.62E-05	1.024E-02	No	No
4th Quarter 1998	12/1/1998	LX-21	1.300E-01	13247.8	-5.62E-05	6.177E-02	No	No
4th Quarter 1998	12/1/1998	LX-3	3.500E-02	5571.9	-5.62E-05	2.559E-02	No	No
4th Quarter 1998	12/1/1998	LX-5	9.800E-02	5583.3	-5.62E-05	7.162E-02	No	No
4th Quarter 1998	12/1/1998	LX-6	1.200E-01	5587.7	-5.62E-05	8.767E-02	No	No
4th Quarter 1998	12/1/1998	LX-7	5.500E-02	5597.5	-5.62E-05	4.016E-02	No	No
4th Quarter 1998	12/1/1998	LX-8	8.300E-02	5623.3	-5.62E-05	6.052E-02	No	No
4th Quarter 1998	12/1/1998	LX-9	3.950E-02	5653.9	-5.62E-05	2.875E-02	No	No
4th Quarter 1998	12/1/1998	PA-381	2.600E-02	7283.1	-5.62E-05	1.727E-02	No	Yes
4th Quarter 1998	12/1/1998	PA-383	9.000E-04	7758.7	-5.62E-05	5.821E-04	No	Yes
4th Quarter 1998	12/1/1998	T-01	2.000E-03	3217.7	-5.62E-05	1.669E-03	No	No
4th Quarter 1998	12/1/1998	T-04	3.200E-03	3048.1	-5.62E-05	2.696E-03	No	Yes
4th Quarter 1998	12/1/1998	T-08	2.700E-03	2000.0	-5.62E-05	2.413E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-03	8.000E-04	8375.0	-2.44E-04	1.039E-04	Yes	Yes
1st Quarter 1999	3/1/1999	LC-05	6.000E-03	6047.2	-2.44E-04	1.374E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-06	9.800E-03	9348.3	-2.44E-04	1.004E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-108	6.400E-03	13354.3	-2.44E-04	2.470E-04	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1st Quarter 1999	3/1/1999	LC-111b	2.000E-04	5567.9	-2.44E-04	5.149E-05	Yes	Yes
1st Quarter 1999	3/1/1999	LC-116b	3.000E-04	5601.7	-2.44E-04	7.660E-05	Yes	Yes
1st Quarter 1999	3/1/1999	LC-122b	5.000E-04	5795.4	-2.44E-04	1.218E-04	Yes	Yes
1st Quarter 1999	3/1/1999	LC-128	9.500E-03	4681.9	-2.44E-04	3.035E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-132	4.500E-02	6644.7	-2.44E-04	8.910E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-134	1.400E+00	13661.3	-2.44E-04	5.013E-02	No	No
1st Quarter 1999	3/1/1999	LC-136a	1.200E+02	13352.7	-2.44E-04	4.633E+00	No	No
1st Quarter 1999	3/1/1999	LC-136b	1.100E-01	13348.8	-2.44E-04	4.251E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-137a	3.700E-02	13077.8	-2.44E-04	1.527E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-137b	5.500E-02	13082.4	-2.44E-04	2.268E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-137c	1.600E-02	13086.6	-2.44E-04	6.591E-04	No	Yes
1st Quarter 1999	3/1/1999	LC-149c	1.000E-04	15796.4	-2.44E-04	2.128E-06	Yes	Yes
1st Quarter 1999	3/1/1999	LC-149d	1.000E-04	15773.9	-2.44E-04	2.140E-06	Yes	Yes
1st Quarter 1999	3/1/1999	LC-14a	4.000E-02	4382.6	-2.44E-04	1.375E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-162	5.000E-01	13847.7	-2.44E-04	1.711E-02	No	No
1st Quarter 1999	3/1/1999	LC-165	1.000E-04	5190.8	-2.44E-04	2.822E-05	Yes	Yes
1st Quarter 1999	3/1/1999	LC-19a	2.200E-01	12025.9	-2.44E-04	1.174E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-19b	3.300E-01	12024.1	-2.44E-04	1.761E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-19c	5.100E-02	12022.5	-2.44E-04	2.723E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-26	3.000E-04	14654.1	-2.44E-04	8.434E-06	Yes	Yes
1st Quarter 1999	3/1/1999	LC-41a	1.700E-01	8203.5	-2.44E-04	2.302E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-44a	1.300E-02	8149.5	-2.44E-04	1.784E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-49	2.500E-01	10390.6	-2.44E-04	1.987E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-51	1.800E-01	13040.1	-2.44E-04	7.500E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-53	1.800E-01	12161.4	-2.44E-04	9.291E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-64a	1.100E+00	13561.5	-2.44E-04	4.036E-02	No	No
1st Quarter 1999	3/1/1999	LC-64b	5.600E-02	13560.8	-2.44E-04	2.055E-03	No	Yes
1st Quarter 1999	3/1/1999	LC-66a	1.100E-01	7311.6	-2.44E-04	1.851E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-66b	1.600E-01	7318.1	-2.44E-04	2.689E-02	No	Yes
1st Quarter 1999	3/1/1999	LC-73a	1.350E-03	4830.2	-2.44E-04	4.160E-04	No	Yes
1st Quarter 1999	3/1/1999	LX-1	1.300E-02	5553.1	-2.44E-04	3.359E-03	No	No
1st Quarter 1999	3/1/1999	LX-10	7.800E-02	5684.8	-2.44E-04	1.952E-02	No	No
1st Quarter 1999	3/1/1999	LX-11	5.000E-02	5715.9	-2.44E-04	1.242E-02	No	No
1st Quarter 1999	3/1/1999	LX-12	3.300E-02	5746.4	-2.44E-04	8.134E-03	No	No
1st Quarter 1999	3/1/1999	LX-13	5.400E-03	5777.3	-2.44E-04	1.321E-03	No	No
1st Quarter 1999	3/1/1999	LX-14	6.000E-03	5809.2	-2.44E-04	1.456E-03	No	No
1st Quarter 1999	3/1/1999	LX-15	3.500E-03	5840.1	-2.44E-04	8.432E-04	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

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Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1st Quarter 1999	3/1/1999	LX-17	5.800E-01	13512.4	-2.44E-04	2.154E-02	No	No
1st Quarter 1999	3/1/1999	LX-18	9.600E-01	13499.3	-2.44E-04	3.576E-02	No	No
1st Quarter 1999	3/1/1999	LX-19	1.400E-01	13245.1	-2.44E-04	5.549E-03	No	No
1st Quarter 1999	3/1/1999	LX-2	1.400E-02	5563.1	-2.44E-04	3.608E-03	No	No
1st Quarter 1999	3/1/1999	LX-21	1.100E-01	13247.8	-2.44E-04	4.357E-03	No	No
1st Quarter 1999	3/1/1999	LX-3	3.200E-02	5571.9	-2.44E-04	8.230E-03	No	No
1st Quarter 1999	3/1/1999	LX-4	9.200E-02	5580.3	-2.44E-04	2.361E-02	No	No
1st Quarter 1999	3/1/1999	LX-6	1.300E-01	5587.7	-2.44E-04	3.331E-02	No	No
1st Quarter 1999	3/1/1999	LX-7	4.500E-02	5597.5	-2.44E-04	1.150E-02	No	No
1st Quarter 1999	3/1/1999	LX-8	8.600E-02	5623.3	-2.44E-04	2.184E-02	No	No
1st Quarter 1999	3/1/1999	LX-9	8.300E-02	5653.9	-2.44E-04	2.092E-02	No	No
1st Quarter 1999	3/1/1999	PA-381	4.200E-02	7283.1	-2.44E-04	7.118E-03	No	Yes
1st Quarter 1999	3/1/1999	PA-383	1.800E-03	7758.7	-2.44E-04	2.717E-04	No	Yes
1st Quarter 1999	3/1/1999	T-01	1.600E-03	3217.7	-2.44E-04	7.304E-04	No	No
1st Quarter 1999	3/1/1999	T-04	5.300E-03	3048.1	-2.44E-04	2.521E-03	No	Yes
1st Quarter 1999	3/1/1999	T-08	2.500E-03	2000.0	-2.44E-04	1.535E-03	No	Yes
1st Quarter 1999	3/1/1999	T-13b	5.300E-03	2931.0	-2.44E-04	2.594E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-03	4.500E-04	8375.0	-1.95E-04	8.783E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-05	2.200E-02	6047.2	-1.95E-04	6.762E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-06	5.000E-02	9348.3	-1.95E-04	8.071E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-108	2.000E-02	13354.3	-1.95E-04	1.478E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-111b	1.000E-04	5567.9	-1.95E-04	3.375E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-116b	1.000E-04	5601.7	-1.95E-04	3.353E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-122b	1.000E-04	5795.4	-1.95E-04	3.228E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-128	2.100E-02	4681.9	-1.95E-04	8.425E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-132	8.000E-02	6644.7	-1.95E-04	2.188E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-134	5.600E-01	13661.3	-1.95E-04	3.897E-02	No	No
2nd Quarter 1999	6/1/1999	LC-136a	1.000E+02	13352.7	-1.95E-04	7.391E+00	No	No
2nd Quarter 1999	6/1/1999	LC-136b	5.000E-02	13348.8	-1.95E-04	3.698E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-137a	9.500E-02	13077.8	-1.95E-04	7.409E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-137b	8.000E-02	13082.4	-1.95E-04	6.233E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-137c	4.000E-04	13086.6	-1.95E-04	3.114E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-149c	1.000E-04	15796.4	-1.95E-04	4.589E-06	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-149d	1.000E-04	15773.9	-1.95E-04	4.609E-06	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-14a	5.800E-02	4382.6	-1.95E-04	2.467E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-162	1.850E-01	13847.7	-1.95E-04	1.242E-02	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

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Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
2nd Quarter 1999	6/1/1999	LC-165	1.000E-04	5190.8	-1.95E-04	3.633E-05	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-19a	9.000E-02	12025.9	-1.95E-04	8.617E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-19b	9.000E-02	12024.1	-1.95E-04	8.620E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-19c	5.400E-02	12022.5	-1.95E-04	5.174E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-26	1.000E-04	14654.1	-1.95E-04	5.734E-06	Yes	Yes
2nd Quarter 1999	6/1/1999	LC-41a	1.500E-01	8203.5	-1.95E-04	3.027E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-44a	1.750E-02	8149.5	-1.95E-04	3.569E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-49	1.000E-01	10390.6	-1.95E-04	1.317E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-51	9.000E-02	13040.1	-1.95E-04	7.070E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-53	1.000E-01	12161.4	-1.95E-04	9.325E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-64a	5.100E-01	13561.5	-1.95E-04	3.619E-02	No	No
2nd Quarter 1999	6/1/1999	LC-64b	6.400E-02	13560.8	-1.95E-04	4.542E-03	No	Yes
2nd Quarter 1999	6/1/1999	LC-66a	7.150E-02	7311.6	-1.95E-04	1.717E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-66b	7.000E-02	7318.1	-1.95E-04	1.679E-02	No	Yes
2nd Quarter 1999	6/1/1999	LC-73a	4.500E-04	4830.2	-1.95E-04	1.754E-04	Yes	Yes
2nd Quarter 1999	6/1/1999	LX-1	9.800E-03	5553.1	-1.95E-04	3.317E-03	No	No
2nd Quarter 1999	6/1/1999	LX-10	6.300E-02	5684.8	-1.95E-04	2.078E-02	No	No
2nd Quarter 1999	6/1/1999	LX-11	4.500E-02	5715.9	-1.95E-04	1.476E-02	No	No
2nd Quarter 1999	6/1/1999	LX-12	2.700E-02	5746.4	-1.95E-04	8.801E-03	No	No
2nd Quarter 1999	6/1/1999	LX-13	6.800E-03	5777.3	-1.95E-04	2.203E-03	No	No
2nd Quarter 1999	6/1/1999	LX-14	7.500E-03	5809.2	-1.95E-04	2.415E-03	No	No
2nd Quarter 1999	6/1/1999	LX-15	4.400E-03	5840.1	-1.95E-04	1.408E-03	No	No
2nd Quarter 1999	6/1/1999	LX-17	3.900E-01	13512.4	-1.95E-04	2.794E-02	No	No
2nd Quarter 1999	6/1/1999	LX-18	5.400E-01	13499.3	-1.95E-04	3.879E-02	No	No
2nd Quarter 1999	6/1/1999	LX-19	1.200E-01	13245.1	-1.95E-04	9.058E-03	No	No
2nd Quarter 1999	6/1/1999	LX-2	1.200E-02	5563.1	-1.95E-04	4.054E-03	No	No
2nd Quarter 1999	6/1/1999	LX-21	9.300E-02	13247.8	-1.95E-04	7.016E-03	No	No
2nd Quarter 1999	6/1/1999	LX-3	2.500E-02	5571.9	-1.95E-04	8.431E-03	No	No
2nd Quarter 1999	6/1/1999	LX-4	5.700E-02	5580.3	-1.95E-04	1.919E-02	No	No
2nd Quarter 1999	6/1/1999	LX-5	9.950E-02	5583.3	-1.95E-04	3.348E-02	No	No
2nd Quarter 1999	6/1/1999	LX-6	9.400E-02	5587.7	-1.95E-04	3.160E-02	No	No
2nd Quarter 1999	6/1/1999	LX-7	8.300E-02	5597.5	-1.95E-04	2.785E-02	No	No
2nd Quarter 1999	6/1/1999	LX-8	7.400E-02	5623.3	-1.95E-04	2.471E-02	No	No
2nd Quarter 1999	6/1/1999	LX-9	6.900E-02	5653.9	-1.95E-04	2.290E-02	No	No
2nd Quarter 1999	6/1/1999	PA-381	5.200E-02	7283.1	-1.95E-04	1.256E-02	No	Yes
2nd Quarter 1999	6/1/1999	PA-383	2.000E-03	7758.7	-1.95E-04	4.402E-04	No	Yes
2nd Quarter 1999	6/1/1999	T-01	1.650E-03	3217.7	-1.95E-04	8.808E-04	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

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TRICHLOROETHYLENE (TCE)								
2nd Quarter 1999	6/1/1999	T-04	8.800E-03	3048.1	-1.95E-04	4.856E-03	No	Yes
2nd Quarter 1999	6/1/1999	T-08	3.100E-03	2000.0	-1.95E-04	2.099E-03	No	Yes
2nd Quarter 1999	6/1/1999	T-13b	5.500E-03	2931.0	-1.95E-04	3.105E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-03	1.200E-03	8375.0	-2.80E-04	1.147E-04	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-05	4.400E-02	6047.2	-2.80E-04	8.075E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-06	1.200E-01	9348.3	-2.80E-04	8.729E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-108	4.000E-04	13354.3	-2.80E-04	9.465E-06	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-111b	1.000E-04	5567.9	-2.80E-04	2.099E-05	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-116b	3.000E-04	5601.7	-2.80E-04	6.239E-05	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-122b	1.000E-04	5795.4	-2.80E-04	1.970E-05	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-128	2.200E-02	4681.9	-2.80E-04	5.921E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-132	9.100E-02	6644.7	-2.80E-04	1.413E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-134	2.000E+00	13661.3	-2.80E-04	4.342E-02	No	No
3rd Quarter 1999	9/1/1999	LC-136a	1.300E+02	13352.7	-2.80E-04	3.077E+00	No	No
3rd Quarter 1999	9/1/1999	LC-136b	8.100E-02	13348.8	-2.80E-04	1.919E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-137a	2.700E-01	13077.8	-2.80E-04	6.903E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-137b	2.100E-01	13082.4	-2.80E-04	5.362E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-137c	8.100E-03	13086.6	-2.80E-04	2.066E-04	No	Yes
3rd Quarter 1999	9/1/1999	LC-149c	1.000E-04	15796.4	-2.80E-04	1.193E-06	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-149d	1.000E-04	15773.9	-2.80E-04	1.201E-06	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-14a	6.200E-02	4382.6	-2.80E-04	1.815E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-162	2.800E-01	13847.7	-2.80E-04	5.769E-03	No	No
3rd Quarter 1999	9/1/1999	LC-165	1.000E-04	5190.8	-2.80E-04	2.333E-05	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-19a	1.700E-01	12025.9	-2.80E-04	5.838E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-19b	1.200E-01	12024.1	-2.80E-04	4.123E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-19c	4.600E-02	12022.5	-2.80E-04	1.581E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-26	1.000E-04	14654.1	-2.80E-04	1.644E-06	Yes	Yes
3rd Quarter 1999	9/1/1999	LC-41a	1.900E-01	8203.5	-2.80E-04	1.905E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-44a	1.800E-02	8149.5	-2.80E-04	1.832E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-49	1.700E-01	10390.6	-2.80E-04	9.233E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-51	1.600E-01	13040.1	-2.80E-04	4.134E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-53	1.700E-01	12161.4	-2.80E-04	5.620E-03	No	Yes
3rd Quarter 1999	9/1/1999	LC-64a	3.700E-01	13561.5	-2.80E-04	8.261E-03	No	No
3rd Quarter 1999	9/1/1999	LC-64b	3.600E-02	13560.8	-2.80E-04	8.039E-04	No	Yes
3rd Quarter 1999	9/1/1999	LC-66a	8.250E-02	7311.6	-2.80E-04	1.062E-02	No	Yes
3rd Quarter 1999	9/1/1999	LC-66b	1.200E-01	7318.1	-2.80E-04	1.542E-02	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 1999	9/1/1999	LC-73a	8.000E-04	4830.2	-2.80E-04	2.065E-04	No	Yes
3rd Quarter 1999	9/1/1999	LX-1	1.400E-02	5553.1	-2.80E-04	2.951E-03	No	No
3rd Quarter 1999	9/1/1999	LX-10	6.100E-02	5684.8	-2.80E-04	1.239E-02	No	No
3rd Quarter 1999	9/1/1999	LX-11	4.000E-02	5715.9	-2.80E-04	8.056E-03	No	No
3rd Quarter 1999	9/1/1999	LX-12	2.300E-02	5746.4	-2.80E-04	4.593E-03	No	No
3rd Quarter 1999	9/1/1999	LX-14	7.300E-03	5809.2	-2.80E-04	1.432E-03	No	No
3rd Quarter 1999	9/1/1999	LX-15	4.000E-03	5840.1	-2.80E-04	7.780E-04	No	No
3rd Quarter 1999	9/1/1999	LX-17	4.800E-01	13512.4	-2.80E-04	1.086E-02	No	No
3rd Quarter 1999	9/1/1999	LX-18	5.350E-01	13499.3	-2.80E-04	1.215E-02	No	No
3rd Quarter 1999	9/1/1999	LX-19	1.000E-01	13245.1	-2.80E-04	2.440E-03	No	No
3rd Quarter 1999	9/1/1999	LX-2	1.100E-02	5563.1	-2.80E-04	2.312E-03	No	No
3rd Quarter 1999	9/1/1999	LX-21	1.100E-01	13247.8	-2.80E-04	2.682E-03	No	No
3rd Quarter 1999	9/1/1999	LX-3	2.400E-02	5571.9	-2.80E-04	5.033E-03	No	No
3rd Quarter 1999	9/1/1999	LX-4	5.900E-02	5580.3	-2.80E-04	1.234E-02	No	No
3rd Quarter 1999	9/1/1999	LX-5	1.000E-01	5583.3	-2.80E-04	2.090E-02	No	No
3rd Quarter 1999	9/1/1999	LX-6	9.200E-02	5587.7	-2.80E-04	1.921E-02	No	No
3rd Quarter 1999	9/1/1999	LX-7	8.300E-02	5597.5	-2.80E-04	1.728E-02	No	No
3rd Quarter 1999	9/1/1999	LX-8	7.200E-02	5623.3	-2.80E-04	1.488E-02	No	No
3rd Quarter 1999	9/1/1999	LX-9	6.900E-02	5653.9	-2.80E-04	1.414E-02	No	No
3rd Quarter 1999	9/1/1999	PA-381	4.400E-02	7283.1	-2.80E-04	5.711E-03	No	Yes
3rd Quarter 1999	9/1/1999	PA-383	2.100E-03	7758.7	-2.80E-04	2.385E-04	No	Yes
3rd Quarter 1999	9/1/1999	T-01	2.400E-03	3217.7	-2.80E-04	9.737E-04	No	No
3rd Quarter 1999	9/1/1999	T-04	1.000E-02	3048.1	-2.80E-04	4.255E-03	No	Yes
3rd Quarter 1999	9/1/1999	T-08	3.800E-03	2000.0	-2.80E-04	2.169E-03	No	Yes
3rd Quarter 1999	9/1/1999	T-13b	5.300E-03	2931.0	-2.80E-04	2.330E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-03	8.500E-04	8375.0	-2.71E-04	8.789E-05	Yes	Yes
4th Quarter 1999	12/1/1999	LC-05	2.700E-02	6047.2	-2.71E-04	5.245E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-06	1.100E-01	9348.3	-2.71E-04	8.737E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-108	3.400E-02	13354.3	-2.71E-04	9.121E-04	No	Yes
4th Quarter 1999	12/1/1999	LC-111b	1.000E-04	5567.9	-2.71E-04	2.212E-05	Yes	Yes
4th Quarter 1999	12/1/1999	LC-116b	1.000E-04	5601.7	-2.71E-04	2.192E-05	Yes	Yes
4th Quarter 1999	12/1/1999	LC-122b	1.000E-04	5795.4	-2.71E-04	2.080E-05	Yes	Yes
4th Quarter 1999	12/1/1999	LC-128	2.850E-02	4681.9	-2.71E-04	8.015E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-132	1.000E-01	6644.7	-2.71E-04	1.652E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-134	1.975E+00	13661.3	-2.71E-04	4.875E-02	No	No
4th Quarter 1999	12/1/1999	LC-136a	1.800E+02	13352.7	-2.71E-04	4.831E+00	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
4th Quarter 1999	12/1/1999	LC-136b	5.000E-02	13348.8	-2.71E-04	1.343E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-137a	5.700E-02	13077.8	-2.71E-04	1.648E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-137b	1.300E-01	13082.4	-2.71E-04	3.754E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-137c	3.000E-04	13086.6	-2.71E-04	8.654E-06	Yes	Yes
4th Quarter 1999	12/1/1999	LC-149c	1.000E-04	15796.4	-2.71E-04	1.384E-06	Yes	Yes
4th Quarter 1999	12/1/1999	LC-149d	1.000E-04	15773.9	-2.71E-04	1.393E-06	Yes	Yes
4th Quarter 1999	12/1/1999	LC-14a	5.200E-02	4382.6	-2.71E-04	1.586E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-162	1.700E-01	13847.7	-2.71E-04	3.990E-03	No	No
4th Quarter 1999	12/1/1999	LC-165	1.000E-04	5190.8	-2.71E-04	2.450E-05	Yes	Yes
4th Quarter 1999	12/1/1999	LC-19a	1.700E-01	12025.9	-2.71E-04	6.537E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-19b	7.300E-02	12024.1	-2.71E-04	2.808E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-19c	4.700E-02	12022.5	-2.71E-04	1.809E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-26	1.000E-04	14654.1	-2.71E-04	1.886E-06	Yes	Yes
4th Quarter 1999	12/1/1999	LC-41a	1.600E-01	8203.5	-2.71E-04	1.733E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-44a	3.700E-02	8149.5	-2.71E-04	4.067E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-49	2.700E-01	10390.6	-2.71E-04	1.617E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-51	8.000E-02	13040.1	-2.71E-04	2.337E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-53	2.300E-01	12161.4	-2.71E-04	8.525E-03	No	Yes
4th Quarter 1999	12/1/1999	LC-64a	4.300E-01	13561.5	-2.71E-04	1.091E-02	No	No
4th Quarter 1999	12/1/1999	LC-64b	9.000E-03	13560.8	-2.71E-04	2.283E-04	No	Yes
4th Quarter 1999	12/1/1999	LC-66a	1.000E-01	7311.6	-2.71E-04	1.379E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-66b	1.300E-01	7318.1	-2.71E-04	1.790E-02	No	Yes
4th Quarter 1999	12/1/1999	LC-73a	1.200E-03	4830.2	-2.71E-04	3.242E-04	No	Yes
4th Quarter 1999	12/1/1999	LX-1	1.100E-02	5553.1	-2.71E-04	2.443E-03	No	No
4th Quarter 1999	12/1/1999	LX-10	6.300E-02	5684.8	-2.71E-04	1.350E-02	No	No
4th Quarter 1999	12/1/1999	LX-11	3.600E-02	5715.9	-2.71E-04	7.651E-03	No	No
4th Quarter 1999	12/1/1999	LX-12	2.200E-02	5746.4	-2.71E-04	4.637E-03	No	No
4th Quarter 1999	12/1/1999	LX-14	6.800E-03	5809.2	-2.71E-04	1.409E-03	No	No
4th Quarter 1999	12/1/1999	LX-15	3.400E-03	5840.1	-2.71E-04	6.987E-04	No	No
4th Quarter 1999	12/1/1999	LX-17	5.500E-01	13512.4	-2.71E-04	1.414E-02	No	No
4th Quarter 1999	12/1/1999	LX-18	7.900E-01	13499.3	-2.71E-04	2.038E-02	No	No
4th Quarter 1999	12/1/1999	LX-19	1.100E-01	13245.1	-2.71E-04	3.040E-03	No	No
4th Quarter 1999	12/1/1999	LX-2	1.500E-02	5563.1	-2.71E-04	3.323E-03	No	No
4th Quarter 1999	12/1/1999	LX-21	1.100E-01	13247.8	-2.71E-04	3.037E-03	No	No
4th Quarter 1999	12/1/1999	LX-3	2.400E-02	5571.9	-2.71E-04	5.303E-03	No	No
4th Quarter 1999	12/1/1999	LX-4	6.000E-02	5580.3	-2.71E-04	1.323E-02	No	No
4th Quarter 1999	12/1/1999	LX-5	1.000E-01	5583.3	-2.71E-04	2.203E-02	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
4th Quarter 1999	12/1/1999	LX-6	9.300E-02	5587.7	-2.71E-04	2.046E-02	No	No
4th Quarter 1999	12/1/1999	LX-7	8.800E-02	5597.5	-2.71E-04	1.931E-02	No	No
4th Quarter 1999	12/1/1999	LX-8	7.700E-02	5623.3	-2.71E-04	1.678E-02	No	No
4th Quarter 1999	12/1/1999	LX-9	6.800E-02	5653.9	-2.71E-04	1.470E-02	No	No
4th Quarter 1999	12/1/1999	PA-381	2.800E-02	7283.1	-2.71E-04	3.892E-03	No	Yes
4th Quarter 1999	12/1/1999	PA-383	1.500E-03	7758.7	-2.71E-04	1.833E-04	Yes	Yes
4th Quarter 1999	12/1/1999	T-04	1.200E-02	3048.1	-2.71E-04	5.254E-03	No	Yes
4th Quarter 1999	12/1/1999	T-08	3.000E-03	2000.0	-2.71E-04	1.745E-03	No	Yes
4th Quarter 1999	12/1/1999	T-12b	4.400E-03	3981.5	-2.71E-04	1.496E-03	No	Yes
4th Quarter 1999	12/1/1999	T-13b	5.400E-03	2931.0	-2.71E-04	2.441E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-03	6.500E-04	8375.0	-2.73E-04	6.583E-05	Yes	Yes
1st Quarter 2000	3/1/2000	LC-05	1.100E-02	6047.2	-2.73E-04	2.105E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-06	6.800E-02	9348.3	-2.73E-04	5.278E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-108	5.100E-03	13354.3	-2.73E-04	1.324E-04	Yes	Yes
1st Quarter 2000	3/1/2000	LC-111b	1.000E-04	5567.9	-2.73E-04	2.182E-05	Yes	Yes
1st Quarter 2000	3/1/2000	LC-116b	1.000E-04	5601.7	-2.73E-04	2.162E-05	Yes	Yes
1st Quarter 2000	3/1/2000	LC-122b	1.000E-04	5795.4	-2.73E-04	2.050E-05	Yes	Yes
1st Quarter 2000	3/1/2000	LC-128	2.500E-02	4681.9	-2.73E-04	6.950E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-132	8.300E-02	6644.7	-2.73E-04	1.349E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-134	1.250E+00	13661.3	-2.73E-04	2.983E-02	No	No
1st Quarter 2000	3/1/2000	LC-136a	1.900E+02	13352.7	-2.73E-04	4.934E+00	No	No
1st Quarter 2000	3/1/2000	LC-136b	9.800E-02	13348.8	-2.73E-04	2.547E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-137a	6.100E-02	13077.8	-2.73E-04	1.708E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-137b	1.350E-01	13082.4	-2.73E-04	3.774E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-137c	2.000E-04	13086.6	-2.73E-04	5.585E-06	Yes	Yes
1st Quarter 2000	3/1/2000	LC-149c	1.000E-04	15796.4	-2.73E-04	1.331E-06	Yes	Yes
1st Quarter 2000	3/1/2000	LC-149d	1.000E-04	15773.9	-2.73E-04	1.339E-06	Yes	Yes
1st Quarter 2000	3/1/2000	LC-14a	5.800E-02	4382.6	-2.73E-04	1.750E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-162	3.800E-01	13847.7	-2.73E-04	8.618E-03	No	No
1st Quarter 2000	3/1/2000	LC-165	1.000E-04	5190.8	-2.73E-04	2.419E-05	Yes	Yes
1st Quarter 2000	3/1/2000	LC-19a	1.800E-01	12025.9	-2.73E-04	6.718E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-19b	8.300E-02	12024.1	-2.73E-04	3.099E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-19c	3.900E-02	12022.5	-2.73E-04	1.457E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-26	1.000E-04	14654.1	-2.73E-04	1.819E-06	Yes	Yes
1st Quarter 2000	3/1/2000	LC-41a	1.500E-01	8203.5	-2.73E-04	1.592E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-44a	1.400E-02	8149.5	-2.73E-04	1.508E-03	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

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TRICHLOROETHYLENE (TCE)								
1st Quarter 2000	3/1/2000	LC-49	2.000E-01	10390.6	-2.73E-04	1.167E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-51	1.700E-01	13040.1	-2.73E-04	4.808E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-53	1.700E-01	12161.4	-2.73E-04	6.114E-03	No	Yes
1st Quarter 2000	3/1/2000	LC-64a	3.900E-01	13561.5	-2.73E-04	9.565E-03	No	No
1st Quarter 2000	3/1/2000	LC-64b	1.800E-02	13560.8	-2.73E-04	4.416E-04	No	Yes
1st Quarter 2000	3/1/2000	LC-66a	1.100E-01	7311.6	-2.73E-04	1.490E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-66b	1.300E-01	7318.1	-2.73E-04	1.758E-02	No	Yes
1st Quarter 2000	3/1/2000	LC-73a	1.100E-03	4830.2	-2.73E-04	2.936E-04	No	Yes
1st Quarter 2000	3/1/2000	LX-1	1.100E-02	5553.1	-2.73E-04	2.410E-03	No	No
1st Quarter 2000	3/1/2000	LX-10	1.100E-01	5684.8	-2.73E-04	2.325E-02	No	No
1st Quarter 2000	3/1/2000	LX-11	4.300E-02	5715.9	-2.73E-04	9.010E-03	No	No
1st Quarter 2000	3/1/2000	LX-12	3.000E-02	5746.4	-2.73E-04	6.234E-03	No	No
1st Quarter 2000	3/1/2000	LX-14	8.200E-03	5809.2	-2.73E-04	1.675E-03	No	No
1st Quarter 2000	3/1/2000	LX-15	4.300E-03	5840.1	-2.73E-04	8.709E-04	No	No
1st Quarter 2000	3/1/2000	LX-17	4.600E-01	13512.4	-2.73E-04	1.143E-02	No	No
1st Quarter 2000	3/1/2000	LX-18	7.700E-01	13499.3	-2.73E-04	1.921E-02	No	No
1st Quarter 2000	3/1/2000	LX-19	1.000E-01	13245.1	-2.73E-04	2.674E-03	No	No
1st Quarter 2000	3/1/2000	LX-2	1.300E-02	5563.1	-2.73E-04	2.840E-03	No	No
1st Quarter 2000	3/1/2000	LX-21	9.700E-02	13247.8	-2.73E-04	2.592E-03	No	No
1st Quarter 2000	3/1/2000	LX-3	2.200E-02	5571.9	-2.73E-04	4.795E-03	No	No
1st Quarter 2000	3/1/2000	LX-4	5.100E-02	5580.3	-2.73E-04	1.109E-02	No	No
1st Quarter 2000	3/1/2000	LX-5	9.000E-02	5583.3	-2.73E-04	1.955E-02	No	No
1st Quarter 2000	3/1/2000	LX-6	8.800E-02	5587.7	-2.73E-04	1.910E-02	No	No
1st Quarter 2000	3/1/2000	LX-7	8.400E-02	5597.5	-2.73E-04	1.818E-02	No	No
1st Quarter 2000	3/1/2000	LX-8	7.600E-02	5623.3	-2.73E-04	1.633E-02	No	No
1st Quarter 2000	3/1/2000	LX-9	6.800E-02	5653.9	-2.73E-04	1.449E-02	No	No
1st Quarter 2000	3/1/2000	PA-381	4.700E-02	7283.1	-2.73E-04	6.416E-03	No	Yes
1st Quarter 2000	3/1/2000	PA-383	1.400E-03	7758.7	-2.73E-04	1.678E-04	Yes	Yes
1st Quarter 2000	3/1/2000	T-04	8.500E-03	3048.1	-2.73E-04	3.694E-03	No	Yes
1st Quarter 2000	3/1/2000	T-08	2.600E-03	2000.0	-2.73E-04	1.505E-03	No	Yes
1st Quarter 2000	3/1/2000	T-12b	1.000E-04	3981.5	-2.73E-04	3.367E-05	Yes	Yes
1st Quarter 2000	3/1/2000	T-13b	4.600E-03	2931.0	-2.73E-04	2.064E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-03	8.000E-04	8375.0	-2.55E-04	9.478E-05	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-05	2.400E-02	6047.2	-2.55E-04	5.144E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-06	1.400E-01	9348.3	-2.55E-04	1.294E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-108	2.400E-02	13354.3	-2.55E-04	7.999E-04	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
2nd Quarter 2000	6/1/2000	LC-111b	1.000E-04	5567.9	-2.55E-04	2.422E-05	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-116b	4.000E-04	5601.7	-2.55E-04	9.604E-05	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-122b	1.000E-04	5795.4	-2.55E-04	2.285E-05	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-128	2.100E-02	4681.9	-2.55E-04	6.373E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-132	1.000E-01	6644.7	-2.55E-04	1.841E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-134	1.450E+00	13661.3	-2.55E-04	4.469E-02	No	No
2nd Quarter 2000	6/1/2000	LC-136a	1.600E+02	13352.7	-2.55E-04	5.335E+00	No	No
2nd Quarter 2000	6/1/2000	LC-136b	9.000E-02	13348.8	-2.55E-04	3.004E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-137a	5.400E-02	13077.8	-2.55E-04	1.931E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-137b	1.100E-01	13082.4	-2.55E-04	3.929E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-137c	1.000E-04	13086.6	-2.55E-04	3.568E-06	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-149c	1.000E-04	15796.4	-2.55E-04	1.789E-06	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-149d	1.000E-04	15773.9	-2.55E-04	1.800E-06	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-14a	6.700E-02	4382.6	-2.55E-04	2.194E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-162	2.800E-01	13847.7	-2.55E-04	8.230E-03	No	No
2nd Quarter 2000	6/1/2000	LC-165	1.000E-04	5190.8	-2.55E-04	2.666E-05	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-19a	1.700E-01	12025.9	-2.55E-04	7.947E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-19b	7.000E-02	12024.1	-2.55E-04	3.274E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-19c	4.200E-02	12022.5	-2.55E-04	1.965E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-26	7.500E-05	14654.1	-2.55E-04	1.795E-06	Yes	Yes
2nd Quarter 2000	6/1/2000	LC-41a	1.600E-01	8203.5	-2.55E-04	1.980E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-44a	4.200E-02	8149.5	-2.55E-04	5.270E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-49	2.200E-01	10390.6	-2.55E-04	1.560E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-51	1.500E-01	13040.1	-2.55E-04	5.416E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-53	9.500E-02	12161.4	-2.55E-04	4.290E-03	No	Yes
2nd Quarter 2000	6/1/2000	LC-64a	3.400E-01	13561.5	-2.55E-04	1.075E-02	No	No
2nd Quarter 2000	6/1/2000	LC-64b	1.800E-02	13560.8	-2.55E-04	5.692E-04	No	Yes
2nd Quarter 2000	6/1/2000	LC-66a	1.000E-01	7311.6	-2.55E-04	1.553E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-66b	1.100E-01	7318.1	-2.55E-04	1.706E-02	No	Yes
2nd Quarter 2000	6/1/2000	LC-73a	9.000E-04	4830.2	-2.55E-04	2.630E-04	No	Yes
2nd Quarter 2000	6/1/2000	LX-1	9.200E-03	5553.1	-2.55E-04	2.236E-03	No	No
2nd Quarter 2000	6/1/2000	LX-10	7.700E-02	5684.8	-2.55E-04	1.810E-02	No	No
2nd Quarter 2000	6/1/2000	LX-11	5.100E-02	5715.9	-2.55E-04	1.189E-02	No	No
2nd Quarter 2000	6/1/2000	LX-12	3.600E-02	5746.4	-2.55E-04	8.330E-03	No	No
2nd Quarter 2000	6/1/2000	LX-14	7.600E-03	5809.2	-2.55E-04	1.731E-03	No	No
2nd Quarter 2000	6/1/2000	LX-15	4.500E-03	5840.1	-2.55E-04	1.017E-03	No	No
2nd Quarter 2000	6/1/2000	LX-17	4.000E-01	13512.4	-2.55E-04	1.281E-02	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
2nd Quarter 2000	6/1/2000	LX-18	5.800E-01	13499.3	-2.55E-04	1.863E-02	No	No
2nd Quarter 2000	6/1/2000	LX-19	9.200E-02	13245.1	-2.55E-04	3.153E-03	No	No
2nd Quarter 2000	6/1/2000	LX-2	1.300E-02	5563.1	-2.55E-04	3.152E-03	No	No
2nd Quarter 2000	6/1/2000	LX-21	9.600E-02	13247.8	-2.55E-04	3.288E-03	No	No
2nd Quarter 2000	6/1/2000	LX-3	2.000E-02	5571.9	-2.55E-04	4.838E-03	No	No
2nd Quarter 2000	6/1/2000	LX-4	5.000E-02	5580.3	-2.55E-04	1.207E-02	No	No
2nd Quarter 2000	6/1/2000	LX-5	1.000E-01	5583.3	-2.55E-04	2.412E-02	No	No
2nd Quarter 2000	6/1/2000	LX-6	1.000E-01	5587.7	-2.55E-04	2.409E-02	No	No
2nd Quarter 2000	6/1/2000	LX-7	9.600E-02	5597.5	-2.55E-04	2.307E-02	No	No
2nd Quarter 2000	6/1/2000	LX-8	8.900E-02	5623.3	-2.55E-04	2.125E-02	No	No
2nd Quarter 2000	6/1/2000	LX-9	8.000E-02	5653.9	-2.55E-04	1.895E-02	No	No
2nd Quarter 2000	6/1/2000	PA-381	6.600E-02	7283.1	-2.55E-04	1.033E-02	No	Yes
2nd Quarter 2000	6/1/2000	PA-383	1.600E-03	7758.7	-2.55E-04	2.218E-04	No	Yes
2nd Quarter 2000	6/1/2000	T-04	1.200E-02	3048.1	-2.55E-04	5.521E-03	No	Yes
2nd Quarter 2000	6/1/2000	T-08	2.400E-03	2000.0	-2.55E-04	1.442E-03	No	Yes
2nd Quarter 2000	6/1/2000	T-12b	1.000E-04	3981.5	-2.55E-04	3.627E-05	Yes	Yes
2nd Quarter 2000	6/1/2000	T-13b	4.800E-03	2931.0	-2.55E-04	2.275E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-03	1.800E-02	8375.0	-3.21E-04	1.226E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-05	4.800E-02	6047.2	-3.21E-04	6.897E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-06	1.000E-01	9348.3	-3.21E-04	4.983E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-108	2.400E-02	13354.3	-3.21E-04	3.308E-04	No	Yes
3rd Quarter 2000	9/1/2000	LC-111b	1.000E-04	5567.9	-3.21E-04	1.676E-05	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-116b	4.100E-03	5601.7	-3.21E-04	6.796E-04	No	Yes
3rd Quarter 2000	9/1/2000	LC-122b	1.000E-04	5795.4	-3.21E-04	1.558E-05	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-128	6.200E-02	4681.9	-3.21E-04	1.381E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-132	9.100E-02	6644.7	-3.21E-04	1.079E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-134	2.050E+00	13661.3	-3.21E-04	2.560E-02	No	No
3rd Quarter 2000	9/1/2000	LC-136a	1.900E+02	13352.7	-3.21E-04	2.620E+00	No	No
3rd Quarter 2000	9/1/2000	LC-136b	8.300E-02	13348.8	-3.21E-04	1.146E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-137a	3.300E-01	13077.8	-3.21E-04	4.970E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-137b	2.100E-01	13082.4	-3.21E-04	3.158E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-137c	3.000E-04	13086.6	-3.21E-04	4.505E-06	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-149c	1.000E-04	15796.4	-3.21E-04	6.296E-07	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-149d	1.000E-04	15773.9	-3.21E-04	6.341E-07	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-14a	5.200E-02	4382.6	-3.21E-04	1.275E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-162	2.300E-01	13847.7	-3.21E-04	2.706E-03	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 2000	9/1/2000	LC-165	1.000E-04	5190.8	-3.21E-04	1.891E-05	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-19a	1.800E-01	12025.9	-3.21E-04	3.799E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-19b	9.800E-02	12024.1	-3.21E-04	2.070E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-19c	5.300E-02	12022.5	-3.21E-04	1.120E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-26	1.000E-04	14654.1	-3.21E-04	9.082E-07	Yes	Yes
3rd Quarter 2000	9/1/2000	LC-41a	1.800E-01	8203.5	-3.21E-04	1.295E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-44a	2.700E-02	8149.5	-3.21E-04	1.976E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-49	2.300E-01	10390.6	-3.21E-04	8.203E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-51	1.600E-01	13040.1	-3.21E-04	2.439E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-53	2.100E-01	12161.4	-3.21E-04	4.244E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-64a	2.500E-01	13561.5	-3.21E-04	3.224E-03	No	No
3rd Quarter 2000	9/1/2000	LC-64b	2.100E-02	13560.8	-3.21E-04	2.709E-04	No	Yes
3rd Quarter 2000	9/1/2000	LC-66a	8.000E-02	7311.6	-3.21E-04	7.662E-03	No	Yes
3rd Quarter 2000	9/1/2000	LC-66b	1.100E-01	7318.1	-3.21E-04	1.051E-02	No	Yes
3rd Quarter 2000	9/1/2000	LC-73a	7.000E-04	4830.2	-3.21E-04	1.486E-04	Yes	Yes
3rd Quarter 2000	9/1/2000	LX-1	7.600E-03	5553.1	-3.21E-04	1.280E-03	No	No
3rd Quarter 2000	9/1/2000	LX-10	6.400E-02	5684.8	-3.21E-04	1.033E-02	No	No
3rd Quarter 2000	9/1/2000	LX-11	3.500E-02	5715.9	-3.21E-04	5.593E-03	No	No
3rd Quarter 2000	9/1/2000	LX-12	2.300E-02	5746.4	-3.21E-04	3.640E-03	No	No
3rd Quarter 2000	9/1/2000	LX-13	5.300E-03	5777.3	-3.21E-04	8.304E-04	No	No
3rd Quarter 2000	9/1/2000	LX-14	5.800E-03	5809.2	-3.21E-04	8.995E-04	No	No
3rd Quarter 2000	9/1/2000	LX-15	2.900E-03	5840.1	-3.21E-04	4.453E-04	No	No
3rd Quarter 2000	9/1/2000	LX-17	4.700E-01	13512.4	-3.21E-04	6.157E-03	No	No
3rd Quarter 2000	9/1/2000	LX-18	6.550E-01	13499.3	-3.21E-04	8.617E-03	No	No
3rd Quarter 2000	9/1/2000	LX-19	8.800E-02	13245.1	-3.21E-04	1.256E-03	No	No
3rd Quarter 2000	9/1/2000	LX-2	9.800E-03	5563.1	-3.21E-04	1.645E-03	No	No
3rd Quarter 2000	9/1/2000	LX-21	1.000E-01	13247.8	-3.21E-04	1.426E-03	No	No
3rd Quarter 2000	9/1/2000	LX-3	2.000E-02	5571.9	-3.21E-04	3.347E-03	No	No
3rd Quarter 2000	9/1/2000	LX-4	5.600E-02	5580.3	-3.21E-04	9.347E-03	No	No
3rd Quarter 2000	9/1/2000	LX-5	6.300E-02	5583.3	-3.21E-04	1.051E-02	No	No
3rd Quarter 2000	9/1/2000	LX-6	8.900E-02	5587.7	-3.21E-04	1.482E-02	No	No
3rd Quarter 2000	9/1/2000	LX-7	8.300E-02	5597.5	-3.21E-04	1.378E-02	No	No
3rd Quarter 2000	9/1/2000	LX-9	6.700E-02	5653.9	-3.21E-04	1.092E-02	No	No
3rd Quarter 2000	9/1/2000	PA-381	3.500E-02	7283.1	-3.21E-04	3.383E-03	No	Yes
3rd Quarter 2000	9/1/2000	PA-383	1.000E-03	7758.7	-3.21E-04	8.298E-05	Yes	Yes
3rd Quarter 2000	9/1/2000	T-04	8.300E-03	3048.1	-3.21E-04	3.122E-03	No	Yes
3rd Quarter 2000	9/1/2000	T-08	2.200E-03	2000.0	-3.21E-04	1.158E-03	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 2000	9/1/2000	T-12b	1.000E-04	3981.5	-3.21E-04	2.788E-05	Yes	Yes
3rd Quarter 2000	9/1/2000	T-13b	3.750E-03	2931.0	-3.21E-04	1.464E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-03	2.000E-03	8375.0	-3.03E-04	1.580E-04	Yes	Yes
4th Quarter 2000	12/1/2000	LC-05	7.600E-02	6047.2	-3.03E-04	1.216E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-06	4.600E-02	9348.3	-3.03E-04	2.706E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-108	4.200E-03	13354.3	-3.03E-04	7.337E-05	Yes	Yes
4th Quarter 2000	12/1/2000	LC-111b	1.000E-04	5567.9	-3.03E-04	1.850E-05	Yes	Yes
4th Quarter 2000	12/1/2000	LC-116b	5.700E-03	5601.7	-3.03E-04	1.044E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-122b	1.000E-04	5795.4	-3.03E-04	1.727E-05	Yes	Yes
4th Quarter 2000	12/1/2000	LC-128	2.200E-02	4681.9	-3.03E-04	5.323E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-132	1.000E-01	6644.7	-3.03E-04	1.335E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-136a	7.500E+01	13352.7	-3.03E-04	1.311E+00	No	No
4th Quarter 2000	12/1/2000	LC-136b	1.000E-01	13348.8	-3.03E-04	1.750E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-137a	2.800E-01	13077.8	-3.03E-04	5.319E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-137b	2.800E-01	13082.4	-3.03E-04	5.311E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-137c	1.000E-04	13086.6	-3.03E-04	1.895E-06	Yes	Yes
4th Quarter 2000	12/1/2000	LC-149c	1.000E-04	15796.4	-3.03E-04	8.333E-07	Yes	Yes
4th Quarter 2000	12/1/2000	LC-149d	1.000E-04	15773.9	-3.03E-04	8.391E-07	Yes	Yes
4th Quarter 2000	12/1/2000	LC-14a	5.000E-02	4382.6	-3.03E-04	1.325E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-165	1.000E-04	5190.8	-3.03E-04	2.074E-05	Yes	Yes
4th Quarter 2000	12/1/2000	LC-19a	1.000E-01	12025.9	-3.03E-04	2.613E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-19b	1.100E-01	12024.1	-3.03E-04	2.876E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-19c	3.700E-02	12022.5	-3.03E-04	9.677E-04	No	Yes
4th Quarter 2000	12/1/2000	LC-26	4.700E-02	14654.1	-3.03E-04	5.537E-04	No	Yes
4th Quarter 2000	12/1/2000	LC-41a	8.000E-02	8203.5	-3.03E-04	6.658E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-44a	3.000E-02	8149.5	-3.03E-04	2.538E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-49	3.300E-01	10390.6	-3.03E-04	1.415E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-51	1.700E-01	13040.1	-3.03E-04	3.266E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-53	2.700E-01	12161.4	-3.03E-04	6.771E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-64a	1.000E-02	13561.5	-3.03E-04	1.641E-04	Yes	No
4th Quarter 2000	12/1/2000	LC-64b	2.350E-02	13560.8	-3.03E-04	3.856E-04	No	Yes
4th Quarter 2000	12/1/2000	LC-66a	8.300E-02	7311.6	-3.03E-04	9.051E-03	No	Yes
4th Quarter 2000	12/1/2000	LC-66b	1.300E-01	7318.1	-3.03E-04	1.415E-02	No	Yes
4th Quarter 2000	12/1/2000	LC-73a	9.000E-04	4830.2	-3.03E-04	2.082E-04	No	Yes
4th Quarter 2000	12/1/2000	LX-1	4.900E-03	5553.1	-3.03E-04	9.105E-04	No	No
4th Quarter 2000	12/1/2000	LX-10	3.550E-02	5684.8	-3.03E-04	6.338E-03	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
4th Quarter 2000	12/1/2000	LX-11	1.600E-02	5715.9	-3.03E-04	2.830E-03	No	No
4th Quarter 2000	12/1/2000	LX-12	1.000E-02	5746.4	-3.03E-04	1.752E-03	No	No
4th Quarter 2000	12/1/2000	LX-13	2.900E-03	5777.3	-3.03E-04	5.035E-04	No	No
4th Quarter 2000	12/1/2000	LX-14	2.700E-03	5809.2	-3.03E-04	4.642E-04	No	No
4th Quarter 2000	12/1/2000	LX-15	1.550E-03	5840.1	-3.03E-04	2.640E-04	No	No
4th Quarter 2000	12/1/2000	LX-17	2.900E-01	13512.4	-3.03E-04	4.829E-03	No	No
4th Quarter 2000	12/1/2000	LX-18	3.825E-01	13499.3	-3.03E-04	6.395E-03	No	No
4th Quarter 2000	12/1/2000	LX-19	5.500E-02	13245.1	-3.03E-04	9.931E-04	No	No
4th Quarter 2000	12/1/2000	LX-2	6.000E-03	5563.1	-3.03E-04	1.112E-03	No	No
4th Quarter 2000	12/1/2000	LX-21	5.000E-02	13247.8	-3.03E-04	9.021E-04	No	No
4th Quarter 2000	12/1/2000	LX-3	1.350E-02	5571.9	-3.03E-04	2.494E-03	No	No
4th Quarter 2000	12/1/2000	LX-4	3.600E-02	5580.3	-3.03E-04	6.634E-03	No	No
4th Quarter 2000	12/1/2000	LX-5	5.250E-02	5583.3	-3.03E-04	9.666E-03	No	No
4th Quarter 2000	12/1/2000	LX-6	5.500E-02	5587.7	-3.03E-04	1.011E-02	No	No
4th Quarter 2000	12/1/2000	LX-7	5.000E-02	5597.5	-3.03E-04	9.167E-03	No	No
4th Quarter 2000	12/1/2000	LX-9	3.900E-02	5653.9	-3.03E-04	7.029E-03	No	No
4th Quarter 2000	12/1/2000	PA-381	4.300E-02	7283.1	-3.03E-04	4.730E-03	No	Yes
4th Quarter 2000	12/1/2000	PA-383	1.100E-03	7758.7	-3.03E-04	1.048E-04	Yes	Yes
4th Quarter 2000	12/1/2000	T-04	8.000E-03	3048.1	-3.03E-04	3.176E-03	No	Yes
4th Quarter 2000	12/1/2000	T-08	2.900E-03	2000.0	-3.03E-04	1.582E-03	No	Yes
4th Quarter 2000	12/1/2000	T-12b	1.000E-04	3981.5	-3.03E-04	2.992E-05	Yes	Yes
4th Quarter 2000	12/1/2000	T-13b	4.900E-03	2931.0	-3.03E-04	2.016E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-03	1.500E-03	8375.0	-3.13E-04	1.086E-04	Yes	Yes
1st Quarter 2001	3/1/2001	LC-05	8.300E-02	6047.2	-3.13E-04	1.247E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-06	6.700E-02	9348.3	-3.13E-04	3.576E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-108	1.300E-02	13354.3	-3.13E-04	1.977E-04	Yes	Yes
1st Quarter 2001	3/1/2001	LC-111b	1.000E-04	5567.9	-3.13E-04	1.746E-05	Yes	Yes
1st Quarter 2001	3/1/2001	LC-116b	1.400E-02	5601.7	-3.13E-04	2.418E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-122b	1.000E-04	5795.4	-3.13E-04	1.626E-05	Yes	Yes
1st Quarter 2001	3/1/2001	LC-128	2.100E-02	4681.9	-3.13E-04	4.840E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-132	9.700E-02	6644.7	-3.13E-04	1.208E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-136a	1.900E+02	13352.7	-3.13E-04	2.890E+00	No	No
1st Quarter 2001	3/1/2001	LC-136b	1.100E-01	13348.8	-3.13E-04	1.675E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-137a	2.700E-01	13077.8	-3.13E-04	4.477E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-137b	2.500E-01	13082.4	-3.13E-04	4.139E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-137c	1.000E-04	13086.6	-3.13E-04	1.653E-06	Yes	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1st Quarter 2001	3/1/2001	LC-149c	1.000E-04	15796.4	-3.13E-04	7.071E-07	Yes	Yes
1st Quarter 2001	3/1/2001	LC-149d	1.000E-04	15773.9	-3.13E-04	7.121E-07	Yes	Yes
1st Quarter 2001	3/1/2001	LC-14a	5.800E-02	4382.6	-3.13E-04	1.468E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-165	1.000E-04	5190.8	-3.13E-04	1.965E-05	Yes	Yes
1st Quarter 2001	3/1/2001	LC-19a	1.600E-01	12025.9	-3.13E-04	3.689E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-19b	8.600E-02	12024.1	-3.13E-04	1.984E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-19c	4.400E-02	12022.5	-3.13E-04	1.016E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-26	3.000E-04	14654.1	-3.13E-04	3.035E-06	Yes	Yes
1st Quarter 2001	3/1/2001	LC-41a	1.900E-01	8203.5	-3.13E-04	1.452E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-44a	3.400E-02	8149.5	-3.13E-04	2.642E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-49	2.400E-01	10390.6	-3.13E-04	9.239E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-51	1.500E-01	13040.1	-3.13E-04	2.517E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-53	2.200E-01	12161.4	-3.13E-04	4.862E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-64a	8.600E+00	13561.5	-3.13E-04	1.225E-01	No	No
1st Quarter 2001	3/1/2001	LC-64b	1.600E-02	13560.8	-3.13E-04	2.280E-04	No	Yes
1st Quarter 2001	3/1/2001	LC-66a	6.700E-02	7311.6	-3.13E-04	6.771E-03	No	Yes
1st Quarter 2001	3/1/2001	LC-66b	1.100E-01	7318.1	-3.13E-04	1.109E-02	No	Yes
1st Quarter 2001	3/1/2001	LC-73a	7.000E-04	4830.2	-3.13E-04	1.540E-04	Yes	Yes
1st Quarter 2001	3/1/2001	LX-1	1.100E-02	5553.1	-3.13E-04	1.929E-03	No	No
1st Quarter 2001	3/1/2001	LX-10	4.300E-02	5684.8	-3.13E-04	7.237E-03	No	No
1st Quarter 2001	3/1/2001	LX-11	2.600E-02	5715.9	-3.13E-04	4.333E-03	No	No
1st Quarter 2001	3/1/2001	LX-12	2.000E-02	5746.4	-3.13E-04	3.302E-03	No	No
1st Quarter 2001	3/1/2001	LX-13	6.500E-03	5777.3	-3.13E-04	1.063E-03	No	No
1st Quarter 2001	3/1/2001	LX-14	5.900E-03	5809.2	-3.13E-04	9.550E-04	No	No
1st Quarter 2001	3/1/2001	LX-15	3.000E-03	5840.1	-3.13E-04	4.809E-04	No	No
1st Quarter 2001	3/1/2001	LX-18	8.000E-01	13499.3	-3.13E-04	1.162E-02	No	No
1st Quarter 2001	3/1/2001	LX-19	1.200E-01	13245.1	-3.13E-04	1.888E-03	No	No
1st Quarter 2001	3/1/2001	LX-2	1.400E-02	5563.1	-3.13E-04	2.448E-03	No	No
1st Quarter 2001	3/1/2001	LX-21	9.200E-02	13247.8	-3.13E-04	1.446E-03	No	No
1st Quarter 2001	3/1/2001	LX-3	2.300E-02	5571.9	-3.13E-04	4.010E-03	No	No
1st Quarter 2001	3/1/2001	LX-4	5.800E-02	5580.3	-3.13E-04	1.009E-02	No	No
1st Quarter 2001	3/1/2001	LX-5	9.100E-02	5583.3	-3.13E-04	1.581E-02	No	No
1st Quarter 2001	3/1/2001	LX-6	8.200E-02	5587.7	-3.13E-04	1.423E-02	No	No
1st Quarter 2001	3/1/2001	LX-7	7.900E-02	5597.5	-3.13E-04	1.366E-02	No	No
1st Quarter 2001	3/1/2001	LX-8	7.300E-02	5623.3	-3.13E-04	1.252E-02	No	No
1st Quarter 2001	3/1/2001	LX-9	6.100E-02	5653.9	-3.13E-04	1.037E-02	No	No
1st Quarter 2001	3/1/2001	PA-381	2.300E-02	7283.1	-3.13E-04	2.345E-03	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1st Quarter 2001	3/1/2001	PA-383	8.000E-04	7758.7	-3.13E-04	7.028E-05	Yes	Yes
1st Quarter 2001	3/1/2001	T-04	1.200E-02	3048.1	-3.13E-04	4.615E-03	No	Yes
1st Quarter 2001	3/1/2001	T-08	2.400E-03	2000.0	-3.13E-04	1.282E-03	No	Yes
1st Quarter 2001	3/1/2001	T-12b	1.000E-04	3981.5	-3.13E-04	2.870E-05	Yes	Yes
1st Quarter 2001	3/1/2001	T-13b	4.250E-03	2931.0	-3.13E-04	1.696E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-03	1.500E-03	8375.0	-3.54E-04	7.731E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-05	4.100E-02	6047.2	-3.54E-04	4.818E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-06	7.400E-02	9348.3	-3.54E-04	2.702E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-108	1.600E-02	13354.3	-3.54E-04	1.414E-04	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-111b	1.000E-04	5567.9	-3.54E-04	1.392E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-116b	1.100E-02	5601.7	-3.54E-04	1.514E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-122b	1.000E-04	5795.4	-3.54E-04	1.285E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-128	2.200E-02	4681.9	-3.54E-04	4.192E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-132	9.900E-02	6644.7	-3.54E-04	9.415E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-136a	1.800E+02	13352.7	-3.54E-04	1.592E+00	No	No
2nd Quarter 2001	6/1/2001	LC-136b	9.200E-02	13348.8	-3.54E-04	8.148E-04	No	Yes
2nd Quarter 2001	6/1/2001	LC-137a	3.500E-01	13077.8	-3.54E-04	3.412E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-137b	3.200E-01	13082.4	-3.54E-04	3.114E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-137c	1.000E-04	13086.6	-3.54E-04	9.718E-07	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-149c	1.000E-04	15796.4	-3.54E-04	3.723E-07	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-149d	1.000E-04	15773.9	-3.54E-04	3.753E-07	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-14a	3.500E-02	4382.6	-3.54E-04	7.415E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-165	1.000E-04	5190.8	-3.54E-04	1.591E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-19a	1.600E-01	12025.9	-3.54E-04	2.264E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-19b	4.500E-02	12024.1	-3.54E-04	6.371E-04	No	Yes
2nd Quarter 2001	6/1/2001	LC-19c	6.200E-02	12022.5	-3.54E-04	8.782E-04	No	Yes
2nd Quarter 2001	6/1/2001	LC-26	3.000E-04	14654.1	-3.54E-04	1.674E-06	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-41a	2.000E-01	8203.5	-3.54E-04	1.095E-02	No	Yes
2nd Quarter 2001	6/1/2001	LC-44a	2.800E-02	8149.5	-3.54E-04	1.563E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-49	2.400E-01	10390.6	-3.54E-04	6.059E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-51	1.500E-01	13040.1	-3.54E-04	1.482E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-53	1.900E-01	12161.4	-3.54E-04	2.562E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-64a	1.400E+01	13561.5	-3.54E-04	1.150E-01	No	No
2nd Quarter 2001	6/1/2001	LC-64b	2.200E-02	13560.8	-3.54E-04	1.808E-04	Yes	Yes
2nd Quarter 2001	6/1/2001	LC-66a	6.800E-02	7311.6	-3.54E-04	5.107E-03	No	Yes
2nd Quarter 2001	6/1/2001	LC-66b	1.100E-01	7318.1	-3.54E-04	8.242E-03	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
2nd Quarter 2001	6/1/2001	LC-73a	6.000E-04	4830.2	-3.54E-04	1.085E-04	Yes	Yes
2nd Quarter 2001	6/1/2001	LX-1	1.000E-02	5553.1	-3.54E-04	1.400E-03	No	No
2nd Quarter 2001	6/1/2001	LX-10	3.900E-02	5684.8	-3.54E-04	5.210E-03	No	No
2nd Quarter 2001	6/1/2001	LX-11	2.100E-02	5715.9	-3.54E-04	2.775E-03	No	No
2nd Quarter 2001	6/1/2001	LX-12	1.600E-02	5746.4	-3.54E-04	2.092E-03	No	No
2nd Quarter 2001	6/1/2001	LX-13	5.600E-03	5777.3	-3.54E-04	7.240E-04	No	No
2nd Quarter 2001	6/1/2001	LX-14	4.700E-03	5809.2	-3.54E-04	6.009E-04	No	No
2nd Quarter 2001	6/1/2001	LX-15	2.400E-03	5840.1	-3.54E-04	3.035E-04	No	No
2nd Quarter 2001	6/1/2001	LX-16	1.200E-01	11934.0	-3.54E-04	1.754E-03	No	No
2nd Quarter 2001	6/1/2001	LX-17	1.100E+00	13512.4	-3.54E-04	9.194E-03	No	No
2nd Quarter 2001	6/1/2001	LX-18	1.050E+00	13499.3	-3.54E-04	8.817E-03	No	No
2nd Quarter 2001	6/1/2001	LX-19	1.300E-01	13245.1	-3.54E-04	1.194E-03	No	No
2nd Quarter 2001	6/1/2001	LX-2	1.300E-02	5563.1	-3.54E-04	1.813E-03	No	No
2nd Quarter 2001	6/1/2001	LX-21	9.600E-02	13247.8	-3.54E-04	8.812E-04	No	No
2nd Quarter 2001	6/1/2001	LX-3	2.700E-02	5571.9	-3.54E-04	3.754E-03	No	No
2nd Quarter 2001	6/1/2001	LX-4	5.400E-02	5580.3	-3.54E-04	7.486E-03	No	No
2nd Quarter 2001	6/1/2001	LX-5	8.550E-02	5583.3	-3.54E-04	1.184E-02	No	No
2nd Quarter 2001	6/1/2001	LX-6	7.900E-02	5587.7	-3.54E-04	1.092E-02	No	No
2nd Quarter 2001	6/1/2001	LX-7	7.200E-02	5597.5	-3.54E-04	9.921E-03	No	No
2nd Quarter 2001	6/1/2001	LX-8	8.200E-02	5623.3	-3.54E-04	1.120E-02	No	No
2nd Quarter 2001	6/1/2001	LX-9	5.500E-02	5653.9	-3.54E-04	7.429E-03	No	No
2nd Quarter 2001	6/1/2001	PA-381	3.600E-02	7283.1	-3.54E-04	2.731E-03	No	Yes
2nd Quarter 2001	6/1/2001	PA-383	8.000E-04	7758.7	-3.54E-04	5.128E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	RW-1	1.500E-01	11572.4	-3.54E-04	2.492E-03	No	No
2nd Quarter 2001	6/1/2001	T-04	8.800E-03	3048.1	-3.54E-04	2.991E-03	No	Yes
2nd Quarter 2001	6/1/2001	T-08	1.900E-03	2000.0	-3.54E-04	9.358E-04	No	Yes
2nd Quarter 2001	6/1/2001	T-12b	1.000E-04	3981.5	-3.54E-04	2.442E-05	Yes	Yes
2nd Quarter 2001	6/1/2001	T-13b	4.000E-03	2931.0	-3.54E-04	1.417E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-03	2.200E-03	8375.0	-3.43E-04	1.246E-04	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-05	7.300E-02	6047.2	-3.43E-04	9.184E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-06	6.100E-02	9348.3	-3.43E-04	2.475E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-108	4.000E-03	13354.3	-3.43E-04	4.111E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-111b	1.000E-04	5567.9	-3.43E-04	1.483E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-116b	1.400E-02	5601.7	-3.43E-04	2.052E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-122b	1.000E-04	5795.4	-3.43E-04	1.372E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-128	1.350E-02	4681.9	-3.43E-04	2.712E-03	No	Yes

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 2001	9/1/2001	LC-132	1.100E-01	6644.7	-3.43E-04	1.128E-02	No	Yes
3rd Quarter 2001	9/1/2001	LC-136a	2.500E+02	13352.7	-3.43E-04	2.571E+00	No	No
3rd Quarter 2001	9/1/2001	LC-136b	1.250E-01	13348.8	-3.43E-04	1.287E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-137a	4.100E-01	13077.8	-3.43E-04	4.632E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-137b	3.050E-01	13082.4	-3.43E-04	3.440E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-137c	1.000E-04	13086.6	-3.43E-04	1.126E-06	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-149c	1.000E-04	15796.4	-3.43E-04	4.449E-07	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-149d	1.000E-04	15773.9	-3.43E-04	4.484E-07	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-14a	4.600E-02	4382.6	-3.43E-04	1.024E-02	No	Yes
3rd Quarter 2001	9/1/2001	LC-165	1.000E-04	5190.8	-3.43E-04	1.687E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-19a	1.700E-01	12025.9	-3.43E-04	2.755E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-19b	1.400E-01	12024.1	-3.43E-04	2.270E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-19c	6.800E-02	12022.5	-3.43E-04	1.103E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-26	2.000E-03	14654.1	-3.43E-04	1.316E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-41a	1.900E-01	8203.5	-3.43E-04	1.141E-02	No	Yes
3rd Quarter 2001	9/1/2001	LC-44a	3.000E-02	8149.5	-3.43E-04	1.836E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-49	2.500E-01	10390.6	-3.43E-04	7.096E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-51	1.600E-01	13040.1	-3.43E-04	1.831E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-53	1.900E-01	12161.4	-3.43E-04	2.939E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-64a	1.900E+01	13561.5	-3.43E-04	1.819E-01	No	No
3rd Quarter 2001	9/1/2001	LC-64b	1.550E-02	13560.8	-3.43E-04	1.484E-04	Yes	Yes
3rd Quarter 2001	9/1/2001	LC-66a	6.200E-02	7311.6	-3.43E-04	5.057E-03	No	Yes
3rd Quarter 2001	9/1/2001	LC-66b	1.300E-01	7318.1	-3.43E-04	1.058E-02	No	Yes
3rd Quarter 2001	9/1/2001	LC-73a	8.000E-04	4830.2	-3.43E-04	1.527E-04	Yes	Yes
3rd Quarter 2001	9/1/2001	LX-1	1.000E-02	5553.1	-3.43E-04	1.490E-03	No	No
3rd Quarter 2001	9/1/2001	LX-10	4.600E-02	5684.8	-3.43E-04	6.553E-03	No	No
3rd Quarter 2001	9/1/2001	LX-11	2.000E-02	5715.9	-3.43E-04	2.819E-03	No	No
3rd Quarter 2001	9/1/2001	LX-12	1.300E-02	5746.4	-3.43E-04	1.813E-03	No	No
3rd Quarter 2001	9/1/2001	LX-13	5.300E-03	5777.3	-3.43E-04	7.314E-04	No	No
3rd Quarter 2001	9/1/2001	LX-14	4.200E-03	5809.2	-3.43E-04	5.733E-04	No	No
3rd Quarter 2001	9/1/2001	LX-15	2.300E-03	5840.1	-3.43E-04	3.106E-04	No	No
3rd Quarter 2001	9/1/2001	LX-16	1.400E-01	11934.0	-3.43E-04	2.341E-03	No	No
3rd Quarter 2001	9/1/2001	LX-17	7.800E-01	13512.4	-3.43E-04	7.593E-03	No	No
3rd Quarter 2001	9/1/2001	LX-18	1.200E+00	13499.3	-3.43E-04	1.173E-02	No	No
3rd Quarter 2001	9/1/2001	LX-19	1.600E-01	13245.1	-3.43E-04	1.707E-03	No	No
3rd Quarter 2001	9/1/2001	LX-2	1.100E-02	5563.1	-3.43E-04	1.634E-03	No	No
3rd Quarter 2001	9/1/2001	LX-21	1.000E-01	13247.8	-3.43E-04	1.066E-03	No	No

Project: Fort Lewis Upper Aquifer **User Name:** Meng

Location: Seattle **State:** Washington

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
3rd Quarter 2001	9/1/2001	LX-3	2.100E-02	5571.9	-3.43E-04	3.110E-03	No	No
3rd Quarter 2001	9/1/2001	LX-4	5.200E-02	5580.3	-3.43E-04	7.677E-03	No	No
3rd Quarter 2001	9/1/2001	LX-5	7.200E-02	5583.3	-3.43E-04	1.062E-02	No	No
3rd Quarter 2001	9/1/2001	LX-6	7.800E-02	5587.7	-3.43E-04	1.149E-02	No	No
3rd Quarter 2001	9/1/2001	LX-7	7.600E-02	5597.5	-3.43E-04	1.116E-02	No	No
3rd Quarter 2001	9/1/2001	LX-8	6.800E-02	5623.3	-3.43E-04	9.893E-03	No	No
3rd Quarter 2001	9/1/2001	LX-9	5.400E-02	5653.9	-3.43E-04	7.774E-03	No	No
3rd Quarter 2001	9/1/2001	PA-381	3.500E-02	7283.1	-3.43E-04	2.883E-03	No	Yes
3rd Quarter 2001	9/1/2001	PA-383	1.000E-03	7758.7	-3.43E-04	6.997E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	RW-1	1.500E-01	11572.4	-3.43E-04	2.839E-03	No	No
3rd Quarter 2001	9/1/2001	T-04	8.800E-03	3048.1	-3.43E-04	3.095E-03	No	Yes
3rd Quarter 2001	9/1/2001	T-08	2.500E-03	2000.0	-3.43E-04	1.259E-03	No	Yes
3rd Quarter 2001	9/1/2001	T-12b	1.000E-04	3981.5	-3.43E-04	2.554E-05	Yes	Yes
3rd Quarter 2001	9/1/2001	T-13b	3.850E-03	2931.0	-3.43E-04	1.410E-03	No	Yes

Note: Projected Concentrations that are below the user-specified detection limit are indicated by a check mark to its right; for sampling events with less than 3 selected plume centerline wells, NO projected concentrations are calculated because no regression coefficient is available.

DRAFT FINAL

THREE-TIERED
GROUNDWATER MONITORING NETWORK
OPTIMIZATION EVALUATION
FOR THE
FORT LEWIS LOGISTICS CENTER, WASHINGTON

Prepared for

US Environmental Protection Agency

May 2003

PARSONS

Denver, Colorado

EXECUTIVE SUMMARY

This report presents a description and evaluation of the groundwater monitoring program associated with the Logistics Center at Fort Lewis, Washington. The monitoring program at this site was evaluated to identify potential opportunities to streamline monitoring activities while still maintaining an effective monitoring network. This evaluation is being conducted as part of an independent assessment of monitoring network optimization (MNO) methods by the US Environmental Protection Agency (USEPA) and the Air Force Center for Environmental Excellence (AFCEE).

Groundwater monitoring programs have two primary objectives (U.S. Environmental Protection Agency [USEPA], 1994b; Gibbons, 1994):

1. Evaluate long-term temporal trends in contaminant concentrations (*temporal objective*); and

2. Evaluate the extent to which contaminant migration is occurring (*spatial objective*).

The relative success of any remediation system (including the monitoring network) is judged based on the degree to which it achieves the stated objectives of the system. Designing an effective groundwater monitoring program involves locating monitoring points and developing a site-specific strategy for groundwater sampling and analysis that maximizes the amount of relevant information that can be obtained while minimizing incremental costs. The effectiveness of a monitoring network in achieving the two primary monitoring objectives can be evaluated quantitatively using statistical techniques; qualitative evaluation also is important to allow consideration of such factors as hydrostratigraphy, locations of potential receptor exposure points with respect to a dissolved contaminant plume, and the direction(s) and rate(s) of contaminant migration.

Groundwater monitoring has been conducted at the Logistics Center on a quarterly basis since December 1995. As part of this quarterly monitoring program, 38 monitoring wells and 21 groundwater extraction wells have been sampled. In May 2001, US Army Corps of Engineers (USACE) published a *Draft Logistics Center (FTLE-33) Remedial Action Monitoring Optimization Report* that presents the results of a MNO evaluation conducted for the groundwater extraction and treatment system in operation at the Logistics Center. Based on the MNO evaluation, USACE (2001) recommended adding 24 monitoring wells (18 existing and 6 new wells) to the sampling network and removing 11 previously sampled monitoring wells from the sampling network (a net increase of 13 monitoring wells), and generally reducing sampling frequencies. The revised Logistics

Center remedial action monitoring network (LOGRAM) consists of 72 wells-- 51 Vashon Aquifer monitoring wells and 21 extraction wells.

The chemical analytical data used in the evaluation of the remedial action (RA) monitoring program were compiled using groundwater monitoring results for the nearly 7 years of quarterly sampling events performed from February 1995 through December 2001 provided by the Seattle district of the U.S. Army Corps of Engineers. Sampling results for four chlorinated solvent compounds (i.e., tetrachloroethene [PCE], trichloroethene [TCE], *cis*-1,2-dichloroethene [DCE], and vinyl chloride [VC]) were utilized in the MNO analysis. TCE is the primary contaminant of concern in groundwater at the Logistics Center, and TCE sampling results were the primary data used to conduct the three-tiered monitoring network optimization due to the magnitude and spatial extent of TCE concentrations in groundwater at Fort Lewis compared to the other detected compounds.

The general objective of the project was to optimize the Fort Lewis Upper Aquifer long-term monitoring network by applying a three-tiered MNO approach to assess the degree to which the monitoring network addresses each of the two primary objectives of monitoring listed above and other important considerations. The three-tiered MNO evaluation described in this report examines the 83 wells (21 extraction wells and 62 monitoring wells) included in both the original and the revised LOGRAM monitoring networks. The specific objectives of the project included:

- Apply a qualitative methodology that considers factors such as hydrostratigraphy, locations of potential receptors with respect to the dissolved plume, and the direction(s) and rate(s) of contaminant migration to establish the frequency at which monitoring should be conducted, and if each well should be retained in or removed from the monitoring program.

- Conduct a Mann-Kendall statistical analysis to determine the temporal trends of chemicals of concern over time, and apply an algorithm to determine the relevance of the trends within the monitoring network.

- Determine the relative amount of spatial information contributed by each monitoring well by performing a spatial statistical analysis utilizing kriging error predictions.

- Combine and evaluate the results of the three analyses to establish the frequency at which monitoring should be conducted, as well as the number and locations of wells in the monitoring network.

Results from the three-tiered monitoring network optimization for the Fort Lewis site indicate that 6 of the 72 monitoring and extraction wells included in the revised LOGRAM program could be removed from the groundwater LTM program with little loss of information. In addition, the three-tiered analysis supports the deletion of 9 of the 11 wells removed from the LTM program as a result of the USACE (2001) MNO evaluation; continued monitoring of the remaining 68 wells is recommended, as well as the addition of one well to monitor leading edge of southwestern lobe of the plume near Murray Creek. A refined monitoring program, consisting of 69 wells (16 sampled quarterly, 7 sampled semi-annually, 17 sampled annually, 14 sampled biennially, and the 15 I-5 extraction wells sampled every 3 years) would be adequate to address the two primary objectives of monitoring. This refined monitoring network would result in an average of 107 sampling events per year, compared to 180 events per year in the current LOGRAM monitoring program and 236 yearly events in the original sampling program. Implementing these recommendations for optimizing the monitoring program at the Fort Lewis Logistics Center could reduce site monitoring costs by $36,500 a year (more than 40%) from the revised LOGRAM LTM plan**,** and $64,500 (approximately 55%) from the original LTM program (based on a per sample cost of $500 (USACE, 2001).

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ACRONYMS AND ABBREVIATIONS

AFCEE	Air Force Center for Environmental Excellence
ASCE	American Society of Chemical Engineers
bgs	below ground surface
COC	contaminant of concern
DCA	dichloroethane
DCE	dichloroethene
DNAPL	dense nonaqueous-phase liquid
EGDY	East Gate Disposal Yard
ESRI	Environmental Systems Research Institute, Inc.
ft/day	foot (feet) per day
ft/ft	foot per foot
GIS	geographical information system
I-5	Interstate 5
LOGRAM	revised remedial action monitoring plan proposed for implementation in December, 2001
LNAPL	light nonaqueous-phase liquid
LTM	long-term monitoring
μg/L	microgram(s) per liter
MAMC	Madigan Army Medical Center
MCL	maximum contaminant level
MNO	monitoring network optimization
NAPL	nonaqueous-phase liquid
PCE	tetrachloroethene
POL	petroleum, oils, and lubricants
RA	remedial action
TCA	trichloroethane
TCE	trichloroethene
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
VC	vinyl chloride
VOC	volatile organic compound

SECTION 1

INTRODUCTION

Groundwater monitoring programs have two primary objectives (U.S. Environmental Protection Agency [USEPA], 1994; Gibbons, 1994):

1. Evaluate long-term temporal trends in contaminant concentrations at one or more points within or outside of the remediation zone, as a means of monitoring the performance of the remedial measure (*temporal objective*); and

2. Evaluate the extent to which contaminant migration is occurring, particularly if a potential exposure point for a susceptible receptor exists (*spatial objective*).

The relative success of any remediation system and its components (including the monitoring network) must be judged based on the degree to which it achieves the stated objectives of the system. Designing an effective groundwater monitoring program involves locating monitoring points and developing a site-specific strategy for groundwater sampling and analysis so as to maximize the amount of relevant information that can be obtained while minimizing incremental costs. Relevant information is that required to effectively address the temporal and spatial objectives of monitoring. The effectiveness of a monitoring network in achieving these two primary objectives can be evaluated quantitatively using statistical techniques. In addition, there may be other important considerations associated with a particular monitoring network that are most appropriately addressed through a qualitative assessment of the network. The qualitative evaluation may consider such factors as hydrostratigraphy, locations of potential receptor exposure points with respect to a dissolved contaminant plume, and the direction(s) and rate(s) of contaminant migration.

This report presents a description and evaluation of the groundwater monitoring program associated with the Logistics Center at Fort Lewis, Washington. The groundwater monitoring program at this site was evaluated to identify potential opportunities to streamline monitoring activities while still maintaining an effective monitoring network. This effort is being conducted as part of an independent assessment of monitoring network optimization methods by the USEPA and the Air Force Center for Environmental Excellence (AFCEE). A three-tiered approach, consisting of a qualitative evaluation, an evaluation of temporal trends in contaminant concentrations, and a statistical spatial analysis, was conducted to assess the degree to which the monitoring network addresses each of the two primary objectives of monitoring, and other important considerations. The results of the three evaluations were combined and used to assess the optimal frequency of monitoring and the spatial distribution of the components of the monitoring network. The results of the analysis were then used to develop recommendations for optimizing the monitoring program at Fort Lewis.

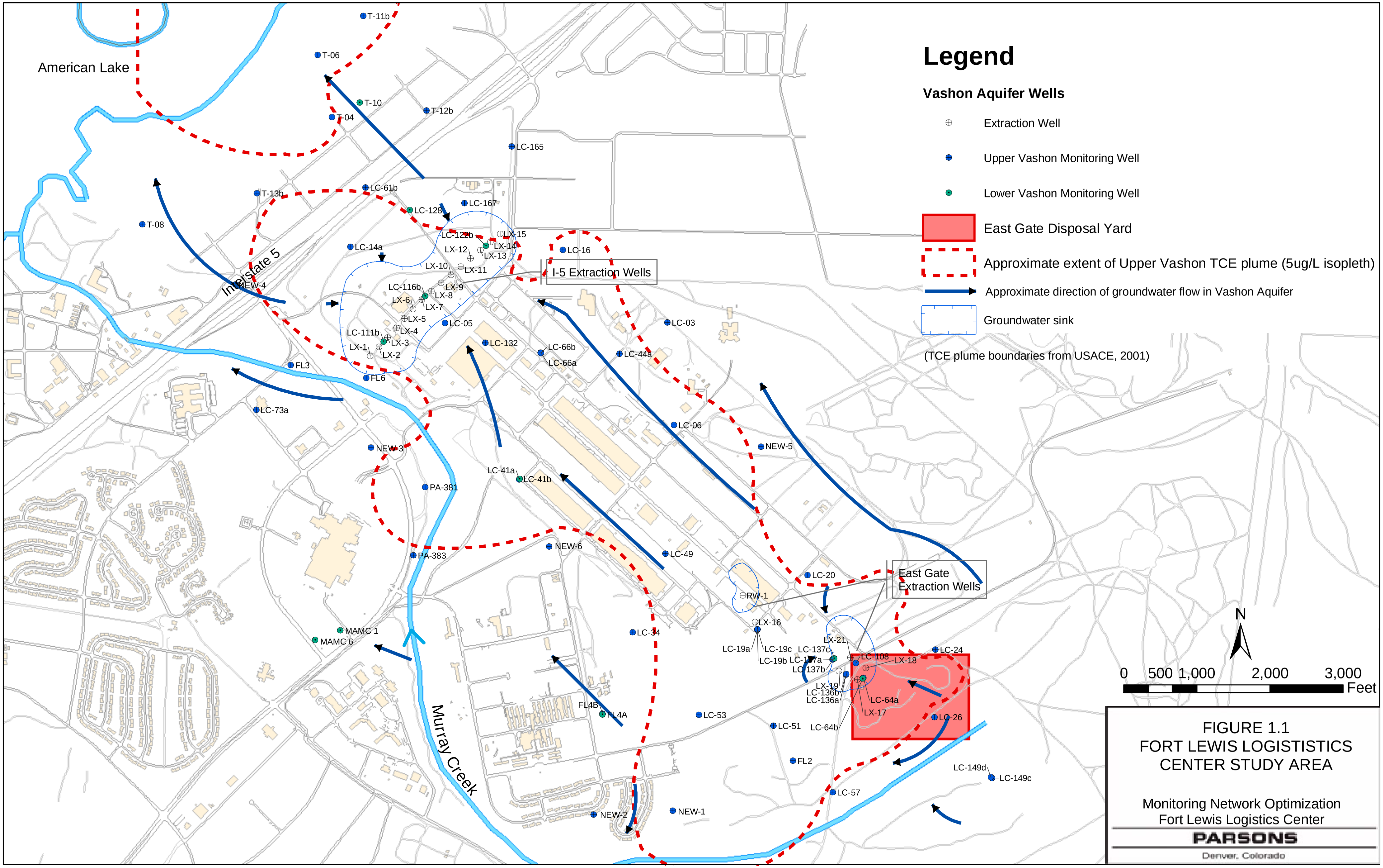


FIGURE 1.1
FORT LEWIS LOGISTICS CENTER STUDY AREA

Monitoring Network Optimization
Fort Lewis Logistics Center

SECTION 2

SITE BACKGROUND INFORMATION

The location, operational history, geology, and hydrogeology of Fort Lewis are briefly described in the following subsections. This information was obtained primarily from the U.S. Army Corps of Engineers (USACE, 2002).

2.1 SITE DESCRIPTION

Fort Lewis is located near the southern end of Puget Sound in Pierce County, approximately 11 miles south of Tacoma and 17 miles northeast of Olympia, Washington. The Logistics Center occupies approximately 650 acres of the Fort Lewis Military Reservation. The installation lies on generally level glacial outwash deposits, and is bounded on the northwest by Interstate 5 and on the south and southwest by Murray Creek. Murray Creek discharges into American Lake, approximately 2 miles northwest of the EGDY.

Process wastes were disposed of at several on- and off-installation locations, including the East Gate Disposal Yard (EGDY), located southeast of the Logistics Center (Figure 1.1). Between 1946 and 1960, waste solvents (primarily TCE) and petroleum, oils, and lubricants (POL) from cleaning, degreasing, and maintenance operations were disposed of in trenches at the EGDY. Liquid wastes have contaminated soils and groundwater at and downgradient from this former landfill, which is no longer active. The dissolved chlorinated solvent plume that originates at the EDGY extends downgradient across the entire width of the Logistics Center, and beyond the northwestern facility boundary to the southeastern shores of American Lake. The well network used to monitor the magnitude and extent of this plume, and to assess the performance of remedial systems installed to address source-area and groundwater contamination (as described in Section 3), is the subject of this MNO evaluation.

2.2 GEOLOGY AND HYDROGEOLOGY

2.2.1 Geology

The study area is underlain by a complex sequence of glacial and non-glacial Quaternary sediments up to 2,000 feet thick. At least three glacial and three non-glacial units have been identified in the sediments that occur above sea level in the study area. Of primary interest for this evaluation is the uppermost water-bearing zone, termed the Vashon Aquifer. The stratigraphic units that comprise the Vashon Aquifer include the Vashon Drift, Olympia beds, and Pre-Olympia Drift.

Vashon Drift deposits typically extend from at or near the ground surface to depths of approximately 60 to 95 feet below ground surface (bgs). However, in the region of a deep erosional trough, these deposits extend to approximately 230 feet bgs. Lithologies encountered in the Vashon Drift consist primarily of sands and gravels, which occasionally are silty. The Vashon Drift deposits consist, from youngest to oldest, of the following units:

- Vashon Recessional Outwash—sandy, cobbly gravel extending from at or near the ground surface to depths of 5 to 50 feet bgs (typically less than 30 feet bgs).

- Vashon Till and Ice-Contact Deposits—Well-graded gravel in a matrix of sand, silt, and clay, ranging from 4 to 35 feet in thickness. This unit is present beneath much of the study area, but is absent at some locations.

- Vashon Advance Outwash—Medium to coarse sandy gravel with cobbles and fine to medium sand.

- Vashon Glaciolacustrine Silt/Clay—Very stiff to hard clayey silt varying in thickness from 10 to 150 feet.

The Olympia beds, which underlie the Vashon Drift, consist of alluvial sands and gravels with silt, silty gravel, scattered wood, and peat. This unit, which is present in some areas beneath the northern portion of the EGDY, may be up to 40 feet thick. The Pre-Olympia Drift, which typically is 10 to 70 feet thick, consists of very fine to coarse sand with lenses of gravelly sand and sandy silt, sandy gravel with cobbles, and silty gravel with sand and clay seams.

2.2.2 Hydrogeology

The Vashon Aquifer, also termed the Upper Aquifer, is unconfined. The aquifer materials consist of Vashon outwash deposits and Pre-Olympia drift deposits; the Vashon till and ice-contact deposits, glaciolacustrine silts/clays, and Olympia beds may act locally as discontinuous aquitards within the Vashon Aquifer. The depth to groundwater is spatially variable, but generally ranges from 5 to 25 feet bgs throughout most of the study area. The elevation of the water table fluctuates approximately 5 to 6 feet seasonally, and by as much as 14.7 feet over periods of several years. The majority of dissolved contamination associated with the EGDY source area occurs within the Vashon Aquifer, and the groundwater monitoring network assessed in this report consists of wells screened in the Vashon Aquifer. There is evidence that contamination has migrated into the underlying confined Sea Level Aquifer as well, however this monitoring network optimization focuses solely on the Vashon Aquifer.

The Vashon Aquifer is subdivided into Upper and Lower Vashon subunits, although regionally these subunits are considered to comprise a single unconfined aquifer. The Upper and Lower Vashon aquifer subunits are separated by the Vashon Till, which acts as a discontinuous aquitard (USACE, 2001). The stratigraphic units comprising the Lower Vashon Aquifer are laterally discontinuous: they are present beneath the EGDY and in the area north and east of well LC-41 (Figure 1.1), but are absent between the EGDY and well LC-41.

The hydraulic conductivity of the permeable Vashon Aquifer units, which are the primary pathways for groundwater and contaminant migration, ranges from 10 to more than 1,000 feet per day (ft/day). Groundwater flow within the Vashon Aquifer is regionally towards the northwest; however, flow directions vary locally and seasonally. Murray Creek, a northwesterly-flowing stream that meanders south and west of the EGDY and discharges into American Lake (Figure 1.1), likely influences local groundwater gradients in the shallow part of the Vashon Aquifer. For example, the extension of the dissolved contaminant plume to the southwest from the EGDY indicates a southwesterly groundwater flow component (toward Murray Creek) in this area; the flow direction beneath the upgradient half of the EGDY also may be locally variable. However, the overall regional flow direction remains relatively constant, toward the northwest. Measured horizontal hydraulic gradients within the Vashon Aquifer typically range from 0.001 to 0.004 foot per foot (ft/ft). Horizontal groundwater flow velocities are estimated to range from 0.05 to 15.2 ft/day.

2.3 NATURE AND EXTENT OF CONTAMINATION

TCE has been identified as the major contaminant dissolved in groundwater beneath the Logistics Center, based on its widespread detection in wells across the site (URS, 2000). Other contaminants of concern (COCs) in groundwater include *cis*-1,2-dichloroethene (*cis*-1,2-DCE), tetrachloroethene (PCE), 1,1,1-TCA, and vinyl chloride (VC) (USACE and URS, 2002). TCE, DCE, and TCA have been detected consistently in many wells, whereas PCE and VC have been only sporadically detected in a few wells. The former waste-disposal trenches at the EGDY are the apparent source of the groundwater contamination. Three major dense non-aqueous-phase liquid (DNAPL) source areas have been identified within the EGDY. DNAPL was detected primarily in the Vashon recessional outwash deposits above the uppermost Vashon till unit, and the extent of DNAPL in the study area is currently assumed to be limited to the EGDY. In addition to these three DNAPL source areas, light NAPL (LNAPL) was detected during exploratory trenching and sonic drilling. The extent of the LNAPL is unknown.

In the Vashon Aquifer, groundwater contaminated with TCE at concentrations exceeding the federal drinking-water maximum contaminant level (MCL) of 5 micrograms per liter (µg/L) extend 2 miles downgradient from the source area (i.e., the

EGDY) to American Lake, where it is presumed to discharge. A lobe of the TCE plume extends west-southwest from the source area toward Murray Creek, reflecting a local westerly hydraulic gradient. A portion of the westward lobe of the TCE plume extends to a gaining reach of Murray Creek, where contaminated groundwater discharges to the stream bed (Figure 1.1).

The 5-μg/L isopleth of the TCE plume has remained relatively stable since it was defined during the remedial investigation, which was completed in 1990. The margin of the westward lobe of the plume, however, was poorly defined until recently. Therefore, it is not known if this portion of the plume is stable, expanding, or contracting. Concentrations of TCE and *cis*-1,2-DCE have remained relatively constant in most monitored wells since the late 1980s. Some wells (primarily extraction wells and monitoring wells near extraction wells) have exhibited slight decreasing trends, while other wells within the interior of the plume have exhibited slight increasing trends over time.

2.4 REMEDIAL SYSTEMS

The engineered remedial action (RA) for contaminated groundwater at the Fort Lewis Logistics Center includes groundwater extraction and treatment, and recharge of treated groundwater via infiltration galleries back into the Upper Aquifer. Operation of the treatment systems began in August 1995. One aquifer cleanup objective for the facility is to restore the Upper Aquifer to MCLs by reducing the TCE concentration to less than 5 μg/L within 30 to 40 years (URS, 2000).

Two groundwater extraction well fields and associated treatment plants and recharge systems have been constructed at the Logistics Center: the Interstate 5 (I-5) system and the East Gate system. The objective of the I-5 system, which consists of 15 extraction wells and 4 infiltration galleries, is to prevent further migration of contaminated groundwater in the Upper Aquifer across the installation boundary. The East Gate system, which comprises primary and secondary extraction well fields, a recharge well, and a infiltration trench field, is designed to remove and treat contaminated groundwater from the Upper Aquifer directly downgradient from the source area in the former EGDY. The 2-well secondary extraction well field is located approximately 1,500 feet downgradient from the 4-well primary field (URS, 2000).

SECTION 3

LONG-TERM MONITORING PROGRAM AT FORT LEWIS

The groundwater monitoring program at Fort Lewis was examined to identify potential opportunities for streamlining monitoring activities while still maintaining an effective RA monitoring program. The monitoring program at Fort Lewis is reviewed in the following subsections.

3.1 DESCRIPTION OF ORIGINAL AND REVISED LOGRAM MONITORING PROGRAM

Groundwater monitoring has been conducted at the Logistics Center on a quarterly basis since December 1995. As part of this quarterly monitoring program, 38 monitoring wells and 21 groundwater extraction wells were sampled, resulting in a total of 59 wells and 236 primary analytical samples per year (Table 3.1). As described by USACE (2001), the following data quality objectives were developed for the RA monitoring program:

- Confirm that the primary EGDY extraction wells are capturing all dissolved COCs migrating from the former landfill source area;

- Confirm that the secondary EGDY wells are capturing groundwater with high contaminant concentrations (> 200 μg/L) in the Vashon Aquifer between the primary and secondary EGDY well fields;

- Confirm that the I-5 extraction well field is intercepting the Vashon Aquifer contaminant plume upgradient from I-5 and between the I-5 well field and the I-5 infiltration gallery;

TABLE 3.1
ORIGINAL AND REVISED GROUNDWATER MONITORING PROGRAMS
THREE-TIERED MONITORING NETWORK OPTIMIZATION
FORT LEWIS, WASHINGTON

Well ID	Screened Interval (fbtoc) [a/]	Hydrologic Unit [b/]	Original Sampling Frequency [c/]	Revised Sampling Frequency [d/]
Original Monitoring Network Wells				
LC-03	20-60	UV	Quarterly	Quarterly
LC-05	19-59.6	UV	Quarterly	Annually
LC-06	20-60	UV	Quarterly	Semi-Annually
LC-14a	42.5-52.5	UV	Quarterly	Annually
LC-19a	45-55	UV	Quarterly	Quarterly
LC-19b	25-35	UV	Quarterly	None
LC-19c	65-75	UV	Quarterly	None
LC-26	11.5-36	UV	Quarterly	Annually
LC-41a	84.7-93.9	UV	Quarterly	Annually
LC-44a	17-32	UV	Quarterly	None
LC-49	43-47.5	UV	Quarterly	Annually
LC-51	26.5-32	UV	Quarterly	None
LC-53	26.5-31.5	UV	Quarterly	Annually
LC-64a	25-30	UV	Quarterly	Quarterly
LC-66a	34.5-39.5	UV	Quarterly	None
LC-66b	68-73	UV	Quarterly	Annually
LC-73a	40-45	UV	Quarterly	None
LC-108	60-65.5	UV	Quarterly	None
LC-132	40-49.6	UV	Quarterly	None
LC-136a	31-40.5	UV	Quarterly	Quarterly
LC-136b	55-74.5	UV	Quarterly	Annually
LC-137a	35-44.5	UV	Quarterly	None
LC-137b	40-60	UV	Quarterly	Quarterly
LC-149c	38-47.93	UV	Quarterly	Annually
LC-149d	60-80	UV	Quarterly	None
LC-165	40-45	UV	Quarterly	None
PA-381	47-57	UV	Quarterly	Annually
PA-383	47-57	UV	Quarterly	Annually
T-04	55-65	UV	Quarterly	Annually
T-08	66-76	UV	Quarterly	Semi-Annually
T-12b	59.1-64.1	UV	Quarterly	Quarterly
T-13b	75.3-80.3	UV	Quarterly	Semi-Annually
LC-111b	105-125	LV	Quarterly	Annually
LC-116b	107-127	LV	Quarterly	Annually
LC-122b	112-132	LV	Quarterly	Annually
LC-128	134-154	LV	Quarterly	Annually
LC-137c	105-125	LV	Quarterly	Annually
LC-64b	74-79	LV	Quarterly	Annually
Extraction Wells				
LX-1	72.5-92.5	EW	Quarterly	Annually
LX-2	70-100	EW	Quarterly	Annually
LX-3	60.5-88.5	EW	Quarterly	Annually
LX-4	64-94	EW	Quarterly	Annually
LX-5	54.5-72, 85-95	EW	Quarterly	Annually
LX-6	58-88	EW	Quarterly	Annually
LX-7	52-65, 72-92	EW	Quarterly	Annually
LX-8	58-88	EW	Quarterly	Annually
LX-9	58.5-88.5	EW	Quarterly	Annually
LX-10	59-89	EW	Quarterly	Annually
LX-11	67-78, 85-99, 104-111	EW	Quarterly	Annually
LX-12	55-85	EW	Quarterly	Annually
LX-13	68.5-99.5	EW	Quarterly	Annually
LX-14	62-92	EW	Quarterly	Annually
LX-15	66-96	EW	Quarterly	Annually
LX-16	42-72	EW	Quarterly	Quarterly
LX-17	34.5-54.5	EW	Quarterly	Quarterly
LX-18	31-41	EW	Quarterly	Quarterly
LX-19	53-83	EW	Quarterly	Quarterly
LX-21	51.6-81.8	EW	Quarterly	Quarterly
RW-1	41.6-66.2	EW	Quarterly	Quarterly
Wells Added to Monitoring Network in December 2001				
FL2	35-40	UV	None	Annually
FL3	37.5-42.5	UV	None	Quarterly
FL4B	32-37	UV	None	Quarterly
FL6	47-57	UV	None	Quarterly
LC-16	18.5-58.5	UV	None	Quarterly
LC-20	37.5-47.5	UV	None	Quarterly
LC-24	26-46	UV	None	Quarterly
LC-34	30-35	UV	None	Quarterly
LC-57	29.3-34.3	UV	None	Quarterly

TABLE 3.1 (Continued)
ORIGINAL AND REVISED GROUNDWATER MONITORING PROGRAMS
THREE-TIERED MONITORING NETWORK OPTIMIZATION
FORT LEWIS, WASHINGTON

Well ID	Screened Interval (fbtoc) [a/]	Hydrologic Unit [b/]	Original Sampling Frequency [c/]	Revised Sampling Frequency [d/]
LC-61b	55-60	UV	None	Quarterly
LC-167	40-50	UV	None	Quarterly
NEW-1	-	UV	None	Quarterly
NEW-2	-	UV	None	Quarterly
NEW-3	-	UV	None	Quarterly
NEW-4	-	UV	None	Quarterly
NEW-5	-	UV	None	Quarterly
NEW-6	-	UV	None	Quarterly
T-06	60-70	UV	None	Quarterly
T-11b	74.2-79.2	UV	None	Quarterly
FL4A	123-133	LV	None	Quarterly
LC-41b	130.1-139.3	LV	None	Quarterly
MAMC 1	-	LV	None	Quarterly
MAMC 6	-	LV	None	Quarterly
T-10	104-114	LV	None	Quarterly

[a/] ft btoc = feet below top of well casing.

[b/] UV = Upper Vashon Aquifer; LV = Lower Vashon Aquifer.

[c/] Sampling frequency prior to December 2001.

[d/] Sampling frequency as revised in December 2001 (USACE, 2001).

- Determine if TCE concentrations in the Vashon Aquifer contaminant plume downgradient from the I-5 infiltration gallery are decreasing to less than 5 μg/L;
- Assess the lateral and vertical extent and concentration of the COCs monitor changes through time in both the Vashon and Salmon Springs Aquifers;
- Confirm that the remedial systems are ensuring that COC concentrations in Murray Creek remain below cleanup goals for COCs (i.e., < 80 μg/L TCE) in surface water;
- Assess COC concentrations in extraction well effluent; and
- Monitor the COC mass-removal rate and total mass of COCs removed for each of the remedial system components (primary and secondary EGDY well fields and I-5 well field).

In May 2001, USACE published a *Draft Logistics Center (FTLE-33) Remedial Action Monitoring Optimization Report* that presents the results of a MNO evaluation conducted for the groundwater extraction and treatment system in operation at the Logistics Center. As part of the MNO evaluation, the analytical data for TCE were assessed to see if a reduction in sampling frequency from quarterly to semiannually or annually was warranted. A corresponding non-statistical sampling-location analysis was performed to assess which monitoring wells were best suited for continued RA monitoring based on a synthesis of spatial uniqueness with average TCE concentration uniqueness. None of the extraction wells was considered for elimination from the remedial-action monitoring network.

Based on the MNO evaluation, USACE (2001) recommended adding 24 monitoring wells (18 existing and 6 new wells) to the sampling network and removing 11 previously sampled monitoring wells from the sampling network (a net increase of 13 monitoring wells), and generally reducing sampling frequencies (Table 3.1). The revised Logistics Center remedial action monitoring network (LOGRAM) consists of 72 wells-- 51 Vashon Aquifer wells (29 sampled quarterly, 3 semiannually, and 19 annually), and all 21 extraction wells (6 sampled quarterly and 15 annually). By reducing the sampling frequency in some of the monitoring wells, the total number of primary analytical samples per year was reduced from 236 to 180 (a 23% reduction). The monitoring program changes were recommended for implementation in December 2001, which marked the 25^{th} quarter of sampling.

The three-tiered MNO evaluation described in this report examines the 83 wells (21 extraction wells and 62 monitoring wells) included in both the original and the LOGRAM monitoring networks (Table 3.1). Figure 3.1 shows the locations of these wells, and their status per the revised monitoring program (USACE, 2001).

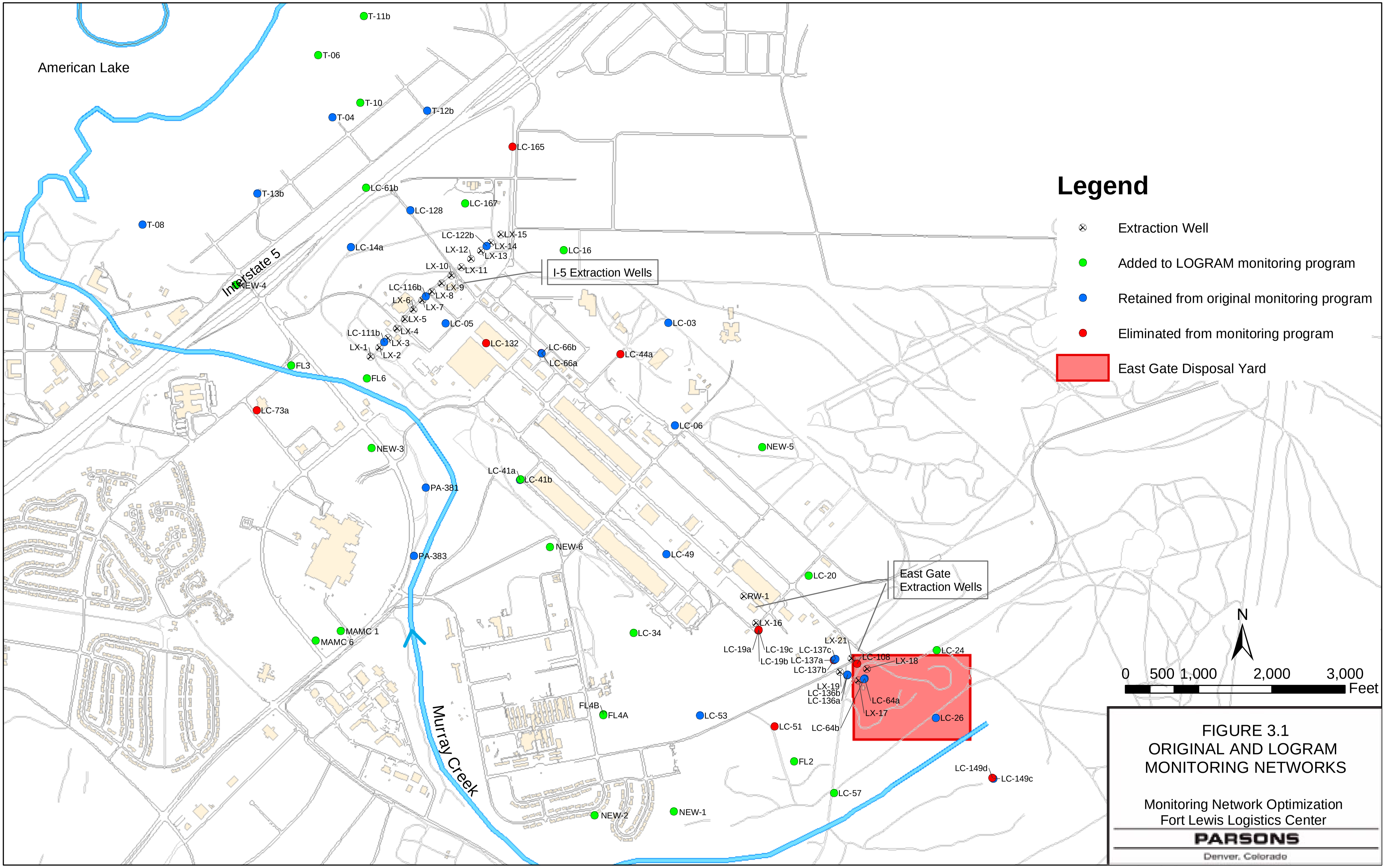
3.2 SUMMARY OF ANALYTICAL DATA

The chemical analytical data used in the evaluation of the RA monitoring program were compiled using groundwater monitoring results for the nearly 7 years of quarterly sampling events performed from February 1995 through December 2001. This analytical data, along with water level and well location information was provided to Parsons Mr. Richard Smith from the Seattle district of the U.S. Army Corps of Engineers. The database was processed to remove duplicate data measurements by retaining the maximum result of the duplicate samples. Analytical data exists for 74 of the 83 wells of included in the original and/or revised monitoring networks. Extensive data (greater than 20 sampling rounds) are available for the 21 extraction wells and the 38 monitoring wells originally included in the sampling program. However, only limited data (typically from fewer than four sampling rounds) are available for the 18 existing wells added to the monitoring network in December 2001. No sampling data were available for 9 of the wells added to the program in 2001, including the 6 NEW wells, wells MAMC 1, MAMC 6 and T-11b.

Extensive sampling results for four chlorinated solvent compounds (i.e., PCE, TCE, *cis*-1,2-DCE, and VC) were included in the analytical database provided to Parsons. Table 3.2 presents a summary of the occurrence of these four analytes in groundwater based on the data collected during the sampling events from February 1995 through December

2001. As indicated in Table 3.2, TCE is the primary contaminant of concern in groundwater at the Logistics Center. TCE has been detected in almost 90% of samples, and has exceeded the MCL of 5 μg/L over 73% of the time. TCE has been detected in 71 of the 74 wells that have been sampled, and has exceeded the MCL in 56 of these wells. *cis*-1,2-DCE is second most prevalent compound and has been detected in over 80% of samples; however, detected concentrations of *cis*-1,2-DCE have exceeded standards in less than 6% of samples. Additionally, although PCE and VC have been detected on site at several wells, groundwater measurements have rarely exceeded standards for these compounds.

TCE sampling results were the primary data used to conduct the three-tiered monitoring network optimization due to the magnitude and spatial extent of TCE concentrations in groundwater at Fort Lewis compared to the other detected compounds.



Legend
Extraction Well
Added to LOGRAM monitoring program
Retained from original monitoring program
Eliminated from monitoring program
East Gate Disposal Yard
American Lake
Interstate 5
Murray Creek
I-5 Extraction Wells
East Gate Extraction Wells
T-11b
T-06
T-10
T-04
T-12b
LC-165
T-13b
LC-61b
LC-128
LC-167
T-08
LC-14a
LC-122b
LX-15
LX-14
LX-12
LX-13
LC-16
LX-10
LX-11
NEW-4
LC-116b
LX-9
LX-8
LX-6
LX-7
LX-5
LC-05
LC-03
LC-111b
LX-4
LX-3
LX-1
LX-2
LC-132
LC-66b
LC-66a
LC-44a
FL3
FL6
LC-73a
LC-06
NEW-3
NEW-5
LC-41a
LC-41b
PA-381
NEW-6
PA-383
LC-49
LC-20
RW-1
LX-16
MAMC 1
MAMC 6
LC-34
LC-19a
LC-19c
LC-19b
LC-137c
LC-137a
LC-137b
LX-21
LC-108
LX-18
LC-24
LX-19
LC-136b
LC-136a
LC-64a
LX-17
FL4B
FL4A
LC-53
LC-51
LC-64b
LC-26
FL2
LC-149d
LC-149c
LC-57
NEW-1
NEW-2
N
0
500
1,000
2,000
3,000
Feet
FIGURE 3.1
ORIGINAL AND LOGRAM
MONITORING NETWORKS
Monitoring Network Optimization
Fort Lewis Logistics Center
PARSONS
Denver, Colorado

TABLE 3.2
SUMMARY OF OCCURRENCE OF GROUNDWATER CONTAMINANTS OF CONCERN
THREE-TIERED MONITORING NETWORK OPTIMIZATION
FORT LEWIS, WASHINGTON

Parameter	Total Samples[a/]	Percentage of Detects	Range of Detects (µg/L)[b/]	MCL (µg/L)[b/]	Percentage of MCL Exceedances	Number of Wells with Results	Number of Wells with Detections	Number of Wells with MCL Exceedances
Trichloroethene	1,402	89.9%	0.2-250000	5	73.8%	74	71	56
cis -1,2-Dichloroethene	1,402	80.5%	0.1-18000	70	5.5%	73	61	6
Tetrachloroethene	1,399	15.8%	0.1-420	5	0.5%	73	43	3
Vinyl Chloride	1,396	1.3%	0.023-3600	2	0.5%	73	10	3

[a/] Analytical data analyzed includes sampling results from February, 1995 to December, 2001.

[b/] MCL = maximum contamiant level; µg/L = micrograms per liter.

SECTION 4

QUALITATIVE MNO EVALUATION

An effective groundwater monitoring program will provide information regarding contaminant plume migration and changes in chemical concentrations through time at appropriate locations, enabling decision-makers to verify that contaminants are not endangering potential receptors, and that remediation is occurring at rates sufficient to achieve RA objectives within a reasonable time frame. The design of the monitoring program should therefore include consideration of existing receptor exposure pathways, as well as exposure pathways arising from potential future use of the groundwater.

Performance monitoring wells located upgradient, within, and immediately downgradient from a plume provide a means of evaluating effectiveness of a groundwater remedy relative to performance criteria. Long-term monitoring (LTM) of these wells also provides information about migration of the plume and temporal trends in chemical concentrations. Groundwater monitoring wells located at greater distances downgradient from a plume (i.e., sentry wells) are used to evaluate possible changes in the extent of the plume and, if warranted, to trigger a contingency response action if contaminants are detected.

Primary factors to consider when developing a groundwater monitoring program include at a minimum:

- Aquifer heterogeneity,
- Types of contaminants,
- Distance to potential receptor exposure points,
- Groundwater seepage velocity,

- Potential surface-water impacts, and
- The effects of the remediation system.

These factors will influence the locations and spacing of monitoring points and the sampling frequency. Typically, the greater the seepage velocity and the shorter the distance to receptor exposure points, the more frequently groundwater sampling should be conducted.

One of the most important purposes of LTM is to confirm that the contaminant plume is behaving as predicted. Graphical and statistical tests can be used to evaluate plume stability. If a groundwater remediation system or strategy is effective, then over the long term, groundwater-monitoring data should demonstrate a clear and meaningful decreasing trend in concentrations at appropriate monitoring points. The current groundwater monitoring program at the Fort Lewis Logistics Center was evaluated to identify potential opportunities to assess the recent MNO results (USACE, 2001) and, if appropriate, to further refine the RA monitoring program.

4.1 METHODOLOGY FOR QUALITATIVE EVALUATION OF MONITORING NETWORK

The three-tiered MNO evaluation of the Logistics Center groundwater LTM program considered information for 83 wells in the Logistics Center study area that were included in the original and/or revised groundwater monitoring networks (38 monitoring wells in the original network, 24 existing and new wells added to the monitoring network in December 2001, and the 21 groundwater extraction wells screened in the Vashon Aquifer). These wells are listed in Table 3.1, and their locations are depicted on Figure 3.1. Subsets of these wells were evaluated in the temporal and spatial tiers of the MNO evaluation, as required by the statistical and geostatistical methods employed (see Sections 5 and 6). Wells screened in the underlying Salmon Springs Aquifer were not included in this MNO evaluation.

Multiple factors were considered in developing recommendations for continuation or cessation of groundwater monitoring at each well. In some cases, a recommendation was made to continue monitoring a particular well, but at a reduced frequency. A recommendation to discontinue monitoring at a particular well based on the information reviewed does not necessarily constitute a recommendation to physically abandon the well. A change in site conditions might warrant resumption of monitoring at some time in the future at wells that are not currently recommended for continued sampling. Typical factors considered in developing recommendations to retain a well in, or remove a well from the monitoring program are summarized in Table 4.1. Typical factors considered in developing recommendations for monitoring frequency are summarized in Table 4.2.

TABLE 4.1
MONITORING NETWORK OPTIMIZATION DECISION LOGIC
THREE-TIERED MONITORING NETWORK OPTIMIZATION
FORT LEWIS LOGISTICS CENTER, WASHINGTON

Reasons for Retaining a Well in Monitoring Network	Reasons for Removing a Well From Monitoring Network
Well is needed to further characterize the site or monitor changes in contaminant concentrations through time	Well provides spatially redundant information with a neighboring well (e.g., same constituents, and/or short distance between wells)
Well is important for defining the lateral or vertical extent of contaminants	Well has been dry for more than 2 years[a/]
Well is needed to monitor water quality at compliance point or receptor exposure point (e.g., domestic well)	Contaminant concentrations are consistently below laboratory detection limits or cleanup goals
Well is important for defining background water quality	Well is completed in same water-bearing zone as nearby well(s)

a/ Water-level measurements in dry wells should continue, and groundwater sampling should be resumed if the well becomes re-wetted.

TABLE 4.2
MONITORING FREQUENCY DECISION LOGIC
THREE-TIERED MONITORING NETWORK OPTIMIZATION
FORT LEWIS LOGISTICS CENTER, WASHINGTON

Reasons for Increasing Sampling Frequency	Reasons for Decreasing Sampling Frequency
Groundwater velocity is high	Groundwater velocity is low
Change in contaminant concentration would significantly alter a decision or course of action	Change in contaminant concentration would not significantly alter a decision or course of action
Well is close to source area or operating remedial system	Well is distal from source area or remedial system
Cannot predict if concentrations will change significantly over time	Concentrations are not expected to change significantly over time, or contaminant levels have been below groundwater cleanup objectives for some prescribed period of time

4.2 RESULTS OF QUALITATIVE MNO EVALUATION

The results of the qualitative evaluation of the 83 monitoring and extraction wells screened in the Vashon Aquifer at the Fort Lewis Logistics Center included in the original and/or revised monitoring programs are summarized in Table 4.3, and described in the following subsections. The table includes recommendations for retaining or deleting each existing monitoring well, and for changing the sampling frequency, and lists the rationale for the recommendations.

4.2.1 Monitoring Network and Sampling Frequency

The following subsections describe the recommended groundwater sampling locations and frequencies in the Upper and Lower Vashon Aquifer.

4.2.1.1 Upper Vashon Aquifer

The Upper Vashon Aquifer wells recommended for retention in the Logistics Center LTM program are identified in Table 4.3 and on Figure 4.1, and are discussed in the following paragraphs.

TABLE 4.3

QUALITATIVE EVALUATION OF GROUNDWATER MONITORING NETWORK
THREE-TIERED MONITORING NETWORK OPTIMIZATION
FORT LEWIS, WASHINGTON

Well ID	Hydrologic Unit [a/]	Original Sampling Frequency	Revised Sampling Frequency [b/]	Qualitative Analysis: Remove	Qualitative Analysis: Retain	Qualitative Analysis: Monitoring Frequency Recommendation	Rationale
Source Area Monitoring Wells							
LC-64a	UV	Quarterly	Quarterly		√	Quarterly	Monitors upwardly-trending and elevated TCE concentrations in source are
LC-108	UV	Quarterly	None	√		--	Monitors relatively deep, low-concentration zone; however, deeper wells (e.g., LC-64b) are better indication of maximum contaminant concentrations at de
LC-136a	UV	Quarterly	Quarterly		√	Quarterly	Monitors maximum, upwardly-trending TCE concentrations in source are
LC-136b	UV	Quarterly	Annually		√	Annually	Indicates whether increasing TCE levels in LC-136a are resulting in vertical expansion of plum
Plume Interior Wells							
FL2	UV	None	Annually		√	Annually	Monitors elevated TCE concentrations in southwesterly-migrating lobe of TCE plum
LC-05	UV	Quarterly	Annually	√		--	Monitoring of this well is not necessary to define the extent and magnitude of the plume over time.
LC-06	UV	Quarterly	Semi-Annually		√	Annually	Plume interior well faciltates obtaining periodic snapshot of plume conditions..
LC-14a	UV	Quarterly	Annually		√	Annually	Monitors concentrations along plume axis downgradient of I-5 extraction system near plume toe.
LC-19a	UV	Quarterly	Quarterly		√	Annually	Monitors plume axis downgradient of source area.
LC-19b	UV	Quarterly	None	√		--	Monitors shallower, lower-concentration zone than LC-19a.
LC-19c	UV	Quarterly	None	√		--	Similar screen interval as LC-19a, and lower TCE concentrations.
LC-41a	UV	Quarterly	Annually		√	Annually	Monitors elevated TCE concentrations in portion of plume with low well density.
LC-44a	UV	Quarterly	None	√		--	Redundant with nearby well LC-66b, which monitors a higher-concentration zone.
LC-49	UV	Quarterly	Annually		√	Annually	Located along plume axis, relatively high TCE concentration
LC-51	UV	Quarterly	None	√		--	Redundant with LC-53 and FL2.
LC-53	UV	Quarterly	Annually		√	Annually	Monitors elevated TCE concentrations in southwesterly-migrating "plumelet
LC-66a	UV	Quarterly	None	√		--	Paired (and slightly deeper) well LC-66B monitors higher-concentration zor
LC-66b	UV	Quarterly	Annually		√	Annually	Monitors elevated TCE concentrations along plume axis in LV/SSA "window" area. CHECK WINDOW LOCATIO
LC-132	UV	Quarterly	None	√		--	Redundant with nearby well LC-66b, which monitors a higher concentration zon
LC-137a	UV	Quarterly	None	√		--	Relatively low TCE concentrations; not indicative of plume magnitude in source area; does not provide useful data to define plume magnitude/ext
LC-137b	UV	Quarterly	Quarterly	√		--	Relatively low TCE concentrations; not indicative of plume magnitude in source area; does not provide useful data to define plume magnitude/ext
PA-381	UV	Quarterly	Annually		√	Biennially	Uniform TCE concentrations over 38 sampling events since 1986, indicating that very infrequent monitoring is adequate and protecti
Newly-Installed Monitoring Wells							
MAMC 1	LV	None	Quarterly		√	Quarterly	Sample for 4 quarters, then reassess to determine if monitoring frequency can be reduced or monitoring can be discontinu
MAMC 6	LV	None	Quarterly		√	Quarterly	Sample for 4 quarters, then reassess to determine if monitoring frequency can be reduced or monitoring can be discontinu
NEW-1	UV	None	Quarterly		√	Quarterly	Improves definition of southwestern "plumelet". Sample for 4 quarters then reassess to determine if monitoring frequency can be reduc
NEW-2	UV	None	Quarterly		√	Quarterly	Improves definition of southwestern "plumelet". Sample for 4 quarters then reassess to determine if monitoring frequency can be reduc
NEW-3	UV	None	Quarterly		√	Quarterly	Defines plume boundary downgradient of I-5 extraction system; Sample for 4 quarters then reassess to determine if monitoring frequency can be reduc
NEW-4	UV	None	Quarterly		√	Quarterly	Same as for NEW-3.
NEW-5	UV	None	Quarterly		√	Quarterly	Plume boundary definition well; Sample for 4 quarters then reassess to determine if monitoring frequency can be reduced or monitoring can be discontinu
NEW-6	UV	None	Quarterly		√	Quarterly	Plume boundary definition well; Sample for 4 quarters then reassess to determine if monitoring frequency can be reduced or monitoring can be discontinu
Upgradient and Cross-Gradient Wells							
FL3	UV	None	Quarterly	√		--	Redundant with well FL-6.
FL4B	UV	None	Quarterly		√	Biennially	Plume stability and consistently low TCE levels at this well support very low-frequency monitoring unless hydraulic conditions change or recent data indicate increasing trend. If historical trends continue, sampling of this well could be discontinued with sampling continued at NEW-2 and LC-3
FL6	UV	None	Quarterly		√	Biennially	Monitors southwestern extent of plume at I-5 extraction system; demonstrated plume stability supports very low-frequency monitoiri
LC-03	UV	Quarterly	Quarterly		√	Biennially	Frequency reduction justified by measured plume stability. Only one MCL exceedance in the 34 samples collected since January 1985.
LC-16	UV	None	Quarterly	√		--	Wells LC-03 to SE and LC-167 to NW adequately define plume boundary in this area. TCE levels very stable over 14 events from 1985 to 2001 unless 2002 data indicate increasing tre
LC-20	UV	None	Quarterly		√	Biennially	TCE low and stable over 9 events from 1995 to 2001; demonstrated plume stability supports low-frequency monitoring unless hydraulic conditions chan
LC-24	UV	None	Quarterly		√	Biennially	TCE low and stable over 7 events from 1985 to 2001; demonstrated plume stability supports low-frequency monitoring unless hydraulic conditions change or 2002 data indicate increasing tr
LC-26	UV	Quarterly	Annually	√		--	Upgradient well, no temporal trend. Wells LC-149d and LC-149c adequately monitor potential upgradient release.
LC-34	UV	None	Quarterly		√	Biennially	TCE low and stable over 5 events from 1986 to 2001; demonstrated plume stability supports low-frequency monitoring unless hydraulic conditions change or 2002 data indicate increasing tr
LC-57	UV	None	Quarterly		√	Biennially	TCE low and stable over 6 events from 1987 to 2001; demonstrated plume stability supports low-frequency monitoring unless hydraulic conditions change or recent data indicate increasing tr
LC-73a	UV	Quarterly	None	√		--	Cross-gradient of TCE plume; well FL-6, screened at a similar depth, better defines plume boundar
LC-149c	UV	Quarterly	Annually		√	Biennially	Upgradient well, max 1.2 ug/L TCE since Dec. 1992 (mostly non-detect); more frequent monitoring unnecessary unless upgradient release is suspect
LC-149d	UV	Quarterly	None		√	Biennially	Advisable to infrequently assess background water quality deeper in aquifer given potential for TCE to be more prevalent at dep
LC-165	UV	Quarterly	None	√		--	Substantially cross-gradient of TCE plume; other wells (e.g., LC-61b) better define plume boundar
PA-383	UV	Quarterly	Annually		√	Biennially	29 of 29 TCE results < MCL since 1986. Plume stability indicates infrequent monitoring adequate and protectiv
Downgradient Wells							
LC-61b	UV	None	Quarterly		√	Semi-Annually	Defines approximate plume boundary near downgradient plume toe

TABLE 4.3 (Continued)

QUALITATIVE EVALUATION OF GROUNDWATER MONITORING NETWORK
THREE-TIERED MONITORING NETWORK OPTIMIZATION
FORT LEWIS, WASHINGTON

Well ID	Hydrologic Unit [a/]	Original Sampling Frequency	Revised Sampling Frequency [b/]	Qualitative Analysis			Rationale
				Remove	Retain	Monitoring Frequency Recommendation	
LC-167	UV	None	Quarterly		√	Semi-Annually	New well; potential downgradient sentry well near plume toe
T-08	UV	Quarterly	Semi-Annually		√	Semi-Annually	Sentry well facilitating assessment of plume toe stability downgradient from I-5 extraction syster
T-12b	UV	Quarterly	Quarterly		√	Biennially	TCE < MCL; well is distant from estimated plume boundaries but potentially downgradient of main TCE plume; infrequent monitoring sufficient. LC-167 should give early warning of plume expansion in this direction
T-13b	UV	Quarterly	Semi-Annually		√	Semi-Annually	Defines downgradient extent of 5-ug/L TCE contour in Upper Vashon; semiannual sampling justified given potential for relatively high groundwater veloc
Northern Plume Wells							
T-04	UV	Quarterly	Annually		√	Annually	Monitors contamination north of I-5
T-06	UV	None	Quarterly		√	Quarterly	Monitors contamination north of I-5; Sample for 4 quarters then reassess to determine if monitoring frequency can be reduce
T-11b	UV	None	Quarterly		√	Quarterly	Monitors contamination north of I-5; Sample for 4 quarters then reassess to determine if monitoring frequency can be reduce
Extraction Wells							
LX-1	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-2	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-3	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-4	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-5	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-6	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-7	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-8	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-9	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-10	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-11	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-12	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-13	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-14	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-15	EW	Quarterly	Annually		√	Every 3 years	Primary objective for this well is hydraulic plume control, not mass removal. Plume control can be assessed by sampling downgradient monitoring we
LX-16	EW	Quarterly	Quarterly		√	Semi-Annually	Relatively high mass removal rates; assess effects of recent source removal on groundwater quality downgradient from source are
LX-17	EW	Quarterly	Quarterly		√	Quarterly	Relatively high mass removal rates; assess effects of recent source removal on groundwater quality in source are
LX-18	EW	Quarterly	Quarterly		√	Quarterly	Relatively high mass removal rates; assess effects of recent source removal on groundwater quality in source are
LX-19	EW	Quarterly	Quarterly		√	Quarterly	Relatively high mass removal rates; assess effects of recent source removal on groundwater quality in source are
LX-21	EW	Quarterly	Quarterly		√	Quarterly	Relatively high mass removal rates; assess effects of recent source removal on groundwater quality in source are
RW-1	EW	Quarterly	Quarterly		√	Annually	Relatively high mass removal rates; assess effects of recent source removal on groundwater quality downgradient from source are
Lower Vashon Wells							
FL4A	LV	None	Quarterly		√	Biennially	Low and stable TCE levels; demonstrated plume stability supports low-frequency monitoring unless hydraulic conditions change or recent data indicate increasing tre
LC-41b	LV	None	Quarterly		√	Annually	Monitors deeper zone in Vashon Aquifer containing relatively elevated TCE levels. Plume stability supports less-frequent montoring unless recent data indicate increasing tre
LC-64b	LV	Quarterly	Annually		√	Annually	Monitors Lower Vashon water quality in source area beneath elevated TCE concentrations in Upper Vasho
LC-111b	LV	Quarterly	Annually		√	Biennially	TCE low to non-detect over 25 events since 1995; potentially increasing cis-1,2-DCI
LC-116b	LV	Quarterly	Annually		√	Annually	Recent increasing trend for TCE suggests annual monitoring appropriate
LC-122b	LV	Quarterly	Annually	√		Biennially	TCE trace to non-detect over 25 events since 1993; stable situation does not require future monitorin
LC-128	LV	Quarterly	Annually		√	Annually	Monitors water quality in Lower Vashon downgradient of I-5 extraction systen
LC-137c	LV	Quarterly	Annually		√	Annually	Monitors Lower Vashon water quality and helps define vertical extent of plume at downgradient edge of source are
T-10	LV	None	Quarterly		√	Semi-Annually	Monitors L. Vashon downgradient of LC-128. Given large distance from LC-128 to T-10 (1500') and low TCE levels, semiannual sampling should be adequately protecti
Proposed Additional Well							
LC-180	??	None	None		**ADD**	Annually	Add to monitor leading edge of southwestern lobe of plume near Murray Creel

[a/] UV = Upper Vashon Aquifer; LV = Lower Vashon Aquifer.

[b/] Revised by US Army Corps of Engineers (2001).

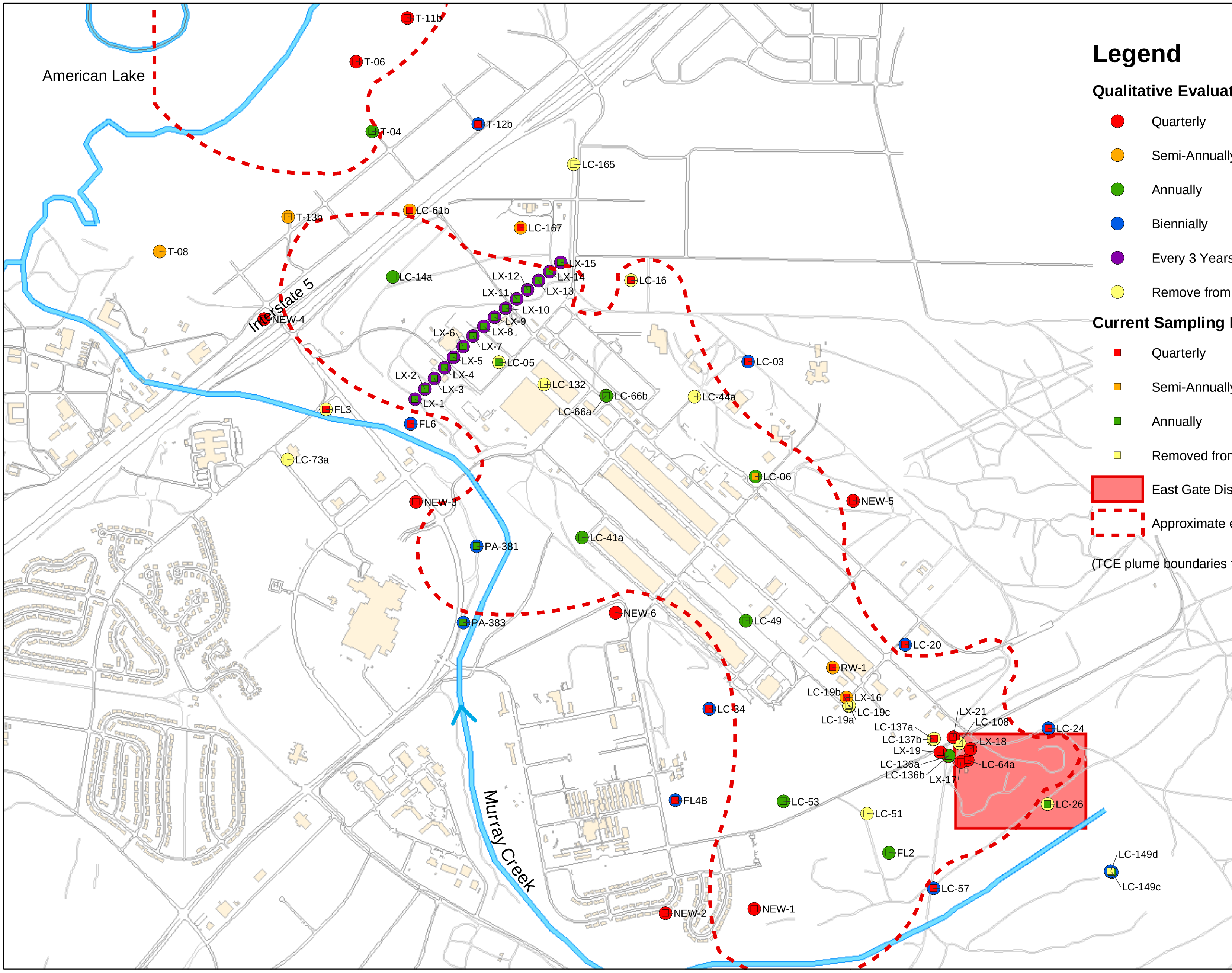


FIGURE 4.1
QUALITATIVE EVALUATION
RECOMMENDATIONS FOR
UPPER VASHON WELLS

Monitoring Network Optimization
Fort Lewis Logistics Center

PARSONS
Denver, Colorado

- Source-Area Monitoring Wells. Sampling of monitoring wells LC-64a and LC-136a, located in the EGDY source area (Figure 4.1), facilitates assessment of maximum TCE concentrations present in source-area groundwater, as well as assessment of the effectiveness of source-removal actions (i.e., the recent drum removal action and the *in situ* soil heating activities in the NAPL areas, scheduled to begin in 2004). Given the prior and planned future source removal actions, relatively frequent (i.e., quarterly) monitoring of these wells is reasonable to gauge the effect of the RAs on source-area groundwater quality. Available hydrogeologic data suggest that groundwater velocities within the cone of depression of the primary EGDY extraction well field may be relatively high (i.e., greater than 10 ft/day). Therefore, the effects of source removal efforts may become apparent relatively quickly as highly contaminated groundwater is extracted from the aquifer and replaced by less-contaminated influent groundwater from surrounding areas. Currently, these wells are monitored on a quarterly basis.

  Source-area well LC-136b is screened in a deeper, lower-concentration zone than its shallower paired well LC-136a. Continued monitoring of this well is recommended to assess the vertical extent of substantially elevated TCE concentrations detected in groundwater from LC-136a. However, given the substantially lower TCE concentrations in LC-136b, a less-frequent (i.e., annual) monitoring frequency is recommended (Table 4.3).

- Plume Interior Wells. These wells are located within the TCE plume in areas where dissolved TCE concentrations are relatively elevated (e.g., along the longitudinal axis of the TCE plume, defined as the northwest/southeast-trending zone containing the highest TCE concentrations along the primary flow axis of the plume). Specific wells recommended for continued monitoring include FL2, LC-06, LC-14a, LC-19a, LC-41a, LC-49, LC-53, LC-66b, and PA-381 (Figure 4.1). Monitoring of these wells tracks the magnitude of the dissolved TCE plume over time.

According to USACE (2001), the rate at which the COCs migrate in groundwater at the site is sufficiently slow that significant concentration changes do not occur between quarterly monitoring periods. TCE concentrations detected in the Upper Aquifer throughout the monitoring network indicates that the plume footprint has not expanded or decreased significantly and has remained largely stable since startup of the groundwater extraction systems in August 1995 (USACE and URS, 2002). Given that the plume is hydraulically controlled, and has been relatively stable in terms of areal extent and magnitude over the post-RA monitoring period, annual monitoring is recommended for most of these wells. This frequency should be adequate to monitor changes in the magnitude of the plume over time. The only recommended exception to this monitoring frequency is for well PA-381, where biennial (i.e., every other year) monitoring is recommended. This well, which is located near the inferred western edge of the TCE plume along Murray Creek, near the Madigan Army Medical Center (MAMC), has exhibited stable TCE concentrations over 38 sampling events from 1986 to December 2001. Therefore, relatively infrequent monitoring is recommended.

Well LC-14a is located downgradient from the I-5 extraction system and upgradient from the I-5 system infiltration gallery. Given that sampling results for this well are indicative of the effectiveness of the extraction system at minimizing or preventing northwesterly migration of contamination across the line of extraction wells, a more frequent monitoring frequency for this well was considered. However, TCE data for this well collected from 1995 to 2001 indicate a decreasing trend. Therefore, more-frequent monitoring is not recommended unless hydraulic conditions change (e.g., the collective groundwater extraction rate at the I-5 extraction system decreases substantially, indicating a lower degree of plume capture).

- Newly-Installed Monitoring Wells. Six Upper Vashon monitoring wells installed in 2002 were only recently included in the LTM program; therefore, groundwater analytical results for these wells were not available during this MNO evaluation.

These wells include NEW-1 through NEW-6 (Figure 4.1). Quarterly monitoring of these wells for a 1-year period is recommended to establish baseline concentrations. At the end of the first year of monitoring, the four quarters of data should be reviewed, and the monitoring frequency should be revised as appropriate (or monitoring should be discontinued) using the guidelines discussed in this section. For example, plume boundary wells should be assigned a relatively low monitoring frequency, as described in the following paragraph.

- Upgradient and Cross-Gradient Wells. These wells are located near the upgradient (eastern or southern) or crossgradient (northeastern or southwestern) edges of the TCE plume and define the approximate location of the 5-µg/L TCE concentration contour over time. Starting at and including upgradient well cluster LC-149c/d at the southeastern end of the plume, and moving around the plume in a clockwise direction, these wells include LC-57, NEW-2, FL4B, LC-34, NEW-6, PA-383, FL6, LC-03, NEW-5, LC-20, LC-24, and LC-26 (Figure 4.1). Excluding the new wells (discussed above). several of these wells have been sampled many times since the mid- to late 1980s, and results have consistently indicated that the plume is not expanding in the cross- or upgradient directions. For example, well PA-383 was sampled 29 times from 1986 through December 2001, and TCE concentrations in the 28 samples in which this compound was detected ranged from 0.4 to 3.4 µg/L. Given the apparent stability of the TCE plume, the recommended sampling frequency for these cross- and upgradient wells is biennial.

- Downgradient Wells. Wells NEW-4, T-08, T-13b, LC-61b, and LC-167) are located downgradient from the leading edge of the primary TCE plume, and act as sentry wells that facilitate assessment of plume migration over time (Figure 2). TCE results for T-08 and T-13b do not indicate a temporal trend, and insufficient data were available to assess contaminant concentration trends at wells LC-61b and LC-167. The consistently low TCE concentrations and lack of temporal trends in T-08 and T-13b indicate that the plume is stable, neither expanding nor receding significantly. However, given the presence of relatively steep hydraulic gradients, high hydraulic conductivities (Table 5-2 in USACE and URS, 2002), and correspondingly high groundwater and solute migration velocities in this area, a conservative semiannual monitoring schedule for these three wells is recommended should hydraulic conditions change and plume expansion occur in the future. Well T-12B also is potentially downgradient from the main TCE plume. However, this well is almost 1,500 feet from the estimated location of the 5-µg/L TCE concentration contour, and semiannual monitoring of LC-167 should provide an early warning of plume expansion in this direction. Therefore, biennial monitoring of T-12b is recommended unless data for LC-167 indicate plume expansion in this direction. Currently, the monitoring program does not include a well to monitor the leading (southern) edge of the southwestern lobe of the TCE plume, which appears to extend south of Murray Creek in this are (Figure 4.1). Existing well LC-180, not currently monitored on a routine basis, should be considered for incorporation into the LTM program to monitor plume stability in this area.

- <u>Wells Located in Plume Extension North of I-5.</u> Wells T-04, T-06, and T-11b are located north of I-5 in what appears to be an extension of the TCE plume that is inferred to be separated from the main plume by a zone of lower TCE concentrations (i.e., < 5 µg/L) (Figure 4.1). This portion of the plume is inferred to discharge into American Lake. Monitoring of wells T-06 and T-11b was renewed in December 2001 (T-06) and March 2002 (T-11b) after a sampling hiatus of 8 to 13 years. Completion of four quarters of monitoring is recommended to reestablish the baseline for these wells. The monitoring frequency should then be adjusted appropriately following review of the first-year results. Preliminary results for these wells indicate the presence of TCE concentrations that slightly exceed the 5-µg/L MCL. If concentrations appear to be stable, then annual monitoring of these wells would be appropriate. Annual monitoring is recommended for well T-04, based on the stable concentrations of

TCE detected over the past few years (8 to 12 µg/L) and the lack of a temporal trend.

- Extraction Wells. Continued quarterly monitoring of the groundwater extraction wells LX-17 through LX-21 in the primary EGDY well field (Figure 4.1) is recommended to assess the effects of recent and pending source-removal activities on groundwater quality. Given the source-area location of these extraction wells, the average contaminant mass-removal rate is relatively high, and RA-related changes should be closely monitored. Extraction wells LX-16 and RW-1 are located in the secondary EGDY well field, approximately 1,000 feet downgradient from the EGDY source area. Assuming an average hydraulic conductivity in the vicinity of the primary and secondary EGDY well fields of 120 ft/day (average of the geometric mean hydraulic conductivity values for these well fields derived from pumping tests (Table 5-2 in USACE and URS, 2002), a hydraulic gradient between the EGDY and the secondary well field of 0.0013 ft/ft, and an average effective porosity of 0.30, the average groundwater velocity between the EGDY and the secondary well field is 0.5 ft/day. The TCE migration rate would probably be slower due to the effects of retardation. Therefore, the effects of source-removal at the EGDY may not be apparent at the secondary East Gate well field for years. Therefore, less frequent (i.e., semiannual) monitoring of LX-16 and RW-1 is recommended to track mass-removal rates at these wells given the historically stable TCE concentrations detected in their effluent.

The primary purpose of the I-5 extraction system is hydraulic control of the downgradient portion of the plume rather than mass removal. In 2001, the average TCE concentration in the I-5 extraction well field effluent was approximately 50 µg/L (computed using the maximum concentration detected in the effluent from each well during the four quarters ending in December 2001). In contrast, the average TCE concentration in the primary and secondary EGDY extraction wells during the same period was approximately 900 µg/L. Therefore, annual sampling of the I-5 extraction well effluent for VOCs is not recommended. Instead, the effectiveness of this well field at preventing further downgradient migration of the plume should be assessed via a combination of periodic sampling of monitoring wells located downgradient from the line of extraction wells and capture zone analyses using measured water levels. The I-5 extraction wells could be sampled relatively infrequently (e.g., once every 2 to 3 years) to assess contaminant concentrations in the effluent and confirm that continued pumping of all of the wells, and operation of the air stripper, are necessary.

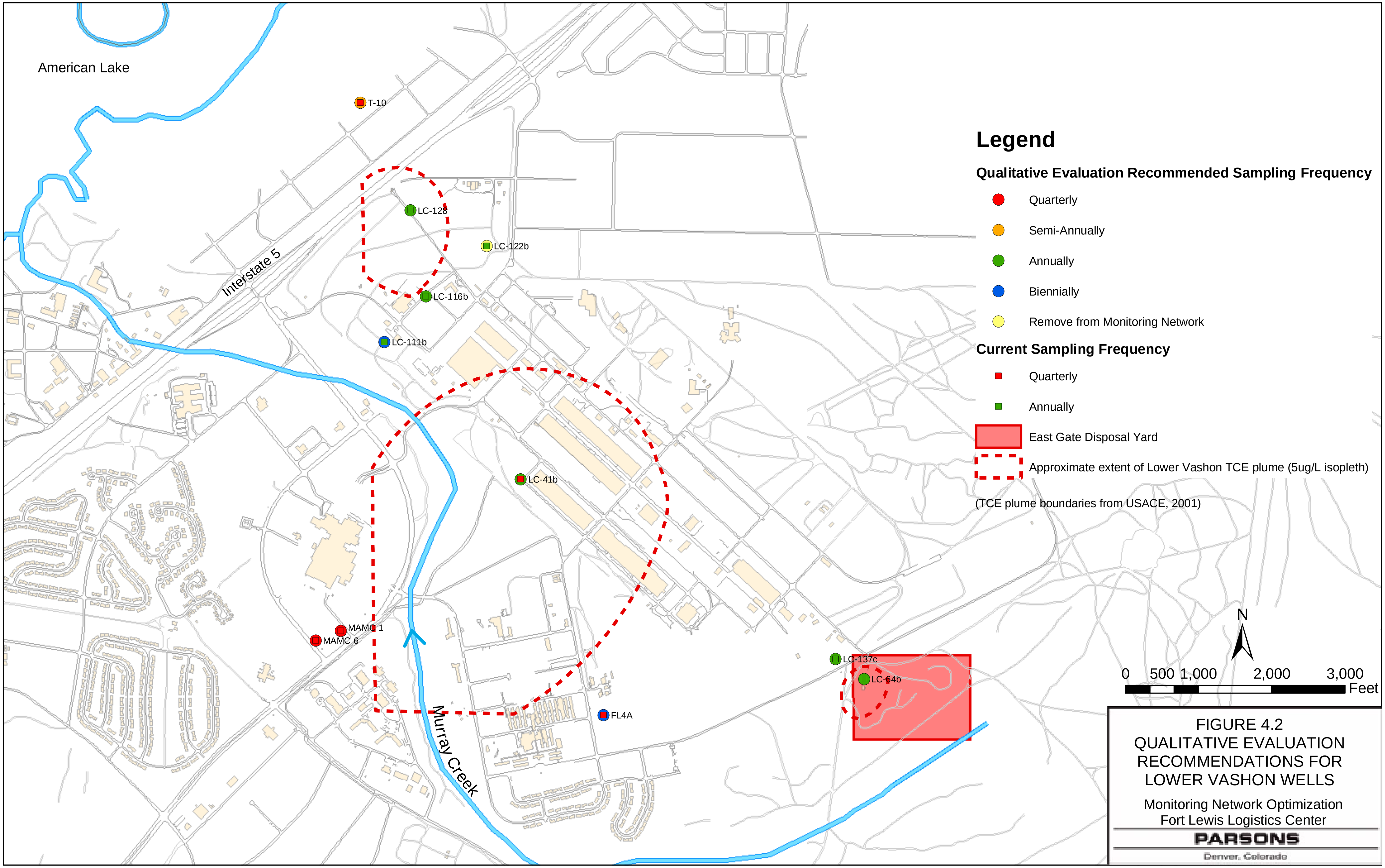
4.2.1.2 Lower Vashon Aquifer

Compared with the Upper Vashon Aquifer, a relatively small number of wells are screened within the Lower Vashon Aquifer. Eleven Lower Vashon wells currently are included in the LTM program, and continued monitoring of 10 of these wells is recommended for the reasons summarized in Table 4.3.

Two of the Lower Vashon wells (LC-64b and LC-137c) are located in or immediately adjacent to the EGDY source area (Figure 4.2). TCE concentrations detected in groundwater samples collected from these wells between December 1995 and December 2001 are much lower than the paired Upper Vashon wells, and exhibit a statistical decreasing trend (see Section 5). The beneficial effects of source removal activities in this area will likely be evident more rapidly in the Upper Vashon Aquifer than in the Lower Vashon. Therefore, an annual monitoring frequency for these two Lower Vashon wells is recommended.

Other than source-area well LC-64b, wells LC-41b and LC-128 are the only Lower Vashon wells that contain TCE at concentrations exceeding the 5-µg/L MCL. Annual monitoring of these wells is recommended, similar to the annual monitoring schedule recommended for wells in the interior of the Upper Vashon TCE plume.

Wells MAMC 1 and MAMC 6 are new, and have been monitored for less than 1 year. Similar to wells NEW-1 through NEW-6 in the Upper Vashon Aquifer, quarterly monitoring of these wells for a 1-year period is recommended to establish baseline concentrations. At the end of the first year of monitoring, the four quarters of data should


American Lake
T-10
LC-128
LC-122b
LC-116b
LC-111b
LC-41b
Interstate 5
MAMC 1
MAMC 6
Murray Creek
FL4A
LC-137c
LC-64b
Legend
Qualitative Evaluation Recommended Sampling Frequency
Quarterly
Semi-Annually
Annually
Biennially
Remove from Monitoring Network
Current Sampling Frequency
Quarterly
Annually
East Gate Disposal Yard
Approximate extent of Lower Vashon TCE plume (5ug/L isopleth)
(TCE plume boundaries from USACE, 2001)
N
0 500 1,000 2,000 3,000
Feet
FIGURE 4.2
QUALITATIVE EVALUATION
RECOMMENDATIONS FOR
LOWER VASHON WELLS
Monitoring Network Optimization
Fort Lewis Logistics Center
PARSONS
Denver, Colorado

be reviewed, and the monitoring frequency should be revised as appropriate, or monitoring should be discontinued.

Similar to Upper Vashon well FL4B (Figure 4.1), Lower Vashon well FL4A is located near the estimated southwestern boundary of the contaminant plume, and the low and stable magnitude of detected TCE concentrations supports a very low-frequency (i.e., biennial) monitoring schedule.

Lower Vashon Aquifer wells LC-111b, LC-116b, and LC-122b are located in the line of extraction wells comprising the I-5 well field, but are screened at greater depths than the extraction wells. In addition, these wells are located potentially downgradient from TCE contamination detected in Lower Vashon well LC-41b (Figure 4.2). TCE concentrations at wells LC-111b and LC-122b have been less than 2 µg/L over 25 sampling events since 1993, and recent concentrations exhibit a decreasing trend. Therefore, removal of well LC-122b from the RA monitoring program is recommended, and low-frequency (i.e., biennial) monitoring of well LC-111b is recommended because of its potentially increasing *cis*-1,2-DCE concentrations. In contrast, TCE concentrations at LC-116b slightly exceed the 5-µg/L MCL and have recently exhibited a statistical increasing trend. Therefore, continued annual monitoring of this well is recommended.

Lower Vashon well T-10 is located off-site (i.e., northwest of I-5) and potentially downgradient from TCE contamination detected in the Lower Vashon at well LC-128. Similar to sentry wells screened in the Upper Vashon, a conservative semiannual monitoring schedule is recommended for this sentry well, should hydraulic conditions change or plume expansion occur in the future.

4.2.2 Laboratory Analytical Program

Groundwater samples have been analyzed for VOCs using USEPA Method SW8260B since the 12^{th} quarter of monitoring (September 1998) (USACE and URS, 2002). The previous analytical program had used USEPA Methods SW8010A and SW8260. Beginning in the 24^{th} quarter (September 2001), selected samples have been analyzed for VC using USEPA Method SW8260B modified for select ion monitoring (SIM) in response to elevated Method 8260B reporting limits for VC (up to 4,000 µg/L) and other compounds due to the high TCE concentrations in several samples (USACE and URS, 2002).

Because the characterization of conditions in the Fort Lewis Logistics Center groundwater plume has been largely completed, groundwater samples collected from monitoring wells could be analyzed for selected COCs using Method 8021B, rather than the currently-used Method 8260B. Method 8021B can be used to analyze for the primary COCs at the site, and could potentially result in a considerable reduction in analytical costs. The cost for analysis of a groundwater sample using Method 8021B (a gas-chromatographic [GC] method) can be substantially lower than the cost of analysis using Method 8260B (a gas-chromatographic/mass-spectrographic [GC/MS] method), especially if the target analyte list is reduced. USEPA Method 8260B/SIM could still be used for samples from wells that contain substantially elevated TCE concentrations.

4.2.4 LTM Program Flexibility

The LTM program recommendations made in Sections 4.2.1 through 4.2.3 are based on available data regarding current (and expected future) site conditions. Changing site conditions (e.g., lengthy malfunction or significant adjustment of the groundwater extraction/infiltration systems) could affect plume behavior. Therefore, the LTM program should be reviewed if hydraulic conditions change significantly. and revised as necessary to adequately track changes in plume magnitude and extent over time.

SECTION 5

TEMPORAL STATISTICAL EVALUATION

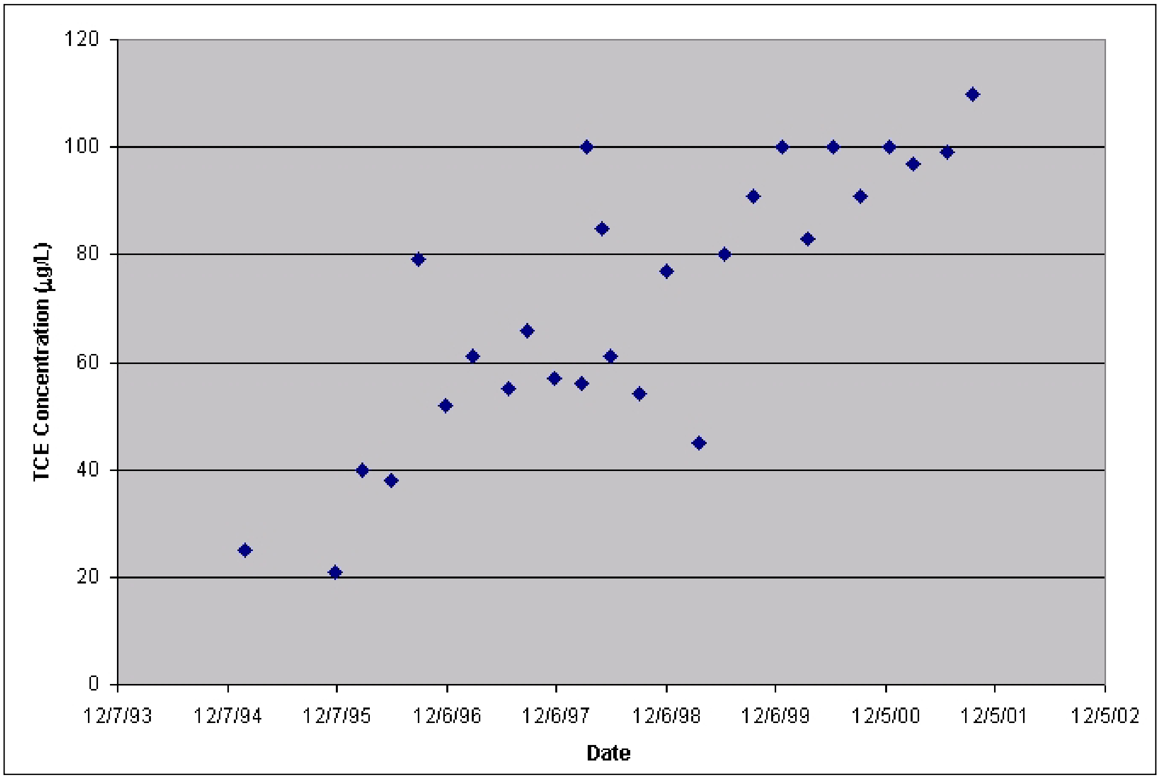
Temporal data (chemical concentrations measured at different points in time) can be examined graphically, or using statistical tests, to evaluate dissolved-contaminant plume stability. If removal of chemical mass is occurring in the subsurface as a consequence of attenuation processes or operation of a remediation system, mass removal will be apparent as a decrease in chemical concentrations through time at a particular sampling location, as a decrease in chemical concentrations with increasing distance from chemical source areas, and/or as a change in the suite of chemicals through time or with increasing migration distance.

5.1 METHODOLOGY FOR TEMPORAL TREND ANALYSIS OF CONTAMINANT CONCENTRATIONS

Temporal chemical-concentration data can be evaluated by plotting contaminant concentrations through time for individual monitoring wells (Figure 5.1), or by plotting contaminant concentrations versus downgradient distance from the contaminant source for several wells along the groundwater flowpath, over several monitoring events. Plotting temporal concentration data is recommended for any analysis of plume stability (Wiedemeier and Haas, 2000); however, visual identification of trends in plotted data may be a subjective process, particularly if (as is likely) the concentration data do not exhibit a uniform trend, but are variable through time (Figure 5.2).

The possibility of arriving at incorrect conclusions regarding plume stability on the basis of visual examination of temporal concentration data can be reduced by examining temporal trends in chemical concentrations using various statistical procedures, including

FIGURE 5.1
TCE CONCENTRATIONS THROUGH TIME
AT WELL LC-132
THREE-TIERD MONITORING NETWORK OPTIMIZATION
FORT LEWIS LOGISTICS CENTER, WASHINGTON



regression analyses and the Mann-Kendall test for trends. The Mann-Kendall nonparametric test (Gibbons, 1994) is well-suited for evaluation of environmental data because the sample size can be small (as few as four data points), no assumptions are made regarding the underlying statistical distribution of the data, and the test can be adapted to account for seasonal variations in the data. The Mann-Kendall test statistic can be calculated at a specified level of confidence to evaluate whether a temporal trend is exhibited by contaminant concentrations detected through time in samples from an individual well. If a trend is identified, a nonparametric slope of the trend line (change in concentration per unit time) also can be estimated using the test procedure. A negative slope (indicating decreasing contaminant concentrations through time) or a positive slope

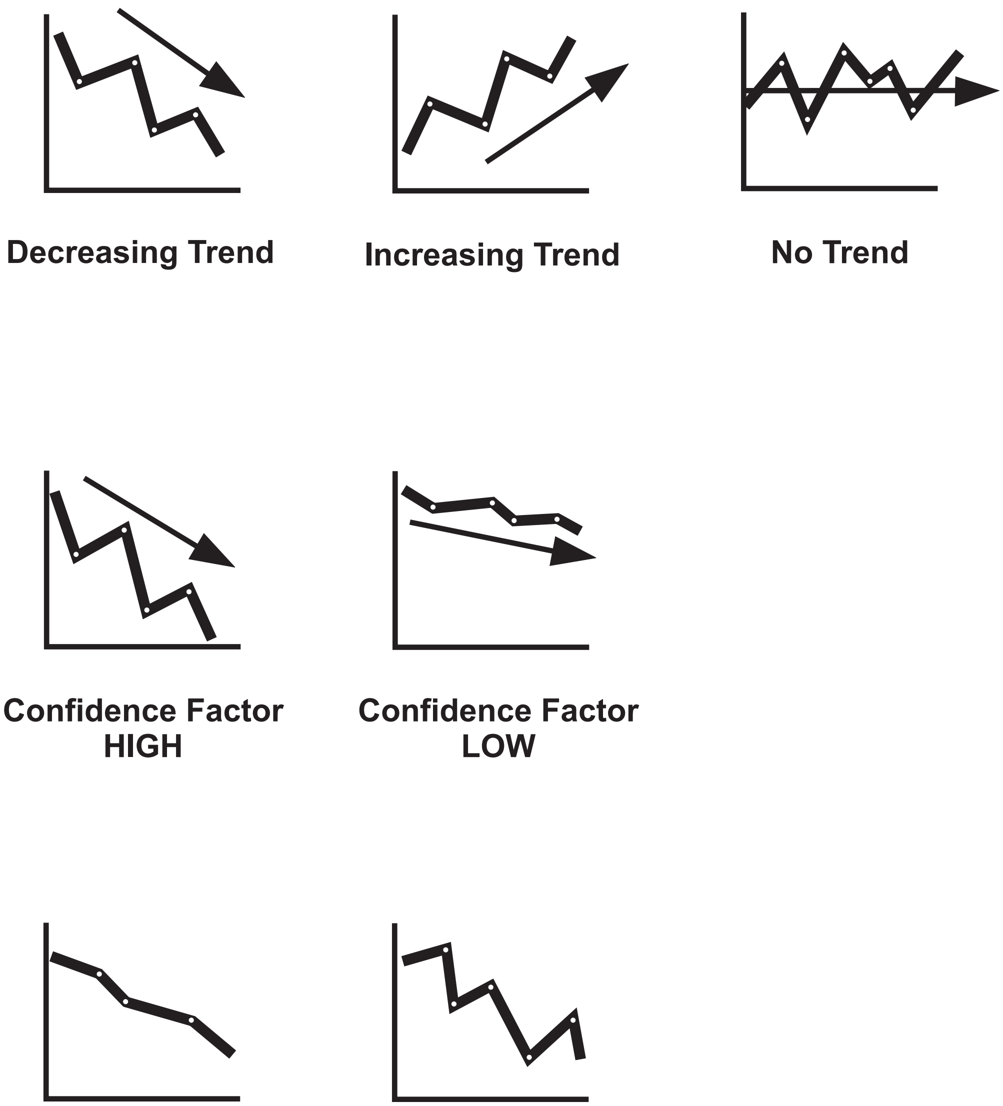


FIGURE 5.2

CONCEPTUAL REPRESENTATION OF TEMPORAL TRENDS AND TEMPORAL VARIATIONS IN CONCENTRATIONS

Monitoring Network Optimization
Fort Lewis Logistics Center, Washington

draw\739732\diffusion\williamsA.cdr pg1 nap 4/3/02 (increasing concentrations through time) provides statistical confirmation of temporal trends that may have been identified visually from plotted data (Figure 5.2).

The relative value of information obtained from periodic monitoring at a particular monitoring well can be evaluated by considering the location of the well with respect to the dissolved contaminant plume and potential receptor exposure points, and the presence or absence of temporal trends in contaminant concentrations in samples collected from the well. The degree to which the amount and quality of information that can be obtained at a particular monitoring point serve the two primary (i.e., temporal and spatial) objectives of monitoring must be considered in this evaluation. For example, the continued non-detection of a target contaminant in groundwater at a particular monitoring location provides no information about temporal trends in contaminant concentrations at that location, or about the extent to which contaminant migration is occurring, unless the monitoring location lies along a groundwater flowpath between a contaminant source and a potential receptor exposure point. Therefore, a monitoring well having a history of contaminant concentrations below detection limits may be providing little or no useful information, depending on its location.

A trend of increasing contaminant concentrations in groundwater at a location between a contaminant source and a potential receptor exposure point may represent information critical in evaluating whether contaminants are migrating to the exposure point, thereby completing an exposure pathway. Identification of a trend of decreasing contaminant concentrations at the same location may be useful in evaluating decreases in the areal extent of dissolved contaminants, but does not represent information that is critical to the protection of a potential receptor. Similarly, a trend of decreasing contaminant concentrations in groundwater near a contaminant source may represent important information regarding the progress of remediation near, and downgradient from the source, while identification of a trend of increasing contaminant concentrations at the same location does not provide as much useful information regarding contaminant conditions. By contrast, the absence of a temporal trend in contaminant concentrations at a particular location within or downgradient from a plume indicates that virtually no additional information can be obtained by continued monitoring of groundwater at that location, in that the results of continued monitoring through time are likely to fall within the historic range of concentrations that have already been detected (Figure 5.3). Continued monitoring at locations where no temporal trend in contaminant concentrations is present serves merely to confirm the results of previous monitoring activities at that location. The relative amounts of information generated by the results of temporal trend evaluation at monitoring points near, upgradient from, and downgradient from contaminant sources are presented schematically as follow:

Monitoring Point Near Contaminant Source

Relatively less information	Nondetect or no trend
↓	Increasing trend in concentrations
Relatively more information	Decreasing trend in concentrations

Monitoring Point Upgradient from Contaminant Source

Relatively less information	Nondetect or no trend
↓	
	Decreasing trend in concentrations
Relatively more information	Increasing trend in concentrations

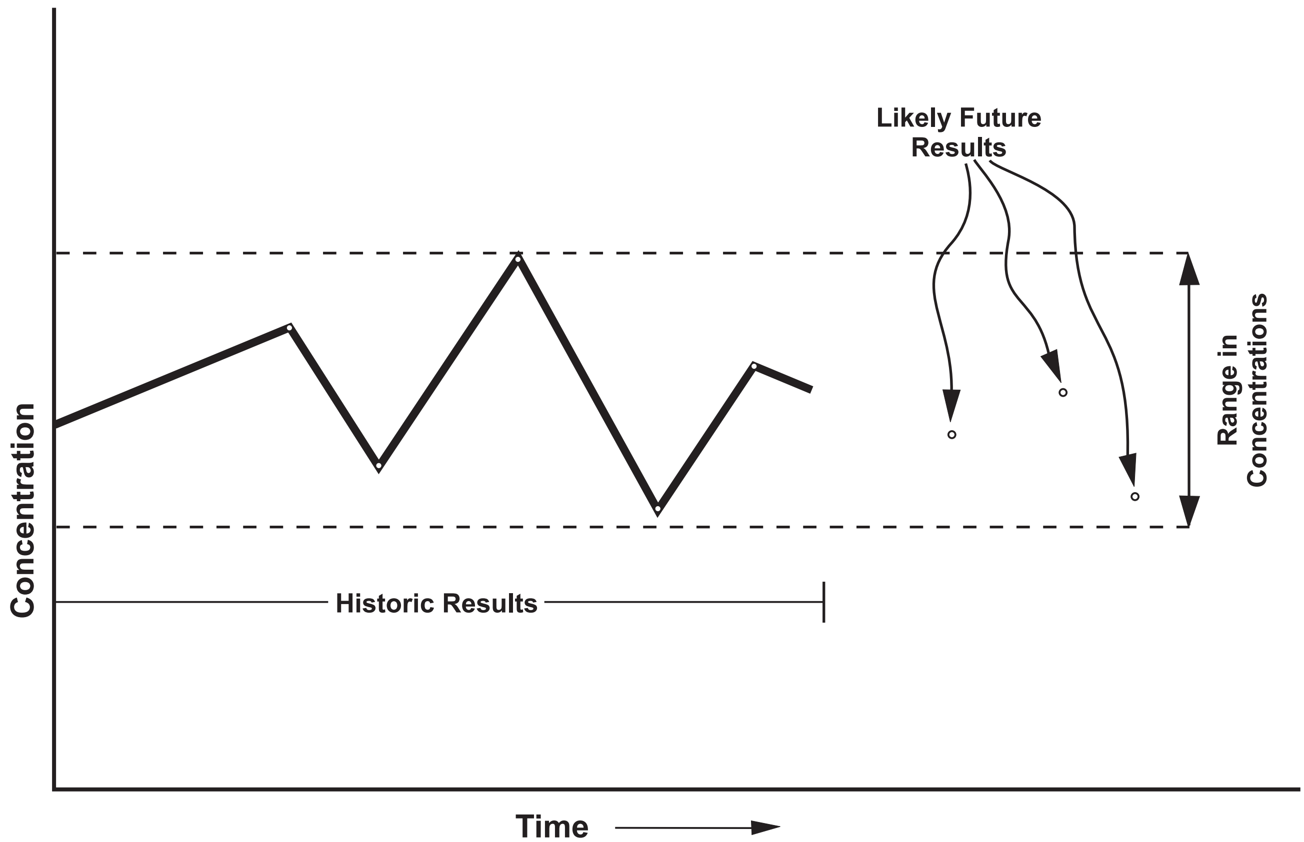


FIGURE 5.3
CONCEPTUAL REPRESENTATION OF CONTINUED MONITORING AT LOCATION WHERE NO TEMPORAL TREND IN CONCENTRATIONS IS PRESENT

Monitoring Network Optimization
Fort Lewis Logistics Center, Washingon

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Monitoring Point Downgradient from Contaminant Source

Relatively less information ↓	Decreasing trend in concentrations
	Nondetect or no trend
Relatively more information	Increasing trend in concentrations

5.2 TEMPORAL EVALUATION RESULTS

The analytical data for groundwater samples collected the 59 wells in the original monitoring program from February 1995 through December 2001 at the Fort Lewis Logistics Center were examined for temporal trends using the Mann-Kendall test. Wells for which results from fewer than four sampling events were available (i.e., the 24 wells added to the monitoring program in December 2001; see Table 3.1) did not meet the minimum data requirements for the Mann-Kendall test, and therefore were not evaluated. The objective of the evaluation was to identify those wells having increasing or decreasing concentration trends for each COC, and to consider the quality of information represented by the existence or absence of concentration trends in terms of the location of each monitoring point.

Summary results of Mann-Kendall temporal trend analyses for COCs in groundwater samples from wells in the TCE plume area are presented in Table 5.1. As implemented, the algorithm used to evaluate concentration trends assigned a value of “ND”(not detected) to those wells with sampling results that were consistently below analytical detection limits through time, rather than assigning a surrogate value corresponding to the detection limit – a procedure that could generate potentially-misleading and anomalous “trends” in concentrations. In addition, a value of “<PQL” was assigned to those constituents for which no values were measured above the practical quantitation limit. For example, TCE results measured in groundwater samples from well LC-122b had 3

TABLE 5.1

RESULTS OF TEMPORAL TREND ANALYSIS OF GROUNDWATER MONITORING RESULTS

THREE-TIERED MONITORING NETWORK OPTIMIZATION

FORT LEWIS, WASHINGTON

Well ID[a/]	Hydro-logic Unit	TCE	cis-1,2-DCE	PCE	VC	Remove	Retain	Rationale
Original Monitoring Network Wells								
LC-03	UV	Increasing	ND	ND	ND		√	Increasing down/cross gradient.
LC-05	UV	Increasing	Increasing	Decreasing	ND		√	Increasing downgradient of source area.
LC-06	UV	Increasing	No Trend	Decreasing	ND		√	Increasing downgradient of source area.
LC-14a	UV	Decreasing	Decreasing	<PQL	ND	√		Decreasing downgradient of extraction system.
LC-19a	UV	Decreasing	Decreasing	Decreasing	ND		√	Decreasing near extraction system, measure remediation.
LC-19b	UV	No Trend	Decreasing	Increasing	ND	√		No trend TCE downgradient. cis-1,2 DCE and PCE at very low concentrations.
LC-19c	UV	No Trend	No Trend	ND	ND	√		No trend downgradient.
LC-26	UV	No Trend	No Trend	ND	ND	√		No trend slightly upgradient of source area.
LC-41a	UV	No Trend	Decreasing	ND	ND	√		No trend in center of plume, low coefficient of variation (COV).
LC-44a	UV	No Trend	No Trend	Decreasing	ND	√		No trend in center of plume, low coefficient of variation (COV).
LC-49	UV	Increasing	No Trend	<PQL	ND		√	Increasing downgradient of source area.
LC-51	UV	Increasing	No Trend	<PQL	ND		√	Increasing TCE downgradient of source, high TCE concentration.
LC-53	UV	Increasing	Decreasing	ND	Increasing		√	Increasing TCE downgradient of source, high TCE concentration.
LC-64a	UV	Increasing	Increasing	No Trend	Increasing		√	Increasing in DNAPL area, potential DNAPL migration.
LC-66a	UV	No Trend	Decreasing	<PQL	ND	√		No trend/decreasing in center of plume, low COV.
LC-66b	UV	No Trend	Decreasing	<PQL	ND	√		No trend/decreasing in center of plume, low COV.
LC-73a	UV	No Trend	<PQL	ND	ND	√		No trend cross gradient of plume, TCE<MCL.
LC-108	UV	Decreasing	No Trend	No Trend	ND	√		Decreasing in source area, but TCE < MCL, limited future temporal information.
LC-132	UV	Increasing	Decreasing	No Trend	ND		√	Increasing downgradient of source area.
LC-136a	UV	Increasing	Increasing	No Trend	No Trend		√	Increasing in DNAPL area, potential DNAPL migration.
LC-136b	UV	No Trend	Decreasing	<PQL	ND		√	Decreasing cis-1,2-DCE in source area measures remedy.
LC-137a	UV	Decreasing	No Trend	<PQL	ND	√		Decreasing trend downgradient of source.
LC-137b	UV	No Trend	No Trend	<PQL	ND	√		No trend downgradient of source area.
LC-149c	UV	ND	ND	ND	ND	√		Concentrations not detected upgradient of source area.
LC-149d	UV	<PQL	ND	ND	ND	√		<PQL upgradient of source area, TCE not detected since 1999.
LC-165	UV	<PQL	ND	ND	ND	√		<PQL down/cross gradient, outside of plume. Not detected since 1995.
PA-381	UV	No Trend	Decreasing	<PQL	ND	√		No trend potentially down gradient, low COV.
PA-383	UV	Decreasing	No Trend	ND	ND		√	<MCL historically, downgradient sentry well.
T-04	UV	No Trend	No Trend	<PQL	ND	√		No trend downgradient, low COV.
T-08	UV	No Trend	No Trend	No Trend	ND		√	Sentry well furthest downgradient.
T-12b	UV	Decreasing	ND	ND	ND	√		Decreasing downgradient of extraction wells.
T-13b	UV	No Trend	Decreasing	<PQL	ND		√	Sentry well furthest downgradient.

TABLE 5.1 (Continued)

RESULTS OF TEMPORAL TREND ANALYSIS OF GROUNDWATER MONITORING RESULTS

THREE-TIERED MONITORING NETWORK OPTIMIZATION

FORT LEWIS, WASHINGTON

Well ID[a/]	Hydro-logic Unit	TCE	cis-1,2-DCE	PCE	VC	Remove	Retain	Rationale
LC-111b	LV	Decreasing	Increasing	ND	ND		√	Increasing cis-1-2-DCE downgradient.
LC-116b	LV	Increasing	Increasing	ND	ND		√	Increasing in LV under extraction well system.
LC-122b	LV	<PQL	ND	<PQL	ND	√		<PQL, under EW system, LC-128 downgradient.
LC-128	LV	Increasing	No Trend	ND	ND		√	Increasing downgradient of extraction well field in LV.
LC-137c	LV	Decreasing	Decreasing	ND	ND	√		Decreasing in source area, but not detected since 1999, trends no longer valuable.
LC-64b	LV	Decreasing	Decreasing	ND	ND		√	Decreasing trend measures remedy in source area.
Extraction Wells								
LX-1	EW	Decreasing	Decreasing	Decreasing	ND	√		Decreasing trend downgradient.
LX-2	EW	Decreasing	Decreasing	Decreasing	ND	√		Decreasing trend downgradient.
LX-3	EW	Decreasing	Decreasing	Decreasing	ND	√		Decreasing trend downgradient.
LX-4	EW	Decreasing	Decreasing	Decreasing	ND	√		Decreasing trend downgradient.
LX-5	EW	Decreasing	Decreasing	Decreasing	ND	√		Decreasing trend downgradient.
LX-6	EW	Decreasing	Decreasing	Decreasing	ND	√		Decreasing trend downgradient.
LX-7	EW	Decreasing	Decreasing	Decreasing	ND	√		Decreasing trend downgradient.
LX-8	EW	No Trend	Decreasing	Decreasing	ND	√		No trend/decreasing trend downgradient.
LX-9	EW	Decreasing	Decreasing	Decreasing	ND	√		Decreasing trend downgradient.
LX-10	EW	Decreasing	Decreasing	Decreasing	ND	√		Decreasing trend downgradient.
LX-11	EW	Decreasing	Decreasing	No Trend	ND	√		Decreasing trend downgradient.
LX-12	EW	Decreasing	Decreasing	No Trend	ND	√		Decreasing trend downgradient.
LX-13	EW	Increasing	Increasing	No Trend	ND		√	Increasing trend downgradient
LX-14	EW	No Trend	Decreasing	No Trend	ND	√		No trend/decreasing trend downgradient.
LX-15	EW	Increasing	No Trend	No Trend	ND		√	Increasing trend downgradient
LX-16	EW	No Trend	No Trend	No Trend	ND	√		No trend downgradient.
LX-17	EW	Decreasing	Decreasing	Decreasing	Increasing		√	Decreasing in source area, measures remedy and mass removal.
LX-18	EW	Decreasing	Decreasing	Decreasing	Increasing		√	Decreasing in source area, measures remedy and mass removal.
LX-19	EW	No Trend	Decreasing	Decreasing	Increasing		√	Decreasing in source area, measures remedy and mass removal.
LX-21	EW	Decreasing	Decreasing	Decreasing	Increasing		√	Decreasing in source area, measures remedy and mass removal.
RW-1	EW	No Trend	ND	No Trend	Increasing	√		No trend downgradient.

ND	= Constituent has not been detected during history of monitoring at inidcated well.
No Trend	= No statistically significant temporal trend in concentrations.
Increasing	= Statistically significant increasing trend in concentrations.
Decreasing	= Statistically significant decreasing trend in concentrations.
<PQL	= Concentrations consistently below practical quantitation limit.

[a/] The 24 wells added to the monitoring network in December 2001 were not included in the temporal evaluation because data were available for fewer than four sampling events.

trace detections that were less than practical quantitation limits, and 21 measurements in which TCE was not detected during the sampling events from 1995 to 2001. In the absence of the "<PQL" classification category, the results of trend analysis would indicate a decreasing trend for TCE in these samples, which is primarily an artifact of the analytical procedures, and could generate false conclusions regarding concentration trends. The color-coding of the Table 5.1 entries denotes the presence/absence of temporal trends, and allows those monitoring points having nondetectable concentrations, concentrations below PQLs, decreasing or increasing concentrations, or no discernible trend in concentrations to be readily identified.

Figure 5.4 thematically displays the Mann-Kendall results for TCE by well and hydraulic unit; the most recent analytical results (from the December or September 2001 sampling rounds) for TCE are also presented. If a well's most recent available TCE measurement was prior to 2001 (e.g., wells T-11b, T-10, FL2), or if no TCE data exist for the well in the database (wells MAMC 1, MAMC 6, and the NEW-1 through NEW-6 wells), analytical results are not included on Figure 5.4.

The basis of the decision to remove or retain a well in the monitoring program based on the value of its temporal information is described in the "Rationale" column in Table 5.1. In general, monitoring wells at which detected chemical concentrations display no discernible temporal trend (e.g., wells LC-19c, LC-26, LC-41a, and LC-44a) represent points generating the least amount of useful information, and can be recommended for removal from the monitoring network. Monitoring wells upgradient from the source or crossgradient from the plume (e.g., wells LC-149c/d and LC-165) and for which concentrations of chemicals consistently have been non-detected or <PQL through time, and downgradient wells with decreasing trends (e.g., wells T-12b and LC-14a) also may represent relatively little information. Monitoring wells downgradient from or in the source area (e.g., LC-128, LC-116b, LC-51, and LC-53), at which one or more of the identified COCs display increasing trends in concentrations, represent points at which monitoring should probably continue. Additionally, monitoring wells (e.g., LC-64b and LC-137a) that have decreasing temporal trends in a source area are valuable and should

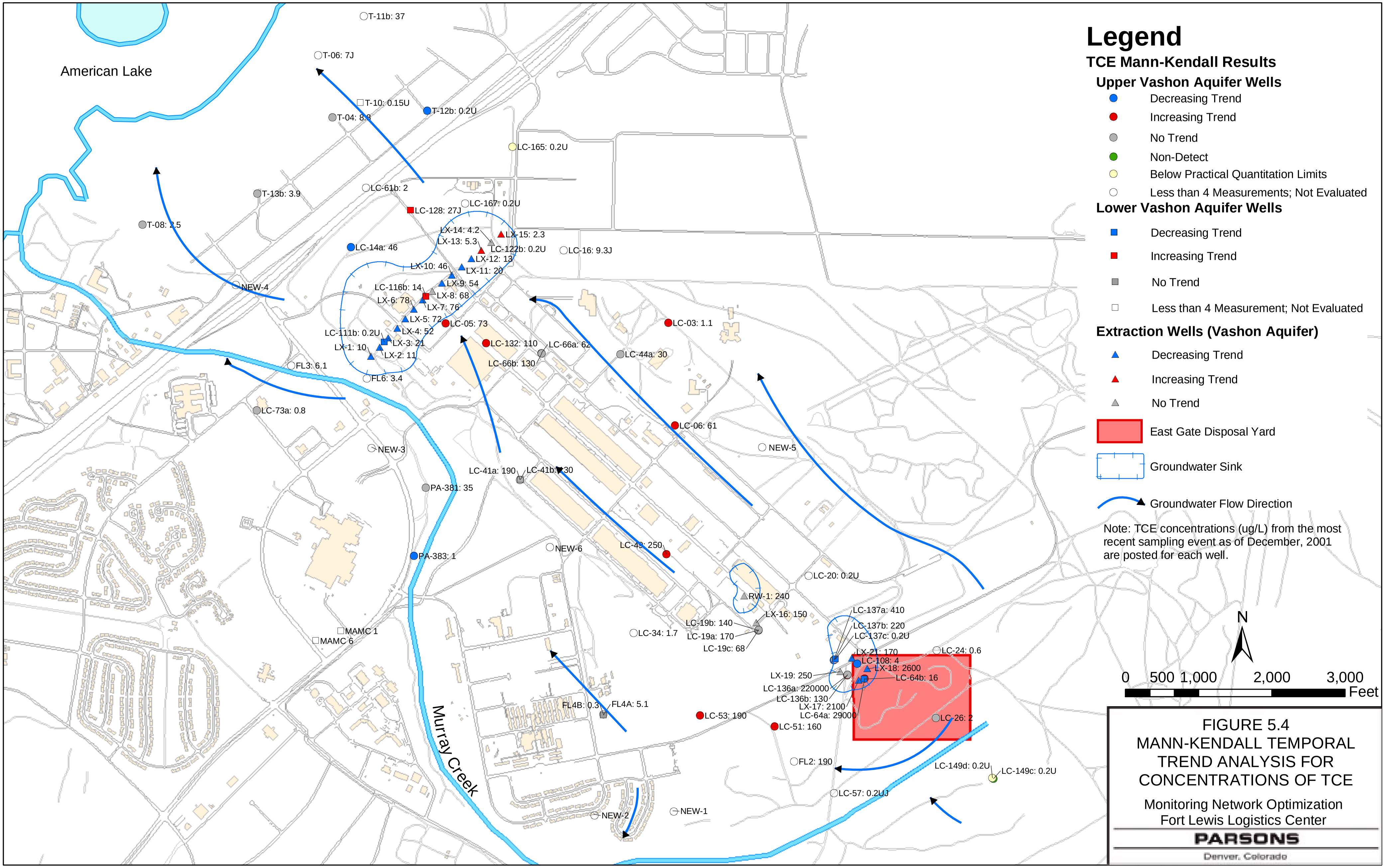

FIGURE 5.4
MANN-KENDALL TEMPORAL TREND ANALYSIS FOR CONCENTRATIONS OF TCE

Monitoring Network Optimization
Fort Lewis Logistics Center

be retained because they provide information on the effectiveness of the source-area RA(s). A flow chart of the decision logic applied to the temporal trend analysis results is presented in Figure 5.5.

Table 5.1 summarizes recommendations to retain 18 of the original 38 monitoring wells and 6 of the 21 extraction wells in a revised monitoring program for the Logistics Center TCE plume. Note that the recommendations provided in Table 5.1 are based on the evaluation of temporal statistical results only, and must be used in conjunction with the results of the qualitative and spatial evaluations to generate final recommendations regarding retention of monitoring points in the LTM program, and the frequency of monitoring at particular locations at the Fort Lewis Logistics Center.

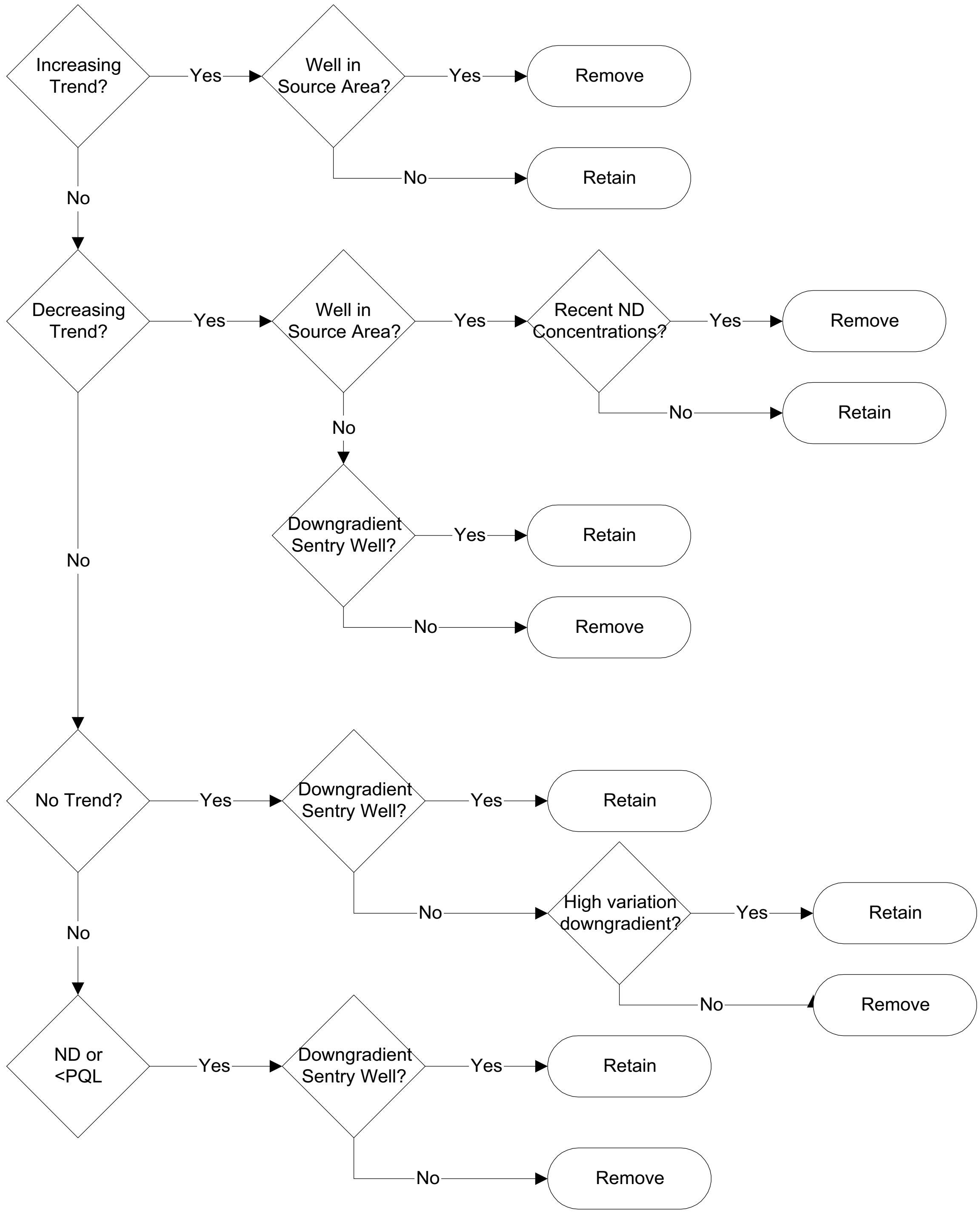

FIGURE 5.5
TEMPORAL TREND DECISION RATIONALE FLOW CHART

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SECTION 6

SPATIAL STATISTICAL EVALUATION

Spatial statistical techniques also can be applied to the design and evaluation of groundwater monitoring programs to assess the quality of information generated during monitoring, and to evaluate monitoring networks. *Geostatistics*, or the Theory of Regionalized Variables (Clark, 1987; Rock 1988; American Society of Civil Engineers [ASCE] Task Committee on Geostatistical Techniques in Hydrology, 1990a and 1990b), is concerned with variables having values dependent on location, and which are continuous in space, but which vary in a manner too complex for simple mathematical description. Geostatistics is based on the premise that the differences in values of a spatial variable depend only on the distances between sampling locations, and the relative orientations of sampling locations -- that is, the values of a variable (e.g., chemical concentrations) measured at two locations that are spatially "close together" will be more similar than values of that variable measured at two locations that are "far apart".

6.1 GEOSTATISTICAL METHODS FOR EVALUATING MONITORING NETWORKS

Ideally, application of geostatistical methods to the results of the groundwater monitoring program at Fort Lewis Logistics Center could be used to estimate COC concentrations at every point within the dissolved contaminant plume, and also could be used to generate estimates of the "error," or uncertainty, associated with each estimated concentration value. Therefore, the monitoring program could be "optimized" by using available information to identify those areas having the greatest uncertainty associated with the estimated plume extent and configuration. Conversely, sampling points could be successively eliminated from simulations, and the resulting uncertainty examined, to evaluate if significant loss of information (represented by increasing error or uncertainty in estimated chemical concentrations) occurs as the number of sampling locations is reduced. Repeated application of geostatistical estimating techniques, using tentatively identified sampling locations, then could be used to generate a sampling program that would provide an acceptable level of uncertainty regarding the distribution of COCs with the minimum possible number of samples collected. Furthermore, application of geostatistical methods can provide unbiased representations of the distribution of COCs at different locations in the subsurface, enabling the extent of COCs to be evaluated more precisely.

Fundamental to geostatistics is the concept of semivariance [$\gamma(h)$], which is a measure of the spatial dependence between samples (e.g., chemical concentrations) in a specified direction. Semivariance is defined for a constant spacing between samples (h) by:

$$\gamma(h) = \frac{1}{2n} \sum [g(x) - g(x + h)]^2 \qquad \text{Equation 1}$$

Where:

$\gamma(h)$ = semivariance calculated for all samples at a distance h from each other;

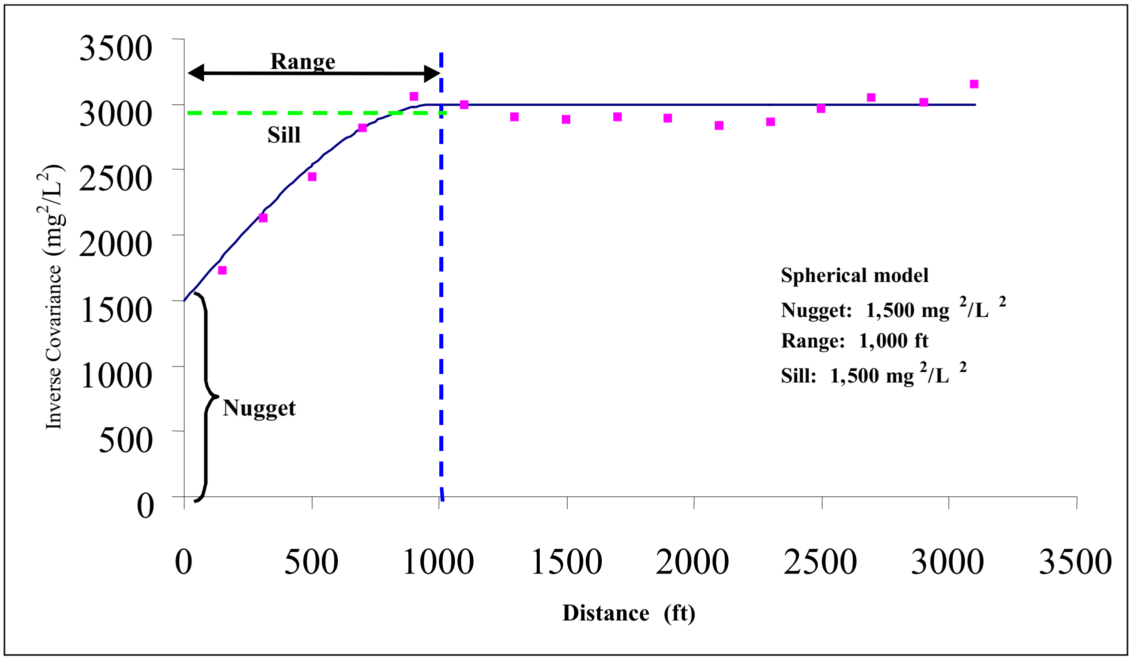
$g(x)$ = value of the variable in sample at location x;

$g(x + h)$ = value of the variable in sample at a distance h from sample at location x; and

n = number of samples in which the variable has been determined.

Semivariograms (plots of $\gamma(h)$ versus h) are a means of depicting graphically the range of distances over which, and the degree to which, sample values at a given point are related to sample values at adjacent, or nearby, points, and conversely, indicate how close together sample points must be for a value determined at one point to be useful in predicting unknown values at other points. For $h = 0$, for example, a sample is being compared with itself, so normally $\gamma(0) = 0$ (the semivariance at a spacing of zero, is zero), except where a so-called nugget effect is present (Figure 6.1), which implies that

FIGURE 6.1
IDEALIZED SEMVARIOGRAM MODEL
THREE-TIERED MONITORING NETWORK OPTIMIZATION
FORT LEWIS LOGISTICS CENTER, WASHINGTON



sample values are highly variable at distances less than the sampling interval. As the distance between samples increases, sample values become less and less closely related, and the semivariance, therefore, increases, until a sill is eventually reached, where ***γ(h)*** equals the overall variance (i.e., the variance around the average value). The sill is reached at a sample spacing called the range of influence, beyond which sample values are not related. Only values between points at spacings less than the range of influence can be predicted; but within that distance, the semivariogram provides the proper weightings, which apply to sample values separated by different distances.

When a semivariogram is calculated for a variable over an area (e.g., concentrations of TCE in the groundwater plume at Fort Lewis), an irregular spread of points across the semivariogram plot is the usual result (Rock, 1988). One of the most subjective tasks of geostatistical analysis is to identify a continuous, theoretical semivariogram model that most closely follows the real data. Fitting a theoretical model to calculated semivariance points is accomplished by trial-and-error, rather than by a formal statistical procedure (Davis, 1986; Clark, 1987; Rock, 1988). If a "good" model fit results, then $\gamma(h)$ (the semivariance) can be confidently estimated for any value of h, and not only at the sampled points.

6.2 SPATIAL EVALUATION OF MONITORING NETWORK AT FORT LEWIS LOGISTICS CENTER

TCE was used as the indicator chemical for the spatial evaluation of the groundwater monitoring network at Fort Lewis because this COC has the largest percentage and spatial distribution of measurements that exceeded groundwater MCLs. The Upper Vashon Aquifer wells were considered separately from the Lower Vashon Aquifer wells for the spatial analysis due to the hydrogeological conditions discussed in Section 2.2.

The combined original and revised monitoring networks include a total of 11 Lower Vashon wells. MAMC 1 and MAMC 6 do not have analytical results for the sampling period selected for evaluation, and well T-10 was not sampled recently. Because a minimum of 10 wells is required for the kriging analysis (and 30 or more data points are strongly preferred to ensure a more rigorous analysis), a kriging analysis could not be conducted for the Lower Vashon wells. The original and revised monitoring networks contain a total of 51 Upper Vashon wells (Table 3.1). However, only wells that were sampled in September or December 2001 (the most recent analytical data available) were included in the kriging analysis because a spatial “snapshot” is required in order to conduct the geospatial statistical analysis.

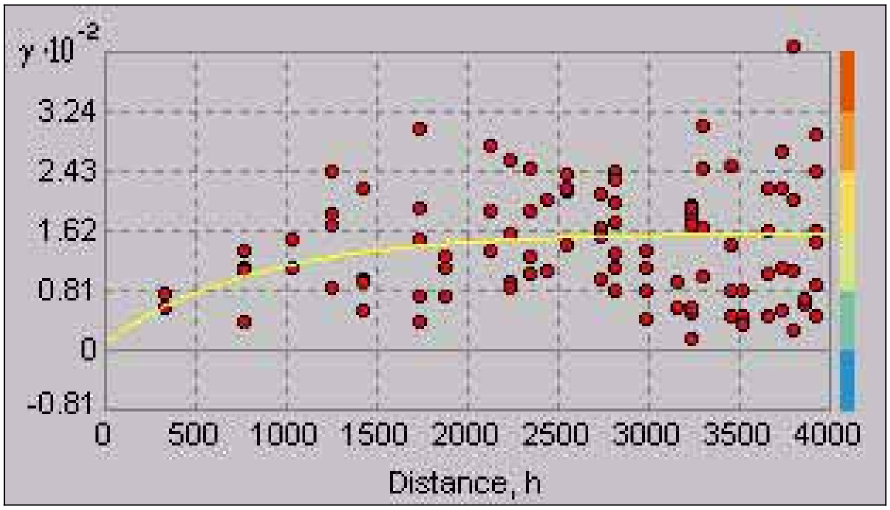
A kriging analysis was conducted only on those Upper Vashon Aquifer monitoring wells with recent analytical data. Extraction wells were excluded from the analysis because some of them have multiple screen intervals and because of their nature, they monitor water drawn from a wider region as opposed to the “point” sampled obtained from the monitoring wells. Of the 51 Upper Vashon monitoring wells, wells NEW-1 through -6 do not have analytical data, and wells T-11b and FL2 do not have current TCE measurements. Additionally, well LC-41a was not included in the analysis because is screened deeper than the other Upper Vashon wells, and because this well is considered a "spatially unique window" to the Upper Salmon Springs Aquifer (USACE, 2001). Thus, 2001 TCE measurements from 42 of the Upper Vashon wells were used to develop the semivariogram model. The commercially available geostatistical software package Geostatistical Analyst™ (an extension to the ArcView® geographic information system [GIS] software package) (Environmental Systems Research Institute, Inc. [ESRI], 2001) was used to develop a semivariogram model depicting the spatial variation in TCE concentrations in groundwater for 42 wells in the Upper Vashon aquifer the Fort Lewis Logistics Center.

As semivariogram models were calculated for TCE (Equation 1), considerable scatter of the data was apparent during fitting of the models. Several data transformations (including a log transformation) were attempted to obtain a representative semivariogram model. Ultimately, the concentration data were transformed to "rank statistics," in which the 42 values were ranked according to their concentration from 1 to 42 (tie values were assigned the median rank of the set). Transformations of this type can be less sensitive to outliers, skewed distributions, or clustered data than semivariograms based on raw concentration values, and thus may enable recognition and description of the underlying spatial structure of the data in cases where ordinary data are too "noisy".

The TCE rank statistics were used to develop a semivariogram that most accurately modeled the spatial distribution of the data. Figure 6.2 shows the semivariogram model in comparison to the site data. The best-fit semivariogram had the following parameters:

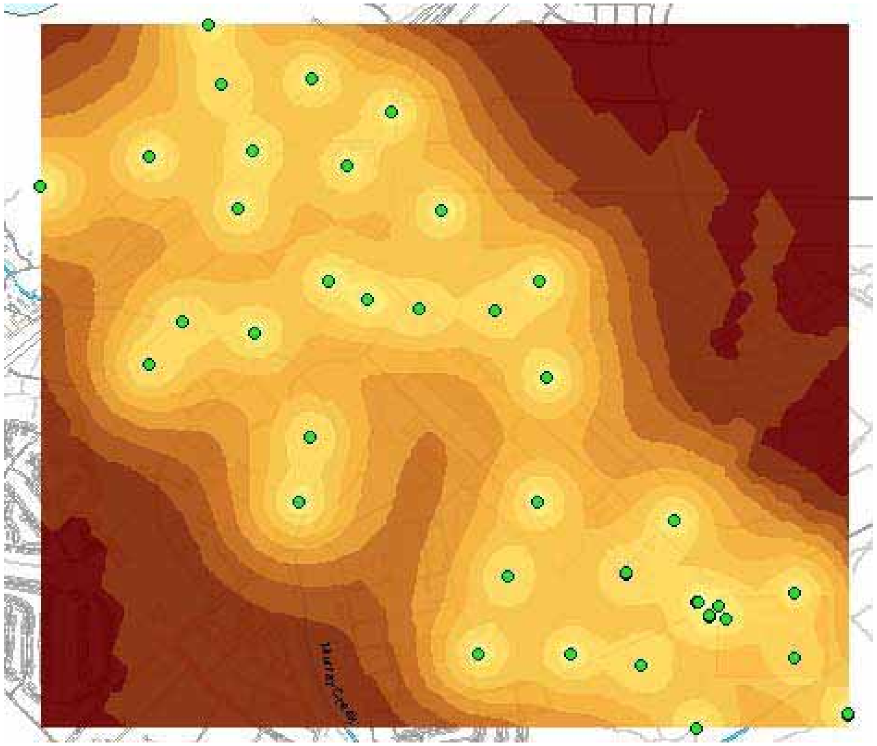
- Exponential Model
- Range: 2,500 feet
- Sill: 150
- Nugget: 10

FIGURE 6.2
FORT LEWIS UPPER VASHION SEMVARIOGRAM MODEL
THREE-TIERED MONITORING NETWORK OPTIMIZATION
FORT LEWIS LOGISTICS CENTER, WASHINGTON

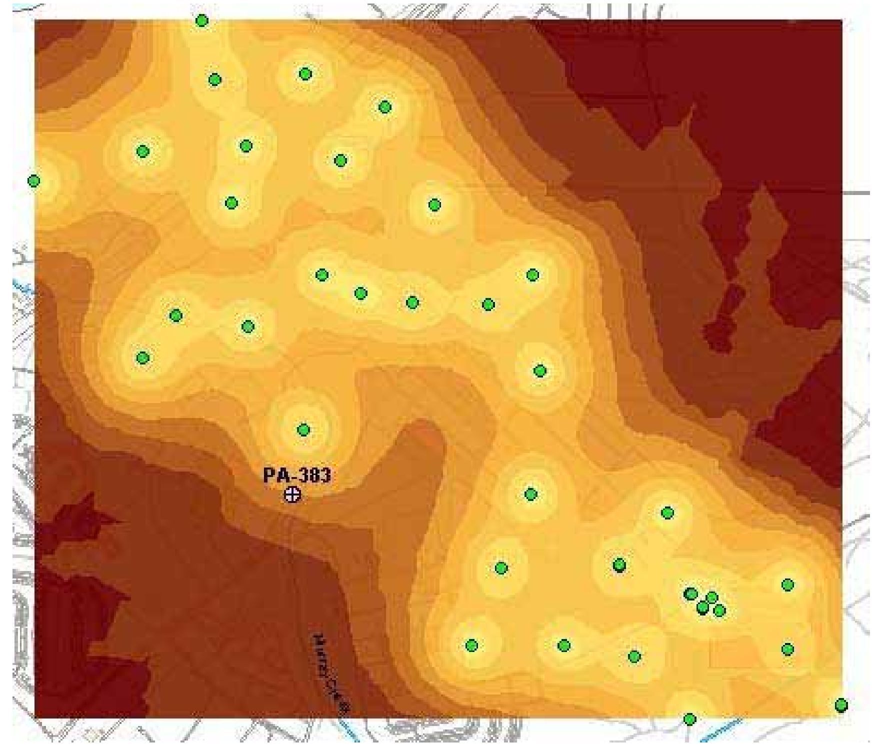


After this semivariogram model had been developed, it was used in the kriging system implemented by the Geostatistical Analyst™ software package (ESRI, 2001) to develop kriging realizations (estimates of the spatial distribution of TCE in groundwater at Fort Lewis), and to calculate the associated kriging prediction standard errors. The median kriging standard deviation was obtained from the standard errors calculated using the entire 42-well Upper Vashon monitoring network for the Logistics Center. Next, each of the 42 monitoring wells was sequentially removed from the network, and for each resulting 41-well network configuration, a kriging realization was completed using the TCE concentration rankings from the remaining 41 wells. The "missing well" monitoring network realizations were used to calculate prediction standard errors, and the median kriging standard deviations were obtained for each "missing well" realization and compared with the median kriging standard deviation for the "base-case" realization (obtained using the complete 42-well monitoring network), as a means of evaluating the amount of information loss (as indicated by increases in kriging error) resulting from the use of fewer monitoring points.

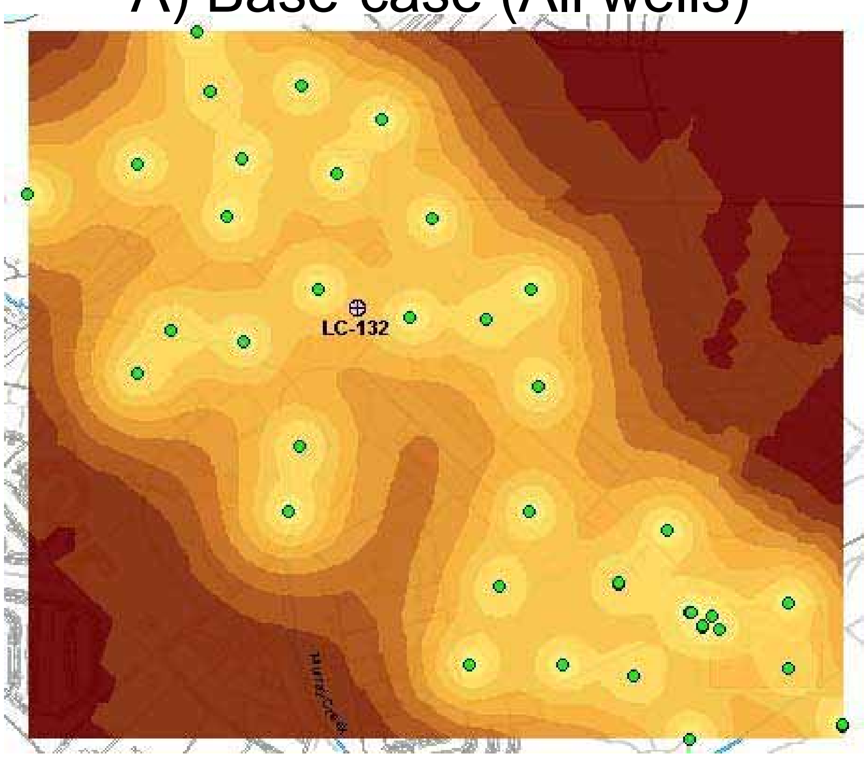
Figure 6.3 illustrates the spatial evaluation procedure by showing kriging prediction standard error maps for three kriging realizations. Each map shows the predicted



A) Base-case (All wells)



B) "Missing" Well PA-383



C) "Missing" Well LC-132

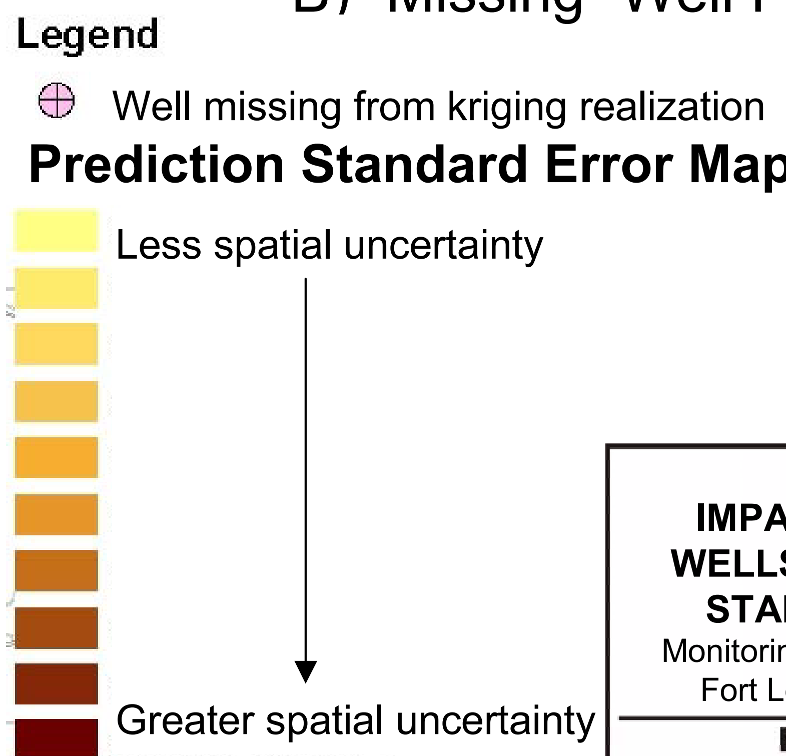


FIGURE 6.2
IMPACT OF MISSING WELLS ON PREDICTED STANDARD ERROR
Monitoring Network Optimization
Fort Lewis Logistics Center

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standard error associated with a given group of wells based on the semivariogram parameters discussed above. Lighter colors represent areas with lower spatial uncertainty, and darker colors represent areas with higher uncertainty; regions in the vicinity of wells (i.e., data points) have the lowest associated uncertainty. Map A on Figure 6.4 shows the predicted standard error map for the "base-case" realization in which all 42 wells are included. Map B shows the realization in which well PA-383 was removed from the monitoring network, and Map C shows the realization in which well LC-132 was removed. Figure 6.3 shows that when a well is removed from the network, the predicted standard error in the vicinity of the missing well increases. If a "removed" (missing) well is in an area with several other wells (e.g., well LC-132; Map B on Figure 6.3), the predicted standard error may not increase as much as if a well (e.g., PA-381; Map C) is missing from an area with fewer surrounding wells.

If removal of a particular well from the monitoring network caused very little change in the resulting median kriging standard deviation (less than about 1%), that well was regarded as contributing only a limited amount of information to the LTM program. Likewise, if removal of a well from the monitoring network produced larger increases in the kriging standard deviation, this was regarded as an indication that the well contributes a relatively greater amount of information, and is relatively more important to the monitoring network. At the conclusion of the kriging realizations, each well was ranked from 1 (providing the least information) to 42 (providing the most information), based on the amount of information (as measured by changes in median kriging standard deviation) the well contributed toward describing the spatial distribution of TCE, as shown in Table 6.1. Wells providing the least amount of information represent possible candidates for removal from the monitoring network at the Logistics Center.

6.3 SPATIAL STATISTICAL EVALUATION RESULTS

6.3.1 Kriging Ranking Results

Figure 6.5 and Table 6.1 present the ranking of monitoring locations based on the relative value of TCE information provided by each well, as calculated based on the

TABLE 6.1

RESULTS OF GEOSTATISTICAL EVALUATION
RANKING OF UPPER VASHON AQUIFER WELLS
BY RELATIVE VALUE OF TCE INFORMATION

THREE-TIERED MONITORING NETWORK OPTIMIZATION
FORT LEWIS, WASHINGTON

Well ID [a/]	Kriging Ranking [b/]	Well ID	Kriging Ranking
T-08	1	LC-51	23
LC-66b	2	LC-44a	23
T-04	12[c/]	FL6	23
LC-66a	12	T-06	26
LC-64a	12	LC-57	26
LC-61b	12	FL3	26
LC-26	12	LC-53	28.5
LC-19c	12	LC-34	28.5
LC-19b	12	LC-24	30
LC-19a	12	LC-165	32
LC-167	12	LC-16	32
LC-14a	12	LC-03	32
LC-149d	12	LC-73a	34.5
LC-149c	12	LC-20	34.5
LC-137b	12	PA-381	36.5
LC-137a	12	FL4b	36.5
LC-136b	12	T-12b	38.5
LC-136a	12	PA-383	38.5
LC-132	12	LC-49	40
LC-108	12	LC-06	41
LC-05	12	T-13b	42

[a/] Upper Vashon wells T-11b, FL2, and wells NEW-1 through -6 were not included in the kriging rankings because they did not have current analytical results to contribute to the spatial distribution analysis. Well LC-41a was excluded because its screened interval is in a unit that is not representative of the Upper Vashon Aquifer.

[b/] 1= least relative amount of information; 42= most relative amount of information.

[c/] Tie values receive the median ranking of the set.

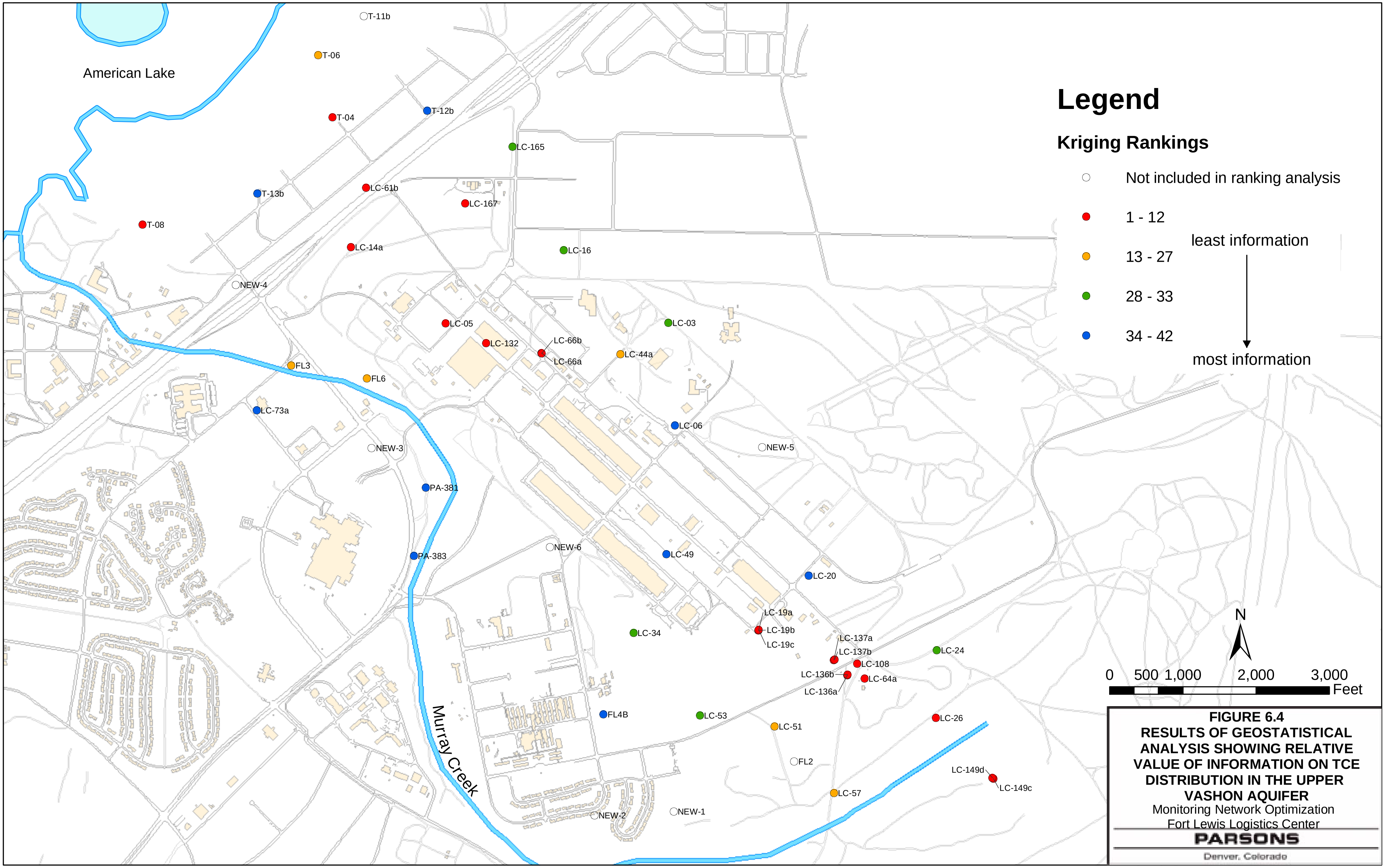

FIGURE 6.4
RESULTS OF GEOSTATISTICAL ANALYSIS SHOWING RELATIVE VALUE OF INFORMATION ON TCE DISTRIBUTION IN THE UPPER VASHON AQUIFER
Monitoring Network Optimization
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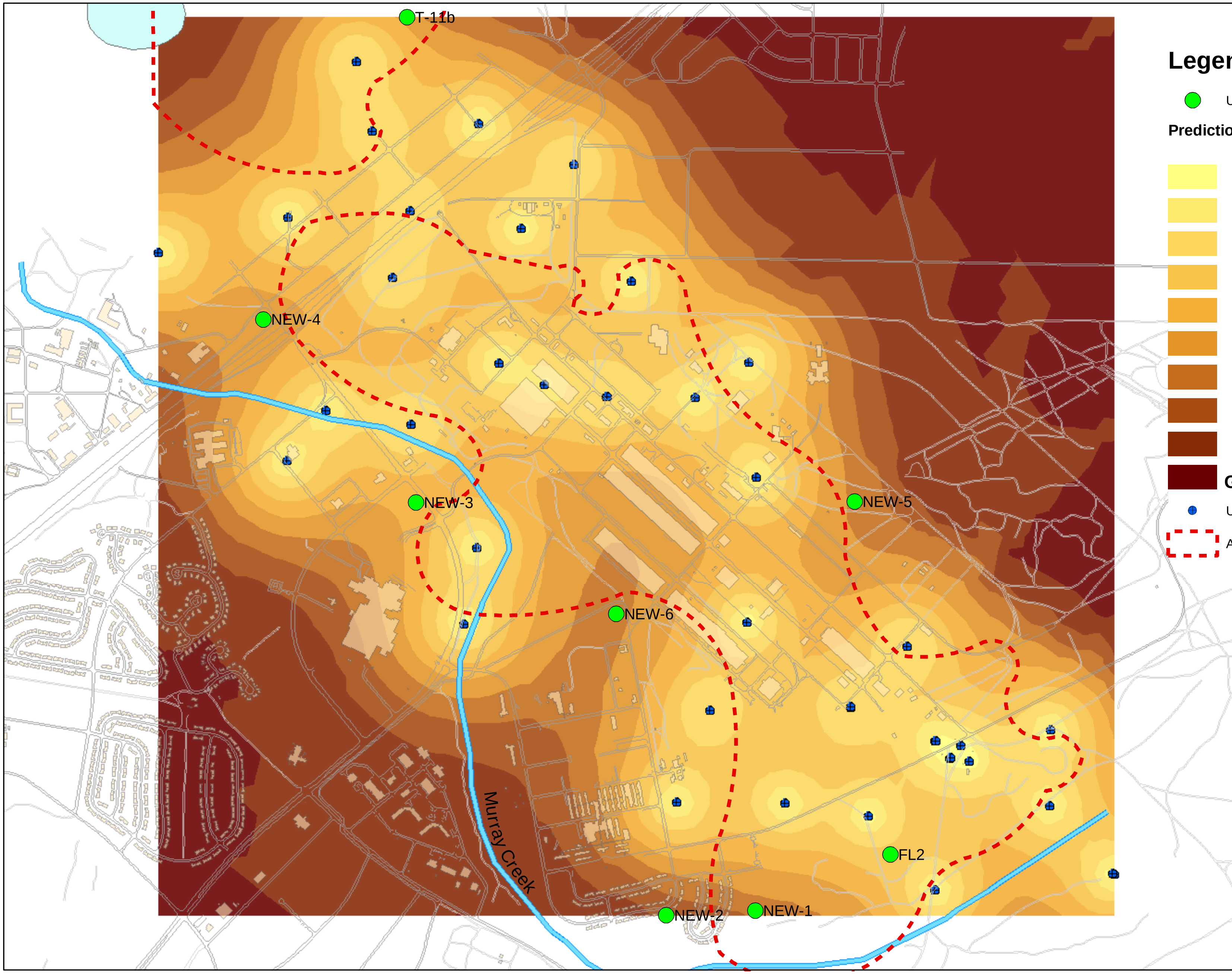

FIGURE 6.5
LOCATION OF "NEW" WELLS RELATIVE TO PREDICTED STANDARD ERROR OF TCE DISTRIBUTION

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kriging realizations. Examination of these results indicate that monitoring wells in close proximity to several other monitoring wells (red color coding on Figure 6.5) generally provide relatively lesser amounts of information than do wells at greater distances from other wells, or wells located in areas having limited numbers of monitoring points (blue color coding on Figure 6.5). This is intuitively obvious, but the analysis allows the most valuable and least valuable wells to be identified quantitatively. For example, Table 6.1 identifies the 21 wells (ranked 1-12) that provide the relative least amount of information (potential candidates for removal from the monitoring program) and the 9 wells (ranked 34-42) that provide the greatest amount of information (candidates for retention in the monitoring program) regarding the occurrence and distribution of TCE in groundwater in the Upper Vashon Aquifer. Wells ranked from 23 to 32 fall in the "intermediate" range and receive no recommendation for removal or retention.

6.3.2 Additional Well Analysis

The kriging predicted standard error map and plume delineation also can be used to evaluate the addition of new wells to the monitoring program. Figure 6.5 shows the eight Upper Vashon wells not included in the kriging ranking analysis, along with the predicted standard error map for the kriging realization containing the "base-case" data from the other 42 wells in the Upper Vashon aquifer. The map also shows an estimate of the extent of the TCE plume (as defined by the 5-µg/L isopleth) (USACE, 2001). The lighter yellow shading represents areas with less spatial uncertainty, and the darker shading represents area with greater spatial uncertainty. Figure 6.4 shows that, with the potential exception of well FL2, all of the new wells are located in areas with higher spatial uncertainty. Once a final monitoring network program is established, a similar standard error map could be created to determine the optimal locations for the new wells. For example, well NEW-5 could provide better spatial information if it were shifted about 500 feet to the south, based on the predicted standard error map shown on Figure 6.4.

SECTION 7

SUMMARY OF THREE-TIERED MONITORING NETWORK EVALUATION

The 83 wells included in the original and/or revised groundwater monitoring programs at the Fort Lewis Logistics Center were evaluated using qualitative hydrogeologic and RA knowledge, temporal statistical techniques, and spatial statistics. At each tier of the evaluation, monitoring points that provide relatively greater amounts of information regarding the occurrence and distribution of COCs in groundwater were identified, and were distinguished from those monitoring points that provide relatively lesser amounts of information. In this section, the results of the evaluations are combined to generate a refined monitoring program that could potentially provide information sufficient to address the primary objectives of monitoring, at reduced cost. Monitoring wells not retained in the refined monitoring network could be removed from the monitoring program with relatively little loss of information. The results of the evaluations were combined and summarized in accordance with the following decision logic:

1. Each well retained in the monitoring network on the basis of the qualitative hydrogeologic evaluation is recommended to be retained in the refined monitoring program.

2. Those wells recommended for removal from the monitoring program on the basis of all three evaluations, or on the basis of the qualitative and temporal evaluations (with no recommendation resulting from the spatial evaluation) should be removed from the monitoring program.

3. If a well is recommended for removal based on the qualitative evaluation and recommended for retention based on the temporal or spatial evaluation, the final recommendation is based on a case-by-case review of well information.

The results of the qualitative, temporal, and spatial evaluations are summarized in Table 7.1. These results indicate that 15 of the 83 monitoring wells could be removed from the groundwater LTM program with little loss of information. The justification for the recommendations for the 5 wells that fell into case 3 of the decision logic is as follows:

- LC-05 and LC-132 are both recommended for removal from the monitoring program based on the qualitative and spatial evaluations (Tables 4.3 and 6.1), but are recommended for retention based on the on the temporal analysis, which showed their TCE concentrations to be increasing (Table 5.1). However, these wells provide redundant data because of their relative physical proximity (about 500 feet; Figure 5.4). It is recommended that LC-132 be retained and that well LC-05 be removed from the program because LC-132 has higher TCE concentrations that are increasing at a faster rate than the concentrations at well LC-05.

- Well LC-51 is recommended for removal from the monitoring program based on the qualitative evaluation (Table 4.3) and for retention in the temporal analysis due to increasing TCE trends (Table 5.1). The decision was made to recommend removal of well LC-51 from the monitoring program because wells FL2 and LC-53 provide adequate plume coverage in the area, and LC-53 also exhibits an increasing TCE concentration trend, as well as higher TCE concentrations than those measured at well LC-51.

- Well LC-73a is recommended for removal from the monitoring program based on the qualitative and temporal analyses, and for retention on basis of the spatial analysis. A decision was made to recommend removal of the well from the monitoring program because the well is outside the area of pertinent spatial information (i.e., outside of the 5-µg/L TCE isopleth and across Murray Creek).

TABLE 7.1
SUMMARY OF EVALUATION OF CURRENT GROUNDWATER MONITORING PROGRAM
MONITORING NETWORK OPTIMIZATION
FORT LEWIS, WASHINGTON

Well ID	Hydrologic Unit [a/]	Revised Sampling Frequency [b/]	Qualitative Evaluation		Temporal		Spatial Evaluation		Summary		
			Remove	Retain	Remove	Retain	Remove	Retain	Remove	Retain	Recommended Monitoring Frequency
Original Monitoring Network Wells											
LC-03	UV	Quarterly		√		√				√	Biennially
LC-05	UV	Annually	√			√	√		√		--
LC-06	UV	Semi-Annually		√		√		√		√	Annually
LC-14a	UV	Annually		√	√		√			√	Annually
LC-19a	UV	Quarterly		√		√	√			√	Annually
LC-19b	UV	None	√		√		√		√		--
LC-19c	UV	None	√		√		√		√		--
LC-26	UV	Annually	√		√		√		√		--
LC-41a	UV	Annually		√	√					√	Annually
LC-44a	UV	None	√		√				√		--
LC-49	UV	Annually		√		√		√		√	Annually
LC-51	UV	None	√			√			√		--
LC-53	UV	Annually		√		√				√	Annually
LC-64a	UV	Quarterly		√		√	√			√	Quarterly
LC-66a	UV	None	√		√		√		√		--
LC-66b	UV	Annually		√	√		√			√	Annually
LC-73a	UV	None	√		√			√	√		--
LC-108	UV	None	√		√		√		√		--
LC-132	UV	None	√			√	√			√	Annually
LC-136a	UV	Quarterly		√		√	√			√	Quarterly
LC-136b	UV	Annually		√		√	√			√	Annually
LC-137a	UV	None	√		√		√		√		--
LC-137b	UV	Quarterly	√		√		√		√		--
LC-149c	UV	Annually		√	√		√			√	Biennially
LC-149d	UV	None		√	√		√			√	Biennially
LC-165	UV	None	√		√				√		--
PA-381	UV	Annually		√	√			√		√	Biennially
PA-383	UV	Annually		√		√		√		√	Biennially
T-04	UV	Annually		√	√		√			√	Annually
T-08	UV	Semi-Annually		√		√	√			√	Semi-Annually
T-12b	UV	Quarterly		√	√			√		√	Biennially
T-13b	UV	Semi-Annually		√		√		√		√	Semi-Annually
LC-111b	LV	Annually		√		√	NI[d/]			√	Biennially
LC-116b	LV	Annually		√		√	NI			√	Annually
LC-122b	LV	Annually	√		√		NI		√		--
LC-128	LV	Annually		√		√	NI			√	Annually
LC-137c	LV	Annually		√	√		NI			√	Annually
LC-64b	LV	Annually		√		√	NI			√	Annually
Extraction Wells											
LX-1	EW	Annually		√	√		NI			√	Every 3 Years
LX-2	EW	Annually		√	√		NI			√	Every 3 Years
LX-3	EW	Annually		√	√		NI			√	Every 3 Years
LX-4	EW	Annually		√	√		NI			√	Every 3 Years
LX-5	EW	Annually		√	√		NI			√	Every 3 Years
LX-6	EW	Annually		√	√		NI			√	Every 3 Years
LX-7	EW	Annually		√	√		NI			√	Every 3 Years
LX-8	EW	Annually		√	√		NI			√	Every 3 Years
LX-9	EW	Annually		√	√		NI			√	Every 3 Years
LX-10	EW	Annually		√	√		NI			√	Every 3 Years
LX-11	EW	Annually		√	√		NI			√	Every 3 Years
LX-12	EW	Annually		√	√		NI			√	Every 3 Years
LX-13	EW	Annually		√		√	NI			√	Every 3 Years
LX-14	EW	Annually		√	√		NI			√	Every 3 Years
LX-15	EW	Annually		√		√	NI			√	Every 3 Years
LX-16	EW	Quarterly		√	√		NI			√	Semi-Annually
LX-17	EW	Quarterly		√		√	NI			√	Quarterly
LX-18	EW	Quarterly		√		√	NI			√	Quarterly
LX-19	EW	Quarterly		√		√	NI			√	Quarterly
LX-21	EW	Quarterly		√		√	NI			√	Quarterly
RW-1	EW	Quarterly		√	√		NI			√	Semi-Annually
Wells Added to Monitoring Network in December 2001											
FL2	UV	Annually		√	NA[c/]					√	Annually
FL3	UV	Quarterly	√		NA				√		--
FL4B	UV	Quarterly		√	NA			√		√	Biennially
FL6	UV	Quarterly		√	NA					√	Biennially
LC-16	UV	Quarterly	√		NA				√		--
LC-20	UV	Quarterly		√	NA			√		√	Biennially
LC-24	UV	Quarterly		√	NA					√	Biennially
LC-34	UV	Quarterly		√	NA					√	Biennially
LC-57	UV	Quarterly		√	NA					√	Biennially
LC-61b	UV	Quarterly		√	NA		√			√	Semi-Annually
LC-167	UV	Quarterly		√	NA		√			√	Semi-Annually
NEW-1	UV	Quarterly		√	NA				√		Quarterly
NEW-2	UV	Quarterly		√	NA				√		Quarterly
NEW-3	UV	Quarterly		√	NA				√		Quarterly

TABLE 7.1 (Continued)
SUMMARY OF EVALUATION OF CURRENT GROUNDWATER MONITORING PROGRAM
MONITORING NETWORK OPTIMIZATION
FORT LEWIS, WASHINGTON

Well ID	Hydrologic Unit [a/]	Revised Sampling Frequency [b/]	Qualitative Evaluation		Temporal		Spatial Evaluation		Summary		
			Remove	Retain	Remove	Retain	Remove	Retain	Remove	Retain	Recommended Monitoring Frequency
NEW-4	UV	Quarterly		√	NA				√		Quarterly
NEW-5	UV	Quarterly		√	NA				√		Quarterly
NEW-6	UV	Quarterly		√	NA				√		Quarterly
T-06	UV	Quarterly		√	NA				√		Quarterly
T-11b	UV	Quarterly		√	NA				√		Quarterly
FL4A	LV	Quarterly		√	NA		NI		√		Biennially
LC-41b	LV	Quarterly		√	NA		NI		√		Annually
MAMC 1	LV	Quarterly		√	NA		NI		√		Quarterly
MAMC 6	LV	Quarterly		√	NA		NI		√		Quarterly
T-10	LV	Quarterly		√	NA		NI		√		Semi-Annually
Proposed Additional Well											
LC-180	UV	None		**ADD**	NA		NI			**ADD**	Annually

[a/] UV=Upper Vashon Aquifer; LV= Lower Vashon Aquifer; EW=(Vashon Aquifer) Extraction Well.
[b/] Sampling frequency established by the remedial action monitoring network optimization report (USACE, 2001).
[c/] NA = Fewer than four samples; not applicable for temporal trend analysis.
[d/] NI = Extraction well or Lower Vashon well not included in spatial analysis.

A refined monitoring program, consisting of 69 wells (16 sampled quarterly, 7 sampled semi-annually, 17 sampled annually, 14 sampled biennially, and the 15 I-5 extraction wells sampled every 3 years) would be adequate to address the two primary objectives of monitoring. This refined monitoring network would result in 107 sampling events per year, compared to 180 events per year in the current LOGRAM monitoring program and 236 yearly events in the original sampling program. ***Implementing these recommendations for optimizing the RA monitoring program at the Fort Lewis Logistics Center could reduce site monitoring costs by $36,500 a year (more than 40%) from the LOGRAM LTM strategy, and $64,500 (approximately 55%) from the original LTM program*** (based on a per sample cost of $500 (USACE, 2001)). Additional cost savings could be realized if groundwater samples collected from select wells (e.g., wells along the lateral and upgradient plume margins) were analyzed for a short list of halogenated VOCs using Method 8021B instead of Method 8260B.

SECTION 8

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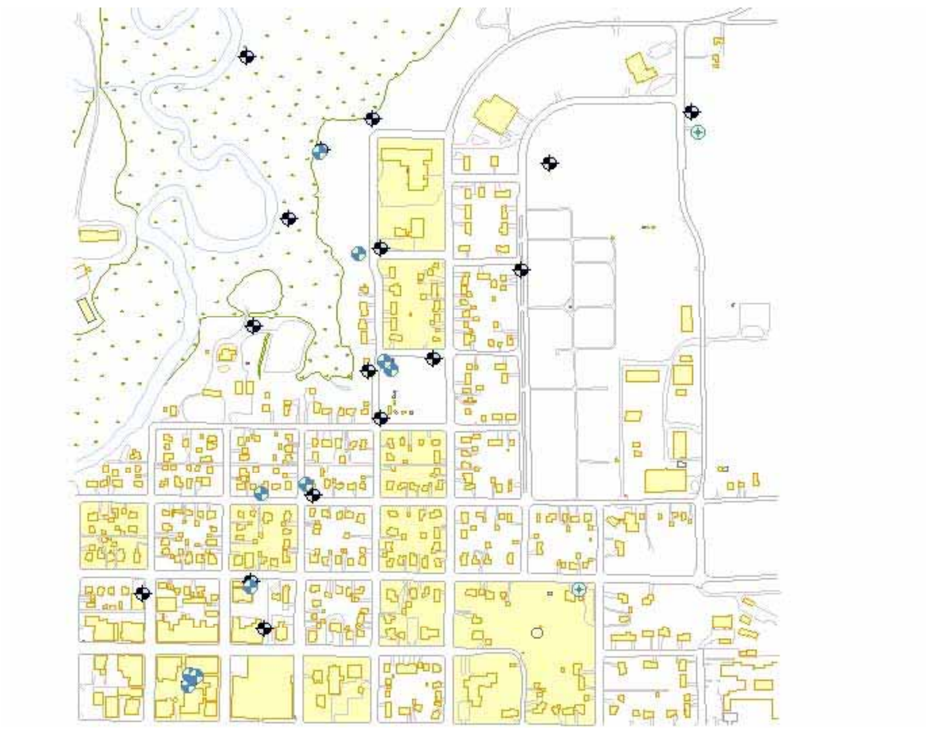
APPENDIX D-2

OPTIMIZATION OF MONITORING PROGRAM AT LONG PRAIRIE GROUNDWATER CONTAMINATION SUPERFUND SITE, MINNESOTA

G-2236-15

MAROS 2.0 Application: Upper Outwash Aquifer Monitoring Network Optimization Long Prairie Site

Long Prairie, Minnesota



Submitted to
Air Force Center for Environmental Excellence

May 8, 2003

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SERVICES, INC.

MAROS 2.0 APPLICATION
UPPER OUTWASH AQUIFER MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE SITE

Long Prairie, Minnesota

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Revision No. ***DRAFT***
Date: 5/08/03

GROUNDWATER SERVICES, INC.

MAROS 2.0 APPLICATION UPPER OUTWASH AQUIFER MONITORING NETWORK OPTIMIZATION, LONG PRAIRIE SITE

Long Prairie, Minnesota

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February 19, 2003

GROUNDWATER SERVICES, INC.

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UPPER OUTWASH AQUIFER MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE SITE

EXECUTIVE SUMMARY

Long-term monitoring programs, whether applied for process control, performance measurement, or compliance purposes, require large scale data collection effort and time commitment, making their cumulative costs very high. With the increasing use of risk-based goals and natural attenuation in recent years as well as the move toward long-term closure upon completion of cleanup activities, the need for better-designed long-term monitoring plans that are cost-effective, efficient, and protective of human and ecological health has greatly increased. The Monitoring and Remediation Optimization System (MAROS) methodology provides an optimal monitoring network solution, given the parameters within a complicated groundwater system which will increase its effectiveness. By applying statistical techniques to existing historical and current site analytical data, as well as considering hydrogeologic factors and the location of potential receptors, the software suggests an optimal plan along with an analysis of individual monitoring wells for the current monitoring system. This report summarizes the findings of an application of the MAROS 2.0 software to the Upper Outwash Aquifer long-term monitoring well networks at the Long Prairie Site in Long Prairie, Minnesota.

The primary constituent of concern at the site is tetrachloroethylene (PCE) which is analyzed at a total of 44 wells consisting of 31 monitoring wells, 3 city wells, and 10 extraction wells (Figure 1). Sampling frequency for these wells varies: extraction wells were generally sampled quarterly while monitoring wells were generally sampled semiannually or annually since the implementation of the long-term monitoring plan in 1996. For some wells, sampling was even terminated for 3 years before they were sampled again in October 2002. This resulted in some monitoring wells having only 5 ~ 7 data records during the 7-year period (from 1996 to 2002). The historical PCE data for all or in some cases a subset of wells were analyzed using the MAROS 2.0 software in order to: 1) gain an overall understanding of the plume stability, and 2) recommend changes in sampling frequency and sampling locations without compromising the effectiveness of the long-term monitoring network.

Project Objectives

The general objective of the project was to optimize the Long Prairie long-term monitoring network and sampling plan applying the MAROS 2.0 statistical and decision support methodology. The key objectives of the project included:

- Determining the overall plume stability through trend analysis and moment analysis;
- Evaluating individual well PCE concentration trends over time;

- Addressing adequate and effective sampling through reduction of redundant wells without information loss and addition of new wells for future sampling;
- Assessing future sampling frequency recommendations while maintaining sufficient plume stability information;
- Evaluating risk-based site cleanup status using data sufficiency analysis.

Results

The MAROS 2.0 sampling optimization software/methodology has been applied to the Long Prairie's existing monitoring program as of October 2002. Results from the temporal trend analysis, moment analysis, sampling location determination, sampling frequency determination, and data sufficiency analysis indicate that:

- Site monitoring wells were divided into source wells and tail wells where source wells are near the dry cleaner site or have historically elevated concentrations of PCE.

- 2 out of 4 source wells and 24 out of 27 tail wells have a Probably Decreasing, Decreasing, or Stable trend. Both of the statistical methods used to evaluate trends (Mann-Kendall and Linear Regression) gave similar trend estimates for each well.

- 7 out of 10 recovery wells have Probably Decreasing or Decreasing trends. Both the Mann-Kendall and Linear Regression methods gave similar trend estimates for each well.

- The dissolved mass shows stability over time, whereas the center of mass shows increase in distance over time in relation to the source location, and the statistical distribution of the plume in the x and y directions show a show a relatively stable trend over time. The results from the moment analysis are dependent on a changing dataset over time due to the change in the wells sampled over the sampling period analyzed. Overall these results indicate that the plume is not increasing in size.

- Overall plume stability results indicate that a monitoring system of "Moderate" intensity is appropriate for this plume compared to "Limited" or "Extensive" systems due to a stable Upper Outwash Aquifer plume.

- The well redundancy optimization tool, using the Delaunay method aided with a qualitative analysis, indicates that 12 existing monitoring wells (27% of all) may not be needed in the current monitoring system without compromising the accuracy of the monitoring network.

- The well sufficiency optimization tool, based on the Delaunay method, indicates that there are no areas within the existing monitoring network that have significantly high uncertainty in the PCE concentration estimation. Therefore, no new monitoring wells are recommended.

- Application of the well sampling frequency determination tool, the Modified CES method, leads to significant reduction in sampling frequency. Among the 44 wells in the current monitoring system, 19 are recommended for annual sampling and 25 for biennial sampling. Considering only wells that have been sampled consistently up to October 2002 (26 wells) and the sampling frequency reduction alone, a reduction of approximately 57% in total samples each year can be achieved.

- The MAROS Data Sufficiency (Power Analysis) application indicates that the monitoring record has sufficient statistical power to conclude that the site has attained cleanup goal at (or farther than) the "hypothetical statistical compliance boundary" located near the most downgradient well at the site. As the plume shrinks, this hypothetical statistical compliance boundary will move upgradient gradually.

The recommended long-term monitoring strategy results in a significant reduction in sampling costs and allows site personnel to develop a better understanding of plume behavior over time. A reduction in the number of redundant wells will still maintain adequate delineation of the plume as well as knowledge of the plume state over time. The MAROS optimized plan results in a monitoring network of 32 wells: 16 sampled annually, and 16 sampled biennially. The MAROS optimized plan would result in 24 samples per year, compared to 51 samples per year if all the monitoring wells in the current network were sampled every year. Implementing these recommendations could lead to a 52% reduction from the current monitoring plan in terms of the samples to be collected per year. The reduction in the number of redundant wells and decreased sampling frequency is expected to result in a moderate cost savings over the long-term at the Long Prairie site. An approximate cost savings estimate range from $2,700 to $7,560 per year (based on an average per sample cost range of $100 to $280) is projected while still maintaining adequate delineation of the plume as well as knowledge of the plume state over time.

1.0 INTRODUCTION

Long-term monitoring programs, whether applied for process control, performance measurement, or compliance purposes, require large scale data collection effort and time commitment, making their cumulative costs very high. With the increasing use of risk-based goals and natural attenuation in recent years as well as the move toward long-term closure upon completion of cleanup activities, the need for better-designed long-term monitoring plans that are cost-effective, efficient, and protective of human and ecological health has greatly increased. AFCEE's Monitoring and Remediation Optimization System (MAROS) methodology provides an optimal monitoring network solution, given the parameters within a complicated groundwater system which will increase its effectiveness. By applying statistical techniques to existing historical and current site analytical data, as well as considering hydrogeologic factors and the location of potential receptors, the software suggests an optimal plan along with an analysis of individual monitoring wells for the current monitoring system. This report summarizes the findings of an application of the MAROS 2.0 software to the Upper Outwash Aquifer long-term monitoring well network at the Long Prairie site, Long Prairie, Minnesota.

1.1 Geology/Hydrogeology

The Long Prairie groundwater contamination site is a groundwater plume of chlorinated organic compounds (mostly Tetrachlorothene (PCE)) located below portions of the city of Long Prairie, Minnesota.

The subsurface in the vicinity of Long Prairie consists of a series of glacial till and outwash deposits approximately 700 feet thick. The aquifer system near Long Prairie consists of two water-bearing outwash units. However, in some areas the separating aquitard is not present between the upper and lower outwash units within the outwash valley. A sandy clay till aquitard separates the two outwash units on the eastern side of the city. Leakage is inhibited primarily by the low vertical hydraulic conductivity of the till. The lower outwash is in direct contact with the upper outwash unit below the western side of Long Prairie (Barr, 2001). The uppermost geologic unit is silty sand with some coarser sand and gravel (glacial outwash deposit), the most prolific aquifer in the area. The aquifer is essentially a wedge of outwash sand and gravel approximately 60 feet thick near municipal well #4 and thins to less than 5 feet to the southeast and maybe locally absent beyond. Underlying the glacial outwash sediments is glacial till composed of sandy clay with varying concentrations of gravel. The till extends to a depth of at least 200 ft bgs and appears to be continuous beneath the site. The backlot, where the PCE release occurred, is located over an area where the till is present between the two outwash units and it near the western limit of the till. The saturated thickness of the upper outwash is only about 10 feet near the source, near MW-10.

The groundwater table in the vicinity of the source area is significantly higher possibly due to a continuation of the water table as it comes into town from the south in a broad, shallow valley that contains the Charlotte Lake. Just north of this area, the lower till pinches out, so the aquifer is much thicker and water elevations are largely controlled by the Long Prairie River. The water table configuration suggests that the groundwater discharges to the Long Prairie River from the area of well MW-7A and south (approximately Northwesterly direction). North of well MW-5A, the groundwater flow direction appears to be approximately parallel with the river (approximately Northerly direction). Base wells, domestic production wells, extraction wells, and regional pumping affect local groundwater flow directions. Groundwater elevations range from 1280 to 1290 ft msl at the northern and southern edges of the area, respectively. The groundwater seepage velocity is approximately 472 ft/yr. For a detailed description of site geology and hydrogeology refer to Barr (2001).

1.2 Remedial Action

The Long Prairie site is has an approximate 7,000 square foot source area with a one-half mile long ground water plume located on Long Prairie, Todd County, Minnesota. The chlorinated plume originates in the commercial area of Long Prairie and extends through an older residential area of the city. The source of PCE in the groundwater was a dry-cleaning facility which operated from 1978 until mid-1984, located near well MW-10. The site was discovered in 1983 during the Minnesota Department of Health's VOC state wide analysis of public water supplies. The municipal water supply of Long Prairie was found to be contaminated with PCE and its degradation products trichloroethylene (TCE) and cis-1,2-dichloroethylene (DCE). The United States Environmental Protection Agency (U.S. EPA) placed the site on the National Priority List (NPL) in 1986. The Remedial Investigation/Feasibility Study (RI/FS) and the Remedial Design/Remedial Action (RD/RA) were conducted under a Multi-Site Cooperative Agreement between U.S. EPA and the Minnesota Pollution Control Agency (MPCA).

A soil vapor extraction system was installed in 1997 to remove PCE in the soil above the water table in the alley adjacent to the dry cleaning business, the source area. This system operated until the end of 1999. A groundwater recovery system and GAC plant was started up in 1996, with two additional recovery wells added in 1999. The system is still operating today and consists of nine groundwater recovery wells in the plume area for groundwater flow control. The objective of the remediation is to restore the Upper Outwash aquifer to drinking water standards by reducing the PCE concentration to less than the MCL (5 ppb) as well as preventing the spread of the plume to wells presently unaffected, including the city of Long Prairie municipal supply well 6.

The groundwater long-term monitoring plan started in 1996 consists of 31 monitoring wells, 3 city wells, and 10 extraction wells (Figure 1). The monitoring well naming convention includes: “a” wells, shallow wells screened at the water table; “b” wells, mid-depth wells screened at the base of the upper outwash; and “c” wells, deep wells screened in the lower outwash. The monitoring system is used for performance monitoring and compliance monitoring with the following goals: 1) plume containment monitoring to confirm that the plume remains hydraulically controlled; and 2) plume reduction monitoring to verify progress toward achieving cleanup goals.
The sampling frequency for the long-term monitoring wells varies: extraction wells have generally been sampled quarterly while monitoring wells were generally sampled

semiannually or annually since the implementation of the long-term monitoring plan in 1996. For some wells, sampling was even terminated for 3 years before they were sampled again in October 2002. This resulted in some monitoring wells having only 5 ~ 7 data records during the 7-year period (from 1996 to 2002). The historical PCE data for all or in some cases a subset of wells were analyzed using the MAROS 2.0 software in order to: 1) gain an overall understanding of the plume stability, and 2) recommend changes in sampling frequency and sampling locations without compromising the effectiveness of the long-term monitoring network.

2.0 MAROS METHODOLOGY

The MAROS 2.0 software used to optimize the LTM network at the Long Prairie site is explained in general terms in this section. MAROS is a collection of tools in one software package that is used in an explanatory, non-linear fashion. The tool includes models, statistics, heuristic rules, and empirical relationships to assist the user in optimizing a groundwater monitoring network system while maintaining adequate delineation of the plume as well as knowledge of the plume state over time. Different users utilize the tool in different ways and interpret the results from a different viewpoint. For a detailed description of the structure of the software and further utilities, refer to the MAROS 2.0 Manual (Aziz et al. 2002).

2.1 MAROS Conceptual Model

In MAROS 2.0, two levels of analysis are used for optimizing long-term monitoring plans: 1) an overview statistical evaluation with interpretive trend analysis based on temporal trend analysis and plume stability information; and 2) a more detailed statistical optimization based on spatial and temporal redundancy reduction methods (see Figure 2 for further details). In general, the MAROS method applies to 2-D aquifers that have relatively simple site hydrogeology. However, for a multi-aquifer (3-D) system, the user could apply the statistical analysis layer-by-layer.

The overview statistics or interpretive trend analysis assesses the general monitoring system category by considering individual well concentration trends, overall plume stability, hydrogeologic factors (e.g., seepage velocity, and current plume length), and the location of potential receptors (e.g., property boundaries or drinking water wells). The analysis relies on temporal trend analysis to assess plume stability, which is then used to determine the general monitoring system category. Since the temporal trend analysis focuses on where the monitoring well is located, the site wells are divided into two different zones: the source zone or the tail zone. The source zone includes areas with non-aqueous phase liquids (NAPLs), contaminated vadose zone soils, and areas where aqueous-phase releases have been introduced into ground water. The tail zone is usually the area downgradient of the contaminant source zone. Although this classification is a simplification of the well location, this broadness makes the user aware on an individual well basis that the concentration trend results can have a different interpretation depending on the well location in and around the plume. The location and type of the individual wells allows further interpretation of the trend results, depending on what type of well is being analyzed (e.g., remediation well, leading plume edge well, or monitoring well). General recommendations for the monitoring network frequency and density are suggested based on heuristic rules applied to the source and tail trend results.

The detailed statistics level of analysis or sampling optimization, on the other hand, consists of a well redundancy analysis and well sufficiency analysis using the Delaunay method, a sampling frequency analysis using the Modified Cost Effective Sampling (CES) method and a data sufficiency analysis using power analysis. The well redundancy analysis is designed to minimize monitoring locations and the Modified CES method is designed to minimize the frequency of sampling. The data sufficiency analysis uses power analysis to assess the sampling record to determine if the current monitoring network and record is sufficient in terms of evaluating risk-based site target level status.

2.2 Data Management

In MAROS, ground water monitoring data can be imported from simple database-format Microsoft® Excel spreadsheets, Microsoft Access tables, previously created MAROS database archive files, or entered manually. Compliance monitoring data interpretation in MAROS is based on historical ground water monitoring data from a consistent set of wells over a series of sampling events. Statistical validity of the concentration trend analysis requires constraints on the minimum data input of at least four wells (ASTM 1998) in which COCs have been detected. Individual sampling locations need to include data from at least the six most-recent sampling events. To ensure a meaningful comparison of COC concentrations over time and space, both data quality and data quantity need to be considered. Prior to statistical analysis, the user can consolidate irregularly sampled data or smooth data that might result from seasonal fluctuations or a change in site conditions.

Imported ground water monitoring data and the site-specific information entered in Site Details can be archived and exported as MAROS archive files. These archive files can be appended as new monitoring data becomes available, resulting in a dynamic long-term monitoring database that reflects the changing conditions at the site (i.e. biodegradation, compliance attainment, completion of remediation phase, etc.).

2.3 Site Details

Information needed for the MAROS analysis includes site-specific parameters such as seepage velocity and current plume length. Part of the trend analysis methodology applied in MAROS focuses on where the monitoring well is located, therefore the user needs to divide site wells into two different zones: the source zone or the tail zone. The source zone includes areas with non-aqueous phase liquids (NAPLs), contaminated vadose zone soils, and areas where aqueous-phase releases have been introduced into ground water. The source zone generally contains locations with historical high ground water concentrations of the COCs. The tail zone is usually the area downgradient of the contaminant source zone. It is up to the user to make further interpretation of the trend results, depending on what type of well is being analyzed (e.g., remediation well, leading plume edge well, or monitoring well).

MAROS allows the analysis of up to 5 COCs concurrently and users can pick COCs from a list of compounds existing in the monitoring data, or select COCs based on recommendations provided in MAROS based on toxicity, prevalence, and mobility of compounds.

2.4 Data Consolidation

Typically long-term monitoring raw data have been measured irregularly in time or contain many non-detects, trace level results, and duplicates. Therefore, before the data can be further analyzed, raw data are filtered, consolidated, transformed, and possibly smoothed to allow for a consistent dataset meeting the minimum data requirements for statistical analysis mentioned previously.

MAROS allows users to specify the period of interest in which data will be consolidated (i.e., monthly, bi-monthly, quarterly, semi-annual, yearly, or a biennial basis). In computing the representative value when consolidating, one of four statistics can be used: median, geometric mean, mean, and maximum. Non-detects can be transformed to one half the reporting or method detection limit (DL), the DL, or a fraction of the DL. Trace level results can be represented by their actual values, one half of the DL, the DL, or a fraction of their actual values. Duplicates are reduced in MAROS by one of three ways: assigning the average, maximum, or first value. The reduced data for each COC and each well can be viewed as a time series in a graphical form on a linear or semi-log plot generated by the software.

2.5 Overview Statistics: Plume Trend Analysis

Within the MAROS software there are historical data analyses that support a conclusion about plume stability (e.g., increasing plume, etc.) through statistical trend analysis of historical monitoring data. Plume stability results are assessed from time-series concentration data with the application of three statistical tools: Mann-Kendall Trend analysis, linear regression trend analysis and moment analysis. The two trend methods are used to estimate the concentration trend for each well and each COC based on a statistical trend analysis of concentrations versus time at each well (Figure 2). These trend analyses are then consolidated to give the user a general plume stability and general monitoring frequency and density recommendations (see Figure 3 for further step-by-step details). Both qualitative and quantitative plume information can be gained by these evaluations of monitoring network historical data trends both spatially and temporally. The MAROS Overview Statistics are the foundation the user needs to make informed optimization decisions at the site. The Overview Statistics are designed to allow site personnel to develop a better understanding of the plume behavior over time and understand how the individual well concentration trends are spatially distributed within the plume. This step allows the user to gain information that will support a more informed decision to be made in the next level or detailed statistics optimization analysis (Figure 2).

2.5.1 Mann-Kendall Analysis

The Mann-Kendall test is a non-parametric statistical procedure that is well suited for analyzing trends in data over time. The Mann-Kendall test can be viewed as a nonparametric test for zero slope of the first-order regression of time-ordered concentration data versus time. The Mann-Kendall test does not require any assumptions as to the statistical distribution of the data (e.g. normal, lognormal, etc.) and can be used with data sets which include irregular sampling intervals and missing data. The Mann-Kendall test is designed for analyzing a single groundwater constituent, multiple constituents are analyzed separately. The Mann-Kendall S statistic measures the trend in the data: positive values indicate an increase in concentrations over time and negative values indicate a decrease in concentrations over time. The strength of the trend is proportional to the magnitude of the Mann-Kendall statistic (i.e., a large value indicates a strong trend). The confidence in the trend is determined by consulting the S statistic and the sample size n in a Kendall probability table such as the one reported in Hollander and Wolfe (1973).

The concentration trend is determined for each well and each COC based on results of the S statistic, the confidence in the trend, and the Coefficient of Variation (COV). The decision matrix for this evaluation is shown in Table 2. A Mann-Kendall statistic that is greater than 0 combined with a confidence of greater than 95% is categorized as an Increasing trend while a Mann-Kendall statistic of less than 0 with a confidence between 90% and 95% is defined as a Probably Increasing trend, and so on.

Depending on statistical indicators, the concentration trend is classified into six categories:

- Decreasing (D),
- Probably Decreasing (PD),
- Stable (S),
- No Trend (NT),
- Probably Increasing (PI)
- Increasing (I).

These trend estimates are then analyzed to identify the source and tail region overall stability category (see Figure 2 for further details).

2.5.2 Linear Regression Analysis

Linear Regression is a parametric statistical procedure that is typically used for analyzing trends in data over time. Using this type of analysis, a higher degree of scatter simply corresponds to a wider confidence interval about the average log-slope. Assuming the sign (i.e., positive or negative) of the estimated log-slope is correct, a level of confidence that the slope is not zero can be easily determined. Thus, despite a poor goodness of fit, the overall trend in the data may still be ascertained, where low levels of confidence correspond to "Stable" or "No Trend" conditions (depending on the degree of scatter) and higher levels of confidence indicate the stronger likelihood of a trend. The linear regression analysis is based on the first-order linear regression of the log-transformed concentration data versus time. The slope obtained from this log-transformed regression, the confidence level for this log-slope, and the COV of the untransformed data are used to determine the concentration trend. The decision matrix for this evaluation is shown in Table 3. To estimate the confidence in the log-slope, the standard error of the log-slope is calculated. The coefficient of variation, defined as the standard deviation divided by the average, is used as a secondary measure of scatter to distinguish between “Stable” or “No Trend” conditions for negative slopes. The Linear Regression Analysis is designed for analyzing a single groundwater constituent; multiple constituents are analyzed separately, (up to five COCs simultaneously). For this evaluation, a decision matrix developed by Groundwater Services, Inc. is also used to determine the “Concentration Trend” category (plume stability) for each well.

Depending on statistical indicators, the concentration trend is classified into six categories:

- Decreasing (D),
- Probably Decreasing (PD),
- Stable (S),
- No Trend (NT),
- Probably Increasing (PI)
- Increasing (I).

The resulting confidence in the trend, together with the log-slope and the COV of the untransformed data, are used in the linear regression analysis decision matrix to determine the concentration trend. For example, a positive log-slope with a confidence of less than 90% is categorized as having No Trend whereas a negative log-slope is considered Stable if the COV is less than 1 and categorized as No Trend if the COV is greater than 1.

2.5.3 Overall Plume Analysis

General recommendations for the monitoring network frequency and density are suggested based on heuristic rules applied to the source and tail trend results. Individual well trend results are consolidated and weighted by the MAROS software according to user input, and the direction and strength of contaminant concentration trends in the source zone and tail zone for each COC are determined. Based on

- **i)** the consolidated trend analysis,
- **ii)** hydrogeologic factors (e.g., seepage velocity), and
- **iii)** location of potential receptors (e.g., wells, discharge points, or property boundaries),

the software suggests an general optimization plan for the current monitoring system in order to efficiently effectively monitor in the future. A flow chart of the MAROS methodology utilizing trend analysis results and other site-specific parameters to form a general sampling frequency and well density recommendation is outlined in Figure 3. For example, a generic plan for a shrinking petroleum hydrocarbon plume (BTEX) in a slow hydrogeologic environment (silt) with no nearby receptors would entail minimal, low frequency sampling of just a few indicators. On the other hand, the generic plan for a chlorinated solvent plume in a fast hydrogeologic environment that is expanding but has very erratic concentrations over time would entail more extensive, higher frequency sampling. The generic plan is based on a heuristically derived algorithm for assessing future sampling duration, location and density that takes into consideration plume stability. For a detailed description of the heuristic rules used in the MAROS software, refer to the MAROS 2.0 Manual (Aziz et al. 2002).

2.5.3 Moment Analysis

An analysis of moments can help resolve plume trends, where the zeroth moment shows change in dissolved mass vs. time, the first moment shows the center of mass location vs. time, and the second moment shows the spread of the plume vs. time. Moment calculations can predict how the plume will change in the future if further statistical analysis is applied to the moments to identify a trend (in this case, Mann Kendall Trend Analysis is applied). The trend analysis of moments can be summarized as:

- Zeroth Moment: Change in dissolved mass over time
- First Moment: Change in the center of mass location over time
- Second Moment: Spread of the plume over time

The role of moment analysis in MAROS is to provide a relative measure of plume stability and condition. Plume stability may vary by constituent, therefore the MAROS moment analysis can be used to evaluate multiple COCs simultaneously in order to provide used to provide a quick way of comparing individual plume parameters to determine the size and movement of constituents relative to one another. Moment analysis in the MAROS software can also be used to assist the user in evaluating the impact on plume delineation in future sampling events by removing identified “redundant” wells from a long-term monitoring program (this analysis was not performed as part of this study, for more details on this application of moment analysis refer to the MAROS 2.0 Manual (Aziz et al. 2002).

The **zeroth moment** is a mass estimate. The zeroth moment calculation can show high variability over time, largely due to the fluctuating concentrations at the most contaminated wells as well as varying monitoring well network. Plume analysis and delineation based exclusively on concentration can exhibit a fluctuating degree of temporal and spatial variability. The mass estimate is also sensitive to the extent of the site monitoring well network over time. The zeroth moment trend over time is determined by using the Mann-Kendall Trend Methodology. The zeroth Moment trend test allows the user to understand how the plume mass has changed over time. Results for the trend include: Increasing, Probably Increasing, No Trend, Stable, Probably Decreasing, Decreasing or Not Applicable (Insufficient Data). When considering the results of the Zeroth moment trend, the following factors should be considered which could effect the calculation and interpretation of the plume mass over time: 1) Change in the spatial distribution of the wells sampled historically 2) Different wells sampled within the well network over time (addition and subtraction of well within the network). 3) Adequate versus inadequate delineation of the plume over time.

The **first moment** estimates the center of mass, coordinates (Xc and Yc) for each sample event and COC. The changing center of mass locations indicate the movement of the center of mass over time. Whereas, the distance from the original source location to the center of mass locations indicate the movement of the center of mass over time relative to the original source. Calculation of the first moment normalizes the spread by the concentration indicating the center of mass. The first moment trend of the distance to the center of mass over time shows movement of the plume in relation to the original source location over time. Analysis of the movement of mass should be viewed as it relates to 1) the original source location of contamination 2) the direction of groundwater flow and/or 3) source removal or remediation. Spatial and temporal trends in the center of mass can indicate spreading or shrinking or transient movement based on seasonal variation in rainfall or other hydraulic considerations. No appreciable movement or a neutral trend in the center of mass would indicate plume stability. However, changes in the first moment over time do not necessarily completely characterize the changes in the concentration distribution (and the mass) over time. Therefore, in order to fully characterize the plume the First Moment trend should be compared to the Zeroth moment trend (mass change over time).

The **second moment** indicates the spread of the contaminant about the center of mass (Sxx and Syy), or the distance of contamination from the center of mass for a particular COC and sample event. The Second Moment represents the spread of the plume over time in both the x and y directions. The Second Moment trend indicates the spread of the plume about the center of mass. Analysis of the spread of the plume should be viewed as it relates to the direction of groundwater flow. An increasing trend in the second moment indicates an expanding plume, whereas a declining trend in the plume indicates a shrinking plume. No appreciable movement or a neutral trend in the center of mass would indicate plume stability. The second moment provides a measure of the spread of the concentration distribution about the plume's center of mass. However, changes in the second moment over time do not necessarily completely characterize the changes in the concentration distribution (and the mass) over time. Therefore, in order to fully characterize the plume the Second Moment trend should be compared to the zeroth moment trend (mass change over time).

2.6 Detailed Statistics: Optimization Analysis

Although the overall plume analysis shows a general recommendation regarding sampling frequency reduction and general sampling density, a more detailed analysis is also available with the MAROS 2.0 software in order to allow for further reductions on a well-by-well basis for frequency, well redundancy, well sufficiency and sampling sufficiency. The MAROS Detailed Statistics allows for a quantitative analysis for spatial and temporal optimization of the well network on a well-by-well basis. The results from the Overview Statistics should be considered along with the MAROS optimization recommendations gained from the Detailed Statistical Analysis described previously. The MAROS Detailed Statistics results should be reassessed in view of site knowledge and regulatory requirements as well as in consideration of the Overview Statistics (Figure 2).

The Detailed Statistics or Sampling Optimization MAROS module can be used to determine the minimal number of sampling locations and the lowest frequency of sampling that can still meet the requirements of sampling spatially and temporally for an existing monitoring program. It also provides an analysis of the sufficiency of data for the monitoring program.

Sampling optimization in MAROS consists of four parts:

- Well redundancy analysis using the Delaunay method
- Well sufficiency analysis using the Delaunay method
- Sampling frequency determination using the Modified CES method
- Data sufficiency analysis using statistical power analysis.

The well redundancy analysis using the Delaunay method identifies and eliminates redundant locations from the monitoring network. The well sufficiency analysis can determine the areas where new sampling locations might be needed. The Modified CES method determines the optimal sampling frequency for a sampling location based on the direction, magnitude, and uncertainty in its concentration trend. The data sufficiency analysis examines the risk-based site cleanup status and power and expected sample size associated with the cleanup status evaluation.

2.6.1 Well Redundancy Analysis – Delaunay Method

The well redundancy analysis using the Delaunay method is designed to select the minimum number of sampling locations based on the spatial analysis of the relative importance of each sampling location in the monitoring network. The approach allows elimination of sampling locations that have little impact on the historical characterization of a contaminant plume. The delaunay methodology application assumes that the current sampling network adequately delineates the plume (bounding wells have non-detect values) and that if a hydraulic containment system is currently in operation, this will continue. An extended method or wells sufficiency analysis, based on the Delaunay method, can also be used for recommending new sampling locations. Details about the Delaunay method can be found in Appendix A.2 of the MAROS Manual (AFCEE 2002).

Well redundancy analysis uses the Delaunay triangulation method to determine the significance of the current sampling locations relative to the overall monitoring network. The Delaunay method calculates the network Area and Average concentration of the plume using data from multiple monitoring wells. A slope factor (SF) is calculated for each well to indicate the significance of this well in the system (i.e. how removing a well changes the average concentration.)

The well redundancy optimization process is performed in a stepwise fashion. Step one involves assessing the significance of the well in the system, if a well has a small SF (little significance to the network), the well may be removed from the monitoring network. Step two involves evaluating the information loss of removing a well from the network. If one well has a small SF, it may or may not be eliminated depending on whether the information loss is significant. If the information loss is not significant, the well can be eliminated from the monitoring network and the process of optimization continues with fewer wells. However if the well information loss is significant then the optimization terminates. This sampling optimization process allows the user to assess “redundant” wells that will not incur significant information loss on a constituent-by-constituent basis for individual sampling events.

Before applying the Delaunay method for spatial redundancy analysis, it is important to select the appropriate set of wells for analysis, i.e., only the wells that contribute to the spatial delineation of the plume. For example, if wells are far from the plume and contribute little or nothing to the delineation of the plume (e.g., some sentry wells or background wells far from the plume), they should be excluded from the analysis. One reason not to use these wells is that these wells usually are on the boundary of the triangulation and are hard to be eliminated since the Delaunay method protects boundary wells from being easily removed. The elimination status of these wells, in fact, should be determined from the regulatory standpoint. Another well type that could be excluded from analysis is one of a clustered well set because the Delaunay method is a two-dimensional method. Generally, only one well is picked from the clustered well set to represent the concentration at this point. This well can be the one that has the highest concentration or is screened in the representative aquifer interval with the geologic unit. Data from clustered wells can also be averaged to form a single sample and then used in the Delaunay method.

2.6.2 Well Sufficiency Analysis – Delaunay Method

The well sufficiency analysis, using the Delaunay method, is designed to recommend new sampling locations in areas within the existing monitoring network where there is a high level uncertainty in plume concentration. Details about the well sufficiency analysis can be found in Appendix A.2 of the MAROS Manual (AFCEE 2002).

In many cases, new sampling locations need to be added to the existing network to enhance the spatial plume characterization. In MAROS, the method for determining new sampling locations recommends the area for a possible new sampling location where there is a high level of uncertainty in concentration estimation. The Slope Factor (SF) values obtained from the redundancy reduction described above are used to calculate the concentration estimation error at each triangle area formed in the Delaunay triangulation. The estimated SF value at each triangle area is then classified into four levels: Small, Moderate, Large, or Extremely large because the larger the estimated SF value, the higher the estimation error at this area. Therefore, the triangle areas with the estimated SF value at the Extremely large or Large level are candidate regions for new sampling locations.

The results from the Delaunay method and the method for determining new sampling locations are derived solely from the spatial configuration of the monitoring network and the spatial pattern of the contaminant plume. No parameters such as the hydrogeologic conditions are considered in the analysis. Therefore, professional judgement and regulatory considerations must be used to make final decisions.

2.6.3 Sampling Frequency Determination - Modified CES Method

The Modified Cost Effective Sampling (MCES) method optimizes sampling frequency for each sampling location based on the magnitude, direction, and uncertainty of its concentration trend derived from its recent and historical monitoring records. The MCES estimates the lowest-frequency sampling schedule for a given groundwater monitoring location yet still provide needed information for regulatory and remedial decision-making. The Modified CES method was developed on the basis of the Cost Effective Sampling (Ridley et al. 1995). Details about the Modified CES method can be found in Appendix A.3 of the MAROS Manual (AFCEE 2002).

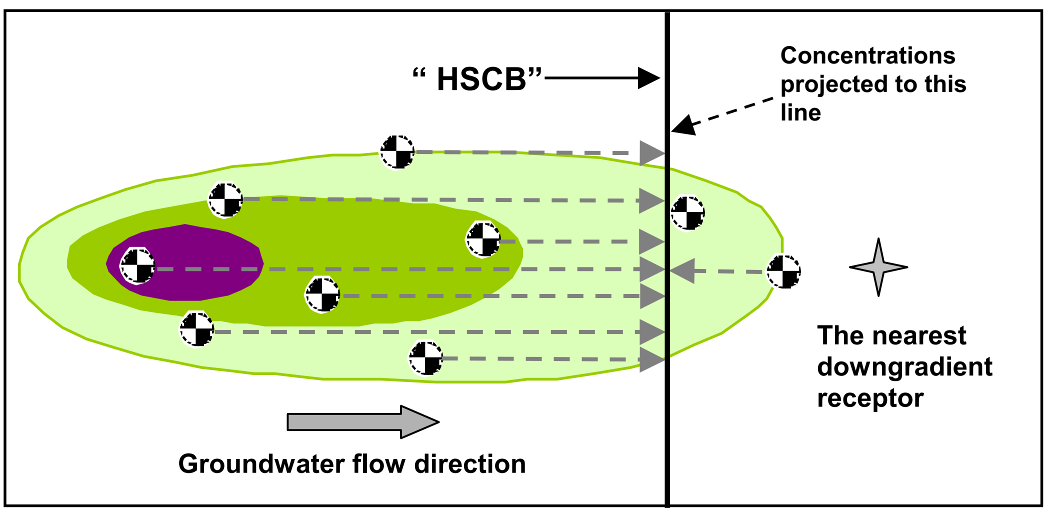
In order to estimate the least frequent sampling schedule for a monitoring location that still provides enough information for regulatory and remedial decision-making, MCES employs three steps to determine the sampling frequency. The first step involves analyzing frequency based on recent trends (Figure 4). A preliminary location sampling frequency (PLSF) is determined based on the trends determined by rates of change from linear regression and Mann-Kendall analysis of the most recent monitoring data. The variability of the sequential sampling data is accounted for by the Mann-Kendall analysis. The PLSF is then adjusted based on overall trends. If the long-term history of change is significantly greater than the recent trend, the frequency may be reduced by one level. Otherwise, no change could be made. The final step in the analysis involves reducing frequency based on risk. Since not all compounds in the target being assessed are equally harmful, frequency is reduced by one level if recent maximum concentration for compound of high risk is less than 1/2 of the Maximum Concentration Limit (MCL). The result of applying this method is a suggested sampling frequency based on recent sampling data trends and overall sampling data trends.

The finally determined sampling frequency from the Modified CES method can be Quarterly, Semiannual, Annual, and Biennial. Users can further reduce the sampling frequency to, for example, once every three years, if the trend estimated from Biennial data (i.e., data drawn once every two years from the original data) is the same as that estimated from the original data.

2.6.4 Data Sufficiency Analysis – Power Analysis

Statistical power analysis is a technique for interpreting the results of statistical tests. It provides additional information about a statistical test: 1) the power of the statistical test, i.e., the probability of finding a difference in the variable of interest when a difference truly exists; and 2) the expected sample size of a future sampling plan given the minimum detectable difference it is supposed to detect. For example, if the mean concentration is lower than the cleanup goal but a statistical test cannot prove this, the power and expected sample size can tell the reason and how many more samples are needed to result in a significant test. The additional samples can be obtained by a longer period of sampling or an increased sampling frequency. Details about the data sufficiency analysis can be found in Appendix A.6 of the MAROS Manual (AFCEE 2002).

When applying the MAROS power analysis method, a hypothetical statistical compliance boundary (HSCB) is assigned to be a line perpendicular to the groundwater flow direction (see figure below). Monitoring well concentrations are projected onto the HSCB using the distance from each well to the compliance boundary along with a decay coefficient. The projected concentrations from each well and each sampling event are then used in the risk-based power analysis. Since there may be more than one sampling event selected by the user, the risk-based power analysis results are given on an event-by-event basis. This power analysis can then indicate if target are statistically achieved at the HSCB. For instance, at a site where the historical monitoring record is short with few wells, the HSCB would be distant; whereas, at a site with longer duration of sampling with many wells, the HSCB would be close. Ultimately, at a site the goal would be to have the HSCB coincide with or be within the actual compliance boundary (typically the site property line).



In order to perform a risk-based cleanup status evaluation for the whole site, a strategy was developed as follows.

- Estimate concentration versus distance decay coefficient from plume centerline wells.
- Extrapolate concentration versus distance for each well using this decay coefficient.
- Comparing the extrapolated concentrations with the compliance concentration using power analysis.

Results from this analysis can be *Attained* or *Not Attained*, providing a statistical interpretation of whether the cleanup goal has been met on the site-scale from the risk-based point of view. The results as a function of time can be used to evaluate if the monitoring system has enough power at each step in the sampling record to indicate certainty of compliance by the plume location and condition relative to the compliance boundary. For example, if results are *Not Attained* at early sampling events but are *Attained* in recent sampling events, it indicates that the recent sampling record provides a powerful enough result to indicate compliance of the plume relative to the location of the receptor or compliance boundary.

3.0 SITE RESULTS

The groundwater long-term monitoring plan for Long Prairie was started in 1996. The monitoring plan consisted of performance monitoring and compliance monitoring with the following goals:

1) plume containment monitoring to confirm that the PCE plume remains hydraulically controlled; and
2) plume reduction monitoring to verify progress toward achieving cleanup goals.

31 monitoring wells, 3 city wells, and 10 extraction wells were included in the long-term monitoring network as of 2002 (Figure 1). The monitoring well naming convention includes: “a” wells, shallow wells screened at the water table; “b” wells, mid-depth wells screened at the base of the upper outwash; and “c” wells, deep wells screened in the lower outwash. The sampling frequency for the long-term monitoring wells varies: extraction wells have generally been sampled quarterly while monitoring wells were generally sampled semiannually or annually since the implementation of the long-term monitoring plan in 1996. For some wells, sampling was even terminated for 3 years before they were sampled again in October 2002. This resulted in some monitoring wells having only 5 ~ 7 data records during the 7-year period (from 1996 to 2002). Monitoring data from 1996 to 2002 were used for the detailed optimization analysis, with a subset of this data used in some of the analyses.

In applying the MAROS methodology to develop a revised monitoring strategy for the Long Prairie site, many site and dataset parameters were applied. General site assumptions include:

- All wells that were part of the network in between 1996 and 2002 were considered in the temporal concentration trend analysis.
- Four chemicals of concern (COCs) that have been historically present at the site: tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cis-1,2-DCE), and vinyl chloride (VC), however, PCE is the predominant chemical and has been used as an indicator parameter in the MAROS analyses.
- All source/tail assignments were made based on the PCE plume. Source wells were selected based on historically elevated concentrations of PCE, near the dry cleaner site in the vicinity of well MW-10.
- Site-specific hydrogeologic parameters related to the upper outwash aquifer including groundwater flow direction, seepage velocity, saturated thickness, porosity, receptor locations, can be found in the Table 4.
- Monitoring data from 1996 to 2002 were used for the “overall” trend analysis in the sampling frequency optimization and other analyses in the MAROS detailed optimization analysis.

3.1 Data Consolidation

In MAROS, ground water monitoring data can be imported from simple database-format Microsoft® Excel spreadsheets, Microsoft® Access tables, previously created MAROS database archive files, or entered manually. The historical monitoring data from Long Prairie were received in Excel database format. The columns in the file where formatted to the MAROS Access file import format and then imported into the MAROS software using the import tool. The long-term monitoring raw data contained many non-detects, trace level results, and duplicates. Therefore, in the MAROS software the raw data are filtered, consolidated, and the period of interest was specified (i.e. monitoring data from 1996 to 2002) as well as the wells of interest for the zone of interest. For statistical evaluation of the data, a representative value for each sample point in time is needed. MAROS has many automated options to choose how these values are assigned. For the Long Prairie data, non-detects values were chosen to be set to the minimum detection limit, allowing for uniform detection limits over time. Trace level results were chosen to be represented by their actual values and duplicates samples were chosen to be assigned the average of the two samples. The reduced data for each well were viewed as a time series in a graphical form on a linear or semi-log plot generated by the software.

3.2 Overview Statistics: Plume Trend Analysis

3.2.1 Mann-Kendall/Linear Regression Analysis

The goal of the Mann-Kendall and Linear Regression temporal trend analysis is to assess the historical trend in the concentrations over time. These trend estimates are then analyzed to identify the source and tail region overall stability category as well as gaining an understanding of the individual well concentrations over time (see Figure 2 for further details). The PCE historical data for monitoring wells the Upper Outwash Aquifer as well as the recovery wells were assessed for trends. No data consolidation was performed to condense the sampling into regular sample intervals.

Only 31 monitoring wells and 9 recovery wells had sufficient data within the time period of 1996 to 2002 (at least 6 sample events) to assess the trends in the wells. Trend results from the Mann-Kendall and Linear Regression temporal trend analysis for both Upper Outwash Aquifer monitoring wells and extraction wells are given in Table 5. The monitoring well trend results show that 2 out of 4 source wells and 24 out of 27 tail wells have a Probably Decreasing, Decreasing, or Stable trend. Both methods gave similar trend estimates for each well. The recovery well trend results show that 7 out of 10 wells have a Probably Decreasing, Decreasing, or Stable trend. Both methods gave similar trend estimates for each well. When considering the spatial distribution of the trend results (Figures 5 and 6 – maps created in ArcGIS from MAROS results), the majority of the decreasing trend results are located in the interior of the plume or near the source, indicating a decreasing source. Another area of decreasing trends is in the vicinity of the line of recovery or plume containment wells (Figures 7 and 8 – maps created in ArcGIS from MAROS results).

Well Type	Zone A MAROS Trend Analysis	
	PD, D, S	I, PI
Source	2 of 4 (50%)	0 of 4 (0%)
Tail	24 of 27 (90%)	3 of 27 (10%)
Recovery	7 of 10 (70%)	0 of 10 (0%)

Note: Decreasing (D), Probably Decreasing (PD), Stable (S), Probably Increasing (PI), and Increasing (I)

Although monitoring wells and recovery wells are present in the well network, these well trend results need to be treated differently for the purpose of individual trend analysis interpretation primarily due to the different course of action possible for the two types of wells. For monitoring wells, strongly decreasing concentration trends may lead the site manager to decrease their monitoring frequency, as well look at the well as possibly attaining its remediation goal. Conversely, strongly decreasing concentration trends in recovery wells may indicate ineffective or near-asymptotic contamination extraction, which may in turn lead to either the shutting down of the well or a drastic change in the extraction scheme. Other reasons favoring the separation of these two types of wells in the trend analysis interpretation is the fact that they produce very different types of samples. On average, the extraction wells possess screens that are twice as large and extraction wells pull water from a much wider area than the average monitoring well. Therefore, the potential for the dilution of extraction well samples is far greater than monitoring well samples.

3.2.2 Moment Analysis

The moment analysis in the MAROS software was applied at the Long Prairie site in order to gain a better understanding of the overall plume stability in the Upper Outwash Aquifer. Monitoring well data from 1996 to 2002 were used for the moment analysis, the wells utilized for the analysis are listed in Table 1. Sampling frequency for these wells was very irregular, therefore, the spatial moment analyses were based on sampling events redefined on a yearly basis, that is, data collected between January 1st and December 31st of a year were treated as if from the same sampling event performed on July 1st of that year, with the geometric mean result utilized for each location.

Moment trend results from the Zeroth, First, and Second Moment analyses for the Zone A monitoring well network were varied. Moment Trend results from the moment trend analysis for the selected Upper Outwash well dataset are given in the Moment Analysis Report, Appendix B. Approximately 17 wells were used in the moment analysis. Wells with redundant spatial concentration information were not utilized in the moment analysis (i.e. MW-1A).

The zeroth moment analysis showed a stable trend (no change in dissolved mass) over time (Appendix B). The zeroth moment or mass estimate can show high variability over time, largely due to the fluctuating concentrations at the most contaminated wells as well as a varying monitoring well network. In order to reduce the fluctuating factors that could influence a mass trend, the data were consolidated to annual sampling and the zeroth moment trend evaluated. Another factor to consider when interpreting the mass increase over time is the change in the spatial distribution of the wells sampled historically. At the Long Prairie site there were changes in the well distribution over time, due to addition and subtraction of wells from the well network as well as changes in sampling frequency.

Moment Type	Mann-Kendall Trend Analysis	
	Trend	**Comment**
Zeroth	Stable	The amount of dissolved mass has not fluctuated appreciably over time. This matches results in Table 5, where 15% of wells had stable trends.
First	Increasing	The center of mass moved away from the source area over along the direction of groundwater flow.
Second	Stable to No Trend	Stable to no trend, indicating that wells representing very large areas both on the tip and the sides of the plume show little change in concentrations. The shape of the plume is relatively constant over time.

The first moment, or center of mass, for each sample event in the Upper Outwash aquifer had an increasing distance relative to the approximate source location, see Figure 9, as well as the MAROS First Moment Reports in Appendix B. The center of mass showed some movement forward along the direction of groundwater flow. These spatial and temporal trends in the center of mass distance from the source location can indicate transient movement based on season variation in rainfall or other hydraulic considerations. With appreciable movement in the center of mass as is the case at Long Prairie as well as a stable to decreasing source (zeroth moment and individual well trend analysis results), there is an indication that the near source area is remediating faster (on a mass basis) than the other areas of the plume. So although the plume is stable the relative concentrations in the source area are decreasing faster than the other areas of the plume. This concentration decrease can be seen in comparing the1996 and 2002 maps in Appendix A.

The second moment, or spread of the plume over time in both the x and y directions for the sample events, showed a stable to no trend, Appendix B. The second moment provides a measure of the spread of the concentration distribution about the plume's center of mass. Analysis of the spread of the plume indicates stability in the plume in the y direction and stable to no trend in the x direction, indicating that wells representing very large areas both on the tip and the sides of the plume show little change in concentrations over time and that the overall shape of the plume is relatively constant with time. This stable trend in the spread of the plume strengthens the individual well Mann-Kendall and Linear Regression trend analysis spatially, where most of the tail wells showed a decreasing or probably decreasing PCE concentration trend.

3.2.3 Overview Statistics: Plume Analysis

In evaluating overall plume stability, the trend analysis results and all monitoring wells were assigned "Medium" weights within the MAROS software (as described in Figure 3), assuming equal importance for each well and each trend result in the overall analysis.

Overview Statistics Results:

- Overall trend for Source region: Stable,
- Overall trend for Tail region: near Stable,
- Overall results from moment analysis indicate a stable to decreasing plume,
- Overall monitoring intensity needed: Moderate.

These results matched with the judgment based on the visual comparison of PCE plumes over time, as well as the Moment Analysis. The PCE concentrations observed over the history of monitoring at the site are plotted in Appendix A. The PCE plume observed in 1996 was very similar to that of 2002, indicating that the PCE plume is relatively stable over time.

For a generic plume, the MAROS software indicates:

- No recommendation for sampling frequency
- Upper Outwash Aquifer may need 35 wells for the sampling network

These MAROS results are for a generic site, and are based on knowledge gained from applying the MAROS Overview Statistics. There is no recommendation for frequency of sampling for the whole monitoring network due to some uncertainty in the trends and the presence of an active remediation system. Also, the recommended the number of wells seems high when applied to the entire site. So, although the overall plume trend analysis shows a stable plume, no general sampling frequency recommendation was assessed by the MAROS software. Therefore, a more detailed analysis was performed using the MAROS 2.0 software in order to allow for possible reductions on a well-by-well basis, frequency and well redundancy analysis were conducted. These overview statistics were also used when evaluating a final recommendation for each well after the detailed statistical analysis was applied.

3.3 Detailed Statistics: Optimization Analysis

From May 1996 to October 2002, a total of 44 wells were sampled, among which there are 31 monitoring wells, 3 city wells, and 10 extraction wells (Table 1). Sampling frequency for these wells varies: extraction wells were generally sampled quarterly while monitoring wells were generally sampled semiannually or annually. A brief sampling history for these wells is summarized in the last column of Table 1. All 44 wells were used in the MAROS sampling optimization analysis. In the well redundancy and well sufficiency analyses, the monitoring wells and some of the city wells were used (mostly "B" wells, i.e., wells screened in the middle of the aquifer). In the sampling frequency analysis, all 44 wells were analyzed. In data sufficiency analysis, only monitoring wells were used. Results for well redundancy and sufficiency analyses, sampling frequency analysis, and data sufficiency analysis are detailed in the following sub-sections.

3.3.1 Well Redundancy Analysis – Delaunay Method

The goal of the well redundancy analysis is to identify wells that are redundant within monitoring network as candidates for removal from the sampling plan. The approach allows elimination of sampling locations that have little impact on the historical characterization of a groundwater plume. The analysis assumes that the current state of hydraulic containment at the site will continue and than the monitoring network adequately delineates the plume.

A monitoring network of 17 monitoring wells was used in the well redundancy analysis. Clustered wells that are screened in different zones of the aquifer and had equivalent duplicates or lower concentrations were excluded from the analysis (Table 1 lists the wells excluded and the 17 wells used in the analysis). For example, wells MW-2A and MW-2C are screened above and below the aquifer zone in which MW-2B is screened (the middle zone or "B" zone), respectively, and both had concentrations lower than MW-2B. Therefore, MW-2B instead of MW-2A and MW-2C was used in the well redundancy analysis. In most cases, the "B" zone wells were used. But for well cluster MW-11A, MW-1B, and MW-11C, MW-11C was used because it had more sampling records for analysis and had the same concentration level as MW-2B. The well redundancy analysis was conducted with the latest 3 years' sampling events (May 1999 to October 2002). The results show that no monitoring wells can be eliminated from this 17-well network (Table 6).

However, after a qualitative consideration of the need for plume and site characterization and the wells' concentration history, 9 monitoring wells (all "A" zone wells) can be eliminated (Table 6). Using similar qualitative analysis, 3 extraction wells in the source area can be eliminated since their concentrations were always below MCL or DL (Table 6). This resulted in a total of 12 wells recommended for removal, that is, a reduction of 27% in the well network (12 out of 44 wells).

Well removal candidates include:

Monitoring wells	Monitoring wells	Extraction wells
• MW-1A • MW-2A • MW-3A • MW-4A • Mw-5A	• MW-6A • MW-11A • MW-16A • MW-18A	• RW-1A • RW-1B • RW-1C

Eliminating the above 12 wells has negligible influence on spatial plume characterization (Figure 10). For monitoring wells that have sampling ports at different levels ("A", "B", or "C" zones), only "B" zone or "C" zone wells were used in the 2-D plume contouring. "B" zone and "C" zone wells were generally higher in PCE concentrations than their corresponding "A" zone wells, resulting in conservative estimates of the spatial plume distribution. All monitoring wells that are candidates for elimination from the monitoring network, generally "A" zone wells, plume contouring was not affected and therefore the plumes before and after well elimination (Figure 10) are identical.

In considering the MAROS redundancy analysis results, other factors needed to be taken into consideration before recommending well removals. Recent concentrations in 7 of the 9 wells were all below detection limits (MW-1A, MW-3A, MW-5A, MW-11A, MW-15A, MW-16A, MW-18A), indicating that these wells do not and probably will not contribute to the vertical plume delineation. In the case of MW-2A and MW-4A, these were eliminated because their concentrations were all lower than their corresponding "B" zone wells. Since the dissolved PCE plume was originated from DNAPL, without vertical upward movement of groundwater, it typically tends to migrate downward vertically and stay at the bottom of the aquifer. Therefore, although the "A" zone wells are candidates for elimination, their corresponding "B" (or "C") zone wells were kept. Also, in plume contouring for the purpose of delineating the plume extent horizontally, using "B" wells can provide a more conservative estimate (i.e., a larger plume) than using "A" zone wells due to their typically higher concentrations. For example, Figure 11 depicts the approximate PCE plumes observed in May 1999 and October 2002 using data from "B" zone wells only. In order to monitor the possible vertical migration of the plume in the aquifer, all "C" zone wells were kept, ensuring enough information will be available for plume characterization vertically. In considering the recovery wells, three wells were identified for removal from the monitoring network because these 3 wells (RW-1A, RW-1B, and RW-1C) have been extracting groundwater have been consistently below detection limits or the MCL.

3.3.2 Well Sufficiency Analysis – Delaunay Method

The well sufficiency analysis for recommending new sampling locations was performed using the same set of monitoring wells as in the well redundancy analysis. With this analysis, areas within the monitoring well network where there is high uncertainty for predicting concentrations are recommended for additional sample locations within the existing well network. The SF values obtained from the well redundancy analysis were used to generate Figure 12, which indicates the triangular regions for placing new sampling locations. It is seen that almost all triangular regions (except one to the east of the plume source area) have M (medium) estimation errors. The region with L (large) result has a SF value of 0.602, which is not significantly larger than the M regions whose estimated SF values range from 0.3 to 0.6. Considering that the plume is stable to decreasing (Figure 10 and Section 3.2 results) and that the source of contamination has been remediated (Barr, 2001), a new sampling location to the east of the plume source area is not necessary. Therefore, no new locations were recommended.

3.3.3 Sampling Frequency Analysis– Modified CES Method

Results from the sampling frequency analysis for the 31 monitoring wells, 3 city wells, and 10 extraction wells are given in Table 7. Some of the annual or quarterly sampling frequency recommendations were due to insufficient overall or recent data (i.e., less than 6 data records), which prevented the MAROS estimation of concentration trend using overall or recent monitoring data for some wells. After considering the MAROS results along with the historical and recent concentration levels at these wells, final sampling frequency recommendations are provided in Table 7. For the monitoring well system well, considering all 31 wells prior to the well redundancy analysis, 18 wells can be sampled biennially, and 13 annually. All 3 city wells are recommended to be sampled biennially. For the recovery well system, considering all 10 wells prior to the well redundancy analysis, 4 can be sampled biennially, and 6 annually. If only considering wells that have been sampled consistently up to October 2002 (27 wells) and the sample frequency reduction alone, a reduction of approximately 44% in total samples per year can be achieved (see the breakdown table below).

Current Sampling Frequency		**Recommended Sampling Frequency**	
Frequency	**Number of Wells**	**Frequency**	**Number of Wells**
Quarterly	8	Biennial	9
Annually	19	Annual	18
Total samples per year	51	Total samples per year	22.5

In some cases, the frequency recommendations from the MAROS software were not adopted due to data inadequacy. Sampling frequencies for some of the wells were irregular, ranging from quarterly to annual during the period between 1996 and 2002. For some wells, sampling was even terminated for 3 years before they were sampled again in October 2002. This resulted in some monitoring wells having only 5 ~ 7 data records available during the 7-year period (from 1996 to 2002). Because the minimum data requirement for the sampling frequency trend analysis is 6 sampling events, the overall or recent trends for many wells could not be estimated. This resulted in frequency results that were solely estimated from the overall data trend. For instance, well MW-3B has only 3 concentration records between May 1999 and October 2002, making the estimation of recent trend impossible. In cases of data inadequacy, the MAROS frequency analysis will assign conservative results, i.e., semiannual or annual instead of annual or biennial. However, with the incorporation of a qualitative assessment of the concentration levels and concentration history for these wells, more reasonable sampling frequencies were recommended (Table 7). For example, well MW-3B was suggested for a biennial sampling because all its historical concentrations were below the detection limit. Considering the plume stability which remains stable according to the overview statistical analysis, it is unlikely that the plume will show rapid changes over the long-term. Therefore, keeping the frequency of wells at annual and biennial level will continue to allow for adequate plume delineation.

3.3.4 Data Sufficiency – Power Analysis

In the MAROS data sufficiency analysis, statistical power analysis was used to assess the sufficiency of monitoring plans for detecting difference between the mean concentration and cleanup goal. Results from the analysis indicate remediation progress from the risk-based standpoint at a hypothetical statistical compliance boundary (HSCB). The power and expected sample size associated with the target level evaluation may indicate the need for expansion or redundancy reduction of future sampling plans.

In the risk-based site cleanup evaluation, two analyses were performed (see Appendix B for all related MAROS reports). In the first analysis, the distance from the most downgradient well (MW-15 A and B) to the nearest downgradient receptor (HSCB) was assumed to be 10 ft (just upgradient of the Long Prairie river). The general groundwater flow angle is to the North. Selected plume centerline wells are MW-15B, MW-16B, MW-17B, MW-4B, and MW-2B (Table 8). Sampling events from May 1999 to October 2002 were selected for the analysis (Table 9). Among these only 5 sampling events have sufficient data for plume centerline concentration regression. Regression coefficients for the 5 sampling events range from 1.5×10^{-3} to 5.4×10^{-3} per ft, all with high confidence (Table 9 and see Appendix B for individual well projected concentration values). The second analysis used the same parameters except that the distance to receptor was assumed to be -100 ft, i.e., assuming that the HSCB is 100 ft upgradient of the most downgradient well.

Table 10 shows the risk-based site cleanup status at selected sampling events for both analyses (i.e., HSCB at 10 ft and HSCB at -100 ft downgradient of the monitoring system). The results show that the risk-based site cleanup status in most cases for both analyses is “attained”, i.e., the projected mean site concentration at the HSCB is statistically significantly lower than the target level. Similarly, the associated power is high and the expected sample size is relatively small. The “not attained” results, all have low power (<0.5) but not S/E (significantly exceed) status, indicate that the projected mean site concentration at the HSCB is lower than the target level but is not statistically significant. The “not attained” results can be explained by the small dataset (18 samples) available for these sampling events (September 2000 and September 2001), while all other sampling events have more than 20 samples for analysis. Therefore, the results indicate that the site is clean at the HSCB that is –100 ft downgradient (equal to 100 ft upgradient of the monitoring system from the risk-based standpoint). Also, with the plume stable to shrinking over time, the HSCB will move upgradient gradually. The HSCB is getting tighter and tighter as the monitoring record increases. In general, monitoring networks become more powerful over time. This analysis indicates that the monitoring system is working because it is powerful enough to accurately reflect the location of the plume relative to the compliance point. Therefore, the current monitoring network is sufficient in terms of evaluating risk-based site target level status, if the pump-and-treat remedial system continues to contain the plume and keeps reducing the contaminant concentration.

4.0 SUMMARY AND RECOMMENDATIONS

In recent years, the high cost of long-term monitoring as part of active or passive remediation of affected ground water has made the design of efficient and effective ground water monitoring plans a pressing concern. Periodically updating and revising long-term monitoring programs with changing conditions at the site can mean considerable savings in site monitoring costs. The MAROS decision-support software presented in this report assists in revising existing long-term monitoring plans based on the historical and current monitoring data and plume behavior over time.

The MAROS 2.0 sampling optimization software/methodology has been applied to the Long Prairie existing long-term monitoring program as of October 2002. The optimization results and subsequent recommendations allow for optimization of the spatial and temporal groundwater monitoring system in place at the Long Prairie site. The current long-term monitoring network could be optimized through reduction in both sampling locations and sampling frequency (results are summarized in Table 11 and MAROS Reports in Appendix B).

Overview Statistics

Both the Mann-Kendall and Linear Regression temporal trend methods gave similar trend estimates for each well. Results from the temporal trend analysis indicate that 90% of the plume tail and edge area monitoring wells in the Upper Outwash Aquifer indicate a Probably Decreasing, Decreasing, or Stable PCE concentration trend, whereas only about half of the wells in the source area have similar trends. The trend results for the recovery wells along the centerline of the plume indicate most wells have Probably Decreasing, or Decreasing concentrations over time. These temporal trend results were applied to the

Results from the moment trend analysis give evidence of a stable plume as well, with the dissolved mass showing stability over time, whereas the center of mass shows movement away from the source area due to decreasing source area concentrations and the plume spread shows stability over time. Overall plume stability temporal results recommend a moderate monitoring strategy due to the stable PCE plume. The overview results are relatively generic and not well-by-well specific, therefore, a detailed statistical analysis with a well-by-well analysis was performed.

Detailed Statistics

Further analysis from the well redundancy analysis using the Delaunay method indicate that 12 monitoring wells could be eliminated from the original monitoring network of 44 wells without any significant loss of plume information (Table 11). The well sufficiency analysis indicated no need for adding new wells into the current monitoring system. The resulting reduction in sampling locations would therefore be 27% (12 out of 44).

The sampling frequency optimization analysis using the modified CES method, indicated that the wells in the monitoring system could be sampled at annual or biennial frequency, lower than the current sampling frequency overall. If only considering wells that have been sampled consistently up to October 2002 (27 wells) and the sample frequency reduction alone, this is a reduction of approximately 47% in total samples per year.

Data sufficiency analysis using power analysis methods, shows that the site has reached the target cleanup levels (0.005 mg/L for PCE) at the HSCB that is 100 ft upgradient from the most downgradient well. With the plume stable to shrinking over time, the HSCB will move upgradient gradually. This analysis indicates that the monitoring system is working because it is powerful enough to accurately reflect the location of the plume relative to the compliance boundary. This analysis shows the sufficiency of the monitoring system in terms of evaluating risk-based site target level status if the pump-and-treat remedial system continues to contain the plume and keeps reducing the contaminant concentration in the aquifer.

The recommended long-term monitoring strategy results in a reduction in sampling costs and allows site personnel to develop a better understanding of plume behavior over time. A reduction in the number of redundant wells is expected to result in a moderate cost savings over the long-term at the Long Prairie site. Overall, the MAROS optimized plan consists of 32 wells: 16 sampled annually, and 16 sampled biennially ($6,720). The MAROS optimized plan would result in 24 samples per year, compared to 51 samples per year in the current monitoring program (Table 11). Implementing these recommendations could lead to a 52% reduction from the current monitoring plan in terms of the samples to be collected per year. An approximate cost savings estimate range from $2,700 to $7,560 per year (based on an average per sample cost range of $100 to $280) is projected while still maintaining adequate delineation of the plume as well as knowledge of the plume state over time.

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MAROS 2.0 APPLICATION
MONITORING NETWORK OPTIMIZATION

Long Prairie Site
Long Prairie, Minnesota

TABLES

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Table 1
Sampling Locations Used in the MAROS Analysis

Long Prairie Site
Long Prairie, Minnesota

Well Name	Used in Delaunay Analysis?	Used in Modified CES Analysis?	Summary of Sampling History (sampling data available since 1996)
BAL2B	No, city well and far from the plume	Yes	Sampled only once in October 2002, below DL
BAL2C	Yes	Yes	Sampled semiannually until October 1999, then sampled in October 2002; all records were below DL
CW-3	Yes	Yes	Sampled quarterly on average; all records were below DL
CW-6	No, city well and far from the plume	Yes	Sampled quarterly until March 2000, then sampled quarterly since April 2002; all records were below DL
MW-1A	No, screened above and duplicates MW-1B	Yes	Sampled semiannually until October 1999, then sampled in October 2002; all records were below DL
MW-1B	Yes	Yes	Sampled semiannually until October 1999, then sampled in October 2002; all records were below DL
MW-2A	No, screened above MW-2B and lower in concentration	Yes	Sampled annually since 1997
MW-2B	Yes	Yes	Sampled annually since 1997
MW-2C	No, screened below MW-2B and lower in concentration	Yes	Sampled annually since 1997 except when in 1999 it was sampled several times
MW-3A	No, screened above and duplicates MW-3B	Yes	Sampled semiannually until October 1999, then sampled in October 2002; all records were below MCL or DL
MW-3B	Yes	Yes	Sampled semiannually until October 1999, then sampled in October 2002; all records were below DL
MW-4A	No, screened above MW-4B and lower in concentration	Yes	Sampled only in 1999, then sampled in October 2002
MW-4B	Yes	Yes	Sampled annually since 1997
MW-4C	No, screened below MW-4B and lower in concentration	Yes	Sampled annually except when in 1999 it was sampled several times
MW-5A	No, screened above and duplicates MW-5B	Yes	Sampled semiannually until October 1999, then sampled in October 2002; all records were below DL

Notes: MCL= the maximum contaminant level of PCE (0.005 mg/L)
DL = detection limit

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Table 1
Sampling Locations Used in the MAROS Analysis

Long Prairie Site
Long Prairie, Minnesota

Well Name	Used in Delaunay Analysis?	Used in Modified CES Analysis?	Summary of Sampling History (sampling data available since 1996)
MW-5B	Yes	Yes	Sampled semiannually until October 1999, then sampled in October 2002; all records were below DL
MW-6A	No, screened above MW-6B and generally lower in concentration	Yes	Sampled annually since 1997
MW-6B	Yes	Yes	Sampled annually since 1997
MW-6C	No, screened below MW-6B and lower in concentration	Yes	Sampled annually since 1998 except when in 1999 it was sampled several times
MW-10	Yes	Yes	Sampled semiannually until October 1999, then sampled in October 2002
MW-11A	No, screened above and duplicates MW-11C	Yes	Sampled only in 1999, then sampled in October 2002; all records were below DL
MW-11B	No, screened above and duplicates MW-11C	Yes	Sampled annually since 1999; all records were below DL
MW-11C	Yes, it has more records than MW-11B	Yes	Sampled annually since 1997 except when in 1999 it was sampled several times; all records were below MCL or DL
MW-13C	Yes	Yes	Sampled semiannually until October 1999, then sampled in October 2002; all records were below MCL or DL
MW-14B	Yes	Yes	Sampled semiannually until October 1999, then sampled annually
MW-14C	No, screened below MW-14B and lower in concentration	Yes	Sampled semiannually until October 1999, then sampled annually; all records were below MCL or DL
MW-15A	No, screened above and duplicates MW-5B	Yes	Sampled semiannually since October 1998, then sampled annually since October 1999; all records were below DL
MW-15B	Yes	Yes	Sampled semiannually since October 1998, then sampled annually since October 1999; all records were below DL
MW-16A	No, screened above MW-5B and lower in concentration	Yes	Sampled 5 times between 1998 and 1999, then sampled in October 2002; all records were below MCL or DL
MW-16B	Yes	Yes	Sampled 5 times between 1998 and 1999, then sampled annually

Notes: MCL= the maximum contaminant level of PCE (0.005 mg/L)
DL = detection limit

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SERVICES, INC.

Table 1
Sampling Locations Used in the MAROS Analysis

Long Prairie Site
Long Prairie, Minnesota

Well Name	Used in Delaunay Analysis?	Used in Modified CES Analysis?	Summary of Sampling History (sampling data available since 1996)
MW-17B	Yes	Yes	Sampled 4 times between 1998 and 1999, then sampled annually
MW-18A	No, screened above MW-18B and lower in concentration	Yes	Sampled 4 times between 1998 and 1999, then sampled in October 2002; all records were below DL
MW-18B	Yes	Yes	Sampled 4 times between 1998 and 1999, then sampled in October 2002; all records were below MCL but higher than DL
MW-19B	Yes	Yes	Sampled 4 times between 1998 and 1999, then sampled annually; all records were below DL
RW-1A	No, recovery well	Yes	Sampled quarterly on average until 1999, then sampled in October 2002
RW-1B	No, recovery well	Yes	Sampled quarterly on average until 1999, then sampled in October 2002
RW-1C	No, recovery well	Yes	Sampled only once in October 2002
RW-3	No, recovery well	Yes	Sampled quarterly
RW-4	No, recovery well	Yes	Sampled quarterly until 99, then sampled annually
RW-5	No, recovery well	Yes	Sampled quarterly
RW-6	No, recovery well	Yes	Sampled quarterly
RW-7	No, recovery well	Yes	Sampled quarterly
RW-8	No, recovery well	Yes	Sampled quarterly since 1999
RW-9	No, recovery well	Yes	Sampled quarterly since 1999

Notes: MCL= the maximum contaminant level of PCE (0.005 mg/L)
DL = detection limit

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Table 2
Mann-Kendall Analysis Decision Matrix (Aziz, et. al., 2002)

Mann-Kendall Statistic	Confidence in the Trend	Concentration Trend
S > 0	> 95%	Increasing
S > 0	90 - 95%	Probably Increasing
S > 0	< 90%	No Trend
$S \leq 0$	< 90% and COV $\geq$ 1	No Trend
$S \leq 0$	< 90% and COV < 1	Stable
S < 0	90 - 95%	Probably Decreasing
S < 0	> 95%	Decreasing

Table 3
Linear Regression Analysis Decision Matrix (Aziz, et. al., 2002)

Confidence in the Trend	Log-slope	
	Positive	Negative
< 90%	No Trend	COV < 1 Stable COV > 1 No Trend
90 - 95%	Probably Increasing	Probably Decreasing
> 95%	Increasing	Decreasing

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TABLE 4
Upper Outwash Aquifer Site-Specific Parameters

Long Prairie Site
Long Prairie, Minnesota

Parameter	Value
Seepage Velocity	476 ft/yr [1]
Porosity	30% [2]
Approximate Upper Outwash Source Location	Well MW-10 [3]
Approximate Upper Outwash Saturated Thickness	60 ft [1]
General Groundwater Flow Direction	NW [1]

Notes:

1. Barr, 2000: regional groundwater flow direction. Pumping in the vicinity of the plume results in local variations in groundwater flow direction.
2. Approximation based on type of aquifer material, outwash gravel and sand.
3. Location of source area obtained from high historical PCE concentration and the location of the former dry-cleaning establishment.

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TABLE 5
Upper Outwash Aquifer Trend Analysis

Long Prairie Site
Long Prairie, Minnesota

Well	Well Type [3]	Well Category [5]	Mann-Kendall Trend [4]	Linear Regression Trend [4]	Overall Trend [6]	Number of Samples	Number of Detects
CW-3	CSW	T	S	S	S	24	0
CW-6	CSW	T	S	I	PI	14	0
BAL2C	MW	T	S	S	S	8	0
MW-1A	MW	T	S	S	S	8	0
MW-1B	MW	T	S	S	S	8	0
MW-2A	MW	S	NT	NT	NT	6	6
MW-2B	MW	S	NT	NT	NT	6	6
MW-2C	MW	S	S	S	S	8	5
MW-3A	MW	T	NT	NT	NT	8	1
MW-3B	MW	T	S	S	S	8	0
MW-4B	MW	T	D	D	D	6	6
MW-4C	MW	T	S	S	S	8	8
MW-5A	MW	T	S	S	S	8	0
MW-5B	MW	T	S	S	S	8	0
MW-6A	MW	T	NT	NT	NT	6	5
MW-6B	MW	T	D	D	D	6	6
MW-6C	MW	T	PD	D	D	7	7
MW-10	MW	S	D	D	D	8	8
MW-11B	MW	T	S	S	S	4	0
MW-11C	MW	T	S	PD	S	8	1
MW-13C	MW	T	NT	NT	NT	9	2
MW-14B	MW	T	PD	D	D	10	10
MW-14C	MW	T	S	S	S	11	1
MW-15A	MW	T	S	D	PD	7	0
MW-15B	MW	T	S	D	PD	7	0
MW-16A	MW	T	S	S	S	6	1
MW-16B	MW	T	S	NT	S	8	8
MW-17B	MW	T	D	D	D	7	7
MW-18A	MW	T	S	S	S	5	0
MW-18B	MW	T	S	I	PI	5	5
MW-19B	MW	T	S	I	PI	7	0
RW-1A	RW	T	PD	NT	S	12	11
RW-1B	RW	T	NT	NT	NT	12	1
RW-3	RW	S	D	D	D	25	25
RW-4	RW	T	D	D	D	15	6
RW-5	RW	T	D	D	D	25	25
RW-6	RW	T	D	D	D	25	25
RW-7	RW	T	D	D	D	25	25
RW-8	RW	T	D	D	D	12	12
RW-9	RW	T	NT	NT	NT	12	12

Notes:
1. Consolidation of data included non-detect values set to the minium detection limit (0.001 mg/L) and duplicate data for the quarter were averaged.
2. All wells that were part of the network in between 1996 and 2002 with more than 4 sample events were analyzed.
3. RW = Recovery Well; MW = Monitoring Well; CSW = City Supply Well
4. Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)
5. S = Source Zone Well; T = Tail Zone Well
6. Overall Trend is calculated from a weighted average of the Linear Regression and Mann-Kendall Trends. For further details on this methodolgy refer to the MAROS Manual Appendix A.8.

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Table 6
Well Redundancy Analysis Results – Delaunay Method

Long Prairie Site
Long Prairie, Minnesota

Well Name	Well Used in Analysis?	MAROS Well Redundancy Analysis Result	MAROS Interpreted Well Redundancy	Comments
BAL2B	No, city well and far from the plume	-	Keep	City well monitoring
BAL2C	Yes	Keep	Keep	Downgradient sentry well
CW-3	Yes	Keep	Keep	City well monitoring
CW-6	No, city well and far from the plume	-	Keep	City well monitoring
MW-1A	No, screened above and duplicates MW-1B	-	**Eliminate**	Duplicates MW-1B and concentrations below DL
MW-1B	Yes	Keep	Keep	Cross gradient sentry well
MW-2A	No, screened above MW-2B and lower in concentration	-	**Eliminate**	Monitors only the upper zone at MW-4 and concentrations dropped to below MCL
MW-2B	Yes	Keep	Keep	Inside plume well and close the source
MW-2C	No, screened below MW-2B and lower in concentration	-	Keep	Monitors the lower zone at MW-2 for possible downward or lower zone contaminant migration
MW-3A	No, screened above and duplicates MW-3B	-	**Eliminate**	Duplicates MW-3B and historical concentrations below MCL or DL
MW-3B	Yes	Keep	Keep	Downgradient of the source
MW-4A	No, screened above MW-4B and lower in concentration	-	**Eliminate**	Monitors only the upper zone at MW-4 and lower in concentration than MW-4B
MW-4B	Yes	Keep	Keep	Inside plume well
MW-4C	No, screened below MW-4B and lower in concentration	-	Keep	Monitors the lower zone at MW-4 for possible downward or lower zone contaminant migration
MW-5A	No, screened above and duplicates MW-5B	-	**Eliminate**	Duplicates MW-5B and historical concentrations below DL

Notes: Sampling events from May 1999 to October 2002 were used in the analysis
InsideSF = 0.1, HullSF = 0.01, AR = CR = 0.95
MCL = the maximum contaminant level of PCE (0.005 mg/L)
DL = detection limit

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Table 6
Well Redundancy Analysis Results – Delaunay Method

Long Prairie Site
Long Prairie, Minnesota

Well Name	Well Used in Analysis?	MAROS Well Redundancy Analysis Result	MAROS Interpreted Well Redundancy	Comments
MW-5B	Yes	Keep	Keep	Cross gradient sentry well
MW-6A	No, screened above MW-6B and generally lower in concentration	-	**Eliminate**	Monitors only the upper zone at MW-4 and lower in concentrations than MW-6B
MW-6B	Yes	Keep	Keep	Inside plume well
MW-6C	No, screened below MW-6B and lower in concentration	-	Keep	Monitors the lower zone at MW-6 for possible downward or lower zone contaminant migration
MW-10	Yes	Keep	Keep	Continues to monitor the source for abnormal conditions
MW-11A	No, screened above and duplicates MW-11C	-	**Eliminate**	Monitors only the upper zone at MW-11 and concentrations below DL
MW-11B	No, screened above and duplicates MW-11C	-	Keep	Monitors the middle zone at MW-11
MW-11C	Yes, it has more records than MW-11B	Keep	Keep	Monitors the lower zone at MW-11 for possible downward or lower zone contaminant migration
MW-13C	Yes	Keep	Keep	Inside plume well
MW-14B	Yes	Keep	Keep	On plume edge
MW-14C	No, screened below MW-14B and lower in concentration	-	Keep	Monitors the lower zone at MW-14 for possible downward or lower zone contaminant migration
MW-15A	No, screened above and duplicates MW-5B	-	Keep	Monitors the upper zone at MW-15 since it is just upgradient of the Long Prairie river
MW-15B	Yes	Keep	Keep	Downgradient sentry well just upgradient of the Long Prairie river
MW-16A	No, screened above MW-5B and lower in concentration	-	**Eliminate**	Monitors only the upper zone at MW-16 and concentrations below MCL or DL
MW-16B	Yes	Keep	Keep	Downgradient well on plume edge

Notes: Sampling events from May 1999 to October 2002 were used in the analysis
InsideSF = 0.1, HullSF = 0.01, AR = CR = 0.95
MCL = the maximum contaminant level of PCE (0.005 mg/L)
DL = detection limit

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Table 6
Well Redundancy Analysis Results – Delaunay Method

Long Prairie Site
Long Prairie, Minnesota

Well Name	Well Used in Analysis?	MAROS Well Redundancy Analysis Result	MAROS Interpreted Well Redundancy	Comments
MW-17B	Yes	Keep	Keep	Inside plume well
MW-18A	No, screened above MW-18B and lower in concentration	-	**Eliminate**	Monitors only the upper zone at MW-18 and concentrations below DL
MW-18B	Yes	Keep	Keep	Downgradient well on plume edge
MW-19B	Yes	Keep	Keep	Downgradient well close to plume tail
RW-1A	No, recovery well	-	**Eliminate**	Source has been cleaned up and concentrations below MCL or DL
RW-1B	No, recovery well	-	**Eliminate**	Source has been cleaned up and concentrations below MCL or DL
RW-1C	No, recovery well	-	**Eliminate**	Source has been cleaned up and concentrations below MCL or DL
RW-3	No, recovery well	-	Keep	Recovery well for performance monitoring
RW-4	No, recovery well	-	Keep	Recovery well for performance monitoring
RW-5	No, recovery well	-	Keep	Recovery well for performance monitoring
RW-6	No, recovery well	-	Keep	Recovery well for performance monitoring
RW-7	No, recovery well	-	Keep	Recovery well for performance monitoring
RW-8	No, recovery well	-	Keep	Recovery well for performance monitoring
RW-9	No, recovery well	-	Keep	Recovery well for performance monitoring

Notes: Sampling events from May 1999 to October 2002 were used in the analysis
InsideSF = 0.1, HullSF = 0.01, AR = CR = 0.95
MCL = the maximum contaminant level of PCE (0.005 mg/L)
DL = detection limit

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Table 7
Sampling Frequency Analysis Results – Modified CES

Long Prairie Site
Long Prairie, Minnesota

Well Name	MAROS Frequency Based on Recent Trend(1)	MAROS Frequency Based on Overall Trend(2)	MAROS Recommended Frequency(3)	MAROS Interpreted Sampling Frequency Result	Comments
BAL2B	Annual	Annual	Annual	Biennial	Concentrations below DL (the MAROS result was due to insufficient data)
BAL2C	Annual	Annual	Annual	Biennial	Historical concentrations below DL (the MAROS result was due to insufficient recent data)
CW-3	Annual	Annual	Biennial	Biennial	Historical concentrations below DL
CW-6	Annual	Annual	Biennial	Biennial	Historical concentrations below DL
MW-1A	Annual	Annual	Annual	Biennial	Historical concentrations below DL (the MAROS result was due to insufficient recent data)
MW-1B	Annual	Annual	Annual	Biennial	Historical concentrations below DL (the MAROS result was due to insufficient recent data)
MW-2A	Annual	Annual	Annual	Annual	Recent concentrations above MCL
MW-2B	Annual	Annual	Annual	Annual	Recent concentrations above MCL
MW-2C	Annual	Annual	Annual	Annual	Recent concentrations below MCL but above DL
MW-3A	Annual	Annual	Annual	Biennial	Historical concentrations below MCL or DL (the MAROS result was due to insufficient recent data)
MW-3B	Annual	Annual	Annual	Biennial	Historical concentrations below DL (the MAROS result was due to insufficient recent data)
MW-4A	Quarterly	Quarterly	Quarterly	Annual	Recent concentrations above MCL (the MAROS result was due to insufficient data)
MW-4B	Annual	Annual	Annual	Annual	Recent concentrations above MCL
MW-4C	Annual	Annual	Annual	Annual	Recent concentrations above MCL
MW-5A	Annual	Annual	Annual	Biennial	Historical concentrations below DL (the MAROS result was due to insufficient recent data)

Notes:
1) The frequency determined by MAROS based on the analysis of recent data (May 1999 ~ October 2002)
2) The frequency determined by MAROS based on the analysis of overall data (May 1996 ~ October 2002)
3) The frequency finally recommended by MAROS after considering recent and overall frequency results as well as the rates of change in these trends

Rate parameters used are 0.5MCL/year, 1.0MCL/year, and 2.0MCL/year for Low, Medium, and High rates, respectively; MCL = the maximum contaminant level of PCE (0.005 mg/L); DL = detection limit

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Table 7
Sampling Frequency Analysis Results – Modified CES

Long Prairie Site
Long Prairie, Minnesota

Well Name	MAROS Frequency Based on Recent Trend(1)	MAROS Frequency Based on Overall Trend(2)	MAROS Recommended Frequency(3)	MAROS Interpreted Sampling Frequency Result	Comments
MW-5B	Annual	Annual	Annual	Biennial	Historical concentrations below DL (the MAROS result was due to insufficient recent data)
MW-6A	Annual	Annual	Annual	Annual	Recent concentrations above MCL
MW-6B	Annual	Annual	Annual	Annual	Recent concentrations above MCL
MW-6C	Annual	Annual	Annual	Annual	Recent concentrations above MCL
MW-10	Quarterly	Quarterly	Quarterly	Annual	Historical concentrations have dropped significantly but recent concentrations still above MCL (the MAROS result was due to insufficient recent data)
MW-11A	Annual	Annual	Annual	Biennial	Historical concentrations below DL (the MAROS result was due to insufficient data)
MW-11B	Annual	Annual	Biennial	Biennial	Historical concentrations below DL
MW-11C	Annual	Annual	Biennial	Biennial	Historical concentrations below MCL or DL
MW-13C	Annual	Annual	Biennial	Biennial	Historical concentrations below MCL or DL
MW-14B	Annual	Annual	Annual	Annual	Recent concentrations above MCL
MW-14C	Annual	Annual	Biennial	Biennial	Historical concentrations below MCL or DL
MW-15A	Annual	Annual	Biennial	Biennial	Historical concentrations below DL
MW-15B	Annual	Annual	Biennial	Biennial	Historical concentrations below DL
MW-16A	Annual	Annual	Biennial	Biennial	Historical concentrations below MCL or DL
MW-16B	Annual	Annual	Annual	Annual	Recent concentrations above MCL

Notes:
1) The frequency determined by MAROS based on the analysis of recent data (May 1999 ~ October 2002)
2) The frequency determined by MAROS based on the analysis of overall data (May 1996 ~ October 2002)
3) The frequency finally recommended by MAROS after considering recent and overall frequency results as well as the rates of change in these trends

Rate parameters used are 0.5MCL/year, 1.0MCL/year, and 2.0MCL/year for Low, Medium, and High rates, respectively; MCL = the maximum contaminant level of PCE (0.005 mg/L); DL = detection limit

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Table 7
Sampling Frequency Analysis Results – Modified CES

Long Prairie Site
Long Prairie, Minnesota

Well Name	MAROS Frequency Based on Recent Trend(1)	MAROS Frequency Based on Overall Trend(2)	MAROS Recommended Frequency(3)	MAROS Interpreted Sampling Frequency Result	Comments
MW-17B	Annual	Annual	Annual	Annual	Recent concentrations above MCL
MW-18A	Annual	Annual	Annual	Biennial	Historical concentrations below DL (the MAROS result was due to insufficient data)
MW-18B	Annual	Annual	Annual	Biennial	Historical concentrations below MCL (the MAROS result was due to insufficient data)
MW-19B	Annual	Annual	Biennial	Biennial	Historical concentrations below DL
RW-1A	Annual	Annual	Annual	Biennial	Historical concentrations below MCL or DL (the MAROS result was due to insufficient recent data)
RW-1B	Annual	Annual	Annual	Biennial	Historical concentrations below DL (the MAROS result was due to insufficient recent data)
RW-1C	Annual	Annual	Annual	Biennial	Recent concentrations below DL (the MAROS result was due to insufficient data)
RW-3	Annual	Annual	Annual	Annual	Recent concentrations above MCL
RW-4	Annual	Annual	Biennial	Biennial	Recent concentrations below DL
RW-5	Annual	Annual	Annual	Annual	Recent concentrations above MCL
RW-6	Annual	Annual	Annual	Annual	Recent concentrations above MCL
RW-7	Annual	Annual	Annual	Annual	Recent concentrations above MCL
RW-8	Annual	Annual	Annual	Annual	Recent concentrations above MCL
RW-9	Annual	Annual	Annual	Annual	Recent concentrations above MCL

Notes: 1) The frequency determined by MAROS based on the analysis of recent data (May 1999 ~ October 2002)
2) The frequency determined by MAROS based on the analysis of overall data (May 1996 ~ October 2002)
3) The frequency finally recommended by MAROS after considering recent and overall frequency results as well as the rates of change in these trends
Rate parameters used are 0.5MCL/year, 1.0MCL/year, and 2.0MCL/year for Low, Medium, and High rates, respectively; MCL = the maximum contaminant level of PCE (0.005 mg/L); DL = detection limit

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Table 8
Selected Plume Centerline Wells
Risk-Based Site Cleanup Evaluation – Power Analysis

Long Prairie Site
Long Prairie, Minnesota

Well Name	Distance from Well to Receptor (ft)	
	HSCB = 10 ft	HSCB = -100 ft
MW-15B	10.0	-100
MW-16B	520.6	410.6
MW-17B	1063.2	953.2
MW-4B	1998.1	1888.1
MW-2B	2897.1	2787.1

Notes: Groundwater flow angle is to the north/northwest (assumed 90 degrees counterclockwise from East in this analysis); Distance from Well to Receptor refers to the most downgradient well's Distance to the Hypothetical Statistical Compliance Boundary (HSCB).

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Table 9
Plume Centerline Concentration
Regression Results – Power Analysis

Long Prairie Site
Long Prairie, Minnesota

Sampling Event	Number of Centerline Wells	Regression Coefficient (1/ft)	Confidence in Coefficient
May 1999	5	-2.31E-03	97.9%
July 1999	0	-	-
September 1999	2	-	-
October 1999	3	-5.38E-03	91.5%
March 2000	0	-	-
June 2000	0	-	-
September 2000	5	-1.50E-03	92.7%
October 2000	0	-	-
December 2000	0	-	-
March 2001	0	-	-
May 2001	0	-	-
September 2001	5	-1.51E-03	92.1%
November 2001	0	-	-
January 2002	0	-	-
April 2002	0	-	-
July 2002	0	-	-
October 2002	5	-1.24E-03	91.3%

Notes: Regression is on natural log concentration of PCE versus distance from source centerline wells shown in Table M4; no regression was performed for sampling event with less than 3 centerline wells.

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Table 10
Risk-Based Site Cleanup Evaluation Results – Power Analysis

Long Prairie Site
Long Prairie, Minnesota

Sampling Event	Sample Size	Distance to HSCB = 10 ft			Distance to HSCB = -100 ft		
		Cleanup Status	Power	Expected Sample Size	Cleanup Status	Power	Expected Sample Size
May 1999	30	Attained	1.000	7	Attained	0.992	12
October 1999	25	Attained	1.000	<=3	Attained	1.000	<=3
September 2000	18	Not Attained	0.414	54	Not Attained	0.211	>100
September 2001	18	Attained	0.685	25	Not Attained	0.432	50
October 2002	34	Attained	1.000	8	Attained	0.998	11

Notes: The power analysis used for this application assumes normality of data. Distance to the Hypothetical Statistical Compliance Boundary (HSCB) is the distance from the most downgradient well to the HSCB; S/E = extrapolated result significantly exceeds the target level (0.005 mg/L).

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Table 11
Summary of MAROS Sampling Optimization Results

Long Prairie Site
Long Prairie, Minnesota

Well Name	MAROS Well Category(1)	Current Sampling Frequency(2)	MAROS Trend Result(3)	MAROS Interpreted Well Redundancy and Well Sufficiency Results	MAROS Interpreted Sampling Frequency Results	Comments
BAL2B	T	Biennial*	NA	***Keep***	***Biennial***	Concentration below DL & city well monitoring
BAL2C	T	Annual	S	***Keep***	***Biennial***	Historical concentrations below DL & downgradient sentry well
CW-3	T	Quarterly	S	***Keep***	***Biennial***	Historical concentrations below DL & city well monitoring
CW-6	T	Quarterly	PI	***Keep***	***Biennial***	Historical concentrations below DL & city well monitoring
MW-1A	T	Biennial*	S	***Eliminate***	**-**	Duplicates MW-1B & historical concentrations below DL
MW-1B	T	Biennial*	S	***Keep***	***Biennial***	Historical concentrations below DL & cross gradient sentry well
MW-2A	S	Annual	NT	***Eliminate***	**-**	Monitors only the upper zone at MW-4 and concentrations dropped to below MCL
MW-2B	S	Annual	NT	***Keep***	***Annual***	Recent concentrations above MCL & inside plume well
MW-2C	S	Annual	S	***Keep***	***Annual***	Recent concentrations below MCL but above DL & monitors the lower zone at MW-2
MW-3A	T	Biennial*	NT	***Eliminate***	**-**	Duplicates MW-3B & historical concentrations below MCL or DL
MW-3B	T	Biennial*	S	***Keep***	***Biennial***	Historical concentrations below DL & downgradient of the source
MW-4A	T	Biennial*	NA	***Eliminate***	**-**	Monitors only the upper zone at MW-4 and lower in concentration than MW-4B
MW-4B	T	Annual	D	***Keep***	***Annual***	Recent concentrations above MCL & inside plume well
MW-4C	T	Annual	S	***Keep***	***Annual***	Recent concentrations above MCL & monitors the lower zone at MW-4
MW-5A	T	Biennial*	S	***Eliminate***	**-**	Duplicates MW-5B & historical concentrations below DL

Notes: (1) S = Source well, T = Tail well
(2) Sampling frequency based on recent sampling results, *assumed biennial due to lack of data in 2000 and 2001
(3) D = Decreasing, PD = Probably Decreasing, S = Stable, NT = No Trend, PI = Probably Increasing, I = Increasing
MCL = the maximum contaminant level of PCE (0.005 mg/L), DL = detection limit, "-" = Not Applicable

GROUNDWATER SERVICES, INC.

Table 11
Summary of MAROS Sampling Optimization Results

Long Prairie Site
Long Prairie, Minnesota

Well Name	MAROS Well Category(1)	Current Sampling Frequency(2)	MAROS Trend Result(3)	MAROS Interpreted Well Redundancy and Well Sufficiency Results	MAROS Interpreted Sampling Frequency Results	Comments
MW-5B	T	Biennial*	S	***Keep***	***Biennial***	Historical concentrations below DL & cross gradient sentry well
MW-6A	T	Annual	NT	***Eliminate***	-	Monitors only the upper zone at MW-4 and lower in concentrations than MW-6B
MW-6B	T	Annual	D	***Keep***	***Annual***	Recent concentrations above MCL & inside plume well
MW-6C	T	Annual	D	***Keep***	***Annual***	Recent concentrations above MCL & monitors the lower zone at MW-6
MW-10	S	Annual	D	***Keep***	***Annual***	Recent concentrations above MCL & monitors the source
MW-11A	T	Biennial*	NA	***Eliminate***	-	Monitors only the upper zone at MW-11 and concentrations below DL
MW-11B	T	Annual	S	***Keep***	***Biennial***	Historical concentrations below DL & monitors the middle zone at MW-11
MW-11C	T	Annual	PD	***Keep***	***Biennial***	Historical concentrations below MCL or DL & Monitors the lower zone at MW-11
MW-13C	T	Biennial*	NT	***Keep***	***Biennial***	Historical concentrations below MCL or DL & Inside plume well
MW-14B	T	Annual	D	***Keep***	***Annual***	Recent concentrations above MCL & on plume edge
MW-14C	T	Annual	S	***Keep***	***Biennial***	Historical concentrations below MCL or DL & monitors the lower zone at MW-14
MW-15A	T	Annual	PD	***Keep***	***Biennial***	Historical concentrations below DL & monitors the upper zone at MW-15
MW-15B	T	Annual	PD	***Keep***	***Biennial***	Historical concentrations below DL & downgradient sentry well just upgradient of the Long Prairie river
MW-16A	T	Biennial*	S	***Eliminate***	-	Monitors only the upper zone at MW-16 & concentrations below MCL or DL
MW-16B	T	Annual	S	***Keep***	***Annual***	Recent concentrations above MCL & downgradient well on plume edge

Notes: (1) S = Source well, T = Tail well
(2) Sampling frequency based on recent sampling results, *assumed biennial due to lack of data in 2000 and 2001
(3) D = Decreasing, PD = Probably Decreasing, S = Stable, NT = No Trend, PI = Probably Increasing, I = Increasing
MCL = the maximum contaminant level of PCE (0.005 mg/L), DL = detection limit

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Table 11
Summary of MAROS Sampling Optimization Results

Long Prairie Site
Long Prairie, Minnesota

Well Name	MAROS Well Category(1)	Current Sampling Frequency(2)	MAROS Trend Result(3)	MAROS Interpreted Well Redundancy and Well Sufficiency Results	MAROS Interpreted Sampling Frequency Results	Comments
MW-17B	T	Annual	D	***Keep***	***Annual***	Recent concentrations above MCL & inside plume well
MW-18A	T	Biennial*	S	***Eliminate***	-	Monitors only the upper zone at MW-18 & concentrations below DL
MW-18B	T	Biennial*	PI	***Keep***	***Biennial***	Historical concentrations below MCL & downgradient well on plume edge
MW-19B	T	Annual	PI	***Keep***	***Biennial***	Historical concentrations below DL & downgradient well close to plume tail
RW-1A	T	Biennial*	S	***Eliminate***	-	Source has been cleaned up and concentrations below MCL or DL
RW-1B	T	Biennial*	NT	***Eliminate***	-	Source has been cleaned up and concentrations below MCL or DL
RW-1C	T	Biennial*	NA	***Eliminate***	-	Source has been cleaned up and concentrations below MCL or DL
RW-3	S	Quarterly	D	***Keep***	***Annual***	Recent concentrations above MCL & recovery well for performance monitoring
RW-4	T	Annual	D	***Keep***	***Biennial***	Recent concentrations below DL & recovery well for performance monitoring
RW-5	T	Quarterly	D	***Keep***	***Annual***	Recent concentrations above MCL & recovery well for performance monitoring
RW-6	T	Quarterly	D	***Keep***	***Annual***	Recent concentrations above MCL & recovery well for performance monitoring
RW-7	T	Quarterly	D	***Keep***	***Annual***	Recent concentrations above MCL & recovery well for performance monitoring
RW-8	T	Quarterly	D	***Keep***	***Annual***	Recent concentrations above MCL & recovery well for performance monitoring
RW-9	T	Quarterly	NT	***Keep***	***Annual***	Recent concentrations above MCL & recovery well for performance monitoring

Notes: (1) S = Source well, T = Tail well
(2) Sampling frequency based on recent sampling results, *assumed biennial due to lack of data in 2000 and 2001
(3) D = Decreasing, PD = Probably Decreasing, S = Stable, NT = No Trend, PI = Probably Increasing, I = Increasing
MCL = the maximum contaminant level of PCE (0.005 mg/L), DL = detection limit

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MAROS 2.0 APPLICATION
MONITORING NETWORK OPTIMIZATION

Long Prairie Site
Long Prairie, Minnesota

FIGURES

GSI Job No. G-2236
Date Issued: 2/19/03

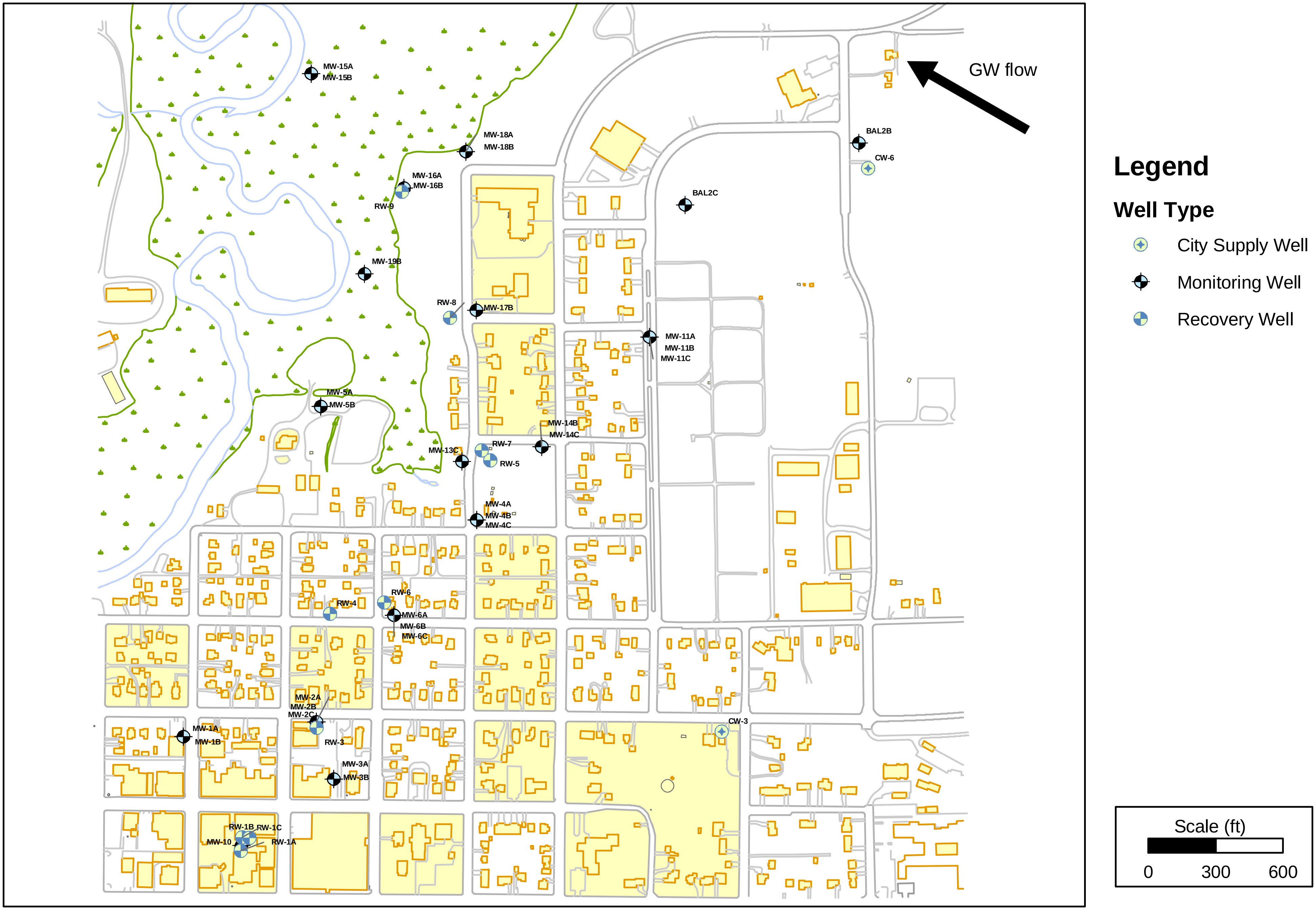

Figure 1 Groundwater Monitoring Well Network
Long Prairie Site, Long Prairie, Minnesota

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MAROS: Decision Support Tool

MAROS is a collection of tools in one software package that is used in an explanatory, non-linear fashion. The tool includes models, geostatistics, heuristic rules, and empirical relationships to assist the user in optimizing a groundwater monitoring network system while maintaining adequate delineation of the plume as well as knowledge of the plume state over time. Different users utilize the tool in different ways and interpret the results from a different viewpoint.

↓

Overview Statistics

What it is: Simple, qualitative and quantitative plume information can be gained through evaluation of monitoring network historical data trends both spatially and temporally. The MAROS Overview Statistics are the foundation the user needs to make informed optimization decisions at the site.

What it does: The Overview Statistics are designed to allow site personnel to develop a better understanding of the plume behavior over time and understand how the individual well concentration trends are spatially distributed within the plume. This step allows the user to gain information that will support a more informed decision to be made in the next level of optimization analysis.

What are the tools: Overview Statistics includes two analytical tools:

1) **Trend Analysis:** includes Mann-Kendall and Linear Regression statistics for individual wells and results in general heuristically-derived monitoring categories with a suggested sampling density and monitoring frequency.

2) **Moment Analysis:** includes dissolved mass estimation (0^{th} Moment), center of mass (1^{st} Moment), and plume spread (2^{nd} Moment) over time. Trends of these moments show the user another piece of information about the plume stability over time.

What is the product: A first-cut blueprint for a future long-term monitoring program that is intended to be a foundation for more detailed statistical analysis.

↓

Detailed Statistics

What it is: The MAROS Detailed Statistics allows for a quantitative analysis for spatial and temporal optimization of the well network on a well-by-well basis.

What it does: The results from the Overview Statistics should be considered along side the MAROS optimization recommendations gained from the Detailed Statistical Analysis. The MAROS Detailed Statistics results should be reassessed in view of site knowledge and regulatory requirements as well as the Overview Statistics.

What are the tools: Detailed Statistics includes four analytical tools:

1) **Sampling Frequency Optimization:** uses the Modified CES method to establish a recommended future sampling frequency.

2) **Well Redundancy Analysis:** uses the Delaunay Method to evaluate if any wells within the monitoring network are redundant and can be eliminated without any significant loss of plume information.

3) **Well Sufficiency Analysis:** uses the Delaunay Method to evaluate areas where new wells are recommended within the monitoring network due to high levels of concentration uncertainty.

4) **Data Sufficiency Analysis:** uses Power Analysis to assess if the historical monitoring data record has sufficient power to accurately reflect the location of the plume relative to the nearest receptor or compliance point.

What is the product: List of wells to remove from the monitoring program, locations where monitoring wells may need to be added, recommended frequency of sampling for each well, analysis if the overall system is statistically powerful to monitor the plume.

Figure 2. MAROS Decision Support Tool Flow Chart

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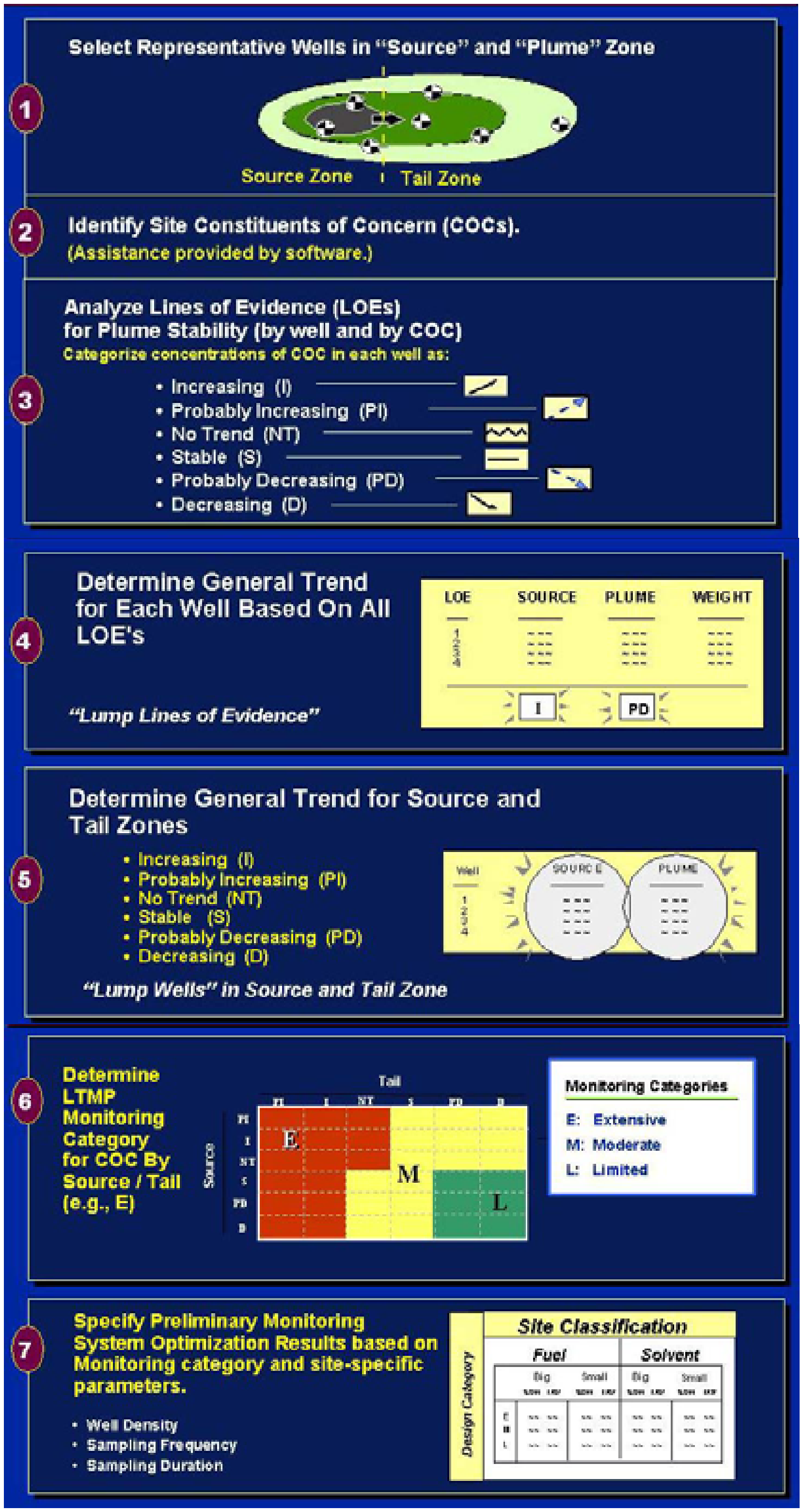

Figure 3:
MAROS Overview Statistics Trend Analysis Methodology

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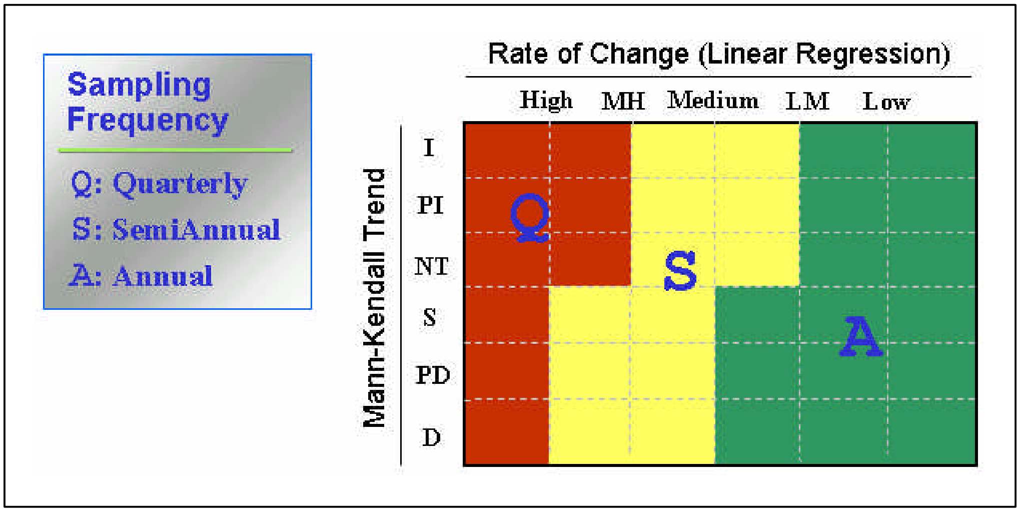

Figure 4. Decision Matrix for Determining Provisional Frequency (*Figure A.3.1 of the MAROS Manual (AFCEE 2001)*)

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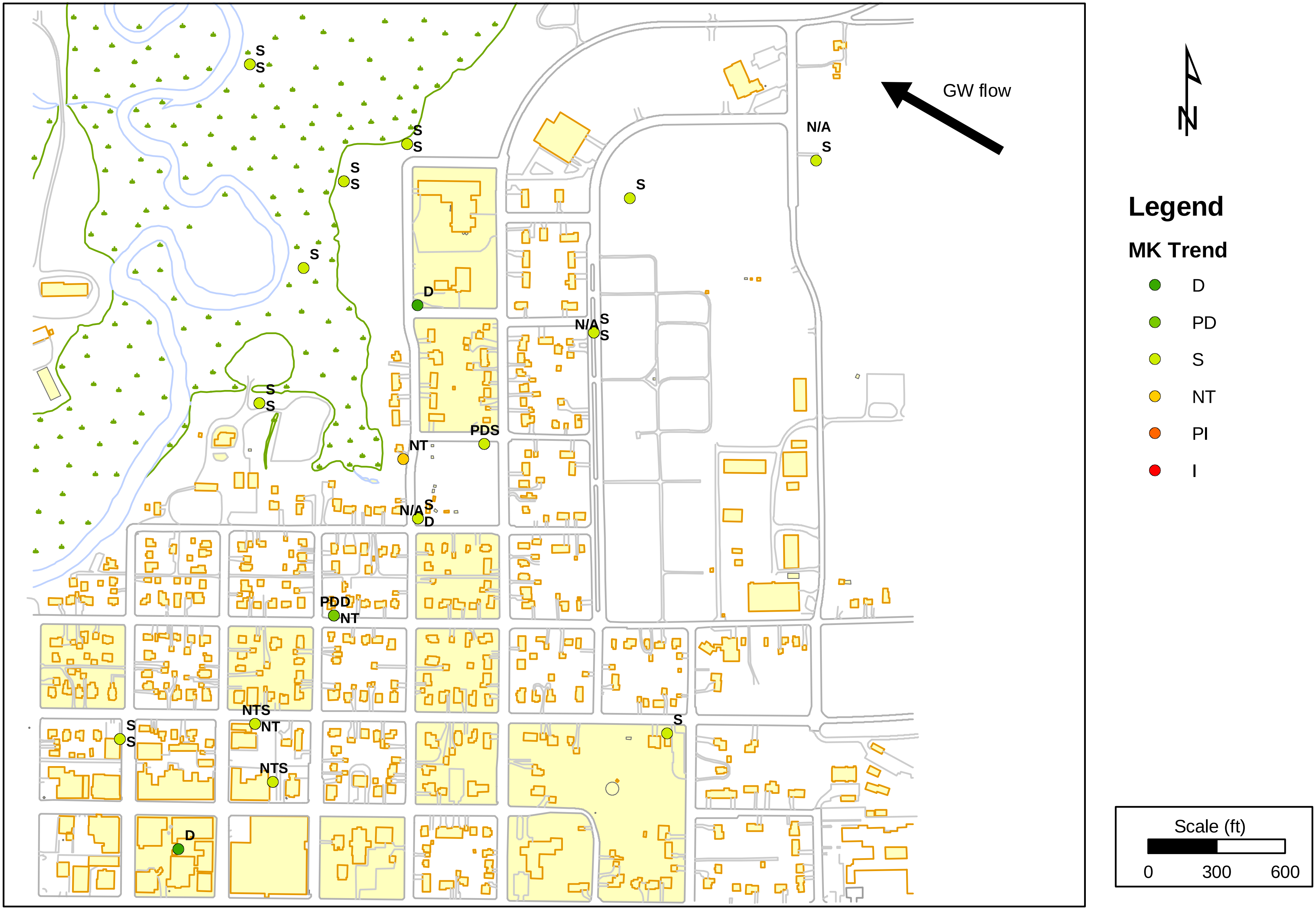

Note: Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)

Figure 5 PCE Mann-Kendall Trend Results
Long Prairie Site, Long Prairie, Minnesota

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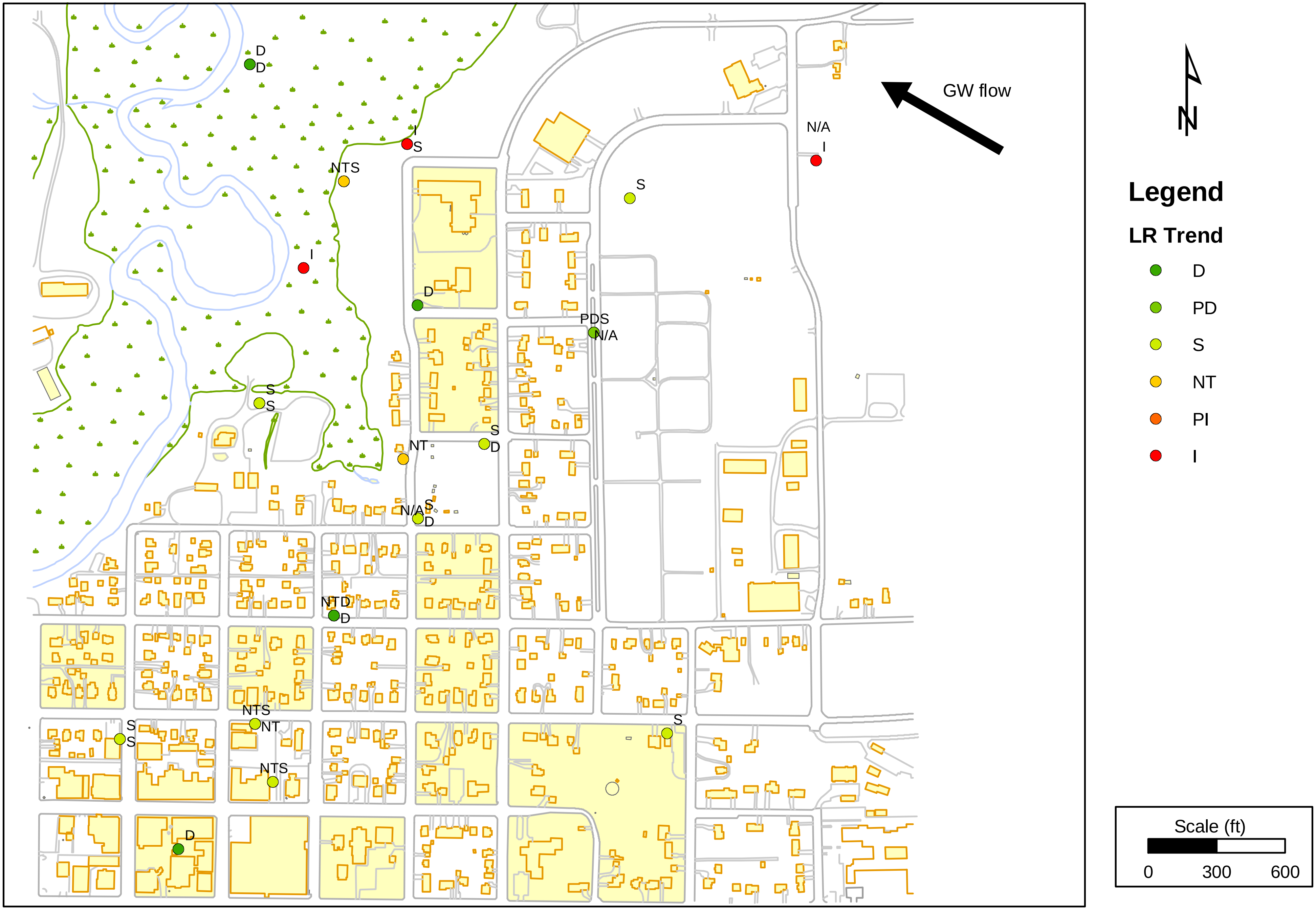

Note: Decreasing (D), Probably Decreasing (PD), Stable (S),
No Trend (NT), Probably Increasing (PI), and Increasing (I)

Figure 6 PCE Linear Regression Trend Results
Long Prairie Site, Long Prairie, Minnesota

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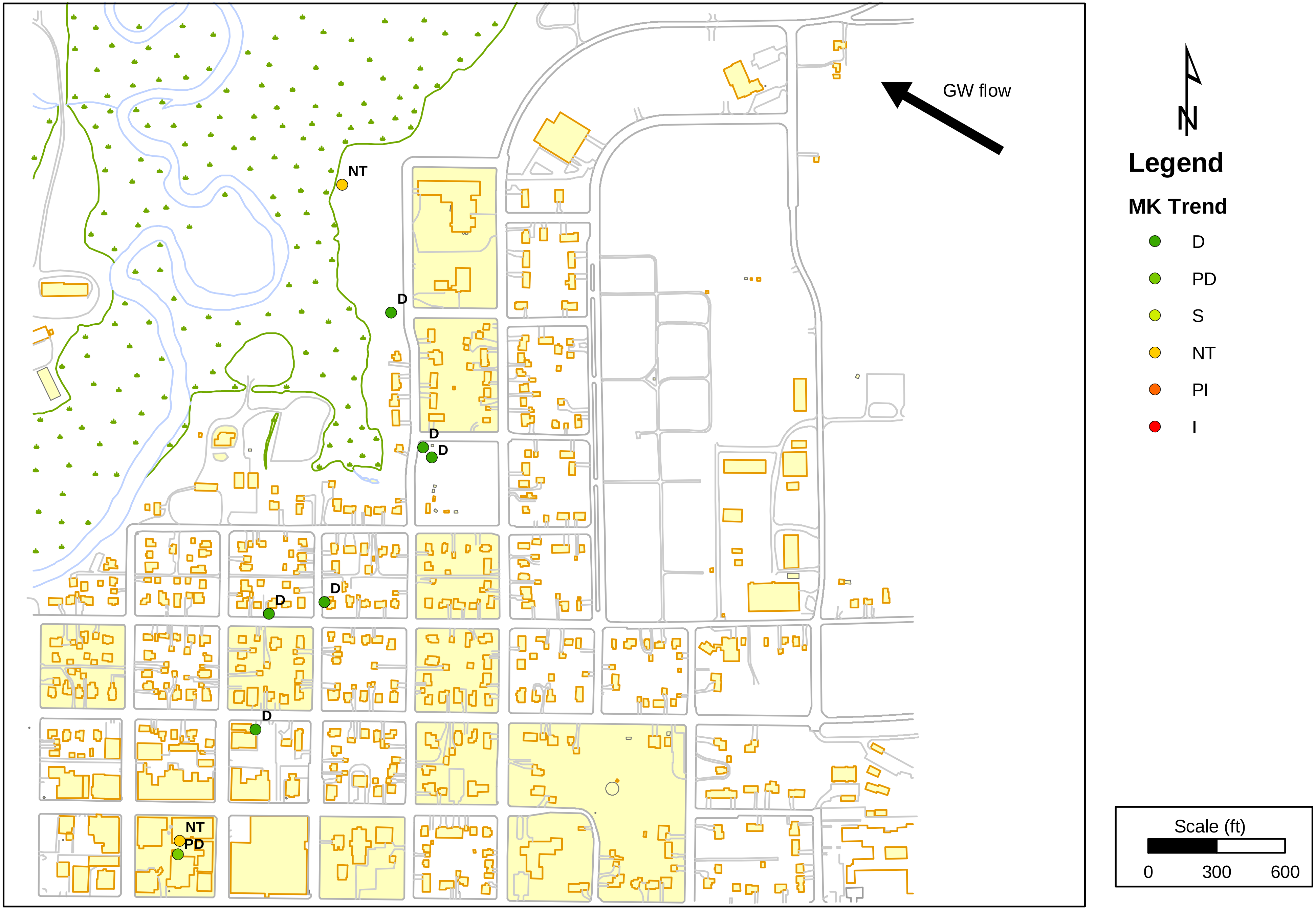
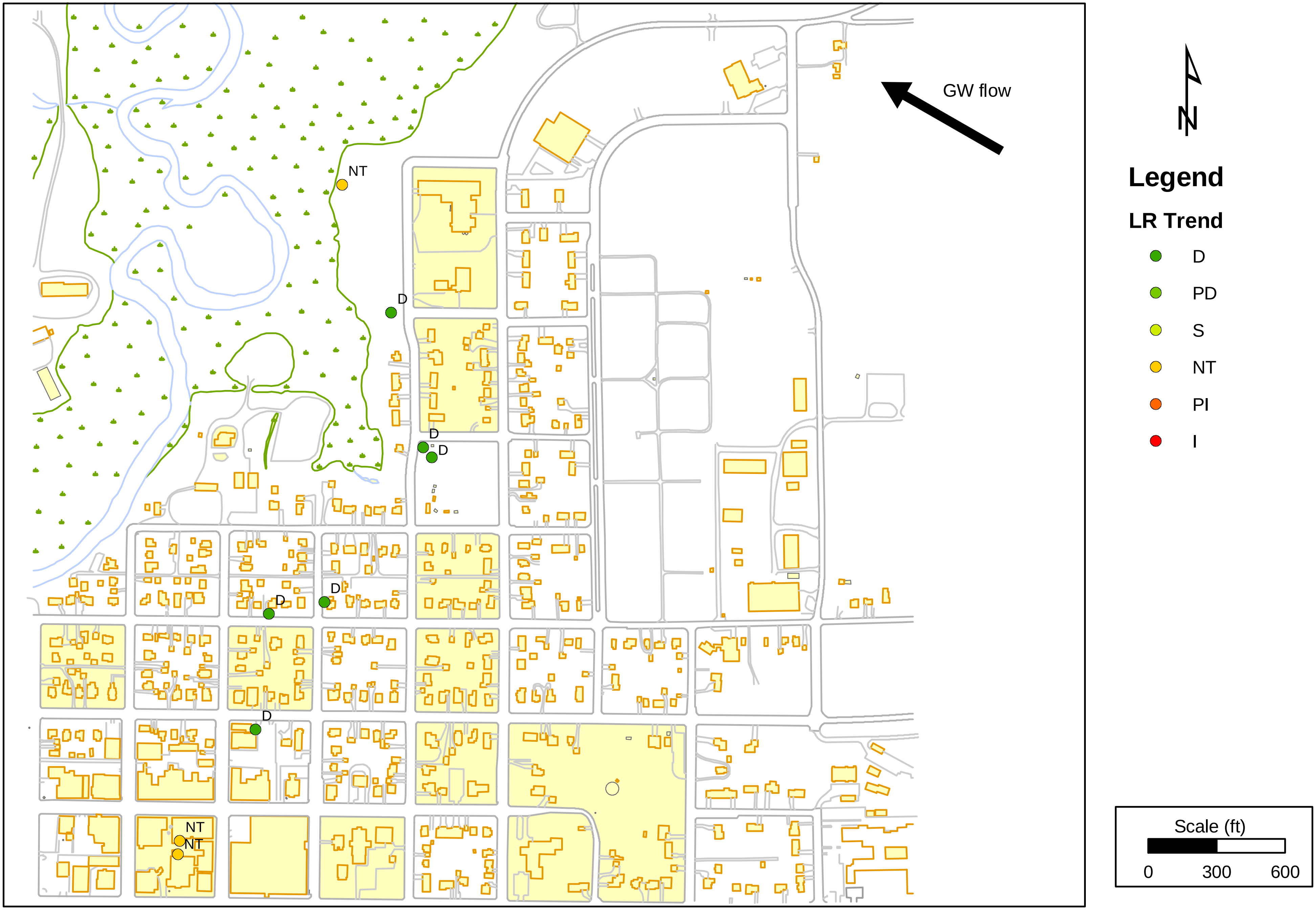


Note: Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)

Figure 7 PCE Mann-Kendall Recovery Well Trend Results
Long Prairie Site, Long Prairie, Minnesota

GSI Job No. G-2236
Date Issued: 2/19/03



Note: Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)

Figure 8 PCE Linear Regression Recovery Well Trend Results
Long Prairie Site, Long Prairie, Minnesota

GSI Job No. G-2236
Date Issued: 2/19/03

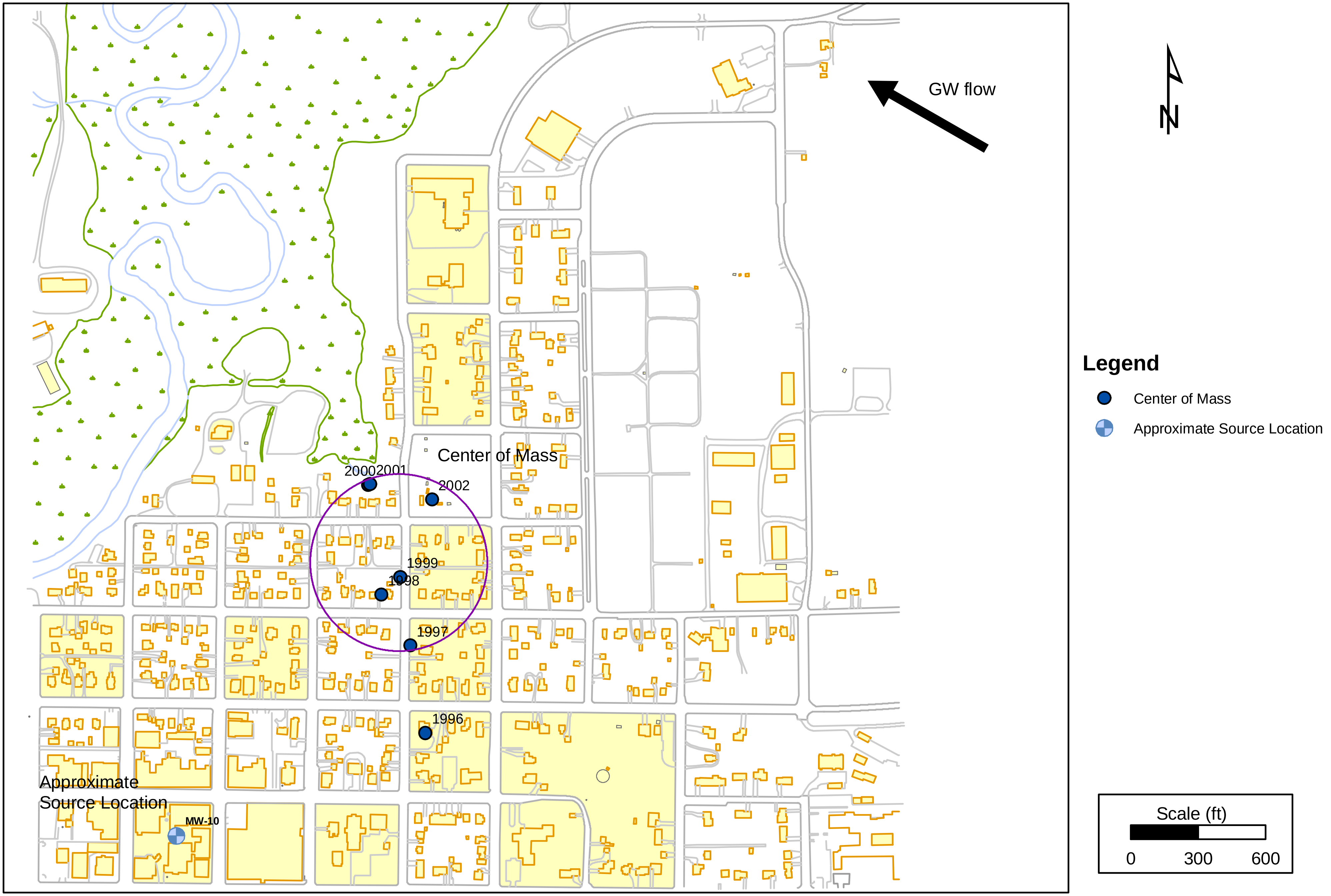


Figure 9 Upper Outwash Aquifer: PCE First Moment (Center of Mass) Over Time
Long Prairie Site, Long Prairie, Minnesota

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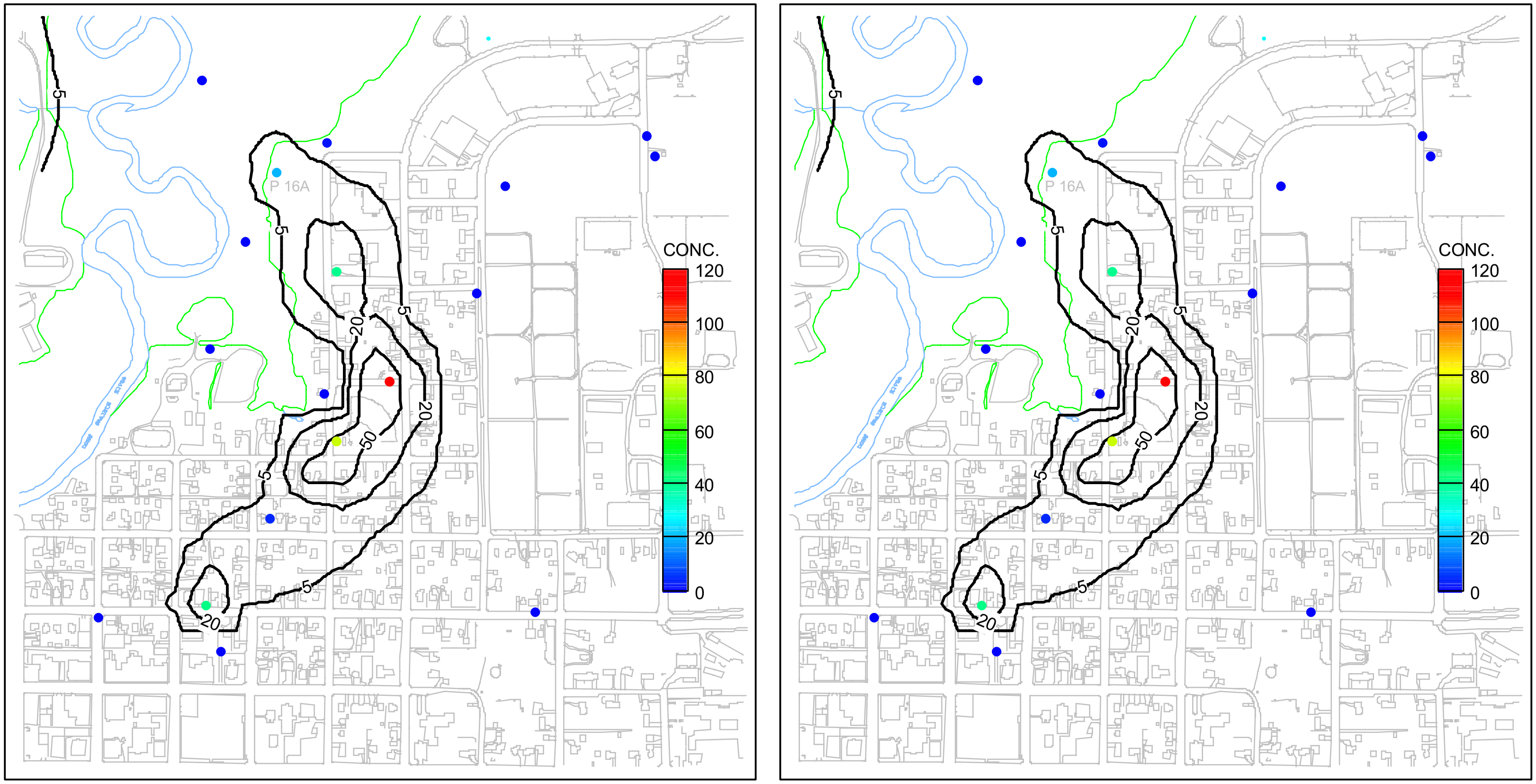

Figure 10. Groundwater PCE plumes contoured with October 2002 data before (left) and after (right) well redundancy analysis. Wells used in contouring are mostly “B” zone wells. Monitoring wells are depicted by colored dots with different colors representing different concentration levels (ug/L).

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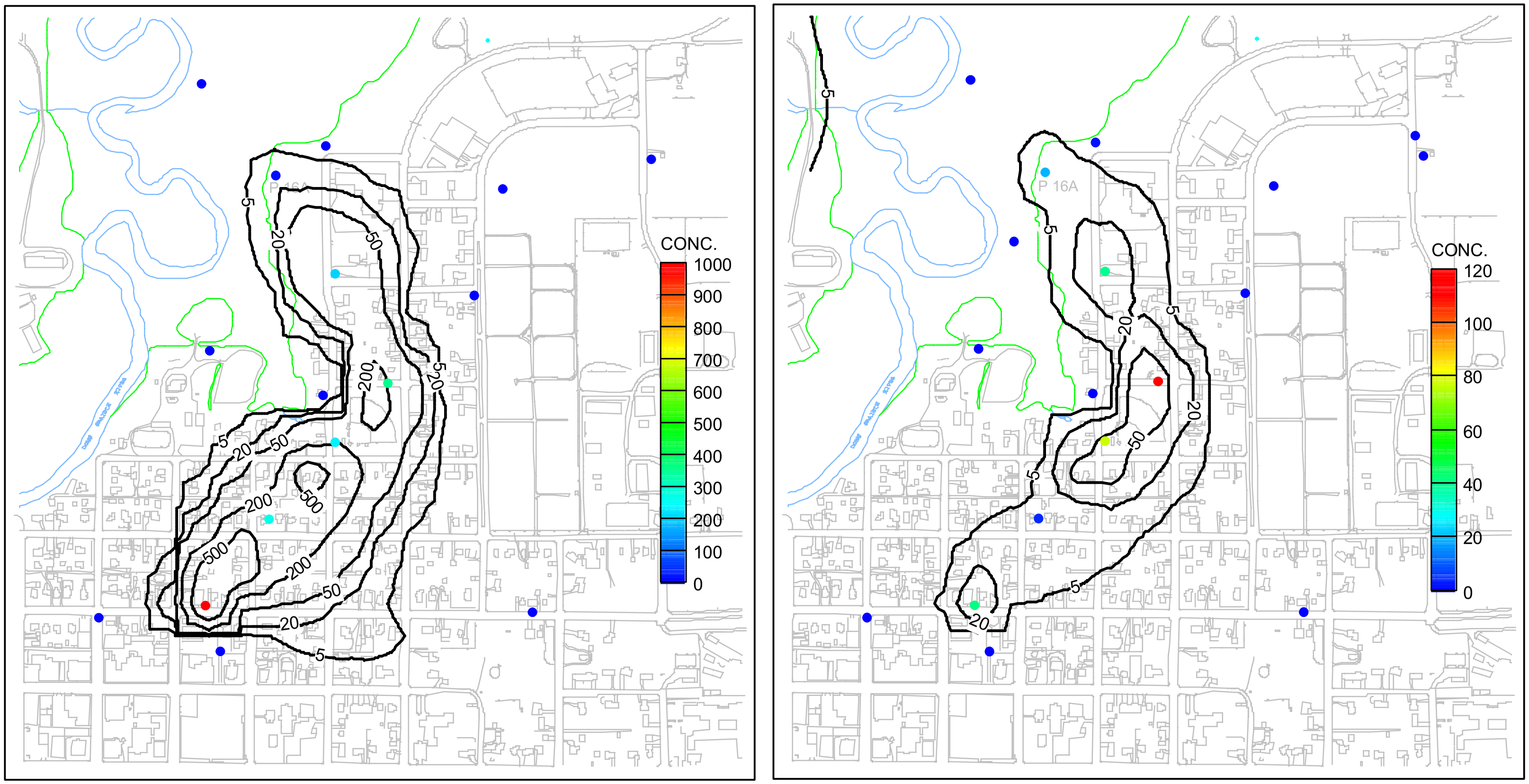

Figure 11. Approximate groundwater PCE plumes in May 1999 (left) and October 2002 (right). Monitoring wells are depicted by colored dots with different colors representing different concentration levels (units µg/L) for both the plume contours and the wells.

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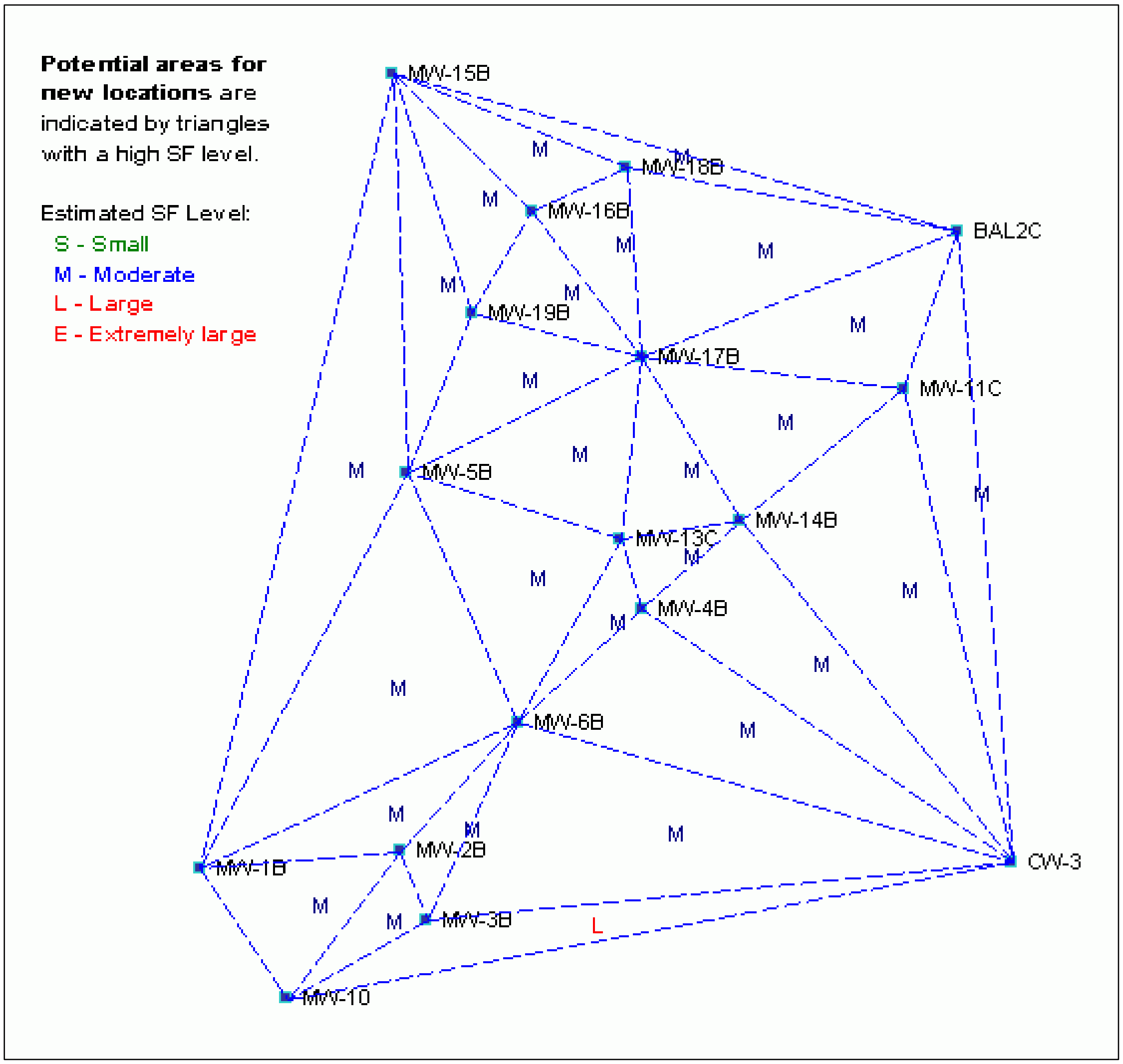

Figure 12. Well Sufficiency Analysis for possible new sampling locations. Areas with **L** or **E** symbols are candidate regions for placing new wells.

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APPENDICES

Appendix A: Upper Outwash Aquifer Long Prairie site Historical PCE Maps

Appendix B: Upper Outwash Aquifer Long Prairie site MAROS 2.0 Reports

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MAROS 2.0 APPLICATION
MONITORING NETWORK OPTIMIZATION

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APPENDIX A: Upper Outwash Aquifer Long Prairie Historical PCE Maps

Appendix A: Upper Outwash Aquifer Long Prairie site Historical PCE Maps

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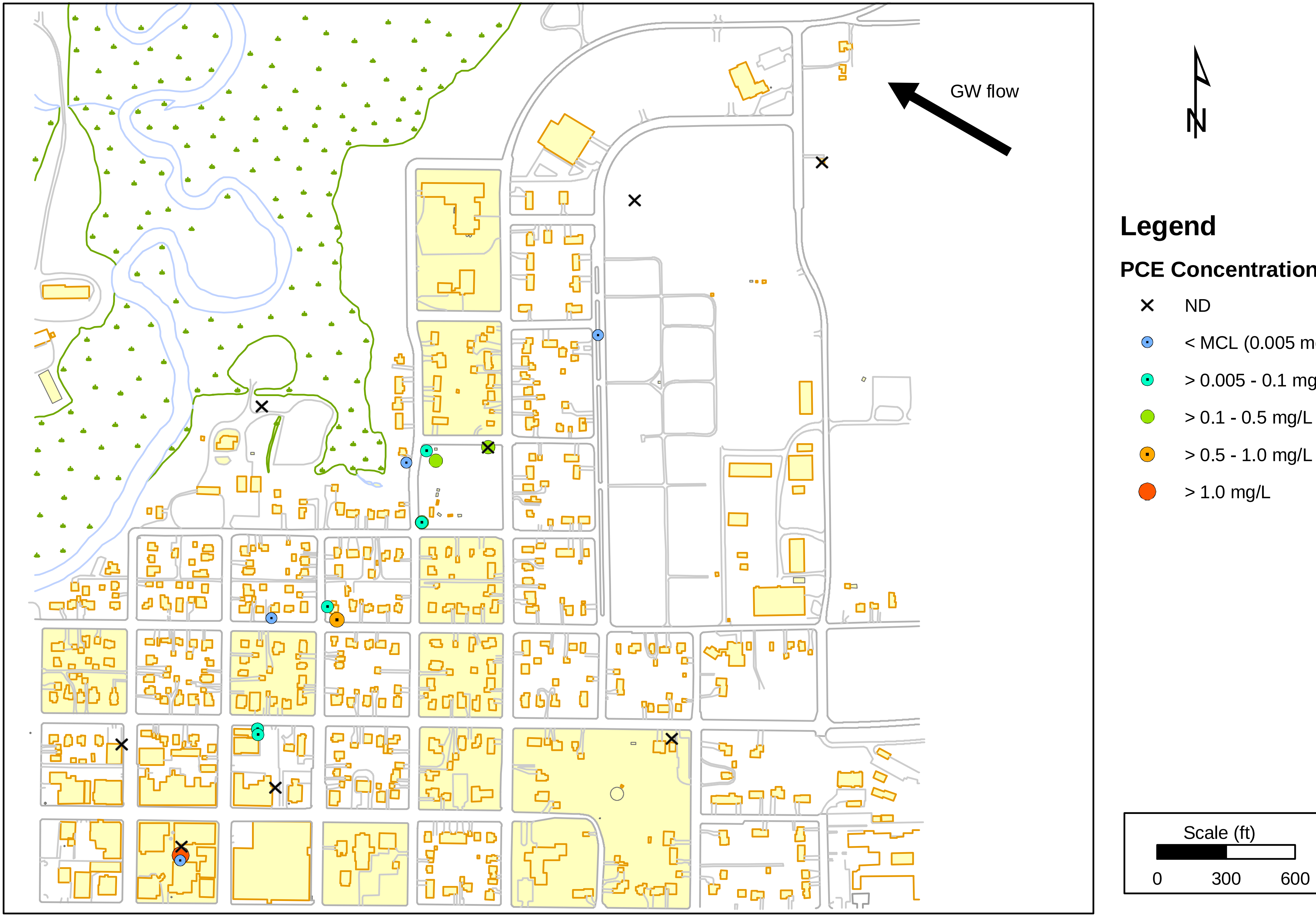
Note: Representative PCE Concentrations shown are the Geometric Mean concentration for the year.

1996 Groundwater Monitoring: PCE
Long Prairie Site, Long Prairie, Minnesota

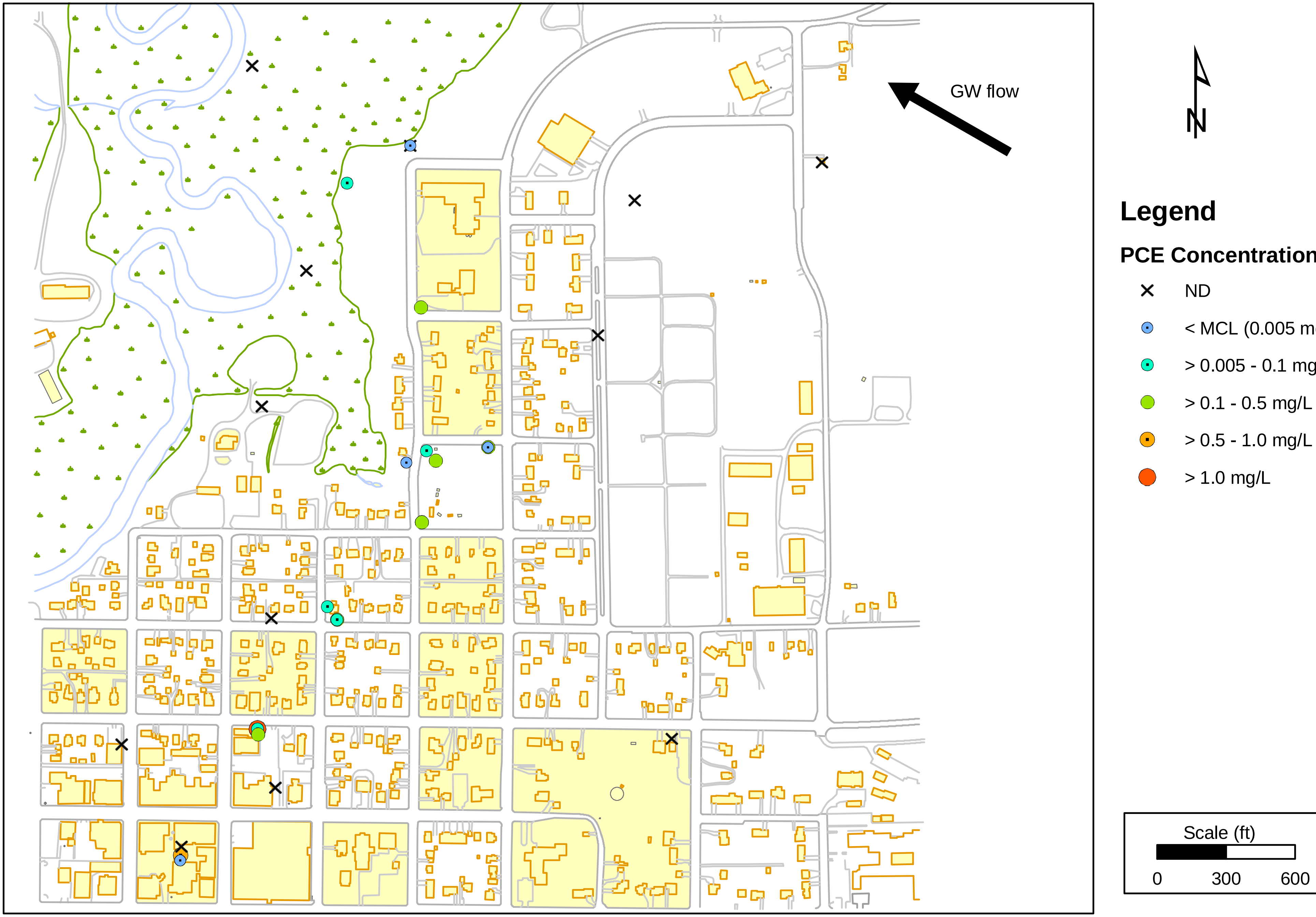
GSI Job No. G-2236
Date Issued: 2/19/03



Note: Representative PCE Concentrations shown are the Geometric Mean concentration for the year.

1997 Groundwater Monitoring: PCE
Long Prairie Site, Long Prairie, Minnesota

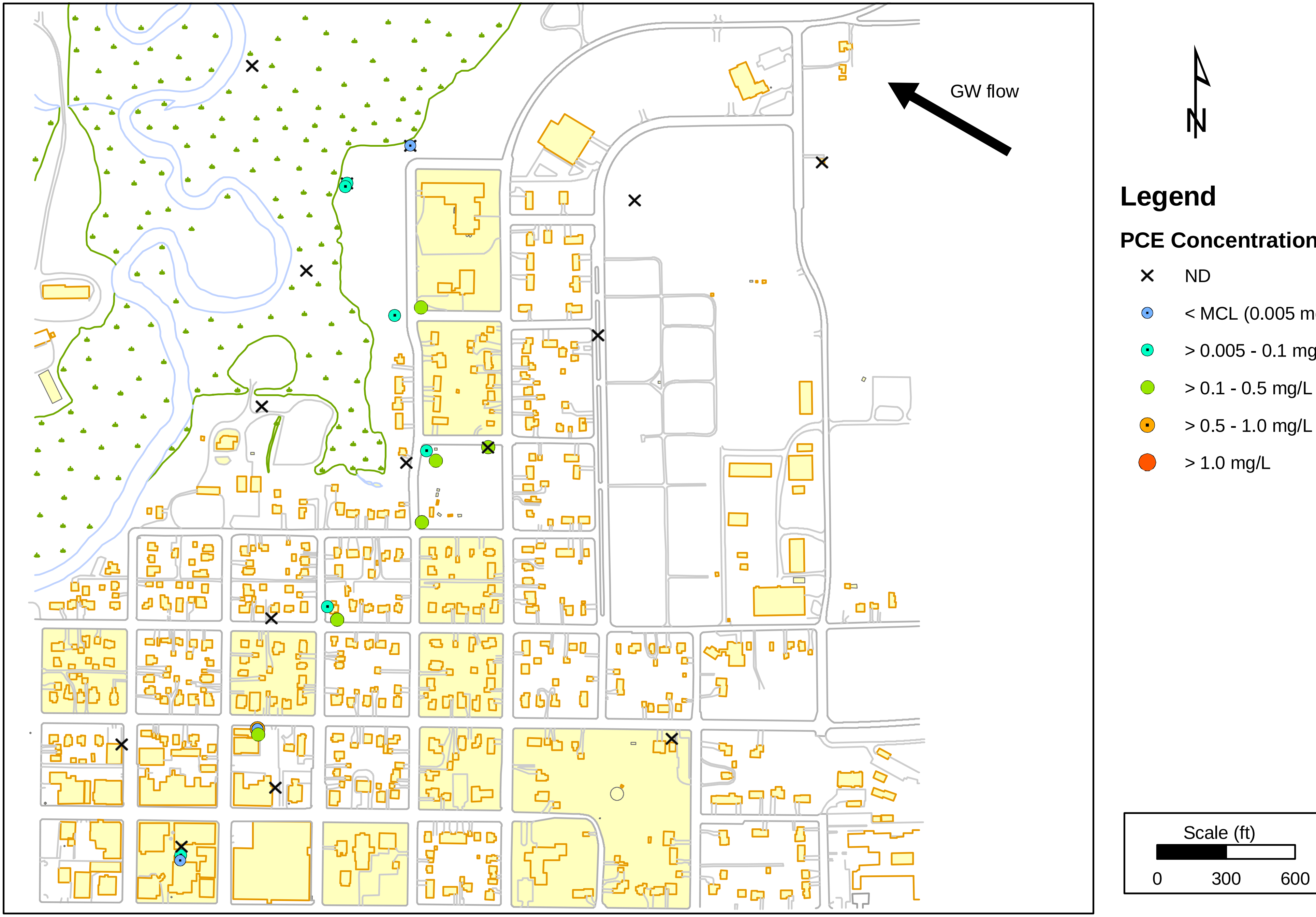
GSI Job No. G-2236
Date Issued: 2/19/03



Note: Representative PCE Concentrations shown are the Geometric Mean concentration for the year.

1998 Groundwater Monitoring: PCE
Long Prairie Site, Long Prairie, Minnesota

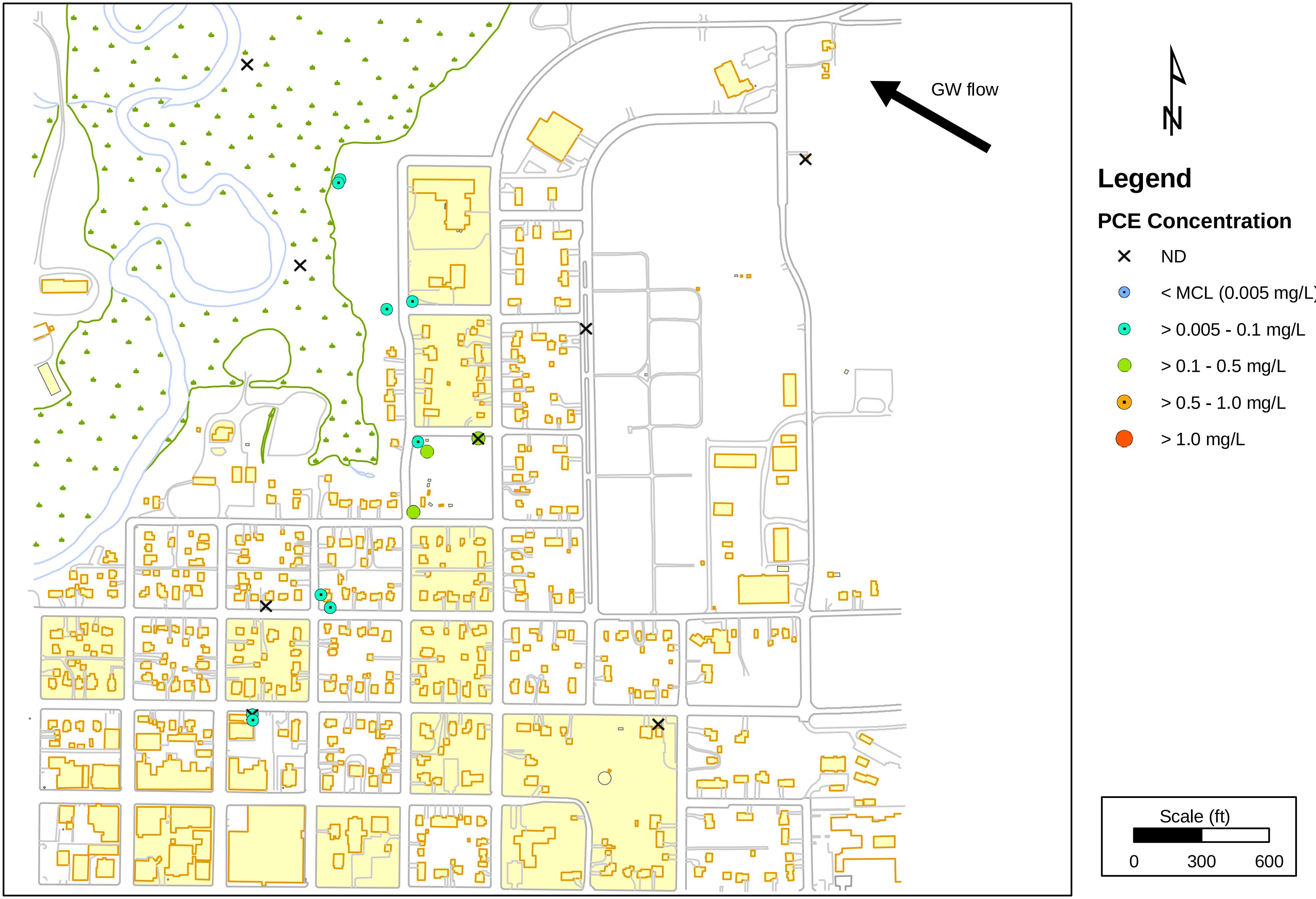
GSI Job No. G-2236
Date Issued: 2/19/03



Note: Representative PCE Concentrations shown are the Geometric Mean concentration for the year.

1999 Groundwater Monitoring: PCE
Long Prairie Site, Long Prairie, Minnesota

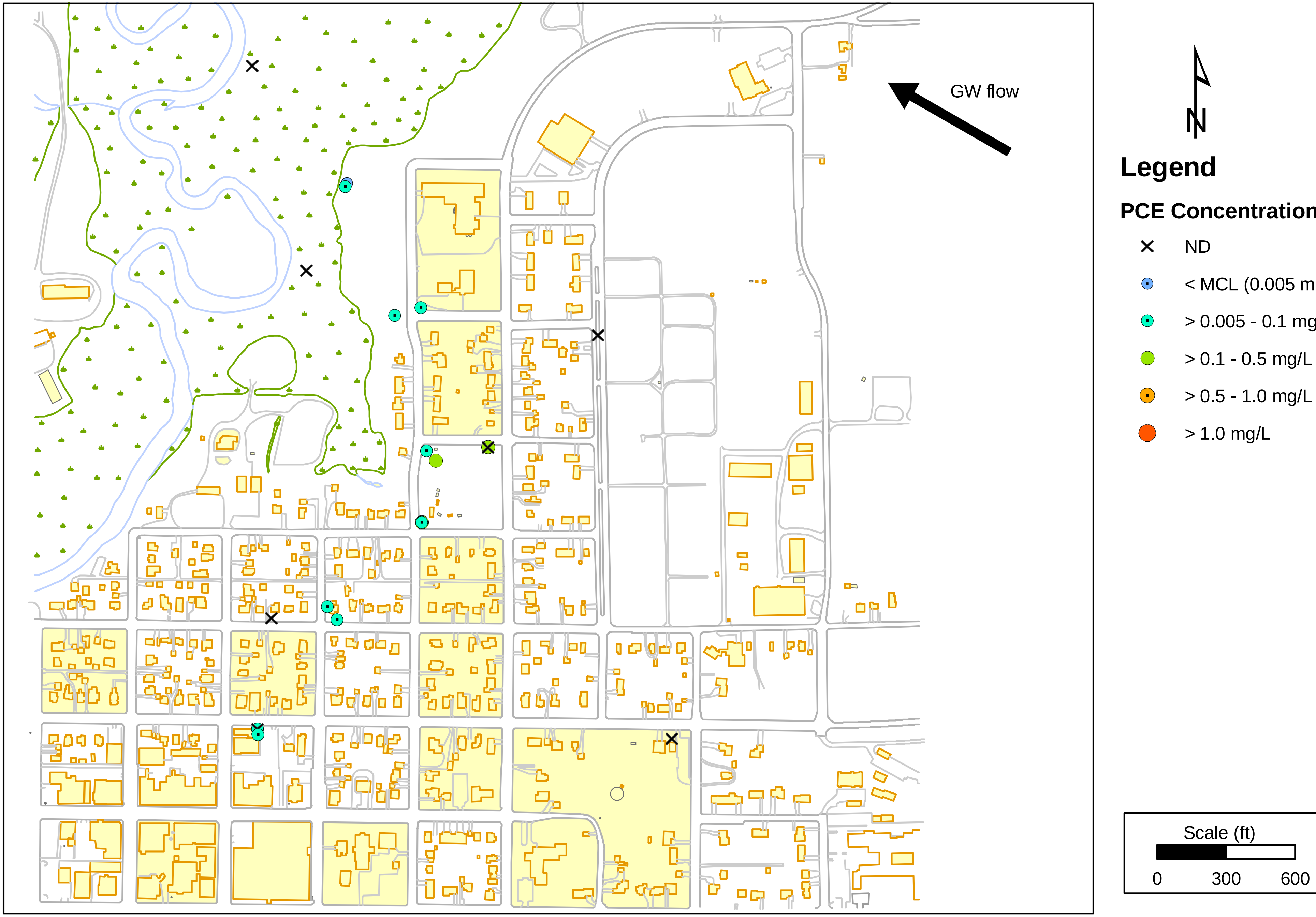
GSI Job No. G-2236
Date Issued: 2/19/03



Note: Representative PCE Concentrations shown are the Geometric Mean concentration for the year.

2000 Groundwater Monitoring: PCE
Long Prairie Site, Long Prairie, Minnesota

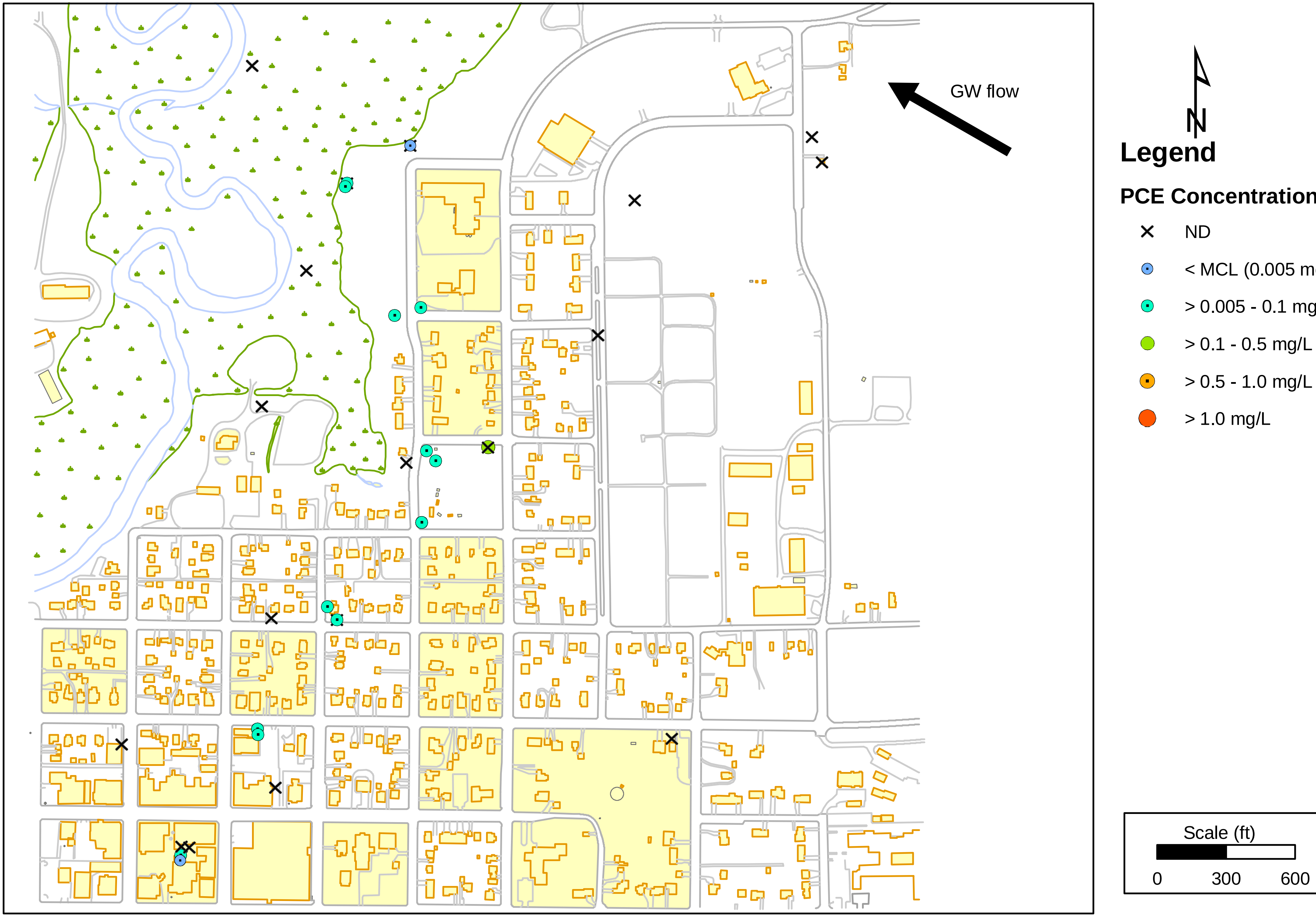
GSI Job No. G-2236
Date Issued: 2/19/03



Note: Representative PCE Concentrations shown are the Geometric Mean concentration for the year.

2001 Groundwater Monitoring: PCE
Long Prairie Site, Long Prairie, Minnesota

GSI Job No. G-2236
Date Issued: 2/19/03



Note: Representative PCE Concentrations shown are the Geometric Mean concentration for the year.

2002 Groundwater Monitoring: PCE
Long Prairie Site, Long Prairie, Minnesota

February 19, 2003
GSI Job No. G-2236-15

GROUNDWATER
SERVICES, INC.

MAROS 2.0 APPLICATION
MONITORING NETWORK OPTIMIZATION

Long Prairie Site
Long Prairie, Minnesota

APPENDIX B: Upper Outwash Aquifer Long Prairie MAROS 2.0 Reports

Linear Regression Statistics Summary
Mann-Kendall Statistics Summary
Spatial Moment Analysis Summary
Zeroth, First, and Second Moment Reports
Plume Analysis Summary
Site Results Summary
Sampling Location Optimization Results
Sampling Frequency Optimization Results
Risk-Based Power Analysis – Plume Centerline Concentrations
Risk-Based Power Analysis – Site Cleanup Status

MAROS Linear Regression Statistics Summary

Project: Long Prairie Site
User Name: Julia Aziz
Location: Todd County
State: Minnesota

Time Period: 5/20/1996 **to** 10/14/2002
Consolidation Period: No Time Consolidation
Consolidation Type: Median
Duplicate Consolidation: Average
ND Values: Specified Detection Limit
J Flag Values : Actual Value

Well	Source/ Tail	Average Conc (mg/L)	Median Conc (mg/L)	Standard Deviation	All Samples "ND" ?	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
TETRACHLOROETHYLENE(PCE)									
MW-2A	S	1.8E-02	7.3E-03	2.9E-02	No	-9.4E-04	1.59	84.0%	NT
MW-2B	S	4.0E-01	6.7E-02	5.4E-01	No	-1.2E-03	1.35	86.6%	NT
MW-2C	S	4.2E-03	4.3E-03	3.6E-03	No	-8.6E-04	0.86	82.0%	S
RW-3	S	8.6E-02	8.7E-02	4.7E-02	No	-8.3E-04	0.55	100.0%	D
MW-10	S	2.0E+01	9.3E-01	5.3E+01	No	-3.4E-03	2.63	99.6%	D
MW-11B	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	100.0%	S
MW-17B	T	1.3E-01	1.4E-01	5.5E-02	No	-8.8E-04	0.43	99.8%	D
MW-16B	T	1.1E-02	1.1E-02	7.4E-03	No	5.5E-05	0.66	53.2%	NT
MW-16A	T	5.2E-04	4.0E-04	2.9E-04	No	-2.6E-04	0.55	74.6%	S
MW-15B	T	4.0E-04	4.0E-04	0.0E+00	Yes	-2.6E-34	0.00	100.0%	D
MW-15A	T	4.0E-04	4.0E-04	0.0E+00	Yes	-2.6E-34	0.00	100.0%	D
MW-14C	T	4.6E-04	4.0E-04	2.1E-04	No	-5.0E-05	0.46	62.4%	S
MW-14B	T	2.2E-01	2.1E-01	9.2E-02	No	-3.7E-04	0.41	97.4%	D
MW-18B	T	2.2E-03	2.4E-03	5.5E-04	No	2.6E-06	0.26	100.0%	I
MW-11C	T	5.3E-04	4.0E-04	3.5E-04	No	-4.2E-04	0.67	94.1%	PD
MW-19B	T	4.0E-04	4.0E-04	0.0E+00	Yes	1.1E-34	0.00	100.0%	I
MW-11A	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	0.0%	N/A
CW-6	T	4.0E-04	4.0E-04	0.0E+00	Yes	1.6E-34	0.00	100.0%	I
CW-3	T	4.0E-04	4.0E-04	8.6E-12	Yes	0.0E+00	0.00	100.0%	S
BAL2C	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	100.0%	S
BAL2B	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	0.0%	N/A
MW-13C	T	8.1E-04	4.0E-04	8.3E-04	No	-2.4E-04	1.03	69.5%	NT
MW-6A	T	8.6E-02	4.1E-02	1.4E-01	No	-1.1E-03	1.66	74.8%	NT
RW-8	T	2.5E-02	2.3E-02	1.2E-02	No	-1.0E-03	0.48	100.0%	D
RW-7	T	5.2E-02	4.0E-02	3.0E-02	No	-7.2E-04	0.57	100.0%	D
RW-6	T	4.3E-02	4.1E-02	3.2E-02	No	-1.1E-03	0.75	100.0%	D
RW-5	T	1.6E-01	1.6E-01	7.0E-02	No	-3.5E-04	0.44	99.6%	D
RW-4	T	9.8E-04	4.0E-04	8.3E-04	No	-8.4E-04	0.84	99.9%	D
RW-1C	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	0.0%	N/A
RW-1B	T	8.7E-04	4.0E-04	1.6E-03	No	-4.9E-04	1.87	89.4%	NT
RW-1A	T	2.5E-03	1.7E-03	3.4E-03	No	-4.6E-04	1.39	87.1%	NT
MW-18A	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	100.0%	S
MW-6B	T	2.8E-01	1.5E-01	3.8E-01	No	-2.5E-03	1.35	100.0%	D
RW-9	T	1.4E-02	1.3E-02	2.3E-03	No	1.7E-04	0.17	86.1%	NT
MW-5B	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	100.0%	S
MW-5A	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	100.0%	S
MW-4C	T	1.1E-01	1.2E-01	4.1E-02	No	-3.1E-04	0.39	87.5%	S
MW-4B	T	2.2E-01	1.9E-01	1.3E-01	No	-7.9E-04	0.57	99.8%	D
MW-4A	T	2.0E-02	2.0E-02	1.8E-02	No	0.0E+00	0.00	0.0%	N/A

Project: Long Prairie Site **User Name:** Julia Aziz

Location: Todd County **State:** Minnesota

Well	Source/ Tail	Average Conc (mg/L)	Median Conc (mg/L)	Standard Deviation	All Samples "ND" ?	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
TETRACHLOROETHYLENE(PCE)									
MW-3B	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	100.0%	S
MW-3A	T	9.3E-04	4.0E-04	1.5E-03	No	-5.8E-04	1.61	87.2%	NT
MW-1B	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	100.0%	S
MW-1A	T	4.0E-04	4.0E-04	0.0E+00	Yes	0.0E+00	0.00	100.0%	S
MW-6C	T	8.4E-02	1.0E-01	7.1E-02	No	-1.6E-03	0.84	98.2%	D

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); COV = Coefficient of Variation

MAROS Mann-Kendall Statistics Summary

Project: Long Prairie Site **User Name:** Julia Aziz

Location: Todd County **State:** Minnesota

Time Period: 5/20/1996 **to** 10/14/2002
Consolidation Period: No Time Consolidation
Consolidation Type: Median
Duplicate Consolidation: Average
ND Values: Specified Detection Limit
J Flag Values : Actual Value

Well	Source/ Tail	Number of Samples	Number of Detects	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	All Samples "ND" ?	Concentration Trend
TETRACHLOROETHYLENE(PCE)								
MW-2B	S	6	6	1.35	-7	86.4%	No	NT
MW-10	S	8	8	2.63	-28	100.0%	No	D
MW-2A	S	6	6	1.59	-5	76.5%	No	NT
MW-2C	S	8	5	0.86	-11	88.7%	No	S
RW-3	S	25	25	0.55	-173	100.0%	No	D
MW-13C	T	9	2	1.03	-3	58.0%	No	NT
MW-18B	T	5	5	0.26	-3	67.5%	No	S
MW-18A	T	5	0	0.00	0	40.8%	Yes	S
MW-17B	T	7	7	0.43	-14	97.5%	No	D
MW-16B	T	8	8	0.66	-4	64.0%	No	S
MW-16A	T	6	1	0.55	-3	64.0%	No	S
MW-15B	T	7	0	0.00	0	43.7%	Yes	S
MW-15A	T	7	0	0.00	0	43.7%	Yes	S
MW-1B	T	8	0	0.00	0	45.2%	Yes	S
MW-14B	T	10	10	0.41	-18	93.4%	No	PD
BAL2B	T	1	0	0.00	0	0.0%	Yes	N/A
MW-11C	T	8	1	0.67	-7	76.4%	No	S
MW-11B	T	4	0	0.00	0	37.5%	Yes	S
MW-11A	T	2	0	0.00	0	0.0%	Yes	N/A
RW-8	T	12	12	0.48	-46	100.0%	No	D
CW-6	T	14	0	0.00	0	47.8%	Yes	S
CW-3	T	24	0	0.00	0	49.0%	Yes	S
BAL2C	T	8	0	0.00	0	45.2%	Yes	S
MW-14C	T	11	1	0.46	-2	53.0%	No	S
MW-4C	T	8	8	0.39	-11	88.7%	No	S
RW-5	T	25	25	0.44	-132	99.9%	No	D
RW-1C	T	1	0	0.00	0	0.0%	Yes	N/A
RW-1B	T	12	1	1.87	-11	74.9%	No	NT
RW-1A	T	12	11	1.39	-24	94.2%	No	PD
MW-6C	T	7	7	0.84	-10	90.7%	No	PD
MW-6B	T	6	6	1.35	-15	99.9%	No	D
MW-6A	T	6	5	1.66	0	42.3%	No	NT
MW-19B	T	7	0	0.00	0	43.7%	Yes	S
MW-5A	T	8	0	0.00	0	45.2%	Yes	S
MW-1A	T	8	0	0.00	0	45.2%	Yes	S
MW-4B	T	6	6	0.57	-12	98.2%	No	D
MW-4A	T	2	2	0.00	0	0.0%	No	N/A
MW-3B	T	8	0	0.00	0	45.2%	Yes	S

Project: Long Prairie Site

User Name: Julia Aziz

Location: Todd County

State: Minnesota

Well	Source/ Tail	Number of Samples	Number of Detects	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	All Samples "ND" ?	Concentration Trend
TETRACHLOROETHYLENE(PCE)								
MW-3A	T	8	1	1.61	-7	76.4%	No	NT
RW-6	T	25	25	0.75	-234	100.0%	No	D
RW-9	T	12	12	0.17	2	52.7%	No	NT
RW-7	T	25	25	0.57	-255	100.0%	No	D
RW-4	T	15	6	0.84	-61	99.9%	No	D
MW-5B	T	8	0	0.00	0	45.2%	Yes	S

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)- Due to insufficient Data (< 4 sampling events); Source/Tail (S/T)

The Number of Samples and Number of Detects shown above are post-consolidation values.

MAROS Statistical Trend Analysis Summary

Project: Long Prairie Site

Location: Todd County

User Name: Julia Aziz

State: Minnesota

Time Period: 5/20/1996 **to** 10/14/2002

Consolidation Period: No Time Consolidation

Consolidation Type: Median

Duplicate Consolidation: Average

ND Values: Specified Detection Limit

J Flag Values : Actual Value

Well	Source/ Tail	Number of Samples	Number of Detects	Average Conc. (mg/L)	Median Conc. (mg/L)	All Samples "ND" ?	Mann-Kendall Trend	Linear Regression Trend
TETRACHLOROETHYLENE(PCE)								
BAL2B	T	1	0	4.0E-04	4.0E-04	Yes	N/A	N/A
BAL2C	T	8	0	4.0E-04	4.0E-04	Yes	S	S
CW-3	T	24	0	4.0E-04	4.0E-04	Yes	S	S
CW-6	T	14	0	4.0E-04	4.0E-04	Yes	S	I
MW-10	S	8	8	2.0E+01	9.3E-01	No	D	D
MW-11A	T	2	0	4.0E-04	4.0E-04	Yes	N/A	N/A
MW-11B	T	4	0	4.0E-04	4.0E-04	Yes	S	S
MW-11C	T	8	1	5.3E-04	4.0E-04	No	S	PD
MW-13C	T	9	2	8.1E-04	4.0E-04	No	NT	NT
MW-14B	T	10	10	2.2E-01	2.1E-01	No	PD	D
MW-14C	T	11	1	4.6E-04	4.0E-04	No	S	S
MW-15A	T	7	0	4.0E-04	4.0E-04	Yes	S	D
MW-15B	T	7	0	4.0E-04	4.0E-04	Yes	S	D
MW-16A	T	6	1	5.2E-04	4.0E-04	No	S	S
MW-16B	T	8	8	1.1E-02	1.1E-02	No	S	NT
MW-17B	T	7	7	1.3E-01	1.4E-01	No	D	D
MW-18A	T	5	0	4.0E-04	4.0E-04	Yes	S	S
MW-18B	T	5	5	2.2E-03	2.4E-03	No	S	I
MW-19B	T	7	0	4.0E-04	4.0E-04	Yes	S	I
MW-1A	T	8	0	4.0E-04	4.0E-04	Yes	S	S
MW-1B	T	8	0	4.0E-04	4.0E-04	Yes	S	S
MW-2A	S	6	6	1.8E-02	7.3E-03	No	NT	NT
MW-2B	S	6	6	4.0E-01	6.7E-02	No	NT	NT
MW-2C	S	8	5	4.2E-03	4.3E-03	No	S	S
MW-3A	T	8	1	9.3E-04	4.0E-04	No	NT	NT
MW-3B	T	8	0	4.0E-04	4.0E-04	Yes	S	S
MW-4A	T	2	2	2.0E-02	2.0E-02	No	N/A	N/A
MW-4B	T	6	6	2.2E-01	1.9E-01	No	D	D
MW-4C	T	8	8	1.1E-01	1.2E-01	No	S	S
MW-5A	T	8	0	4.0E-04	4.0E-04	Yes	S	S
MW-5B	T	8	0	4.0E-04	4.0E-04	Yes	S	S
MW-6A	T	6	5	8.6E-02	4.1E-02	No	NT	NT
MW-6B	T	6	6	2.8E-01	1.5E-01	No	D	D
MW-6C	T	7	7	8.4E-02	1.0E-01	No	PD	D
RW-1A	T	12	11	2.5E-03	1.7E-03	No	PD	NT

MAROS Statistical Trend Analysis Summary

Well	Source/ Tail	Number of Samples	Number of Detects	Average Conc. (mg/L)	Median Conc. (mg/L)	All Samples "ND" ?	Mann-Kendall Trend	Linear Regression Trend
TETRACHLOROETHYLENE(PCE)								
RW-1B	T	12	1	8.7E-04	4.0E-04	No	NT	NT
RW-1C	T	1	0	4.0E-04	4.0E-04	Yes	N/A	N/A
RW-3	S	25	25	8.6E-02	8.7E-02	No	D	D
RW-4	T	15	6	9.8E-04	4.0E-04	No	D	D
RW-5	T	25	25	1.6E-01	1.6E-01	No	D	D
RW-6	T	25	25	4.3E-02	4.1E-02	No	D	D
RW-7	T	25	25	5.2E-02	4.0E-02	No	D	D
RW-8	T	12	12	2.5E-02	2.3E-02	No	D	D
RW-9	T	12	12	1.4E-02	1.3E-02	No	NT	NT

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); No Detectable Concentration (NDC)

The Number of Samples and Number of Detects shown above are post-consolidation values.

MAROS Spatial Moment Analysis Summary

Project: Long Prairie Site

Location: Todd County

User Name: Julia Aziz

State: Minnesota

	0th Moment	1st Moment (Center of Mass)			2nd Moment (Spread)		
Effective Date	Estimated Mass (Kg)	Xc (ft)	Yc (ft)	Source Distance (ft)	Sigma XX (sq ft)	Sigma YY (sq ft)	Number of Wells
TETRACHLOROETHYLENE(PCE)							
7/1/1996	4.7E+00	510,952	173,519	1,199	865,855	2,257,891	8
7/1/1997	2.4E+01	510,886	173,907	1,342	458,802	271,873	12
7/1/1998	2.9E+01	510,757	174,134	1,408	484,020	567,076	17
7/1/1999	2.1E+01	510,842	174,212	1,523	483,456	544,788	17
7/1/2000	1.5E+01	510,698	174,623	1,779	516,718	488,253	10
7/1/2001	1.3E+01	510,705	174,626	1,786	477,288	427,496	10
7/1/2002	7.3E+00	510,983	174,558	1,880	537,329	849,155	17

Project: Long Prairie Site

Location: Todd County

User Name: Julia Aziz

State: Minnesota

Moment Type	Consituent	Coefficient of Variation	Mann-Kendall S Statistic	Confidence in Trend	Moment Trend
Zeroth Moment: Mass					
	TETRACHLOROETHYLENE(PCE)	0.54	-7	80.9%	S
1st Moment: Distance to Source					
	TETRACHLOROETHYLENE(PCE)	0.17	21	100.0%	I
2nd Moment: Sigma XX					
	TETRACHLOROETHYLENE(PCE)	0.26	1	50.0%	NT
2nd Moment: Sigma YY					
	TETRACHLOROETHYLENE(PCE)	0.88	-3	61.4%	S

Note: The following assumptions were applied for the calculation of the Zeroth Moment:

Porosity: 0.30 **Saturated Thickness:** Uniform: 60 ft

Mann-Kendall Trend test performed on all sample events for each constituent. Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)-Due to insufficient Data (< 4 sampling events).

Note: The Sigma XX and Sigma YY components are estimated using the given field coordinate system and then rotated to align with the estimated groundwater flow direction. Moments are not calculated for sample events with less than 6 wells.

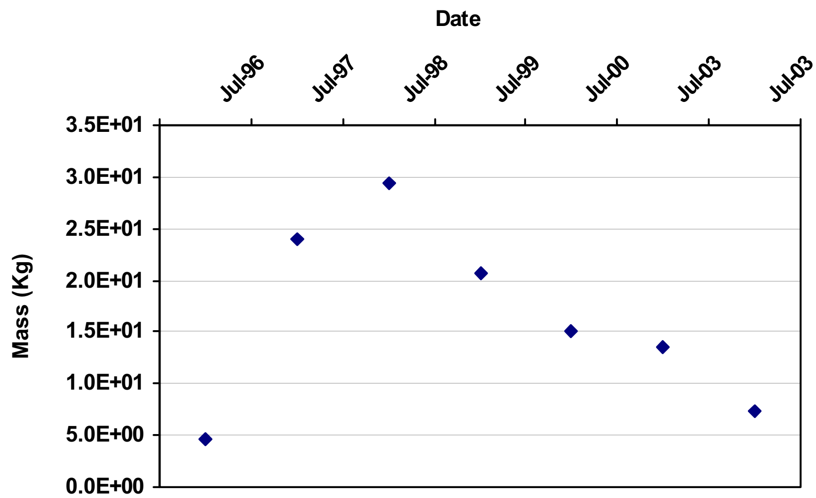
MAROS Zeroth Moment Analysis

Project: Long Prairie Site **User Name:** Julia Aziz

Location: Todd County **State:** Minnesota

COC: TETRACHLOROETHYLENE(PCE)

Change in Dissolved Mass Over Time



Porosity: 0.30

Saturated Thickness:

Uniform: 60 ft

Mann Kendall S Statistic:

-7

Confidence in Trend:

80.9%

Coefficient of Variation:

0.54

Zeroth Moment Trend:

S

Data Table:

Effective Date	Constituent	Estimated Mass (Kg)	Number of Wells
7/1/1996	TETRACHLOROETHYLENE(PCE)	4.7E+00	8
7/1/1997	TETRACHLOROETHYLENE(PCE)	2.4E+01	12
7/1/1998	TETRACHLOROETHYLENE(PCE)	2.9E+01	17
7/1/1999	TETRACHLOROETHYLENE(PCE)	2.1E+01	17
7/1/2000	TETRACHLOROETHYLENE(PCE)	1.5E+01	10
7/1/2001	TETRACHLOROETHYLENE(PCE)	1.3E+01	10
7/1/2002	TETRACHLOROETHYLENE(PCE)	7.3E+00	17

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); ND = Non-detect. Moments are not calculated for sample events with less than 6 wells.

MAROS First Moment Analysis

Project: Long Prairie Site

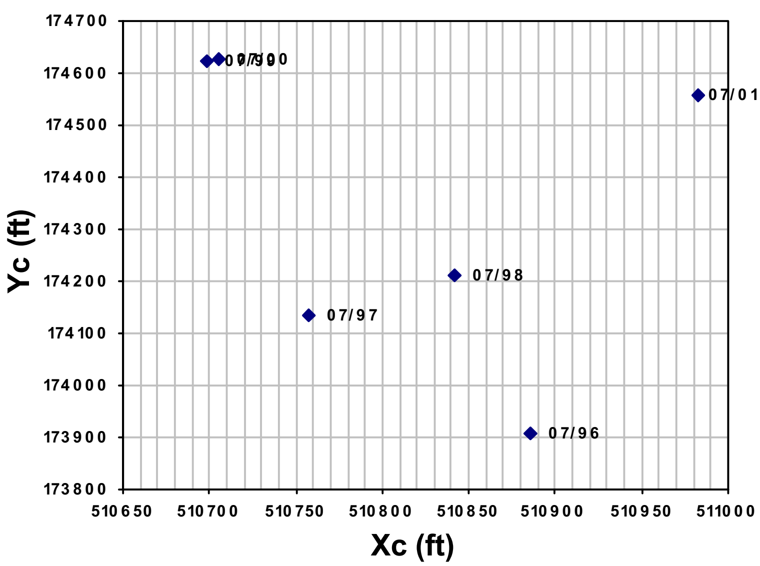
User Name: Julia Aziz

Location: Todd County

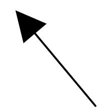
State: Minnesota

COC: TETRACHLOROETHYLENE(PCE)

Change in Location of Center of Mass Over Time



Groundwater Flow Direction:



Source Coordinate:

X: 509,844

Y: 173,062

Effective Date	Constituent	Xc (ft)	Yc (ft)	Distance from Source (ft)	Number of Wells
7/1/1996	TETRACHLOROETHYLENE(P	510,952	173,519	1,199	8
7/1/1997	TETRACHLOROETHYLENE(P	510,886	173,907	1,342	12
7/1/1998	TETRACHLOROETHYLENE(P	510,757	174,134	1,408	17
7/1/1999	TETRACHLOROETHYLENE(P	510,842	174,212	1,523	17
7/1/2000	TETRACHLOROETHYLENE(P	510,698	174,623	1,779	10
7/1/2001	TETRACHLOROETHYLENE(P	510,705	174,626	1,786	10
7/1/2002	TETRACHLOROETHYLENE(P	510,983	174,558	1,880	17

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events). Moments are not calculated for sample events with less than 6 wells.

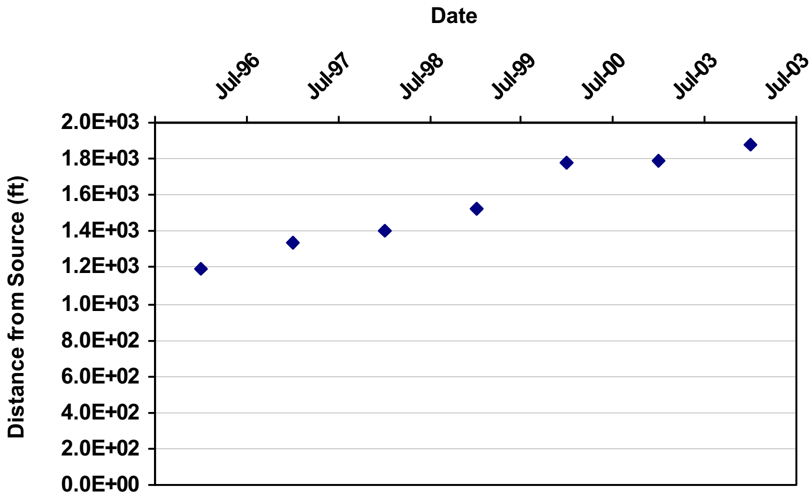
MAROS First Moment Analysis

Project: Long Prairie Site **User Name:** Julia Aziz

Location: Todd County **State:** Minnesota

COC: TETRACHLOROETHYLENE(PCE)

Distance from Source to Center of Mass



Mann Kendall S Statistic: 21

Confidence in Trend: 100.0%

Coefficient of Variation: 0.17

First Moment Trend: I

Data Table:

Effective Date	Constituent	Xc (ft)	Yc (ft)	Distance from Source (ft)	Number of Wells
7/1/1996	TETRACHLOROETHYLENE(P	510,952	173,519	1,199	8
7/1/1997	TETRACHLOROETHYLENE(P	510,886	173,907	1,342	12
7/1/1998	TETRACHLOROETHYLENE(P	510,757	174,134	1,408	17
7/1/1999	TETRACHLOROETHYLENE(P	510,842	174,212	1,523	17
7/1/2000	TETRACHLOROETHYLENE(P	510,698	174,623	1,779	10
7/1/2001	TETRACHLOROETHYLENE(P	510,705	174,626	1,786	10
7/1/2002	TETRACHLOROETHYLENE(P	510,983	174,558	1,880	17

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events). Moments are not calculated for sample events with less than 6 wells.

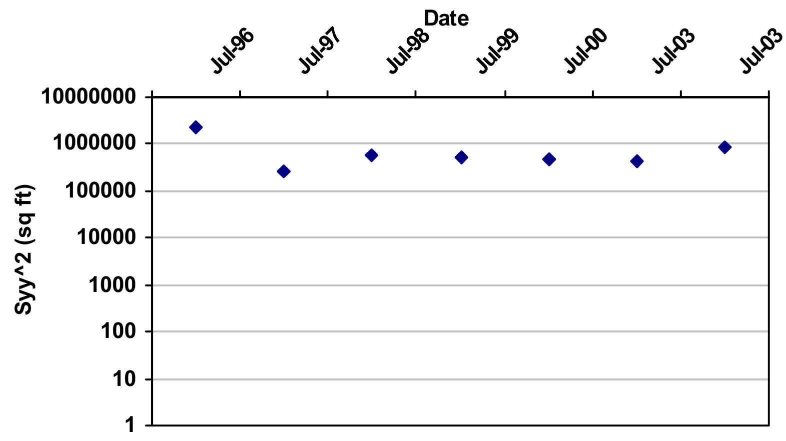
MAROS Second Moment Analysis

Project: Long Prairie Site **User Name:** Julia Aziz

Location: Todd County **State:** Minnesota

COC: TETRACHLOROETHYLENE(PCE)

Change in Plume Spread Over Time

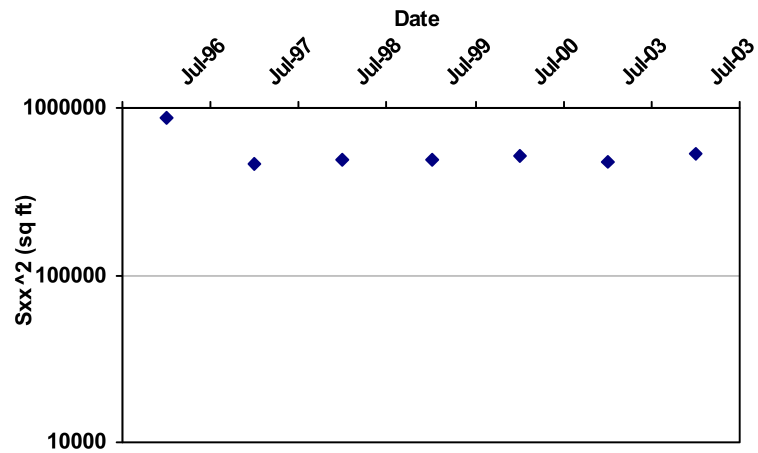


Mann Kendall S Statistic: -3

Confidence in Trend: 61.4%

Coefficient of Variation: 0.88

Second Moment Trend: S



Mann Kendall S Statistic: 1

Confidence in Trend: 50.0%

Coefficient of Variation: 0.26

Second Moment Trend: NT

Data Table:

Effective Date	Constituent	Sigma XX (sq ft)	Sigma YY (sq ft)	Number of Wells
7/1/1996	TETRACHLOROETHYLENE(P	865,855	2,257,891	8
7/1/1997	TETRACHLOROETHYLENE(P	458,802	271,873	12
7/1/1998	TETRACHLOROETHYLENE(P	484,020	567,076	17
7/1/1999	TETRACHLOROETHYLENE(P	483,456	544,788	17
7/1/2000	TETRACHLOROETHYLENE(P	516,718	488,253	10
7/1/2001	TETRACHLOROETHYLENE(P	477,288	427,496	10
7/1/2002	TETRACHLOROETHYLENE(P	537,329	849,155	17

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events)

The Sigma XX and Sigma YY components are estimated using the given field coordinate system and then rotated to align with the estimated groundwater flow direction. Moments are not calculated for sample events with less than 6 wells.

MAROS Site Results

Project: Long Prairie Site

User Name: Julia Aziz

Location: Todd County

State: Minnesota

User Defined Site and Data Assumptions:

Hydrogeology and Plume Information:

Groundwater Seepage Velocity: 476 ft/yr

Current Plume Length: 2100 ft

Current Plume Width 1000 ft

Number of Tail Wells: 15

Number of Source Wells: 2

Source Information:

Source Treatment: SVG

NAPL is not observed at this site.

Down-gradient Information:

Distance from Edge of Tail to Nearest:

Down-gradient receptor: 1000 ft

Down-gradient property: 1 ft

Distance from Source to Nearest:

Down-gradient receptor: 3000 ft

Down-gradient property: 1 ft

Data Consolidation Assumptions:

Time Period: 10/31/1996 **to** 10/14/2002

Consolidation Period: Yearly

Consolidation Type: Geometric Mean

Duplicate Consolidation: Average

ND Values: Specified Detection Limit

J Flag Values : Actual Value

Plume Information Weighting Assumptions:

Consolidation Step 1. Weight Plume Information by Chemical

Summary Weighting: Weighting Applied to All Chemicals Equally

Consolidation Step 2. Weight Well Information by Chemical

Well Weighting: No Weighting of Wells was Applied.

Chemical Weighting: No Weighting of Chemicals was Applied.

Note: These assumptions were made when consolidating the historical montoring data and lumping the Wells and COCs.

1. Compliance Monitoring/Remediation Optimization Results:

Preliminary Monitoring System Optimization Results: Based on site classification, source treatment and Monitoring System Category the following suggestions are made for site Sampling Frequency, Duration of Sampling, and Well Density. These criteria take into consideration: Plume Stability, Type of Plume, and Groundwater Velocity.

COC	Tail Stability	Source Stability	Level of Effort	Sampling Duration	Sampling Frequency	Sampling Density
TETRACHLOROETHYLENE(PCE)	S	S	M	Remove treatment system if previously reducing concentation	No Recommendation	35

Note:

Plume Status: (I) Increasing; (PI)Probably Increasing; (S) Stable; (NT) No Trend; (PD) Probably Decreasing; (D) Decreasing

Design Categories: (E) Extensive; (M) Moderate; (L) Limited (N/A) Not Applicable, Insufficient Data Available

Level of Monitoring Effort Indicated by Analysi Moderate

2. Spatial Moment Analysis Results:

Moment Type	Consituent	Coefficient of Variation	Mann-Kendall S Statistic	Confidence in Trend	Moment Trend
Zeroth Moment: Mass					
	TETRACHLOROETHYLENE(PCE)	0.54	-7	80.9%	S
1st Moment: Distance to Source					
	TETRACHLOROETHYLENE(PCE)	0.17	21	100.0%	I
2nd Moment: Sigma XX					
	TETRACHLOROETHYLENE(PCE)	0.26	1	50.0%	NT
2nd Moment: Sigma YY					
	TETRACHLOROETHYLENE(PCE)	0.88	-3	61.4%	S

Note: The following assumptions were applied for the calculation of the Zeroth Moment:

Porosity: 0.30 **Saturated Thickness:** Uniform: 60 ft

Mann-Kendall Trend test performed on all sample events for each constituent. Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)-Due to insufficient Data (< 4 sampling events).

MAROS Sampling Location Optimization Results

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Sampling Events Analyzed: **From** May 1999 **to** October 2002

5/20/1999 10/14/2002

Parameters used:

Constituent	Inside SF	Hull SF	Area Ratio	Conc. Ratio
TETRACHLOROETHYLENE(PCE	0.1	0.01	0.95	0.95

Well	X (feet)	Y (feet)	Removable?	Average Slope Factor*	Minimum Slope Factor*	Maximum Slope Factor*	Eliminated?
TETRACHLOROETHYLENE(PCE)							
BAL2C	511820.13	175912.75	☑	0.488	0.463	0.519	☐
CW-3	511983.13	173568.70	☑	0.628	0.470	0.720	☐
MW-10	509843.81	173061.80	☑	0.498	0.338	0.752	☐
MW-11C	511661.88	175323.95	☑	0.678	0.629	0.730	☐
MW-13C	510827.19	174770.72	☑	0.726	0.690	0.770	☐
MW-14B	511182.03	174835.77	☑	0.450	0.288	0.619	☐
MW-15B	510155.53	176497.39	☑	0.474	0.291	0.588	☐
MW-16B	510567.59	175986.83	☑	0.269	0.011	0.437	☐
MW-17B	510889.94	175444.19	☑	0.506	0.378	0.627	☐
MW-18B	510844.34	176150.06	☑	0.270	0.244	0.296	☐
MW-19B	510391.47	175606.44	☑	0.624	0.556	0.704	☐
MW-1B	509586.91	173544.45	☑	0.685	0.587	0.776	☐
MW-2B	510177.97	173610.33	☑	0.463	0.281	0.588	☐
MW-3B	510256.16	173355.97	☑	0.680	0.532	0.793	☐
MW-4B	510892.31	174509.33	☑	0.357	0.225	0.468	☐
MW-5B	510198.19	175015.45	☑	0.490	0.409	0.637	☐
MW-6B	510524.09	174085.47	☑	0.206	0.090	0.447	☐

Note: The Slope Factor indicates the relative importance of a well in the monitoring network at a given sampling event; the larger the SF value of a well, the more important the well is and vice versa; the Average Slope Factor measures the overall well importance in the selected time period; the state coordinates system (i.e., X and Y refer to Easting and Northing respectively) or local coordinates systems may be used; wells that are NOT selected for analysis are not shown above.

* When the report is generated after running the Excel module, SF values will NOT be shown above.

MAROS Sampling Frequency Optimization Results

Project: Long Prairie site

User Name: Meng

Location: Todd County

State: Minnesota

The Overall Number of Sampling Events: 28

"Recent Period" defined by events: **From** May 1999 5/20/1999 **To** October 2002 10/14/2002

"Rate of Change" parameters used:

Constituent	Cleanup Goal	Low Rate	Medium Rate	High Rate
TETRACHLOROETHYLENE(PCE	0.005	0.0025	0.005	0.01

Units: Cleanup Goal is in mg/L; all rate parameters are in mg/L/year.

Well	Recommended Sampling Frequency	Frequency Based on Recent Data	Frequency Based on Overall Data
TETRACHLOROETHYLENE(PCE)			
BAL2B	Annual	Annual	Annual
BAL2C	Annual	Annual	Annual
CW-3	Biennial	Annual	Annual
CW-6	Biennial	Annual	Annual
MW-10	Quarterly	Quarterly	Quarterly
MW-11A	Annual	Annual	Annual
MW-11B	Biennial	Annual	Annual
MW-11C	Biennial	Annual	Annual
MW-13C	Biennial	Annual	Annual
MW-14B	Annual	Annual	Annual
MW-14C	Biennial	Annual	Annual
MW-15A	Biennial	Annual	Annual
MW-15B	Biennial	Annual	Annual
MW-16A	Biennial	Annual	Annual
MW-16B	Annual	Annual	Annual
MW-17B	Annual	Annual	Annual
MW-18A	Annual	Annual	Annual
MW-18B	Annual	Annual	Annual
MW-19B	Biennial	Annual	Annual
MW-1A	Annual	Annual	Annual
MW-1B	Annual	Annual	Annual
MW-2A	Annual	Annual	Annual
MW-2B	Annual	Annual	Annual
MW-2C	Annual	Annual	Annual

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Well	Recommended Sampling Frequency	Frequency Based on Recent Data	Frequency Based on Overall Data
MW-3A	Annual	Annual	Annual
MW-3B	Annual	Annual	Annual
MW-4A	Quarterly	Quarterly	Quarterly
MW-4B	Annual	Annual	Annual
MW-4C	Annual	Annual	Annual
MW-5A	Annual	Annual	Annual
MW-5B	Annual	Annual	Annual
MW-6A	Annual	Annual	Annual
MW-6B	Annual	Annual	Annual
MW-6C	Annual	Annual	Annual
RW-1A	Annual	Annual	Annual
RW-1B	Annual	Annual	Annual
RW-1C	Annual	Annual	Annual
RW-3	Annual	Annual	Annual
RW-4	Biennial	Annual	Annual
RW-5	Annual	Annual	Annual
RW-6	Annual	Annual	Annual
RW-7	Annual	Annual	Annual
RW-8	Annual	Annual	Annual
RW-9	Annual	Annual	Annual

Note: Sampling frequency is determined considering both recent and overall concentration trends. Sampling Frequency is the final recommendation; Frequency Based on Recent Data is the frequency determined using recent (short) period of monitoring data; Frequency Based on Overall Data is the frequency determined using overall (long) period of monitoring data. If the "recent period" is defined using a different series of sampling events, the results could be different.

Regression of Plume Centerline Concentrations

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Groundwater Flow Direction: 90 degrees **Distance to Receptor:** 10 feet

From Period: 5/20/1999 **to** 10/14/2002

Selected Plume Centerline Wells:

Well	Distance to Receptor (feet)
MW-15B	10.0
MW-16B	520.6
MW-17B	1063.2
MW-4B	1998.1
MW-2B	2897.1

The distance is measured in the Groundwater Flow Angle from the well to the compliance boundary.

Sample Event	Effective Date	Number of Centerline Wells	Regression Coefficient (1/ft)	Confidence in Coefficient
TETRACHLOROETHYLENE(PCE)				
May 1999	5/20/1999	5	-2.31E-03	97.9%
July 1999	7/7/1999	0	0.00E+00	0.0%
September 1999	9/15/1999	2	0.00E+00	0.0%
October 1999	10/26/1999	3	-5.38E-03	91.5%
March 2000	3/15/2000	0	0.00E+00	0.0%
June 2000	7/1/2000	0	0.00E+00	0.0%
September 2000	9/10/2000	5	-1.50E-03	92.7%
October 2000	10/26/2000	0	0.00E+00	0.0%
December 2000	12/31/2000	0	0.00E+00	0.0%
March 2001	3/23/2001	0	0.00E+00	0.0%
May 2001	5/22/2001	0	0.00E+00	0.0%
September 2001	9/15/2001	5	-1.51E-03	92.1%
November 2001	11/29/2001	0	0.00E+00	0.0%
January 2002	1/31/2002	0	0.00E+00	0.0%
April 2002	4/3/2002	0	0.00E+00	0.0%
July 2002	7/25/2002	0	0.00E+00	0.0%
October 2002	10/14/2002	5	-1.24E-03	91.3%

Note: when the number of plume centerline wells is less than 3, no analysis is performed and all related values are set to ZERO; Confidence in Coefficient is the statistical confidence that the estimated coefficient is different from ZERO (for details, please refer to "Conference in Trend" in Linear Regression Analysis).

Risk-Based Power Analysis -- Projected Concentrations

Project: Long Prairie site

User Name: Meng

Location: Todd County

State: Minnesota

From Period: 5/20/1999 **to** 10/14/2002 **Distance from the most downgradient well to receptor:** 10 feet

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TETRACHLOROETHYLENE(PCE)								
May 1999	5/20/1999	BAL2C	5.000E-04	594.6	-2.31E-03	1.268E-04	Yes	Yes
May 1999	5/20/1999	CW-3	5.000E-04	2938.7	-2.31E-03	5.684E-07	Yes	Yes
May 1999	5/20/1999	CW-6	5.000E-04	430.4	-2.31E-03	1.852E-04	Yes	Yes
May 1999	5/20/1999	MW-10	9.900E-02	3445.6	-2.31E-03	3.495E-05	Yes	Yes
May 1999	5/20/1999	MW-11C	5.000E-04	1183.4	-2.31E-03	3.260E-05	Yes	Yes
May 1999	5/20/1999	MW-13C	5.000E-04	1736.7	-2.31E-03	9.099E-06	Yes	Yes
May 1999	5/20/1999	MW-14B	3.500E-01	1671.6	-2.31E-03	7.400E-03	No	Yes
May 1999	5/20/1999	MW-14C	5.000E-04	1671.6	-2.31E-03	1.057E-05	Yes	Yes
May 1999	5/20/1999	MW-15A	5.000E-04	10.0	-2.31E-03	4.886E-04	Yes	Yes
May 1999	5/20/1999	MW-15B	5.000E-04	10.0	-2.31E-03	4.886E-04	Yes	Yes
May 1999	5/20/1999	MW-16A	5.000E-04	520.6	-2.31E-03	1.505E-04	Yes	Yes
May 1999	5/20/1999	MW-16B	1.450E-02	520.6	-2.31E-03	4.363E-03	No	Yes
May 1999	5/20/1999	MW-17B	2.000E-01	1063.2	-2.31E-03	1.721E-02	No	Yes
May 1999	5/20/1999	MW-18A	5.000E-04	357.3	-2.31E-03	2.193E-04	Yes	Yes
May 1999	5/20/1999	MW-18B	2.200E-03	357.3	-2.31E-03	9.647E-04	No	Yes
May 1999	5/20/1999	MW-1A	5.000E-04	2962.9	-2.31E-03	5.375E-07	Yes	Yes
May 1999	5/20/1999	MW-1B	5.000E-04	2962.9	-2.31E-03	5.375E-07	Yes	Yes
May 1999	5/20/1999	MW-2A	7.600E-02	2897.1	-2.31E-03	9.511E-05	Yes	Yes
May 1999	5/20/1999	MW-2B	9.700E-01	2897.1	-2.31E-03	1.214E-03	No	Yes
May 1999	5/20/1999	MW-2C	5.100E-03	2897.1	-2.31E-03	6.382E-06	Yes	Yes
May 1999	5/20/1999	MW-3A	5.000E-04	3151.4	-2.31E-03	3.479E-07	Yes	Yes
May 1999	5/20/1999	MW-3B	5.000E-04	3151.4	-2.31E-03	3.479E-07	Yes	Yes
May 1999	5/20/1999	MW-4A	7.400E-03	1998.1	-2.31E-03	7.368E-05	Yes	Yes
May 1999	5/20/1999	MW-4B	2.300E-01	1998.1	-2.31E-03	2.290E-03	No	Yes
May 1999	5/20/1999	MW-4C	1.700E-01	1998.1	-2.31E-03	1.693E-03	No	Yes
May 1999	5/20/1999	MW-5A	5.000E-04	1491.9	-2.31E-03	1.600E-05	Yes	Yes
May 1999	5/20/1999	MW-5B	5.000E-04	1491.9	-2.31E-03	1.600E-05	Yes	Yes
May 1999	5/20/1999	MW-6A	3.750E-01	2421.9	-2.31E-03	1.404E-03	No	Yes
May 1999	5/20/1999	MW-6B	2.600E-01	2421.9	-2.31E-03	9.737E-04	No	Yes
May 1999	5/20/1999	MW-6C	2.100E-01	2421.9	-2.31E-03	7.864E-04	No	Yes
May 1999	5/20/1999	RW-1A	1.500E-03	3468.7	-2.31E-03	5.020E-07	Yes	No
May 1999	5/20/1999	RW-1B	5.000E-04	3409.4	-2.31E-03	1.919E-07	Yes	No

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TETRACHLOROETHYLENE(PCE)								
May 1999	5/20/1999	RW-3	1.350E-01	2922.2	-2.31E-03	1.594E-04	Yes	No
May 1999	5/20/1999	RW-4	5.000E-04	2414.7	-2.31E-03	1.904E-06	Yes	No
May 1999	5/20/1999	RW-5	1.900E-01	1730.8	-2.31E-03	3.505E-03	No	No
May 1999	5/20/1999	RW-6	4.100E-02	2364.6	-2.31E-03	1.753E-04	Yes	No
May 1999	5/20/1999	RW-7	4.000E-02	1686.5	-2.31E-03	8.172E-04	No	No
October 1999	10/26/1999	BAL2C	5.000E-04	594.6	-5.38E-03	2.045E-05	Yes	Yes
October 1999	10/26/1999	CW-3	5.000E-04	2938.7	-5.38E-03	6.882E-11	Yes	Yes
October 1999	10/26/1999	CW-6	5.000E-04	430.4	-5.38E-03	4.943E-05	Yes	Yes
October 1999	10/26/1999	MW-10	6.500E-02	3445.6	-5.38E-03	5.863E-10	Yes	Yes
October 1999	10/26/1999	MW-11C	5.000E-04	1183.4	-5.38E-03	8.627E-07	Yes	Yes
October 1999	10/26/1999	MW-13C	5.000E-04	1736.7	-5.38E-03	4.407E-08	Yes	Yes
October 1999	10/26/1999	MW-14B	2.100E-01	1671.6	-5.38E-03	2.626E-05	Yes	Yes
October 1999	10/26/1999	MW-14C	5.000E-04	1671.6	-5.38E-03	6.253E-08	Yes	Yes
October 1999	10/26/1999	MW-15A	5.000E-04	10.0	-5.38E-03	4.738E-04	Yes	Yes
October 1999	10/26/1999	MW-15B	5.000E-04	10.0	-5.38E-03	4.738E-04	Yes	Yes
October 1999	10/26/1999	MW-16A	5.000E-04	520.6	-5.38E-03	3.045E-05	Yes	Yes
October 1999	10/26/1999	MW-16B	2.000E-03	520.6	-5.38E-03	1.218E-04	Yes	Yes
October 1999	10/26/1999	MW-17B	1.400E-01	1063.2	-5.38E-03	4.611E-04	Yes	Yes
October 1999	10/26/1999	MW-18A	5.000E-04	357.3	-5.38E-03	7.323E-05	Yes	Yes
October 1999	10/26/1999	MW-18B	1.200E-03	357.3	-5.38E-03	1.757E-04	Yes	Yes
October 1999	10/26/1999	MW-19B	5.000E-04	901.0	-5.38E-03	3.939E-06	Yes	Yes
October 1999	10/26/1999	MW-1A	5.000E-04	2962.9	-5.38E-03	6.041E-11	Yes	Yes
October 1999	10/26/1999	MW-1B	5.000E-04	2962.9	-5.38E-03	6.041E-11	Yes	Yes
October 1999	10/26/1999	MW-2C	3.400E-03	2897.1	-5.38E-03	5.854E-10	Yes	Yes
October 1999	10/26/1999	MW-3A	5.000E-04	3151.4	-5.38E-03	2.193E-11	Yes	Yes
October 1999	10/26/1999	MW-3B	5.000E-04	3151.4	-5.38E-03	2.193E-11	Yes	Yes
October 1999	10/26/1999	MW-4C	1.400E-01	1998.1	-5.38E-03	3.027E-06	Yes	Yes
October 1999	10/26/1999	MW-5A	5.000E-04	1491.9	-5.38E-03	1.643E-07	Yes	Yes
October 1999	10/26/1999	MW-5B	5.000E-04	1491.9	-5.38E-03	1.643E-07	Yes	Yes
October 1999	10/26/1999	MW-6C	1.100E-01	2421.9	-5.38E-03	2.436E-07	Yes	Yes
October 1999	10/26/1999	RW-1A	1.000E-03	3468.7	-5.38E-03	7.966E-12	Yes	No
October 1999	10/26/1999	RW-1B	5.000E-04	3409.4	-5.38E-03	5.478E-12	Yes	No
October 1999	10/26/1999	RW-3	8.750E-02	2922.2	-5.38E-03	1.316E-08	Yes	No
October 1999	10/26/1999	RW-4	5.000E-04	2414.7	-5.38E-03	1.151E-09	Yes	No
October 1999	10/26/1999	RW-5	2.200E-01	1730.8	-5.38E-03	2.002E-05	Yes	No
October 1999	10/26/1999	RW-6	4.400E-02	2364.6	-5.38E-03	1.326E-07	Yes	No

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TETRACHLOROETHYLENE(PCE)								
October 1999	10/26/1999	RW-7	3.600E-02	1686.5	-5.38E-03	4.156E-06	Yes	No
September 2000	9/10/2000	CW-3	5.000E-04	2938.7	-1.50E-03	6.121E-06	Yes	Yes
September 2000	9/10/2000	MW-11B	5.000E-04	1183.4	-1.50E-03	8.490E-05	Yes	Yes
September 2000	9/10/2000	MW-11C	5.000E-04	1183.4	-1.50E-03	8.490E-05	Yes	Yes
September 2000	9/10/2000	MW-14B	1.400E-01	1671.6	-1.50E-03	1.144E-02	No	Yes
September 2000	9/10/2000	MW-14C	5.000E-04	1671.6	-1.50E-03	4.086E-05	Yes	Yes
September 2000	9/10/2000	MW-15A	5.000E-04	10.0	-1.50E-03	4.926E-04	Yes	Yes
September 2000	9/10/2000	MW-15B	5.000E-04	10.0	-1.50E-03	4.926E-04	Yes	Yes
September 2000	9/10/2000	MW-16B	1.400E-02	520.6	-1.50E-03	6.418E-03	No	Yes
September 2000	9/10/2000	MW-17B	1.000E-01	1063.2	-1.50E-03	2.033E-02	No	Yes
September 2000	9/10/2000	MW-19B	5.000E-04	901.0	-1.50E-03	1.296E-04	Yes	Yes
September 2000	9/10/2000	MW-2A	1.100E-02	2897.1	-1.50E-03	1.433E-04	Yes	Yes
September 2000	9/10/2000	MW-2B	7.100E-02	2897.1	-1.50E-03	9.251E-04	No	Yes
September 2000	9/10/2000	MW-2C	5.000E-04	2897.1	-1.50E-03	6.515E-06	Yes	Yes
September 2000	9/10/2000	MW-4B	1.400E-01	1998.1	-1.50E-03	7.015E-03	No	Yes
September 2000	9/10/2000	MW-4C	1.150E-01	1998.1	-1.50E-03	5.762E-03	No	Yes
September 2000	9/10/2000	MW-6A	5.400E-02	2421.9	-1.50E-03	1.434E-03	No	Yes
September 2000	9/10/2000	MW-6B	4.700E-02	2421.9	-1.50E-03	1.248E-03	No	Yes
September 2000	9/10/2000	MW-6C	2.100E-02	2421.9	-1.50E-03	5.576E-04	No	Yes
September 2000	9/10/2000	RW-3	5.100E-02	2922.2	-1.50E-03	6.399E-04	No	No
September 2000	9/10/2000	RW-4	5.000E-04	2414.7	-1.50E-03	1.342E-05	Yes	No
September 2000	9/10/2000	RW-5	7.400E-02	1730.8	-1.50E-03	5.534E-03	No	No
September 2000	9/10/2000	RW-6	2.000E-02	2364.6	-1.50E-03	5.787E-04	No	No
September 2000	9/10/2000	RW-7	3.100E-02	1686.5	-1.50E-03	2.477E-03	No	No
September 2000	9/10/2000	RW-8	3.000E-02	1096.9	-1.50E-03	5.799E-03	No	No
September 2000	9/10/2000	RW-9	1.600E-02	535.7	-1.50E-03	7.170E-03	No	No
September 2001	9/15/2001	CW-3	5.000E-04	2938.7	-1.51E-03	5.942E-06	Yes	Yes
September 2001	9/15/2001	MW-11B	5.000E-04	1183.4	-1.51E-03	8.390E-05	Yes	Yes
September 2001	9/15/2001	MW-11C	5.000E-04	1183.4	-1.51E-03	8.390E-05	Yes	Yes
September 2001	9/15/2001	MW-14B	1.300E-01	1671.6	-1.51E-03	1.045E-02	No	Yes
September 2001	9/15/2001	MW-14C	5.000E-04	1671.6	-1.51E-03	4.017E-05	Yes	Yes
September 2001	9/15/2001	MW-15A	5.000E-04	10.0	-1.51E-03	4.925E-04	Yes	Yes
September 2001	9/15/2001	MW-15B	5.000E-04	10.0	-1.51E-03	4.925E-04	Yes	Yes
September 2001	9/15/2001	MW-16B	3.700E-03	520.6	-1.51E-03	1.687E-03	No	Yes
September 2001	9/15/2001	MW-17B	9.200E-02	1063.2	-1.51E-03	1.851E-02	No	Yes
September 2001	9/15/2001	MW-19B	5.000E-04	901.0	-1.51E-03	1.285E-04	Yes	Yes

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TETRACHLOROETHYLENE(PCE)								
September 2001	9/15/2001	MW-2A	5.200E-03	2897.1	-1.51E-03	6.580E-05	Yes	Yes
September 2001	9/15/2001	MW-2B	3.800E-02	2897.1	-1.51E-03	4.809E-04	Yes	Yes
September 2001	9/15/2001	MW-2C	5.000E-04	2897.1	-1.51E-03	6.327E-06	Yes	Yes
September 2001	9/15/2001	MW-4B	1.400E-01	1998.1	-1.51E-03	6.875E-03	No	Yes
September 2001	9/15/2001	MW-4C	6.450E-02	1998.1	-1.51E-03	3.167E-03	No	Yes
September 2001	9/15/2001	MW-6A	5.400E-02	2421.9	-1.51E-03	1.399E-03	No	Yes
September 2001	9/15/2001	MW-6B	3.700E-02	2421.9	-1.51E-03	9.587E-04	No	Yes
September 2001	9/15/2001	MW-6C	1.200E-02	2421.9	-1.51E-03	3.109E-04	Yes	Yes
September 2001	9/15/2001	RW-3	2.550E-02	2922.2	-1.51E-03	3.107E-04	Yes	No
September 2001	9/15/2001	RW-4	5.000E-04	2414.7	-1.51E-03	1.310E-05	Yes	No
September 2001	9/15/2001	RW-5	1.025E-01	1730.8	-1.51E-03	7.533E-03	No	No
September 2001	9/15/2001	RW-6	1.250E-02	2364.6	-1.51E-03	3.531E-04	Yes	No
September 2001	9/15/2001	RW-7	2.800E-02	1686.5	-1.51E-03	2.200E-03	No	No
September 2001	9/15/2001	RW-8	1.950E-02	1096.9	-1.51E-03	3.728E-03	No	No
September 2001	9/15/2001	RW-9	1.400E-02	535.7	-1.51E-03	6.240E-03	No	No
October 2002	10/14/2002	BAL2B	5.000E-04	318.8	-1.24E-03	3.362E-04	Yes	Yes
October 2002	10/14/2002	BAL2C	5.000E-04	594.6	-1.24E-03	2.385E-04	Yes	Yes
October 2002	10/14/2002	CW-3	5.000E-04	2938.7	-1.24E-03	1.288E-05	Yes	Yes
October 2002	10/14/2002	CW-6	5.000E-04	430.4	-1.24E-03	2.926E-04	Yes	Yes
October 2002	10/14/2002	MW-10	3.800E-02	3445.6	-1.24E-03	5.210E-04	No	Yes
October 2002	10/14/2002	MW-11A	5.000E-04	1183.4	-1.24E-03	1.146E-04	Yes	Yes
October 2002	10/14/2002	MW-11B	5.000E-04	1183.4	-1.24E-03	1.146E-04	Yes	Yes
October 2002	10/14/2002	MW-11C	5.000E-04	1183.4	-1.24E-03	1.146E-04	Yes	Yes
October 2002	10/14/2002	MW-13C	5.000E-04	1736.7	-1.24E-03	5.754E-05	Yes	Yes
October 2002	10/14/2002	MW-14B	1.100E-01	1671.6	-1.24E-03	1.373E-02	No	Yes
October 2002	10/14/2002	MW-14C	5.000E-04	1671.6	-1.24E-03	6.240E-05	Yes	Yes
October 2002	10/14/2002	MW-15A	5.000E-04	10.0	-1.24E-03	4.938E-04	Yes	Yes
October 2002	10/14/2002	MW-15B	5.000E-04	10.0	-1.24E-03	4.938E-04	Yes	Yes
October 2002	10/14/2002	MW-16A	5.000E-04	520.6	-1.24E-03	2.615E-04	Yes	Yes
October 2002	10/14/2002	MW-16B	2.000E-02	520.6	-1.24E-03	1.046E-02	No	Yes
October 2002	10/14/2002	MW-17B	4.000E-02	1063.2	-1.24E-03	1.065E-02	No	Yes
October 2002	10/14/2002	MW-18A	5.000E-04	357.3	-1.24E-03	3.205E-04	Yes	Yes
October 2002	10/14/2002	MW-18B	2.400E-03	357.3	-1.24E-03	1.538E-03	No	Yes
October 2002	10/14/2002	MW-19B	5.000E-04	901.0	-1.24E-03	1.629E-04	Yes	Yes
October 2002	10/14/2002	MW-1A	5.000E-04	2962.9	-1.24E-03	1.250E-05	Yes	Yes
October 2002	10/14/2002	MW-1B	5.000E-04	2962.9	-1.24E-03	1.250E-05	Yes	Yes

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TETRACHLOROETHYLENE(PCE)								
October 2002	10/14/2002	MW-2A	9.700E-04	2897.1	-1.24E-03	2.633E-05	Yes	Yes
October 2002	10/14/2002	MW-2B	4.100E-02	2897.1	-1.24E-03	1.113E-03	No	Yes
October 2002	10/14/2002	MW-2C	6.900E-03	2897.1	-1.24E-03	1.873E-04	Yes	Yes
October 2002	10/14/2002	MW-3A	5.000E-04	3151.4	-1.24E-03	9.887E-06	Yes	Yes
October 2002	10/14/2002	MW-3B	5.000E-04	3151.4	-1.24E-03	9.887E-06	Yes	Yes
October 2002	10/14/2002	MW-4A	3.300E-02	1998.1	-1.24E-03	2.743E-03	No	Yes
October 2002	10/14/2002	MW-4B	7.700E-02	1998.1	-1.24E-03	6.400E-03	No	Yes
October 2002	10/14/2002	MW-4C	5.100E-02	1998.1	-1.24E-03	4.239E-03	No	Yes
October 2002	10/14/2002	MW-5A	5.000E-04	1491.9	-1.24E-03	7.804E-05	Yes	Yes
October 2002	10/14/2002	MW-5B	5.000E-04	1491.9	-1.24E-03	7.804E-05	Yes	Yes
October 2002	10/14/2002	MW-6A	5.000E-04	2421.9	-1.24E-03	2.452E-05	Yes	Yes
October 2002	10/14/2002	MW-6B	4.700E-03	2421.9	-1.24E-03	2.305E-04	Yes	Yes
October 2002	10/14/2002	MW-6C	2.500E-02	2421.9	-1.24E-03	1.226E-03	No	Yes
October 2002	10/14/2002	RW-1A	1.000E-03	3468.7	-1.24E-03	1.332E-05	Yes	No
October 2002	10/14/2002	RW-1B	5.000E-04	3409.4	-1.24E-03	7.171E-06	Yes	No
October 2002	10/14/2002	RW-1C	5.000E-04	3412.5	-1.24E-03	7.144E-06	Yes	No
October 2002	10/14/2002	RW-3	2.000E-02	2922.2	-1.24E-03	5.261E-04	No	No
October 2002	10/14/2002	RW-4	5.000E-04	2414.7	-1.24E-03	2.474E-05	Yes	No
October 2002	10/14/2002	RW-5	8.400E-02	1730.8	-1.24E-03	9.739E-03	No	No
October 2002	10/14/2002	RW-6	9.500E-03	2364.6	-1.24E-03	5.003E-04	No	No
October 2002	10/14/2002	RW-7	2.200E-02	1686.5	-1.24E-03	2.695E-03	No	No
October 2002	10/14/2002	RW-8	1.800E-02	1096.9	-1.24E-03	4.594E-03	No	No
October 2002	10/14/2002	RW-9	1.500E-02	535.7	-1.24E-03	7.699E-03	No	No

Note: Projected Concentrations that are below the user-specified detection limit are indicated by a check mark to its right; for sampling events with less than 3 selected plume centerline wells, NO projected concentrations are calculated because no regression coefficient is available.

MAROS Risk-Based Power Analysis for Site Cleanup

Project: Long Prairie site

User Name: Meng

Location: Todd County

State: Minnesota

Parameters:

Groundwater Flow Direction: 90 degrees **Distance to Receptor:** 10 feet

From Period: May 1999 **to** October 2002

5/20/1999 10/14/2002

Selected Plume Centerline Wells:

Well	Distance to Receptor (feet)
MW-15B	10.0
MW-16B	520.6
MW-17B	1063.2
MW-4B	1998.1
MW-2B	2897.1

The distance is measured in the Groundwater Flow Angle from the well to the compliance boundary.

Sample Event	Sample Szie	Sample Mean	Sample Stdev.	Normal Distribution Assumption: Cleanup Status	Normal Distribution Assumption: Power	Normal Distribution Assumption: Expected Sample Size	Lognormal Distribution Assumption: Celanup Status	Lognormal Distribution Assumption: Power	Lognormal Distribution Assumption: Expected Sample Size	Alpha Level	Expected Power
TETRACHLOROETHYLENE(PCE)				Cleanup Goal = 0.005							
May 1999	30	1.34E-03	3.38E-03	Attained	1.000	7	Not Attained	S/E	S/E	0.05	0.8
October 1999	25	7.66E-05	1.54E-04	Attained	1.000	<=3	Not Attained	S/E	S/E	0.05	0.8
September 2000	18	3.15E-03	5.40E-03	Not Attained	0.414	54	Not Attained	S/E	S/E	0.05	0.8
September 2001	18	2.51E-03	4.86E-03	Attained	0.685	25	Not Attained	S/E	S/E	0.05	0.8
October 2002	34	1.66E-03	3.44E-03	Attained	1.000	8	Attained	0.728	42	0.05	0.8

Note: #N/C means "not conducted" due to a small sample size (N<4) or that the mean concentration is much greater than the cleanup level; Sample Size is the number of sampling locations used in the power analysis; Expected Sample Size is the number of concentration data needed to reach the Expected Power under current sample variability.

Risk-Based Power Analysis -- Projected Concentrations

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

From Period: 5/20/1999 **to** 10/14/2002 **Distance from the most downgradient well to receptor:** -100 feet

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TETRACHLOROETHYLENE(PCE)								
May 1999	5/20/1999	BAL2C	5.000E-04	484.6	-2.31E-03	1.635E-04	Yes	Yes
May 1999	5/20/1999	CW-3	5.000E-04	2828.7	-2.31E-03	7.326E-07	Yes	Yes
May 1999	5/20/1999	CW-6	5.000E-04	320.4	-2.31E-03	2.387E-04	Yes	Yes
May 1999	5/20/1999	MW-10	9.900E-02	3335.6	-2.31E-03	4.505E-05	Yes	Yes
May 1999	5/20/1999	MW-11C	5.000E-04	1073.4	-2.31E-03	4.202E-05	Yes	Yes
May 1999	5/20/1999	MW-13C	5.000E-04	1626.7	-2.31E-03	1.173E-05	Yes	Yes
May 1999	5/20/1999	MW-14B	3.500E-01	1561.6	-2.31E-03	9.538E-03	No	Yes
May 1999	5/20/1999	MW-14C	5.000E-04	1561.6	-2.31E-03	1.363E-05	Yes	Yes
May 1999	5/20/1999	MW-15A	5.000E-04	-100.0	-2.31E-03	6.297E-04	No	Yes
May 1999	5/20/1999	MW-15B	5.000E-04	-100.0	-2.31E-03	6.297E-04	No	Yes
May 1999	5/20/1999	MW-16A	5.000E-04	410.6	-2.31E-03	1.939E-04	Yes	Yes
May 1999	5/20/1999	MW-16B	1.450E-02	410.6	-2.31E-03	5.624E-03	No	Yes
May 1999	5/20/1999	MW-17B	2.000E-01	953.2	-2.31E-03	2.218E-02	No	Yes
May 1999	5/20/1999	MW-18A	5.000E-04	247.3	-2.31E-03	2.826E-04	Yes	Yes
May 1999	5/20/1999	MW-18B	2.200E-03	247.3	-2.31E-03	1.243E-03	No	Yes
May 1999	5/20/1999	MW-1A	5.000E-04	2852.9	-2.31E-03	6.927E-07	Yes	Yes
May 1999	5/20/1999	MW-1B	5.000E-04	2852.9	-2.31E-03	6.927E-07	Yes	Yes
May 1999	5/20/1999	MW-2A	7.600E-02	2787.1	-2.31E-03	1.226E-04	Yes	Yes
May 1999	5/20/1999	MW-2B	9.700E-01	2787.1	-2.31E-03	1.564E-03	No	Yes
May 1999	5/20/1999	MW-2C	5.100E-03	2787.1	-2.31E-03	8.226E-06	Yes	Yes
May 1999	5/20/1999	MW-3A	5.000E-04	3041.4	-2.31E-03	4.485E-07	Yes	Yes
May 1999	5/20/1999	MW-3B	5.000E-04	3041.4	-2.31E-03	4.485E-07	Yes	Yes
May 1999	5/20/1999	MW-4A	7.400E-03	1888.1	-2.31E-03	9.496E-05	Yes	Yes
May 1999	5/20/1999	MW-4B	2.300E-01	1888.1	-2.31E-03	2.952E-03	No	Yes
May 1999	5/20/1999	MW-4C	1.700E-01	1888.1	-2.31E-03	2.182E-03	No	Yes
May 1999	5/20/1999	MW-5A	5.000E-04	1381.9	-2.31E-03	2.062E-05	Yes	Yes
May 1999	5/20/1999	MW-5B	5.000E-04	1381.9	-2.31E-03	2.062E-05	Yes	Yes
May 1999	5/20/1999	MW-6A	3.750E-01	2311.9	-2.31E-03	1.810E-03	No	Yes
May 1999	5/20/1999	MW-6B	2.600E-01	2311.9	-2.31E-03	1.255E-03	No	Yes
May 1999	5/20/1999	MW-6C	2.100E-01	2311.9	-2.31E-03	1.014E-03	No	Yes
May 1999	5/20/1999	RW-1A	1.500E-03	3358.7	-2.31E-03	6.471E-07	Yes	No
May 1999	5/20/1999	RW-1B	5.000E-04	3299.4	-2.31E-03	2.473E-07	Yes	No

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TETRACHLOROETHYLENE(PCE)								
May 1999	5/20/1999	RW-3	1.350E-01	2812.2	-2.31E-03	2.055E-04	Yes	No
May 1999	5/20/1999	RW-4	5.000E-04	2304.7	-2.31E-03	2.454E-06	Yes	No
May 1999	5/20/1999	RW-5	1.900E-01	1620.8	-2.31E-03	4.518E-03	No	No
May 1999	5/20/1999	RW-6	4.100E-02	2254.6	-2.31E-03	2.259E-04	Yes	No
May 1999	5/20/1999	RW-7	4.000E-02	1576.5	-2.31E-03	1.053E-03	No	No
October 1999	10/26/1999	BAL2C	5.000E-04	484.6	-5.38E-03	3.693E-05	Yes	Yes
October 1999	10/26/1999	CW-3	5.000E-04	2828.7	-5.38E-03	1.243E-10	Yes	Yes
October 1999	10/26/1999	CW-6	5.000E-04	320.4	-5.38E-03	8.929E-05	Yes	Yes
October 1999	10/26/1999	MW-10	6.500E-02	3335.6	-5.38E-03	1.059E-09	Yes	Yes
October 1999	10/26/1999	MW-11C	5.000E-04	1073.4	-5.38E-03	1.559E-06	Yes	Yes
October 1999	10/26/1999	MW-13C	5.000E-04	1626.7	-5.38E-03	7.962E-08	Yes	Yes
October 1999	10/26/1999	MW-14B	2.100E-01	1561.6	-5.38E-03	4.744E-05	Yes	Yes
October 1999	10/26/1999	MW-14C	5.000E-04	1561.6	-5.38E-03	1.130E-07	Yes	Yes
October 1999	10/26/1999	MW-15A	5.000E-04	-100.0	-5.38E-03	8.560E-04	No	Yes
October 1999	10/26/1999	MW-15B	5.000E-04	-100.0	-5.38E-03	8.560E-04	No	Yes
October 1999	10/26/1999	MW-16A	5.000E-04	410.6	-5.38E-03	5.500E-05	Yes	Yes
October 1999	10/26/1999	MW-16B	2.000E-03	410.6	-5.38E-03	2.200E-04	Yes	Yes
October 1999	10/26/1999	MW-17B	1.400E-01	953.2	-5.38E-03	8.329E-04	No	Yes
October 1999	10/26/1999	MW-18A	5.000E-04	247.3	-5.38E-03	1.323E-04	Yes	Yes
October 1999	10/26/1999	MW-18B	1.200E-03	247.3	-5.38E-03	3.175E-04	Yes	Yes
October 1999	10/26/1999	MW-19B	5.000E-04	791.0	-5.38E-03	7.116E-06	Yes	Yes
October 1999	10/26/1999	MW-1A	5.000E-04	2852.9	-5.38E-03	1.091E-10	Yes	Yes
October 1999	10/26/1999	MW-1B	5.000E-04	2852.9	-5.38E-03	1.091E-10	Yes	Yes
October 1999	10/26/1999	MW-2C	3.400E-03	2787.1	-5.38E-03	1.057E-09	Yes	Yes
October 1999	10/26/1999	MW-3A	5.000E-04	3041.4	-5.38E-03	3.962E-11	Yes	Yes
October 1999	10/26/1999	MW-3B	5.000E-04	3041.4	-5.38E-03	3.962E-11	Yes	Yes
October 1999	10/26/1999	MW-4C	1.400E-01	1888.1	-5.38E-03	5.469E-06	Yes	Yes
October 1999	10/26/1999	MW-5A	5.000E-04	1381.9	-5.38E-03	2.968E-07	Yes	Yes
October 1999	10/26/1999	MW-5B	5.000E-04	1381.9	-5.38E-03	2.968E-07	Yes	Yes
October 1999	10/26/1999	MW-6C	1.100E-01	2311.9	-5.38E-03	4.401E-07	Yes	Yes
October 1999	10/26/1999	RW-1A	1.000E-03	3358.7	-5.38E-03	1.439E-11	Yes	No
October 1999	10/26/1999	RW-1B	5.000E-04	3299.4	-5.38E-03	9.897E-12	Yes	No
October 1999	10/26/1999	RW-3	8.750E-02	2812.2	-5.38E-03	2.377E-08	Yes	No
October 1999	10/26/1999	RW-4	5.000E-04	2304.7	-5.38E-03	2.080E-09	Yes	No
October 1999	10/26/1999	RW-5	2.200E-01	1620.8	-5.38E-03	3.617E-05	Yes	No
October 1999	10/26/1999	RW-6	4.400E-02	2254.6	-5.38E-03	2.396E-07	Yes	No

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TETRACHLOROETHYLENE(PCE)								
October 1999	10/26/1999	RW-7	3.600E-02	1576.5	-5.38E-03	7.508E-06	Yes	No
September 2000	9/10/2000	CW-3	5.000E-04	2828.7	-1.50E-03	7.217E-06	Yes	Yes
September 2000	9/10/2000	MW-11B	5.000E-04	1073.4	-1.50E-03	1.001E-04	Yes	Yes
September 2000	9/10/2000	MW-11C	5.000E-04	1073.4	-1.50E-03	1.001E-04	Yes	Yes
September 2000	9/10/2000	MW-14B	1.400E-01	1561.6	-1.50E-03	1.349E-02	No	Yes
September 2000	9/10/2000	MW-14C	5.000E-04	1561.6	-1.50E-03	4.818E-05	Yes	Yes
September 2000	9/10/2000	MW-15A	5.000E-04	-100.0	-1.50E-03	5.808E-04	No	Yes
September 2000	9/10/2000	MW-15B	5.000E-04	-100.0	-1.50E-03	5.808E-04	No	Yes
September 2000	9/10/2000	MW-16B	1.400E-02	410.6	-1.50E-03	7.568E-03	No	Yes
September 2000	9/10/2000	MW-17B	1.000E-01	953.2	-1.50E-03	2.398E-02	No	Yes
September 2000	9/10/2000	MW-19B	5.000E-04	791.0	-1.50E-03	1.529E-04	Yes	Yes
September 2000	9/10/2000	MW-2A	1.100E-02	2787.1	-1.50E-03	1.690E-04	Yes	Yes
September 2000	9/10/2000	MW-2B	7.100E-02	2787.1	-1.50E-03	1.091E-03	No	Yes
September 2000	9/10/2000	MW-2C	5.000E-04	2787.1	-1.50E-03	7.682E-06	Yes	Yes
September 2000	9/10/2000	MW-4B	1.400E-01	1888.1	-1.50E-03	8.272E-03	No	Yes
September 2000	9/10/2000	MW-4C	1.150E-01	1888.1	-1.50E-03	6.795E-03	No	Yes
September 2000	9/10/2000	MW-6A	5.400E-02	2311.9	-1.50E-03	1.691E-03	No	Yes
September 2000	9/10/2000	MW-6B	4.700E-02	2311.9	-1.50E-03	1.471E-03	No	Yes
September 2000	9/10/2000	MW-6C	2.100E-02	2311.9	-1.50E-03	6.575E-04	No	Yes
September 2000	9/10/2000	RW-3	5.100E-02	2812.2	-1.50E-03	7.546E-04	No	No
September 2000	9/10/2000	RW-4	5.000E-04	2304.7	-1.50E-03	1.583E-05	Yes	No
September 2000	9/10/2000	RW-5	7.400E-02	1620.8	-1.50E-03	6.526E-03	No	No
September 2000	9/10/2000	RW-6	2.000E-02	2254.6	-1.50E-03	6.823E-04	No	No
September 2000	9/10/2000	RW-7	3.100E-02	1576.5	-1.50E-03	2.921E-03	No	No
September 2000	9/10/2000	RW-8	3.000E-02	986.9	-1.50E-03	6.838E-03	No	No
September 2000	9/10/2000	RW-9	1.600E-02	425.7	-1.50E-03	8.455E-03	No	No
September 2001	9/15/2001	CW-3	5.000E-04	2828.7	-1.51E-03	7.014E-06	Yes	Yes
September 2001	9/15/2001	MW-11B	5.000E-04	1073.4	-1.51E-03	9.904E-05	Yes	Yes
September 2001	9/15/2001	MW-11C	5.000E-04	1073.4	-1.51E-03	9.904E-05	Yes	Yes
September 2001	9/15/2001	MW-14B	1.300E-01	1561.6	-1.51E-03	1.233E-02	No	Yes
September 2001	9/15/2001	MW-14C	5.000E-04	1561.6	-1.51E-03	4.742E-05	Yes	Yes
September 2001	9/15/2001	MW-15A	5.000E-04	-100.0	-1.51E-03	5.814E-04	No	Yes
September 2001	9/15/2001	MW-15B	5.000E-04	-100.0	-1.51E-03	5.814E-04	No	Yes
September 2001	9/15/2001	MW-16B	3.700E-03	410.6	-1.51E-03	1.992E-03	No	Yes
September 2001	9/15/2001	MW-17B	9.200E-02	953.2	-1.51E-03	2.185E-02	No	Yes
September 2001	9/15/2001	MW-19B	5.000E-04	791.0	-1.51E-03	1.516E-04	Yes	Yes

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TETRACHLOROETHYLENE(PCE)								
September 2001	9/15/2001	MW-2A	5.200E-03	2787.1	-1.51E-03	7.768E-05	Yes	Yes
September 2001	9/15/2001	MW-2B	3.800E-02	2787.1	-1.51E-03	5.676E-04	No	Yes
September 2001	9/15/2001	MW-2C	5.000E-04	2787.1	-1.51E-03	7.469E-06	Yes	Yes
September 2001	9/15/2001	MW-4B	1.400E-01	1888.1	-1.51E-03	8.116E-03	No	Yes
September 2001	9/15/2001	MW-4C	6.450E-02	1888.1	-1.51E-03	3.739E-03	No	Yes
September 2001	9/15/2001	MW-6A	5.400E-02	2311.9	-1.51E-03	1.652E-03	No	Yes
September 2001	9/15/2001	MW-6B	3.700E-02	2311.9	-1.51E-03	1.132E-03	No	Yes
September 2001	9/15/2001	MW-6C	1.200E-02	2311.9	-1.51E-03	3.670E-04	Yes	Yes
September 2001	9/15/2001	RW-3	2.550E-02	2812.2	-1.51E-03	3.667E-04	Yes	No
September 2001	9/15/2001	RW-4	5.000E-04	2304.7	-1.51E-03	1.546E-05	Yes	No
September 2001	9/15/2001	RW-5	1.025E-01	1620.8	-1.51E-03	8.892E-03	No	No
September 2001	9/15/2001	RW-6	1.250E-02	2254.6	-1.51E-03	4.169E-04	Yes	No
September 2001	9/15/2001	RW-7	2.800E-02	1576.5	-1.51E-03	2.597E-03	No	No
September 2001	9/15/2001	RW-8	1.950E-02	986.9	-1.51E-03	4.401E-03	No	No
September 2001	9/15/2001	RW-9	1.400E-02	425.7	-1.51E-03	7.366E-03	No	No
October 2002	10/14/2002	BAL2B	5.000E-04	208.8	-1.24E-03	3.855E-04	Yes	Yes
October 2002	10/14/2002	BAL2C	5.000E-04	484.6	-1.24E-03	2.735E-04	Yes	Yes
October 2002	10/14/2002	CW-3	5.000E-04	2828.7	-1.24E-03	1.478E-05	Yes	Yes
October 2002	10/14/2002	CW-6	5.000E-04	320.4	-1.24E-03	3.355E-04	Yes	Yes
October 2002	10/14/2002	MW-10	3.800E-02	3335.6	-1.24E-03	5.974E-04	No	Yes
October 2002	10/14/2002	MW-11A	5.000E-04	1073.4	-1.24E-03	1.314E-04	Yes	Yes
October 2002	10/14/2002	MW-11B	5.000E-04	1073.4	-1.24E-03	1.314E-04	Yes	Yes
October 2002	10/14/2002	MW-11C	5.000E-04	1073.4	-1.24E-03	1.314E-04	Yes	Yes
October 2002	10/14/2002	MW-13C	5.000E-04	1626.7	-1.24E-03	6.599E-05	Yes	Yes
October 2002	10/14/2002	MW-14B	1.100E-01	1561.6	-1.24E-03	1.574E-02	No	Yes
October 2002	10/14/2002	MW-14C	5.000E-04	1561.6	-1.24E-03	7.155E-05	Yes	Yes
October 2002	10/14/2002	MW-15A	5.000E-04	-100.0	-1.24E-03	5.663E-04	No	Yes
October 2002	10/14/2002	MW-15B	5.000E-04	-100.0	-1.24E-03	5.663E-04	No	Yes
October 2002	10/14/2002	MW-16A	5.000E-04	410.6	-1.24E-03	2.999E-04	Yes	Yes
October 2002	10/14/2002	MW-16B	2.000E-02	410.6	-1.24E-03	1.200E-02	No	Yes
October 2002	10/14/2002	MW-17B	4.000E-02	953.2	-1.24E-03	1.221E-02	No	Yes
October 2002	10/14/2002	MW-18A	5.000E-04	247.3	-1.24E-03	3.675E-04	Yes	Yes
October 2002	10/14/2002	MW-18B	2.400E-03	247.3	-1.24E-03	1.764E-03	No	Yes
October 2002	10/14/2002	MW-19B	5.000E-04	791.0	-1.24E-03	1.868E-04	Yes	Yes
October 2002	10/14/2002	MW-1A	5.000E-04	2852.9	-1.24E-03	1.434E-05	Yes	Yes
October 2002	10/14/2002	MW-1B	5.000E-04	2852.9	-1.24E-03	1.434E-05	Yes	Yes

Project: Long Prairie site **User Name:** Meng

Location: Todd County **State:** Minnesota

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TETRACHLOROETHYLENE(PCE)								
October 2002	10/14/2002	MW-2A	9.700E-04	2787.1	-1.24E-03	3.019E-05	Yes	Yes
October 2002	10/14/2002	MW-2B	4.100E-02	2787.1	-1.24E-03	1.276E-03	No	Yes
October 2002	10/14/2002	MW-2C	6.900E-03	2787.1	-1.24E-03	2.148E-04	Yes	Yes
October 2002	10/14/2002	MW-3A	5.000E-04	3041.4	-1.24E-03	1.134E-05	Yes	Yes
October 2002	10/14/2002	MW-3B	5.000E-04	3041.4	-1.24E-03	1.134E-05	Yes	Yes
October 2002	10/14/2002	MW-4A	3.300E-02	1888.1	-1.24E-03	3.145E-03	No	Yes
October 2002	10/14/2002	MW-4B	7.700E-02	1888.1	-1.24E-03	7.339E-03	No	Yes
October 2002	10/14/2002	MW-4C	5.100E-02	1888.1	-1.24E-03	4.861E-03	No	Yes
October 2002	10/14/2002	MW-5A	5.000E-04	1381.9	-1.24E-03	8.949E-05	Yes	Yes
October 2002	10/14/2002	MW-5B	5.000E-04	1381.9	-1.24E-03	8.949E-05	Yes	Yes
October 2002	10/14/2002	MW-6A	5.000E-04	2311.9	-1.24E-03	2.812E-05	Yes	Yes
October 2002	10/14/2002	MW-6B	4.700E-03	2311.9	-1.24E-03	2.643E-04	Yes	Yes
October 2002	10/14/2002	MW-6C	2.500E-02	2311.9	-1.24E-03	1.406E-03	No	Yes
October 2002	10/14/2002	RW-1A	1.000E-03	3358.7	-1.24E-03	1.528E-05	Yes	No
October 2002	10/14/2002	RW-1B	5.000E-04	3299.4	-1.24E-03	8.223E-06	Yes	No
October 2002	10/14/2002	RW-1C	5.000E-04	3302.5	-1.24E-03	8.192E-06	Yes	No
October 2002	10/14/2002	RW-3	2.000E-02	2812.2	-1.24E-03	6.033E-04	No	No
October 2002	10/14/2002	RW-4	5.000E-04	2304.7	-1.24E-03	2.837E-05	Yes	No
October 2002	10/14/2002	RW-5	8.400E-02	1620.8	-1.24E-03	1.117E-02	No	No
October 2002	10/14/2002	RW-6	9.500E-03	2254.6	-1.24E-03	5.737E-04	No	No
October 2002	10/14/2002	RW-7	2.200E-02	1576.5	-1.24E-03	3.091E-03	No	No
October 2002	10/14/2002	RW-8	1.800E-02	986.9	-1.24E-03	5.268E-03	No	No
October 2002	10/14/2002	RW-9	1.500E-02	425.7	-1.24E-03	8.829E-03	No	No

Note: Projected Concentrations that are below the user-specified detection limit are indicated by a check mark to its right; for sampling events with less than 3 selected plume centerline wells, NO projected concentrations are calculated because no regression coefficient is available.

MAROS Risk-Based Power Analysis for Site Cleanup

Project: Long Prairie site

User Name: Meng

Location: Todd County

State: Minnesota

Parameters:

Groundwater Flow Direction: 90 degrees **Distance to Receptor:** -100 feet

From Period: May 1999 **to** October 2002

5/20/1999 10/14/2002

Selected Plume Centerline Wells:

Well	Distance to Receptor (feet)
MW-15B	-100.0
MW-16B	410.6
MW-17B	953.2
MW-4B	1888.1
MW-2B	2787.1

The distance is measured in the Groundwater Flow Angle from the well to the compliance boundary.

				Normal Distribution Assumption			Lognormal Distribution Assumption				
Sample Event	**Sample Szie**	**Sample Mean**	**Sample Stdev.**	**Cleanup Status**	**Power**	**Expected Sample Size**	**Celanup Status**	**Power**	**Expected Sample Size**	**Alpha Level**	**Expected Power**
TETRACHLOROETHYLENE(PCE)				Cleanup Goal = 0.005							
May 1999	30	1.73E-03	4.35E-03	Attained	0.992	12	Not Attained	S/E	S/E	0.05	0.8
October 1999	25	1.38E-04	2.79E-04	Attained	1.000	<=3	Not Attained	S/E	S/E	0.05	0.8
September 2000	18	3.71E-03	6.36E-03	Not Attained	0.211	>100	Not Attained	S/E	S/E	0.05	0.8
September 2001	18	2.97E-03	5.74E-03	Not Attained	0.432	50	Not Attained	S/E	S/E	0.05	0.8
October 2002	34	1.90E-03	3.95E-03	Attained	0.998	11	Attained	0.591	60	0.05	0.8

Note: #N/C means "not conducted" due to a small sample size (N<4) or that the mean concentration is much greater than the cleanup level; Sample Size is the number of sampling locations used in the power analysis; Expected Sample Size is the number of concentration data needed to reach the Expected Power under current sample variability.

DRAFT FINAL

THREE-TIERED

GROUNDWATER MONITORING NETWORK

OPTIMIZATION EVALUATION

FOR

LONG PRAIRIE GROUND WATER CONTAMINATION SUPERFUND SITE, MINNESOTA

Prepared for

US Environmental Protection Agency

MAY 2003

PARSONS
Denver, Colorado

EXECUTIVE SUMMARY

This report presents a description and evaluation of the groundwater monitoring program associated with the Long Prairie Ground Water Contamination Superfund Site in Long Prairie, Minnesota. Groundwater at the site was contaminated by release of dry-cleaning solvents into the primary drinking water aquifer. The monitoring program at this site was evaluated to identify potential opportunities to streamline monitoring activities while still maintaining an effective monitoring network. This evaluation is being conducted as part of an independent assessment of monitoring network optimization (MNO) methods by the US Environmental Protection Agency (USEPA) and the Air Force Center for Environmental Excellence (AFCEE).

Objectives

Groundwater monitoring programs have two primary objectives (USEPA, 1994; Gibbons, 1994):

1. Evaluate long-term temporal trends in contaminant concentrations (*temporal objective*); and

2. Evaluate the extent to which contaminant migration is occurring (*spatial objective*).

The relative success of any remediation system (including the monitoring network) is judged based on the degree to which it achieves the stated objectives of the system. Designing an effective groundwater monitoring program involves locating monitoring points and developing a site-specific strategy for groundwater sampling and analysis that maximizes the amount of relevant information that can be obtained while minimizing incremental costs. The effectiveness of a monitoring network in achieving the two primary monitoring objectives can be evaluated quantitatively using statistical techniques. Qualitative evaluation also is important to allow consideration of such factors as hydrostratigraphy, locations of potential receptor exposure points with respect to a dissolved contaminant plume, and the direction(s) and rate(s) of contaminant migration.

The general objective of the project was to optimize the long-term groundwater monitoring network at the Long Prairie site by applying a three-tiered MNO approach to assess the degree to which the monitoring network addresses each of the two primary objectives of monitoring listed above and other important considerations. The three-tiered MNO evaluation described in this report examines the 44 wells included in the Long Prairie monitoring network. The specific objectives of the project were as follow:

- Apply a qualitative methodology that considers factors such as hydrostratigraphy, locations of potential receptors with respect to the dissolved plume, and the direction(s) and rate(s) of contaminant migration, to establish the frequency at which monitoring should be conducted, and if each well should be retained in or removed from the monitoring program.

- Conduct a Mann-Kendall statistical analysis to determine the temporal trends of contaminants of concern (COCs) over time, and apply an algorithm to determine the relevance of the trends within the monitoring network.

- Determine the relative amount of spatial information contributed by each monitoring well by performing a spatial statistical analysis utilizing kriging error predictions.

- Combine and evaluate the results of the three analyses to establish the frequency at which monitoring should be conducted, as well as the optimal number and locations of wells in the monitoring network.

Current Monitoring Program

The purposes of groundwater monitoring at Long Prairie are 1) to monitor progress toward achieving the remedial action objectives set forth in the Record of Decision (as amended), and 2) to gather adequate information to determine the status and effectiveness of the groundwater extraction and treatment system. Wells are classified as recovery (i.e., extraction) wells, monitoring wells, and municipal water-supply wells. The purposes of the wells included in groundwater monitoring program are to:

- Evaluate the effectiveness of the groundwater recovery system on controlling the plume and improving regional groundwater quality

- Confirm protection of the city of Long Prairie water supply wells (Barr, 2002).

The most recent monitoring event, conducted during October 2002, involved sampling of 44 wells in the Long Prairie contaminant plume area, including 10 recovery wells, 2 municipal water-supply wells, and 32 monitoring wells. Several of the monitoring wells are installed as clusters at a single location, but screened at different depths. The "A" wells are screened across the water table, the "B" wells are screened at the based of the upper glacial outwash deposits, and the "C" wells are screened in the lower outwash deposits. Typically, about half of the wells sampled during the most recent monitoring event are routinely sampled as part of the groundwater monitoring program; for example, in the 2001 and 2000 sampling rounds, a subset of 26 of the 44 wells was sampled. This subset included quarterly sampling of the 6 active extraction wells (RW3 through RW9, excluding RW4) and city well CW3, and annual sampling of 19 monitoring wells (including RW4). In 2002, city well CW6 was added to the quarterly sampling schedule.

The "current" sampling plan includes the 25 extraction and monitoring wells sampled during scheduled 2000 and 2001 monitoring events, plus city wells CW3 and CW6. The three-tiered MNO evaluation in described in this report was used to examine the 44-well network monitored during the October 2002 sampling event and to develop optimization recommendations. The resulting optimized well network is then compared to the currently monitored 27-well network.

Optimization Findings

The Long Prairie groundwater monitoring program was evaluated using results for sampling events performed from May 1996 through October 2002. The analytical database provided to Parsons contained from 1 to 29 sampling results for each constituent for each of the 44 wells in the Long Prairie region. The primary COCs identified for the Long Prairie plume are PCE, TCE, and *cis*-1,2-DCE. PCE is the primary COC because it has been detected at the highest concentrations and has the broadest distribution in groundwater at the site. PCE sampling results were used to conduct the spatial component of the three-tiered MNO evaluation.

Results from the three-tiered MNO evaluation of the 2002 program for Long Prairie indicate that 18 of the 44 wells could be removed from the groundwater monitoring program with little loss of information. Based on these recommendations, the "current" sampling plan (the monitoring and extraction wells included in the 2000 and 2001 sampling schedules, plus CW3 and CW6), could be optimized by removing 4 of the 27 active monitoring wells, and adding 3 additional area wells. A refined monitoring program, consisting of 26 wells (2 to be sampled quarterly, 6 to be sampled semi-annually, 14 to be sampled annually, and 4 to be sampled biennially) would be adequate to address the two primary objectives of monitoring. This refined monitoring network would result in an average 36 sampling events per year, compared to 51 events per year under the current monitoring program. ***Implementing these recommendations for optimizing the LTM monitoring program at Long Prairie could reduce current LTM annual monitoring by over 29 percent. Additionally, based on a per well sampling cost ranging from$100 to $280, these recommendations could reduce costs by an average of $1500 to $4,200 per year.***

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ACRONYMS AND ABBREVIATIONS

AFCEE	Air Force Center for Environmental Excellence
ASCE	American Society of Chemical Engineers
bgs	below ground surface
CAH	chlorinated aliphatic hydrocarbon
ESD	explanation of significant difference
COC	contaminant of concern
DCE	dichloroethene
ESRI	Environmental Systems Research Institute, Inc.
GAC	granular activated carbon
Gpm	gallons per minute
GIS	geographical information system
LTM	long-term monitoring
µg/L	microgram(s) per liter
MCL	maximum contaminant level
MCPA	Minnesota Pollution Control Agency
MDH	Minnesota Department of Health
MNO	monitoring network optimization
NPL	National Priorities List
O&M	operations and maintenance
OU	operable unit
PCE	tetrachloroethene
PQL	practical quantitation limit
RAO	remedial action objective
ROD	Record of Decision
SVE	soil vapor extraction
TCE	trichloroethene
USEPA	United States Environmental Protection Agency
VC	vinyl chloride
VOC	volatile organic compound

SECTION 1

INTRODUCTION

Groundwater monitoring programs have two primary objectives (U.S. Environmental Protection Agency [USEPA], 1994; Gibbons, 1994):

1. Evaluate long-term temporal trends in contaminant concentrations at one or more points within or outside of the remediation zone, as a means of monitoring the performance of the remedial measure (*temporal objective*); and

2. Evaluate the extent to which contaminant migration is occurring, particularly if a potential exposure point for a susceptible receptor exists (*spatial objective*).

The relative success of any remediation system and its components (including the monitoring network) must be judged based on the degree to which it achieves the stated objectives of the system. Designing an effective groundwater monitoring program involves locating monitoring points and developing a site-specific strategy for groundwater sampling and analysis so as to maximize the amount of relevant information that can be obtained while minimizing incremental costs. Relevant information is that required to effectively address the temporal and spatial objectives of monitoring. The effectiveness of a monitoring network in achieving these two primary objectives can be evaluated quantitatively using statistical techniques. In addition, there may be other important considerations associated with a particular monitoring network that are most appropriately addressed through a qualitative assessment of the network. The qualitative evaluation may consider such factors as hydrostratigraphy, locations of potential receptor exposure points with respect to a dissolved contaminant plume, and the direction(s) and rate(s) of contaminant migration.

This report presents a description and evaluation of the groundwater monitoring program associated with the Long Prairie Ground Water Contamination Superfund Site (Long Prairie), Minnesota. A 44-well monitoring network was evaluated to identify potential opportunities to streamline monitoring activities while still maintaining an effective monitoring program. This evaluation is being conducted as part of an independent assessment of monitoring network optimization (MNO) methods by the USEPA and the Air Force Center for Environmental Excellence (AFCEE). A three-tiered approach, consisting of a qualitative evaluation, an evaluation of temporal trends in contaminant concentrations, and a statistical spatial analysis, was conducted to assess the degree to which the monitoring network addresses each of the two primary objectives of monitoring, and other important considerations. The results of the three evaluations were combined and used to assess the optimal frequency of monitoring and the spatial distribution of the components of the monitoring network. The results of the analysis were then used to develop recommendations for optimizing the monitoring program at Long Prairie.

SECTION 2

SITE BACKGROUND INFORMATION

The location, operational history, geology, and hydrogeology of Long Prairie are briefly described in the following subsections.

2.1 SITE DESCRIPTION

The city of Long Prairie, Minnesota is a small farming community of fewer than 5,000 residents, and is located in Todd County in central Minnesota, about 120 miles northwest of Minneapolis/St. Paul. The Long Prairie site comprises a 0.16-acre source area of contaminated soil and an elongate plume of dissolved chlorinated aliphatic hydrocarbons (CAHs) in the drinking-water aquifer underlying the north-central part of the city of Long Prairie in central Minnesota. The source of the groundwater contamination was a dry-cleaning establishment, formerly located in the city's commercial district at 243 Central Street in the city of Long Prairie, which operated from 1949 through 1984. The contamination resulted from the discharge of spent dry-cleaning solvents, primarily tetrachloroethene (PCE), into the subsurface via a shallow, makeshift "french drain." The contaminated soils served as a source of groundwater contamination, and a dissolved CAH plume has migrated northward at least 3,600 feet from the source area, extending beneath an older residential neighborhood and to within 500 feet of the Long Prairie River.

The contamination was discovered in 1983, during a survey of municipal drinking-water-supply wells for synthetic organic contaminants. PCE and other CAHs, including trichloroethene (TCE) and *cis*-1,2-dichloroethene (DCE), were detected in two (CW4 and CW5) of the five Long Prairie municipal water-supply wells, which are screened in the lower unit of the Long Prairie Sand Plain aquifer. Eight of 21 residential wells sampled also were contaminated. Because the detected concentrations of CAHs exceeded federal maximum contaminant levels (MCLs) or other risk-based levels, the Minnesota Department of Health (MDH) recommended that the two affected city wells be removed from service, and issued a health advisory for a 15-block area in the northern part of the city. The Minnesota Pollution Control Agency (MCPA) ordered that bottled water be supplied for the 350 residents on city water or private wells in the advisory area. A new municipal well (CW6) was installed in the deeper outwash deposits northeast of (outside) the contaminant plume in 1984.

After enforcement activities failed to identify any viable potentially responsible parties from among the three owners of the dry-cleaning property, a Multi-Site Cooperative Agreement was signed on September 4, 1984 between MPCA and the US Environmental Protection Agency (USEPA) to implement a remedial investigation and feasibility study. Based on the results of the RI/FS, the Long Prairie Groundwater Contamination Site was promulgated to the National Priorities List (NPL) in 1985, and a Record of Decision (ROD) was signed in 1988.

The ROD and subsequent explanations of significant difference (ESDs) identify the following remedial action objectives (RAOs) for groundwater:

- Provide a safe drinking-water supply for current and future users of the Long Prairie San Plain aquifer by
  - Restoring the aquifer by reducing the major contaminant (PCE) concentrations to a health-based concentration of 5 micrograms per liter (μg/L) or less,
  - Providing an alternate water supply to persons using the contaminated part of the aquifer; and
  - Reducing soil PCE concentrations to 1,200 micrograms per kilogram or less to maintain an acceptable groundwater risk level ($< 1x10^{-6}$) due to PCE leaching from soils;

- Prevent the spread of contaminated groundwater to wells currently unaffected by the CAH contamination, including municipal well CW6; and

- Prevent adverse effects on aquatic organisms in Long Prairie River due to implementation of remedial actions by obtaining a PCE concentration of 5 μg/L or less in treatment system effluent discharged to the river.

Pursuant to achieving these RAOs, the ROD identified three operable units (OUs). OU1 addresses groundwater contamination through extraction of CAH-contaminated groundwater via nine extraction wells (RWs 1 through 9), treatment of the extracted water using granular activated carbon (GAC) filtration, and discharge of treated water to the Long Prairie River. Installation of the pump-and-treat system, with a 250-gallon-per-minute (gpm) treatment capacity, was completed in August 1997, and is intended to restore aquifer quality to MCLs, and to prevent further migration and discharge of the CAH plume to the Long Prairie River. The source area soils were addressed through soil vapor extraction (SVE) under OU2, which operated from June 1997 through 1999, when it was decommissioned. OU3 comprises an alternative water supply system, which provided municipal water hookups to residents with private wells within the health-advisory area; these hookups were completed in 1996.

The OU1 groundwater remedial system performance is monitored through quarterly to annual sampling of a series of monitoring and city wells, and operation and maintenance (O&M) monitoring of the extraction and treatment systems. The monitoring program is fully described in Section 3.

2.2 GEOLOGY AND HYDROGEOLOGY

The city of Long Prairie is situated at an elevation of 1,300 feet above mean sea level (amsl) on the eastern bank of the Long Prairie River. The sediments underlying the city consist of a series of glacial till and outwash deposits nearly 700 feet thick, deposited in a large valley along the Long Prairie River. Outwash sediments in the valley are composed of coarse sands and gravels of deposited during two events, which are separated by finer grained tills. The lower outwash is incised into the lower till, which forms the base of that water-bearing unit. The lower outwash appears to extend to the east of the river, but does not appear to be present west of the river. Above the lower outwash is a younger till (the upper Wadena till). The surficial upper outwash unit incises into the lower outwash unit through the Wadena till just east of the Long Prairie River, where the outwash deposits form a single hydrogeologic unit. However, the till is intact along the eastern side of the outwash valley, and where present, acts as an aquitard between the two outwash units. The upper outwash unit pinches out at the eastern edge of the glacial valley (Barr, 2002). The aquifer is recharged by inflow from upgradient lakes and precipitation. Because of the high transmissivity of the outwash deposits, and the fact that the river is "under-fit" in the much larger underlying glacial valley, the influence of the Long Prairie River on groundwater flow in the site area may limited.

At the Long Prairie site, the solvent release occurred in an area in which the upper till is present between the upper and lower outwash units. However, the saturated thickness of the upper outwash at the source area (well MW10A) is only about 10 feet (Barr, 2002). The till pinches out just north of the source area, and the CAH plume in groundwater is present in both the shallow and deeper portions of the outwash deposits in the incised channel west of the western edge of the upper till. However, because the upper and lower outwash units are in direct hydraulic communication where the confining till is absent, there is a pathway for contaminant migration to be drawn into the city wells screened in the lower outwash unit to the east. The upper till is present east of the longitudinal axis of the north/south-trending CAH plume; municipal wells CW3 and CW6 are screened in the lower outwash deposits below the upper till.

Where the upper till unit is absent (along the incised upper outwash channel), groundwater in the outwash aquifer occurs under water-table (unconfined) conditions. Groundwater flow directions in the upper and lower outwash deposits generally parallel the channel of the Long Prairie River; from the PCE source area, groundwater flows northeast to the vicinity of extraction wells RW5 and RW7, then flows west-northwest toward the Long Prairie River (Figure 2.1). In September 2001, the water table was

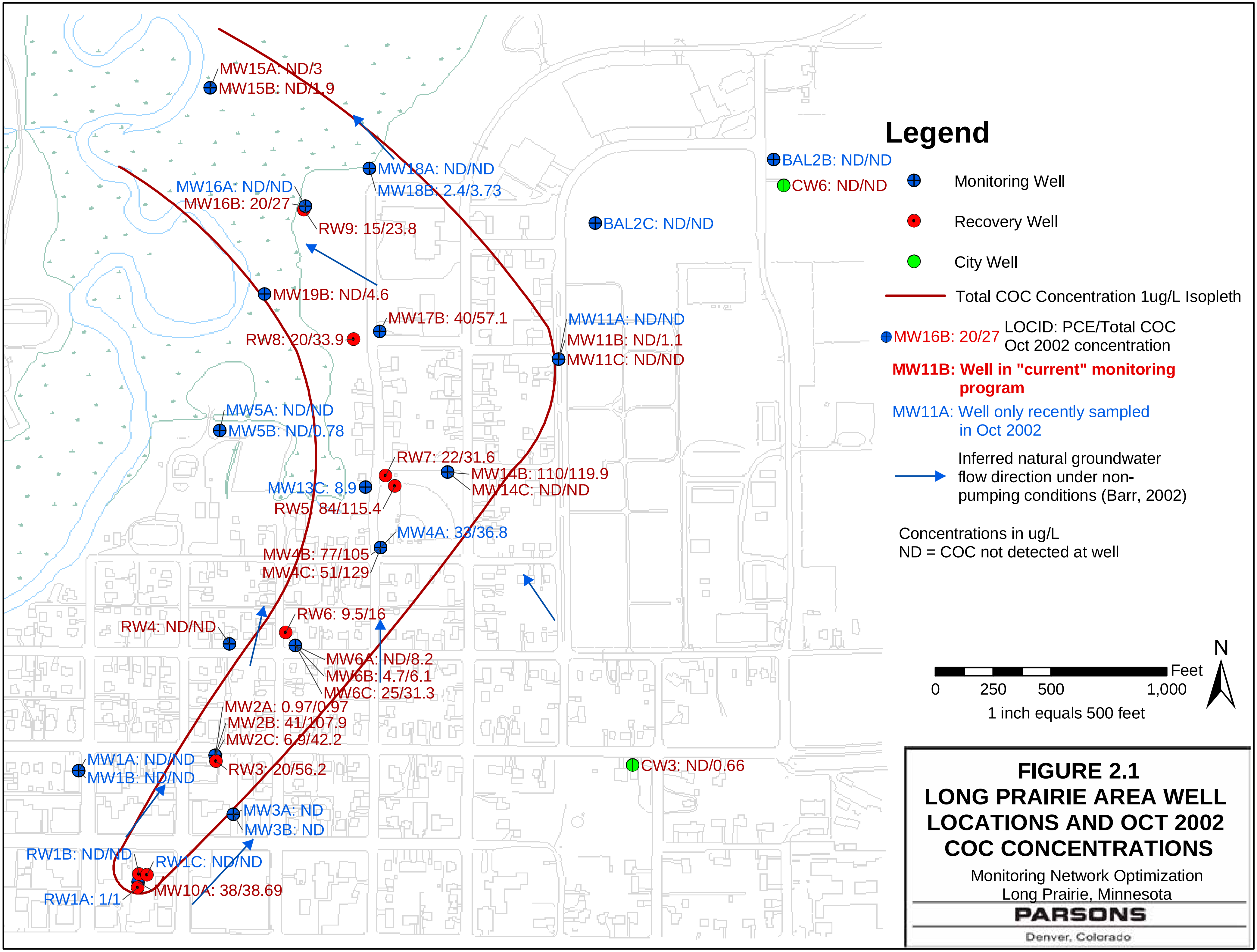


FIGURE 2.1
LONG PRAIRIE AREA WELL LOCATIONS AND OCT 2002 COC CONCENTRATIONS

Monitoring Network Optimization
Long Prairie, Minnesota

PARSONS
Denver, Colorado

measured at elevations ranging from about 1,287 feet amsl near the source area at the south end of the CAH plume, to 1,282 feet amsl at the northern end of the plume (MW15A) (Barr, 2002). The average hydraulic gradient along the plume flowpath (i.e., between MW10A in the source area and MW16A near the plume toe) in the upper outwash aquifer in September 2001 was approximately 0.0012 foot per foot. Using this gradient, the calibrated hydraulic conductivity value of 426 feet per day (ft/day) used in the MODFLOW model constructed for the site (Bangsund, 2003), and an estimated effective porosity for sand and gravel of 0.30, the average advective groundwater flow velocity in the upper outwash aquifer is estimated to be 1.7 ft/day. The vertical gradients in the incised channel deposits are negligible, but appear to be slightly downward at the northern extent of the CAH plume, suggesting that the plume may not directly threaten wetlands in that area (Barr, 2002).

Where the upper till is present, groundwater in the lower outwash deposits is under confined to semi-confined conditions, with a generally northwesterly groundwater flow direction. Hydraulic properties of the lower glacial outwash deposits are inferred to be comparable to those of the upper outwash deposits. Groundwater flow directions are influenced locally by pumping of the city water-supply wells, as well as by operation of the OU1 extraction wells.

2.3 NATURE AND EXTENT OF CONTAMINATION

The source of contamination at the Long Prairie site was discharge of dry-cleaning solvents directly into glacial outwash deposits at the site of the former dry cleaning establishment. Available records indicate that 2,200 gallons of PCE were used during the period of operation from 1949 through 1984. While PCE was the primary solvent disposed of, trace amounts of chlorinated ethanes also have been detected. The waste solvents percolated through the coarse outwash soils at the source to the water table in the Long Prairie Sand Plain aquifer, and subsequently migrated as dissolved constituents in groundwater. PCE and its daughter products TCE and *cis*-1,2-DCE have been detected in a plume about 1,000 feet wide and up to 3,600 feet long. In October 2002, the CAH plume extended from the source area, near the inactive RW1A/1B/1C extraction well cluster, approximately 3,200 feet downgradient to the northwest, to nested monitoring well pair MW18A/B (Figure 2.1).

Contamination has been detected throughout the saturated thickness of the upper glacial outwash deposits, and also historically has been detected in the lower outwash deposits beneath the upper till at city well CW3 (Figure 2.1). Maximum historical concentrations of PCE in groundwater were as high as 150,000 µg/L. Recent monitoring data indicate that maximum PCE concentrations have decreased to around 100 µg/L in the core of the plume, and that PCE is no longer present at detectable concentrations in the lower outwash deposits east of the incised channel. However, contamination persists throughout the saturated upper outwash deposits within the incised channel (along the centerline of the plume), and the overall extent of the plume, as defined by the 5-µg/L isolpleth for PCE, has not changed significantly since pumping began (Barr, 2002). In October 2002, PCE concentrations in the plume ranged from 2.4 µg/L at the northern end of the plume (well MW18B) to 110 µg/L near the center of the plume, at well MW14B (Figure 2.1). In the shallow portion of the upper outwash deposits in the source area, PCE was detected at 38 µg/L at well MW10A.

2.4 REMEDIAL SYSTEMS

As discussed in Section 2.1, an SVE system (OU2) was installed to remove PCE from vadose-zone soils in the source area. The SVE system was pilot tested and completed in June 1997, and operated continuously through the end of 1999, when it was disassembled due to the low magnitude of extracted PCE concentrations.

The OU1 groundwater extraction system consists of 10 recovery wells, 6 of which are currently operational. The RAOs for the OU1 groundwater extraction and treatment system include restoring aquifer quality to MCLs, and preventing further migration and discharge of the CAH plume to the Long Prairie River (Section 2.1). Initially, seven recovery wells (RW1A/1B/1C/3/4/6/7) were installed, and closed municipal well CW5 was retrofitted to become RW5. This eight-well extraction system began operating in May 1996. Two additional recovery wells (RW8 and 9) were installed in September

1999. The recovery wells are distributed along the axis of the plume, and the system is designed to recover and treat up to 250 gpm of groundwater. According to the First Five-Year Review Report (MPCA, 2002), operation of 4 of the 10 recovery wells (RW1A, RW1B, RW1C, and RW4) was discontinued starting in 2000 to allow for higher pumping rates at wells closer to the center of the plume. Recovered groundwater is discharged to the Long Prairie River following treatment with GAC.

SECTION 3

LONG-TERM MONITORING PROGRAM AT LONG PRAIRIE

The current groundwater monitoring program at Long Prairie and the 44 wells sampled during the comprehensive October 2002 monitoring event were examined to identify potential opportunities for streamlining monitoring activities while still maintaining an effective performance and compliance monitoring program. The 2002 and the current (2000/2001) monitoring programs at Long Prairie are reviewed in the following subsections.

3.1 DESCRIPTION OF MONITORING PROGRAM

The purposes of monitoring at Long Prairie are to monitor progress toward achieving the RAOs set forth in the ROD and ESDs, and to gather adequate information to determine the effectiveness of the groundwater recovery and treatment system. Wells are classified as recovery (extraction) wells, monitoring wells, and city wells. The monitoring program is designed to:

- Evaluate the effectiveness of the groundwater extraction system on controlling the plume and improving regional groundwater quality
- Confirm protection of the city of Long Prairie water-supply wells. (Barr, 2002)

The October 2002 sampling event included 44 wells in the Long Prairie region. Several of the monitoring wells are installed as clusters at a single location, and screened at different depths. The “A” wells are screened across the water table, the “B” wells are screened at the based of the upper glacial outwash deposits, and the “C” wells are screened in the lower outwash deposits. Typically, about half of the wells sampled during the most recent monitoring event are routinely sampled as part of the groundwater monitoring program; for example, in the 2001 and 2000 sampling rounds, a subset of 26 of the 44 wells was sampled. This subset included quarterly sampling of the 6 active extraction wells (RW3 through RW9, excluding RW4) and city well CW3, and annual sampling of 19 monitoring wells (including RW4). In 2002, city well CW6 was added to the quarterly sampling schedule. In the second quarter of 2000, the suite of volatile organic compounds (VOCs) for which groundwater samples were analyzed was reduced from the MDH 465E list to the COCs: DCE, PCE, TCE, and vinyl chloride (VC). Additionally, a gas chromatograph (GC) analytical method (assumed to be USEPA Method 8021B) is now used instead of the gas chromatograph/mass spectrometer (GC/MS) method (assumed to be USEPA Method SW8260B) formerly required.

The locations of 44 Long Prairie wells sampled in October 2002 are shown in relation to the COC plume on Figure 2.1. Table 3.1 lists these wells with their screened intervals, well type, and designation. The "current" sampling plan includes the 18 monitoring wells and 7 recovery wells sampled during scheduled monitoring events in 2000 and 2001, as well as city wells CW3 and CW6. The three-tiered MNO evaluation in described in this report examines the 44 wells sampled during October 2002, and compared the recommended optimized well network to the 27-well network included in the "current" monitoring program.

3.2 SUMMARY OF ANALYTICAL DATA

The Long Prairie groundwater monitoring program was evaluated using results for sampling events performed from May 1996 through October 2002. These analytical data were provided to Parsons by Ms. Jonelle Branca, the Data Management Coordinator for Barr Engineering (MPCA's environmental contractor). The database was processed to remove duplicate data by retaining the maximum result for each duplicate sample pair. The analytical database provided to Parsons contained from 1 to 29 sampling results for each constituent for each of the 44 wells in the Long Prairie site area. As discussed in Section 2.3, the primary COCs identified for the Long Prairie plume are PCE, TCE, and *cis*-1,2-DCE, therefore, the MNO evaluation focused on these constituents.

TABLE 3.1
GROUNDWATER MONITORING PROGRAM
THREE-TIERED MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA

Well ID	Screened Interval (ft bgs) [a]	Sampling Frequency [b]
Monitoring Wells in 2000/2001 Sampling Plan		
MW2A	15-20	Annual
MW2B	31-35	Annual
MW2C	48-53	Annual
MW4B	31.5-35.5	Annual
MW4C	42.0-46.0	Annual
MW6A	12.0-17	Annual
MW6B	31.0-37	Annual
MW6C	46.0-59	Annual
MW10A	16-21	Annual
MW11B		Annual
MW11C	50-55	Annual
MW14B	21-26	Annual
MW14C	50-55	Annual
MW15A	12	Annual
MW15B	33	Annual
MW16B	25.3	Annual
MW17B	33	Annual
MW19B	26.5	Annual
City Water-Supply Wells		
CW3	67-85	Quarterly
CW6	53-76	Quarterly
Recovery Wells		
RW1A	15-30	NA [c]
RW1B	13-45	NA
RW1C	12.5-23.5	NA
RW3	17-52	Quarterly
RW4	10.0-50	Annual
RW5	41-56	Quarterly
RW6	10.0-55.5	Quarterly
RW7	15-45	Quarterly
RW8	30-40	Quarterly
RW9	25-35	Quarterly
Other Area Wells Sampled in October 2002		
BAL2B	57-65	NA
BAL2C	40-50	NA
MW1A	9.5-14.5	NA
MW1B	30-35	NA
MW3A	17.8-22.8	NA
MW3B	30-35	NA
MW4A	10.0-15	NA
MW5A	4.5-9.5	NA
MW5B	31.0-35	NA
MW11A		NA
MW13C	50-55	NA
MW16A	15.5	NA
MW18A	15.1	NA
MW18B	35	NA

[a] ft bgs = feet below ground surface

[b] Reduced sampling frequency established prior to

Table 3.2 presents a summary of the occurrence of the three primary COCs in Long Prairie groundwater based on the data collected from 33 site and area monitoring wells during the period from May 1996 through October 2002. The data summarized in Table 3.2 exclude results for the recovery wells (with the exception of inactive extraction well RW4, which is sampled annually as a monitoring well) and city wells CW3 and CW6. As indicated in this table and discussed in Section 2.3, PCE is the primary COC based on its broad distribution at concentrations exceeding its MCL of 5 µg/L. PCE has been detected in approximately 39 percent of groundwater samples, and has exceeded its MCL in approximately 33 percent of the samples. PCE has been detected in 20 of the 33 monitoring wells in the Long Prairie site area, and has exceeded the MCL at 14 of these wells. One of PCE's reductive-dechlorination daughter products, *cis*-1,2-DCE, is another prevalent compound on site, and has been detected in 44 percent of the collected samples. However, detected concentrations of *cis*-1,2-DCE have exceeded the MCL of 70 µg/L in only about 1 percent of samples. TCE, another PCE daughter product, has been detected at Long Prairie in approximately 35 percent of samples. Detected concentrations of TCE have exceeded its MCLs of 5 µg/L in approximately 21 percent of the samples.

PCE sampling results were the primary data used to conduct the qualitative and spatial components of the three-tiered MNO evaluation due to the magnitude and spatial extent of PCE concentrations in groundwater at Long Prairie compared to the other detected compounds.

TABLE 3.2
SUMMARY OF OCCURRENCE OF GROUNDWATER CONTAMINANTS OF CONCERN IN MONITORING WELLS
THREE-TIERED MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA

Parameter	Total Samples[a/]	Percentage of Detects	Range of Detects (µg/L)[c/]	MCL[b/] (µg/L)	Percentage of MCL Exceedances	Number of Wells with Results	Number of Wells with Detections[d/]	Number of Wells with MCL Exceedances
Tetrachloroethene	248	39.1%	0.97-150000	5	32.7%	33	20	14
Trichloroethene	248	34.7%	0.57-85	5	21.4%	33	17	11
cis -1,2-Dichloroethene	248	44.0%	0.34-570	70	1.2%	33	22	2

[a/] Analytical data analyzed includes sampling results from May 1996 through October 2002.

[b/] MCL = federal maximum contamiant level.

SECTION 4

QUALITATIVE MNO EVALUATION

An effective groundwater monitoring program will provide information regarding contaminant plume migration and changes in chemical concentrations through time at appropriate locations, enabling decision-makers to verify that contaminants are not endangering potential receptors, and that remediation is occurring at rates sufficient to achieve RAOs within a reasonable time frame. The design of the monitoring program should therefore include consideration of existing receptor exposure pathways, as well as exposure pathways arising from potential future use of the groundwater.

Performance monitoring wells located upgradient, within, and immediately downgradient from a plume provide a means of evaluating the effectiveness of a groundwater remedy relative to performance criteria. Long-term monitoring (LTM) of these wells also provides information about migration of the plume and temporal trends in chemical concentrations. Groundwater monitoring wells located downgradient from the leading edge of a plume (i.e., sentry wells) are used to evaluate possible changes in the extent of the plume and, if warranted, to trigger a contingency response action if contaminants are detected.

Primary factors to consider when developing a groundwater monitoring program include at a minimum:

- Aquifer heterogeneity,
- Types of contaminants,
- Distance to potential receptor exposure points,

- Groundwater seepage velocity and flow direction(s),
- Potential surface-water impacts, and
- The effects of the remediation system.

These factors will influence the locations and spacing of monitoring points and the sampling frequency. Typically, the greater the seepage velocity and the shorter the distance to receptor exposure points, the more frequently groundwater sampling should be conducted.

One of the most important purposes of LTM is to confirm that the contaminant plume is behaving as predicted. Graphical and statistical tests can be used to evaluate plume stability. If a groundwater remediation system or strategy is effective, then over the long term, groundwater-monitoring data should demonstrate a clear and meaningful decreasing trend in concentrations at appropriate monitoring points. The current groundwater monitoring program at Long Prairie was evaluated to identify potential opportunities to LTM optimization.

4.1 METHODOLOGY FOR QUALITATIVE EVALUATION OF MONITORING NETWORK

The three-tiered MNO evaluation of the Long Prairie groundwater LTM program considered information for the 44 wells sampled during the October 2002 sampling round. These wells, their respective screened intervals, and their current monitoring frequencies are listed in Table 3.1, and their locations are depicted on Figure 2.1.

Multiple factors were considered in developing recommendations for continuation or cessation of groundwater monitoring at each well. In some cases, a recommendation was made to continue monitoring a particular well, but at a reduced frequency. A recommendation to discontinue monitoring at a particular well based on the information reviewed does not necessarily constitute a recommendation to physically abandon the well. A change in site conditions might warrant resumption of monitoring at some time in the future at wells that are not currently recommended for continued sampling.

Typical factors considered in developing recommendations to retain a well in, or remove a well from, the monitoring program are summarized in Table 4.1. Typical factors considered in developing recommendations for monitoring frequency are summarized in Table 4.2.

TABLE 4.1
MONITORING NETWORK OPTIMIZATION DECISION LOGIC
THREE-TIERED MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA

Reasons for Retaining a Well in Monitoring Network	Reasons for Removing a Well From Monitoring Network
Well is needed to further characterize the site or monitor changes in contaminant concentrations through time	Well provides spatially redundant information with a neighboring well (e.g., same constituents, and/or short distance between wells)
Well is important for defining the lateral or vertical extent of contaminants	Well has been dry for more than 2 years[a/]
Well is needed to monitor water quality at compliance point or receptor exposure point (e.g., domestic well)	Contaminant concentrations are consistently below laboratory detection limits or cleanup goals
Well is important for defining background water quality	Well is completed in same water-bearing zone as nearby well(s)

a/ Water-level measurements in dry wells should continue, and groundwater sampling should be resumed if the well becomes re-wetted.

4.2 RESULTS OF QUALITATIVE MNO EVALUATION

The results of the qualitative evaluation of the 44 wells in the Long Prairie plume vicinity are described in this subsection. Recommendations for optimizing the well network are developed, and the basis for each recommendation is provided.

4.2.1 Monitoring Network and Sampling Frequency

The results of the qualitative evaluation of the 18 monitoring wells, 7 extraction wells, and 2 municipal water-supply wells currently included in the LTM program at the Long Prairie Superfund Site are included are summarized in Table 4.3, and described in the following subsections. Other site wells that are not currently monitored on a regular basis (i.e., 3 extraction wells and 14 monitoring wells) also are included in Table 4.3 for completeness. The table includes recommendations for retaining or removing each well, and for changing the sampling frequency, and lists the rationale for the recommendations.

TABLE 4.2
MONITORING FREQUENCY DECISION LOGIC
THREE-TIERED MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA

Reasons for Increasing Sampling Frequency	Reasons for Decreasing Sampling Frequency
Groundwater velocity is high	Groundwater velocity is low
Change in contaminant concentration would significantly alter a decision or course of action	Change in contaminant concentration would not significantly alter a decision or course of action
Well is close to source area or operating remedial system	Well is distal from source area or remedial system
Cannot predict if concentrations will change significantly over time	Concentrations are not expected to change significantly over time, or contaminant levels have been below groundwater cleanup objectives for some prescribed period of time

4.2.1.1 Extraction Wells

Six of the 10 groundwater extraction wells at the site (RW3 and RW5 through RW9) are currently operating and are sampled quarterly. A seventh inactive extraction well (RW4) is sampled annually, and the remaining three extraction wells (source-area wells RW1A/1B/1C) are not sampled.

Continued sampling of the six active extraction wells is recommended to facilitate periodic calculation of contaminant mass-removal rates and assessment of remedial progress and system optimization needs. However, historical sampling data for these wells indicate that temporal concentration trends could be adequately determined from semiannual monitoring. Therefore, reduction in the sampling frequency for these wells from quarterly to semiannually is recommended. This frequency also should be adequate

TABLE 4.3

QUALITATIVE EVALUATION OF GROUNDWATER MONITORING NETWORK
THREE-TIERED MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA

Well ID	Screened Interval (ft bgs)[a/]	Sampling Frequency [b/]	Qualitative Analysis: Remove/ Exclude	Qualitative Analysis: Retain/ Add	Qualitative Analysis: Monitoring Frequency Recommendation	Rationale
Monitoring Wells in 2000/2001 Sampling Plan						
MW2A	15-20	Annual	√		--	No temporal trends; clustered well MW2B monitors higher-concentration zone.
MW2B	31-35	Annual		√	Annual	Monitors relatively high-concentration zone and plume magnitude over time.
MW2C	48-53	Annual	√		--	No temporal trends; clustered well MW2B monitors higher-concentration zone.
MW4B	31.5-35.5	Annual		√	Annual	Monitors plume magnitude over time; this well and clustered well MW4C monitor relatively high-concentration zones.
MW4C	42.0-46.0	Annual		√	Annual	Monitors plume magnitude over time; this well and clustered well MW4B monitor relatively high-concentration zones.
MW6A	12.0-17	Annual	√		Annual	Redundant with MW6B and MW6C; does not provide any useful information that is not provided by these two wells.
MW6B	31.0-37	Annual		√	--	Provides information on plume magnitude over time in intermediate-depth zone, which has had highest historical COC concentrations at this well cluster.
MW6C	46.0-59	Annual		√	Annual	Provides information on plume magnitude over time in deep zone.
MW10A	16-21	Annual		√	Annual	Monitors groundwater quality in source area.
MW11B		Annual		√	Annual	Provides continued assurance that plume turns to the NW and does not migrate toward CW6. Note that screen interval of this well is not known.G48
MW11C	50-55	Annual		√	Annual	Provides continued assurance that plume turns to the NW and does not migrate toward CW6.
MW14B	21-26	Annual		√	Annual	Monitors plume magnitude over time.
MW14C	50-55	Annual	√		--	COC concentrations consistenly trace-level to non-detect. Paired well MW14B monitors higher-concentration zone.
MW15A	12	Annual		√	Annual	Monitors downgradient extent of plume adjacent to river.
MW15B	33	Annual		√	Annual	Monitors downgradient extent of plume adjacent to river.
MW16B	25.3	Annual		√	Annual	Monitors plume magnitude over time near plume toe. Slight increasing trend for cis-1,2-DCE.
MW17B	33	Annual		√	Annual	Monitors plume magnitude over time.
MW19B	26.5	Annual		√	Biennial	Monitors contaminant concentrations adjacent to river. Relatively infrequent monitoring justified by lack of MCL exceedances since sampling began in 1998.
City Water-Supply Wells						
CW3	67-85	Quarterly		√	Quarterly	Frequent monitoring justified due to proximity of CAH plume and probably political sensitivity/community relations.
CW6	53-76	Quarterly		√	Quarterly	Frequent monitoring justified due to proximity of CAH plume and probably political sensitivity/community relations.
Recovery Wells						
RW1A	15-30		√		--	Continued monitoring of MW10A is sufficient to monitor source area groundwater quality.
RW1B	13-45		√		--	Continued monitoring of MW10A is sufficient to monitor source area groundwater quality.
RW1C	12.5-23.5		√		--	Continued monitoring of MW10A is sufficient to monitor source area groundwater quality.
RW3	17-52	Quarterly		√	Semi-Annual	Facilitates calculation of mass removal rates and RPO decision-making. Temporal trends could be adequately detected with semiannual monitoring.
RW4	10.0-50	Annual		√	Biennial	Defines western plume boundary; relatively infrequent monitoring justified by lack of MCL exceedances over at least 18 sampling events.
RW5	41-56	Quarterly		√	Semi-Annual	Facilitates calculation of mass removal rates and RPO decision-making. Temporal trends could be adequately detected with semiannual monitoring.
RW6	10.0-55.5	Quarterly		√	Semi-Annual	Facilitates calculation of mass removal rates and RPO decision-making. Temporal trends could be adequately detected with semiannual monitoring.
RW7	15-45	Quarterly		√	Semi-Annual	Facilitates calculation of mass removal rates and RPO decision-making. Temporal trends could be adequately detected with semiannual monitoring.
RW8	30-40	Quarterly		√	Semi-Annual	Facilitates calculation of mass removal rates and RPO decision-making. Temporal trends could be adequately detected with semiannual monitoring.
RW9	25-35	Quarterly		√	Semi-Annual	Facilitates calculation of mass removal rates and RPO decision-making. Temporal trends could be adequately detected with semiannual monitoring.
Other Area Wells Sampled in October 2002						
BAL2B	57-65		√		--	Continued monitoring of CW6 is sufficient to assess groundwater quality at this location.
BAL2C	40-50		√		--	No COC detections over 6-year monitoring history.
MW1A	9.5-14.5		√		--	COCs not detected throughout monitoring history; no reason to expect changes unless extraction system operation changes.
MW1B	30-35		√		--	COCs not detected throughout monitoring history; no reason to expect changes unless extraction system operation changes.
MW3A	17.8-22.8		√		--	COCs not detected throughout monitoring history; no reason to expect changes unless extraction system operation changes.
MW3B	30-35		√		--	COCs not detected throughout monitoring history; no reason to expect changes unless extraction system operation changes.
MW4A	10.0-15		√		--	Monitors relatively low-concentration zone compared to clustered wells MW4A and MW4B.
MW5A	4.5-9.5		√		--	Distant from estimated plume boundary, and consistently non-detect for COCs.
MW5B	31.0-35		√		--	Distant from estimated plume boundary, and consistently non-detect for COCs.
MW11A			√		--	Continued monitoring of MW11B and 11C is adequate to ensure lack of plume migration toward CW6.
MW13C	50-55			√	Biennial	Increasing trend for cis-1,2-DCE adjacent to wetlands. If continued infrequent monitoring doesn't support this trend, then discontinue.
MW16A	15.5		√		--	Monitors lower-concentration zone than paired well MW16A.
MW18A	15.1		√		--	No historic analyte detections.
MW18B	35			√	Biennial	Monitors plume stability and groundwater quality at edge of wetlands. Infrequent monitoring is justified by low magnitude of COC detections to date.

[a/] ft bgs = feet below ground surface

[b/] Reduced network sampling frequency prior to comprehensive 2002 sampling event (Barr, 2002) to achieve the extraction-system performance monitoring objectives stated above. In addition, reduction in the sampling frequency for inoperative well RW4 from annual to biennial (every other year) is recommended. This well was sampled 18 times from May 1996 through October 2002. Trace-level (i.e., almost exclusively < 3 μg/L) concentrations of COCs were detected until late 1997; since then, COCs have for the most part not been detected. Given this monitoring history, relatively infrequent monitoring of RW4 is sufficient to define the southwestern boundary of the CAH plume over time in this area.

Extraction wells RW1A/1B/1C are located in the source area and provide groundwater quality data for the depth interval ranging from about 10 to 43 feet below the ground surface. Wells RW1A and 1B were sampled regularly from May 1996 through October 1999, and were sampled again in October 2002. Available data indicate that RW1C was only sampled once (in October 2002). Since May 1996, COCs either have not been detected in these wells, or have been present at trace concentrations (i.e., < 3 μg/L). Given that monitoring well MW10A is located immediately adjacent to these extraction wells, and is screened near the water table, where any fresh influx of contaminants from the vadose zone would first be detected, continued monitoring of this well should be sufficient to monitor groundwater quality in the source area. This well has historically had higher COC concentrations than the adjacent extraction wells.

4.2.1.2 Municipal Water-Supply Wells

Two municipal water-supply wells, CW3 and CW6, currently are sampled on a quarterly basis. Available data indicate that the CAH plume is not migrating eastward in the lower outwash deposits toward these wells, and the only COCs detected in samples from these wells have been very low-magnitude (< 1 μg/L) detections of *cis*-1,2-DCE in CW3. This observation is supported by the prevailing groundwater flow direction to the northwest, and by the lack of significant historical contaminant concentrations at other lower-outwash wells (i.e., MW3B, MW11C, and BAL2C) along the eastern margin of the COC plume (Figure 2.1). Therefore, from a purely technical standpoint, quarterly sampling of CW3 and CW6 is probably not necessary. However, continuation of "goodwill" monitoring at this frequency is recommended to reassure the public about the safety of the municipal water supply (Table 4.3).

4.2.1.3 Monitoring Wells

Continued sampling of 14 of the 18 monitoring wells included in the current LTM program is recommended. Wells MW2A, MW2C, MW6A, and MW14C are recommended for removal from the LTM program. As indicated in Table 4.3, the aquifer zones monitored by MW2A and MW2C have consistently contained lower COC concentrations than the zone monitored by clustered well MW2B. Although this is important information to obtain for initial plume characterization purposes, continued monitoring of only the highest-concentration zone (well MW2B) is adequate to track the magnitude of contaminant concentrations within the plume over time. Similarly, continued monitoring of well MW14B should be adequate to track the plume magnitude at the location of the 14B/14C well cluster over time, given the consistently low (to non-detect) COC concentrations at MW14C.

During the first few sampling events for well cluster MW6A/6B/6C, the highest concentrations of PCE, TCE, and *cis*-1,2-DCE were detected in groundwater from the intermediate-depth well (MW6B). More recently, however, COC concentrations at each of the three wells in this cluster have been similar, suggesting that continued sampling of each well is not necessary. Continued sampling of MW6C is recommended because recent samples from this well have contained the highest PCE concentrations. Continued sampling of MW6B also is recommended because this well is screened in the vertical interval that has historically contained the most elevated contaminant concentrations. Removal of MW6A from the LTM program is recommended because the data provided by sampling of this well does not provide any additional useful information that cannot be obtained from other shallow wells downgradient from the MW6 cluster (Figure 2.1)..

Less-frequent monitoring is recommended for one monitoring well currently sampled on an annual basis (MW19B). Retention of this well in the LTM program is recommended due to its location in the wetland area adjacent to the Long Prairie River (a potentially sensitive ecological receptor exposure area). However, the recommendation to reduce the monitoring frequency is based on the low magnitude and stable nature of COC concentrations detected to date. There is no reason to assume that COC concentrations at this location could increase significantly unless the current pumping regime is interrupted or altered.

Low-frequency (e.g., biennial) monitoring of two wells that currently are not included in the LTM program is recommended. Samples from MW13C, which is located adjacent to a potentially sensitive wetland area, have exhibited an increasing trend for *cis*-1,2-DCE. If continued infrequent monitoring of this well does not indicate a continuation of this trend, then monitoring should be discontinued. Sampling of well MW18B also enables periodic evaluation of COC concentrations at the edge of the wetland area. In addition, the location of this well near the downgradient plume toe facilitates continued evaluation of plume dynamics (i.e., expanding, receding, steady-state).

4.2.2 Laboratory Analytical Program

The 2000/2001 Annual Report (Barr, 2002) indicates that the target analyte list (TAL) was reduced to DCE, PCE, TCE, and VC in the second quarter of 2000, and that a relatively inexpensive GC method that provides low detection limits is now used. Parsons assumes that the presence of other VOCs at concentrations of potential concern was ruled out based on previous analytical results obtained for a more extensive TAL (MDH 465E list). If this is the case, then the current laboratory analytical program appears to be reasonably optimized, and no further recommendations are provided. If this is not the case, then the potential presence of other VOCs that could have been present in the PCE as contaminants should be assessed.

4.2.3 LTM Program Flexibility

The LTM program recommendations summarized in Table 4.3 are based on available data regarding current (and expected future) site conditions. Changing site conditions (e.g., lengthy malfunction or significant adjustment of the groundwater extraction system) could affect plume behavior. Therefore, the LTM program should be reviewed if hydraulic conditions change significantly, and revised as necessary to adequately track changes in plume magnitude and extent over time.

SECTION 5

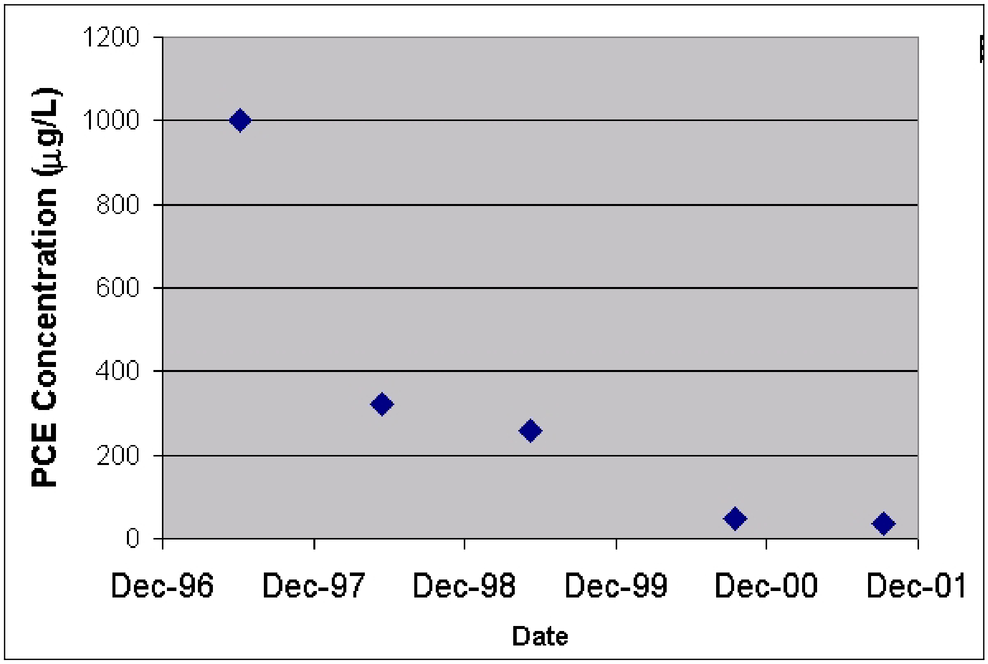
TEMPORAL STATISTICAL EVALUATION

Chemical concentrations measured at different points in time (temporal data) can be examined graphically, or using statistical tests, to evaluate dissolved-contaminant plume stability. If removal of chemical mass is occurring in the subsurface as a consequence of attenuation processes or operation of a remediation system, mass removal will be apparent as a decrease in chemical concentrations through time at a particular sampling location, as a decrease in chemical concentrations with increasing distance from chemical source areas, and/or as a change in the suite of chemicals detected through time or with increasing migration distance.

5.1 METHODOLOGY FOR TEMPORAL TREND ANALYSIS OF CONTAMINANT CONCENTRATIONS

Temporal chemical-concentration data can be evaluated for trends by plotting contaminant concentrations through time for individual monitoring wells (Figure 5.1), or by plotting contaminant concentrations versus downgradient distance from the contaminant source for several wells along the groundwater flowpath, over several monitoring events. Plotting temporal concentration data is recommended for any analysis of plume stability (Wiedemeier and Haas, 2000); however, visual identification of trends in plotted data may be a subjective process, particularly if (as is likely) the concentration data do not exhibit a uniform trend, but are variable through time (Figure 5.2).

FIGURE 5.1
PCE CONCENTRATIONS THROUGH TIME
AT WELL MW6B
THREE-TIERED MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA



The possibility of arriving at incorrect conclusions regarding plume stability on the basis of visual examination of temporal concentration data can be reduced by examining temporal trends in chemical concentrations using various statistical procedures, including regression analyses and the Mann-Kendall test for trends. The Mann-Kendall nonparametric test (Gibbons, 1994) is well-suited for evaluation of environmental data because the sample size can be small (as few as four data points), no assumptions are made regarding the underlying statistical distribution of the data, and the test can be adapted to account for seasonal variations in the data. The Mann-Kendall test statistic can be calculated at a specified level of confidence to evaluate whether a statistically significant temporal trend is exhibited by contaminant concentrations detected through time in samples from an individual well. If a trend is identified, a nonparametric slope of the trend line (change in concentration per unit time) also can be estimated using the test

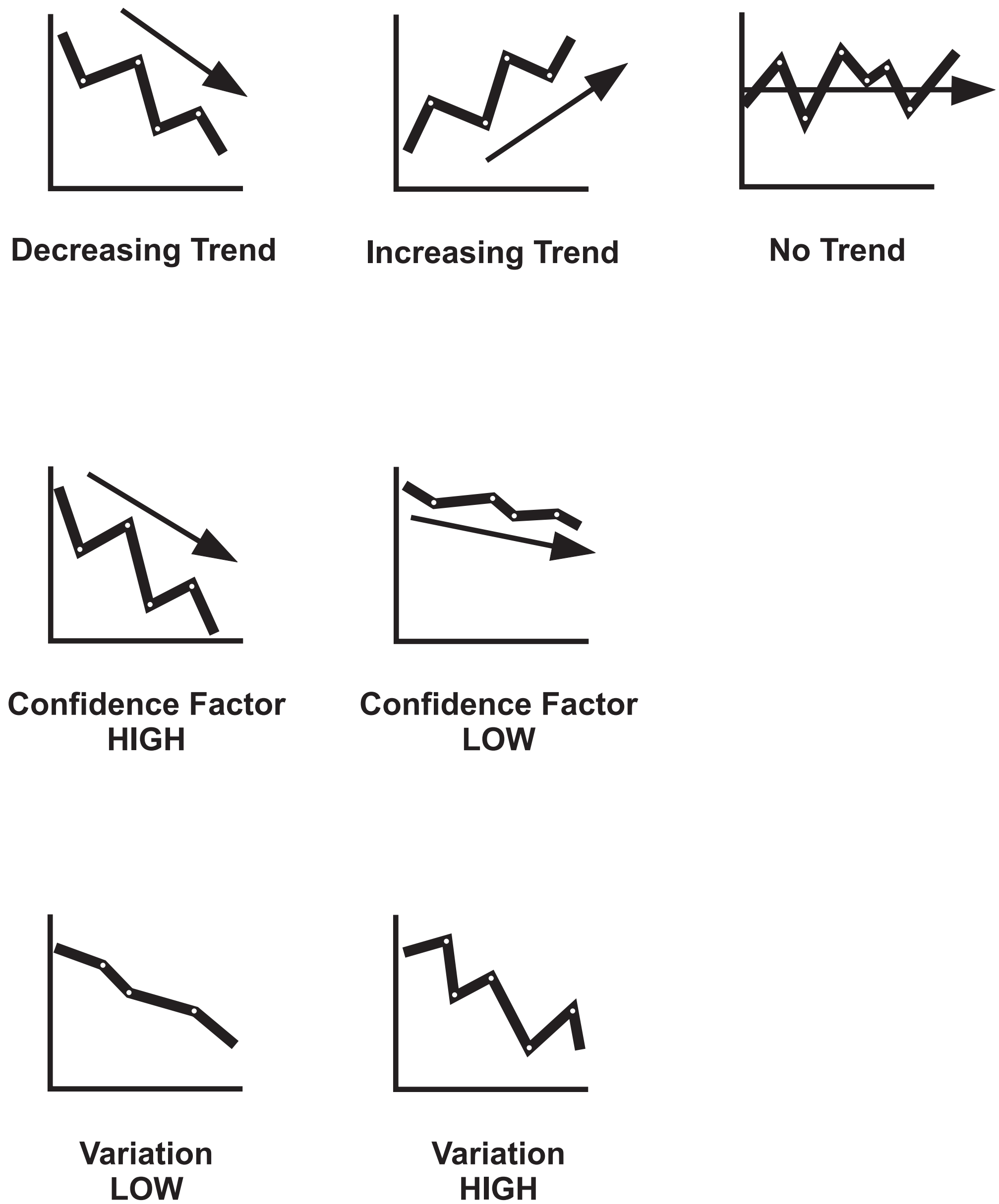


FIGURE 5.2

CONCEPTUAL REPRESENTATION OF TEMPORAL TRENDS AND TEMPORAL VARIATIONS IN CONCENTRATIONS

Monitoring Network Optimization
Long Prairie, Minnesota

procedure. A negative slope (indicating decreasing contaminant concentrations through time) or a positive slope (increasing concentrations through time) provides statistical confirmation of temporal trends that may have been identified visually from plotted data (Figure 5.2).

The relative value of information obtained from periodic monitoring at a particular monitoring well can be evaluated by considering the location of the well with respect to the dissolved contaminant plume and potential receptor exposure points, and the presence or absence of temporal trends in contaminant concentrations in samples collected from the well. The degree to which the amount and quality of information that can be obtained at a particular monitoring point serve the two primary (i.e., temporal and spatial) objectives of monitoring must be considered in this evaluation. For example, the continued non-detection of a target contaminant in groundwater at a particular monitoring location provides no information about temporal trends in contaminant concentrations at that location, or about the extent to which contaminant migration is occurring, unless the monitoring location lies along a groundwater flowpath between a contaminant source and a potential receptor exposure point. Therefore, a monitoring well having a history of contaminant concentrations below detection limits may be providing little or no useful information, depending on its location.

A trend of increasing contaminant concentrations in groundwater at a location between a contaminant source and a potential receptor exposure point may represent information critical in evaluating whether contaminants are migrating to the exposure point, thereby completing an exposure pathway. Identification of a trend of decreasing contaminant concentrations at the same location may be useful in evaluating decreases in the areal extent of dissolved contaminants, but does not represent information that is critical to the protection of a potential receptor. Similarly, a trend of decreasing contaminant concentrations in groundwater near a contaminant source may represent important information regarding the progress of remediation near, and downgradient from the source, while identification of a trend of increasing contaminant concentrations at the same location does not provide as much useful information regarding contaminant conditions. By contrast, the absence of a temporal trend in contaminant concentrations at a particular location within or downgradient from a plume indicates that virtually no additional information can be obtained by continued monitoring of groundwater at that location, in that the results of continued monitoring through time are likely to fall within the historic range of concentrations that have already been detected (Figure 5.3). Continued monitoring at locations where no temporal trend in contaminant concentrations is present serves merely to confirm the results of previous monitoring activities at that location. The relative amounts of information generated by the results of temporal-trend evaluation at monitoring points near, upgradient from, and downgradient from contaminant sources are presented schematically as follow:

Monitoring Point Near Contaminant Source

Relatively less information	Nondetect or no trend
↓	Increasing trend in concentrations
Relatively more information	Decreasing trend in concentrations

Monitoring Point Upgradient from Contaminant Source

Relatively less information	Nondetect or no trend
↓	
	Decreasing trend in concentrations
Relatively more information	Increasing trend in concentrations

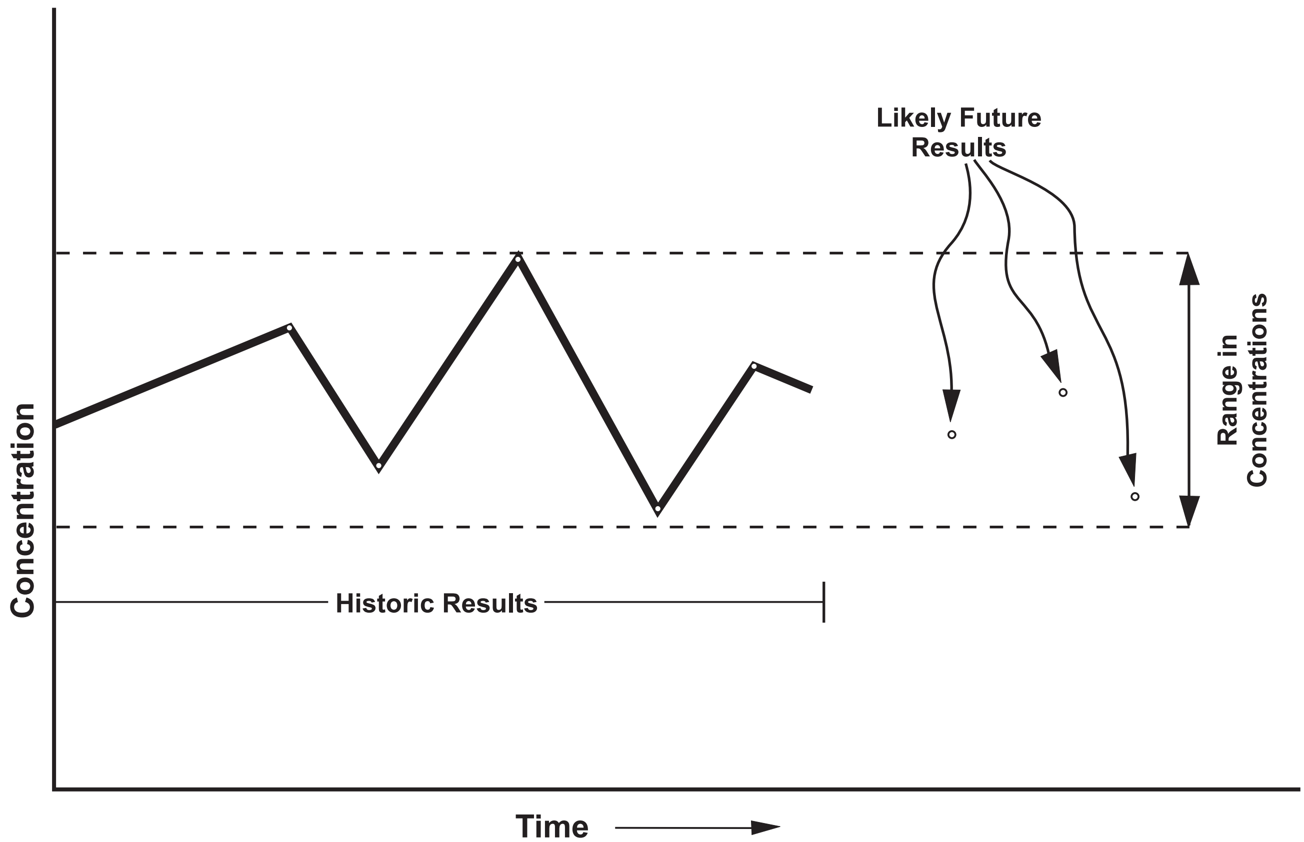


FIGURE 5.3
CONCEPTUAL REPRESENTATION OF CONTINUED MONITORING AT LOCATION WHERE NO TEMPORAL TREND IN CONCENTRATIONS IS PRESENT

Monitoring Network Optimization
Long Prairie, Minnesota

Monitoring Point Downgradient from Contaminant Source

Relatively less information	Decreasing trend in concentrations
↓	
	Nondetect or no trend
Relatively more information	Increasing trend in concentrations

5.2 TEMPORAL EVALUATION RESULTS

The analytical data for groundwater samples collected from the 44 wells in Long Prairie LTM program from May 1996 through October 2002 were examined for temporal trends using the Mann-Kendall test. The objective of the evaluation was to identify those wells having increasing or decreasing concentration trends for each COC, and to consider the quality of information represented by the existence or absence of concentration trends in terms of the location of each monitoring point.

Summary results of Mann-Kendall temporal trend analyses for COCs in groundwater samples from wells in the PCE plume area are presented in Table 5.1. As implemented, the algorithm used to evaluate concentration trends assigned a value of “ND” (not detected) to those wells with sampling results that were consistently below analytical detection limits through time, rather than assigning a surrogate value corresponding to the detection limit – a procedure that could generate potentially misleading and anomalous “trends” in concentrations. The color-coding of the Table 5.1 entries denotes the presence/absence of temporal trends, and allows those monitoring points having nondetectable concentrations, decreasing or increasing concentrations, or no discernible trend in concentrations to be readily identified. The four wells that had fewer than four analytical results for each of the COCs (wells RW1C, BAL2B, MW4A and MW11A)

TABLE 5.1

RESULTS OF TEMPORAL TREND ANALYSIS OF GROUNDWATER MONITORING RESULTS

THREE-TIERED MONITORING NETWORK OPTIMIZATION

LONG PRAIRIE, MINNESOTA

Well ID	Screened Interval (ft bgs)[a/]	*cis*-1,2-DCE	PCE	TCE	Remove/ Exclude	Retain/ Add	Rationale
Monitoring Network Wells in Sampling Plan							
MW2A	15-20	No Trend	No Trend	No Trend	√		No trends/ND provide limited temporal information
MW2B	31-35	No Trend	Decreasing	No Trend		√	decreasing trend measures remediation near recovery well
MW2C	48-53	No Trend	No Trend	No Trend	√		No trends provide limited temporal information
MW4B	31.5-35.5	Decreasing	Decreasing	Decreasing		√	decreasing trend measures remediation near recovery well
MW4C	42.0-46.0	No Trend	No Trend	No Trend	√		No trends provide limited temporal information
MW6A	12.0-17	No Trend	No Trend	No Trend	√		No trends provide limited temporal information
MW6B	31.0-37	Decreasing	Decreasing	Decreasing		√	decreasing trend measures remediation near recovery well
MW6C	46.0-59	No Trend	Decreasing	Decreasing		√	decreasing trend measures remediation near recovery well
MW10A	16-21	Decreasing	Decreasing	No Trend		√	decreasing trend in source area
MW11B		Increasing	ND	ND		√	increasing concentrations of cis-1,2-DCE <<MCL but on edge of plume
MW11C	50-55	ND	Decreasing	ND		√	1.4 µg/L PCE in 1997, all other samples non-detect; sentry well for CW6
MW14B	21-26	Decreasing	Decreasing	Decreasing		√	decreasing trend measures remediation in plume hot spot
MW14C	50-55	No Trend	No Trend	ND	√		No trends/ND provide limited temporal information
MW15A	12	Increasing	ND	ND		√	increasing concentrations of cis-1,2-DCE <<MCL, on edge of plume
MW15B	33	No Trend	ND	ND		√	sentry well
MW16B	25.3	Increasing	No Trend	No Trend		√	increasing trend downgradient
MW17B	33	No Trend	Decreasing	No Trend		√	decreasing trend measures remediation near recovery well
MW19B	26.5	No Trend	ND	Decreasing		√	all measurements << MCLs; river sentry well
City Supply Well							
CW3	67-85	Increasing	ND	ND		√	water supply well
CW6	53-76	ND	ND	ND		√	water supply well
Recovery Wells							
RW1A	15-30	ND	No Trend	ND	√		inactive recovery well, PCE < MCL since 1996
RW1B	13-45	ND	Decreasing	ND	√		inactive recovery well, PCE non-detect since 1996, trends no longer valuable
RW1C	12.5-23.5	<4meas	<4meas	<4meas	Not Analyzed		
RW3	17-52	Increasing	Decreasing	Decreasing		√	decreasing recovery well measures remediation and mass removal
RW4	10.0-50	Decreasing	Decreasing	Decreasing		√	decreasing recovery well measures remediation and mass removal
RW5	41-56	Decreasing	Decreasing	No Trend		√	decreasing recovery well measures remediation and mass removal
RW6	10.0-55.5	Decreasing	Decreasing	Decreasing		√	decreasing recovery well measures remediation and mass removal
RW7	15-45	Decreasing	Decreasing	Decreasing		√	decreasing recovery well measures remediation and mass removal
RW8	30-40	Decreasing	Decreasing	Decreasing		√	decreasing recovery well measures remediation and mass removal
RW9	25-35	No Trend	No Trend	Increasing		√	TCE < 6 µg/L; increasing trend downgradient

TABLE 5.1 (Continued)
RESULTS OF TEMPORAL TREND ANALYSIS OF GROUNDWATER MONITORING RESULTS
THREE-TIERED MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA

Well ID	Screened Interval (ft bgs)[a/]	*cis*-1,2-DCE	PCE	TCE	Remove/ Exclude	Retain/ Add	Rationale
Additional Area Wells							
BAL2B	57-65	<4meas	<4meas	<4meas	Not Analyzed		
BAL2C	40-50	ND	ND	ND	√		Contaminants not detected in well monitoring history
MW1A	9.5-14.5	ND	ND	ND	√		Contaminants not detected in well monitoring history
MW1B	30-35	ND	ND	ND	√		Contaminants not detected in well monitoring history
MW3A	17.8-22.8	ND	Decreasing	ND	√		PCE non-detect since 1996; trends no longer valuable
MW3B	30-35	ND	ND	ND	√		Contaminants not detected in well monitoring history
MW4A	10.0-15	<4meas	<4meas	<4meas	Not Analyzed		
MW5A	4.5-9.5	ND	ND	ND	√		Contaminants not detected in well monitoring history
MW5B	31.0-35	Increasing	ND	ND		√	one cis-1,2-DCE detect of 0.78 in 10/02, potentially increasing concentration cross-grad
MW11A		<4meas	<4meas	<4meas	Not Analyzed		
MW13C	50-55	Increasing	No Trend	No Trend		√	increasing cis-1,2-DCE trend
MW16A	15.5	ND	No Trend	ND	√		PCE not-detected since 1998, VC 0.073 in 1999, all other samples non-detect
MW18A	15.1	ND	ND	ND	√		Contaminants not detected in well monitoring history
MW18B	35	No Trend	No Trend	No Trend	√		No trends provide limited temporal information

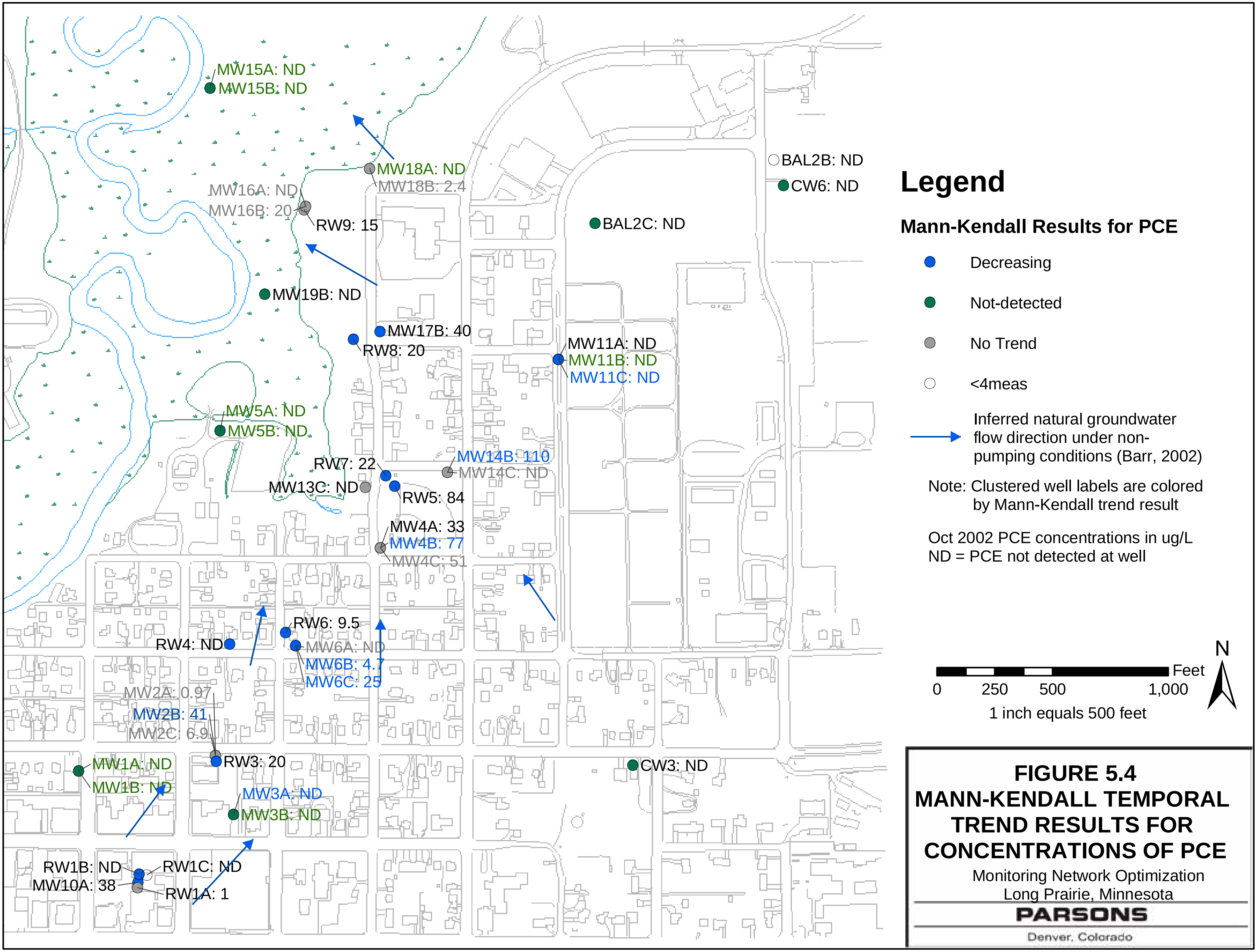
ND	= Constituent has not been detected during history of monitoring at inidcated well.
No Trend	= No statistically significant temporal trend in concentrations.
Increasing	= Statistically significant increasing trend in concentrations.
Decreasing	= Statistically significant decreasing trend in concentrations.
<4meas	= Fewer than 4 analytical results; Mann-Kendall trend not analyzed.

[a/] ft bgs = feet below ground surface

could not be analyzed using the Mann-Kendall trend analysis, and have a “<4meas” designation. Figure 5.4 displays the Mann-Kendall results thematically for PCE by well; the analytical results for PCE in October 2002 are also presented.

The basis for the decision to remove or retain a well in the monitoring program based on the value of its temporal information is described in the “Rationale” column of Table 5.1. In general, monitoring wells at which detected chemical concentrations display no discernible temporal trends (e.g., wells MW2A, MW2C, MW4C, MW6A, MW18B) represent points generating the least amount of useful information, and can be recommended for removal from the monitoring network. Monitoring wells that are not considered “sentry” wells (e.g., wells MW1A, MW1B, MW3B, MW5A, and MW18A) at which concentrations of COCs consistently have been non-detected or <PQL through time also may provide relatively little information. Conversely, monitoring wells (e.g., wells MW2B, MW4B, MW6B, MW6C and MW17B) that have decreasing temporal trends in an area near a recovery well are valuable and should be retained because they provide information on the effectiveness of the OU1 remediation system. Additionally, downgradient wells with increasing COC concentration trends (e.g., MW15A, MW16B and MW11B) provide valuable information about potential migration of contaminants, and should be retained. A flow chart of the decision logic applied to the temporal trend analysis results is presented in Figure 5.5.

Table 5.1 summarizes recommendations to retain 24 and remove 16 of the 40 monitoring wells (excluding the four wells with fewer than four measurements) analyzed to optimize the monitoring program for the Long Prairie. The recommendations provided in Table 5.1 are based on the evaluation of temporal statistical results only, and must be used in conjunction with the results of the qualitative and spatial evaluations to generate final recommendations regarding retention of monitoring points in the LTM program, and the frequency of monitoring at particular locations at Long Prairie.


MW15A: ND
MW15B: ND
MW18A: ND
MW18B: 2.4
MW16A: ND
MW16B: 20
RW9: 15
BAL2B: ND
CW6: ND
BAL2C: ND
MW19B: ND
MW17B: 40
RW8: 20
MW11A: ND
MW11B: ND
MW11C: ND
MW5A: ND
MW5B: ND
RW7: 22
MW13C: ND
MW14B: 110
MW14C: ND
RW5: 84
MW4A: 33
MW4B: 77
MW4C: 51
RW6: 9.5
RW4: ND
MW6A: ND
MW6B: 4.7
MW6C: 25
MW2A: 0.97
MW2B: 41
MW2C: 6.9
RW3: 20
CW3: ND
MW1A: ND
MW1B: ND
MW3A: ND
MW3B: ND
RW1B: ND
MW10A: 38
RW1C: ND
RW1A: 1
Legend
Mann-Kendall Results for PCE
Decreasing
Not-detected
No Trend
<4meas
Inferred natural groundwater flow direction under non-pumping conditions (Barr, 2002)
Note: Clustered well labels are colored by Mann-Kendall trend result
Oct 2002 PCE concentrations in ug/L
ND = PCE not detected at well
0
250
500
1,000
Feet
1 inch equals 500 feet
N
FIGURE 5.4
MANN-KENDALL TEMPORAL TREND RESULTS FOR CONCENTRATIONS OF PCE
Monitoring Network Optimization
Long Prairie, Minnesota
PARSONS
Denver, Colorado

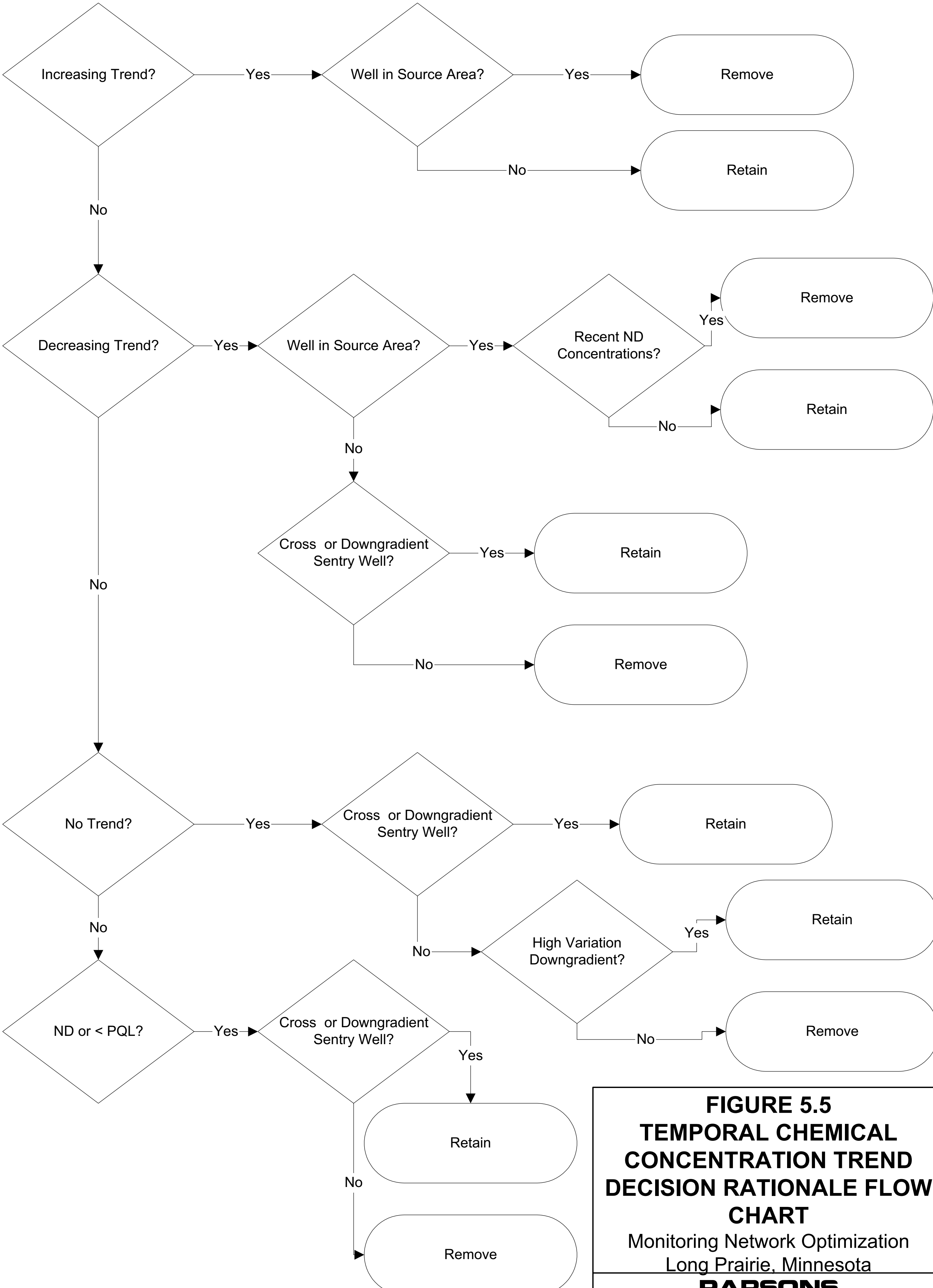


FIGURE 5.5
TEMPORAL CHEMICAL CONCENTRATION TREND DECISION RATIONALE FLOW CHART
Monitoring Network Optimization
Long Prairie, Minnesota

PARSONS
Denver, Colorado

SECTION 6

SPATIAL STATISTICAL EVALUATION

Spatial statistical techniques also can be applied to the design and evaluation of groundwater monitoring programs to assess the quality of information generated during monitoring, and to evaluate monitoring networks. *Geostatistics*, or the Theory of Regionalized Variables (Clark, 1987; Rock 1988; American Society of Civil Engineers [ASCE] Task Committee on Geostatistical Techniques in Hydrology, 1990a and 1990b), is concerned with variables having values dependent on location, and which are continuous in space, but which vary in a manner too complex for simple mathematical description. Geostatistics is based on the premise that the differences in values of a spatial variable depend only on the distances between sampling locations, and the relative orientations of sampling locations -- that is, the values of a variable (e.g., chemical concentrations) measured at two locations that are spatially "close together" will be more similar than values of that variable measured at two locations that are "far apart".

6.1 GEOSTATISTICAL METHODS FOR EVALUATING MONITORING NETWORKS

Ideally, application of geostatistical methods to the results of the groundwater monitoring program at Long Prairie could be used to estimate COC concentrations at every point within the dissolved contaminant plume, and also could be used to generate estimates of the "error," or uncertainty, associated with each estimated concentration value. Thus, the monitoring program could be optimized by using available information to identify those areas having the greatest uncertainty associated with the estimated plume extent and configuration. Conversely, sampling points could be successively eliminated from simulations, and the resulting uncertainty examined, to evaluate if significant loss of information (represented by increasing error or uncertainty in estimated chemical concentrations) occurs as the number of sampling locations is reduced. Repeated application of geostatistical estimating techniques, using tentatively identified sampling locations, then could be used to generate a sampling program that would provide an acceptable level of uncertainty regarding the distribution of COCs with the minimum possible number of samples collected. Furthermore, application of geostatistical methods can provide unbiased representations of the distribution of COCs at different locations in the subsurface, enabling the extent of COCs to be evaluated more precisely.

Fundamental to geostatistics is the concept of semivariance [$\gamma(h)$], which is a measure of the spatial dependence between samples (e.g., chemical concentrations) in a specified direction. Semivariance is defined for a constant spacing between samples (***h***) by:

$$\gamma(h) = \frac{1}{2n} \sum [g(x) - g(x + h)]^2 \qquad \textit{Equation 6-1}$$

Where:

$\gamma(h)$ = semivariance calculated for all samples at a distance ***h*** from each other;

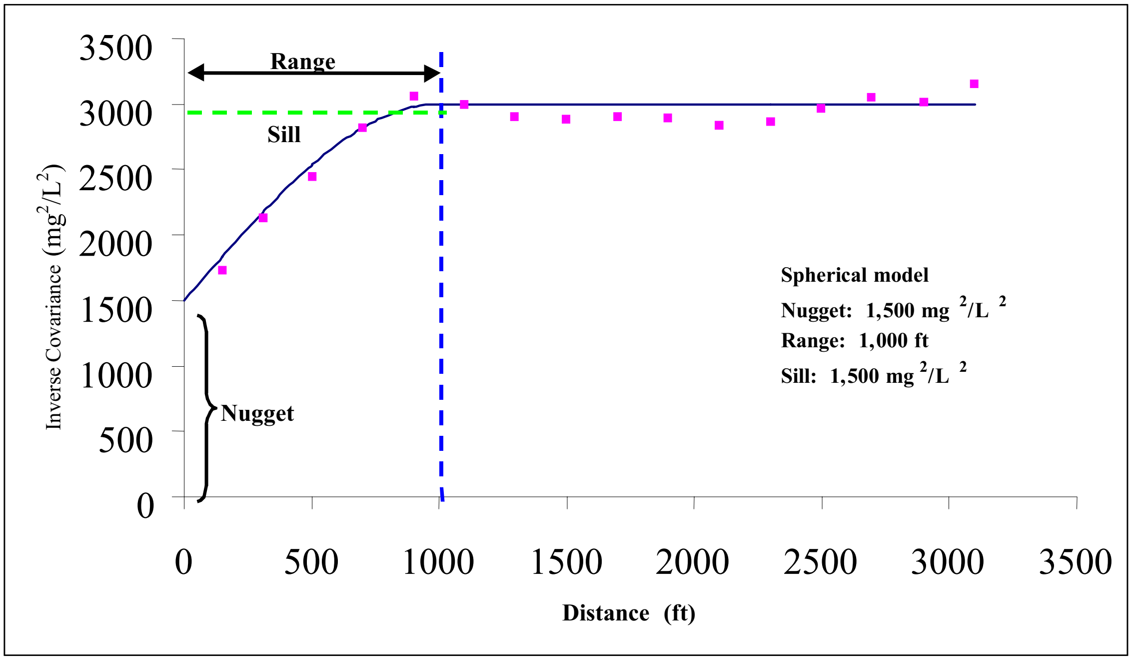
$g(x)$ = value of the variable in sample at location ***x***;

$g(x + h)$ = value of the variable in sample at a distance ***h*** from sample at location ***x***; and

n = number of samples in which the variable has been determined.

Semivariograms (plots of $\gamma(h)$ versus ***h***) are a means of depicting graphically the range of distances over which, and the degree to which, sample values at a given point are related to sample values at adjacent, or nearby, points, and conversely, indicate how close together sample points must be for a value determined at one point to be useful in predicting unknown values at other points. For $h = 0$, for example, a sample is being compared with itself, so normally $\gamma(0) = 0$ (the semivariance at a spacing of zero, is

FIGURE 6.1
IDEALIZED SEMIVARIOGRAM MODEL
THREE-TIERED MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA



zero), except where a so-called nugget effect is present (Figure 6.1), which implies that sample values are highly variable at distances less than the sampling interval. As the distance between samples increases, sample values become less and less closely related, and the semivariance, therefore, increases, until a "sill" is eventually reached, where ***γ(h)*** equals the overall variance (i.e., the variance around the average value). The sill is reached at a sample spacing called the "range of influence," beyond which sample values are not related. Only values between points at spacings less than the range of influence can be predicted; but within that distance, the semivariogram provides the proper weightings, which apply to sample values separated by different distances.

When a semivariogram is calculated for a variable over an area (e.g., concentrations of PCE in the groundwater plume at Long Prairie), an irregular spread of points across the semivariogram plot is the usual result (Rock, 1988). One of the most subjective tasks of geostatistical analysis is to identify a continuous, theoretical semivariogram model that most closely follows the real data. Fitting a theoretical model to calculated semivariance points is accomplished by trial-and-error, rather than by a formal statistical procedure (Davis, 1986; Clark, 1987; Rock, 1988). If a "good" model fit results, then $\gamma(h)$ (the semivariance) can be confidently estimated for <u>any</u> value of h, and not only at the sampled points.

6.2 SPATIAL EVALUATION OF MONITORING NETWORK AT LONG PRAIRIE

PCE was used as the indicator chemical for the spatial evaluation of the groundwater monitoring network at Long Prairie because this COC has the largest spatial distribution of measurements that exceeded groundwater MCLs. The most recent (October 2002) validated analytical data available at the start of this MNO evaluation were used in the kriging evaluation because a spatial "snapshot" is required in order to conduct the geospatial statistical analysis.

Of the 44 wells sampled in October 2002, 16 were included in the kriging evaluation. Although the OU1 extraction wells have historically been used to define the plume extent, data from extraction wells are not appropriate for use in a kriging analysis because they represent COC concentrations averaged over the area within the well's capture zone, and thus are not point specific, nor temporally discrete; the recovery wells are also typically screened across a longer screening interval than the site monitoring wells. Similarly, city wells CW3 and CW6 were excluded from the analysis because they also are pumping wells. Kriging predicts concentrations over a two-dimensional surface and thus including data from multiple co-located wells screened at different depths is not appropriate. In this application, the well within each cluster of well with the highest concentration of PCE was retained for use in the geostatistical evaluation; this methodology is consistent with the values displayed on plume maps in the Long Prairie annual reports (Barr, 2001; Barr, 2002). On the whole, of the clustered wells, the "B" zone wells had the highest October 2002 PCE concentrations and were included in the spatial analysis; however, the "C" zone well MW6C was included from the MW6 cluster. The 16 wells analyzed are shown in Figure 6.3 and listed in Table 6.1.

The commercially available geostatistical software package Geostatistical Analyst™ (an extension to the ArcView® geographic information system [GIS] software package) (Environmental Systems Research Institute, Inc. [ESRI], 2001) was used to develop a semivariogram model depicting the spatial variation in PCE concentrations in groundwater for the 16 Long Prairie area wells.

As semivariogram models were calculated for PCE (Equation 6-1), considerable scatter of the data was apparent during fitting of the models. Several data transformations (including a log transformation) were attempted to obtain a representative semivariogram model. Ultimately, , the concentration data were transformed to "rank statistics," in which the 16 wells were ranked from 1 to 16 (tie values were assigned the median rank of the set) according to their October 2002 PCE concentration. Transformations of this type can be less sensitive to outliers, skewed distributions, or clustered data than semivariograms based on raw concentration values, and thus may enable recognition and description of the underlying spatial structure of the data in cases where ordinary data are too "noisy".

The PCE rank statistics were used to develop a semivariogram that most accurately modeled the spatial distribution of the data. Anisotrophy was incorporated into the model to adjust for the directional influence of groundwater to the northeast. The model was unable to account for the "dog-leg" shift in groundwater flow direction to the northwest in the northern half of the plume (Figure 2.1). Figure 6.2 shows the semivariogram model in comparison to the site data. The large amount of scatter in the data due to the small number of wells and shifting groundwater direction makes it difficult to develop a representative semivariogram model. Thus, the geostatistical evaluation at this site can not be as rigorous as at other sites with more wells and more consistent hydrology. The best-fit semivariogram had the following parameters:

TABLE 6.1

RESULTS OF GEOSTATISTICAL EVALUATION RANKING OF WELLS BY RELATIVE VALUE OF PCE INFORMATION

THREE-TIERED MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA

Well ID [a/]	Kriging Ranking [b/]	Remove/ Exclude	Retain/ Add
MW19B	1	√	
MW13C	2	√	
MW4B	3.5	√	
MW16B	3.5	√	
MW6C	5.5	-- [d/]	--
MW2B	5.5	--	--
MW3B	7	--	--
BAL2C	8	--	--
MW18B	9.5	--	--
MW10A	9.5	--	--
MW11B	11	--	--
MW15B	12	--	--
MW14B	13		√
MW5B	14.5		√
MW17B	14.5		√
MW1B	16		√

[a/] Clustered wells included in the spatial analysis are those with the highest relative October 2002 PCE concentration.

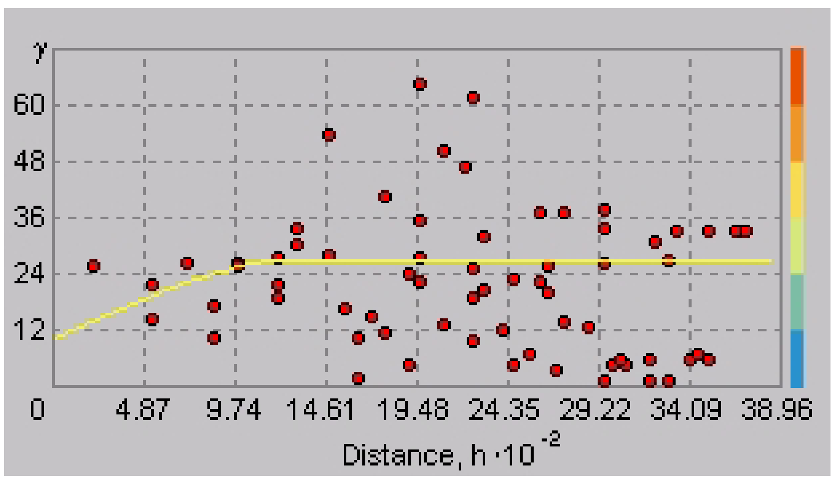
[b/] 1= least relative amount of information; 16= most relative amount of information.

[c/] Tie values receive the median ranking of the set.

[d/] Well in the “intermediate” range; received no recommendation for removal/exclusion or retention/addition (see Section 6.2).

- Circular model
- Range: 1200 feet
- Sill: 17
- Nugget: 10
- Anisotrophy:
  - Minor Range: 400 feet
  - Direction: 20 degrees

FIGURE 6.2
LONG PRAIRIE SEMVARIOGRAM MODEL
THREE-TIERED MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA



After this semivariogram model had been developed, it was used in the kriging system implemented by the Geostatistical Analyst™ software package (ESRI, 2001) to develop kriging realizations (estimates of the spatial distribution of PCE in groundwater at Long Prairie), and to calculate the associated kriging prediction standard errors. The median kriging standard deviation was obtained from the standard errors calculated using the entire 16-well monitoring network for Long Prairie. Next, each of the 16 wells was sequentially removed from the network, and for each resulting well network configuration, a kriging realization was completed using the PCE concentration rankings from the remaining 15 wells. The "missing-well" monitoring network realizations were used to calculate prediction standard errors, and the median kriging standard deviations were obtained for each "missing-well" realization and compared with the median kriging standard deviation for the "base-case" realization (obtained using the complete 16-well monitoring network), as a means of evaluating the amount of information loss (as indicated by increases in kriging error) resulting from the use of fewer monitoring points.

Figure 6.3 illustrates the spatial-evaluation procedure by showing kriging prediction standard-error maps for three kriging realizations. Each map shows the predicted standard error associated with a given group of wells based on the semivariogram parameters discussed above. Lighter colors represent areas with lower spatial uncertainty, and darker colors represent areas with higher uncertainty; regions in the vicinity of wells (i.e., data points) have the lowest associated uncertainty. Map A on Figure 6.3 shows the predicted standard error map for the "base-case" realization in which all 16 wells are included. Map B shows the realization in which well MW13C was removed from the monitoring network, and Map C shows the realization in which well MW17B was removed. Figure 6.3 shows that when a well is removed from the network, the predicted standard error in the vicinity of the missing well increases (as indicated by a darkening of the shading in the vicinity of that well). If a "removed" (missing) well is in an area with several other wells (e.g., well MW13C; Map B on Figure 6.2), the predicted standard error may not increase as much as if a well (e.g., MW17B; Map C) is removed from an area with fewer surrounding wells. If removal of a particular well from the monitoring network caused very little change in the resulting median kriging standard deviation (less than about 1 percent), that well was regarded as contributing only a limited amount of information to the LTM program. Likewise, if removal of a well from the monitoring network produced larger increases in the kriging standard deviation, this was regarded as an indication that the well contributes a relatively greater amount of information, and is relatively more important to the monitoring network.

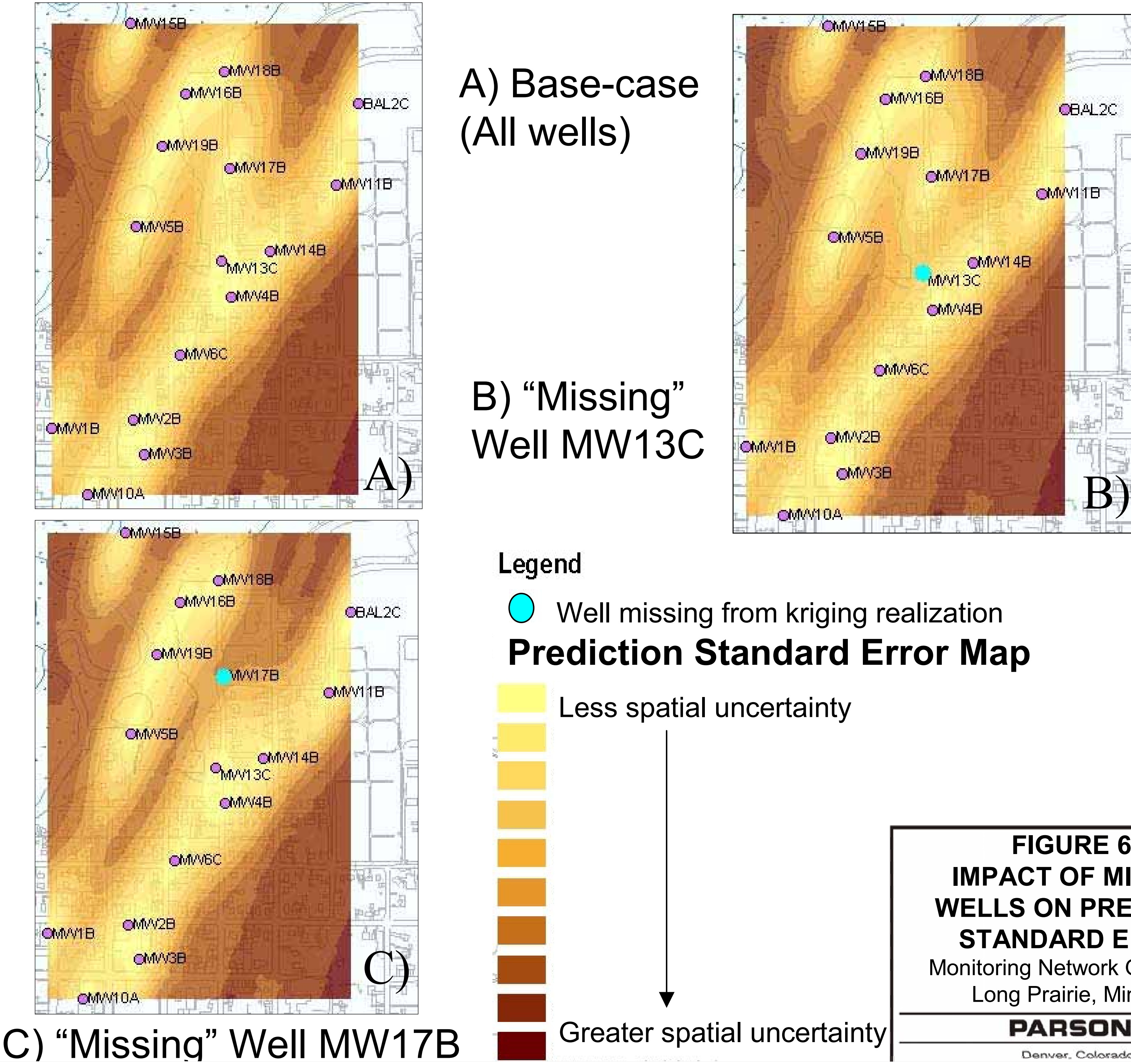


FIGURE 6.3
IMPACT OF MISSING WELLS ON PREDICTED STANDARD ERROR
Monitoring Network Optimization
Long Prairie, Minnesota

PARSONS
Denver, Colorado

At the conclusion of the kriging realizations, each well was ranked from 1 (providing the least information) to 16 (providing the most information), based on the amount of information (as measured by changes in median kriging standard deviation) the well contributed toward describing the spatial distribution of TCE, as shown in Table 6.1. Wells providing the least amount of information represent possible candidates for removal from the monitoring network at the Long Prairie.

6.3 SPATIAL STATISTICAL EVALUATION RESULTS

6.3.1 Kriging Ranking Results

Figure 6.4 and Table 6.1 present the ranking of the evaluated subset of monitoring locations based on the relative value of recent PCE information provided by each well, as calculated based on the kriging realizations. Examination of these results indicate that monitoring wells in close proximity to several other monitoring wells (e.g., red color coding on Figure 6.4) generally provide relatively lesser amounts of information than do wells at greater distances from other wells, or wells located in areas having limited numbers of monitoring points (e.g., blue color coding on Figure 6.4). This is intuitively obvious, but the analysis allows the most valuable and least valuable wells to be identified quantitatively. For example, Table 6.1 identifies the four wells ranked at or below 3.5 (wells MW19B, MW13C, MW4B, MW16B) that provide the relative least amount of information, and the four wells ranked at or above 13 (wells MW14B, MW5B, MW17B, MW1B) that provide the greatest amount of relative information regarding the occurrence and distribution of PCE in groundwater among those wells included in the kriging analysis. The four lowest-ranked wells are potential candidates for removal from the Long Prairie groundwater monitoring program, and the four highest-ranked wells are candidates for retention in the monitoring program, intermediate ranked wells receive no recommendation for removal or retention in the monitoring program based on the spatial analysis.

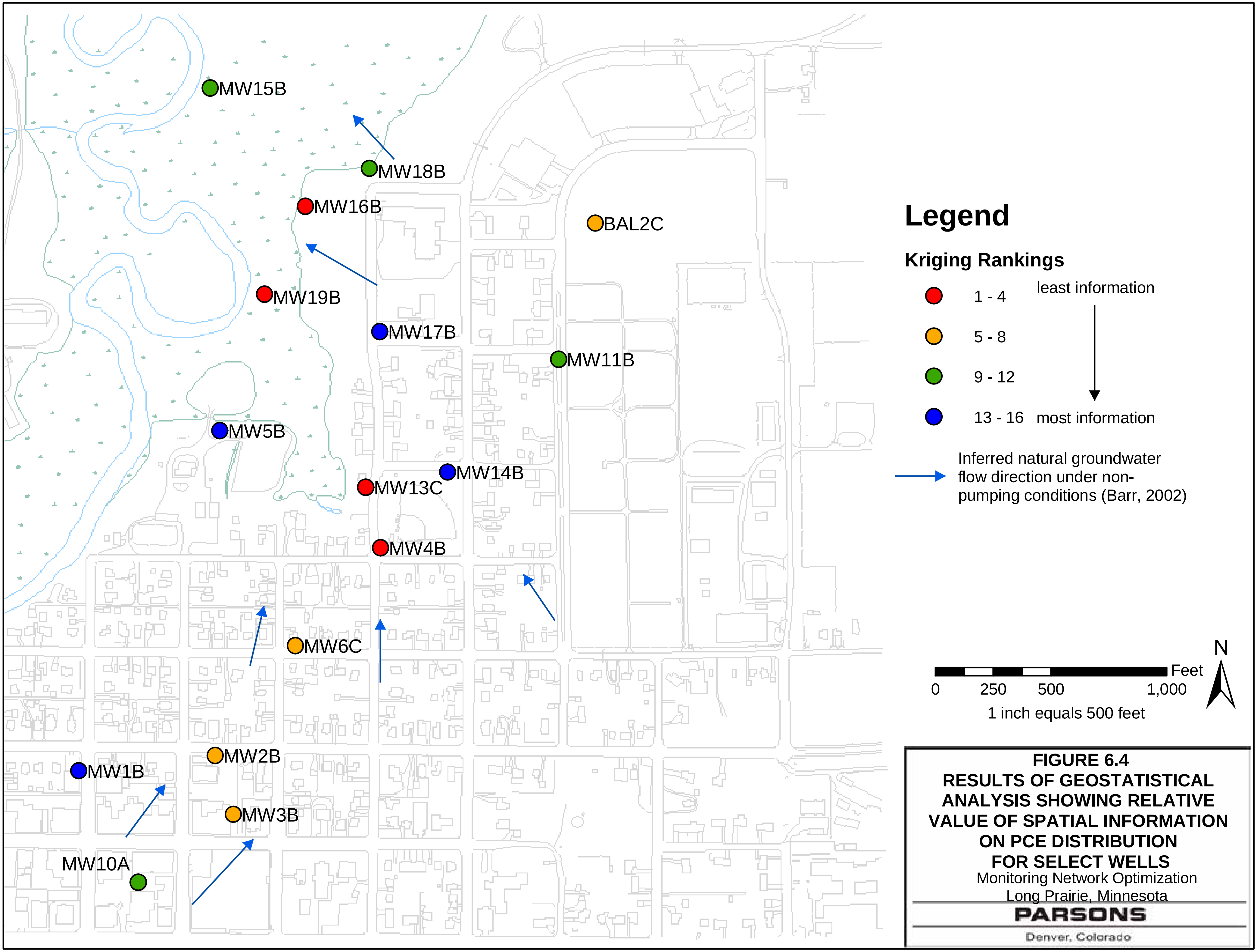


FIGURE 6.4
RESULTS OF GEOSTATISTICAL ANALYSIS SHOWING RELATIVE VALUE OF SPATIAL INFORMATION ON PCE DISTRIBUTION FOR SELECT WELLS
Monitoring Network Optimization
Long Prairie, Minnesota

PARSONS
Denver, Colorado

SECTION 7

SUMMARY OF THREE-TIERED MONITORING NETWORK EVALUATION

The 44 wells sampled in October 2002 at Long Prairie were evaluated using qualitative hydrogeologic and extraction-system information, temporal statistical techniques, and spatial statistics. At each tier of the evaluation, monitoring points that provide relatively greater amounts of information regarding the occurrence and distribution of COCs in groundwater were identified, and were distinguished from those monitoring points that provide relatively lesser amounts of information. In this section, the results of the evaluations are combined to generate a refined monitoring program that potentially could provide information sufficient to address the primary objectives of monitoring, at reduced cost. Monitoring wells not retained in the refined monitoring network could be removed from the monitoring program with relatively little loss of information. The results of the evaluations were combined and summarized in accordance with the following decision logic:

1. Each well retained in the monitoring network on the basis of the qualitative hydrogeologic evaluation is recommended to be retained in the refined monitoring program.

2. Those wells recommended for removal from the monitoring program on the basis of all three evaluations, or on the basis of the qualitative and temporal evaluations (with no recommendation resulting from the spatial evaluation) should be removed from the monitoring program.

3. If a well is recommended for removal based on the qualitative evaluation and recommended for retention based on the temporal or spatial evaluation, the final recommendation is based on a case-by-case review of well information.

The results of the qualitative, temporal, and spatial evaluations are summarized in Table 7.1. These results indicate that 18 of the 44 wells sampled in October 2002 could be excluded from the groundwater monitoring program with little loss of information. These results further suggest that the "current" sampling plan (the 19 monitoring wells and 6 active recovery wells included in the 2000 and 2001 sampling schedules, plus water-supply wells CW3 and CW6) could be optimized by removing four of the 27 wells now in the LTM program, and adding three wells not currently included in the program. Two wells sampled in October 2002, but not included in the current monitoring program, fall into case 3 of the decision logic (as listed above). Justifications for the recommendation to continue to exclude these wells from routine sampling are as follow:

- Well MW1B was recommended for continued exclusion from the monitoring network based on the qualitative and temporal evaluations, and for addition to the program based on the spatial evaluation. This well should not be added to the monitoring program because it is crossgradient from (west of) the plume, and well RW4 provides adequate monitoring of the western boundary of the plume.

- Well MW5B also was recommended for continued exclusion from the monitoring network based on the qualitative evaluation, and addition to the program based on the temporal and spatial evaluations. Well MW5B should be added to the scheduled monitoring program to determine if the recent low detection of *cis*-1,2-DCE truly reflects an increasing concentration trend.

A refined monitoring program, consisting of 26 wells (2 to be sampled quarterly, 6 to be sampled semi-annually, 14 to be sampled annually, and 4 to be sampled biennially) would be adequate to address the two primary objectives of monitoring. This refined monitoring network would result in an average of 36 sampling events per year, compared to 51 events per year under the current (2000/2001) monitoring program. ***Implementing***

these recommendations for optimizing the LTM monitoring program at Long Prairie could reduce current LTM annual monitoring by more than 29 percent. Additionally, based on a per well sampling cost ranging from$100 to $280, these recommendations could reduce costs by an average of $1500 to $4,200 per year.

TABLE 7.1
SUMMARY OF EVALUATION OF GROUNDWATER MONITORING PROGRAM
MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA

Well ID	Screen Interval (ft bgs)[a/]	Sampling Frequency [b/]	Qualitative Evaluation		Temporal		Spatial Evaluation		Summary		
			Remove/ Exclude	Retain/ Add	Remove/ Exclude	Retain/ Add	Remove/ Exclude	Retain/ Add	Remove/ Exclude	Retain/ Add	Recommended Monitoring Frequency
Monitoring Wells in 2000/2001 Sampling Plan											
MW2A	15-20	Annual	√		√		NI[d/]		√		--
MW2B	31-35	Annual		√		√				√	Annual
MW2C	48-53	Annual	√		√		NI		√		--
MW4B	31.5-35.5	Annual		√		√	√			√	Annual
MW4C	42.0-46.0	Annual		√	√		NI			√	Annual
MW6A	12.0-17	Annual	√		√		NI		√		--
MW6B	31.0-37	Annual		√		√	NI			√	Annual
MW6C	46.0-59	Annual		√		√				√	Annual
MW10A	16-21	Annual		√		√				√	Annual
MW11B		Annual		√		√				√	Annual
MW11C	50-55	Annual		√		√	NI			√	Annual
MW14B	21-26	Annual		√		√		√		√	Annual
MW14C	50-55	Annual	√		√		NI		√		--
MW15A	12	Annual		√		√	NI			√	Annual
MW15B	33	Annual		√		√				√	Annual
MW16B	25.3	Annual		√		√	√			√	Annual
MW17B	33	Annual		√		√		√		√	Annual
MW19B	26.5	Annual		√		√	√			√	Biennial
City Water-Supply Wells											
CW3	67-85	Quarterly		√		√	NI			√	Quarterly
CW6	53-76	Quarterly		√		√	NI			√	Quarterly
Recovery Wells											
RW1A	15-30	--	√		√		NI		√		--
RW1B	13-45	--	√		√		NI		√		--
RW1C	12.5-23.5	--	√		Not Analyzed[c/]		NI		√		--
RW3	17-52	Quarterly		√		√	NI			√	Semi-Annual

TABLE 7.1 (Continued)
SUMMARY OF EVALUATION OF GROUNDWATER MONITORING PROGRAM
MONITORING NETWORK OPTIMIZATION
LONG PRAIRIE, MINNESOTA

Well ID	Screen Interval (ft bgs)[a/]	Sampling Frequency [b/]	Qualitative Evaluation		Temporal		Spatial Evaluation		Summary		
			Remove/ Exclude	Retain/ Add	Remove/ Exclude	Retain/ Add	Remove/ Exclude	Retain/ Add	Remove/ Exclude	Retain/ Add	Recommended Monitoring Frequency
RW4	10.0-50	Annual		√		√	NI			√	Biennial
RW5	41-56	Quarterly		√		√	NI			√	Semi-Annual
RW6	10.0-55.5	Quarterly		√		√	NI			√	Semi-Annual
RW7	15-45	Quarterly		√		√	NI			√	Semi-Annual
RW8	30-40	Quarterly		√		√	NI			√	Semi-Annual
RW9	25-35	Quarterly		√		√	NI			√	Semi-Annual
Other Area Wells Sampled in October 2002											
BAL2B	57-65	--	√		**Not Analyzed**		NI		√		--
BAL2C	40-50	--	√		√				√		--
MW1A	9.5-14.5	--	√		√		NI		√		--
MW1B	30-35	--	√		√			√	√		--
MW3A	17.8-22.8	--	√		√		NI		√		--
MW3B	30-35	--	√		√				√		--
MW4A	10.0-15	--	√		**Not Analyzed**		NI		√		--
MW5A	4.5-9.5	--	√		√		NI		√		--
MW5B	31.0-35	--	√			√		√		√	Annual
MW11A		--	√		**Not Analyzed**		NI		√		--
MW13C	50-55	--		√		√	√			√	Biennial
MW16A	15.5	--	√		√		NI		√		--
MW18A	15.1	--	√		√		NI		√		--
MW18B	35	--		√	√					√	Biennial

[a/] ft bgs = feet below ground surface
[b/] Reduced sampling frequency established prior to comprehensive October 2002 sampling event (Barr, 2002).
[c/] Fewer than four analytical measurements; Mann-Kendall trends not analyzed.
[d/] NI = not included in spatial evaluation.

SECTION 8

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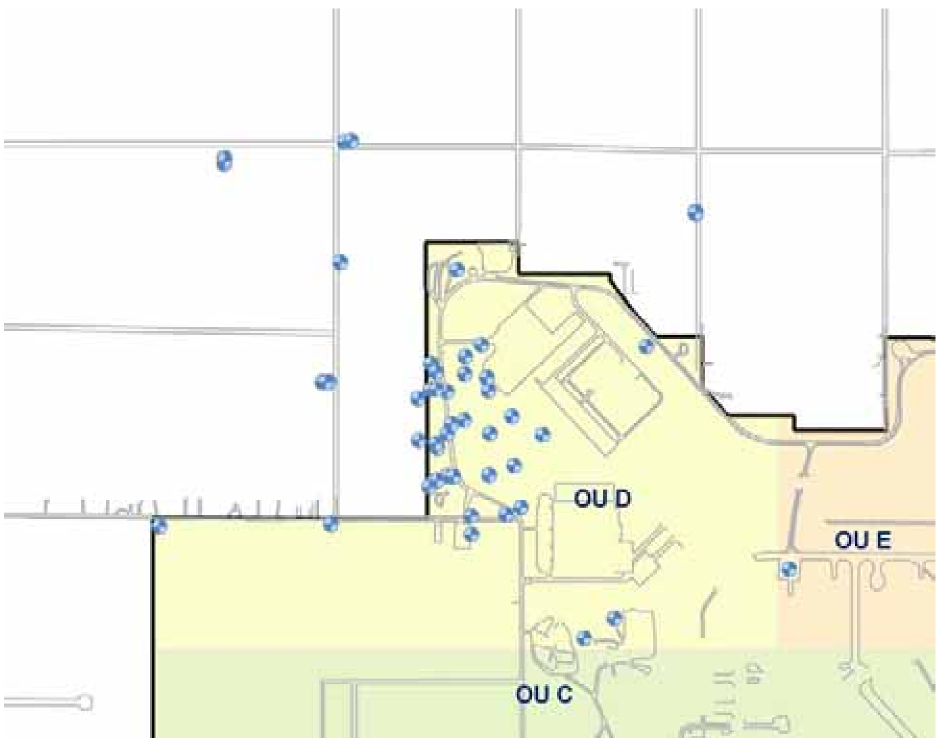
APPENDIX D-3

OPTIMIZATION OF MONITORING PROGRAM
AT
OPERABLE UNIT D
McCLELLAN AIR FORCE BASE, CALIFORNIA

G-2236-15

MAROS 2.0 Application: Zone A & B OU D Monitoring Network Optimization McClellan Air Force Base

Sacramento Valley, California



Submitted to
Air Force Center for Environmental Excellence

June 2, 2003

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GROUNDWATER
SERVICES, INC.

MAROS 2.0 APPLICATION
ZONE A & B OU D MONITORING NETWORK OPTIMIZATION
MCCLELLAN AIR FORCE BASE

Sacramento Valley, California

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GSI Job No. G-2236
Revision No. ***DRAFT***
Date: 6/02/03

GROUNDWATER
SERVICES, INC.

MAROS 2.0 APPLICATION ZONE A & B OU D MONITORING NETWORK OPTIMIZATION, MCCLELLAN AIR FORCE BASE

Sacramento Valley, California

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GROUNDWATER SERVICES, INC.

June 2, 2003

MAROS 2.0 APPLICATION
ZONE A & B OU D MONITORING NETWORK OPTIMIZATION
MCCLELLAN AIR FORCE BASE

EXECUTIVE SUMMARY

Long-term monitoring programs, whether applied for process control, performance measurement, or compliance purposes, require large scale data collection effort and time commitment, making their cumulative costs very high. With the increasing use of risk-based goals and natural attenuation in recent years as well as the move toward long-term closure upon completion of cleanup activities, the need for better-designed long-term monitoring plans that are cost-effective, efficient, and protective of human and ecological health has greatly increased. The Monitoring and Remediation Optimization System (MAROS) methodology provides an optimal monitoring network solution, given the parameters within a complicated groundwater system which will increase its effectiveness. By applying statistical techniques to existing historical and current site analytical data, as well as considering hydrogeologic factors and the location of potential receptors, the software suggests an optimal plan along with an analysis of individual monitoring wells for the current monitoring system. This report summarizes the findings of an application of the MAROS 2.0 software to Zone A and Zone B long-term monitoring well networks in Operating Unit (OU) D at the McClellan Air Force Base in Sacramento Valley, California.

The primary constituent of concern at the site is trichloroethylene (TCE) which is analyzed at 32 and 14 monitoring wells respectively in the OU D Zone A and Zone B well networks (Figures 1 and 2). Monitoring wells in both Zones A and B have been sampled for TCE irregularly, ranging from quarterly to annually and in some cases, biennially (every two years) since the implementation of the long-term monitoring plan in 1990. By December 2000, 40 sampling events had been carried out at the site, however, many wells have only 5 analyses. The historical TCE data for all or in some cases a subset of wells were analyzed using the MAROS 2.0 software in order to: 1) gain an overall understanding of the plume stability, and 2) recommend changes in sampling frequency and sampling locations without compromising the effectiveness of the long-term monitoring network.

Project Objectives

The general objective of the project was to optimize the McClellan OU D long-term monitoring network and sampling plan applying the MAROS 2.0 statistical and decision support methodology. The key objectives of the project included:

- Determining the overall plume stability through trend analysis and moment analysis;
- Evaluating individual well TCE concentration trends over time;

- Addressing adequate and effective sampling through reduction of redundant wells without information loss and addition of new wells for future sampling;
- Assessing future sampling frequency recommendations while maintaining sufficient plume stability information;
- Evaluating risk-based site cleanup status using data sufficiency analysis.

Results

The MAROS 2.0 sampling optimization software/methodology has been applied to the McClellan's existing monitoring program as of December 2000. Historical data from 2001 was not used in this analysis due to anomalous TCE concentrations from the passive diffusion sampling technique utilized only in 2001. Results from the temporal trend analysis, moment analysis, sampling location determination, sampling frequency determination, and data sufficiency analysis indicate that:

- Site monitoring wells were divided into source wells and tail wells where source wells are in the vicinity of NAPL or have historically elevated concentrations of TCE.

- 9 out of 10 source wells and 11 out of 22 tail wells in Zone A have a Probably Decreasing, Decreasing, or Stable trend. Both of the statistical methods used to evaluate trends (Mann-Kendall and Linear Regression) gave similar trend estimates for each well.

- 0 out of 1 source wells and 3 out of 13 tail wells in Zone B have a Probably Decreasing, Decreasing, or Stable trend. The majority of the wells in Zone B have no trend in the historical data. However, as of 2000, only one of the wells in Zone B is actually above the MCL for TCE. Both of the statistical methods used to evaluate trends (Mann-Kendall and Linear Regression) gave similar trend estimates for each well.

- 5 out of 6 source area extraction wells in Zone AB have a Decreasing trend. Both the Mann-Kendall and Linear Regression methods gave similar trend estimates for each well.

- The dissolved mass shows stability over time, whereas the center of mass and the plume spread show no trend over time. The results from the moment analysis are not very strong due to the change in the wells sampled over the sampling period analyzed.

- Overall plume stability results lead to the MAROS analysis system to indicate that a monitoring system of "Moderate" intensity is appropriate for this plume compared to "Limited" or "Extensive" systems due to a stable or decreasing plume in both Zone A and Zone B.

- The well redundancy optimization tool, using the Delaunay method, indicates that 3 existing monitoring wells may not be needed for Zone A plume monitoring and can likely be eliminated from the existing Zone A monitoring network of 32 wells without compromising the accuracy of the monitoring network. Similarly, two existing monitoring wells may be eliminated from the existing Zone B monitoring network of 14 wells.

- The well sufficiency optimization tool, using the Delaunay method, indicates that there are no areas within the existing monitoring network that have high uncertainty in the TCE concentration estimation. Therefore, no new monitoring wells are recommended for Zones A or B.

- Application of the well sampling frequency determination tool, the Modified CES method, leads to results that are in agreement with the sampling frequency currently in use at the site. Therefore, no sampling frequency reduction is recommended for the wells in the current monitoring network.

- The MAROS Data Sufficiency (Power Analysis) application indicates that the monitoring record has sufficient statistical power to conclude that the site has attained cleanup goal at (or farther than) the "hypothetical statistical compliance boundary" located 100 feet downgradient of the most downgradient well at the site. As more sampling records accumulate, this hypothetical statistical compliance boundary will get closer and closer to the downgradient wells of the monitoring system.

The recommended long-term monitoring strategy results in a moderate reduction in sampling costs and allows site personnel to develop a better understanding of plume behavior over time. The MAROS optimized plan results in a monitoring network of 47 wells: 17 sampled annually, and 30 sampled biennially. The MAROS optimized plan would result in 32 samples per year, compared to 34 samples per year (17 annual and 34 biennial) in the current McClellan sampling program. Implementing these recommendations could lead to a 6% reduction from the current monitoring plan in terms of the samples to be collected per year. A reduction in the number of redundant wells is expected to result in a moderate cost savings over the long-term at McClellan Air Force Base. An approximate cost savings estimate of $300 per year is projected while still maintaining adequate delineation of the plume as well as knowledge of the plume state over time.

1.0 INTRODUCTION

Long-term monitoring programs, whether applied for process control, performance measurement, or compliance purposes, require large scale data collection effort and time commitment, making their cumulative costs very high. With the increasing use of risk-based goals and natural attenuation in recent years as well as the move toward long-term closure upon completion of cleanup activities, the need for better-designed long-term monitoring plans that are cost-effective, efficient, and protective of human and ecological health has greatly increased. AFCEE's Monitoring and Remediation Optimization System (MAROS) methodology provides an optimal monitoring network solution, given the parameters within a complicated groundwater system which will increase its effectiveness. By applying statistical techniques to existing historical and current site analytical data, as well as considering hydrogeologic factors and the location of potential receptors, the software suggests an optimal plan along with an analysis of individual monitoring wells for the current monitoring system. This report summarizes the findings of an application of the MAROS 2.0 software to the current Zone A and Zone B OU D long-term monitoring well network at the McClellan Air Force Base, Sacramento Valley, California.

1.1 Geology/Hydrogeology

McClellan Air Force Base (AFB) is located in the Sacramento Valley, approximately seven miles northeast of Sacramento, California. The site has been divided into 8 operable units (OUs). Locations of these OUs at McClellan AFB are available in Figure 2-2 in the GMPF (Radian Corporation 1997). OU D is located in the northwest corner of McClellan AFB.

The subsurface of McClellan AFB consists of alluvial and fluvial sediments, stretching from the ground surface to a depth of 450 feet below ground surface (bgs). The ground surface elevation in OU D is about 62 ft above mean sea level (msl). The subsurface beneath McClellan AFB has been divided into the vadose zone and five monitoring zones (A, B, C, D, and E, from shallowest to deepest) on the basis of lithologic, geologic, and hydrologic characteristics. The monitoring zones are used to track the horizontal migration of contaminants and to monitor local variations in hydraulic gradient. A generalized geologic cross-section illustrating the designated monitoring zones is presented in Figure 2-3 of the GMPF (Radian Corporation 1997). In OU D, the plume has only impacted monitoring Zones A and B. Monitoring Zone A of OU D has an average depth of 35 ft, ranging from 99 to 134 ft bgs; monitoring Zone B of OU D has an average depth of 60 ft, ranging from 134 to 194 ft bgs (Table 2-3 in the GMPF, Radian Corporation 1999).

Base-wide data collected during remedial investigations and groundwater sampling efforts indicate that groundwater from 100 to 425 feet bgs beneath McClellan AFB is one hydraulic system. Fine-grained deposits used to define the monitoring zones are not continuous and allow groundwater movement and contaminant migration between monitoring zones. The water elevation within the aquifer system has been declining continuously for approximately 50 years due to overdrawing by irrigation, pumping for municipal water supply, and extraction wells. Within the last decade, water levels in Zone A across the base have been declining at a rate of 1 to 2 feet per year. Groundwater elevations rise and fall by an average of 5 feet due to seasonal fluctuations. Groundwater elevations range from –38 to –40 ft msl at the northern and southern edges of OU D, respectively, and the horizontal hydraulic gradient at OU D is about 0.0006 ft/ft (1Q02 Monitoring Report, URS 2002).

Flow directions in the hydraulic system have varied over the past 8 decades, but have persisted in a south to southwesterly direction over the past decade. The groundwater flow direction for both monitoring Zone A and Zone B is predominantly toward the South-Southwest and the groundwater seepage velocity is approximately 35 ft/yr. Base wells, domestic production wells, extraction wells, and regional pumping affect local groundwater flow directions. The vertical hydraulic gradients between monitoring zones A and B are predominantly upward in the winter and downward during the rest of the year. The horizontal hydraulic conductivity of layered sediments is about 5 to 15 times the vertical hydraulic conductivity. For a detailed description of site geology and hydrogeology refer to Radian Corporation (1997).

1.2 Remedial Action

McClellan Air Force Base was established in 1936 as an aircraft repair depot and supply base. McClellan AFB and the OUs that have been established were put on the National priorities List (NPL) in 1988. OU D located in the northwestern portion of the base is approximately 192 acres and consists primarily of several disposal pits, sludge/oil pits, fuel solvent pits, runway access, and an Industrial Wastewater Treatment Plant sludge land farm. The RI for OU D was complete in 1994 and indicated TCE is the main constituent of concern for a single plume that extended approximately 1,750 feet off-base to the northwest in Zones A and B.

A pump-and-treat system with 6 extraction wells was installed in OU D in 1987, continuing to the present. The objective of the remediation is to restore Zones A and B to drinking water standards by reducing the TCE concentration to less than the MCL (5 ppb). The groundwater long-term monitoring plan consists of 33 monitoring wells in Zone A, 14 monitoring wells in Zone B and 6 extraction wells in Zone AB. It consists of performance monitoring and compliance monitoring with the following goals: 1) plume containment monitoring to confirm that the plume remains hydraulically controlled; and 2) plume reduction monitoring to verify progress toward achieving cleanup goals.

The number of monitoring wells that are currently sampled include 32 Zone A monitoring wells, 14 Zone B monitoring wells, and 6 extraction wells screened in both Zone A and Zone B (Figures 1 and 2). The sampling frequency for these wells has been very irregular, ranging from quarterly or annual in 1990 to annual or biennial in 2000, although the sampling was conducted on a quarterly basis. The frequency of sampling at the base has been changed over time as part of the McClellan AFB Remediation Monitoring Decision Logic implemented as part of the Installation Restoration Program (IRP)

Groundwater Monitoring Plan (Radian Corporation, 1997). Some monitoring wells have only 5 ~ 7 data records available during this period. This resulted in only a portion of the wells being sampled on each quarterly sampling event. The MAROS 2.0 analysis performed for this study utilizes the data from the current McClellan long-term monitoring plan (1990 to 2000) and is summarized in Table 1. The 2001 data were not used because a new sampling technique was being tested (passive diffusion sampling) in sample collection and results from these sample events were not consistent with previous results.

2.0 MAROS METHODOLOGY

The MAROS 2.0 software used to optimize the LTM network at the McClellan AFB is explained in general terms in this section. MAROS is a collection of tools in one software package that is used in an explanatory, non-linear fashion. The tool includes models, statistics, heuristic rules, and empirical relationships to assist the user in optimizing a groundwater monitoring network system while maintaining adequate delineation of the plume as well as knowledge of the plume state over time. Different users utilize the tool in different ways and interpret the results from a different viewpoint. For a detailed description of the structure of the software and further utilities, refer to the MAROS 2.0 Manual (Aziz et al. 2002).

2.1 MAROS Conceptual Model

In MAROS 2.0, two levels of analysis are used for optimizing long-term monitoring plans: 1) an overview statistical evaluation with interpretive trend analysis based on temporal trend analysis and plume stability information; and 2) a more detailed statistical optimization based on spatial and temporal redundancy reduction methods (see Figure 2 for further details). In general, the MAROS method applies to 2-D aquifers that have relatively simple site hydrogeology. However, for a multi-aquifer (3-D) system, the user could apply the statistical analysis layer-by-layer.

The overview statistics or interpretive trend analysis assesses the general monitoring system category by considering individual well concentration trends, overall plume stability, hydrogeologic factors (e.g., seepage velocity, and current plume length), and the location of potential receptors (e.g., property boundaries or drinking water wells). The analysis relies on temporal trend analysis to assess plume stability, which is then used to determine the general monitoring system category. Since the temporal trend analysis focuses on where the monitoring well is located, the site wells are divided into two different zones: the source zone or the tail zone. The source zone includes areas with non-aqueous phase liquids (NAPLs), contaminated vadose zone soils, and areas where aqueous-phase releases have been introduced into ground water. The tail zone is usually the area downgradient of the contaminant source zone. Although this classification is a simplification of the well location, this broadness makes the user aware on an individual well basis that the concentration trend results can have a different interpretation depending on the well location in and around the plume. The location and type of the individual wells allows further interpretation of the trend results, depending on what type of well is being analyzed (e.g., remediation well, leading plume edge well, or monitoring well). General recommendations for the monitoring network frequency and density are suggested based on heuristic rules applied to the source and tail trend results.

The detailed statistics level of analysis or sampling optimization, on the other hand, consists of a well redundancy analysis and well sufficiency analysis using the Delaunay method, a sampling frequency analysis using the Modified Cost Effective Sampling (CES) method and a data sufficiency analysis using power analysis. The well redundancy analysis is designed to minimize monitoring locations and the Modified CES method is designed to minimize the frequency of sampling. The data sufficiency analysis uses power analysis to assess the sampling record to determine if the current monitoring network and record is sufficient in terms of evaluating risk-based site target level status.

2.2 Data Management

In MAROS, ground water monitoring data can be imported from simple database-format Microsoft® Excel spreadsheets, Microsoft Access tables, previously created MAROS database archive files, or entered manually. Compliance monitoring data interpretation in MAROS is based on historical ground water monitoring data from a consistent set of wells over a series of sampling events. Statistical validity of the concentration trend analysis requires constraints on the minimum data input of at least four wells (ASTM 1998) in which COCs have been detected. Individual sampling locations need to include data from at least the six most-recent sampling events. To ensure a meaningful comparison of COC concentrations over time and space, both data quality and data quantity need to be considered. Prior to statistical analysis, the user can consolidate irregularly sampled data or smooth data that might result from seasonal fluctuations or a change in site conditions.

Imported ground water monitoring data and the site-specific information entered in Site Details can be archived and exported as MAROS archive files. These archive files can be appended as new monitoring data becomes available, resulting in a dynamic long-term monitoring database that reflects the changing conditions at the site (i.e. biodegradation, compliance attainment, completion of remediation phase, etc.).

2.3 Site Details

Information needed for the MAROS analysis includes site-specific parameters such as seepage velocity and current plume length. Part of the trend analysis methodology applied in MAROS focuses on where the monitoring well is located, therefore the user needs to divide site wells into two different zones: the source zone or the tail zone. The source zone includes areas with non-aqueous phase liquids (NAPLs), contaminated vadose zone soils, and areas where aqueous-phase releases have been introduced into ground water. The source zone generally contains locations with historical high ground water concentrations of the COCs. The tail zone is usually the area downgradient of the contaminant source zone. It is up to the user to make further interpretation of the trend results, depending on what type of well is being analyzed (e.g., remediation well, leading plume edge well, or monitoring well).

MAROS allows the analysis of up to 5 COCs concurrently and users can pick COCs from a list of compounds existing in the monitoring data, or select COCs based on recommendations provided in MAROS based on toxicity, prevalence, and mobility of compounds.

2.4 Data Consolidation

Typically long-term monitoring raw data have been measured irregularly in time or contain many non-detects, trace level results, and duplicates. Therefore, before the data can be further analyzed, raw data are filtered, consolidated, transformed, and possibly smoothed to allow for a consistent dataset meeting the minimum data requirements for statistical analysis mentioned previously.

MAROS allows users to specify the period of interest in which data will be consolidated (i.e., monthly, bi-monthly, quarterly, semi-annual, yearly, or a biennial basis). In computing the representative value when consolidating, one of four statistics can be used: median, geometric mean, mean, and maximum. Non-detects can be transformed to one half the reporting or method detection limit (DL), the DL, or a fraction of the DL. Trace level results can be represented by their actual values, one half of the DL, the DL, or a fraction of their actual values. Duplicates are reduced in MAROS by one of three ways: assigning the average, maximum, or first value. The reduced data for each COC and each well can be viewed as a time series in a graphical form on a linear or semi-log plot generated by the software.

2.5 Overview Statistics: Plume Trend Analysis

Within the MAROS software there are historical data analyses that support a conclusion about plume stability (e.g., increasing plume, etc.) through statistical trend analysis of historical monitoring data. Plume stability results are assessed from time-series concentration data with the application of three statistical tools: Mann-Kendall Trend analysis, linear regression trend analysis and moment analysis. The two trend methods are used to estimate the concentration trend for each well and each COC based on a statistical trend analysis of concentrations versus time at each well (Figure 2). These trend analyses are then consolidated to give the user a general plume stability and general monitoring frequency and density recommendations (see Figure 3 for further step-by-step details). Both qualitative and quantitative plume information can be gained by these evaluations of monitoring network historical data trends both spatially and temporally. The MAROS Overview Statistics are the foundation the user needs to make informed optimization decisions at the site. The Overview Statistics are designed to allow site personnel to develop a better understanding of the plume behavior over time and understand how the individual well concentration trends are spatially distributed within the plume. This step allows the user to gain information that will support a more informed decision to be made in the next level or detailed statistics optimization analysis (Figure 2).

2.5.1 Mann-Kendall Analysis

The Mann-Kendall test is a non-parametric statistical procedure that is well suited for analyzing trends in data over time. The Mann-Kendall test can be viewed as a nonparametric test for zero slope of the first-order regression of time-ordered concentration data versus time. The Mann-Kendall test does not require any assumptions as to the statistical distribution of the data (e.g. normal, lognormal, etc.) and can be used with data sets which include irregular sampling intervals and missing data. The Mann-Kendall test is designed for analyzing a single groundwater constituent, multiple constituents are analyzed separately. The Mann-Kendall S statistic measures the trend in the data: positive values indicate an increase in concentrations over time and negative values indicate a decrease in concentrations over time. The strength of the trend is proportional to the magnitude of the Mann-Kendall statistic (i.e., a large value indicates a strong trend). The confidence in the trend is determined by consulting the S statistic and the sample size n in a Kendall probability table such as the one reported in Hollander and Wolfe (1973).

The concentration trend is determined for each well and each COC based on results of the S statistic, the confidence in the trend, and the Coefficient of Variation (COV). The decision matrix for this evaluation is shown in Table 2. A Mann-Kendall statistic that is greater than 0 combined with a confidence of greater than 95% is categorized as an Increasing trend while a Mann-Kendall statistic of less than 0 with a confidence between 90% and 95% is defined as a Probably Increasing trend, and so on.

Depending on statistical indicators, the concentration trend is classified into six categories:

- Decreasing (D),
- Probably Decreasing (PD),
- Stable (S),
- No Trend (NT),
- Probably Increasing (PI)
- Increasing (I).

These trend estimates are then analyzed to identify the source and tail region overall stability category (see Figure 2 for further details).

2.5.2 Linear Regression Analysis

Linear Regression is a parametric statistical procedure that is typically used for analyzing trends in data over time. Using this type of analysis, a higher degree of scatter simply corresponds to a wider confidence interval about the average log-slope. Assuming the sign (i.e., positive or negative) of the estimated log-slope is correct, a level of confidence that the slope is not zero can be easily determined. Thus, despite a poor goodness of fit, the overall trend in the data may still be ascertained, where low levels of confidence correspond to “Stable” or “No Trend” conditions (depending on the degree of scatter) and higher levels of confidence indicate the stronger likelihood of a trend. The linear regression analysis is based on the first-order linear regression of the log-transformed concentration data versus time. The slope obtained from this log-transformed regression, the confidence level for this log-slope, and the COV of the untransformed data are used to determine the concentration trend. The decision matrix for this evaluation is shown in Table 3. To estimate the confidence in the log-slope, the standard error of the log-slope is calculated. The coefficient of variation, defined as the standard deviation divided by the average, is used as a secondary measure of scatter to distinguish between “Stable” or “No Trend” conditions for negative slopes. The Linear Regression Analysis is designed for analyzing a single groundwater constituent; multiple constituents are analyzed separately, (up to five COCs simultaneously). For this evaluation, a decision matrix developed by Groundwater Services, Inc. is also used to determine the “Concentration Trend” category (plume stability) for each well.

Depending on statistical indicators, the concentration trend is classified into six categories:

- Decreasing (D),
- Probably Decreasing (PD),
- Stable (S),
- No Trend (NT),
- Probably Increasing (PI)
- Increasing (I).

The resulting confidence in the trend, together with the log-slope and the COV of the untransformed data, are used in the linear regression analysis decision matrix to determine the concentration trend. For example, a positive log-slope with a confidence of less than 90% is categorized as having No Trend whereas a negative log-slope is considered Stable if the COV is less than 1 and categorized as No Trend if the COV is greater than 1.

2.5.3 Overall Plume Analysis

General recommendations for the monitoring network frequency and density are suggested based on heuristic rules applied to the source and tail trend results. Individual well trend results are consolidated and weighted by the MAROS software according to user input, and the direction and strength of contaminant concentration trends in the source zone and tail zone for each COC are determined. Based on

i) the consolidated trend analysis,
ii) hydrogeologic factors (e.g., seepage velocity), and
iii) location of potential receptors (e.g., wells, discharge points, or property boundaries),

the software suggests an general optimization plan for the current monitoring system in order to efficiently effectively monitor in the future. A flow chart of the MAROS methodology utilizing trend analysis results and other site-specific parameters to form a general sampling frequency and well density recommendation is outlined in Figure 3. For example, a generic plan for a shrinking petroleum hydrocarbon plume (BTEX) in a slow hydrogeologic environment (silt) with no nearby receptors would entail minimal, low frequency sampling of just a few indicators. On the other hand, the generic plan for a chlorinated solvent plume in a fast hydrogeologic environment that is expanding but has very erratic concentrations over time would entail more extensive, higher frequency sampling. The generic plan is based on a heuristically derived algorithm for assessing future sampling duration, location and density that takes into consideration plume stability. For a detailed description of the heuristic rules used in the MAROS software, refer to the MAROS 2.0 Manual (Aziz et al. 2002).

2.5.3 Moment Analysis

An analysis of moments can help resolve plume trends, where the zeroth moment shows change in dissolved mass vs. time, the first moment shows the center of mass location vs. time, and the second moment shows the spread of the plume vs. time. Moment calculations can predict how the plume will change in the future if further statistical analysis is applied to the moments to identify a trend (in this case, Mann Kendall Trend Analysis is applied). The trend analysis of moments can be summarized as:

- Zeroth Moment: Change in dissolved mass over time
- First Moment: Change in the center of mass location over time
- Second Moment: Spread of the plume over time

The role of moment analysis in MAROS is to provide a relative measure of plume stability and condition. Plume stability may vary by constituent, therefore the MAROS moment analysis can be used to evaluate multiple COCs simultaneously in order to provide used to provide a quick way of comparing individual plume parameters to determine the size and movement of constituents relative to one another. Moment analysis in the MAROS software can also be used to assist the user in evaluating the impact on plume delineation in future sampling events by removing identified “redundant” wells from a long-term monitoring program (this analysis was not performed as part of this study, for more details on this application of moment analysis refer to the MAROS 2.0 Manual (Aziz et al. 2002).

The **zeroth moment** is a mass estimate. The zeroth moment calculation can show high variability over time, largely due to the fluctuating concentrations at the most contaminated wells as well as varying monitoring well network. Plume analysis and delineation based exclusively on concentration can exhibit a fluctuating degree of temporal and spatial variability. The mass estimate is also sensitive to the extent of the site monitoring well network over time. The zeroth moment trend over time is determined by using the Mann-Kendall Trend Methodology. The zeroth Moment trend test allows the user to understand how the plume mass has changed over time. Results for the trend include: Increasing, Probably Increasing, No Trend, Stable, Probably Decreasing, Decreasing or Not Applicable (Insufficient Data). When considering the results of the Zeroth moment trend, the following factors should be considered which could effect the calculation and interpretation of the plume mass over time: 1) Change in the spatial distribution of the wells sampled historically 2) Different wells sampled within the well network over time (addition and subtraction of well within the network). 3) Adequate versus inadequate delineation of the plume over time.

The **first moment** estimates the center of mass, coordinates (Xc and Yc) for each sample event and COC. The changing center of mass locations indicate the movement of the center of mass over time. Whereas, the distance from the original source location to the center of mass locations indicate the movement of the center of mass over time relative to the original source. Calculation of the first moment normalizes the spread by the concentration indicating the center of mass. The first moment trend of the distance to the center of mass over time shows movement of the plume in relation to the original source location over time. Analysis of the movement of mass should be viewed as it relates to 1) the original source location of contamination 2) the direction of groundwater flow and/or 3) source removal or remediation. Spatial and temporal trends in the center of mass can indicate spreading or shrinking or transient movement based on seasonal variation in rainfall or other hydraulic considerations. No appreciable movement or a neutral trend in the center of mass would indicate plume stability. However, changes in the first moment over time do not necessarily completely characterize the changes in the concentration distribution (and the mass) over time. Therefore, in order to fully characterize the plume the First Moment trend should be compared to the Zeroth moment trend (mass change over time).

The **second moment** indicates the spread of the contaminant about the center of mass (Sxx and Syy), or the distance of contamination from the center of mass for a particular COC and sample event. The Second Moment represents the spread of the plume over time in both the x and y directions. The Second Moment trend indicates the spread of the plume about the center of mass. Analysis of the spread of the plume should be viewed as it relates to the direction of groundwater flow. An increasing trend in the second moment indicates an expanding plume, whereas a declining trend in the plume indicates a shrinking plume. No appreciable movement or a neutral trend in the center of mass would indicate plume stability. The second moment provides a measure of the spread of the concentration distribution about the plume's center of mass. However, changes in the second moment over time do not necessarily completely characterize the changes in the concentration distribution (and the mass) over time. Therefore, in order to fully characterize the plume the Second Moment trend should be compared to the zeroth moment trend (mass change over time).

2.6 Detailed Statistics: Optimization Analysis

Although the overall plume analysis shows a general recommendation regarding sampling frequency reduction and general sampling density, a more detailed analysis is also available with the MAROS 2.0 software in order to allow for further reductions on a well-by-well basis for frequency, well redundancy, well sufficiency and sampling sufficiency. The MAROS Detailed Statistics allows for a quantitative analysis for spatial and temporal optimization of the well network on a well-by-well basis. The results from the Overview Statistics should be considered along with the MAROS optimization recommendations gained from the Detailed Statistical Analysis described previously. The MAROS Detailed Statistics results should be reassessed in view of site knowledge and regulatory requirements as well as in consideration of the Overview Statistics (Figure 2).

The Detailed Statistics or Sampling Optimization MAROS module can be used to determine the minimal number of sampling locations and the lowest frequency of sampling that can still meet the requirements of sampling spatially and temporally for an existing monitoring program. It also provides an analysis of the sufficiency of data for the monitoring program.

Sampling optimization in MAROS consists of four parts:

- Well redundancy analysis using the Delaunay method
- Well sufficiency analysis using the Delaunay method
- Sampling frequency determination using the Modified CES method
- Data sufficiency analysis using statistical power analysis.

The well redundancy analysis using the Delaunay method identifies and eliminates redundant locations from the monitoring network. The well sufficiency analysis can determine the areas where new sampling locations might be needed. The Modified CES method determines the optimal sampling frequency for a sampling location based on the direction, magnitude, and uncertainty in its concentration trend. The data sufficiency analysis examines the risk-based site cleanup status and power and expected sample size associated with the cleanup status evaluation.

2.6.1 Well Redundancy Analysis – Delaunay Method

The well redundancy analysis using the Delaunay method is designed to select the minimum number of sampling locations based on the spatial analysis of the relative importance of each sampling location in the monitoring network. The approach allows elimination of sampling locations that have little impact on the historical characterization of a contaminant plume. The delaunay methodology application assumes that the current sampling network adequately delineates the plume (bounding wells have non-detect values) and that if a hydraulic containment system is currently in operation, this will continue. An extended method or wells sufficiency analysis, based on the Delaunay method, can also be used for recommending new sampling locations. Details about the Delaunay method can be found in Appendix A.2 of the MAROS Manual (AFCEE 2002).

Well redundancy analysis uses the Delaunay triangulation method to determine the significance of the current sampling locations relative to the overall monitoring network. The Delaunay method calculates the network Area and Average concentration of the plume using data from multiple monitoring wells. A slope factor (SF) is calculated for each well to indicate the significance of this well in the system (i.e. how removing a well changes the average concentration.)

The well redundancy optimization process is performed in a stepwise fashion. Step one involves assessing the significance of the well in the system, if a well has a small SF (little significance to the network), the well may be removed from the monitoring network. Step two involves evaluating the information loss of removing a well from the network. If one well has a small SF, it may or may not be eliminated depending on whether the information loss is significant. If the information loss is not significant, the well can be eliminated from the monitoring network and the process of optimization continues with fewer wells. However if the well information loss is significant then the optimization terminates. This sampling optimization process allows the user to assess "redundant" wells that will not incur significant information loss on a constituent-by-constituent basis for individual sampling events.

Before applying the Delaunay method for spatial redundancy analysis, it is important to select the appropriate set of wells for analysis, i.e., only the wells that contribute to the spatial delineation of the plume. For example, if wells are far from the plume and contribute little or nothing to the delineation of the plume (e.g., some sentry wells or background wells far from the plume), they should be excluded from the analysis. One reason not to use these wells is that these wells usually are on the boundary of the triangulation and are hard to be eliminated since the Delaunay method protects boundary wells from being easily removed. The elimination status of these wells, in fact, should be determined from the regulatory standpoint. Another well type that could be excluded from analysis is one of a clustered well set because the Delaunay method is a two-dimensional method. Generally, only one well is picked from the clustered well set to represent the concentration at this point. This well can be the one that has the highest concentration or is screened in the representative aquifer interval with the geologic unit. Data from clustered wells can also be averaged to form a single sample and then used in the Delaunay method.

2.6.2 Well Sufficiency Analysis – Delaunay Method

The well sufficiency analysis, using the Delaunay method, is designed to recommend new sampling locations in areas within the existing monitoring network where there is a high level uncertainty in plume concentration. Details about the well sufficiency analysis can be found in Appendix A.2 of the MAROS Manual (AFCEE 2002).

In many cases, new sampling locations need to be added to the existing network to enhance the spatial plume characterization. In MAROS, the method for determining new sampling locations recommends the area for a possible new sampling location where there is a high level of uncertainty in concentration estimation. The Slope Factor (SF) values obtained from the redundancy reduction described above are used to calculate the concentration estimation error at each triangle area formed in the Delaunay triangulation. The estimated SF value at each triangle area is then classified into four levels: Small, Moderate, Large, or Extremely large because the larger the estimated SF value, the higher the estimation error at this area. Therefore, the triangle areas with the estimated SF value at the Extremely large or Large level are candidate regions for new sampling locations.

The results from the Delaunay method and the method for determining new sampling locations are derived solely from the spatial configuration of the monitoring network and the spatial pattern of the contaminant plume. No parameters such as the hydrogeologic conditions are considered in the analysis. Therefore, professional judgement and regulatory considerations must be used to make final decisions.

2.6.3 Sampling Frequency Determination - Modified CES Method

The Modified Cost Effective Sampling (MCES) method optimizes sampling frequency for each sampling location based on the magnitude, direction, and uncertainty of its concentration trend derived from its recent and historical monitoring records. The MCES estimates the lowest-frequency sampling schedule for a given groundwater monitoring location yet still provide needed information for regulatory and remedial decision-making. The Modified CES method was developed on the basis of the Cost Effective Sampling (Ridley et al. 1995). Details about the Modified CES method can be found in Appendix A.3 of the MAROS Manual (AFCEE 2002).

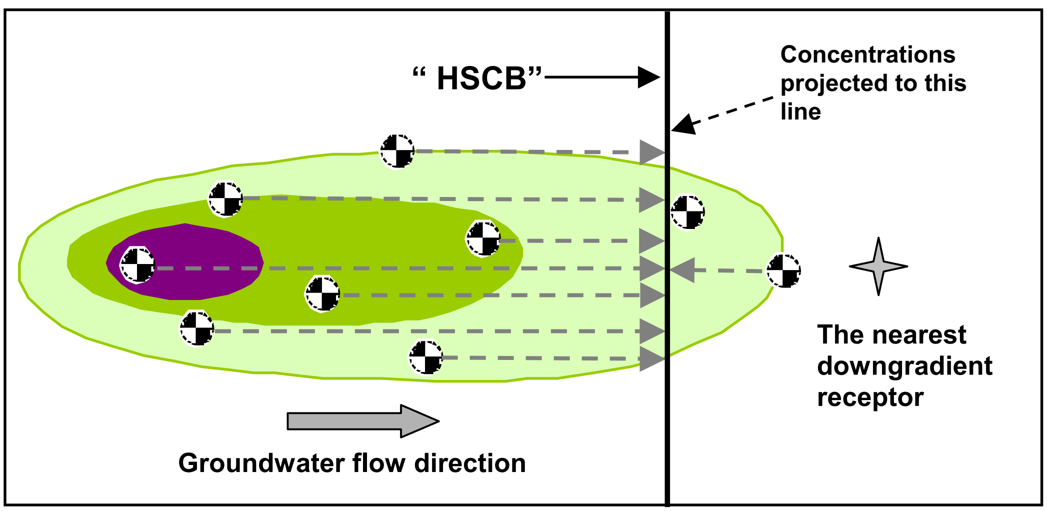
In order to estimate the least frequent sampling schedule for a monitoring location that still provides enough information for regulatory and remedial decision-making, MCES employs three steps to determine the sampling frequency. The first step involves analyzing frequency based on recent trends (Figure 4). A preliminary location sampling frequency (PLSF) is determined based on the trends determined by rates of change from linear regression and Mann-Kendall analysis of the most recent monitoring data. The variability of the sequential sampling data is accounted for by the Mann-Kendall analysis. The PLSF is then adjusted based on overall trends. If the long-term history of change is significantly greater than the recent trend, the frequency may be reduced by one level. Otherwise, no change could be made. The final step in the analysis involves reducing frequency based on risk. Since not all compounds in the target being assessed are equally harmful, frequency is reduced by one level if recent maximum concentration for compound of high risk is less than 1/2 of the Maximum Concentration Limit (MCL). The result of applying this method is a suggested sampling frequency based on recent sampling data trends and overall sampling data trends.

The finally determined sampling frequency from the Modified CES method can be Quarterly, Semiannual, Annual, and Biennial. Users can further reduce the sampling frequency to, for example, once every three years, if the trend estimated from Biennial data (i.e., data drawn once every two years from the original data) is the same as that estimated from the original data.

2.6.4 Data Sufficiency Analysis – Power Analysis

Statistical power analysis is a technique for interpreting the results of statistical tests. It provides additional information about a statistical test: 1) the power of the statistical test, i.e., the probability of finding a difference in the variable of interest when a difference truly exists; and 2) the expected sample size of a future sampling plan given the minimum detectable difference it is supposed to detect. For example, if the mean concentration is lower than the cleanup goal but a statistical test cannot prove this, the power and expected sample size can tell the reason and how many more samples are needed to result in a significant test. The additional samples can be obtained by a longer period of sampling or an increased sampling frequency. Details about the data sufficiency analysis can be found in Appendix A.6 of the MAROS Manual (AFCEE 2002).

When applying the MAROS power analysis method, a hypothetical statistical compliance boundary (HSCB) is assigned to be a line perpendicular to the groundwater flow direction (see figure below). Monitoring well concentrations are projected onto the HSCB using the distance from each well to the compliance boundary along with a decay coefficient. The projected concentrations from each well and each sampling event are then used in the risk-based power analysis. Since there may be more than one sampling event selected by the user, the risk-based power analysis results are given on an event-by-event basis. This power analysis can then indicate if target are statistically achieved at the HSCB. For instance, at a site where the historical monitoring record is short with few wells, the HSCB would be distant; whereas, at a site with longer duration of sampling with many wells, the HSCB would be close. Ultimately, at a site the goal would be to have the HSCB coincide with or be within the actual compliance boundary (typically the site property line).



In order to perform a risk-based cleanup status evaluation for the whole site, a strategy was developed as follows.

- Estimate concentration versus distance decay coefficient from plume centerline wells.
- Extrapolate concentration versus distance for each well using this decay coefficient.
- Comparing the extrapolated concentrations with the compliance concentration using power analysis.

Results from this analysis can be *Attained* or *Not Attained*, providing a statistical interpretation of whether the cleanup goal has been met on the site-scale from the risk-based point of view. The results as a function of time can be used to evaluate if the monitoring system has enough power at each step in the sampling record to indicate certainty of compliance by the plume location and condition relative to the compliance boundary. For example, if results are *Not Attained* at early sampling events but are *Attained* in recent sampling events, it indicates that the recent sampling record provides a powerful enough result to indicate compliance of the plume relative to the location of the receptor or compliance boundary.

3.0 SITE RESULTS

The groundwater long-term monitoring plan for McClellan AFB was started in 1990. The monitoring plan consisted of performance monitoring and compliance monitoring with the following goals:

1) plume containment monitoring to confirm that the TCE plume remains hydraulically controlled; and
2) plume reduction monitoring to verify progress toward achieving cleanup goals.

32 monitoring wells in Zone A were included in the long-term monitoring network as of 2000 along with 14 monitoring wells in Zone B, and 6 extraction wells screened in both Zone A and Zone B (Figures 1 and 2). The sampling frequency for these wells has been irregular, ranging from quarterly or annual in 1990 to annual or biennial in 2000, although the sampling was conducted on a quarterly basis. Some monitoring wells have only 5 ~ 7 data records available during this period. This resulted in only a portion of the wells being sampled on each quarterly sampling event.

Monitoring data from 1990 to 2000 were used for the detailed optimization analysis, with a subset of this data used in some of the analyses. The 2001 data were not used in the overview analysis or the detailed analysis because a new sampling technique was being tested (passive diffusion sampling) in sample collection and results from these sample events were not consistent with previous results.

In applying the MAROS methodology to develop a revised monitoring strategy for the McClellan AFB Zones A and B, many site and dataset parameters were applied. General site assumptions include:

- All wells that were part of the network in between 1990 and 2000 were considered in the temporal concentration trend analysis.
- Five chemicals of concern (COCs) that have been historically present at the site: tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cis-1,2-DCE), and 1,2-dichloroethane (DCA), however, TCE is the only constituent that is currently above the MCL in the OU D plume.
- All source/tail assignments were made based on the TCE Plume. Source wells were selected based on historically elevated concentrations of TCE.
- Site-specific hydrogeologic parameters related to Zones A and B including groundwater flow direction, seepage velocity, saturated thickness, porosity, receptor locations, can be found in the Table 4.
- Monitoring data from 1990 to 2000 were used for the “overall” trend analysis in the sampling frequency optimization, and data from January, 1995 to December, 2000 “recent” trend analysis and other analyses in the MAROS detailed optimization analysis.

- There will be a continuation of the current hydraulic containment system in place for the near future of the monitoring network.
- The current monitoring network adequately delineates the plume at the site for the constituent of concern, TCE.

3.1 Data Consolidation

In MAROS, ground water monitoring data can be imported from simple database-format Microsoft® Excel spreadsheets, Microsoft® Access tables, previously created MAROS database archive files, or entered manually. The historical monitoring data from McClellan were received in Excel database format. The URS, 2002 report defined the wells into Zone A, Zone B and Zone AB (URS 2002, Tables 3.2 and 3.3). The columns in the file where formatted to the MAROS Access file import format and then imported into the MAROS software using the import tool. The long-term monitoring raw data contained many non-detects, trace level results, and duplicates. Therefore, in the MAROS software the raw data are filtered, consolidated, and the period of interest was specified (i.e. monitoring data from 1990 to 2000) as well as the wells of interest for the zone of interest. The MAROS analysis was applied separately for Zone A and Zone B monitoring networks. For statistical evaluation of the data, a representative value for each sample point in time is needed. MAROS has many automated options to choose how these values are assigned. For the McClellan data, non-detects values were chosen to be set to the minimum detection limit, allowing for uniform detection limits over time. Trace level results were chosen to be represented by their actual values and duplicates samples were chosen to be assigned the average of the two samples. The reduced data for each well were viewed as a time series in a graphical form on a linear or semi-log plot generated by the software.

3.2 Overview Statistics: Plume Trend Analysis

3.2.1 Mann-Kendall/Linear Regression Analysis

The goal of the Mann-Kendall and Linear Regression temporal trend analysis is to assess the historical trend in the concentrations over time. These trend estimates are then analyzed to identify the source and tail region overall stability category as well as gaining an understanding of the individual well concentrations over time (see Figure 3 for further details). The TCE historical data for monitoring wells in both Zones A and B as well as the extraction wells in Zone AB were assessed for trends. No data consolidation was performed to condense the sampling into regular sample intervals.

Zone A

All 32 monitoring wells in Zone A had sufficient data within the time period of 1990 to 2000 (greater than 6 sample events) to assess the trends in the wells. Trend results from the Mann-Kendall and Linear Regression temporal trend analysis for Zone A monitoring wells are given in Table 5. The monitoring well trend results for Zone A show that 9 out of 10 source wells and 9 out of 22 tail wells have a Probably Decreasing, Decreasing, or Stable trend. Both methods gave similar trend estimates for each well. When considering the spatial distribution of the trend results (Figures 6 and 7 – maps created in ArcGIS from MAROS results), the majority of the decreasing or stable trend results are located near in the source area, indicating a decreasing source region concentration. Areas with no trend tended to be in the tail or edge of the plume where the wells have been sampled less frequently.

Well Type	Zone A MAROS Trend Analysis	
	PD, D, S	I, PI
Source	9 of 10 (90%)	0 of 10 (0%)
Tail	11 of 22 (50%)	1 of 22 (5%)
Extraction (Zone AB)	5 of 6 (83%)	0 of 6 (0%)

Note: Decreasing (D), Probably Decreasing (PD), Stable (S), Probably Increasing (PI), and Increasing (I)

Zone B

All 14 monitoring wells in Zone B had sufficient data within the time period of 1990 to 2000 (greater than 6 sample events) to assess the trends in the wells. Trend results from the Mann-Kendall and Linear Regression temporal trend analysis for Zone B monitoring wells are given in Table 6. The majority of the wells in Zone B have no trend in the historical data. However, as of 2000, only one of the wells in Zone B is actually above the MCL for TCE. Both of the statistical methods used to evaluate trends (Mann-Kendall and Linear Regression) gave similar trend estimates for each well. When considering the spatial distribution of the trend results (Figures 8 and 9 – maps created in ArcGIS from MAROS results), the majority of the decreasing or stable trend results are located near in the source area, indicating a decreasing source region concentration. Areas with no trend tended to be in the tail or edge of the plume where the wells have been sampled less frequently.

Well Type	Zone B MAROS Trend Analysis	
	PD, D, S	I, PI
Source	0 of 1 (0%)	1 of 1 (100%)
Tail	6 of 13 (50%)	1 of 13 (8%)

Note: Decreasing (D), Probably Decreasing (PD), Stable (S), Probably Increasing (PI), and Increasing (I)

Zone AB

All 6 extraction wells had sufficient data within the time period of 1990 to 2000 (greater than 6 sample events) to assess the trends in the wells. Trend results from the Mann-Kendall and Linear Regression temporal trend analysis for Zone AB extraction wells are given in Table 5. The extraction well trend results show that 5 out of 6 wells have a

Probably Decreasing, Decreasing, or Stable trend. Both methods gave similar trend estimates for each well. The extraction wells in the source mostly show decreasing or probably decreasing trends (Figures 10 and 11 – maps created in ArcGIS from MAROS results).

Although monitoring wells and extraction wells are present in the well network, these well trend results need to be treated differently for the purpose of individual trend analysis interpretation primarily due to the different course of action possible for the two types of wells. For monitoring wells, strongly decreasing concentration trends may lead the site manager to decrease their monitoring frequency, as well look at the well as possibly attaining its remediation goal. Conversely, strongly decreasing concentration trends in extraction wells may indicate ineffective or near-asymptotic contamination extraction, which may in turn lead to either the shutting down of the well or a drastic change in the extraction scheme. Other reasons favoring the separation of these two types of wells in the trend analysis interpretation is the fact that they produce very different types of samples. Typically extraction wells possess screens that are much larger than those of the average monitoring well. Therefore, the potential for the dilution of extraction well samples is far greater than monitoring well samples.

3.2.2 Moment Analysis

The moment analysis in the MAROS software was applied at the McClellan site in order to gain a better understanding of the overall plume stability in both Zones A and B. Monitoring well data from 1990 to 2000 were used for the moment analysis. Sampling frequency for these wells was very irregular, ranging from quarterly or annual in 1990 to annual or biennial in 2000. Therefore, all Zone A spatial moment analyses were based on sampling events redefined on a yearly basis, that is, data collected between January 1st and December 31st of a year were treated as if from the same sampling event performed on July 1st of that year, with the geometric mean result utilized for each location. Whereas, all Zone B spatial moment analyses were based on sampling events redefined on a biennial basis, that is, data collected between January 1st and December 31st of two years were treated as is from the same sampling event performed on July 1st of the first year, with the geometric mean result utilized for each location.

Zone A

Moment trend results from the Zeroth, First, and Second Moment analyses for the Zone A monitoring well network were varied. Moment Trend results from the moment trend analysis for selected Zone A well dataset are given in the Moment Analysis Report, Appendix B. Approximately 32 wells were used in the Zone A moment analysis. Wells with redundant spatial concentration information were not utilized in the moment analysis (i.e. MW-1041).

The zeroth moment analysis showed a stable trend (no change in dissolved mass) over time (Appendix B). The zeroth moment or mass estimate can show high variability over time, largely due to the fluctuating concentrations at the most contaminated wells as well as a varying monitoring well network. In order to reduce the fluctuating factors that could influence a mass trend, the data were consolidated to annual sampling and the zeroth moment trend evaluated. Another factor to consider when interpreting the mass increase over time is the change in the spatial distribution of the wells sampled historically. At the McClellan OU D site there were changes in the well distribution over time, due to addition and subtraction of wells from the well network as well as changes in sampling frequency. Therefore, the results from the MAROS mass trend over tim at the site should be evaluated along with the trend analysis results. The trend in mass is more likely decreasing over time, in accordance with the decreasing trend results (decreasing concentrations) seen in the majority of wells in the source area.

Moment Type	Zone A Mann-Kendall Trend Analysis	
	Trend Zone A	**Comment**
Zeroth	Stable to Decreasing	The amount of dissolved mass has decreased over time.
First	No Trend	The center of mass remained in relatively the same location through time, with slight movement forward or backward along the direction of groundwater flow.
Second	No Trend	Stable to no trend, indicating that wells representing very large areas both on the tip and the sides of the plume show little conclusive change in concentrations.

The first moment, or center of mass, for each sample event in Zone A remained relatively stable to no trend in distance relative to the approximate source location, see Figure 12, as well as the MAROS First Moment Reports in Appendix B. The center of mass remained in relatively the same location through time, with slight movement forward or backward along the direction of groundwater flow. These spatial and temporal trends in the center of mass distance from the source location can indicate transient movement based on season variation in rainfall or other hydraulic considerations. With no appreciable movement or a neutral trend in center of mass as is the case at McClellan there is additional confirmation separate from the individual well trend analysis, that the plume is relatively stable to decreasing. This stable center of the mass indicates that both the mass and mass movement over time, the plume itself is stable.

Zone B

Moment trend results from the Zeroth, First, and Second Moment analyses for the Both the Zone B monitoring well network were similar. Moment Trend results from the moment trend analysis for selected Zone B monitoring well dataset are given in the Moment Analysis Report, Appendix B. Approximately 12 wells were used in the Zone B moment analysis. Wells with redundant spatial concentration information were not utilized in the moment analysis (i.e. MW-1003 and MW-1028).

The zeroth moment analysis showed a stable trend (no change in dissolved mass) over time (Appendix B). The zeroth moment or mass estimate can show high variability over time, largely due to the fluctuating concentrations at the most contaminated wells as well as a varying monitoring well network. In order to reduce the fluctuating factors that could influence a mass trend, the data were consolidated to biennial sampling and the zeroth moment trend evaluated. Another factor to consider when interpreting the mass increase over time is the change in the spatial distribution of the wells sampled historically. At the McClellan OU D site there were changes in the well distribution over time, due to addition and subtraction of wells from the well network as well as changes in sampling frequency. . Therefore, the results from the MAROS mass trend over time at the site should be evaluated along with the trend analysis results. The trend in mass is more likely decreasing over time, in accordance with the decreasing trend results (decreasing concentrations) seen in the majority of wells.

The first moment, or center of mass, for each sample event in Zone B remained relatively stable in distance relative to the approximate source location, see Figure 13, as well as the MAROS First Moment Reports in Appendix B. The center of mass remained in relatively the same location through time, with slight movement forward or backward along the direction of groundwater flow. Similar to Zone A, these spatial and temporal trends in the center of mass distance from the source location can indicate transient movement based on season variation in rainfall or other hydraulic considerations. With no appreciable movement or a neutral trend in center of mass as is the case at McClellan there is additional confirmation separate from the individual well trend analysis, that the plume is relatively stable to decreasing. This stable center of the mass indicates that both the mass and mass movement over time, the plume itself is stable.

Moment Type	Zone B Mann-Kendall Trend Analysis	
	Trend Zone B	**Comment**
Zeroth	Stable to Decreasing	The amount of dissolved mass has decreased over time.
First	Stable	The center of mass remained in relatively the same location through time, with slight movement forward or backward along the direction of groundwater flow.
Second	No Trend	Stable to no trend, indicating that wells representing very large areas both on the tip and the sides of the plume show little conclusive change in concentrations.

As was the case with the Zone A moment analysis, the second moment, or spread of the plume over time in both the x and y directions for the sample events in Zone B, showed no trend over time, Appendix B. The second moment provides a measure of the spread of the concentration distribution about the plume's center of mass. Analysis of the spread of the plume indicates no trend in the plume, indicating that wells representing very large areas both on the tip and the sides of the plume show highly variable concentrations over time or that the wells have not been sampled consistently enough to show a clear trend. The no trend results indicate that at the McClellan OU D site the highly variable well network from changes in the well distribution over time, due to addition and subtraction of wells from the well network as well as changes in sampling frequency, results in non-specific trend results.

3.2.3 Overview Statistics: Plume Analysis

Overview Statistics Results:

- Overall trend for Source region: Stable,
- Overall trend for Tail region: near Stable (No Trend),
- Overall results from moment analysis indicate a stable to decreasing plume,
- Overall monitoring intensity needed: Moderate.

In evaluating overall plume stability, the trend analysis results and all monitoring wells were assigned "Medium" weights within the MAROS software (as described in Figure 4), assuming equal importance for each well and each trend result in the overall analysis.

These results matched with the judgment based on the visual comparison of TCE plumes over time, as well as the Moment Analysis. The TCE concentrations observed over the history of monitoring at the site are plotted in Appendix A. The Zone A TCE plume observed in 1995 was very similar to that of 2000, indicating that the TCE plume is relatively stable over time, even when the individual well concentration trends in the MAROS analysis indicate a near stable overall plume trend.

For a generic plume, the MAROS software indicates:

- No recommendation for sampling frequency
- Zone A may need 25 wells for sampling network
- Zone B may need 25 wells for sampling network

These MAROS results are for a generic site, and are based on knowledge gained from applying the MAROS Overview Statistics. There is no recommendation for frequency of sampling for the whole monitoring network due to some uncertainty in the trends and the presence of an active remediation system. Also, the recommended the number of wells seems high when applied to each zone individually. So, although the overall plume trend analysis shows a near stable plume, no general sampling frequency recommendation was assessed by the MAROS software. Therefore, a more detailed analysis was performed using the MAROS 2.0 software in order to allow for possible reductions on a well-by-well basis, frequency and well redundancy analysis were conducted. These overview statistics were also used when evaluating a final recommendation for each well after the detailed statistical analysis was applied.

3.3 Detailed Statistics: Optimization Analysis

Monitoring data from 1990 to 2000 were used for the optimization analysis. 2001 data were not used because passive diffusion sampling was used in sample collection, with anomalous results. Wells used in the analysis include 32 Zone A monitoring wells, 14 Zone B monitoring wells and 6 extraction wells screened in Zone AB (Table 1).

Due to the variable and irregular sampling frequency as described in Section 1.2, some monitoring wells have only 5 ~ 7 data records available from 1990 to 2000. This resulted in only a portion of the wells being sampled on each quarterly sampling event. Therefore, all spatial analyses (sampling location determination and risk-based site cleanup evaluation) were based on sampling events redefined on a yearly basis, that is, data collected between January 1st and December 31st of a year were treated as coming from the same sampling event performed on July 1st of that year.

In the well redundancy and well sufficiency analyses, only the monitoring wells were used. For the sampling frequency analysis, both the monitoring wells and the extraction wells were analyzed. Only Zone A was analyzed with the data sufficiency analysis for evaluating the risk-based site cleanup. The data sufficiency or power analysis for Zone B was not performed because Zone B has only one monitoring well with concentrations above MCL. Results for well redundancy, well sufficiency, sampling frequency, and data sufficiency analyses are detailed in the following sub-sections.

3.3.1 Well Redundancy Analysis – Delaunay Method

The goal of the well redundancy analysis is to identify wells that are spatially redundant within monitoring network as candidates for removal from the sampling plan. The approach allows elimination of sampling locations that have little impact on the historical characterization of a contaminant plume.

Zone A

Among the 32 Zone A monitoring wells, 31 were used in the well redundancy analysis (Table 1). MW-1041 was excluded from the analysis because it duplicates MW-1042 both spatially and in concentration levels over time. The Delaunay analysis was conducted with yearly averages from the latest 6 years of data (1995 to 2000). The MAROS results show that 3 monitoring wells (MW-14, MW-241, and MW-72) are candidates for elimination from the existing long-term monitoring network (Table 7). These wells are overall most redundant in the past 6 years, from the standpoint of their contribution to the spatial definition of the plume.

After consideration of the MAROS recommendations and the need for plume and site characterization, 3 wells were recommended for elimination from the existing 32-well Zone A monitoring network, resulting in a reduction of 9%.

Well removal candidates include (Table 7):

- MW-1041
- MW-14
- MW-241

A qualitative confirmation was performed to assess that eliminating these 3 wells from the 32-well monitoring network would not cause inadequate plume delineation and spatial concentration representation. The Zone A TCE plume observed in 2000 was hand contoured before and after removal of the 3 wells resulting in no significant plume size or concentration changes, indicating that the information loss in by eliminating these wells would be negligible. Also, the TCE plume shown in Figure 14 generated based on the existing and optimized networks using 1999 data agree with each other quite well, indicating that eliminating these wells from the monitoring network does not show any significant loss of information. Therefore, information gained from the MAROS trend analysis and a qualitative assessment of the concentration history of the wells, indicated these wells could be removed from the Zone A monitoring network without significant loss of information.

The MAROS software suggested eliminating MW-72 from the monitoring network, however, there were site-specific reasons to keep the well within the monitoring network (Table 7). Well MW-72 currently (as of the 2000 sampling) has concentration greater than the MCL for TCE and the well is located on the plume centerline and is the basis for risk-based power analysis for attainment at the compliance boundary. Similarly, there was a well that was not used in the Delaunay analysis that is clustered with an equivalent duplicate, MW-1041 is very close to MW-1042 with similar concentrations and concentration trends over time (Table 1 and Table 7). The clustered well MW-1041 with similar screen intervals, concentration trends, and concentration ranges to the nearby well, MW-1042, is suggested for elimination without having used them in the MAROS well redundancy analysis.

Zone B

Among the 14 Zone B monitoring wells, 12 were used in the Delaunay analysis (Table 1). MW-1003 and MW-1028 were excluded from the analysis because they duplicate MW-1001 and MW-1027, respectively. The Delaunay analysis was conducted with yearly averages from the latest 6 years (1995 to 2000). The MAROS results show that no monitoring wells that could be eliminated from the existing long-term monitoring network (Table 8).

After consideration of the MAROS recommendations and the need for plume and site characterization, 2 wells were recommended for elimination from the existing 14-well monitoring network, resulting in a reduction of 14%.

Well removal candidates include (Table 8):

- MW-1003
- MW-1028

A qualitative confirmation was performed to assess that eliminating these 2 wells from the 14-well monitoring network would not cause inadequate plume delineation and spatial concentration representation. The Zone B TCE plume observed in 2000 was hand contoured before and after removal of the 2 wells resulting in no significant plume size or concentration changes, indicating that the information loss by eliminating these wells would be negligible. Also, the TCE plume shown in Figure 15 generated based on the existing and optimized networks using 1999 data agree with each other quite well, indicating that eliminating these wells from the monitoring network does not show any significant loss of information. Therefore, information gained from the MAROS trend analysis and a qualitative assessment of the concentration history of the wells, indicated these wells could be removed from the Zone B monitoring network without significant loss of information.

Although these wells (MW-1003 and MW-1028) were not used in the well redundancy analysis they were clustered wells with equivalent duplicates very close to a well that had similar concentrations (lower than the MCL or DL) and concentration trends over time, which indicated these wells could be eliminated without significant loss of information. These clustered wells with similar screen intervals, concentration trends, and concentration ranges to a nearby well were suggested for elimination without having used them in the MAROS well redundancy analysis. However, information gained from the MAROS trend analysis and a qualitative assessment of the concentration history of the well, indicated these wells could be eliminated without significant loss of information.

Zones A & B

An additional redundancy analysis was performed on the McClellan well network that excluded the wells on the extreme periphery of the network (Zone A: far up-gradient wells: MW-1041, 1042, MW-1064; far cross-gradient wells: MW-237, MW-1026; and far down-gradient well: MW-350; Zone B: far up-gradient wells MW-1043 and MW-1010; far cross-gradient wells MW-1027 and MW-1028). The above analysis included these wells in the MAROS analysis, and these wells were not recommended for removal from the network as they are required to define the boundary of the Zone A and Zone B plumes. However, a monitoring network that includes the periphery wells significantly "over-captures" the plume as these wells are located far from the likely plume boundary.

The MAROS analysis that excluded these periphery wells indicated that additional wells would be required at the down-gradient edge of the plume to define the boundary of the plumes in Zone A and B. For example in Zone A, the area East of MW-12 is a likely location for a new down-gradient boundary well. In the Figure 9 from the well sufficiency analysis in the next section, almost all triangles outside the plume region are "Medium" in estimation errors, those areas that are close to the plume could be potential new locations if the periphery network wells were removed.

Although the MAROS analysis indicates that new wells might be able to replace the periphery wells, the decision to stop sampling the periphery wells should be made with consideration to non-statistical considerations, such as regulatory, community, and/or public health issues. Non-statistical considerations may indicate that continued sampling of the periphery wells may be warranted.

3.3.2 Well Sufficiency Analysis – Delaunay Method

The goal of the sampling location determination was to identify wells that are redundant within the monitoring network as candidates for removal from the sampling plan. The approach allows elimination of sampling locations that have little impact on the historical characterization of a contaminant plume. An extended method based on the Delaunay method can also be used for recommending new sampling locations in areas where additional plume information is needed.

Zone A

The well sufficiency analysis SF values obtained from the aforementioned analysis were used to generate Figure 16, which recommends the triangular regions for placing new sampling locations. It is seen that almost all triangular regions (except one) have S (small) or M (medium) estimation errors. Also, considering the relatively small size of the TCE plume, which is adequately delineated by the current monitoring system, the current sampling locations are sufficient. Zone A well sufficiency analysis was performed and no new locations are recommended.

Zone B

The Zone B well sufficiency analysis was not performed because only one well (MW-54) out of the 14 monitoring wells has concentrations above the MCL for TCE. Therefore, considering the relatively small size of the TCE plume, which is adequately delineated by the current monitoring system, the current sampling locations are sufficient. No new locations are recommended for the Zone B monitoring network.

3.3.3 Sampling Frequency Analysis – Modified CES Method

The sampling frequency analysis, using the Modified CES method, was applied to optimize the sampling frequency for each sampling location based on the magnitude, direction, and uncertainty of its concentration trend of its recent and historical TCE data. The Modified Cost Effective Sampling is a temporal analysis that estimates the lowest-frequency sampling schedule for a given groundwater monitoring location yet still provide needed information for regulatory and remedial decision-making. In the sampling frequency analysis, sampling events were defined on a quarterly basis (corresponding to the actual sampling schedules) so that all the data records could be used in the temporal analysis.

<u>*Zone A*</u>

For the monitoring well system, considering all the wells prior to the well redundancy analysis, 20 wells are recommended to be sampled biennially, and 12 annually. All 6 extraction wells are recommended to be sampled annually. Because the pre-optimization sampling frequencies for the Zone A wells were already very low (mostly annual and biennial), the sampling frequency optimization results in no significant reduction and in some cases there is an increase in sampling recommended. Results from the sampling frequency analysis for the 32 Zone A monitoring wells and the 6 extraction wells are given in Table 9. Most of the annual or lower-than-annual sampling frequency recommendations (Table 9) were due to insufficient recent data (i.e., less than 6 data records), which prevented the MAROS estimation of concentration trend using recent monitoring data. After considering the MAROS results and the historic and recent concentration levels at these wells, final sampling frequency recommendations are provided in Table 9.

In most cases, the frequency recommendations from the MAROS software were not adopted due to data inadequacy. Sampling frequencies for all the wells was irregular, ranging between quarterly and biennial from 1990 to 2000 (Table 1). Many monitoring wells have only 5 ~ 7 data records available during an 11-year period (from 1990 to 2000). Because the minimum data requirement for the sampling frequency trend analysis is 6 sampling events, the recent trends for many wells were not able to be estimated. This resulted in frequency results that were solely estimated from the overall data trend, which was not very reliable given the data inadequacy. For instance, well MW-74 has only two concentration records between 1994 and 2000, making the estimation of recent trend impossible. In cases of data inadequacy, the MAROS frequency analysis will always assign conservative results, i.e., quarterly or semiannual instead of annual or biennial.

However, a qualitative assessment of the concentration levels and concentration history for these wells resulted in more reasonable sampling frequency recommendations (Table 9). For example, well MW-1026 was suggested for a biennial sampling because its concentrations have been below the MCL or DL since 1993. Also, the relative size of the plume as well as the plume stability which remains stable according to the overview statistical analysis, it is unlikely that the plume will show rapid changes over the long-term. Therefore, keeping the frequency of most wells at annual and biennial level will continue to allow for adequate plume delineation.

<u>*Zone B*</u>

For the Zone B monitoring well system, assessing all the wells prior to the well redundancy analysis, 12 wells can be sampled biennially and 2 annually. In all cases except for well MW-1028, these sampling recommendations agree with the sampling frequency currently performed at the site. Results from the Modified CES method for the 14 Zone B monitoring wells are given in Table 10. Similar to the MAROS Zone A analysis, some Zone B annual sampling frequency recommendations needed to be adjusted when taking into consideration the historic and recent concentration levels at these wells.

3.3.4 Data Sufficiency – Power Analysis

The MAROS data sufficiency analysis indicates the current monitoring network is sufficient in terms of evaluating risk-based site target level status, if the pump-and-treat remedial system contains the plume and keeps reducing the TCE concentration in the aquifer. Table 11 shows the risk-based site cleanup status at selected sampling events for both analyses (i.e., HSCB at 1000 ft and HSCB at 100 ft downgradient of the monitoring system) assuming normality of the projected data. The cleanup standard has been "attained" for both HSCBs for all the years in the assessment. The high power indicates the site-wide TCE concentration level at the HSCB is much lower than the cleanup goal and the number of sampling points is more than sufficient. This analysis indicates that the monitoring system is working because it is powerful enough to accurately reflect the location of the plume relative to the compliance point.

In the MAROS data sufficiency analysis, statistical power analysis was used to assess the sufficiency of monitoring plans for detecting the difference between the mean concentration and cleanup goal. Results from the analysis indicate plume location from the risk-based standpoint at a hypothetical statistical compliance boundary (HSCB). The power and expected sample size associated with the target level evaluation may indicate the need for expansion or redundancy reduction of future sampling plans. This analysis was performed based on sampling events defined on a yearly basis for the Zone A monitoring well system only.

In the risk-based site cleanup evaluation, two analyses were performed. In the first analysis, the distance from the most downgradient well to the nearest downgradient receptor (HSCB) was assumed to be 1000 ft. The general groundwater flow angle is to the Southwest. Selected plume centerline wells are MW-11, MW-72, MW-91, and MW-92 (Table 12). The analysis was conducted with yearly averages of the TCE data from the latest 6 years (1995 to 2000). The second analysis used the same parameters except that the distance from the HSCB was assumed to be 100 ft. Table 13 shows plume centerline concentration regression results for each selected sampling event, which range from 3.8×10^{-5} to 6.8×10^{-4} per ft.

4.0 SUMMARY AND RECOMMENDATIONS

In recent years, the high cost of long-term monitoring as part of active or passive remediation of affected ground water has made the design of efficient and effective ground water monitoring plans a pressing concern. Periodically updating and revising long-term monitoring programs with changing conditions at the site can mean considerable savings in site monitoring costs. The MAROS decision-support software presented in this report assists in revising existing long-term monitoring plans based on the historical and current monitoring data and plume behavior over time.

The MAROS 2.0 sampling optimization software/methodology has been applied to the McClellan existing OU D long-term monitoring program as of December 2000. The optimization results and subsequent recommendations allow for optimization of the spatial and temporal groundwater monitoring system in place at the McClellan site. The current long-term monitoring network could be optimized through reduction in sampling locations (Results are summarized in Table 14).

Overview Statistics

Both the Mann-Kendall and Linear Regression temporal trend methods gave similar trend estimates for each well. Results from the temporal trend analysis indicate that 90% of the plume source area monitoring wells in Zone A indicate a Probably Decreasing, Decreasing, or Stable TCE concentration trend, whereas only about half of the wells in the tail and edges of the plume have similar trends. The majority of the wells in Zone B have no trend in the historical data. However, as of 2000, only one of the wells in Zone B is actually above the MCL for TCE. The trend results for the extraction wells in the source area indicate most wells have Probably Decreasing, or Decreasing concentrations over time.

Results from the moment trend analysis give some evidence of a stable plume, with the dissolved mass showing a decrease over time, whereas the center of mass and the plume spread shows no trend over time, probably due to the change in sample locations and frequency over time. Overall plume stability temporal results recommend a **moderate monitoring strategy** due to the near stable to decreasing OU D TCE plume. The overview results are relatively generic and not well-by-well specific, therefore, a detailed statistical analysis with a well-by-well analysis was performed.

Detailed Statistics

Further analysis from the well redundancy spatial analysis using the Delaunay method optimization indicate that

- **3 monitoring wells could be eliminated from the existing Zone A** monitoring network of 32 wells and
- **2 wells could be eliminated from the existing Zone B** monitoring network of 14 wells (Table 14)

without compromising the reliability of the monitoring system.

In addition, the well sufficiency spatial analysis indicated there are no areas within the network where there are high uncertainties in the predicted TCE concentration. Therefore there are **no recommended new monitoring wells for Zones A or B**. The sampling frequency optimization analysis using the temporal MCES method, resulted in sampling frequency that is relatively consistent with the sampling schedule currently in use at the site for both Zone A and Zone B well networks (Table 14).

Data sufficiency analysis using power analysis methods, shows that the site has achieved target levels at (or further than) the compliance boundary 100 ft downgradient from the most downgradient well. This analysis indicates that the monitoring system is working because it is powerful enough to accurately reflect the location of the plume relative to the compliance boundary. This shows the sufficiency of the monitoring system in terms of evaluating risk-based site target level status if the pump-and-treat remedial system continues to contain the plume and keeps reducing the TCE concentration in the OU-D plume.

The recommended long-term monitoring strategy results in small reduction in sampling costs and allows site personnel to develop a better understanding of plume behavior over time. A reduction in the number of redundant wells is expected to result in a moderate cost savings over the long-term at McClellan AFB. The MAROS optimized plan consists of 47 wells: 17 sampled annually, and 30 sampled biennially. The MAROS optimized plan would result in 32 samples per year, compared to 34 samples per year (17 annual and 34 biennial) in the current sampling program. Implementing these recommendations could lead to a 6% reduction from the current monitoring plan in terms of the samples to be collected per year. An approximate **cost savings estimate of $300 per year** is projected while still maintaining adequate delineation of the plume as well as knowledge of the plume state over time.

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January 15, 2003
GSI Job No. G-2236-15

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MAROS 2.0 APPLICATION
ZONE A & B OU D MONITORING NETWORK OPTIMIZATION

McClellan AFB
Sacramento Valley, California

TABLES

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Table 1
Sampling Locations Used in the MAROS Analysis

McClellan AFB OU-D
Sacramento Valley, California

Well Name	Monitoring Zone [1]	Used in Delaunay Analysis?	Used in Modified CES Analysis?	Summary of Sampling History (sampling data available since 1990)
MW-10	A	Yes	Yes	Sampled annually; recent data were <= TL but >= MCL
MW-11	A	Yes	Yes	Sampled annually; recent data were <= TL but >= MCL
MW-12	A	Yes	Yes	Sampled annually; it is an interior plume well
MW-14	A	Yes	Yes	Sampled annually since 90, biennially since 99 because data fell below MCL
MW-15	A	Yes	Yes	Sampled annually; it is an interior plume well
MW-38D	IAB or A	Yes	Yes	Sampled annually; recent data were <= TL but >= MCL
MW-52	IAB or A	Yes	Yes	Sampled annually, then biennially since 99 because data fell below MCL
MW-53	IAB or A	Yes	Yes	Sampled annually, then biennially since 99 because data fell below MCL
MW-55	IAB or A	Yes	Yes	Sampled annually on average, then biennially since 01 because data fell below MCL
MW-70	IAB or A	Yes	Yes	Sampled annually or less frequently since 91, then biennially since 01 because data fell below DL
MW-72	IAB or A	Yes	Yes	Sampled annually; recent data were <= TL but >= MCL
MW-74	IAB or A	Yes	Yes	Sampled quarterly the first 6 quarters, then annually on average, then biennially since 01 because data fall below MCL
MW-76	IAB or A	Yes	Yes	Sampled quarterly the first 6 quarters, then biennially on average, then annually since 99 because data were <= TL but >= MCL
MW-88	A	Yes	Yes	Sampled annually, then biennially since 99 because data fell below MCL
MW-89	A	Yes	Yes	Sampled annually, then biennially since 99 because data fell below MCL

Note:
1) Monitoring Zones assigned as shown in URS, 2002, 1Q02 report (Tables 3.2 and 3.3).
2) TL = the upper 90% tolerance limit from Groundwater Monitoring Plan Final (Radian Corporation 1997)
3) MCL = the maximum contaminant level of TCE, DL = detection limit, IAB = intermediate zone between zone A and Zone B, AB = both zone A and zone B

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Table 1
Sampling Locations Used in the MAROS Analysis

McClellan AFB OU-D
Sacramento Valley, California

Well Name	Monitoring Zone	Used in Delaunay Analysis?	Used in Modified CES Analysis?	Summary of Sampling History (sampling started in 1990)
MW-90	A	Yes	Yes	Sampled annually, then biennially since 95 because data fell below MCL
MW-91	A	Yes	Yes	Sampled annually, then biennially since 95 because data fell below MCL
MW-92	A	Yes	Yes	Sampled quarterly the first year, then annually on average, then biennially since 99 because data fall below MCL
MW-237	A	Yes	Yes	Sampled annually since 93, then biennially since 96 because data fell below MCL
MW-240	A	Yes	Yes	Sampled annually since 93, then biennially since 99 because data fell below MCL
MW-241	A	Yes	Yes	Sampled annually since 93; recent data were <= TL but >= MCL
MW-242	A	Yes	Yes	Sampled annually since 93; recent data were <= TL but >= MCL
MW-350	A	Yes	Yes	Sampled at least annually since 95, then biennially since 99 because data fell below MCL
MW-351	A	Yes	Yes	Sampled at least annually since 95, then biennially since 98 because data were <= MCL
MW-412	A	Yes	Yes	Sampled quarterly since 97, then biennially since 99 because data fell below MCL
MW-458	A	Yes	Yes	Sampled quarterly since 99, then biennially since 00 because data fell below MCL
MW-1004	A	Yes	Yes	Sampled quarterly in the first 2 years, then biennially because data fell below MCL
MW-1026	A	Yes	Yes	Sampled biennially since data were <= MCL
MW-1041	A	No, duplicates MW-1042	Yes	Sampled biennially since data were <= MCL
MW-1042	A	Yes	Yes	Sampled annually in the first 4 years, then biennially since 95 because data fell below MCL

Note: 1) Monitoring Zones assigned as shown in URS, 2002, 1Q02 report (Tables 3.2 and 3.3).
2) TL = the upper 90% tolerance limit from Groundwater Monitoring Plan Final (Radian Corporation 1997)
3) MCL = the maximum contaminant level of TCE, DL = detection limit, IAB = intermediate zone between zone A and Zone B, AB = both zone A and zone B

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Table 1
Sampling Locations Used in the MAROS Analysis

McClellan AFB OU-D
Sacramento Valley, California

Well Name	Monitoring Zone	Used in Delaunay Analysis?	Used in Modified CES Analysis?	Summary of Sampling History (sampling started in 1990)
MW-1064	A	Yes	Yes	Sampled quarterly in the first 6 quarters, then biennially since 93 because data fell below MCL
MW-1073	A	Yes	Yes	Sampled biennially since 93 because data were <= MCL
EW-73	AB	No, screened in zones A and B	Yes	Sampled annually except between 94 and 96 it was sampled quarterly
EW-83	AB	No, screened in zones A and B	Yes	Sampled annually except between 94 and 96 it was sampled quarterly
EW-84	AB	No, screened in zones A and B	Yes	Sampled annually except between 94 and 96 it was sampled quarterly
EW-85	AB	No, screened in zones A and B	Yes	Sampled annually except between 94 and 96 it was sampled quarterly
EW-86	AB	No, screened in zones A and B	Yes	Sampled annually except between 94 and 96 it was sampled quarterly
EW-87	AB	No, screened in zones A and B	Yes	Sampled annually except between 94 and 96 it was sampled quarterly
MW-19D	B	Yes	Yes	Sampled annually on average, then biennially since 95 because data fell below MCL
MW-51	B	Yes	Yes	Sampled biennially because data were below MCL or DL
MW-54	B	Yes	Yes	Sampled annually on average, then annually since 98; recent data were <= TL but >= MCL
MW-57	B	Yes	Yes	Sample quarterly in the first 6 quarters, then annually, then biennially since 99 because data fell below MCL
MW-58	B	Yes	Yes	Sample quarterly in the first 6 quarters, then annually, then biennially since 01 because data fell below MCL
MW-59	B	Yes	Yes	Sample quarterly in the first 5 quarters, then annually, then biennially since 97 because data fell below MCL
MW-104	B	Yes	Yes	Sampled annually, then biennially since 95 because data fell below MCL

Note:
1) Monitoring Zones assigned as shown in URS, 2002, 1Q02 report (Tables 3.2 and 3.3).
2) TL = the upper 90% tolerance limit from Groundwater Monitoring Plan Final (Radian Corporation 1997)
3) MCL = the maximum contaminant level of TCE, DL = detection limit, IAB = intermediate zone between zone A and Zone B, AB = both zone A and zone B

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Table 1
Sampling Locations Used in the MAROS Analysis

McClellan AFB OU-D
Sacramento Valley, California

Well Name	Monitoring Zone	Used in Delaunay Analysis?	Used in Modified CES Analysis?	Summary of Sampling History (sampling started in 1990)
MW-105	B	Yes	Yes	Sampled annually on average, then biennially since 01 because data fell below MCL
MW-1001	B	Yes	Yes	Sampled annually on average, then biennially since 96 because data fell below MCL or DL
MW-1003	B	No, duplicates MW-1001	Yes	Sampled annually on average, then biennially since 01 because data fell below MCL
MW-1010	B	Yes	Yes	Sampled biennially on average, then biennially since 01 because data fell below MCL or DL
MW-1027	B	Yes	Yes	Sampled biennially on average, then biennially since 99 because data fell below MCL or DL
MW-1028	B	No, duplicates MW-1027	Yes	Sampled annually on average, then biennially since 99 because data fell below MCL or DL
MW-1043	B	Yes	Yes	Sampled annually, then biennially since 95 because data fell below MCL or DL

Note: 1) Monitoring Zones assigned as shown in URS, 2002, 1Q02 report (Tables 3.2 and 3.3).
2) TL = the upper 90% tolerance limit from Groundwater Monitoring Plan Final (Radian Corporation 1997)
3) MCL = the maximum contaminant level of TCE, DL = detection limit, IAB = intermediate zone between zone A and Zone B, AB = both zone A and zone B

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Table 2 Mann-Kendall Analysis Decision Matrix (Aziz, et. al., 2002)		
Mann-Kendall Statistic	**Confidence in the Trend**	**Concentration Trend**
S > 0	> 95%	Increasing
S > 0	90 - 95%	Probably Increasing
S > 0	< 90%	No Trend
S ≤ 0	< 90% and COV ≥ 1	No Trend
S ≤ 0	< 90% and COV < 1	Stable
S < 0	90 - 95%	Probably Decreasing
S < 0	> 95%	Decreasing

Table 3 Linear Regression Analysis Decision Matrix (Aziz, et. al., 2002)		
Confidence in the Trend	**Log-slope**	
	Positive	**Negative**
< 90%	No Trend	COV < 1 Stable COV > 1 No Trend
90 - 95%	Probably Increasing	Probably Decreasing
> 95%	Increasing	Decreasing

TABLE 4
Zone A and B Site-Specific Parameters

McClellan Air Force Base OU D
Sacramento Valley, California

Parameter	Value
Seepage Velocity	35 ft/yr [1]
Porosity	30% [2]
Approximate Zone A Source Location	Well MW-241 [3]
Approximate Zone B Source Location	Well EW-84 [3]
Approximate Zone A Saturated Thickness	30 ft [1]
Approximate Zone B Saturated Thickness	60 ft [1]
General Groundwater Flow Direction	SW [1]

Notes:

1. Radian, 1997
2. Approximation based on type of aquifer material, outwash gravel and sand.
3. Location of source area obtained from high historical TCE concentration and high surrounding TCE concentrations.

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TABLE 5
Results of Zone A Trend Analysis

McClellan Air Force Base OU D
Sacramento Valley, California

Well	Well Type [3]	Well Category [5]	Mann-Kendall Trend [4]	Linear Regression Trend [4]	Overall Trend [6]	Number of Samples	Number of Detects
MW-10	MW	S	D	D	D	11	11
MW-11	MW	S	D	D	D	11	11
MW-12	MW	S	D	D	D	12	12
MW-14	MW	S	D	D	D	12	12
MW-15	MW	S	D	D	D	11	11
MW-38D	MW	S	D	D	D	8	8
MW-52	MW	T	NT	PD	S	9	3
MW-53	MW	T	I	I	I	10	9
MW-55	MW	T	S	S	S	11	11
MW-70	MW	T	S	S	S	6	0
MW-72	MW	S	D	D	D	10	10
MW-74	MW	T	D	D	D	10	10
MW-76	MW	T	I	I	I	10	4
MW-88	MW	T	NT	NT	NT	11	4
MW-89	MW	T	NT	NT	NT	10	2
MW-90	MW	T	NT	NT	NT	8	6
MW-91	MW	T	D	D	D	10	9
MW-92	MW	T	NT	NT	NT	12	9
MW-237	MW	T	NT	NT	NT	7	5
MW-240	MW	T	NT	NT	NT	9	5
MW-241	MW	S	D	D	D	12	12
MW-242	MW	S	D	D	D	12	12
MW-350	MW	T	D	D	D	8	5
MW-351	MW	S	NT	NT	NT	9	9
MW-412	MW	T	S	S	S	6	4
MW-458	MW	T	S	NT	S	4	3
MW-1004	MW	T	PD	PD	PD	12	6
MW-1026	MW	T	NT	NT	NT	7	5
MW-1041	MW	T	NT	NT	NT	7	1
MW-1042	MW	T	S	S	S	7	1
MW-1064	MW	T	NT	PI	PI	8	4
MW-1073	MW	T	NT	NT	NT	6	5
EW-73	EW	S	D	D	D	15	15
EW-86	EW	S	D	D	D	15	15
EW-87	EW	S	I	I	I	15	15
EW-83	EW	S	NT	NT	NT	16	16
EW-84	EW	S	D	D	D	16	16
EW-85	EW	S	D	D	D	16	16

Notes:
1. Consolidation of data included non-detect values set to the minium detection limit (0.001 mg/L) and duplicate data for the quarter were averaged.
2. All wells that were part of the network in between 1990 and 2000 were analyzed.

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TABLE 6
Results of Zone B Trend Analysis

McClellan Air Force Base OU D
Sacramento Valley, California

Well	Well Type [3]	Well Category [5]	Mann-Kendall Trend [4]	Linear Regression Trend [4]	Overall Trend [6]	Number of Samples	Number of Detects
MW-19D	T	T	NT	NT	NT	10	6
MW-51	T	T	S	PD	S	8	1
MW-54	S	S	I	I	I	10	8
MW-57	T	T	NT	NT	NT	12	5
MW-58	T	T	NT	NT	NT	15	7
MW-59	T	T	S	S	S	12	2
MW-104	T	T	NT	NT	NT	8	2
MW-105	T	T	NT	I	PI	8	2
MW-1001	T	T	S	D	PD	10	1
MW-1003	T	T	PD	D	D	11	3
MW-1010	T	T	S	S	S	5	0
MW-1027	T	T	NT	NT	NT	6	2
MW-1028	T	T	S	S	S	10	2
MW-1043	T	T	NT	NT	NT	6	1

Notes:
1. Consolidation of data included non-detect values set to the minium detection limit (0.001 mg/L) and duplicate data for the quarter were averaged.
2. All wells that were part of the network in between 1990 and 2000 were analyzed.
3. EW = Extraction Well; MW = Monitoring Well
4. Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)
5. S = Source Zone Well; T = Tail Zone Well
6. Overall Trend is calculated from a weighted average of the Linear Regression and Mann-Kendall Trends. For further details on this methodolgy refer to the MAROS Manual Appendix A.8.

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Table 7
Well Redundancy Analysis Results – Delaunay Method

McClellan AFB OU-D Zone A
Sacramento Valley, California

Well Name	Well Used in Analysis?	MAROS Well Redundancy Analysis Result	MAROS Interpreted Well Redundancy	Comments
MW-10	Yes	Keep	Keep	
MW-11	Yes	Keep	Keep	
MW-12	Yes	Keep	Keep	
MW-14	Yes	**Eliminate**	**Eliminate**	Spatially redundant
MW-15	Yes	Keep	Keep	
MW-38D	Yes	Keep	Keep	
MW-52	Yes	Keep	Keep	
MW-53	Yes	Keep	Keep	
MW-55	Yes	Keep	Keep	
MW-70	Yes	Keep	Keep	
MW-72	Yes	**Eliminate**	**Keep**	On plume centerline and used in MAROS data sufficiency analysis
MW-74	Yes	Keep	Keep	
MW-76	Yes	Keep	Keep	
MW-88	Yes	Keep	Keep	
MW-89	Yes	Keep	Keep	
MW-90	Yes	Keep	Keep	
MW-91	Yes	Keep	Keep	
MW-92	Yes	Keep	Keep	
MW-237	Yes	Keep	Keep	
MW-240	Yes	Keep	Keep	

Notes: 1) Yearly averages from 6 sampling events (1995 ~ 2000) were used in the above analysis
2) InsideSF = 0.20, HullSF = 0.01, AR = CR = 0.95
3) “-“ = Not Applicable.

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Table 7
Well Redundancy Analysis Results – Delaunay Method

McClellan AFB OU-D Zone A
Sacramento, California

Well Name	Well Used in Analysis?	MAROS Well Redundancy Analysis Result	MAROS Interpreted Well Redundancy	Comments
MW-241	Yes	**Eliminate**	**Eliminate**	Spatially redundant
MW-242	Yes	Keep	Keep	
MW-350	Yes	Keep	Keep	
MW-351	Yes	Keep	Keep	
MW-412	Yes	Keep	Keep	
MW-458	Yes	Keep	Keep	
MW-1004	Yes	Keep	Keep	
MW-1026	Yes	Keep	Keep	
MW-1041	No: duplicates MW-1042	-	**Eliminate**	Duplicates MW-1042
MW-1042	Yes	Keep	Keep	
MW-1064	Yes	Keep	Keep	
MW-1073	Yes	Keep	Keep	

Notes: Yearly averages from 6 sampling events (1995 ~ 2000) were used in the above analysis
InsideSF = 0.20, HullSF = 0.01, AR = CR = 0.95

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Table 8
Well Redundancy Analysis Results – Delaunay Method

McClellan AFB OU-D Zone B
Sacramento Valley, California

Well Name	Well Used in Analysis?	MAROS Well Redundancy Analysis Result	MAROS Interpreted Well Redundancy	Comments
MW-19D	Yes	Keep	Keep	
MW-51	Yes	Keep	Keep	
MW-54	Yes	Keep	Keep	
MW-57	Yes	Keep	Keep	
MW-58	Yes	Keep	Keep	
MW-59	Yes	Keep	Keep	
MW-104	Yes	Keep	Keep	
MW-105	Yes	Keep	Keep	
MW-1001	Yes	Keep	Keep	
MW-1003	No: duplicates MW-1001	-	**Eliminate**	Duplicates MW-1003
MW-1010	Yes	Keep	Keep	
MW-1027	Yes	Keep	Keep	
MW-1028	No: duplicates MW-1027	-	**Eliminate**	Duplicates MW-1027
MW-1043	Yes	Keep	Keep	

Notes: 1) Yearly averages from 6 sampling events (1995 ~ 2000) were used in the above analysis
2) InsideSF = 0.05 or 0.20, HullSF = 0.01 or 0.05, AR = CR = 0.95
3) "-" = Not Applicable.

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Table 9
Sampling Frequency Analysis Results – Modified CES

McClellan AFB OU-D Zone A
Sacramento Valley, California

Well Name	MAROS Frequency Based on Recent Trend[(1)]	MAROS Frequency Based on Overall Trend[(2)]	MAROS Recommended Frequency[(3)]	Frequency for Optimized Network	Comments
MW-10	Annual	Annual	Annual	Annual	Decreasing trend but still higher than MCL
MW-11	Annual	Annual	Annual	Annual	Decreasing trend but still higher than MCL
MW-12	Annual	Annual	Annual	Annual	Decreasing trend but still higher than MCL
MW-14	Annual	Annual	Annual	-	-
MW-15	Semiannual	Annual	Semiannual	Annual	Inside-plume well although with slightly increasing trend
MW-38D	Annual	Annual	Annual	Annual	Concentrations higher than MCL
MW-52	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-53	Annual	Annual	Annual	Biennial	All historical concentrations (except one) below MCL or DL
MW-55	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-70	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-72	Annual	Annual	Annual	Annual	Recent concentrations higher than MCL
MW-74	Semiannual	Semiannual	Semiannual	Annual	Recent concentrations higher than MCL (the MAROS result was due to insufficient recent data)
MW-76	Quarterly	Quarterly	Quarterly	Annual	Recent concentrations higher than MCL (the MAROS result was due to insufficient recent data)
MW-88	Annual	Annual	Annual	Biennial	Recent concentrations below MCL or DL
MW-89	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-90	Annual	Annual	Annual	Biennial	Recent concentrations (except one) below MCL or DL
MW-91	Annual	Annual	Biennial	Biennial	Recent concentrations below MCL or DL
MW-92	Annual	Annual	Annual	Biennial	Recent concentrations (except one) below MCL or DL
MW-237	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-240	Annual	Annual	Annual	Biennial	All historical concentrations below MCL or DL

Notes:
1) The frequency determined by MAROS based on the analysis of recent data (data between 1994 and 2000)
2) The frequency determined by MAROS based on the analysis of overall data (data between 1990 and 2000)
3) The frequency finally recommended by MAROS after considering recent and overall frequency results as well as the rates of change in these trends Rate parameters used are 0.5MCL/year, 1.0MCL/year, and 2.0MCL/year for Low, Medium, and High rates, respectively; the MCL of TCE is 0.005 mg/L

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Table 9
Sampling Frequency Analysis Results – Modified CES

McClellan AFB OU-D Zone A
Sacramento Valley, California

Well Name	MAROS Frequency Based on Recent Trend(1	MAROS Frequency Based on Overall Trend(2)	MAROS Recommended Frequency(3)	MAROS Interpreted Sampling Frequency Results	Comments
MW-241	Annual	Annual	Annual	-	-
MW-242	Annual	Annual	Annual	Annual	Decreasing trend but still higher than MCL
MW-350	Annual	Annual	Annual	Biennial	Recent concentrations below MCL or DL
MW-351	Annual	Annual	Annual	Annual	Recent concentrations higher than MCL
MW-412	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-458	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-1004	Annual	Annual	Annual	Biennial	All historical concentrations below MCL or DL (the MAORS result was due to insufficient recent data)
MW-1026	Semiannual	Semiannual	Semiannual	Biennial	Concentrations since 93 below MCL or DL (the MAORS result was due to insufficient recent data)
MW-1041	Annual	Annual	Biennial	-	-
MW-1042	Annual	Annual	Biennial	Biennial	Upgradient wells with all historical concentrations below MCL or DL
MW-1064	Quarterly	Quarterly	Quarterly	Biennial	Upgradient well with recent concentrations below MCL or DL (the MAORS result was due to insufficient recent data)
MW-1073	Annual	Annual	Annual	Biennial	Recent concentrations below MCL or DL (the MAORS result was due to insufficient data)
Extraction wells below:					
EW-73	Annual	Annual	Annual	Annual	Performance monitoring
EW-83	Annual	Annual	Annual	Annual	Performance monitoring
EW-84	Annual	Annual	Annual	Annual	Performance monitoring
EW-85	Annual	Annual	Annual	Annual	Performance monitoring
EW-86	Annual	Annual	Annual	Annual	Performance monitoring
EW-87	Quarterly	Quarterly	Quarterly	Annual	Performance monitoring

Notes:
1) The frequency determined by MAROS based on the analysis of recent data (data between 1994 and 2000)
2) The frequency determined by MAROS based on the analysis of overall data (data between 1990 and 2000)
3) The frequency finally recommended by MAROS after considering recent and overall frequency results as well as the rates of change in these trends Rate parameters used are 0.5MCL/year, 1.0MCL/year, and 2.0MCL/year for Low, Medium, and High rates, respectively; the MCL of TCE is 0.005 mg/L

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Table 10
Sampling Frequency Analysis Results – Modified CES

McClellan AFB OU-D Zone B
Sacramento Valley, California

Well Name	MAROS Frequency Based on Recent Trend(1)	MAROS Frequency Based on Overall Trend(2)	MAROS Recommended Frequency(3)	MAROS Interpreted Sampling Frequency Results	Comments
MW-19D	Annual	Annual	Annual	Biennial	All historical concentrations below MCL or DL (the MAORS result was due to insufficient recent data)
MW-51	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-54	Annual	Annual	Annual	Annual	Recent concentrations above MCL
MW-57	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-58	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-59	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-104	Annual	Annual	Annual	Biennial	All historical concentrations below MCL or DL (the MAORS result was due to insufficient recent data)
MW-105	Annual	Annual	Annual	Biennial	All historical concentrations below MCL or DL
MW-1001	Annual	Annual	Biennial	Biennial	All historical concentrations below MCL or DL
MW-1003	Annual	Annual	Biennial	-	-
MW-1010	Annual	Annual	Annual	Biennial	All historical concentrations below MCL or DL (the MAORS result was due to insufficient data)
MW-1027	Annual	Annual	Annual	Biennial	All historical concentrations below MCL or DL (the MAORS result was due to insufficient recent data)
MW-1028	Annual	Annual	Annual	-	-
MW-1043	Annual	Annual	Annual	Biennial	All historical concentrations below MCL or DL (the MAORS result was due to insufficient recent data)

Notes:
1) The frequency determined by MAROS based on the analysis of recent data (data between 1995 and 2000)
2) The frequency determined by MAROS based on the analysis of overall data (data between 1990 and 2000)
3) The frequency finally recommended by MAROS after considering recent and overall frequency results as well as the rates of change in these trends Rate parameters used are 0.5MCL/year, 1.0MCL/year, and 2.0MCL/year for Low, Medium, and High rates, respectively; the MCL of TCE is 0.005 mg/L

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Table 11
Risk-Based Site Cleanup Evaluation Results – Power Analysis

McClellan AFB OU-D Zone A
Sacramento Valley, California

		Distance to HSCB = 1000 ft		Distance to HSCB = 100 ft	
Sampling Event (Yearly Averaged)	**Sample Size**	**Cleanup Status**	**Power**	**Cleanup Status**	**Power**
1995	29	Attained	1.0	Attained	1.0
1997	20	Attained	1.0	Attained	1.0
1998	19	Attained	1.0	Attained	1.0
1999	29	Attained	1.0	Attained	1.0

Note: The power analysis used for this application assumes normality of data. Distance to the Hypothetical Statistical Compliance Boundary (HSCB) is the distance from the most downgradient well to the HSCB; S/E = extrapolated result significantly exceeds the target level (0.005 mg/L).

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Table 12
Selected Plume Centerline Wells
Risk-Based Site Cleanup Evaluation – Power Analysis

McClellan AFB OU-D Zone A
Sacramento Valley, California

Well Name	Distance from Well to Receptor (feet)
MW-92	1866.2
MW-91	1996.1
MW-72	2547.8
MW-11	3115.4

Note: Groundwater flow angle is to the Southeast; the distance from the most downgradient well to the nearest downgradient receptor is assumed to be 1000 feet.

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Table 13
Plume Centerline Concentration
Regression Results – Power Analysis

McClellan AFB OU-D Zone A
Sacramento Valley, California

Sampling Event (Yearly Averaged)	Number of Centerline Wells	Regression Coefficient (1/ft)	Confidence in Coefficient
1995	4	-6.77E-03	99.2%
1996	2	-	-
1997	3	-4.74E-03	83.5%
1998	3	-3.84E-03	88.9%
1999	4	-4.75E-03	96.2%
2000	2	-	-

Note: Regression is on natural log concentration of TCE versus distance from source centerline wells shown in Table 12; no regression was performed for sampling event with less than 3 centerline wells.

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Table 14
Summary of MAROS Sampling Optimization Results

McClellan AFB OU-D
Sacramento Valley, California

Well Name	Monitoring Zone	MAROS Well Category S = Source T= Tail	Current Sampling Frequency(1)	MAROS Trend Result	MAROS Interpreted Well Redundancy and Well Sufficiency Results	MAROS Interpreted Sampling Frequency Results	Comments
MW-10	A	S	Annual	D	***Keep***	***Annual***	Decreasing trend with recent concentrations > MCL & source well
MW-11	A	S	Annual	D	***Keep***	***Annual***	Decreasing trend with recent concentrations > MCL & source well
MW-12	A	S	Annual	D	***Keep***	***Annual***	Decreasing trend with recent concentrations > MCL & source well
MW-14	A	S	Biennial	D	***Eliminate***	***Annual***	Decreasing trend & spatially redundant
MW-15	A	S	Annual	D	***Keep***	***Annual***	Decreasing trend & source well
MW-38D	IAB, A	S	Annual	D	***Keep***	***Annual***	Decreasing trend with recent concentrations > MCL & source well
MW-52	IAB, A	T	Biennial	S	***Keep***	***Biennial***	Historical concentrations < MCL or DL & upgradient of source area
MW-53	IAB, A	T	Biennial	NT	***Keep***	***Biennial***	Historical concentrations < MCL or DL & upgradient of source area
MW-55	IAB, A	T	Biennial	PD	***Keep***	***Biennial***	Probably decreasing trend & historical concentrations < MCL or DL
MW-70	IAB, A	T	Biennial	S	***Keep***	***Biennial***	Historical concentrations < MCL or DL & upgradient of source area
MW-72	IAB, A	S	Annual	D	***Keep***	***Annual***	Decreasing trend with recent concentrations > MCL & source well
MW-74	IAB, A	T	Biennial	D	***Keep***	***Annual***	Decreasing trend with recent concentrations > MCL & close to source area
MW-76	IAB, A	T	Annual	I	***Keep***	***Annual***	Increasing trend with recent concentrations > MCL & upgradient of source area
MW-88	A	T	Biennial	NT	***Keep***	***Biennial***	No trend with recent concentrations < MCL or DL & cross gradient of source area
MW-89	A	T	Biennial	PI	***Keep***	***Biennial***	Historical concentrations < MCL or DL & cross gradient of source area
MW-90	A	T	Biennial	NT	***Keep***	***Biennial***	No trend with recent concentrations < MCL or DL & cross gradient of source area
MW-91	A	T	Biennial	D	***Keep***	***Biennial***	Decreasing trend with recent concentrations < MCL or DL & downgradient of source area
MW-92	A	T	Biennial	D	***Keep***	***Biennial***	Decreasing trend with recent concentrations < MCL or DL & downgradient of source area

Notes:
(1) The frequency currently in use at site, from 1Q02 Monitoring Report (URS 2002)
(2) MCL = the maximum contaminant level of TCE, DL = detection limit, IAB = screened in the intermediate zone between Zone A and Zone B; AB = screened in both Zone A and Zone B, "-" = Not Applicable
(3) Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)

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Table 14
Summary of MAROS Sampling Optimization Results

McClellan AFB OU-D
Sacramento Valley, California

Well Name	Monitoring Zone	MAROS Well Category S = Source T= Tail	Current McClellan Frequency(1)	MAROS Trend Result	MAROS Interpreted Well Redundancy and Well Sufficiency Results	MAROS Interpreted Sampling Frequency Results	Comments
MW-237	A	T	Biennial	PI	***Keep***	***Biennial***	Historical concentrations < MCL or DL & cross-gradient sentry well
MW-240	A	T	Biennial	NT	***Keep***	***Biennial***	Historical concentrations < MCL or DL & cross-gradient sentry well
MW-241	A	S	Annual	D	***Eliminate***	***Annual***	Decreasing trend & spatially redundant
MW-242	A	S	Annual	D	***Keep***	***Annual***	Decreasing trend with recent concentrations > MCL & inside plume well
MW-350	A	T	Biennial	D	***Keep***	***Biennial***	Decreasing trend with recent concentrations < MCL or DL & downgradient sentry well
MW-351	A	S	Annual	NT	***Keep***	***Annual***	No trend with recent concentrations > MCL & downgradient sentry well
MW-412	A	T	Biennial	PD	***Keep***	***Biennial***	Historical concentrations < MCL or DL & downgradient sentry well
MW-458	A	T	Biennial	NT	***Keep***	***Biennial***	Historical concentrations < MCL or DL & downgradient of source area
MW-1004	A	T	Biennial	D	***Keep***	***Biennial***	Historical concentrations < MCL or DL & cross gradient sentry well
MW-1026	A	T	Biennial	NT	***Keep***	***Biennial***	Concentrations since 93 < MCL or DL & up/cross gradient sentry well
MW-1041	A	T	Biennial	NT	***Eliminate***	***Biennial***	Historical concentrations < MCL & duplicates MW-1042
MW-1042	A	T	Biennial	S	***Keep***	***Biennial***	Historical concentrations < MCL or DL & upgradient well far from plume
MW-1064	A	T	Biennial	NT	***Keep***	***Biennial***	Recent concentrations below MCL or DL & upgradient well far from plume
MW-1073	A	T	Biennial	S	***Keep***	***Biennial***	Stable trend with recent concentrations < MCL or DL & upgradient well
EW-73	AB	S	Annual	D	***Keep***	***Annual***	Decreasing trend & inside plume extraction well & performance monitoring
EW-83	AB	S	Annual	NT	***Keep***	***Annual***	No trend & inside plume extraction well & performance monitoring
EW-84	AB	S	Annual	D	***Keep***	***Annual***	Decreasing trend & inside plume extraction well & performance monitoring

Notes:
(1) The frequency currently in use at site, from 1Q02 Monitoring Report (URS 2002)
(2) MCL = the maximum contaminant level of TCE, DL = detection limit, IAB = screened in the intermediate zone between Zone A and Zone B; AB = screened in both Zone A and Zone B, "-" = Not Applicable
(3) Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)

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Table 14
Summary of MAROS Sampling Optimization Results

McClellan AFB OU-D
Sacramento Valley, California

Well Name	Monitoring Zone	MAROS Well Category S = Source T= Tail	Current McClellan Frequency[(1)]	MAROS Trend Result	MAROS Interpreted Well Redundancy and Well Sufficiency Results	MAROS Interpreted Sampling Frequency Results	Comments
EW-85	AB	S	Annual	D	***Keep***	***Annual***	Decreasing trend & inside plume extraction well & performance monitoring
EW-86	AB	S	Annual	D	***Keep***	***Annual***	Decreasing trend & inside plume extraction well & performance monitoring
EW-87	AB	S	Annual	PI	***Keep***	***Annual***	Probably increasing trend & inside plume extraction well & performance monitoring
MW-19D	B	T	Biennial	NT	***Keep***	***Biennial***	Historical concentrations < MCL or DL & downgradient of zone B source well
MW-51	B	T	Biennial	S	***Keep***	***Biennial***	Historical concentrations < MCL or DL & downgradient of zone B source well
MW-54	B	S	Annual	I	***Keep***	***Annual***	Increasing trend & the only zone B well with concentrations > MCL
MW-57	B	T	Biennial	NT	***Keep***	***Biennial***	Historical concentrations < MCL or DL & downgradient of zone B source well
MW-58	B	T	Biennial	NT	***Keep***	***Biennial***	Historical concentrations < MCL or DL & upgradient of zone B source well
MW-59	B	T	Biennial	NT	***Keep***	***Biennial***	Historical concentrations < MCL or DL & downgradient of zone B source well
MW-104	B	T	Biennial	NT	***Keep***	***Biennial***	Historical concentrations < MCL or DL & upgradient well
MW-105	B	T	Biennial	PI	***Keep***	***Biennial***	Historical concentrations < MCL or DL & cross gradient sentry well
MW-1001	B	T	Biennial	PI	***Keep***	***Biennial***	Historical concentrations < MCL or DL & cross gradient sentry well
MW-1003	B	T	Biennial	D	***Eliminate***	***Biennial***	Duplicates MW-1003
MW-1010	B	T	Biennial	PI	***Keep***	***Biennial***	Historical concentrations < MCL or DL & upgradient background well
MW-1027	B	T	Biennial	NT	***Keep***	***Biennial***	Historical concentrations < MCL or DL & up/cross gradient sentry well
MW-1028	B	T	Biennial	NT	***Eliminate***	***Annual***	Duplicates MW-1027
MW-1043	B	T	Biennial	NT	***Keep***	***Biennial***	Historical concentrations < MCL or DL & upgradient background well

Notes:
(1) The frequency currently in use at site, from 1Q02 Monitoring Report (URS 2002)
(2) MCL = the maximum contaminant level of TCE, DL = detection limit, IAB = screened in the intermediate zone between Zone A and Zone B; AB = screened in both Zone A and Zone B, "-" = Not Applicable
(3) Decreasing (D), Probably Decreasing (PD), Stable (S), No Trend (NT), Probably Increasing (PI), and Increasing (I)

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MAROS 2.0 APPLICATION
ZONE A & B OU D MONITORING NETWORK OPTIMIZATION

McClellan AFB
Sacramento Valley, California

FIGURES

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Date Issued: 12/04/02

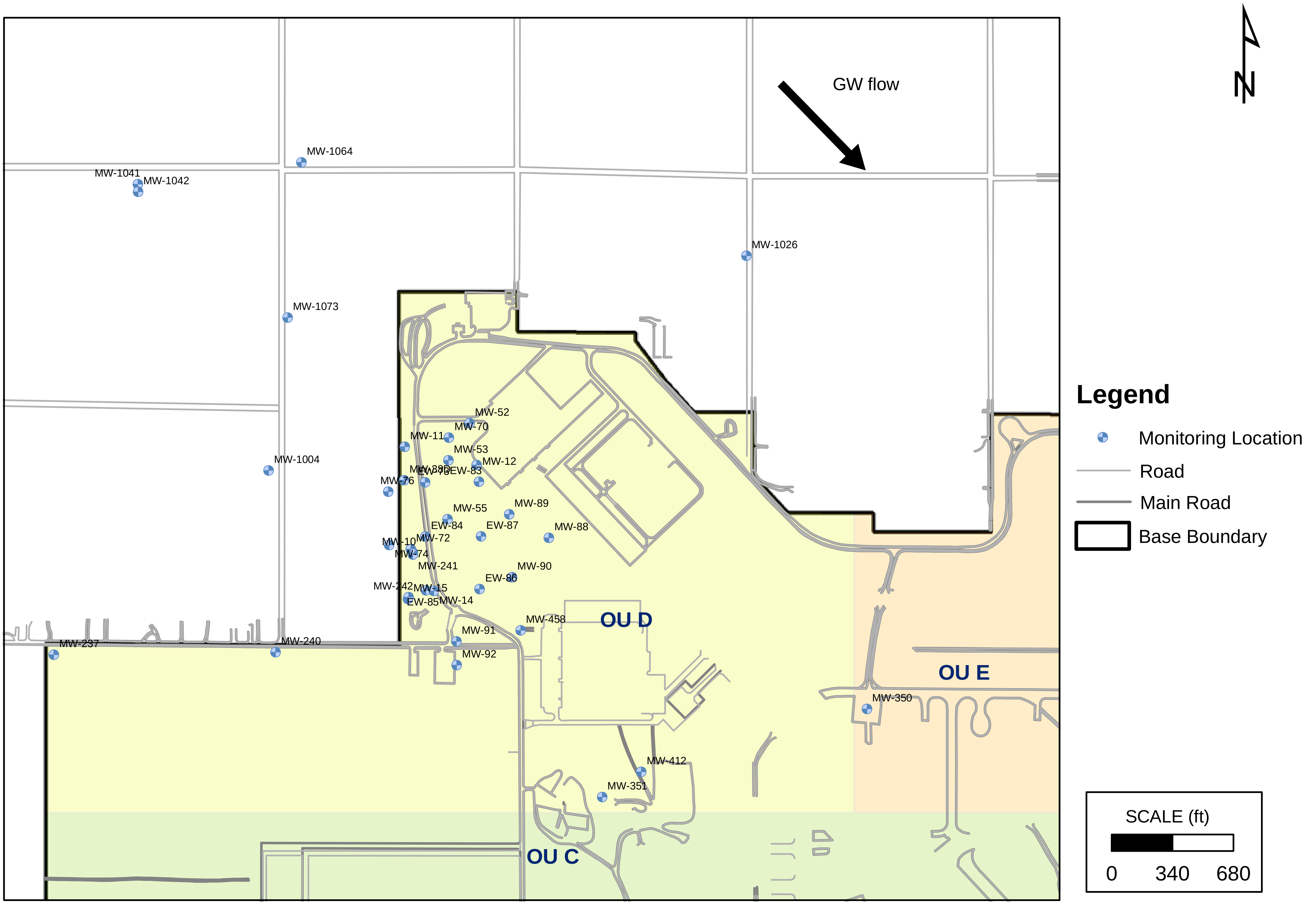

Figure 1: OUD Groundwater Monitoring Network: Zone A
McClellan Air Force Base, Sacramento, California

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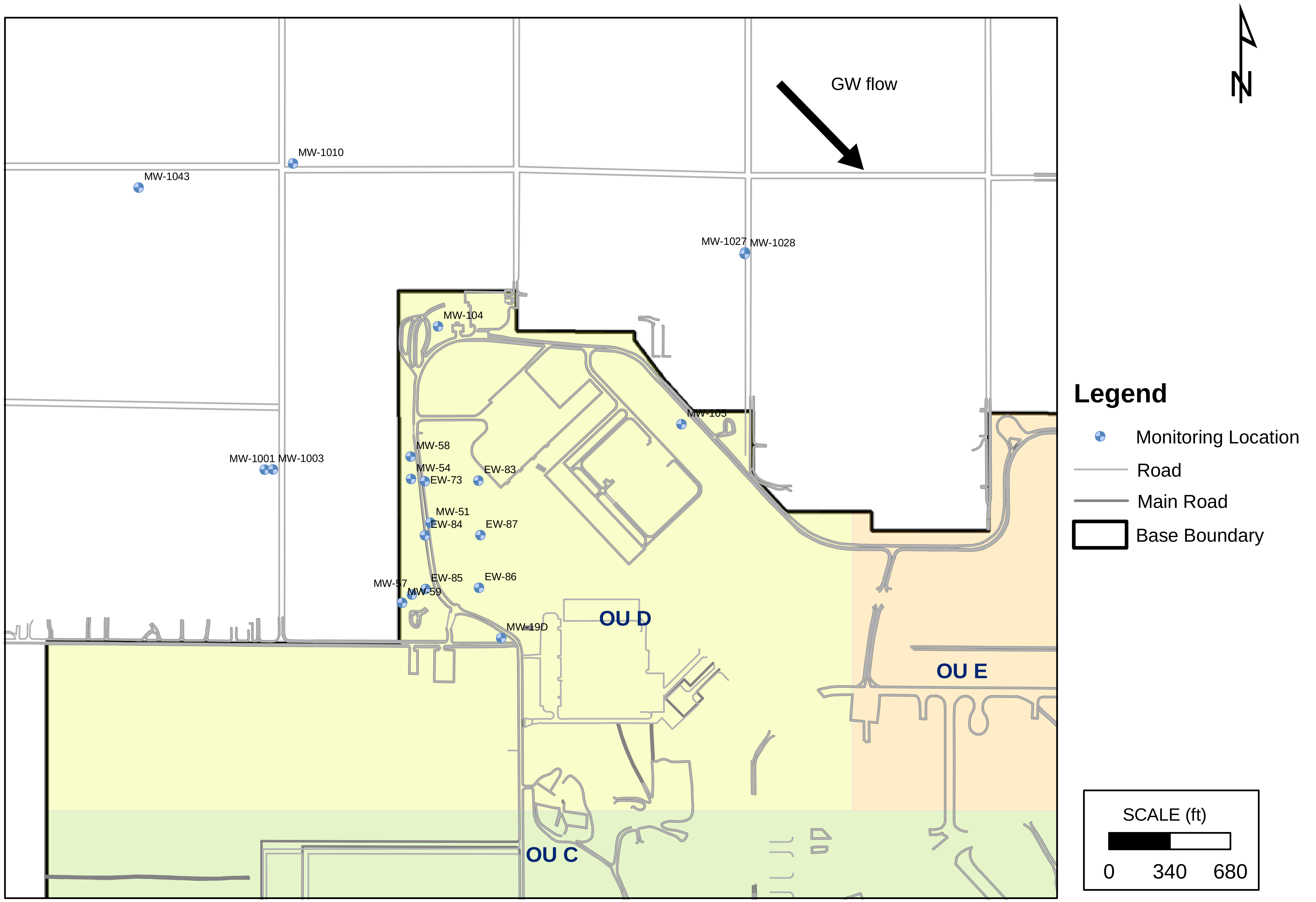

Figure 2: OUD Groundwater Monitoring Network: Zone B
McClellan Air Force Base, Sacramento, California

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MAROS: Decision Support Tool

MAROS is a collection of tools in one software package that is used in an explanatory, non-linear fashion. The tool includes models, geostatistics, heuristic rules, and empirical relationships to assist the user in optimizing a groundwater monitoring network system while maintaining adequate delineation of the plume as well as knowledge of the plume state over time. Different users utilize the tool in different ways and interpret the results from a different viewpoint.

↓

Overview Statistics

What it is: Simple, qualitative and quantitative plume information can be gained through evaluation of monitoring network historical data trends both spatially and temporally. The MAROS Overview Statistics are the foundation the user needs to make informed optimization decisions at the site.

What it does: The Overview Statistics are designed to allow site personnel to develop a better understanding of the plume behavior over time and understand how the individual well concentration trends are spatially distributed within the plume. This step allows the user to gain information that will support a more informed decision to be made in the next level of optimization analysis.

What are the tools: Overview Statistics includes two analytical tools:

1) **Trend Analysis:** includes Mann-Kendall and Linear Regression statistics for individual wells and results in general heuristically-derived monitoring categories with a suggested sampling density and monitoring frequency.

2) **Moment Analysis:** includes dissolved mass estimation (0^{th} Moment), center of mass (1^{st} Moment), and plume spread (2^{nd} Moment) over time. Trends of these moments show the user another piece of information about the plume stability over time.

What is the product: A first-cut blueprint for a future long-term monitoring program that is intended to be a foundation for more detailed statistical analysis.

↓

Detailed Statistics

What it is: The MAROS Detailed Statistics allows for a quantitative analysis for spatial and temporal optimization of the well network on a well-by-well basis.

What it does: The results from the Overview Statistics should be considered along side the MAROS optimization recommendations gained from the Detailed Statistical Analysis. The MAROS Detailed Statistics results should be reassessed in view of site knowledge and regulatory requirements as well as the Overview Statistics.

What are the tools: Detailed Statistics includes four analytical tools:

1) **Sampling Frequency Optimization:** uses the Modified CES method to establish a recommended future sampling frequency.

2) **Well Redundancy Analysis:** uses the Delaunay Method to evaluate if any wells within the monitoring network are redundant and can be eliminated without any significant loss of plume information.

3) **Well Sufficiency Analysis:** uses the Delaunay Method to evaluate areas where new wells are recommended within the monitoring network due to high levels of concentration uncertainty.

4) **Data Sufficiency Analysis:** uses Power Analysis to assess if the historical monitoring data record has sufficient power to accurately reflect the location of the plume relative to the nearest receptor or compliance point.

What is the product: List of wells to remove from the monitoring program, locations where monitoring wells may need to be added, recommended frequency of sampling for each well, analysis if the overall system is statistically powerful to monitor the plume.

Figure 3. MAROS Decision Support Tool Flow Chart

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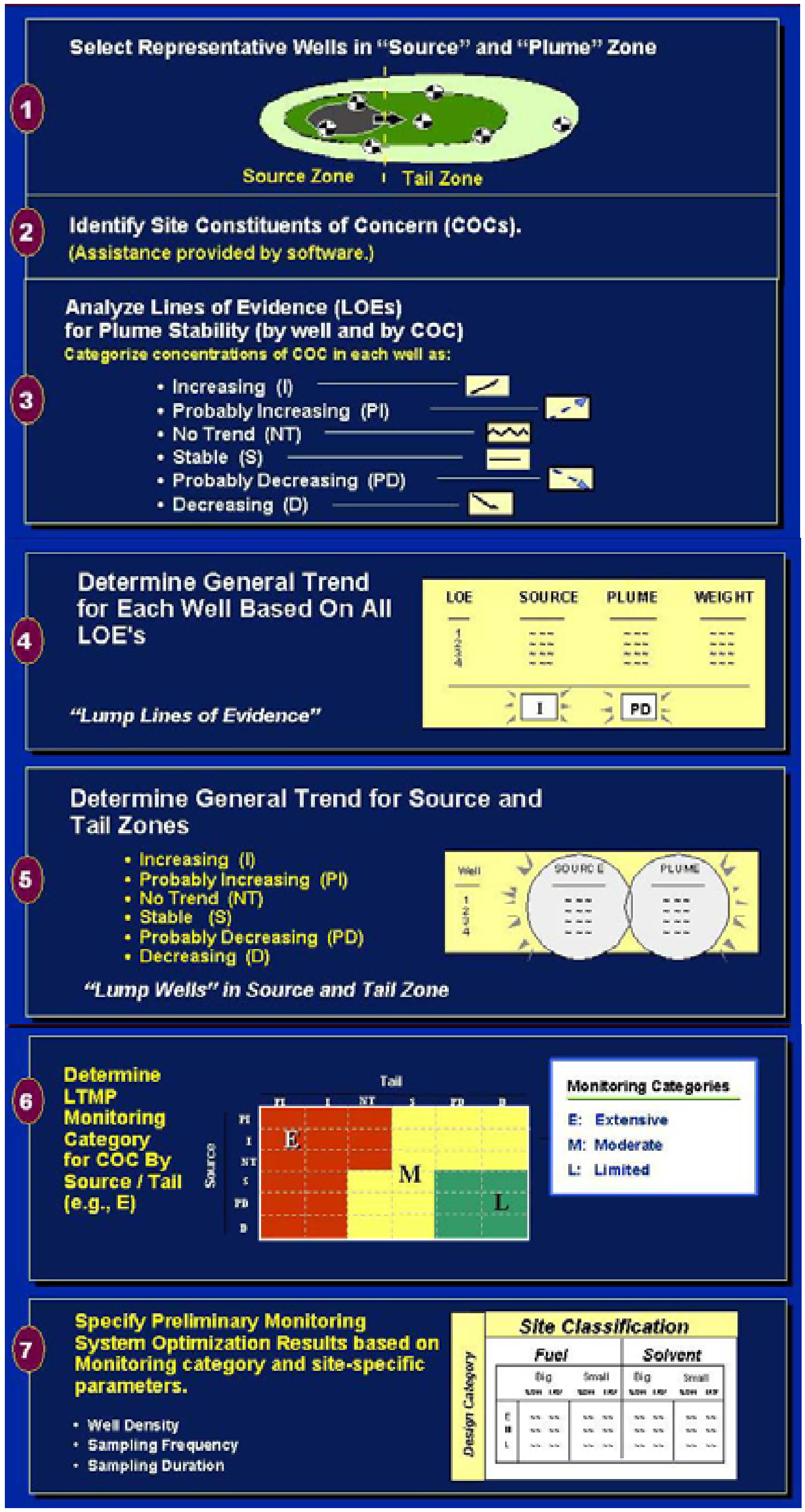

Figure 4:
MAROS Overview Statistics Trend Analysis Methodology

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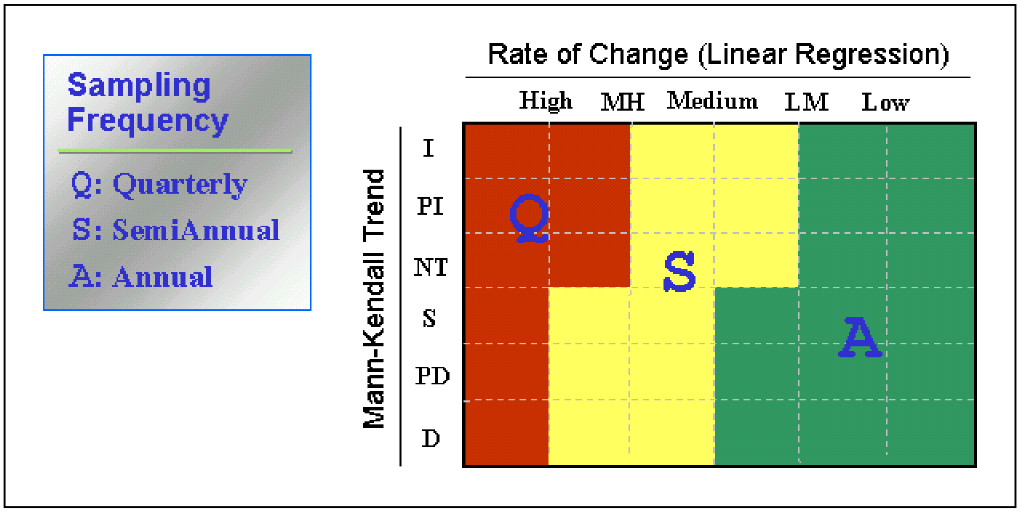

Figure 5. Decision Matrix for Determining Provisional Frequency (*Figure A.3.1 of the MAROS Manual (AFCEE 2001)*)

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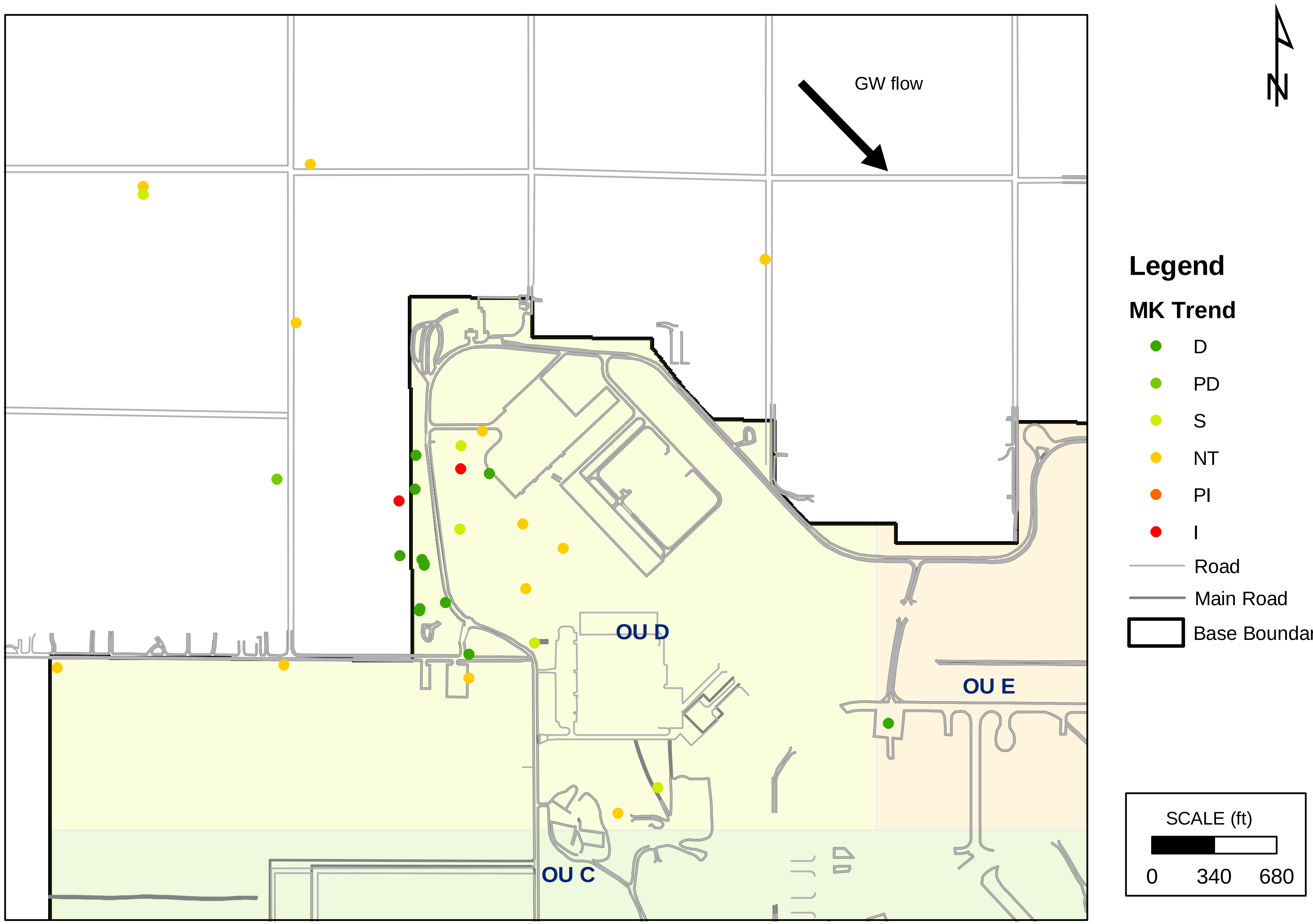

Figure 6 Zone A TCE Mann-Kendall Trend Results
McClellan Air Force Base, Sacramento, California

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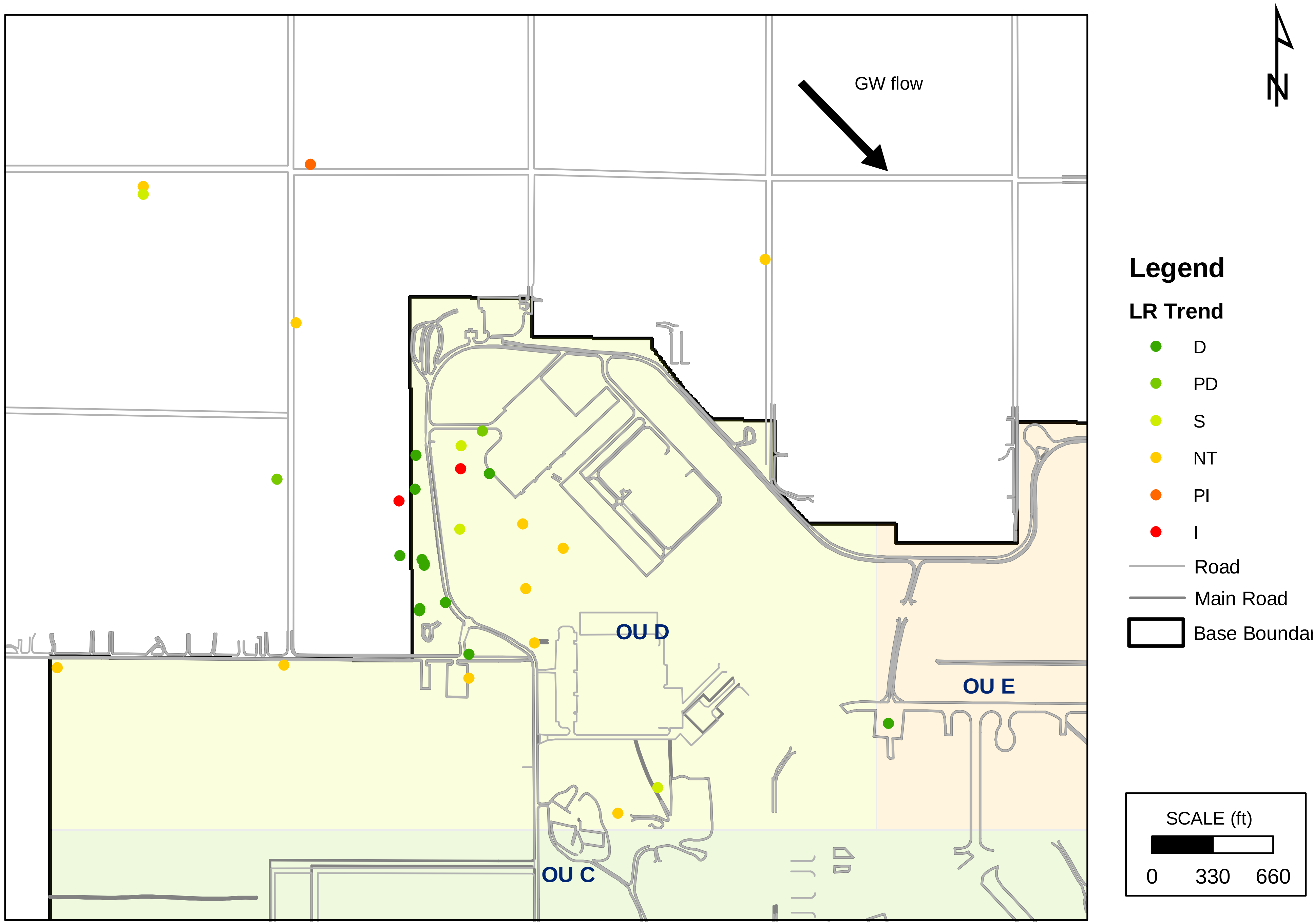

Figure 7 Zone A TCE Linear Regression Trend Results
McClellan Air Force Base, Sacramento, California

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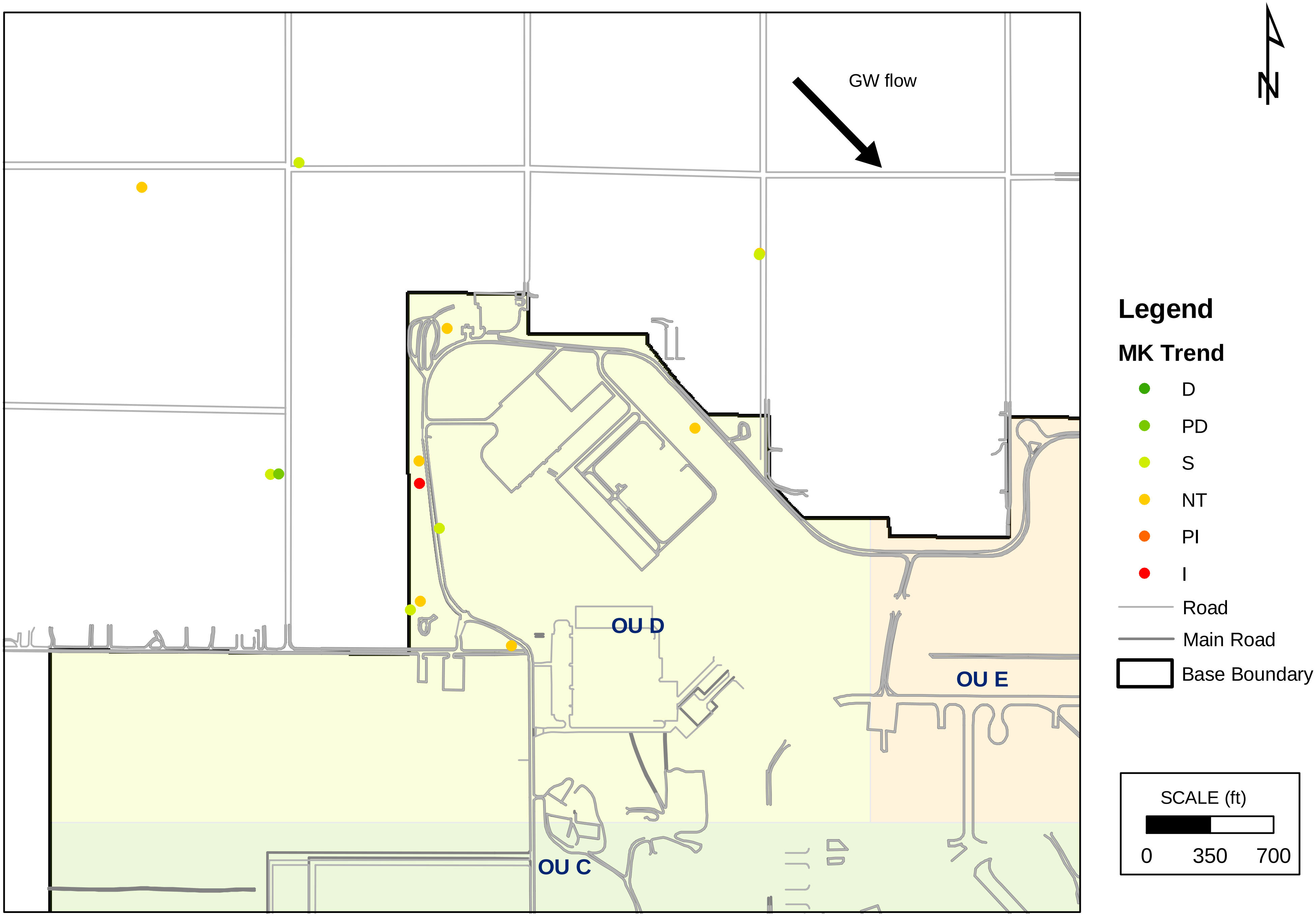

Figure 8 Zone B TCE Mann-Kendall Trend Results
McClellan Air Force Base, Sacramento, California

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Date Issued: 1/15/03

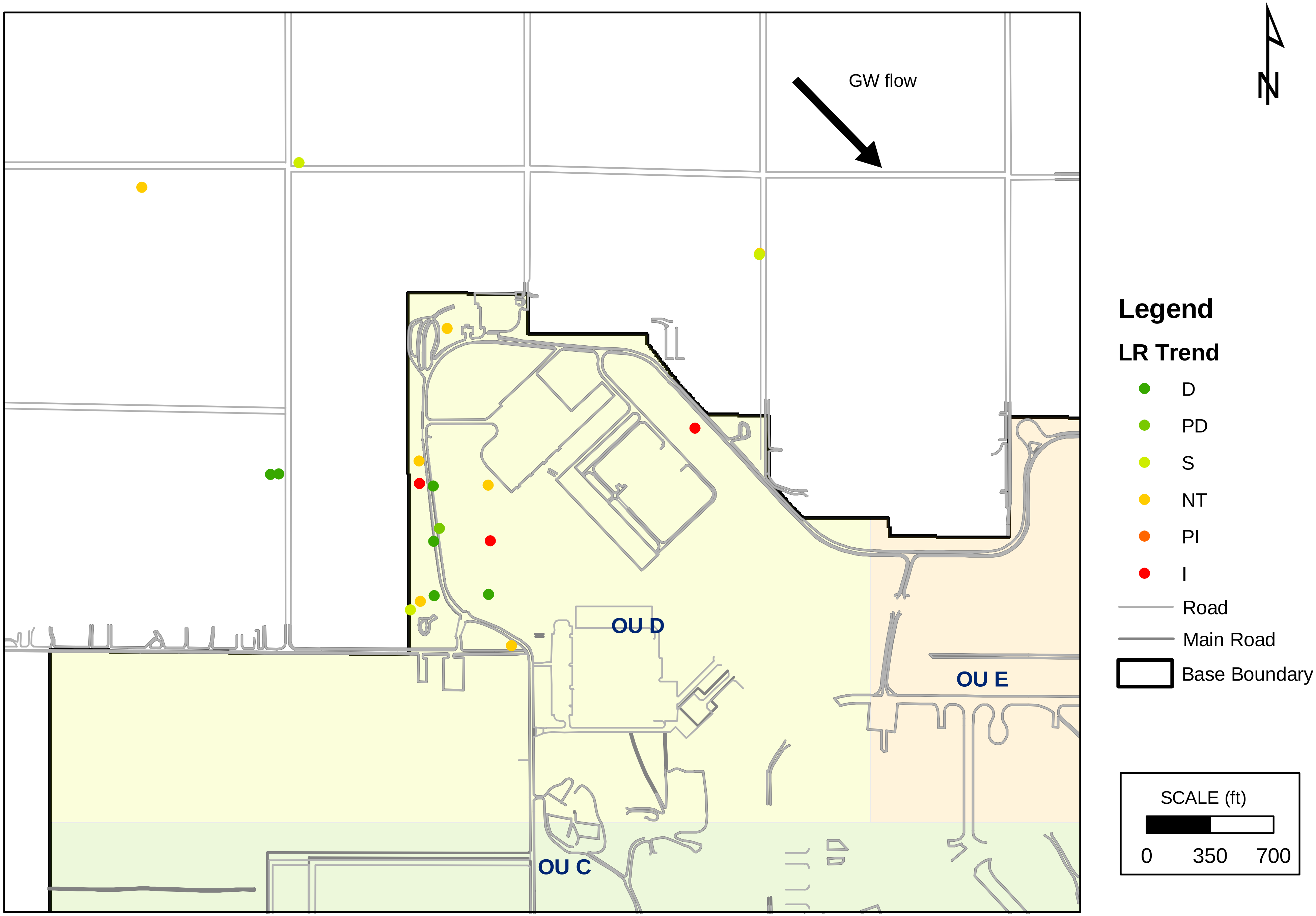

Figure 9 Zone B TCE Linear Regression Trend Results
McClellan Air Force Base, Sacramento, California

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Date Issued: 1/15/03

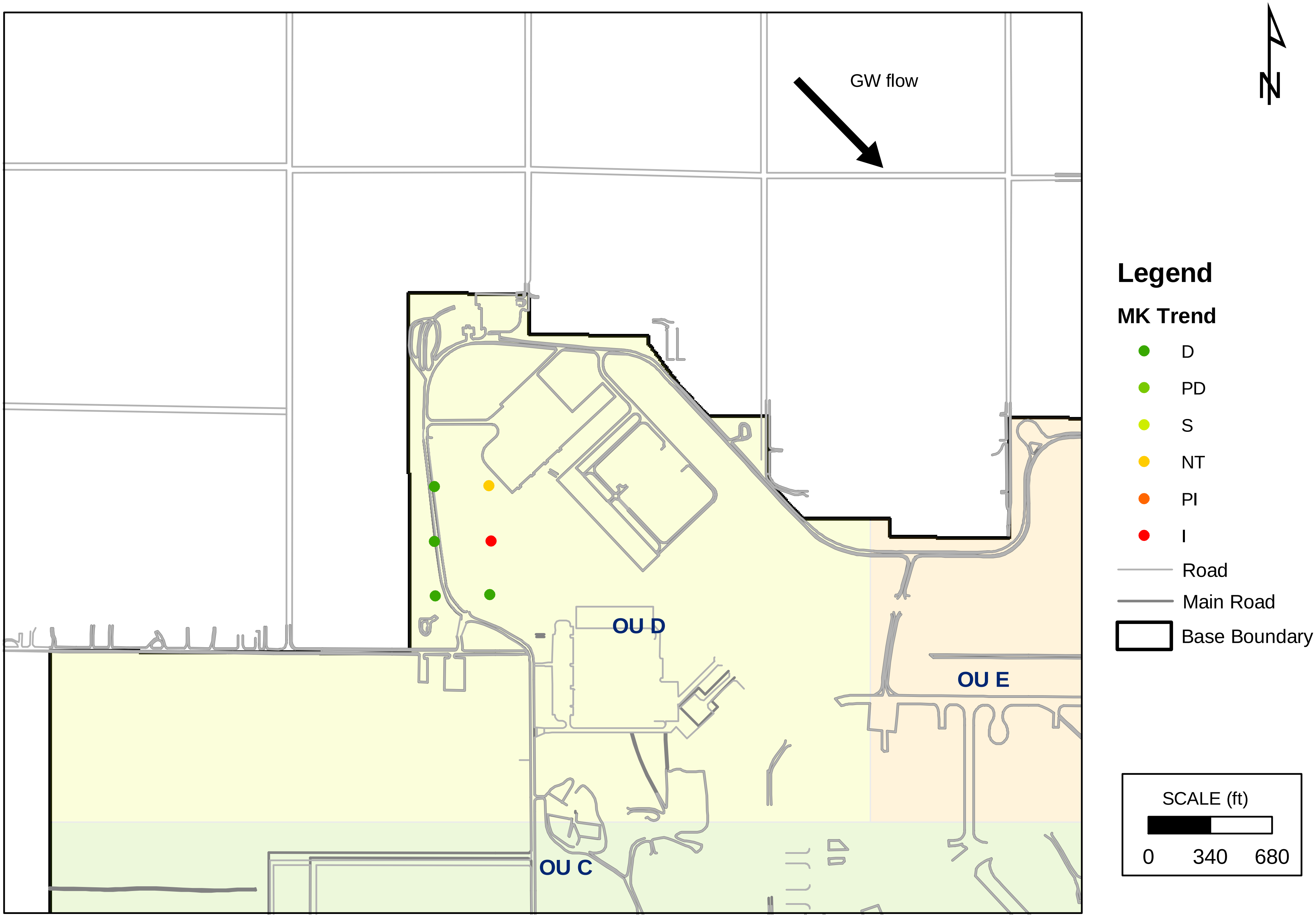

Figure 10 Zone AB TCE Mann-Kendall Trend Results, Extraction Wells
McClellan Air Force Base, Sacramento, California

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Date Issued: 1/15/03

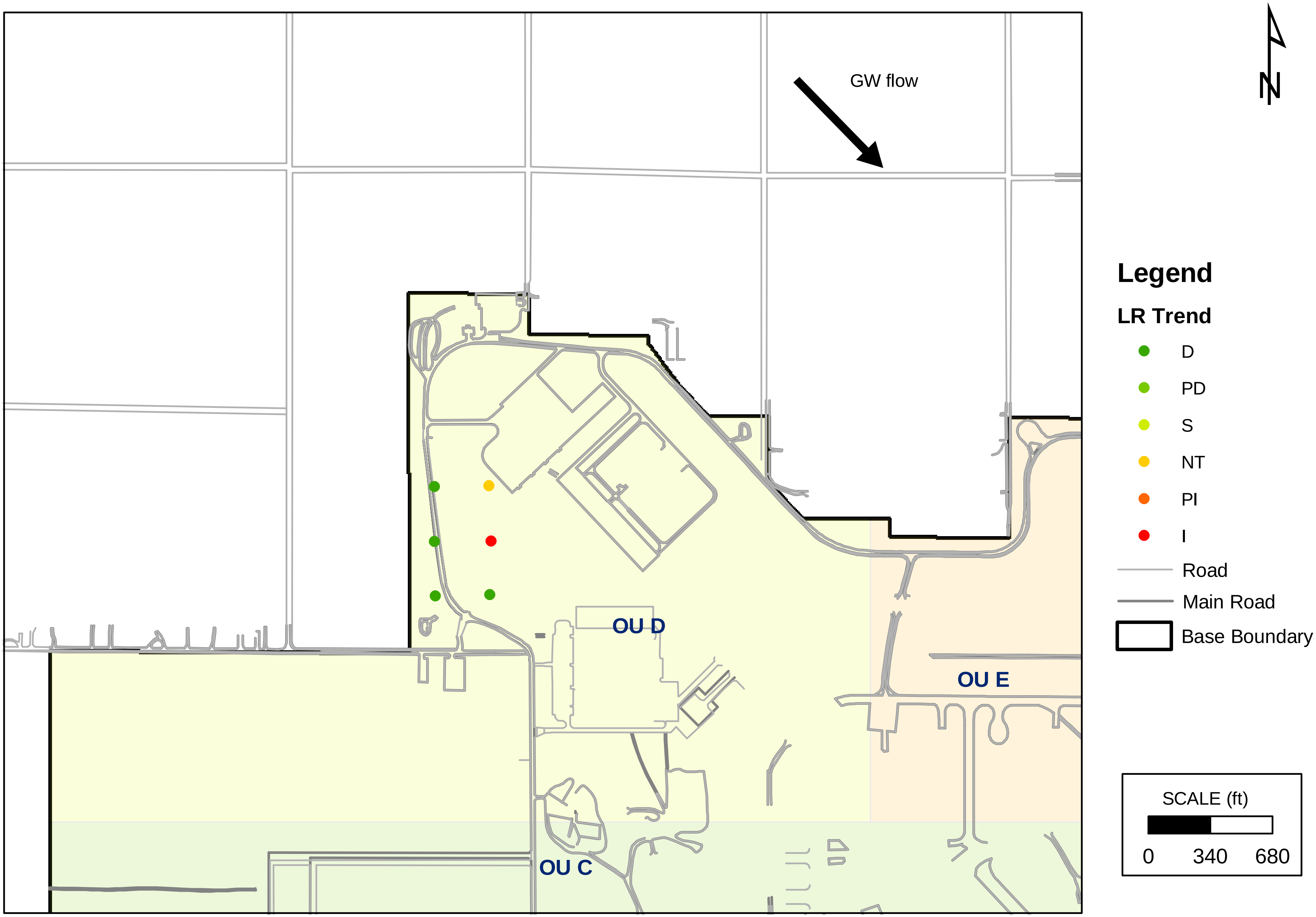

Figure 11 Zone AB TCE Linear Regression Trend Results, Extraction Wells
McClellan Air Force Base, Sacramento, California

GSI Job No. G-2236
Date Issued: 1/15/03

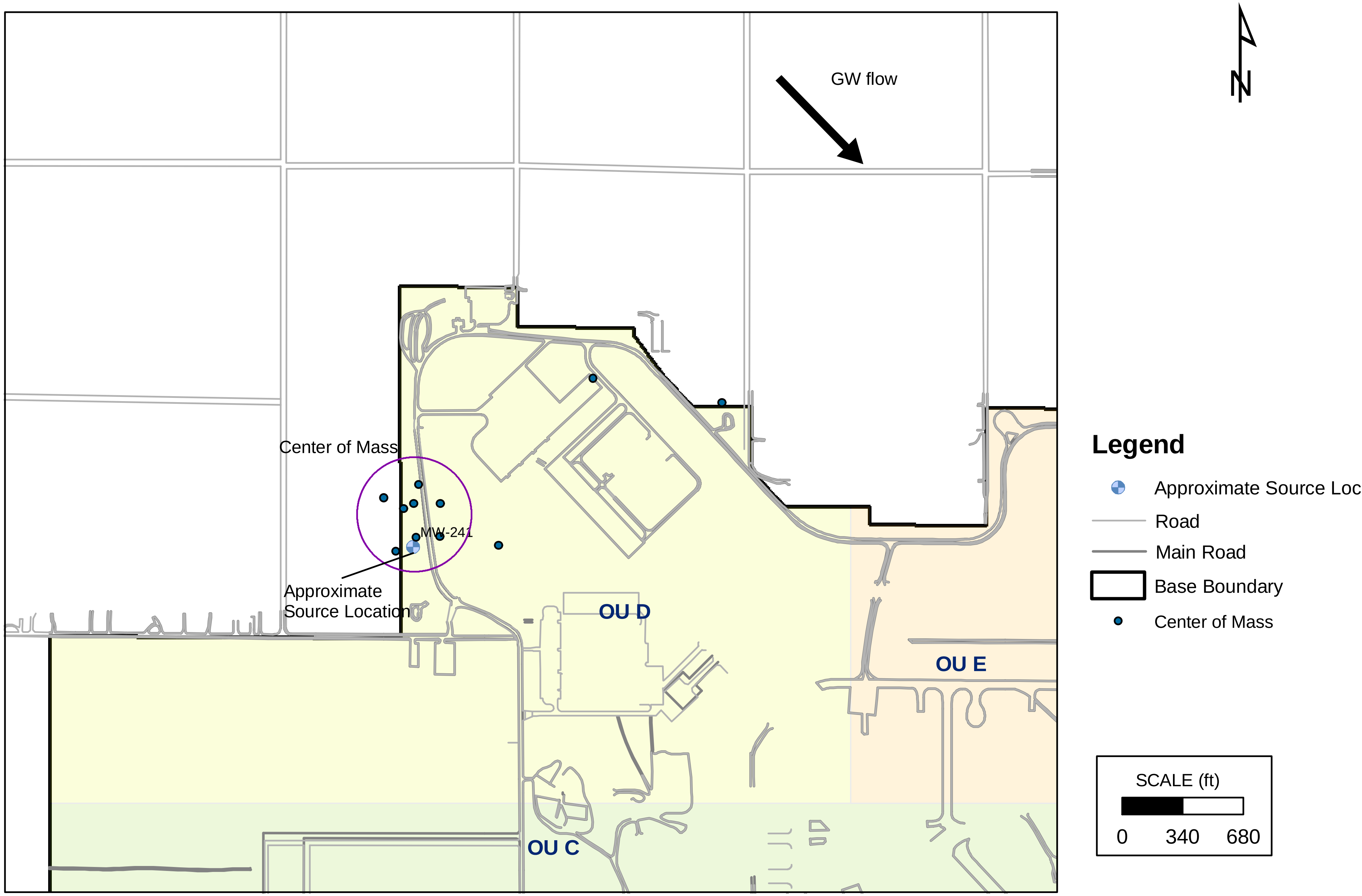

Figure 12 Zone A: TCE First Moment (Center of Mass) Over Time
McClellan Air Force Base, Sacramento, California

GSI Job No. G-2236
Date Issued: 1/15/03

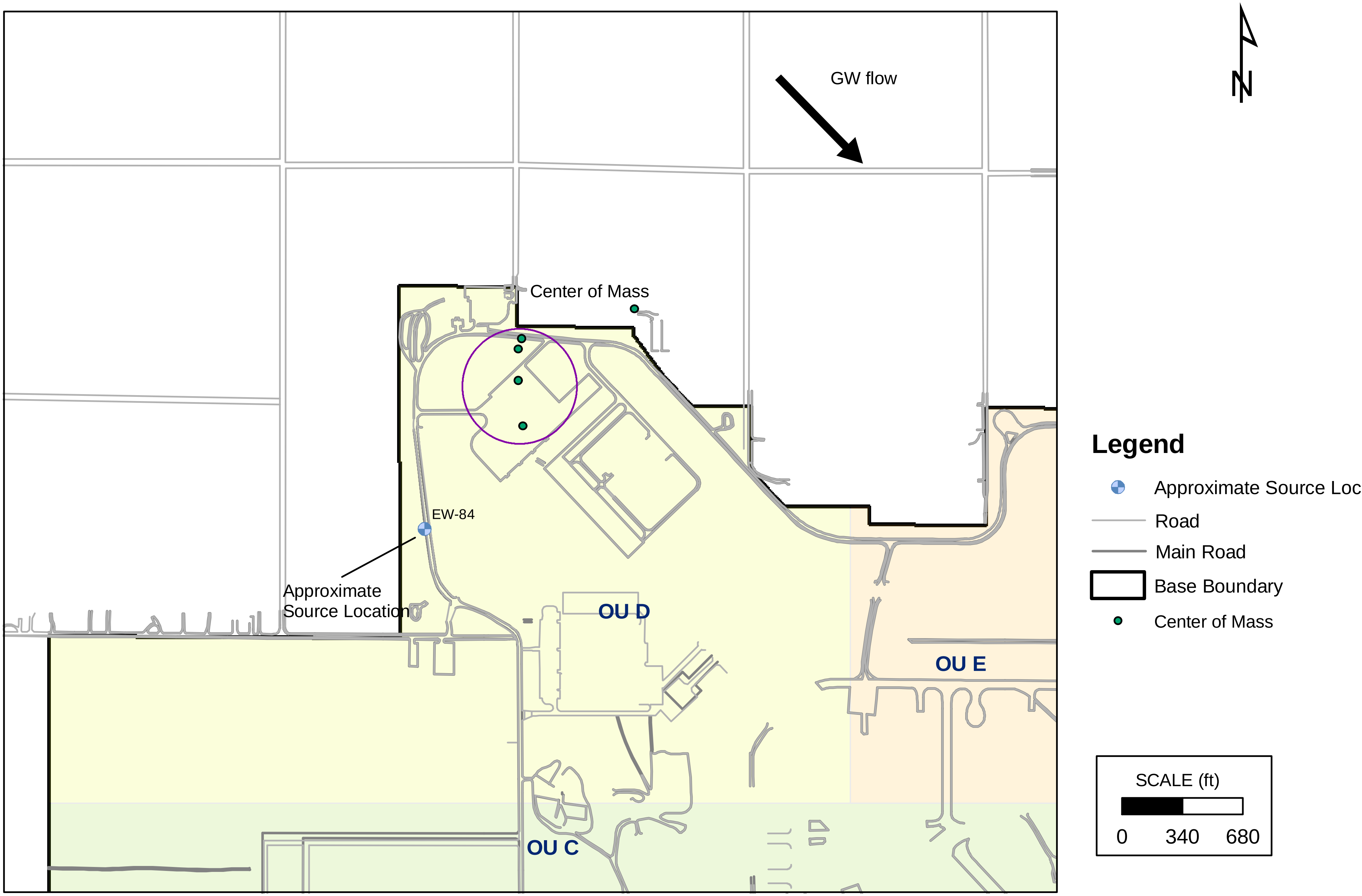

Figure 13 Zone B: TCE First Moment (Center of Mass) Over Time
McClellan Air Force Base, Sacramento, California

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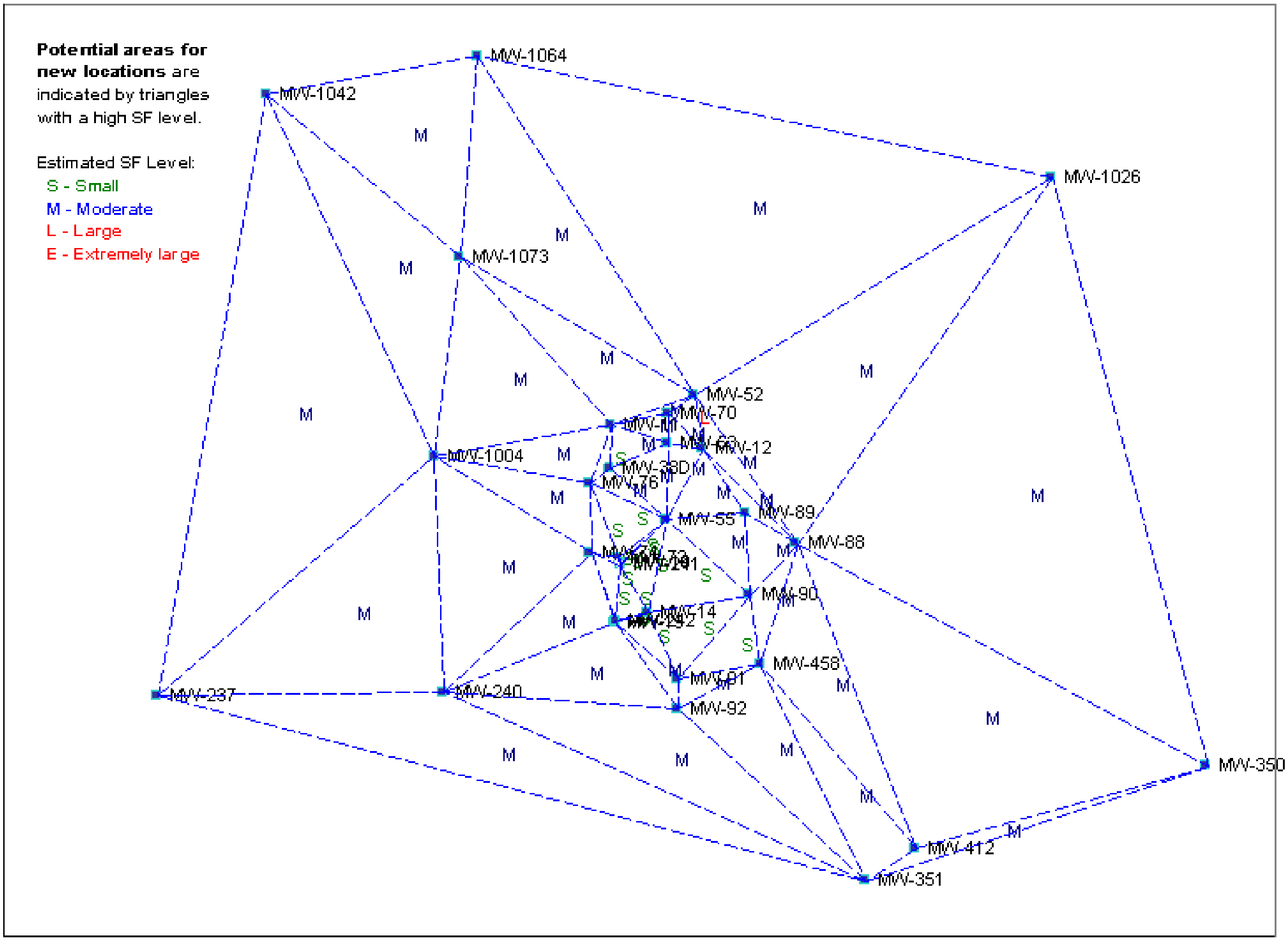

Figure 14. Well Sufficiency Analysis for possible new sampling locations in Zone A. Areas with **L** symbols are candidate regions for placing new wells. No new wells need to be recommended since the current network has enough sampling points.

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MAROS 2.0 APPLICATION
ZONE A & B OU D MONITORING NETWORK OPTIMIZATION

McClellan AFB
Sacramento Valley, California

APPENDICES

Appendix A: Zone A and Zone B McClellan OU D Historical TCE Maps

Appendix B: Zone A and Zone B McClellan OU D MAROS 2.0 Reports

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MAROS 2.0 APPLICATION
ZONE A & B OU D MONITORING NETWORK OPTIMIZATION

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APPENDIX A: Zone A and B McClellan AFB Historical TCE Maps

Zone A and Zone B McClellan OU D Historical TCE Maps (1990 – 2001)

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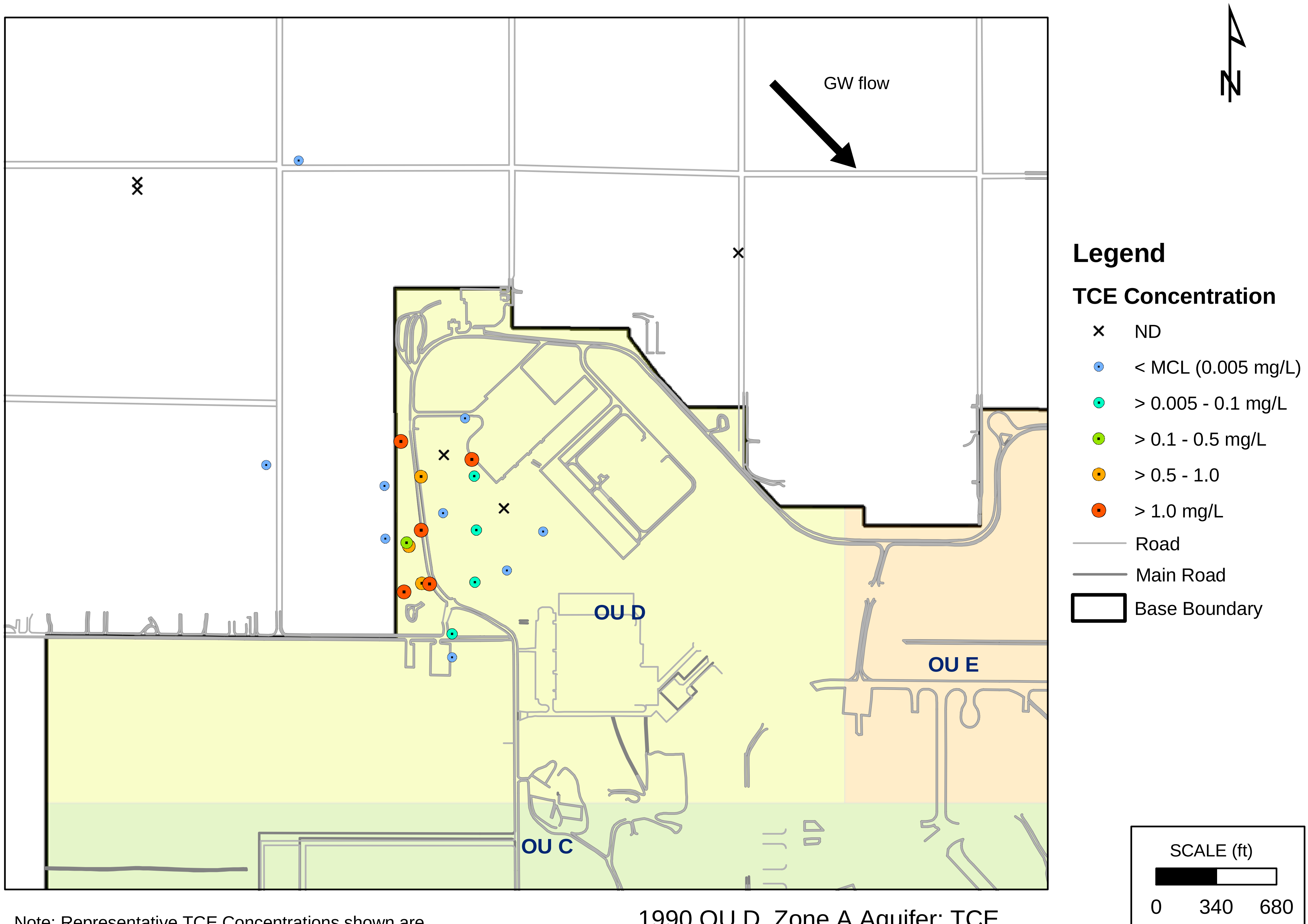

Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1990 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

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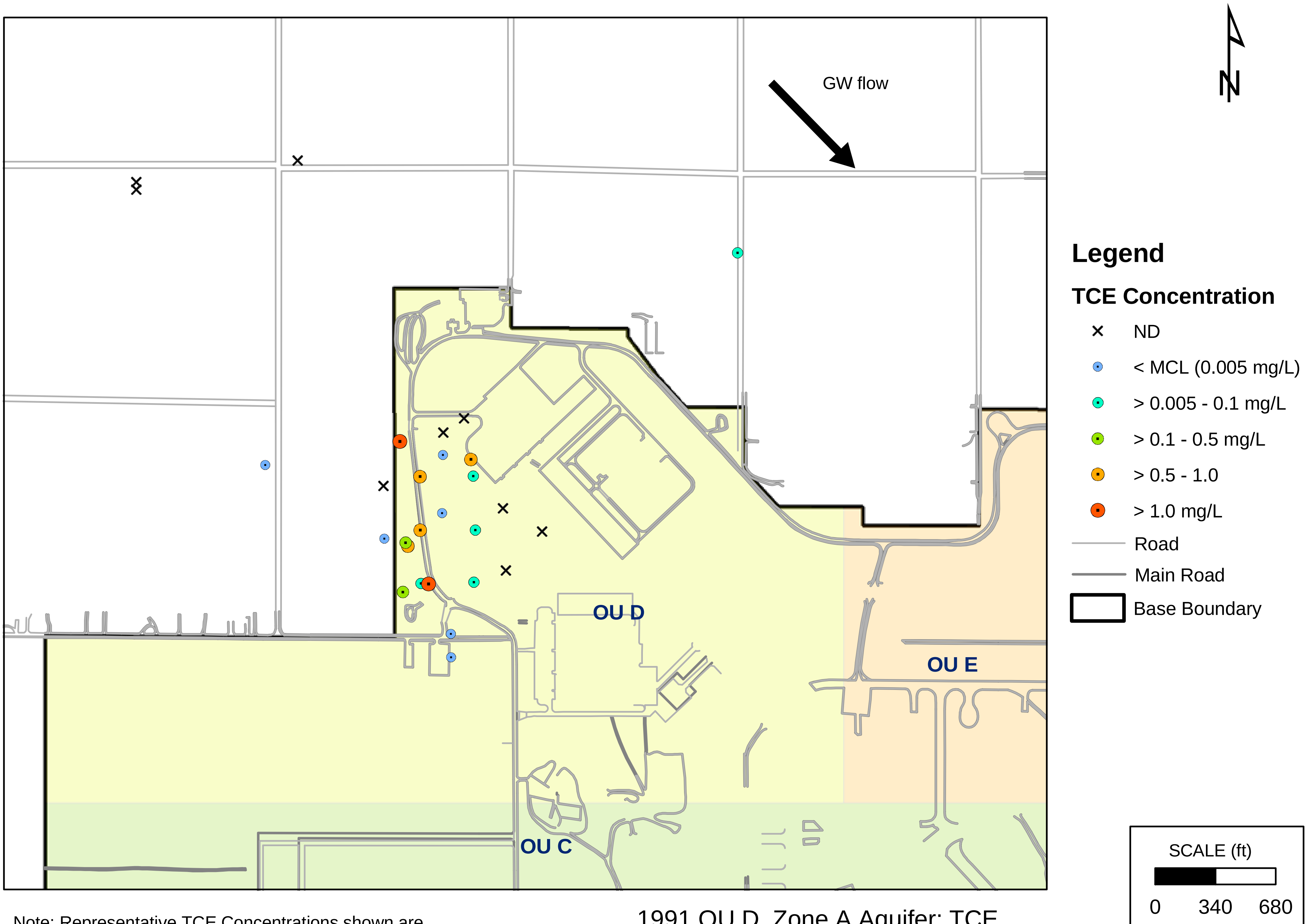
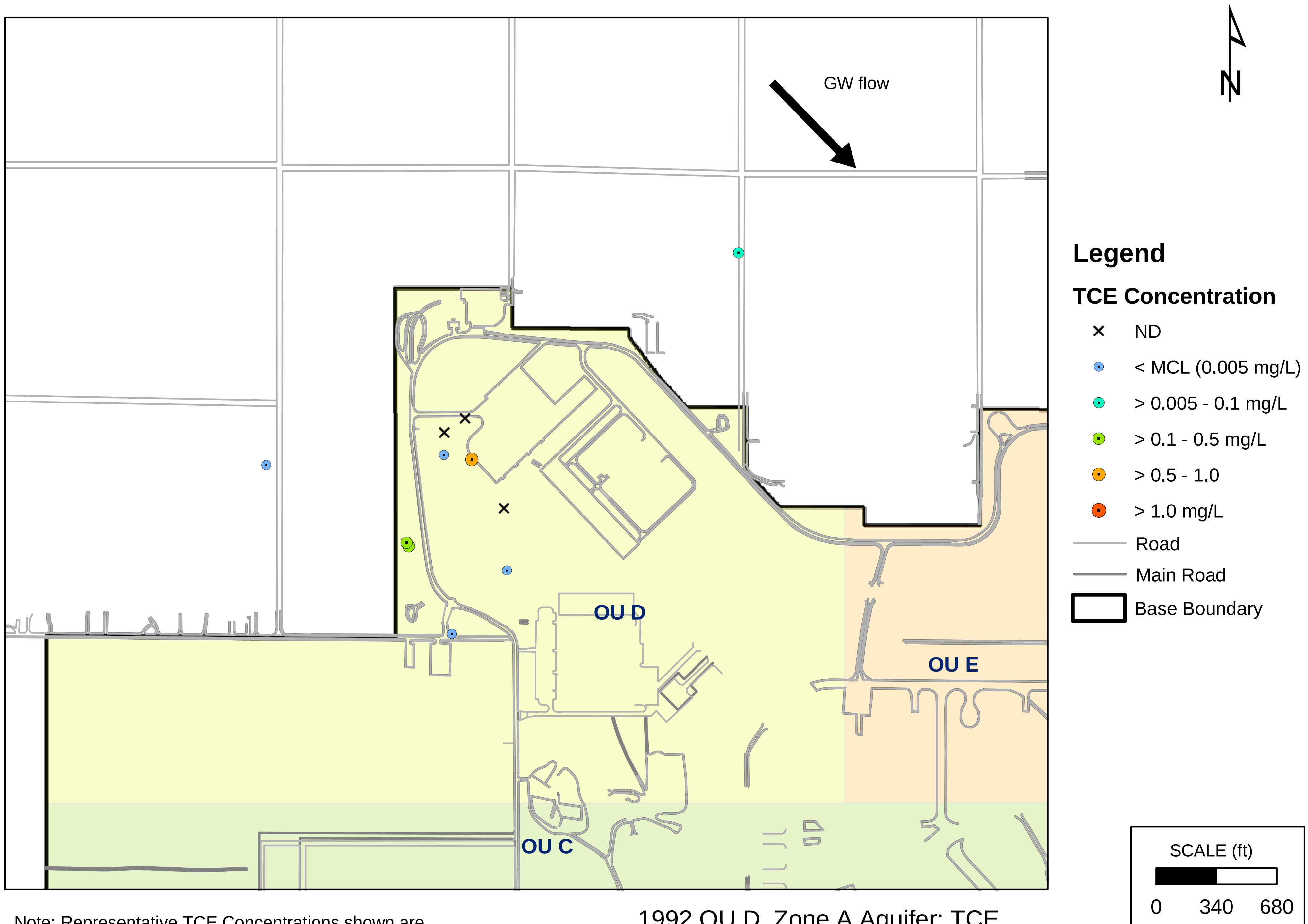
Date Issued: 12/04/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1991 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

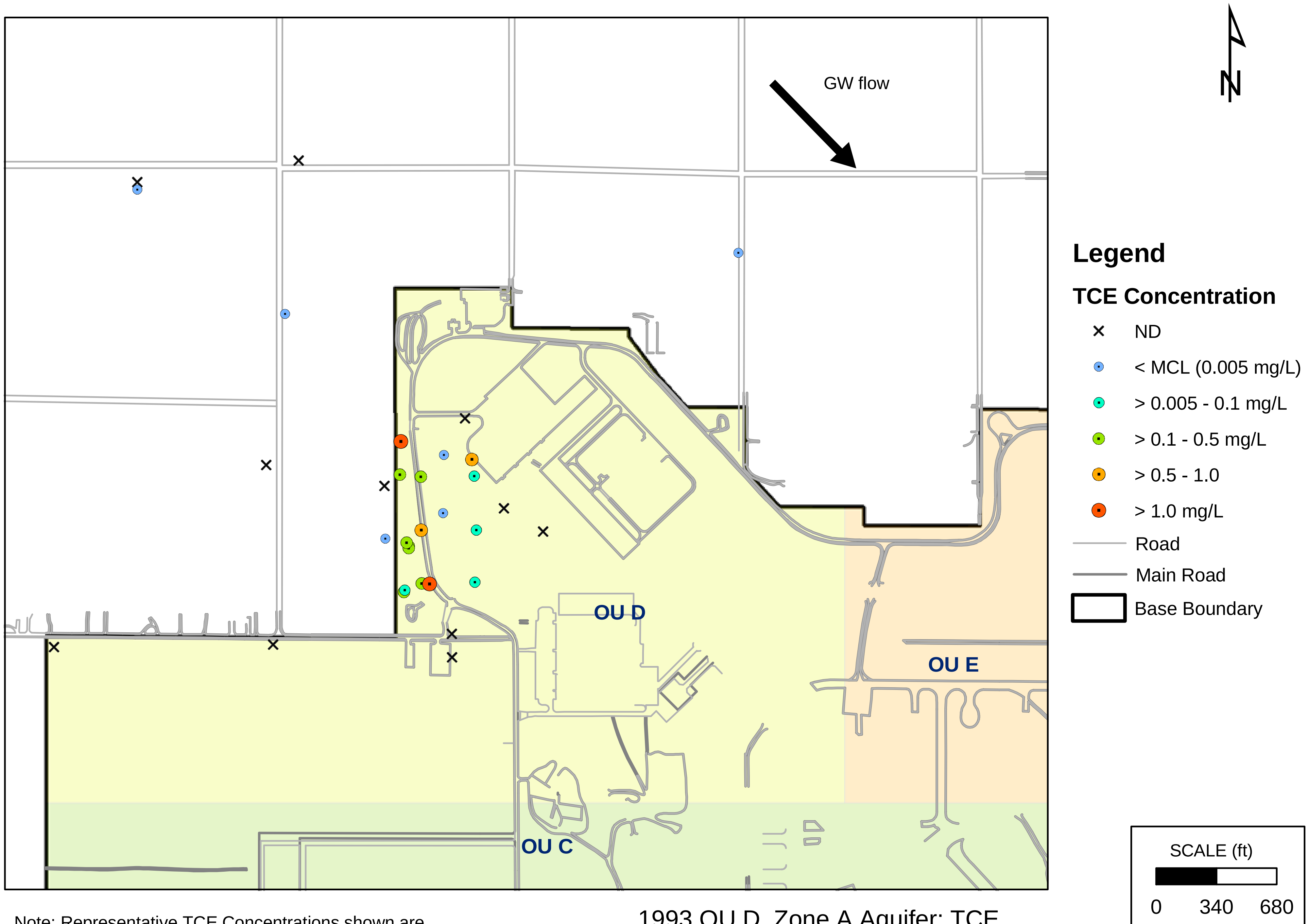
GSI Job No. G-2236
Date Issued: 12/04/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1992 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

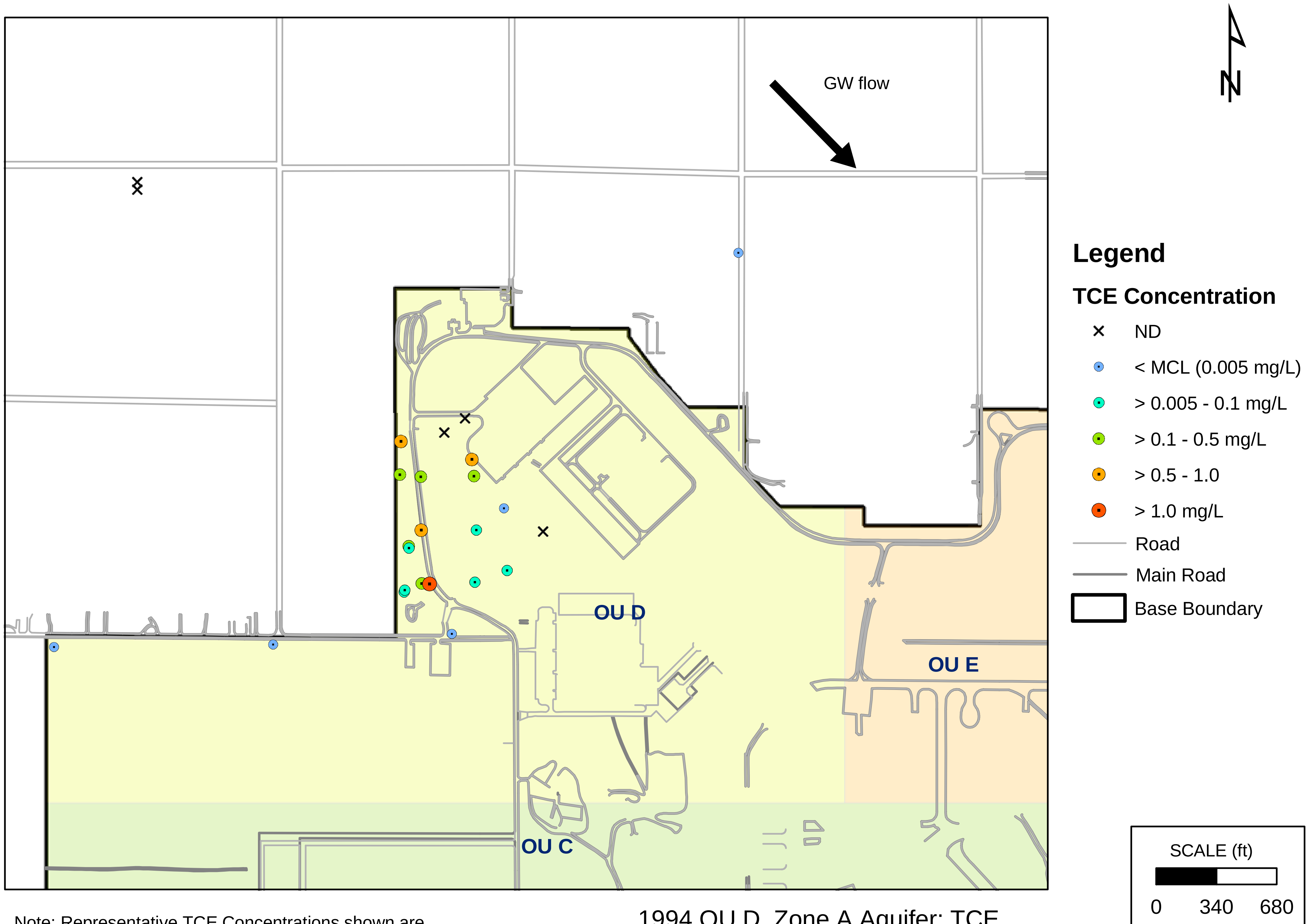
GSI Job No. G-2236
Date Issued: 12/04/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1993 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

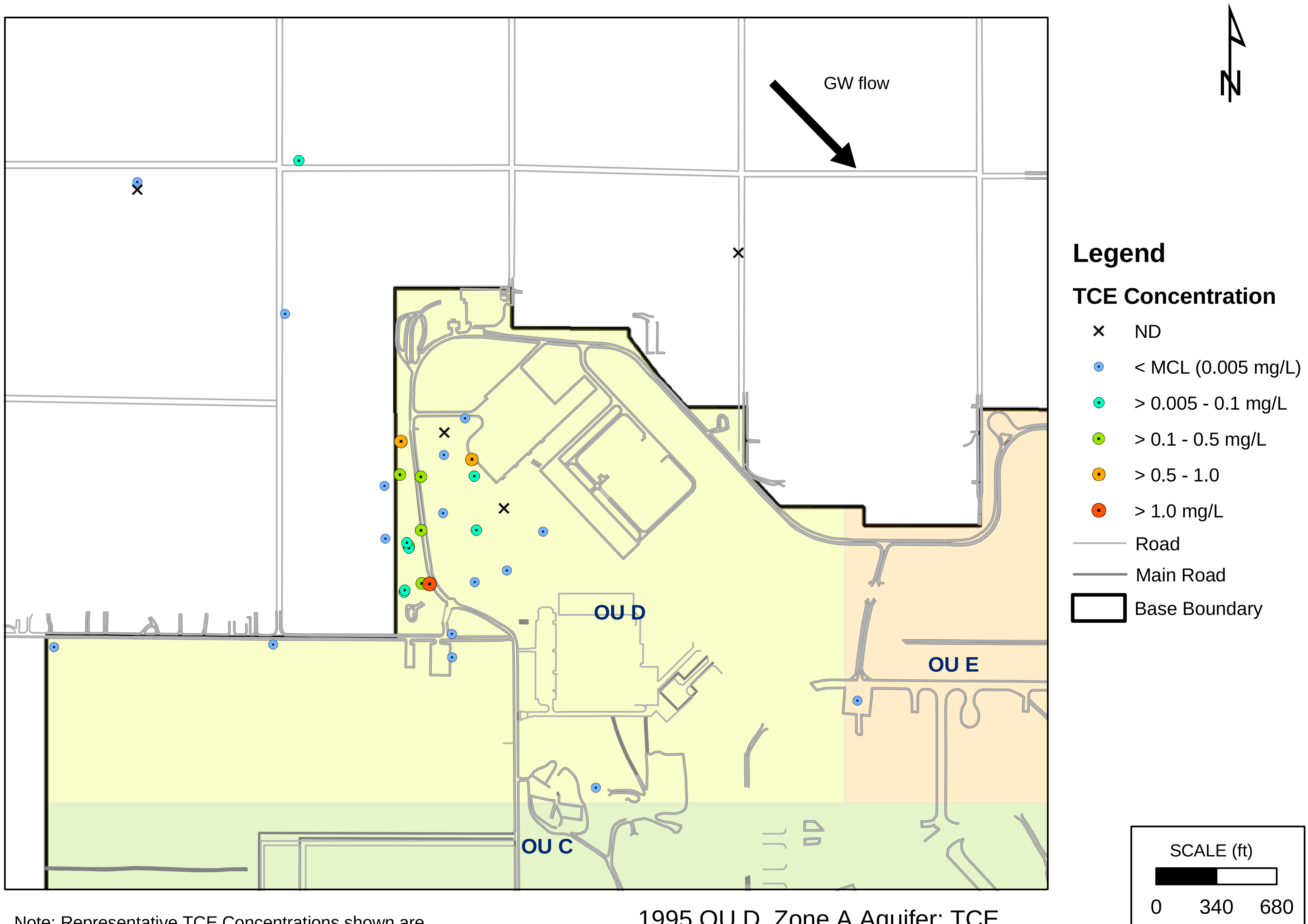
GSI Job No. G-2236
Date Issued: 12/04/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1994 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

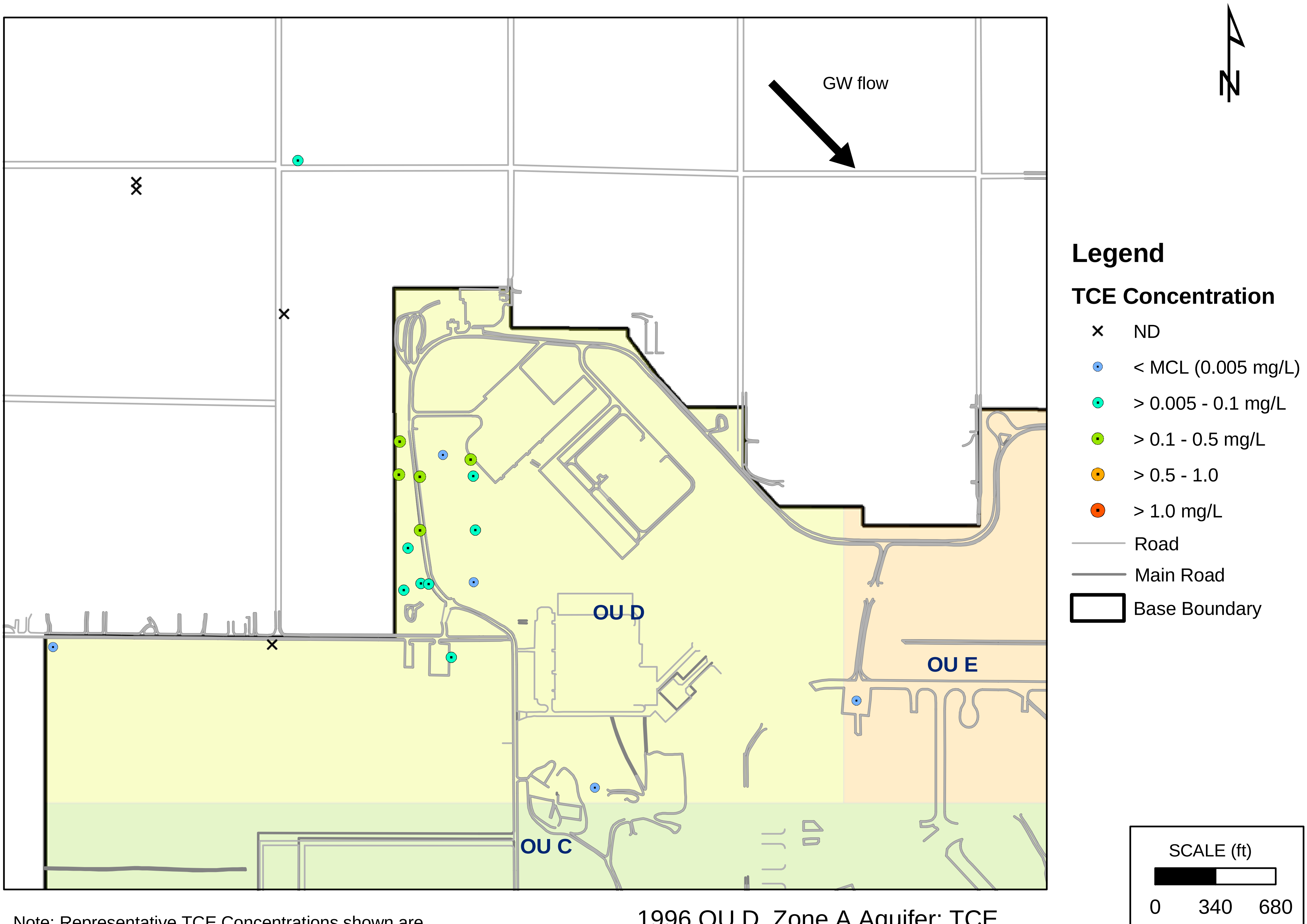
GSI Job No. G-2236
Date Issued: 12/04/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1995 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

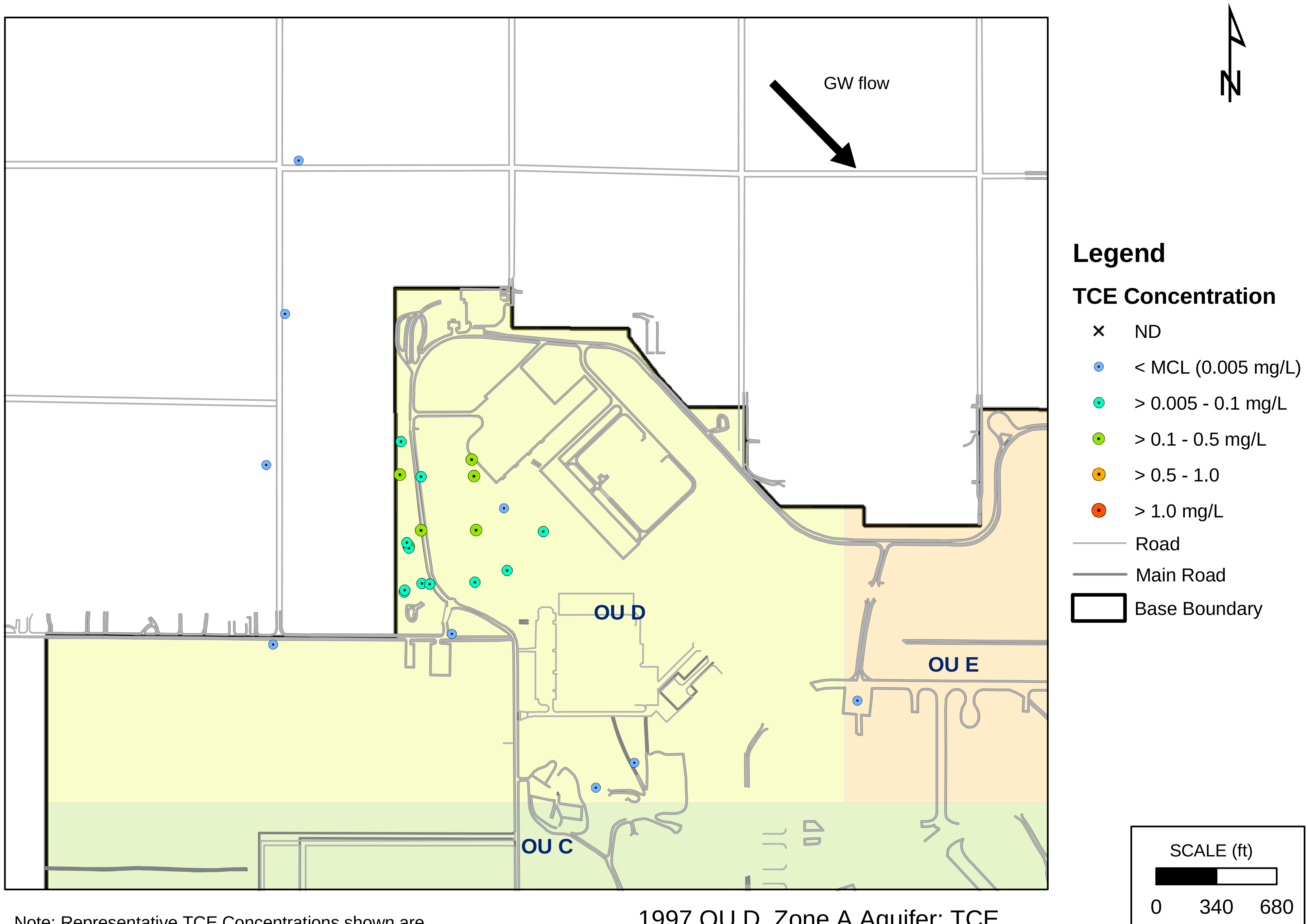
GSI Job No. G-2236
Date Issued: 12/04/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1996 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

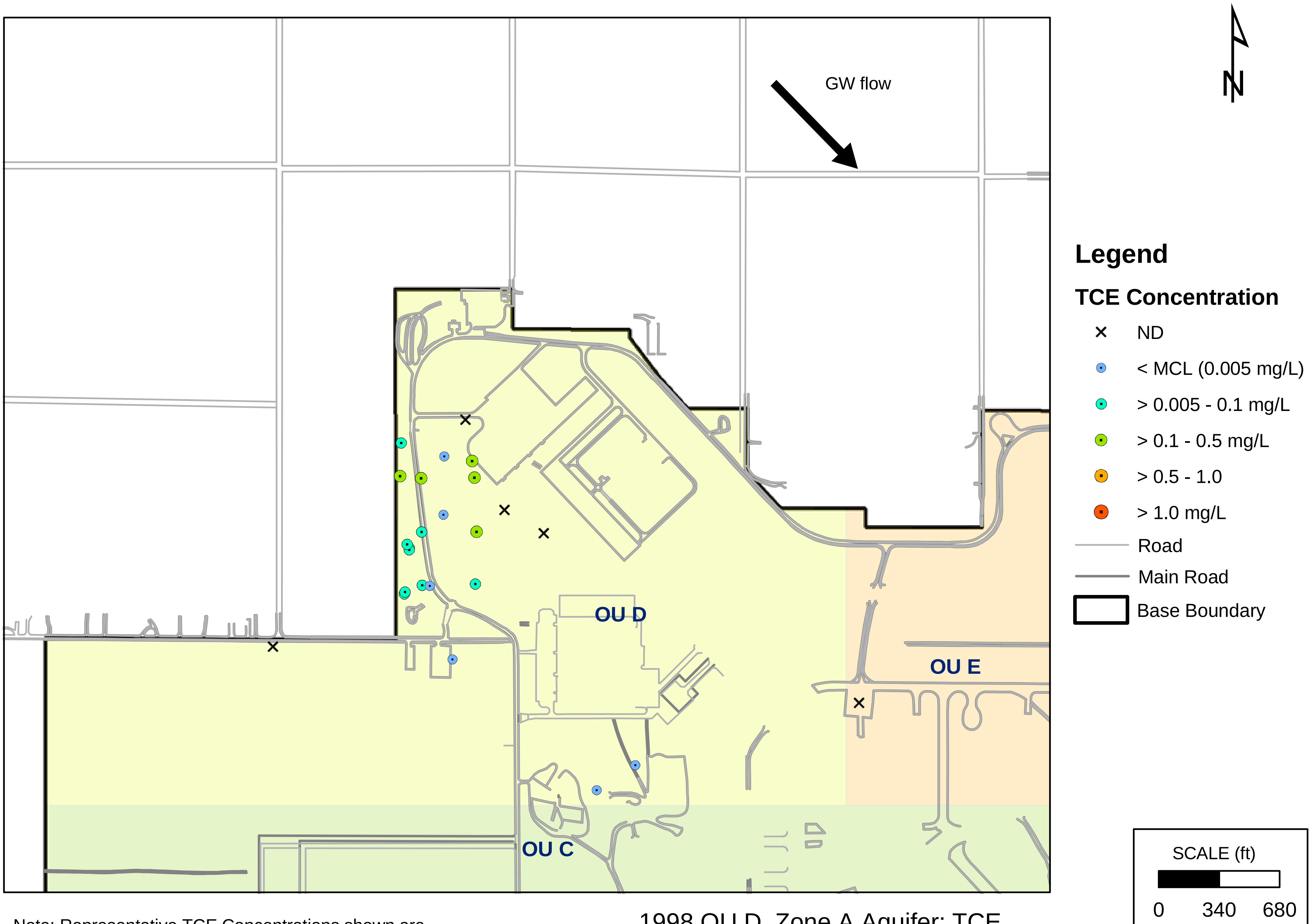
GSI Job No. G-2236
Date Issued: 12/04/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1997 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

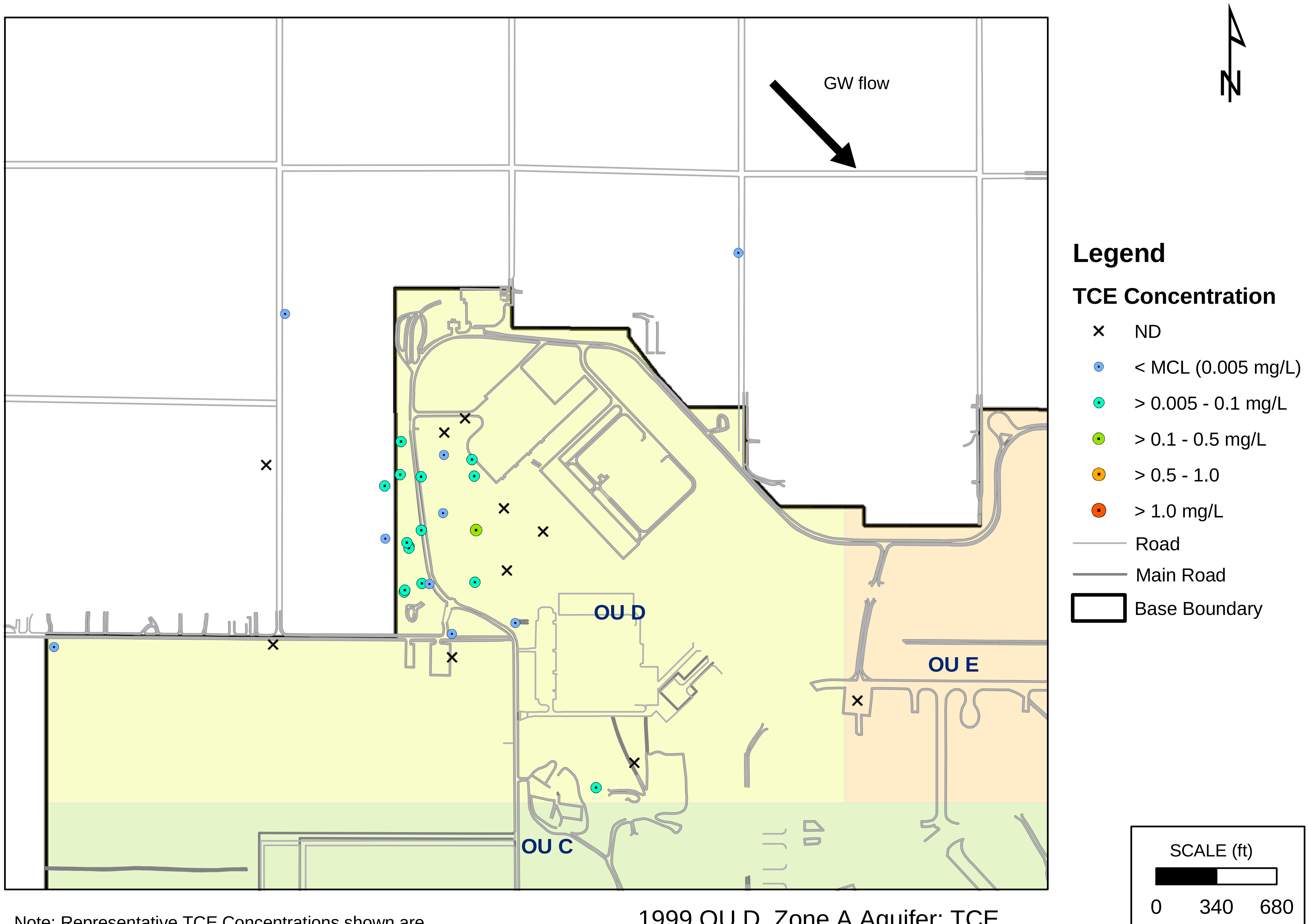
GSI Job No. G-2236
Date Issued: 12/04/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1998 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

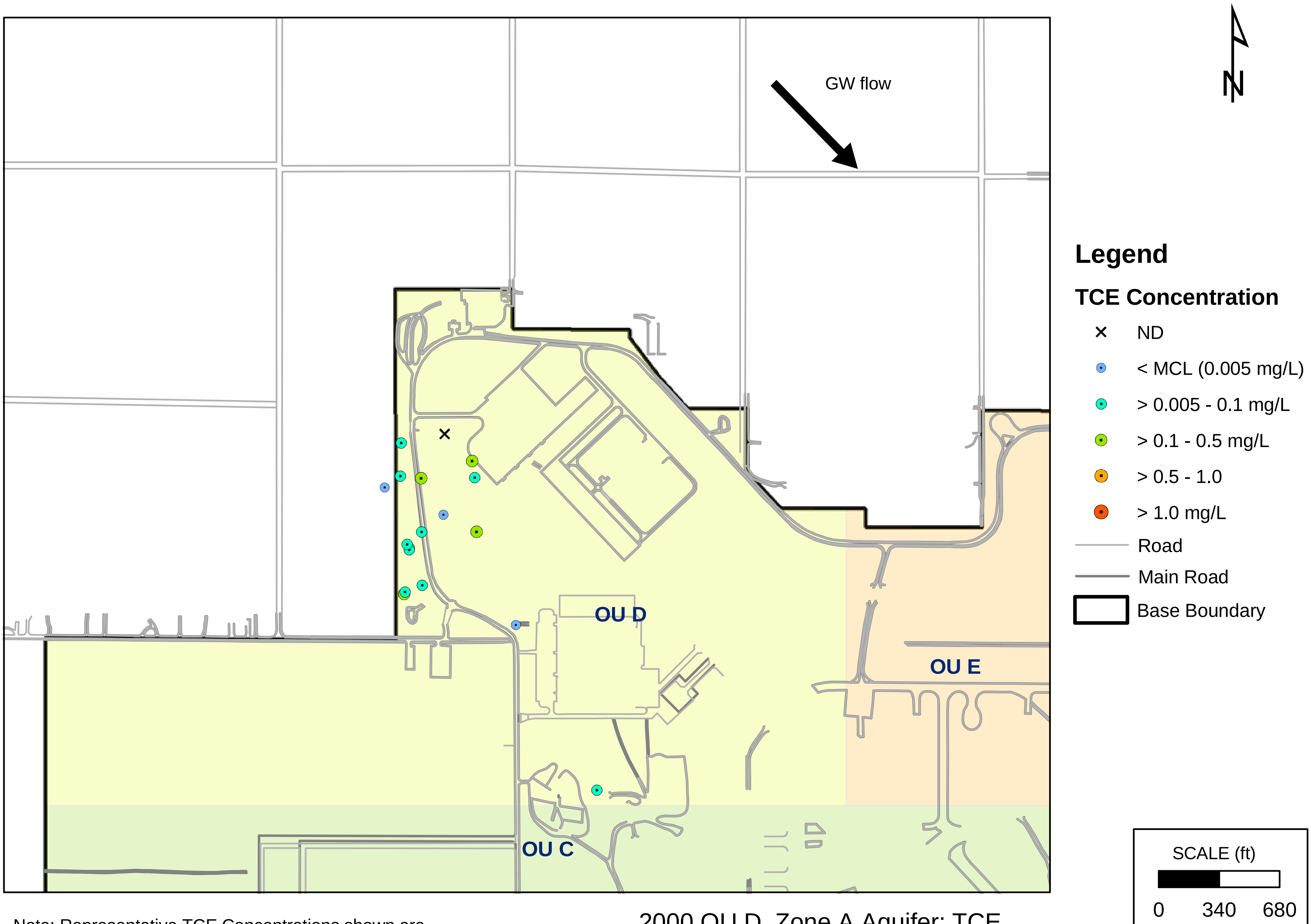
GSI Job No. G-2236
Date Issued: 12/04/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1999 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

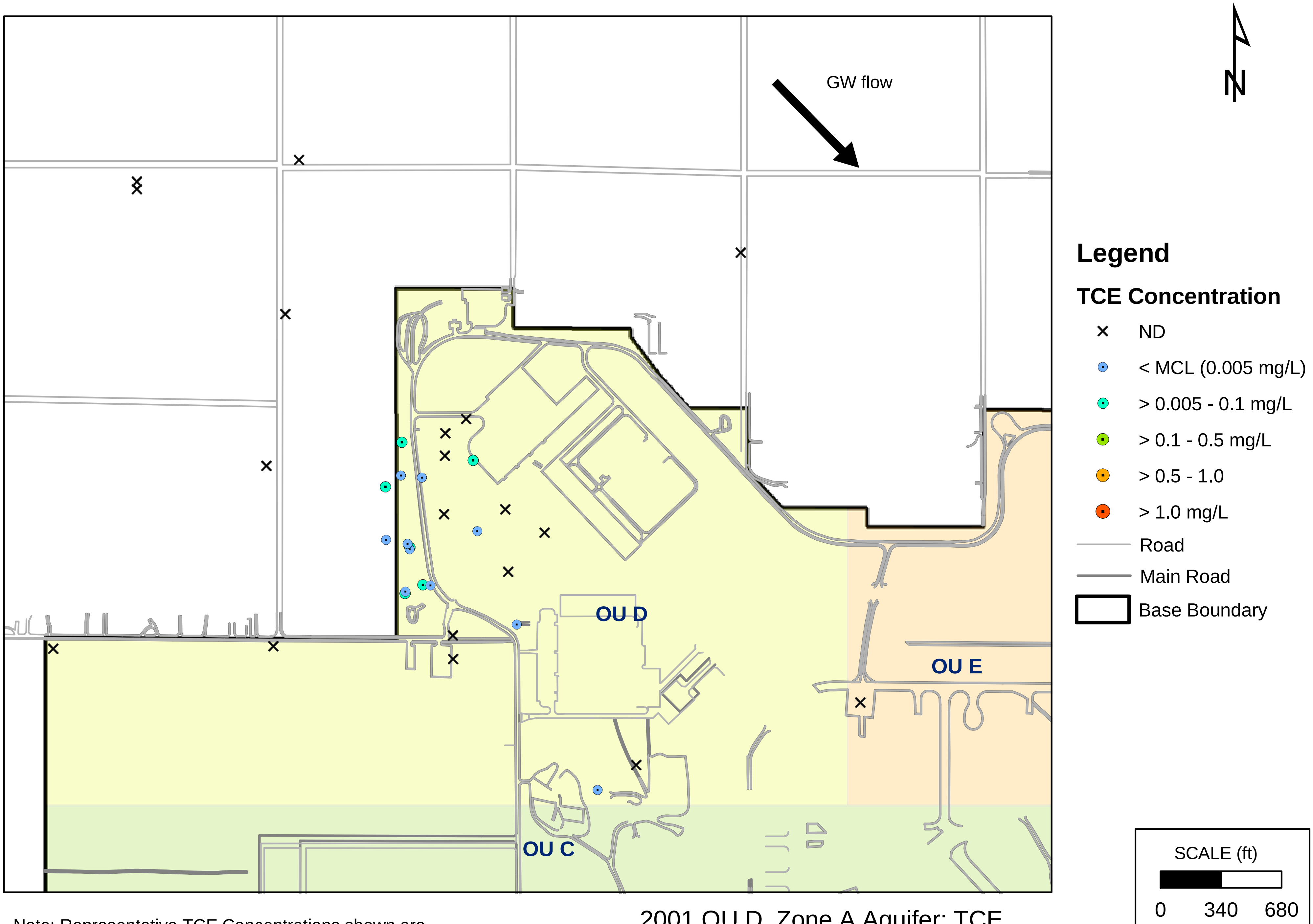
GSI Job No. G-2236
Date Issued: 12/04/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

2000 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

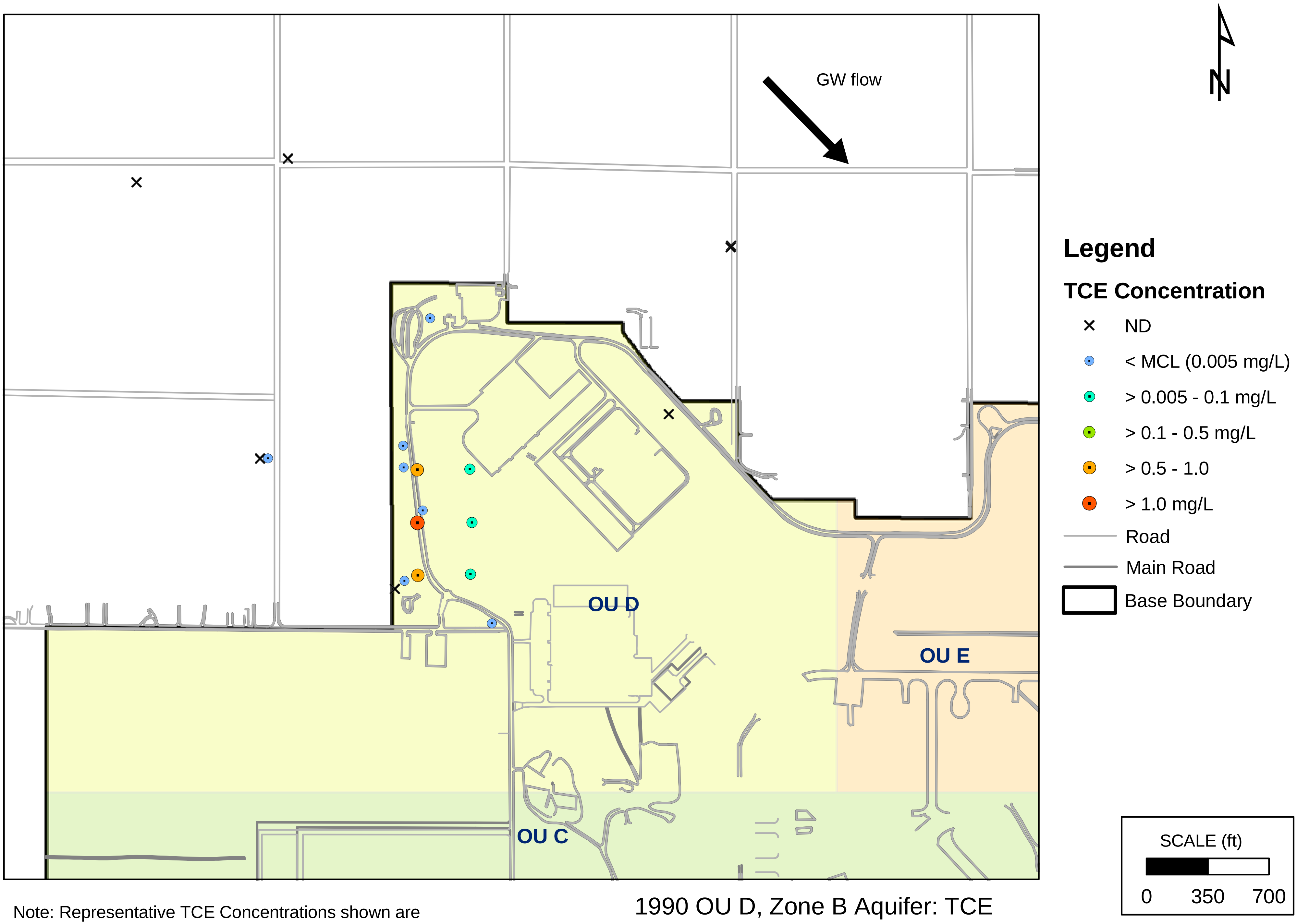
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

2001 OU D, Zone A Aquifer: TCE
McClellan Air Force Base, Sacramento, California

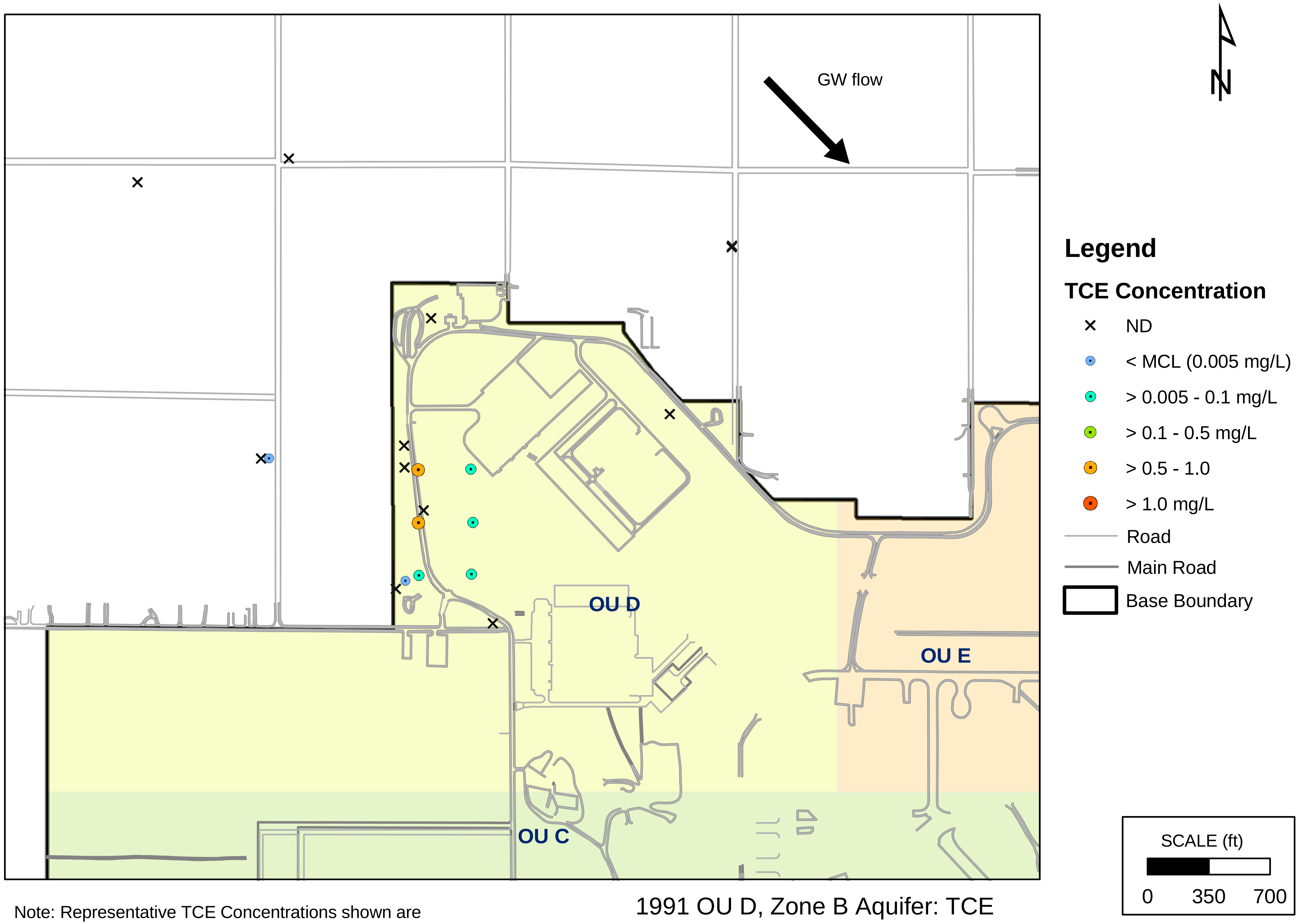
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1990 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

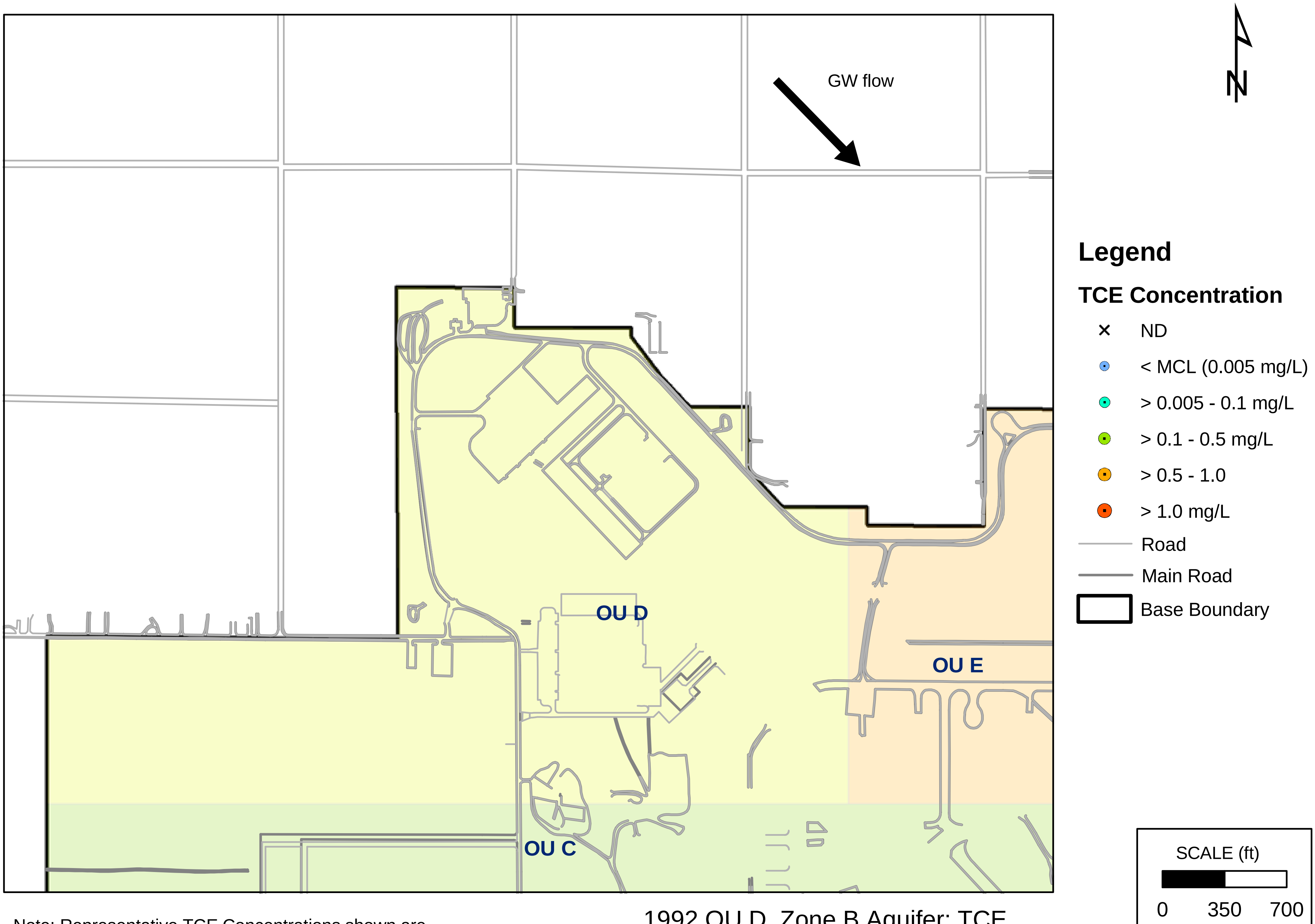
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1991 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

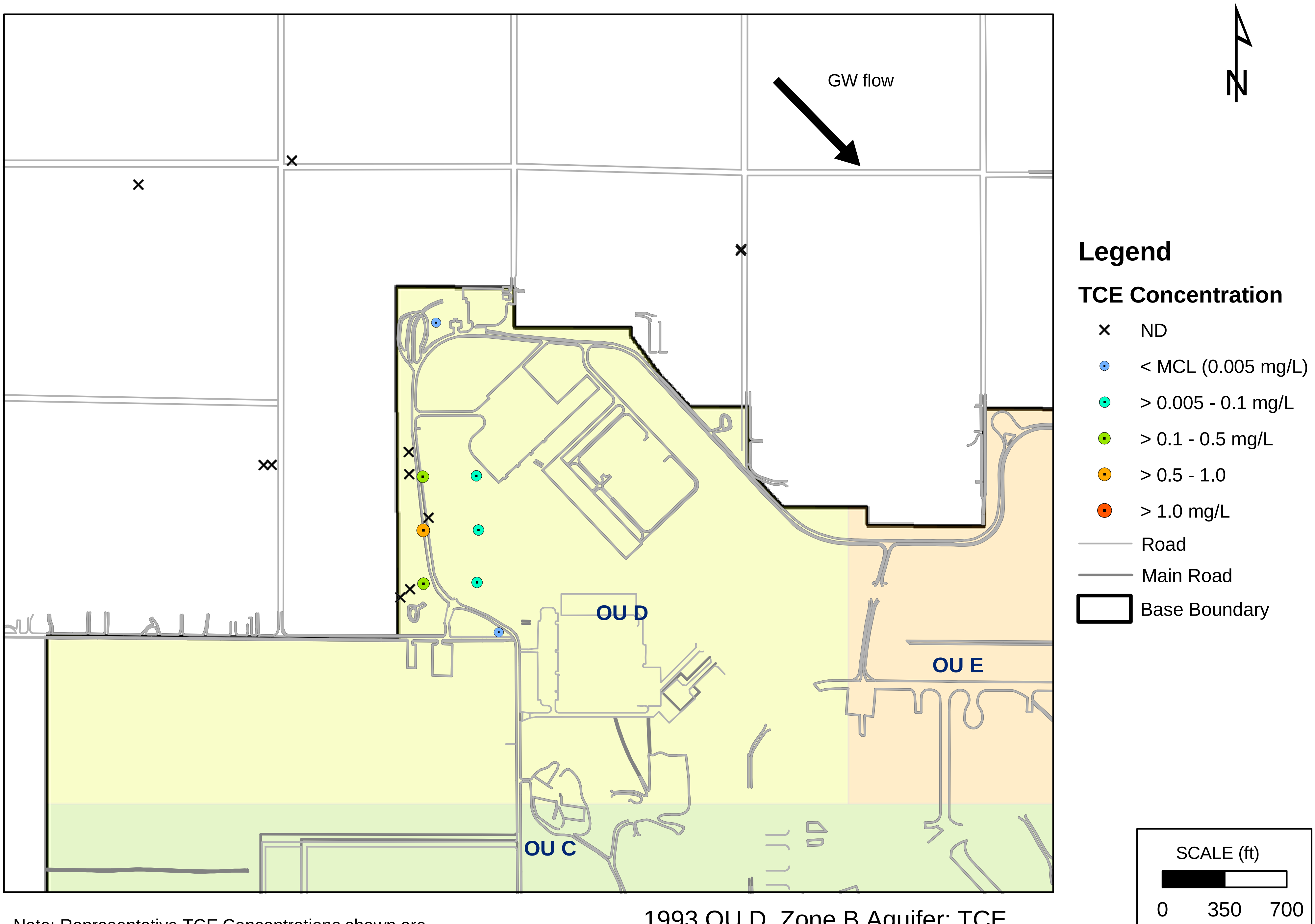
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1992 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

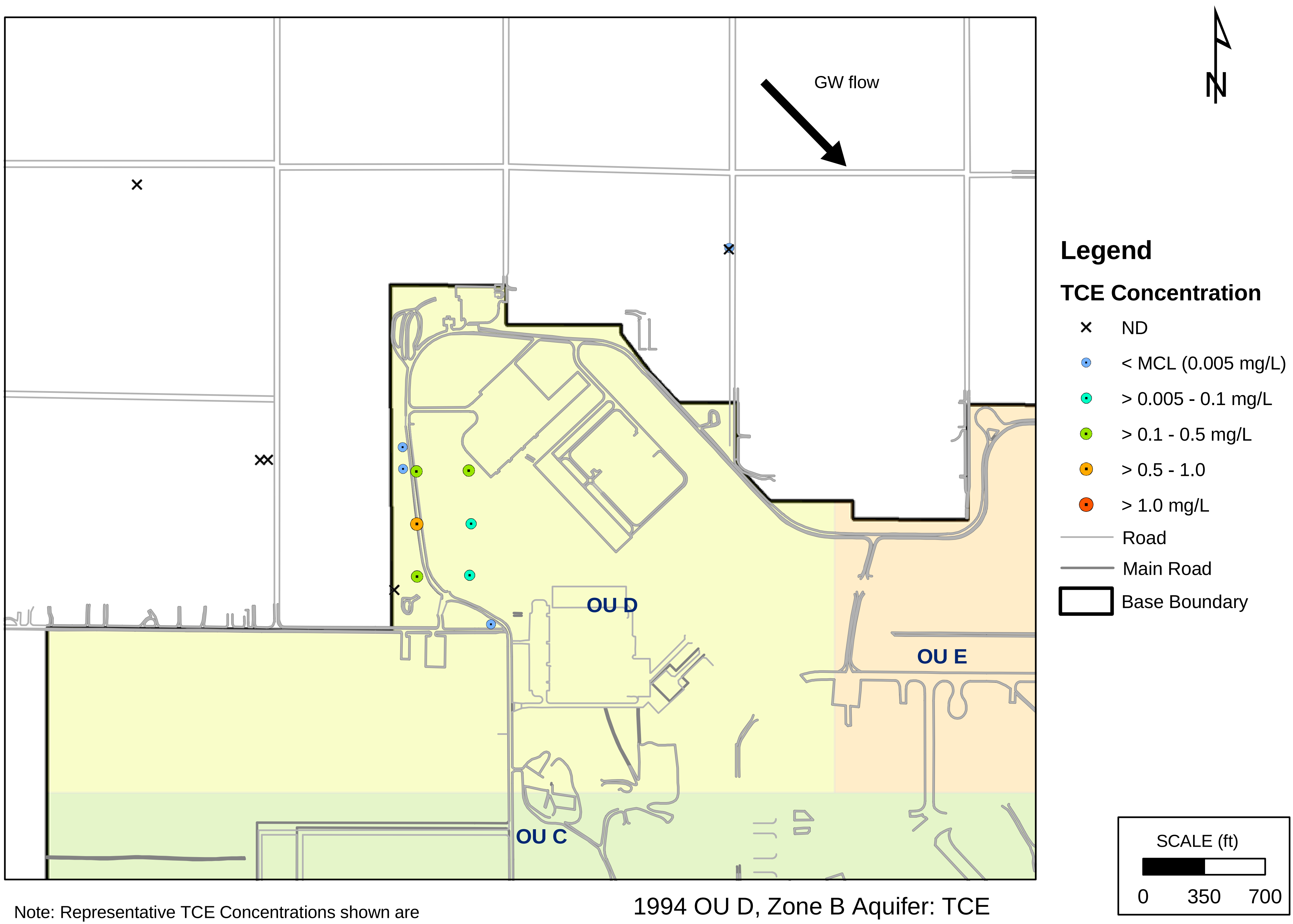
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1993 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

GSI Job No. G-2236
Date Issued: 12/05/02

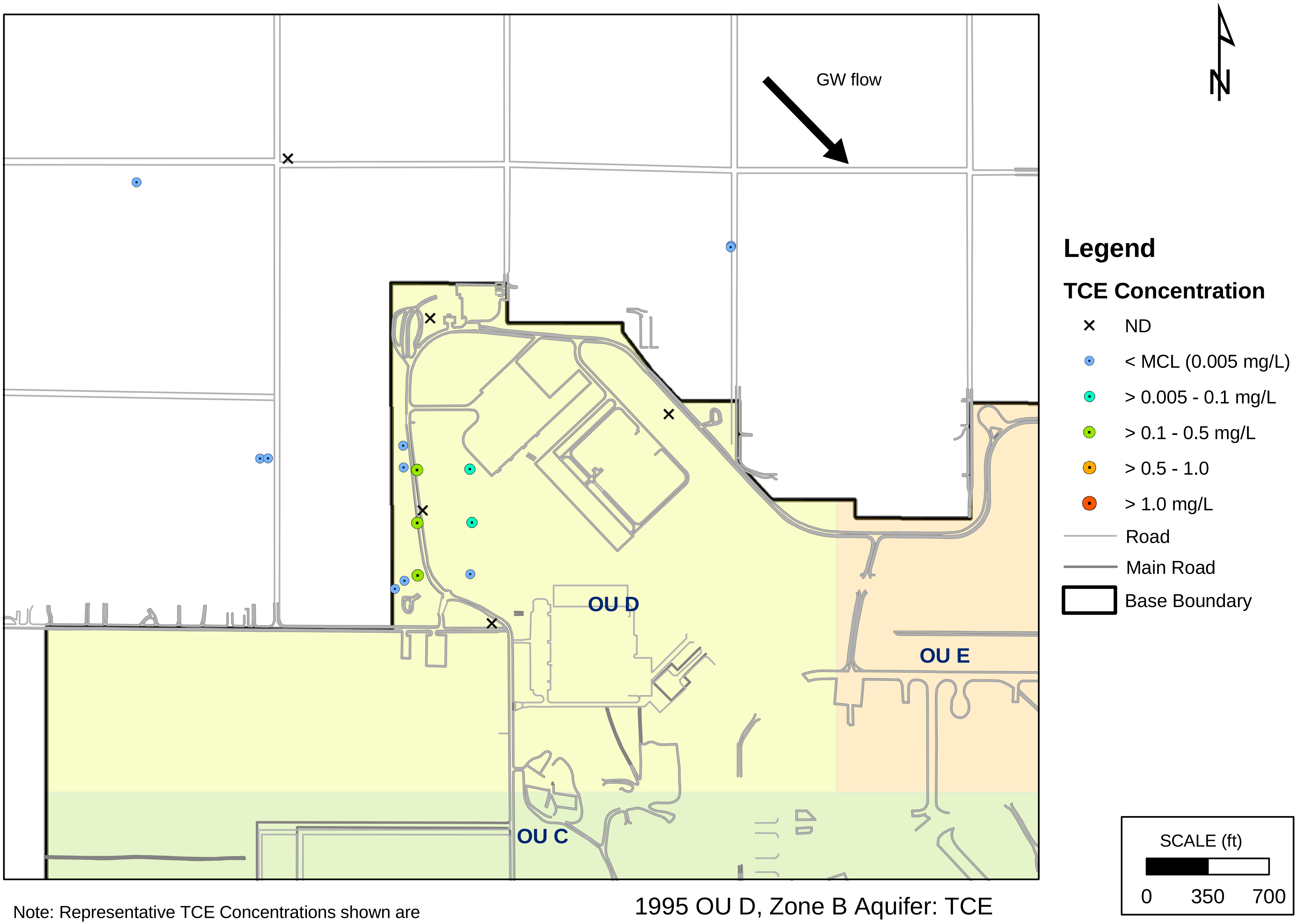


Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1994 OU D, Zone B Aquifer: TCE

McClellan Air Force Base, Sacramento, California

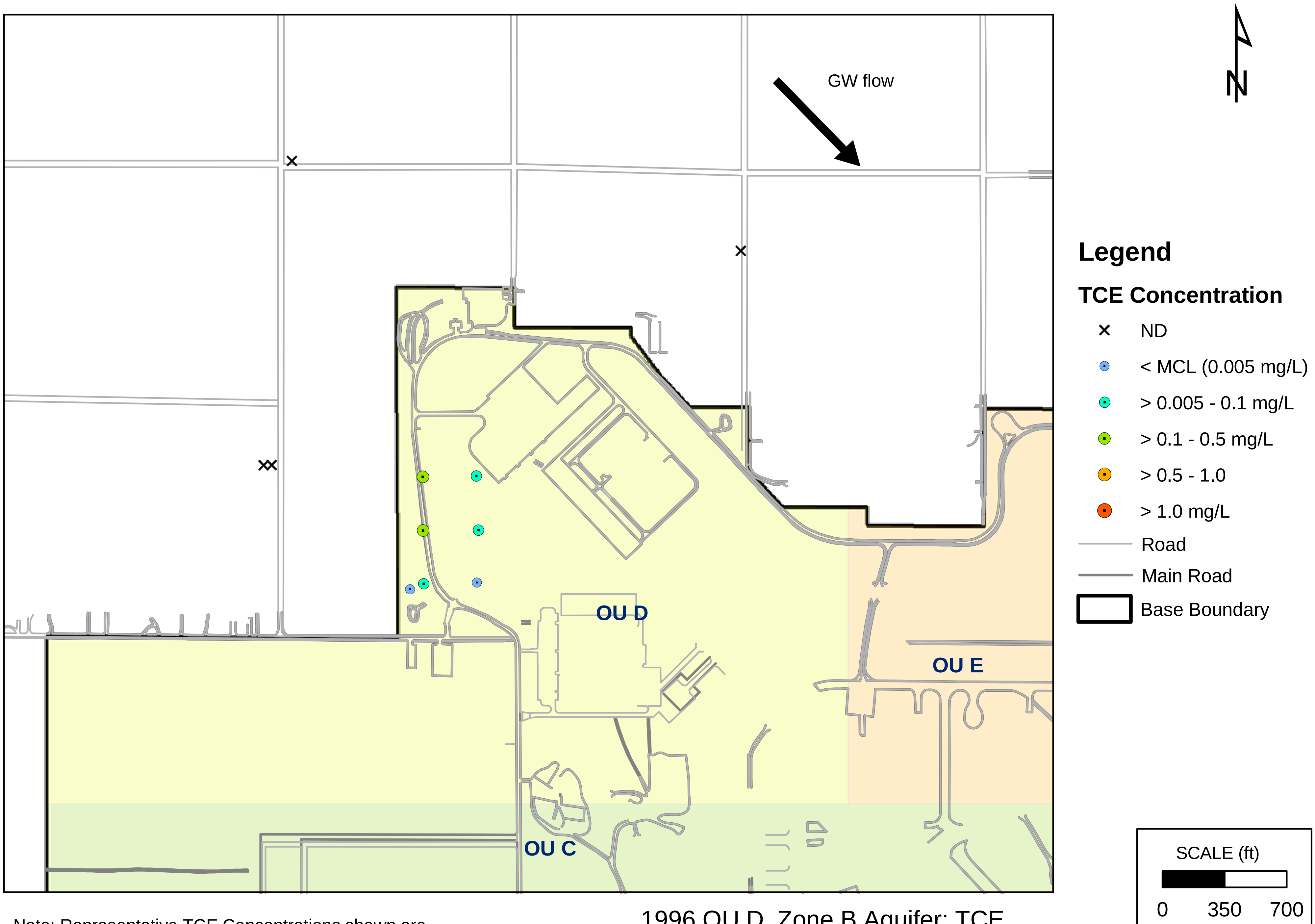
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1995 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

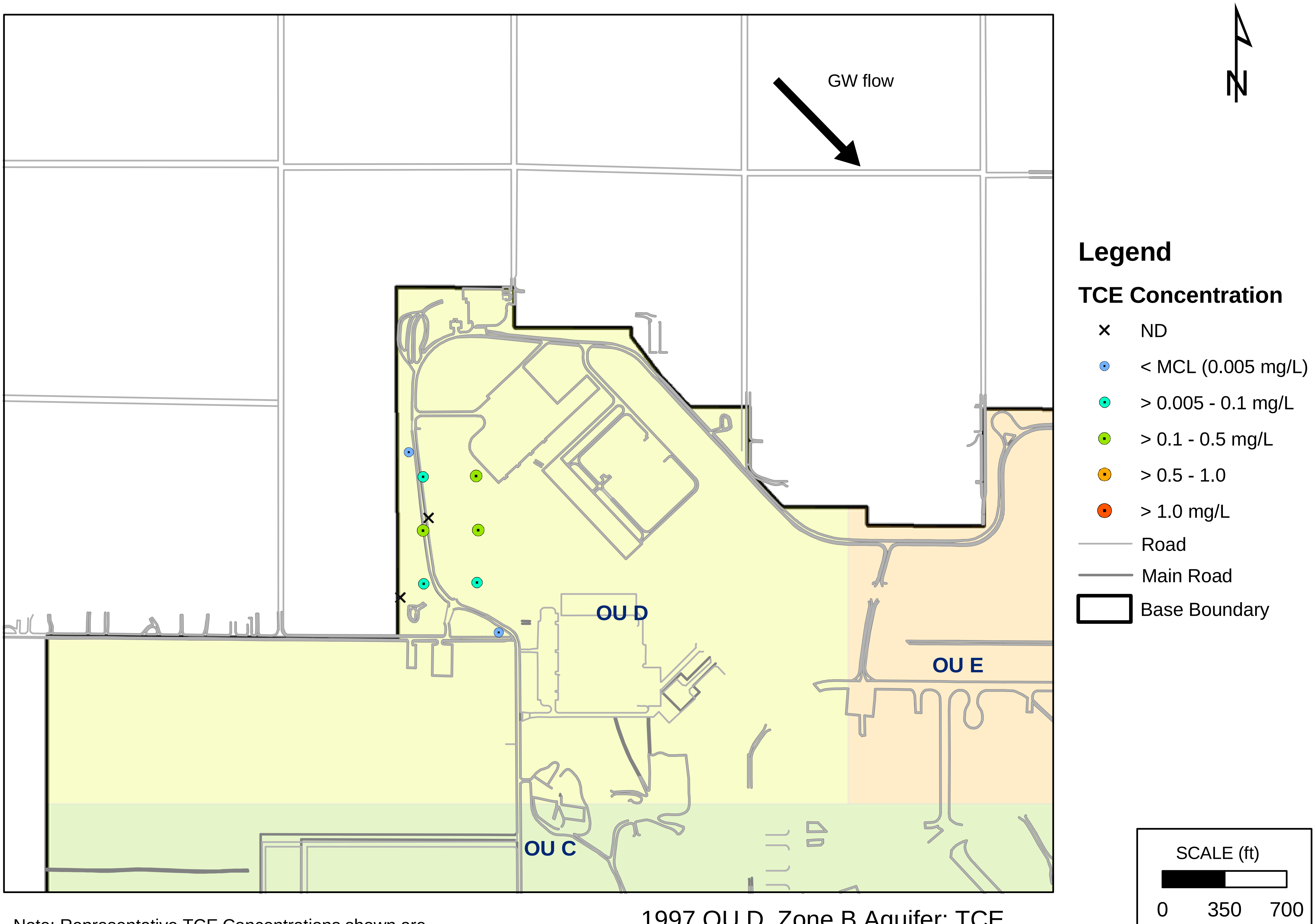
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1996 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

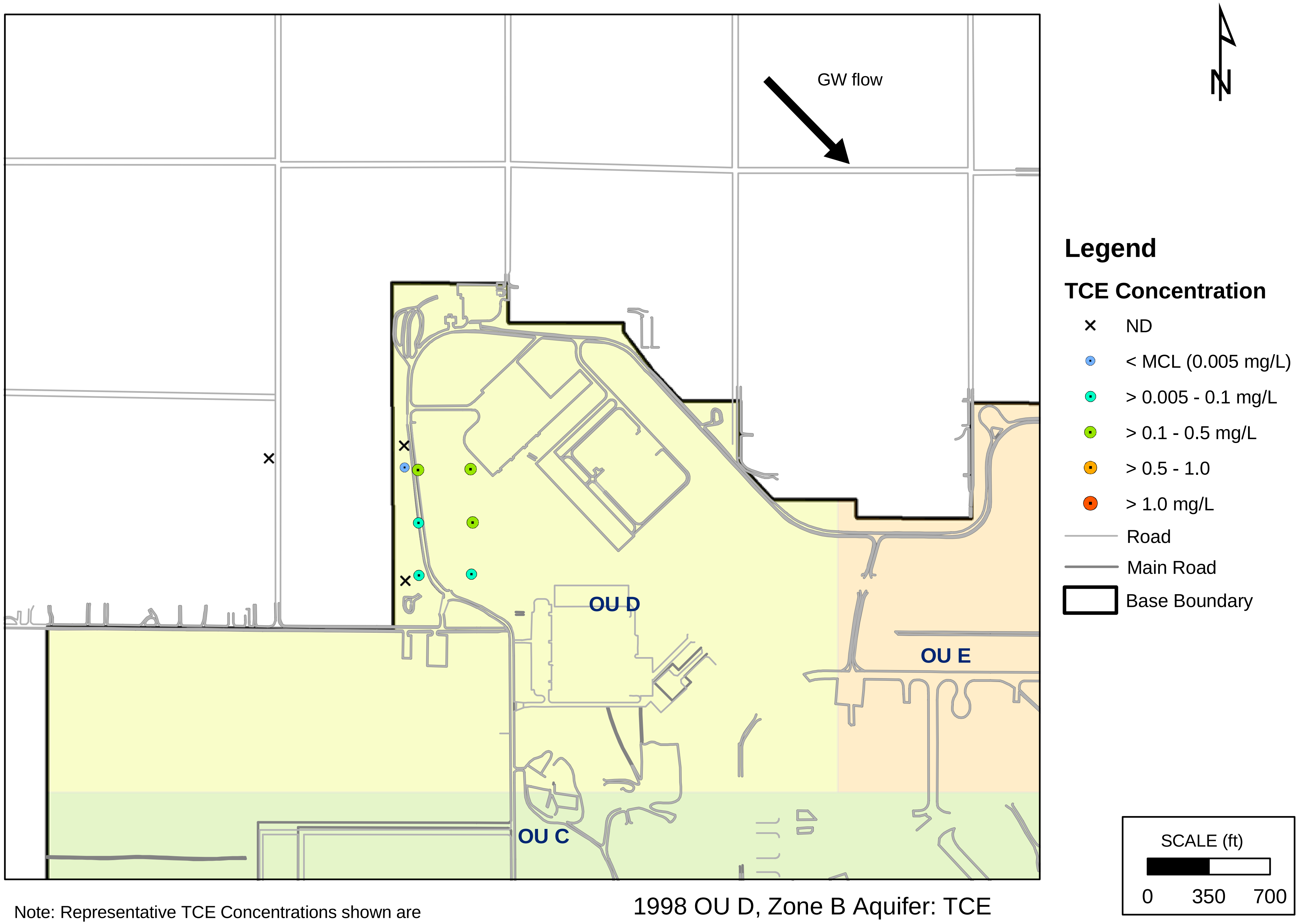
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1997 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

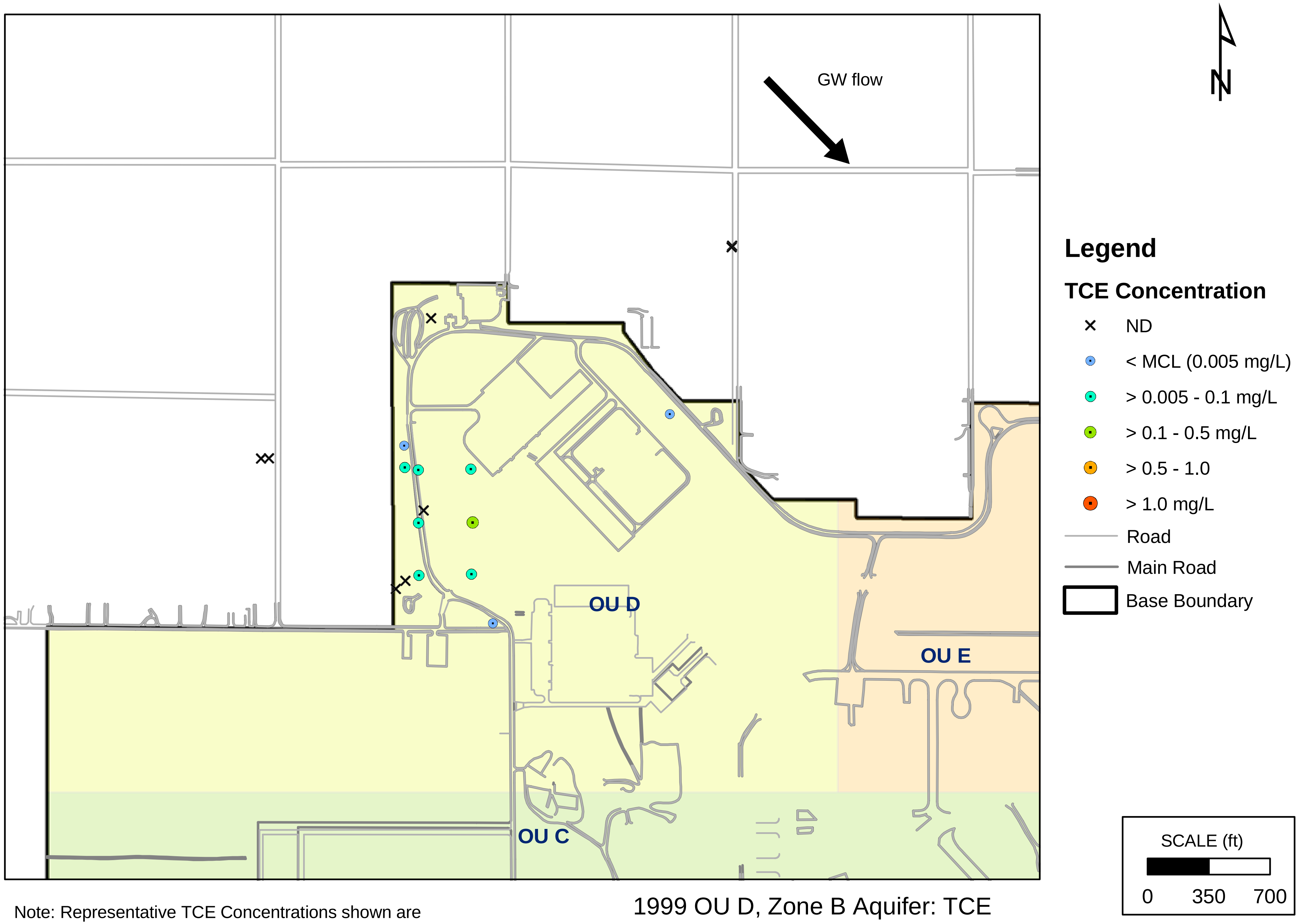
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1998 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

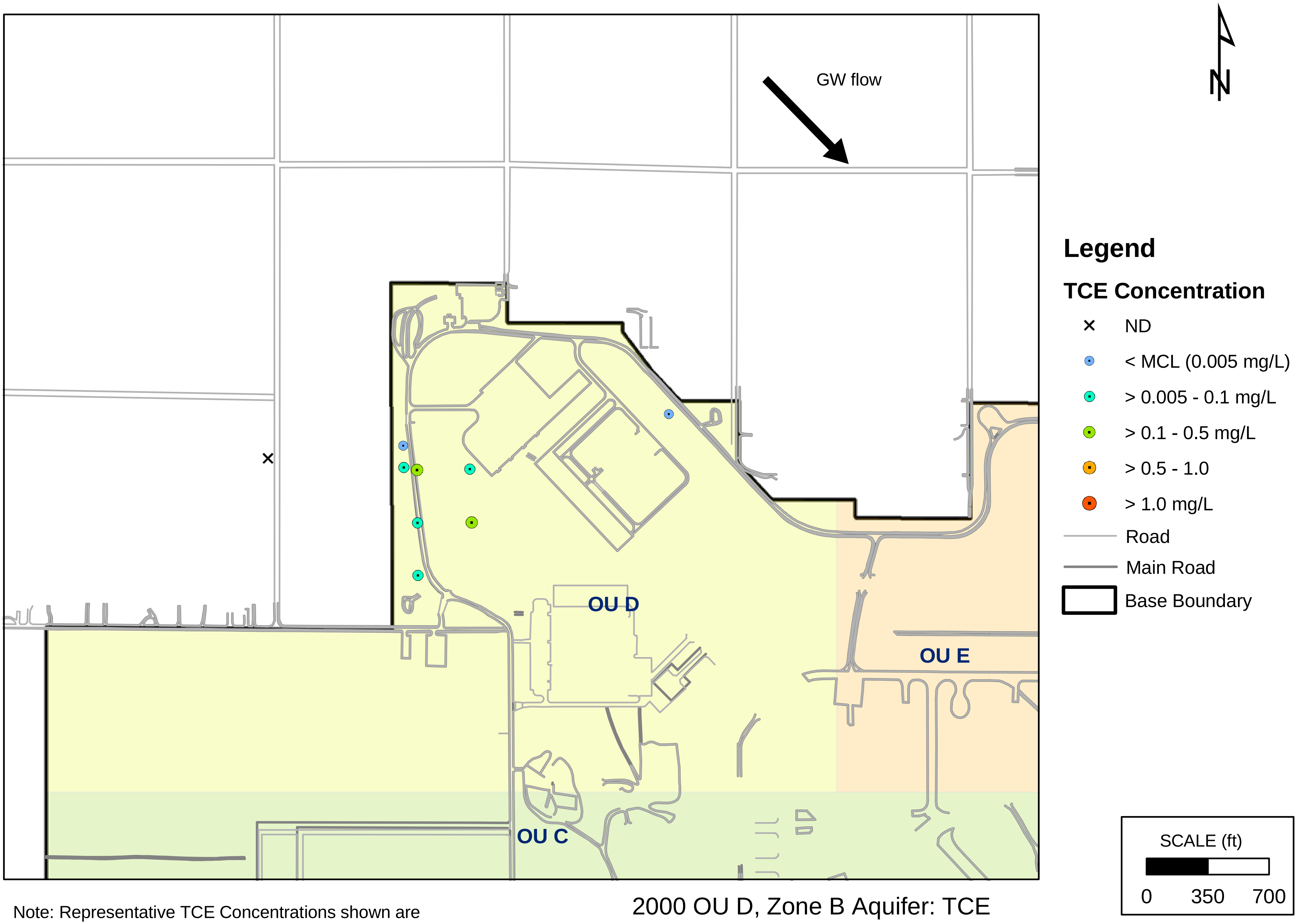
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

1999 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

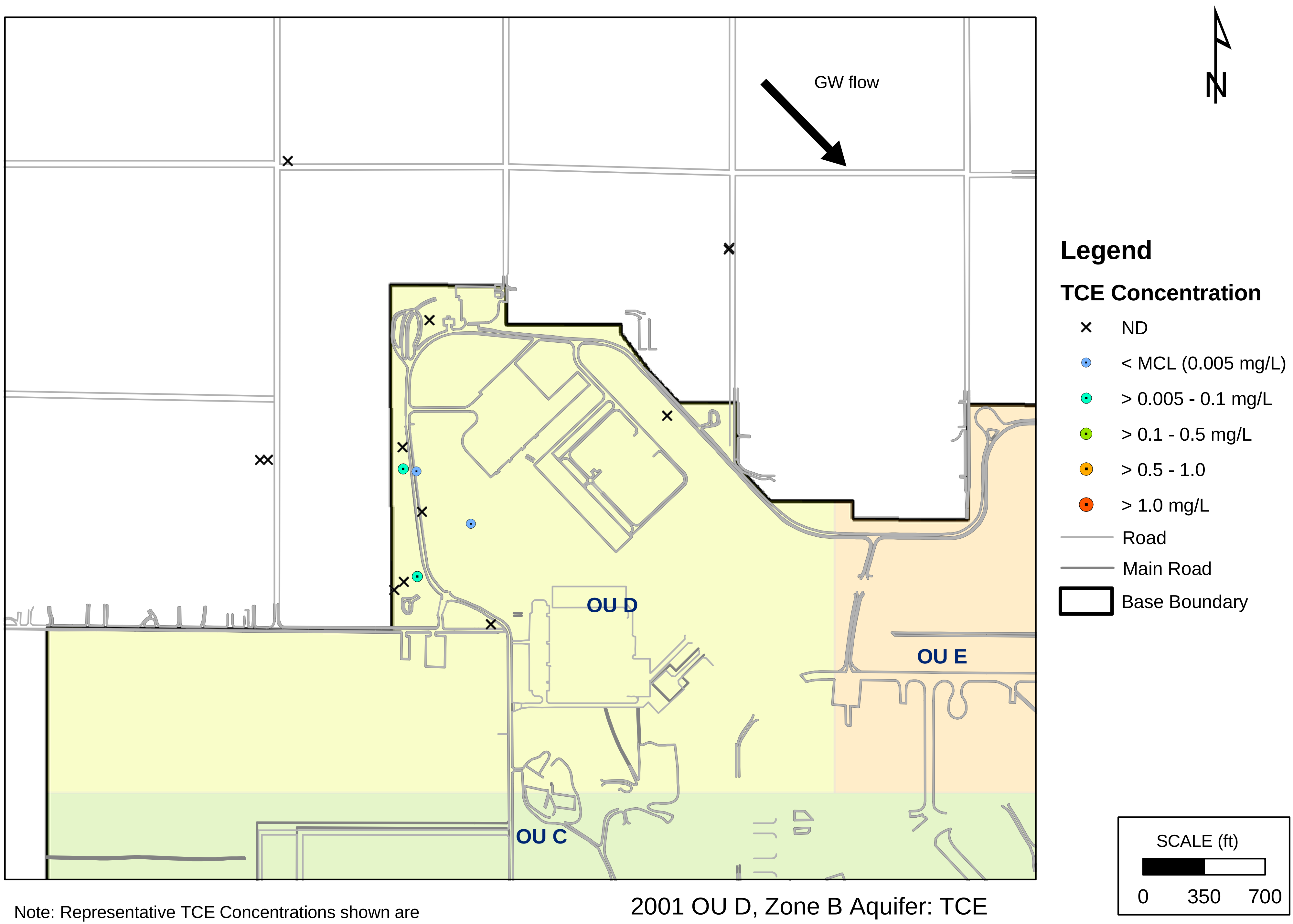
GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

2000 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

GSI Job No. G-2236
Date Issued: 12/05/02



Note: Representative TCE Concentrations shown are the Geometric Mean concentration for the year.

2001 OU D, Zone B Aquifer: TCE
McClellan Air Force Base, Sacramento, California

GROUNDWATER
SERVICES, INC.

January 15, 2003
GSI Job No. G-2236-15

MAROS 2.0 APPLICATION
ZONE A & B OU D MONITORING NETWORK OPTIMIZATION

McClellan AFB
Sacramento Valley, California

APPENDIX B: Zone A and B McClellan AFB MAROS 2.0 Reports

Linear Regression Statistics Summary
Mann-Kendall Statistics Summary
Spatial Moment Analysis Summary
Zeroth, First, and Second Moment Reports
Plume Analysis Summary
Site Results Summary
Sampling Location Optimization Results
Sampling Frequency Optimization Results
Risk-Based Power Analysis – Plume Centerline Concentrations
Risk-Based Power Analysis – Site Cleanup Status

MAROS Linear Regression Statistics Summary

Project: McClellan Zone A OU D

User Name: Julia Aziz

Location: McClellan AFB

State: California

Time Period: 5/1/1990 **to** 12/31/2000

Consolidation Period: No Time Consolidation

Consolidation Type: Median

Duplicate Consolidation: Average

ND Values: Specified Detection Limit

J Flag Values : Actual Value

Well	Source/ Tail	Average Conc (mg/L)	Median Conc (mg/L)	Standard Deviation	All Samples "ND" ?	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
TRICHLOROETHYLENE (TCE)									
MW-12	S	5.8E-01	5.8E-01	3.5E-01	No	-6.9E-04	0.60	100.0%	D
EW-73	S	2.6E-01	1.7E-01	2.4E-01	No	-7.2E-04	0.92	100.0%	D
MW-72	S	1.3E-01	6.7E-02	1.2E-01	No	-7.8E-04	0.92	100.0%	D
MW-38D	S	1.5E-01	1.5E-01	6.4E-02	No	-3.7E-04	0.42	98.9%	D
MW-351	S	5.2E-03	2.6E-03	4.9E-03	No	4.9E-04	0.94	82.3%	NT
MW-242	S	2.2E-02	1.4E-02	2.1E-02	No	-8.8E-04	0.92	100.0%	D
MW-241	S	4.1E-02	2.1E-02	5.7E-02	No	-1.1E-03	1.41	99.8%	D
MW-14	S	1.4E+00	1.0E+00	1.5E+00	No	-2.5E-03	1.12	100.0%	D
MW-11	S	9.5E-01	4.4E-01	1.5E+00	No	-1.4E-03	1.53	100.0%	D
MW-10	S	3.4E-01	3.3E-01	2.8E-01	No	-7.5E-04	0.83	100.0%	D
EW-87	S	1.2E-01	8.4E-02	8.2E-02	No	4.6E-04	0.68	99.9%	I
EW-86	S	1.2E-02	7.7E-03	1.5E-02	No	-7.6E-04	1.23	99.6%	D
EW-85	S	1.9E-01	1.2E-01	1.5E-01	No	-6.6E-04	0.79	99.9%	D
EW-84	S	4.0E-01	2.5E-01	3.3E-01	No	-1.1E-03	0.83	100.0%	D
EW-83	S	1.0E-01	9.6E-02	3.1E-02	No	2.3E-05	0.30	60.7%	NT
MW-15	S	2.4E-01	8.3E-02	3.9E-01	No	-6.5E-04	1.64	99.3%	D
MW-1042	T	1.1E-04	1.0E-04	2.5E-05	No	-4.0E-05	0.23	63.0%	S
MW-1041	T	1.0E-04	1.0E-04	8.7E-06	No	2.9E-05	0.08	72.6%	NT
MW-1004	T	2.0E-04	1.3E-04	1.4E-04	No	-3.0E-04	0.69	94.4%	PD
MW-52	T	1.8E-04	1.0E-04	2.8E-04	No	-4.0E-04	1.52	91.6%	PD
MW-91	T	2.3E-03	1.5E-03	2.8E-03	No	-8.9E-04	1.19	98.6%	D
MW-90	T	3.1E-03	2.4E-04	4.2E-03	No	5.5E-04	1.37	75.7%	NT
MW-89	T	1.7E-04	1.0E-04	2.0E-04	No	3.4E-05	1.14	56.1%	NT
MW-88	T	8.6E-03	1.0E-04	2.8E-02	No	4.9E-04	3.28	77.4%	NT
MW-76	T	1.4E-03	1.0E-04	2.1E-03	No	1.1E-03	1.53	100.0%	I
MW-74	T	2.5E-03	2.8E-03	6.7E-04	No	-1.7E-04	0.26	97.0%	D
MW-70	T	1.0E-04	1.0E-04	0.0E+00	Yes	0.0E+00	0.00	100.0%	S
MW-1026	T	2.7E-03	3.4E-04	3.3E-03	No	2.4E-04	1.26	60.2%	NT
MW-53	T	1.2E-03	4.8E-04	1.8E-03	No	7.4E-04	1.45	99.2%	I
MW-92	T	1.0E-03	6.3E-04	1.4E-03	No	-3.3E-04	1.39	80.5%	NT
MW-458	T	2.0E-04	1.9E-04	8.3E-05	No	1.2E-03	0.42	64.9%	NT
MW-412	T	4.2E-04	2.7E-04	3.7E-04	No	-2.7E-03	0.88	85.0%	S
MW-350	T	2.7E-03	7.1E-04	5.0E-03	No	-2.3E-03	1.88	97.4%	D
MW-240	T	5.9E-04	1.0E-04	1.2E-03	No	-6.9E-05	2.07	53.8%	NT
MW-237	T	4.2E-04	1.0E-04	5.7E-04	No	4.7E-04	1.36	72.2%	NT
MW-1073	T	1.3E-03	4.9E-04	1.8E-03	No	-8.2E-04	1.35	78.6%	NT
MW-1064	T	3.7E-03	3.8E-04	7.1E-03	No	1.2E-03	1.92	91.8%	PI
MW-55	T	1.5E-03	1.7E-03	9.9E-04	No	-1.4E-04	0.65	72.5%	S

Project: McClellan Zone A OU D **User Name:** Julia Aziz

Location: McClellan AFB **State:** California

Well	Source/ Tail	Average Conc (mg/L)	Median Conc (mg/L)	Standard Deviation	All Samples "ND" ?	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
TRICHLOROETHYLENE (TCE)									

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); COV = Coefficient of Variation

MAROS Mann-Kendall Statistics Summary

Project: McClellan Zone A OU D

User Name: Julia Aziz

Location: McClellan AFB

State: California

Time Period: 5/1/1990 **to** 12/31/2000

Consolidation Period: No Time Consolidation

Consolidation Type: Median

Duplicate Consolidation: Average

ND Values: Specified Detection Limit

J Flag Values : Actual Value

Well	Source/ Tail	Number of Samples	Number of Detects	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	All Samples "ND" ?	Concentration Trend
TRICHLOROETHYLENE (TCE)								
MW-72	S	10	10	0.92	-37	100.0%	No	D
MW-351	S	9	9	0.94	7	72.8%	No	NT
MW-38D	S	8	8	0.42	-18	98.4%	No	D
MW-242	S	12	12	0.92	-46	100.0%	No	D
MW-15	S	11	11	1.64	-23	95.7%	No	D
MW-12	S	12	12	0.60	-52	100.0%	No	D
MW-241	S	12	12	1.41	-42	99.8%	No	D
MW-11	S	11	11	1.53	-49	100.0%	No	D
EW-73	S	15	15	0.92	-83	100.0%	No	D
MW-10	S	11	11	0.83	-53	100.0%	No	D
EW-87	S	15	15	0.68	60	99.9%	No	I
EW-86	S	15	15	1.23	-53	99.6%	No	D
EW-85	S	16	16	0.79	-84	100.0%	No	D
EW-84	S	16	16	0.83	-105	100.0%	No	D
EW-83	S	16	16	0.30	22	82.5%	No	NT
MW-14	S	12	12	1.12	-58	100.0%	No	D
MW-1041	T	7	1	0.08	4	66.7%	No	NT
MW-1073	T	6	5	1.35	-3	64.0%	No	NT
MW-1042	T	7	1	0.23	-2	55.7%	No	S
MW-1026	T	7	5	1.26	-4	66.7%	No	NT
MW-1004	T	12	6	0.69	-23	93.3%	No	PD
MW-1064	T	8	4	1.92	6	72.6%	No	NT
MW-55	T	11	11	0.65	-11	77.7%	No	S
MW-91	T	10	9	1.19	-31	99.8%	No	D
MW-90	T	8	6	1.37	7	76.4%	No	NT
MW-89	T	10	2	1.14	3	56.9%	No	NT
MW-88	T	11	4	3.28	-4	59.0%	No	NT
MW-76	T	10	4	1.53	20	95.5%	No	I
MW-237	T	7	5	1.36	2	55.7%	No	NT
MW-70	T	6	0	0.00	0	42.3%	Yes	S
MW-240	T	9	5	2.07	0	46.0%	No	NT
MW-53	T	10	9	1.45	23	97.7%	No	I
MW-52	T	9	3	1.52	-13	89.0%	No	NT
MW-458	T	4	3	0.42	0	37.5%	No	S
MW-412	T	6	4	0.88	-4	70.3%	No	S
MW-350	T	8	5	1.88	-15	95.8%	No	D
MW-92	T	12	9	1.39	-18	87.5%	No	NT
MW-74	T	10	10	0.26	-28	99.4%	No	D

Project: McClellan Zone A OU D **User Name:** Julia Aziz

Location: McClellan AFB **State:** California

Well	Source/ Tail	Number of Samples	Number of Detects	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	All Samples "ND" ?	Concentration Trend
TRICHLOROETHYLENE (TCE)								

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)- Due to insufficient Data (< 4 sampling events); Source/Tail (S/T)

The Number of Samples and Number of Detects shown above are post-consolidation values.

MAROS Statistical Trend Analysis Summary

Project: McClellan Zone A OU D

User Name: Julia Aziz

Location: McClellan AFB

State: California

Time Period: 5/1/1990 **to** 12/31/2000

Consolidation Period: No Time Consolidation

Consolidation Type: Median

Duplicate Consolidation: Average

ND Values: Specified Detection Limit

J Flag Values : Actual Value

Well	Source/ Tail	Number of Samples	Number of Detects	Average Conc. (mg/L)	Median Conc. (mg/L)	All Samples "ND" ?	Mann-Kendall Trend	Linear Regression Trend
TRICHLOROETHYLENE (TCE)								
EW-73	S	15	15	2.6E-01	1.7E-01	No	D	D
EW-83	S	16	16	1.0E-01	9.6E-02	No	NT	NT
EW-84	S	16	16	4.0E-01	2.5E-01	No	D	D
EW-85	S	16	16	1.9E-01	1.2E-01	No	D	D
EW-86	S	15	15	1.2E-02	7.7E-03	No	D	D
EW-87	S	15	15	1.2E-01	8.4E-02	No	I	I
MW-10	S	11	11	3.4E-01	3.3E-01	No	D	D
MW-1004	T	12	6	2.0E-04	1.3E-04	No	PD	PD
MW-1026	T	7	5	2.7E-03	3.4E-04	No	NT	NT
MW-1041	T	7	1	1.0E-04	1.0E-04	No	NT	NT
MW-1042	T	7	1	1.1E-04	1.0E-04	No	S	S
MW-1064	T	8	4	3.7E-03	3.8E-04	No	NT	PI
MW-1073	T	6	5	1.3E-03	4.9E-04	No	NT	NT
MW-11	S	11	11	9.5E-01	4.4E-01	No	D	D
MW-12	S	12	12	5.8E-01	5.8E-01	No	D	D
MW-14	S	12	12	1.4E+00	1.0E+00	No	D	D
MW-15	S	11	11	2.4E-01	8.3E-02	No	D	D
MW-237	T	7	5	4.2E-04	1.0E-04	No	NT	NT
MW-240	T	9	5	5.9E-04	1.0E-04	No	NT	NT
MW-241	S	12	12	4.1E-02	2.1E-02	No	D	D
MW-242	S	12	12	2.2E-02	1.4E-02	No	D	D
MW-350	T	8	5	2.7E-03	7.1E-04	No	D	D
MW-351	S	9	9	5.2E-03	2.6E-03	No	NT	NT
MW-38D	S	8	8	1.5E-01	1.5E-01	No	D	D
MW-412	T	6	4	4.2E-04	2.7E-04	No	S	S
MW-458	T	4	3	2.0E-04	1.9E-04	No	S	NT
MW-52	T	9	3	1.8E-04	1.0E-04	No	NT	PD
MW-53	T	10	9	1.2E-03	4.8E-04	No	I	I
MW-55	T	11	11	1.5E-03	1.7E-03	No	S	S
MW-70	T	6	0	1.0E-04	1.0E-04	Yes	S	S
MW-72	S	10	10	1.3E-01	6.7E-02	No	D	D
MW-74	T	10	10	2.5E-03	2.8E-03	No	D	D
MW-76	T	10	4	1.4E-03	1.0E-04	No	I	I
MW-88	T	11	4	8.6E-03	1.0E-04	No	NT	NT
MW-89	T	10	2	1.7E-04	1.0E-04	No	NT	NT

MAROS Statistical Trend Analysis Summary

Well	Source/ Tail	Number of Samples	Number of Detects	Average Conc. (mg/L)	Median Conc. (mg/L)	All Samples "ND" ?	Mann-Kendall Trend	Linear Regression Trend
TRICHLOROETHYLENE (TCE)								
MW-90	T	8	6	3.1E-03	2.4E-04	No	NT	NT
MW-91	T	10	9	2.3E-03	1.5E-03	No	D	D
MW-92	T	12	9	1.0E-03	6.3E-04	No	NT	NT

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); No Detectable Concentration (NDC)

The Number of Samples and Number of Detects shown above are post-consolidation values.

MAROS Site Results

Project: McClellan Zone A OU D

User Name: Julia Aziz

Location: McClellan AFB

State: California

User Defined Site and Data Assumptions:

Hydrogeology and Plume Information:

Groundwater Seepage Velocity: 35 ft/yr

Current Plume Length: 1000 ft

Current Plume Width 600 ft

Number of Tail Wells: 22

Number of Source Wells: 16

Source Information:

Source Treatment: Pump and Treat

NAPL is not observed at this site.

Down-gradient Information:

Distance from Edge of Tail to Nearest:

Down-gradient receptor: 1000 ft

Down-gradient property: 10 ft

Distance from Source to Nearest:

Down-gradient receptor: 6000 ft

Down-gradient property: 10 ft

Data Consolidation Assumptions:

Time Period: 5/1/1990 **to** 12/31/2000

Consolidation Period: No Time Consolidation

Consolidation Type: Median

Duplicate Consolidation: Average

ND Values: Specified Detection Limit

J Flag Values : Actual Value

Plume Information Weighting Assumptions:

Consolidation Step 1. Weight Plume Information by Chemical

Summary Weighting: Weighting Applied to All Chemicals Equally

Consolidation Step 2. Weight Well Information by Chemical

Well Weighting: No Weighting of Wells was Applied.

Chemical Weighting: No Weighting of Chemicals was Applied.

Note: These assumptions were made when consolidating the historical montoring data and lumping the Wells and COCs.

1. Compliance Monitoring/Remediation Optimization Results:

Preliminary Monitoring System Optimization Results: Based on site classification, source treatment and Monitoring System Category the following suggestions are made for site Sampling Frequency, Duration of Sampling, and Well Density. These criteria take into consideration: Plume Stability, Type of Plume, and Groundwater Velocity.

COC	Tail Stability	Source Stability	Level of Effort	Sampling Duration	Sampling Frequency	Sampling Density
TRICHLOROETHYLENE (TCE)	S	PD	M	Remove treatment system if previously reducing concentation	No Recommendation	25

Note:

Plume Status: (I) Increasing; (PI)Probably Increasing; (S) Stable; (NT) No Trend; (PD) Probably Decreasing; (D) Decreasing

Design Categories: (E) Extensive; (M) Moderate; (L) Limited (N/A) Not Applicable, Insufficient Data Available

Level of Monitoring Effort Indicated by Analysi Moderate

2. Spatial Moment Analysis Results:

Moment Type	Consituent	Coefficient of Variation	Mann-Kendall S Statistic	Confidence in Trend	Moment Trend
Zeroth Moment: Mass					
	TRICHLOROETHYLENE (TCE)	1.44	-116	91.8%	PD
1st Moment: Distance to Source					
	TRICHLOROETHYLENE (TCE)	1.04	48	87.7%	NT
2nd Moment: Sigma XX					
	TRICHLOROETHYLENE (TCE)	1.26	-18	66.2%	NT
2nd Moment: Sigma YY					
	TRICHLOROETHYLENE (TCE)	1.72	-18	66.2%	NT

Note: The following assumptions were applied for the calculation of the Zeroth Moment:

Porosity: 0.30 **Saturated Thickness:** Uniform: 30 ft

Mann-Kendall Trend test performed on all sample events for each constituent. Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)-Due to insufficient Data (< 4 sampling events).

MAROS Zeroth Moment Analysis

Project: McClellan AFB Zone A OU D

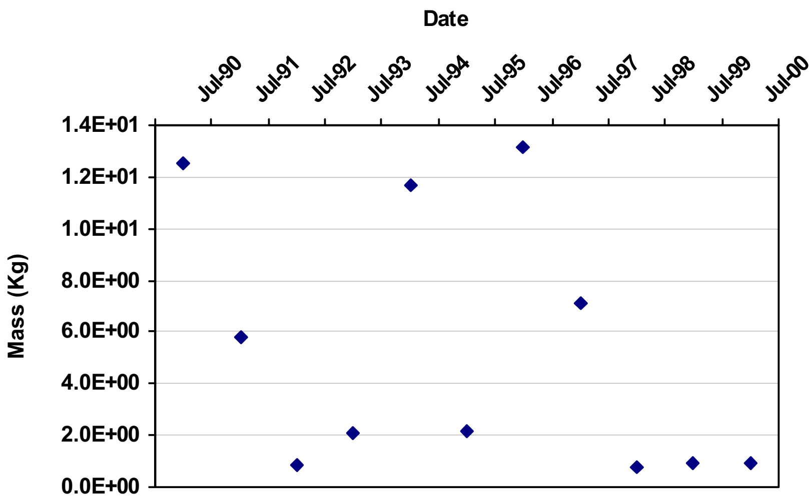
User Name: Julia Aziz

Location: McClellan AFB

State: California

COC: TRICHLOROETHYLENE (TCE)

Change in Dissolved Mass Over Time



Porosity: 0.30

Saturated Thickness:

Uniform: 30 ft

Mann Kendall S Statistic:

-15

Confidence in Trend:

85.9%

Coefficient of Variation:

0.96

Zeroth Moment Trend:

S

Data Table:

Effective Date	Constituent	Estimated Mass (Kg)	Number of Wells
7/1/1990	TRICHLOROETHYLENE (TCE)	1.3E+01	20
7/1/1991	TRICHLOROETHYLENE (TCE)	5.8E+00	21
7/1/1992	TRICHLOROETHYLENE (TCE)	8.8E-01	11
7/1/1993	TRICHLOROETHYLENE (TCE)	2.1E+00	25
7/1/1994	TRICHLOROETHYLENE (TCE)	1.2E+01	18
7/1/1995	TRICHLOROETHYLENE (TCE)	2.2E+00	28
7/1/1996	TRICHLOROETHYLENE (TCE)	1.3E+01	15
7/1/1997	TRICHLOROETHYLENE (TCE)	7.1E+00	20
7/1/1998	TRICHLOROETHYLENE (TCE)	7.9E-01	19
7/1/1999	TRICHLOROETHYLENE (TCE)	9.4E-01	29
7/1/2000	TRICHLOROETHYLENE (TCE)	9.0E-01	13

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); ND = Non-detect. Moments are not calculated for sample events with less than 6 wells.

MAROS First Moment Analysis

Project: McClellan AFB Zone A OU D

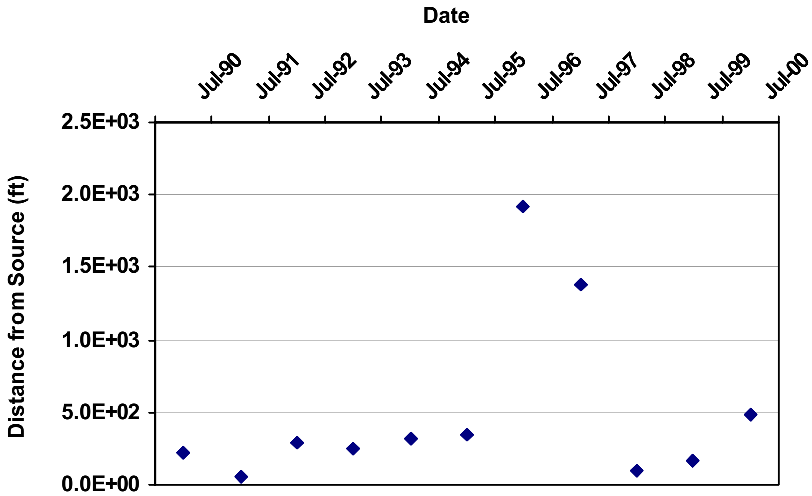
User Name: Julia Aziz

Location: McClellan AFB

State: California

COC: TRICHLOROETHYLENE (TCE)

Distance from Source to Center of Mass



Mann Kendall S Statistic: 17

Confidence in Trend: 89.1%

Coefficient of Variation: 1.18

First Moment Trend: NT

Data Table:

Effective Date	Constituent	Xc (ft)	Yc (ft)	Distance from Source (ft)	Number of Wells
7/1/1990	TRICHLOROETHYLENE (TCE)	2,166,613	366,307	220	20
7/1/1991	TRICHLOROETHYLENE (TCE)	2,166,683	366,147	56	21
7/1/1992	TRICHLOROETHYLENE (TCE)	2,166,819	366,337	287	11
7/1/1993	TRICHLOROETHYLENE (TCE)	2,166,669	366,336	242	25
7/1/1994	TRICHLOROETHYLENE (TCE)	2,166,500	366,370	322	18
7/1/1995	TRICHLOROETHYLENE (TCE)	2,166,698	366,444	351	28
7/1/1996	TRICHLOROETHYLENE (TCE)	2,168,405	366,904	1,918	15
7/1/1997	TRICHLOROETHYLENE (TCE)	2,167,678	367,043	1,387	20
7/1/1998	TRICHLOROETHYLENE (TCE)	2,166,569	366,068	100	19
7/1/1999	TRICHLOROETHYLENE (TCE)	2,166,817	366,152	162	29
7/1/2000	TRICHLOROETHYLENE (TCE)	2,167,148	366,103	482	13

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events). Moments are not calculated for sample events with less than 6 wells.

MAROS First Moment Analysis

Project: McClellan AFB Zone A OU D

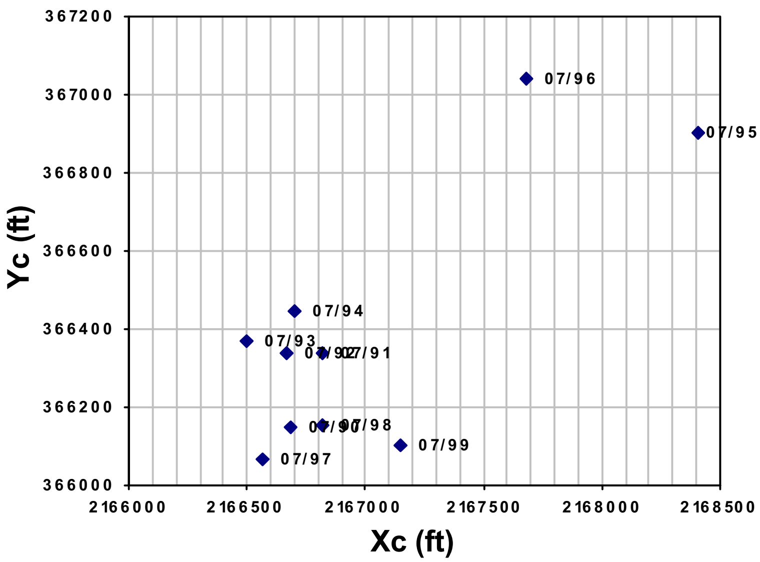
User Name: Julia Aziz

Location: McClellan AFB

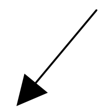
State: California

COC: TRICHLOROETHYLENE (TCE)

Change in Location of Center of Mass Over Time



Groundwater Flow Direction:



Source Coordinate:

X: 2,166,666

Y: 366,094

Effective Date	Constituent	Xc (ft)	Yc (ft)	Distance from Source (ft)	Number of Wells
7/1/1990	TRICHLOROETHYLENE (TCE)	2,166,613	366,307	220	20
7/1/1991	TRICHLOROETHYLENE (TCE)	2,166,683	366,147	56	21
7/1/1992	TRICHLOROETHYLENE (TCE)	2,166,819	366,337	287	11
7/1/1993	TRICHLOROETHYLENE (TCE)	2,166,669	366,336	242	25
7/1/1994	TRICHLOROETHYLENE (TCE)	2,166,500	366,370	322	18
7/1/1995	TRICHLOROETHYLENE (TCE)	2,166,698	366,444	351	28
7/1/1996	TRICHLOROETHYLENE (TCE)	2,168,405	366,904	1,918	15
7/1/1997	TRICHLOROETHYLENE (TCE)	2,167,678	367,043	1,387	20
7/1/1998	TRICHLOROETHYLENE (TCE)	2,166,569	366,068	100	19
7/1/1999	TRICHLOROETHYLENE (TCE)	2,166,817	366,152	162	29
7/1/2000	TRICHLOROETHYLENE (TCE)	2,167,148	366,103	482	13

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events). Moments are not calculated for sample events with less than 6 wells.

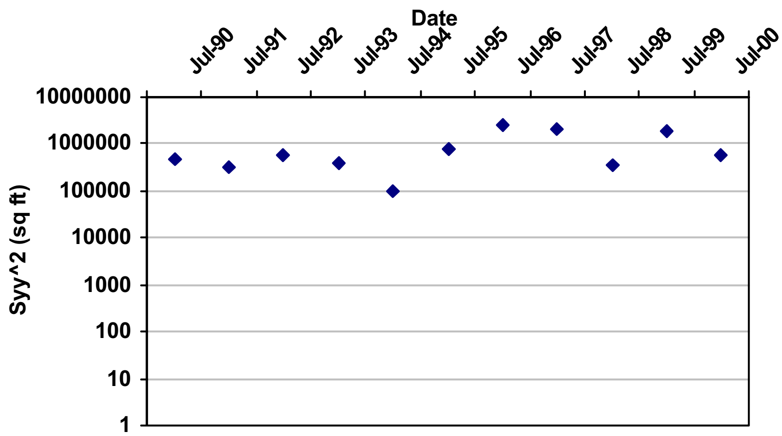
MAROS Second Moment Analysis

Project: McClellan AFB Zone A OU D **User Name:** Julia Aziz

Location: McClellan AFB **State:** California

COC: TRICHLOROETHYLENE (TCE)

Change in Plume Spread Over Time

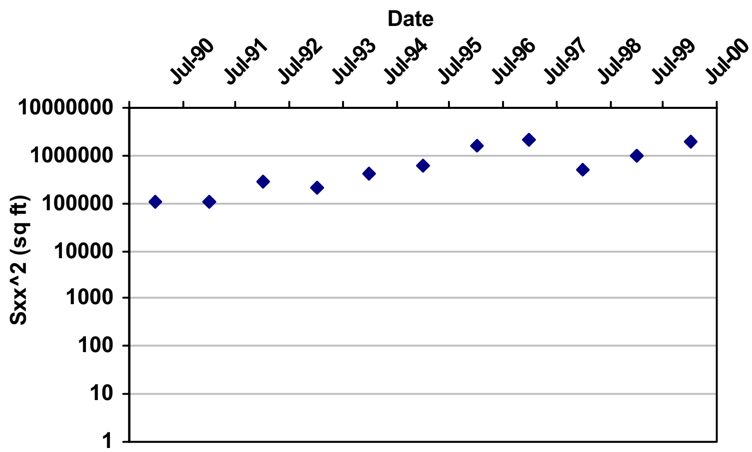


Mann Kendall S Statistic: 15

Confidence in Trend: 85.9%

Coefficient of Variation: 0.91

Second Moment Trend: NT



Mann Kendall S Statistic: 41

Confidence in Trend: 100.0%

Coefficient of Variation: 0.93

Second Moment Trend: I

Data Table:

Effective Date	Constituent	Sigma XX (sq ft)	Sigma YY (sq ft)	Number of Wells
7/1/1990	TRICHLOROETHYLENE (TCE)	103,011	478,732	20
7/1/1991	TRICHLOROETHYLENE (TCE)	107,861	321,324	21
7/1/1992	TRICHLOROETHYLENE (TCE)	282,555	565,080	11
7/1/1993	TRICHLOROETHYLENE (TCE)	209,993	382,557	25
7/1/1994	TRICHLOROETHYLENE (TCE)	432,219	101,139	18
7/1/1995	TRICHLOROETHYLENE (TCE)	617,888	803,729	28
7/1/1996	TRICHLOROETHYLENE (TCE)	1,645,598	2,578,566	15
7/1/1997	TRICHLOROETHYLENE (TCE)	2,180,836	2,062,276	20
7/1/1998	TRICHLOROETHYLENE (TCE)	509,750	338,208	19
7/1/1999	TRICHLOROETHYLENE (TCE)	983,522	1,859,400	29
7/1/2000	TRICHLOROETHYLENE (TCE)	1,997,612	596,906	13

MAROS Second Moment Analysis

Effective Date	Constituent	Sigma XX (sq ft)	Sigma YY (sq ft)	Number of Wells

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events)

The Sigma XX and Sigma YY components are estimated using the given field coordinate system and then rotated to align with the estimated groundwater flow direction. Moments are not calculated for sample events with less than 6 wells.

MAROS Spatial Moment Analysis Summary

Project: McClellan AFB Zone A OU D

Location: McClellan AFB

User Name: Julia Aziz

State: California

	0th Moment	1st Moment (Center of Mass)			2nd Moment (Spread)		
Effective Date	**Estimated Mass (Kg)**	**Xc (ft)**	**Yc (ft)**	**Source Distance (ft)**	**Sigma XX (sq ft)**	**Sigma YY (sq ft)**	**Number of Wells**
TRICHLOROETHYLENE (TCE)							
7/1/1990	1.3E+01	2,166,613	366,307	220	103,011	478,732	20
7/1/1991	5.8E+00	2,166,683	366,147	56	107,861	321,324	21
7/1/1992	8.8E-01	2,166,819	366,337	287	282,555	565,080	11
7/1/1993	2.1E+00	2,166,669	366,336	242	209,993	382,557	25
7/1/1994	1.2E+01	2,166,500	366,370	322	432,219	101,139	18
7/1/1995	2.2E+00	2,166,698	366,444	351	617,888	803,729	28
7/1/1996	1.3E+01	2,168,405	366,904	1,918	1,645,598	2,578,566	15
7/1/1997	7.1E+00	2,167,678	367,043	1,387	2,180,836	2,062,276	20
7/1/1998	7.9E-01	2,166,569	366,068	100	509,750	338,208	19
7/1/1999	9.4E-01	2,166,817	366,152	162	983,522	1,859,400	29
7/1/2000	9.0E-01	2,167,148	366,103	482	1,997,612	596,906	13

Project: McClellan AFB Zone A OU D

Location: McClellan AFB

User Name: Julia Aziz

State: California

Moment Type	Consituent	Coefficient of Variation	Mann-Kendall S Statistic	Confidence in Trend	Moment Trend
Zeroth Moment: Mass					
	TRICHLOROETHYLENE (TCE)	0.96	-15	85.9%	S
1st Moment: Distance to Source					
	TRICHLOROETHYLENE (TCE)	1.18	17	89.1%	NT
2nd Moment: Sigma XX					
	TRICHLOROETHYLENE (TCE)	0.93	41	100.0%	I
2nd Moment: Sigma YY					
	TRICHLOROETHYLENE (TCE)	0.91	15	85.9%	NT

Note: The following assumptions were applied for the calculation of the Zeroth Moment:

Porosity: 0.30 **Saturated Thickness:** Uniform: 30 ft

Mann-Kendall Trend test performed on all sample events for each constituent. Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)-Due to insufficient Data (< 4 sampling events).

Note: The Sigma XX and Sigma YY components are estimated using the given field coordinate system and then rotated to align with the estimated groundwater flow direction. Moments are not calculated for sample events with less than 6 wells.

MAROS Sampling Location Optimization Results

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

Sampling Events Analyzed: **From** 1995 7/1/1995 **to** 2000 7/1/2000

Parameters used:

Constituent	Inside SF	Hull SF	Area Ratio	Conc. Ratio
TRICHLOROETHYLENE (TCE)	0.2	0.01	0.95	0.95

Well	X (feet)	Y (feet)	Removable?	Average Slope Factor*	Minimum Slope Factor*	Maximum Slope Factor*	Eliminated?
TRICHLOROETHYLENE (TCE)							
MW-10	2166666.50	366103.81	☑	0.208	0.156	0.232	☐
MW-1004	2165862.25	366561.97	☑	0.677	0.529	0.892	☐
MW-1026	2168527.25	367760.69	☑	0.506	0.474	0.538	☐
MW-1042	2165134.00	368116.88	☑	0.533	0.398	0.606	☐
MW-1064	2166045.50	368281.13	☑	0.431	0.258	0.555	☐
MW-1073	2165967.75	367415.38	☑	0.373	0.096	0.908	☐
MW-11	2166621.50	366694.28	☑	0.299	0.080	0.542	☐
MW-12	2167022.25	366593.50	☑	0.601	0.387	0.778	☐
MW-14	2166783.25	365890.03	☑	0.135	0.018	0.404	☑
MW-15	2166639.25	365844.72	☑	0.254	0.190	0.323	☐
MW-237	2164664.25	365534.06	☑	0.357	0.261	0.499	☐
MW-240	2165901.00	365548.66	☑	0.591	0.217	0.703	☐
MW-241	2166666.00	366093.94	☑	0.169	0.081	0.241	☑
MW-242	2166642.50	365855.91	☑	0.203	0.081	0.292	☐
MW-350	2169199.50	365231.88	☑	0.392	0.209	0.661	☐
MW-351	2167722.25	364740.31	☑	0.416	0.068	0.675	☐
MW-38D	2166617.50	366507.66	☑	0.294	0.162	0.374	☐
MW-412	2167940.50	364881.28	☑	0.477	0.104	0.721	☐
MW-458	2167267.75	365669.84	☑	0.300	0.187	0.553	☐
MW-52	2166983.75	366826.34	☑	0.663	0.538	0.779	☐
MW-53	2166865.50	366619.34	☑	0.374	0.172	0.458	☐
MW-55	2166860.25	366290.91	☑	0.430	0.212	0.649	☐
MW-70	2166867.50	366745.16	☑	0.664	0.534	0.896	☐
MW-72	2166654.25	366123.69	☑	0.032	0.000	0.070	☑
MW-74	2166534.25	366146.22	☑	0.264	0.262	0.266	☐
MW-76	2166529.50	366444.34	☑	0.235	0.136	0.336	☐
MW-88	2167425.50	366186.38	☑	0.457	0.291	0.549	☐
MW-89	2167204.00	366317.66	☑	0.651	0.481	0.898	☐

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

Well	X (feet)	Y (feet)	Removable?	Average Slope Factor*	Minimum Slope Factor*	Maximum Slope Factor*	Eliminated?
MW-90	2167220.00	365966.75	☑	0.249	0.021	0.347	☐
MW-91	2166909.75	365608.53	☑	0.331	0.095	0.736	☐
MW-92	2166911.50	365476.94	☑	0.364	0.139	0.505	☐

Note: The Slope Factor indicates the relative importance of a well in the monitoring network at a given sampling event; the larger the SF value of a well, the more important the well is and vice versa; the Average Slope Factor measures the overall well importance in the selected time period; the state coordinates system (i.e., X and Y refer to Easting and Northing respectively) or local coordinates systems may be used; wells that are NOT selected for analysis are not shown above.
* When the report is generated after running the Excel module, SF values will NOT be shown above.

MAROS Sampling Frequency Optimization Results

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

The Overall Number of Sampling Events: 42

"Recent Period" defined by events: **From** 1994 1st Quarter **To** 2000 3rd Quarter

1/15/1994 8/15/2000

"Rate of Change" parameters used:

Constituent	Cleanup Goal	Low Rate	Medium Rate	High Rate
TRICHLOROETHYLENE (TCE)	0.005	0.0025	0.005	0.01

Units: Cleanup Goal is in mg/L; all rate parameters are in mg/L/year.

Well	Recommended Sampling Frequency	Frequency Based on Recent Data	Frequency Based on Overall Data
TRICHLOROETHYLENE (TCE)			
EW-73	Annual	Annual	Annual
EW-83	Annual	Annual	Annual
EW-84	Annual	Annual	Annual
EW-85	Annual	Annual	Annual
EW-86	Annual	Annual	Annual
EW-87	Quarterly	Quarterly	Quarterly
MW-10	Annual	Annual	Annual
MW-1004	Annual	Annual	Annual
MW-1026	SemiAnnual	SemiAnnual	SemiAnnual
MW-1041	Biennial	Annual	Annual
MW-1042	Biennial	Annual	Annual
MW-1064	Quarterly	Quarterly	Quarterly
MW-1073	Annual	Annual	Annual
MW-11	Annual	Annual	Annual
MW-12	Annual	Annual	Annual
MW-14	Annual	Annual	Annual
MW-15	SemiAnnual	SemiAnnual	Annual
MW-237	Biennial	Annual	Annual
MW-240	Annual	Annual	Annual
MW-241	Annual	Annual	Annual
MW-242	Annual	Annual	Annual
MW-350	Annual	Annual	Annual
MW-351	Annual	Annual	Annual
MW-38D	Annual	Annual	Annual

Project: McClellan OUD ZoneB **User Name:** Meng

Location: McClellan AFB **State:** California

Well	Recommended Sampling Frequency	Frequency Based on Recent Data	Frequency Based on Overall Data
MW-412	Biennial	Annual	Annual
MW-458	Biennial	Annual	Annual
MW-52	Biennial	Annual	Annual
MW-53	Annual	Annual	Annual
MW-55	Biennial	Annual	Annual
MW-70	Biennial	Annual	Annual
MW-72	Annual	Annual	Annual
MW-74	SemiAnnual	SemiAnnual	SemiAnnual
MW-76	Quarterly	Quarterly	Quarterly
MW-88	Annual	Annual	Annual
MW-89	Biennial	Annual	Annual
MW-90	Annual	Annual	Annual
MW-91	Biennial	Annual	Annual
MW-92	Annual	Annual	Annual

Note: Sampling frequency is determined considering both recent and overall concentration trends. Sampling Frequency is the final recommendation; Frequency Based on Recent Data is the frequency determined using recent (short) period of monitoring data; Frequency Based on Overall Data is the frequency determined using overall (long) period of monitoring data. If the "recent period" is defined using a different series of sampling events, the results could be different.

MAROS Risk-Based Power Analysis for Site Cleanup

Project: McClellan OUD ZoneA

User Name: Meng

Location: McClellan AFB

State: California

Parameters:

Groundwater Flow Direction: 280 degrees **Distance to Receptor:** 1000 feet

From Period: 1995 **to** 2000

7/1/1995 7/1/2000

Selected Plume Centerline Wells:

Well	Distance to Receptor (feet)
MW-92	1866.2
MW-91	1996.1
MW-72	2547.8
MW-11	3115.4

The distance is measured in the Groundwater Flow Angle from the well to the compliance boundary.

				Normal Distribution Assumption			Lognormal Distribution Assumption				
Sample Event	**Sample Szie**	**Sample Mean**	**Sample Stdev.**	**Cleanup Status**	**Power**	**Expected Sample Size**	**Celanup Status**	**Power**	**Expected Sample Size**	**Alpha Level**	**Expected Power**
TRICHLOROETHYLENE (TCE)				Cleanup Goal = 0.005							
1995	29	2.05E-07	9.05E-07	Attained	1.000	<=3	Not Attained	S/E	S/E	0.05	0.8
1997	20	1.60E-06	4.97E-06	Attained	1.000	<=3	Not Attained	S/E	S/E	0.05	0.8
1998	19	4.06E-06	9.41E-06	Attained	1.000	<=3	Attained	1.000	4	0.05	0.8
1999	29	4.23E-06	2.21E-05	Attained	1.000	<=3	Attained	1.000	4	0.05	0.8

Note: #N/C means "not conducted" due to a small sample size (N<4) or that the mean concentration is much greater than the cleanup level; Sample Size is the number of sampling locations used in the power analysis; Expected Sample Size is the number of concentration data needed to reach the Expected Power under current sample variability.

Risk-Based Power Analysis -- Projected Concentrations

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

From Period: 7/1/1995 **to** 7/1/2000 **Distance from the most downgradient well to receptor:** 1000 feet

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1995	7/1/1995	EW-73	3.007E-01	2900.5	-6.77E-03	8.875E-10	Yes	No
1995	7/1/1995	EW-83	1.057E-01	2852.5	-6.77E-03	4.316E-10	Yes	No
1995	7/1/1995	EW-84	2.618E-01	2602.5	-6.77E-03	5.811E-09	Yes	No
1995	7/1/1995	EW-85	2.160E-01	2307.1	-6.77E-03	3.544E-08	Yes	No
1995	7/1/1995	EW-86	5.140E-03	2261.4	-6.77E-03	1.150E-09	Yes	No
1995	7/1/1995	EW-87	8.076E-02	2550.4	-6.77E-03	2.551E-09	Yes	No
1995	7/1/1995	MW-10	2.848E-01	2526.1	-6.77E-03	1.061E-08	Yes	Yes
1995	7/1/1995	MW-1026	6.150E-05	3834.7	-6.77E-03	3.247E-16	Yes	Yes
1995	7/1/1995	MW-1041	1.230E-04	4817.5	-6.77E-03	8.361E-19	Yes	Yes
1995	7/1/1995	MW-1042	6.150E-05	4774.7	-6.77E-03	5.585E-19	Yes	Yes
1995	7/1/1995	MW-1064	2.063E-02	4778.2	-6.77E-03	1.830E-16	Yes	Yes
1995	7/1/1995	MW-1073	3.052E-03	3939.1	-6.77E-03	7.947E-15	Yes	Yes
1995	7/1/1995	MW-11	7.106E-01	3115.4	-6.77E-03	4.893E-10	Yes	Yes
1995	7/1/1995	MW-12	6.823E-01	2946.6	-6.77E-03	1.474E-09	Yes	Yes
1995	7/1/1995	MW-14	1.021E+00	2295.3	-6.77E-03	1.814E-07	Yes	Yes
1995	7/1/1995	MW-15	7.601E-02	2275.7	-6.77E-03	1.543E-08	Yes	Yes
1995	7/1/1995	MW-237	6.945E-05	2312.7	-6.77E-03	1.097E-11	Yes	Yes
1995	7/1/1995	MW-240	7.484E-05	2112.3	-6.77E-03	4.592E-11	Yes	Yes
1995	7/1/1995	MW-241	2.257E-02	2516.5	-6.77E-03	8.972E-10	Yes	Yes
1995	7/1/1995	MW-242	1.425E-02	2286.1	-6.77E-03	2.695E-09	Yes	Yes
1995	7/1/1995	MW-350	3.657E-03	1227.6	-6.77E-03	8.974E-07	Yes	Yes
1995	7/1/1995	MW-351	4.216E-03	1000.0	-6.77E-03	4.831E-06	Yes	Yes
1995	7/1/1995	MW-38D	1.937E-01	2932.3	-6.77E-03	4.607E-10	Yes	Yes
1995	7/1/1995	MW-52	5.514E-05	3182.6	-6.77E-03	2.409E-14	Yes	Yes
1995	7/1/1995	MW-53	4.805E-04	2999.3	-6.77E-03	7.265E-13	Yes	Yes
1995	7/1/1995	MW-55	1.507E-04	2676.7	-6.77E-03	2.023E-12	Yes	Yes
1995	7/1/1995	MW-70	6.150E-05	3122.8	-6.77E-03	4.028E-14	Yes	Yes
1995	7/1/1995	MW-72	6.046E-02	2547.8	-6.77E-03	1.944E-09	Yes	Yes
1995	7/1/1995	MW-74	2.583E-03	2590.8	-6.77E-03	6.206E-11	Yes	Yes
1995	7/1/1995	MW-76	2.093E-03	2885.3	-6.77E-03	6.849E-12	Yes	Yes
1995	7/1/1995	MW-88	8.494E-05	2475.6	-6.77E-03	4.452E-12	Yes	Yes
1995	7/1/1995	MW-89	4.948E-05	2643.4	-6.77E-03	8.328E-13	Yes	Yes

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1995	7/1/1995	MW-90	5.136E-03	2295.0	-6.77E-03	9.147E-10	Yes	Yes
1995	7/1/1995	MW-91	7.550E-04	1996.1	-6.77E-03	1.018E-09	Yes	Yes
1995	7/1/1995	MW-92	1.360E-04	1866.2	-6.77E-03	4.418E-10	Yes	Yes
1997	7/1/1997	EW-73	9.730E-02	2900.5	-4.74E-03	1.040E-07	Yes	No
1997	7/1/1997	EW-83	1.770E-01	2852.5	-4.74E-03	2.374E-07	Yes	No
1997	7/1/1997	EW-84	1.600E-01	2602.5	-4.74E-03	7.020E-07	Yes	No
1997	7/1/1997	EW-85	5.880E-02	2307.1	-4.74E-03	1.046E-06	Yes	No
1997	7/1/1997	EW-86	7.750E-03	2261.4	-4.74E-03	1.713E-07	Yes	No
1997	7/1/1997	EW-87	2.200E-01	2550.4	-4.74E-03	1.236E-06	Yes	No
1997	7/1/1997	MW-10	1.430E-01	2526.1	-4.74E-03	9.011E-07	Yes	Yes
1997	7/1/1997	MW-1004	1.720E-04	3117.0	-4.74E-03	6.585E-11	Yes	Yes
1997	7/1/1997	MW-1064	6.520E-04	4778.2	-4.74E-03	9.492E-14	Yes	Yes
1997	7/1/1997	MW-1073	1.300E-04	3939.1	-4.74E-03	1.010E-12	Yes	Yes
1997	7/1/1997	MW-11	7.190E-02	3115.4	-4.74E-03	2.773E-08	Yes	Yes
1997	7/1/1997	MW-12	3.280E-01	2946.6	-4.74E-03	2.816E-07	Yes	Yes
1997	7/1/1997	MW-14	2.520E-02	2295.3	-4.74E-03	4.743E-07	Yes	Yes
1997	7/1/1997	MW-15	5.175E-02	2275.7	-4.74E-03	1.069E-06	Yes	Yes
1997	7/1/1997	MW-240	3.820E-03	2112.3	-4.74E-03	1.712E-07	Yes	Yes
1997	7/1/1997	MW-241	4.580E-02	2516.5	-4.74E-03	3.021E-07	Yes	Yes
1997	7/1/1997	MW-242	1.150E-02	2286.1	-4.74E-03	2.260E-07	Yes	Yes
1997	7/1/1997	MW-350	1.090E-03	1227.6	-4.74E-03	3.237E-06	Yes	Yes
1997	7/1/1997	MW-351	2.570E-03	1000.0	-4.74E-03	2.245E-05	Yes	Yes
1997	7/1/1997	MW-38D	1.620E-01	2932.3	-4.74E-03	1.488E-07	Yes	Yes
1997	7/1/1997	MW-412	2.563E-04	1100.9	-4.74E-03	1.388E-06	Yes	Yes
1997	7/1/1997	MW-72	6.660E-02	2547.8	-4.74E-03	3.787E-07	Yes	Yes
1997	7/1/1997	MW-88	9.310E-02	2475.6	-4.74E-03	7.453E-07	Yes	Yes
1997	7/1/1997	MW-89	1.940E-04	2643.4	-4.74E-03	7.012E-10	Yes	Yes
1997	7/1/1997	MW-90	5.400E-03	2295.0	-4.74E-03	1.018E-07	Yes	Yes
1997	7/1/1997	MW-91	3.480E-04	1996.1	-4.74E-03	2.705E-08	Yes	Yes
1998	7/1/1998	EW-73	1.210E-01	2900.5	-3.84E-03	1.754E-06	Yes	No
1998	7/1/1998	EW-83	1.480E-01	2852.5	-3.84E-03	2.580E-06	Yes	No
1998	7/1/1998	EW-84	5.120E-02	2602.5	-3.84E-03	2.331E-06	Yes	No
1998	7/1/1998	EW-85	4.080E-02	2307.1	-3.84E-03	5.778E-06	Yes	No
1998	7/1/1998	EW-86	6.700E-03	2261.4	-3.84E-03	1.131E-06	Yes	No
1998	7/1/1998	EW-87	2.850E-01	2550.4	-3.84E-03	1.585E-05	Yes	No
1998	7/1/1998	MW-10	9.990E-02	2526.1	-3.84E-03	6.100E-06	Yes	Yes

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1998	7/1/1998	MW-11	8.695E-02	3115.4	-3.84E-03	5.520E-07	Yes	Yes
1998	7/1/1998	MW-12	2.405E-01	2946.6	-3.84E-03	2.920E-06	Yes	Yes
1998	7/1/1998	MW-14	3.905E-03	2295.3	-3.84E-03	5.787E-07	Yes	Yes
1998	7/1/1998	MW-15	6.195E-02	2275.7	-3.84E-03	9.899E-06	Yes	Yes
1998	7/1/1998	MW-240	9.050E-05	2112.3	-3.84E-03	2.709E-08	Yes	Yes
1998	7/1/1998	MW-241	7.670E-03	2516.5	-3.84E-03	4.860E-07	Yes	Yes
1998	7/1/1998	MW-242	1.290E-02	2286.1	-3.84E-03	1.980E-06	Yes	Yes
1998	7/1/1998	MW-350	1.000E-04	1227.6	-3.84E-03	8.955E-07	Yes	Yes
1998	7/1/1998	MW-351	1.915E-03	1000.0	-3.84E-03	4.111E-05	Yes	Yes
1998	7/1/1998	MW-38D	1.340E-01	2932.3	-3.84E-03	1.719E-06	Yes	Yes
1998	7/1/1998	MW-412	5.224E-04	1100.9	-3.84E-03	7.610E-06	Yes	Yes
1998	7/1/1998	MW-52	5.400E-05	3182.6	-3.84E-03	2.649E-10	Yes	Yes
1998	7/1/1998	MW-53	3.845E-03	2999.3	-3.84E-03	3.814E-08	Yes	Yes
1998	7/1/1998	MW-55	3.580E-04	2676.7	-3.84E-03	1.226E-08	Yes	Yes
1998	7/1/1998	MW-72	4.630E-02	2547.8	-3.84E-03	2.601E-06	Yes	Yes
1998	7/1/1998	MW-88	9.050E-05	2475.6	-3.84E-03	6.709E-09	Yes	Yes
1998	7/1/1998	MW-89	9.050E-05	2643.4	-3.84E-03	3.522E-09	Yes	Yes
1998	7/1/1998	MW-92	7.853E-04	1866.2	-3.84E-03	6.049E-07	Yes	Yes
1999	7/1/1999	EW-73	6.040E-02	2900.5	-4.75E-03	6.351E-08	Yes	No
1999	7/1/1999	EW-83	9.975E-02	2852.5	-4.75E-03	1.317E-07	Yes	No
1999	7/1/1999	EW-84	9.923E-03	2602.5	-4.75E-03	4.291E-08	Yes	No
1999	7/1/1999	EW-85	4.850E-02	2307.1	-4.75E-03	8.521E-07	Yes	No
1999	7/1/1999	EW-86	6.630E-03	2261.4	-4.75E-03	1.447E-07	Yes	No
1999	7/1/1999	EW-87	2.653E-01	2550.4	-4.75E-03	1.469E-06	Yes	No
1999	7/1/1999	MW-10	7.840E-02	2526.1	-4.75E-03	4.872E-07	Yes	Yes
1999	7/1/1999	MW-1004	1.095E-04	3117.0	-4.75E-03	4.120E-11	Yes	Yes
1999	7/1/1999	MW-1026	3.910E-03	3834.7	-4.75E-03	4.879E-11	Yes	Yes
1999	7/1/1999	MW-1073	4.330E-04	3939.1	-4.75E-03	3.292E-12	Yes	Yes
1999	7/1/1999	MW-11	3.475E-02	3115.4	-4.75E-03	1.317E-08	Yes	Yes
1999	7/1/1999	MW-12	8.290E-02	2946.6	-4.75E-03	7.002E-08	Yes	Yes
1999	7/1/1999	MW-14	4.990E-03	2295.3	-4.75E-03	9.272E-08	Yes	Yes
1999	7/1/1999	MW-15	7.890E-02	2275.7	-4.75E-03	1.609E-06	Yes	Yes
1999	7/1/1999	MW-237	4.840E-04	2312.7	-4.75E-03	8.280E-09	Yes	Yes
1999	7/1/1999	MW-240	4.645E-05	2112.3	-4.75E-03	2.057E-09	Yes	Yes
1999	7/1/1999	MW-241	1.030E-02	2516.5	-4.75E-03	6.700E-08	Yes	Yes
1999	7/1/1999	MW-242	5.680E-03	2286.1	-4.75E-03	1.102E-07	Yes	Yes

Project: McClellan OUD ZoneA

User Name: Meng

Location: McClellan AFB

State: California

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1999	7/1/1999	MW-350	1.095E-04	1227.6	-4.75E-03	3.230E-07	Yes	Yes
1999	7/1/1999	MW-351	1.370E-02	1000.0	-4.75E-03	1.190E-04	Yes	Yes
1999	7/1/1999	MW-38D	7.697E-02	2932.3	-4.75E-03	6.956E-08	Yes	Yes
1999	7/1/1999	MW-412	1.095E-04	1100.9	-4.75E-03	5.892E-07	Yes	Yes
1999	7/1/1999	MW-458	1.202E-04	1994.3	-4.75E-03	9.320E-09	Yes	Yes
1999	7/1/1999	MW-52	1.095E-04	3182.6	-4.75E-03	3.018E-11	Yes	Yes
1999	7/1/1999	MW-53	4.420E-04	2999.3	-4.75E-03	2.908E-10	Yes	Yes
1999	7/1/1999	MW-55	1.730E-03	2676.7	-4.75E-03	5.260E-09	Yes	Yes
1999	7/1/1999	MW-70	1.095E-04	3122.8	-4.75E-03	4.008E-11	Yes	Yes
1999	7/1/1999	MW-72	2.770E-02	2547.8	-4.75E-03	1.553E-07	Yes	Yes
1999	7/1/1999	MW-74	1.610E-03	2590.8	-4.75E-03	7.358E-09	Yes	Yes
1999	7/1/1999	MW-76	5.430E-03	2885.3	-4.75E-03	6.136E-09	Yes	Yes
1999	7/1/1999	MW-88	1.095E-04	2475.6	-4.75E-03	8.646E-10	Yes	Yes
1999	7/1/1999	MW-89	1.095E-04	2643.4	-4.75E-03	3.900E-10	Yes	Yes
1999	7/1/1999	MW-90	1.095E-04	2295.0	-4.75E-03	2.037E-09	Yes	Yes
1999	7/1/1999	MW-91	3.970E-04	1996.1	-4.75E-03	3.052E-08	Yes	Yes
1999	7/1/1999	MW-92	1.095E-04	1866.2	-4.75E-03	1.559E-08	Yes	Yes

Note: Projected Concentrations that are below the user-specified detection limit are indicated by a check mark to its right; for sampling events with less than 3 selected plume centerline wells, NO projected concentrations are calculated because no regression coefficient is available.

Regression of Plume Centerline Concentrations

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

Groundwater Flow Direction: 280 degrees **Distance to Receptor:** 1000 feet

From Period: 7/1/1995 **to** 7/1/2000

Selected Plume Centerline Wells:

Well	Distance to Receptor (feet)
MW-92	1866.2
MW-91	1996.1
MW-72	2547.8
MW-11	3115.4

The distance is measured in the Groundwater Flow Angle from the well to the compliance boundary.

Sample Event	Effective Date	Number of Centerline Wells	Regression Coefficient (1/ft)	Confidence in Coefficient
TRICHLOROETHYLENE (TCE)				
1995	7/1/1995	4	-6.77E-03	99.2%
1996	7/1/1996	2	0.00E+00	0.0%
1997	7/1/1997	3	-4.74E-03	83.5%
1998	7/1/1998	3	-3.84E-03	88.9%
1999	7/1/1999	4	-4.75E-03	96.2%
2000	7/1/2000	2	0.00E+00	0.0%

Note: when the number of plume centerline wells is less than 3, no analysis is performed and all related values are set to ZERO; Confidence in Coefficient is the statistical confidence that the estimated coefficient is different from ZERO (for details, please refer to "Conference in Trend" in Linear Regression Analysis).

MAROS Risk-Based Power Analysis for Site Cleanup

Project: McClellan OUD ZoneA

User Name: Meng

Location: McClellan AFB

State: California

Parameters:

Groundwater Flow Direction: 280 degrees **Distance to Receptor:** 100 feet

From Period: 1995 **to** 2000

7/1/1995 7/1/2000

Selected Plume Centerline Wells:

Well	Distance to Receptor (feet)
MW-92	966.2
MW-91	1096.1
MW-72	1647.8
MW-11	2215.4

The distance is measured in the Groundwater Flow Angle from the well to the compliance boundary.

				Normal Distribution Assumption			Lognormal Distribution Assumption				
Sample Event	Sample Szie	Sample Mean	Sample Stdev.	Cleanup Status	Power	Expected Sample Size	Celanup Status	Power	Expected Sample Size	Alpha Level	Expected Power
TRICHLOROETHYLENE (TCE)				Cleanup Goal = 0.005							
1995	29	9.09E-05	4.01E-04	Attained	1.000	<=3	Not Attained	S/E	S/E	0.05	0.8
1997	20	1.14E-04	3.54E-04	Attained	1.000	<=3	Not Attained	S/E	S/E	0.05	0.8
1998	19	1.29E-04	2.99E-04	Attained	1.000	<=3	Not Attained	0.457	49	0.05	0.8
1999	29	3.03E-04	1.58E-03	Attained	1.000	<=3	Attained	0.740	35	0.05	0.8

Note: #N/C means "not conducted" due to a small sample size (N<4) or that the mean concentration is much greater than the cleanup level; Sample Size is the number of sampling locations used in the power analysis; Expected Sample Size is the number of concentration data needed to reach the Expected Power under current sample variability.

Risk-Based Power Analysis -- Projected Concentrations

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

From Period: 7/1/1995 **to** 7/1/2000 **Distance from the most downgradient well to receptor:** 100 feet

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1995	7/1/1995	EW-73	3.007E-01	2000.5	-6.77E-03	3.935E-07	Yes	No
1995	7/1/1995	EW-83	1.057E-01	1952.5	-6.77E-03	1.914E-07	Yes	No
1995	7/1/1995	EW-84	2.618E-01	1702.5	-6.77E-03	2.577E-06	Yes	No
1995	7/1/1995	EW-85	2.160E-01	1407.1	-6.77E-03	1.572E-05	Yes	No
1995	7/1/1995	EW-86	5.140E-03	1361.4	-6.77E-03	5.098E-07	Yes	No
1995	7/1/1995	EW-87	8.076E-02	1650.4	-6.77E-03	1.131E-06	Yes	No
1995	7/1/1995	MW-10	2.848E-01	1626.1	-6.77E-03	4.703E-06	Yes	Yes
1995	7/1/1995	MW-1026	6.150E-05	2934.7	-6.77E-03	1.440E-13	Yes	Yes
1995	7/1/1995	MW-1041	1.230E-04	3917.5	-6.77E-03	3.707E-16	Yes	Yes
1995	7/1/1995	MW-1042	6.150E-05	3874.7	-6.77E-03	2.476E-16	Yes	Yes
1995	7/1/1995	MW-1064	2.063E-02	3878.2	-6.77E-03	8.115E-14	Yes	Yes
1995	7/1/1995	MW-1073	3.052E-03	3039.1	-6.77E-03	3.524E-12	Yes	Yes
1995	7/1/1995	MW-11	7.106E-01	2215.4	-6.77E-03	2.169E-07	Yes	Yes
1995	7/1/1995	MW-12	6.823E-01	2046.6	-6.77E-03	6.535E-07	Yes	Yes
1995	7/1/1995	MW-14	1.021E+00	1395.3	-6.77E-03	8.043E-05	Yes	Yes
1995	7/1/1995	MW-15	7.601E-02	1375.7	-6.77E-03	6.841E-06	Yes	Yes
1995	7/1/1995	MW-237	6.945E-05	1412.7	-6.77E-03	4.865E-09	Yes	Yes
1995	7/1/1995	MW-240	7.484E-05	1212.3	-6.77E-03	2.036E-08	Yes	Yes
1995	7/1/1995	MW-241	2.257E-02	1616.5	-6.77E-03	3.978E-07	Yes	Yes
1995	7/1/1995	MW-242	1.425E-02	1386.1	-6.77E-03	1.195E-06	Yes	Yes
1995	7/1/1995	MW-350	3.657E-03	327.6	-6.77E-03	3.979E-04	No	Yes
1995	7/1/1995	MW-351	4.216E-03	100.0	-6.77E-03	2.142E-03	No	Yes
1995	7/1/1995	MW-38D	1.937E-01	2032.3	-6.77E-03	2.043E-07	Yes	Yes
1995	7/1/1995	MW-52	5.514E-05	2282.6	-6.77E-03	1.068E-11	Yes	Yes
1995	7/1/1995	MW-53	4.805E-04	2099.3	-6.77E-03	3.221E-10	Yes	Yes
1995	7/1/1995	MW-55	1.507E-04	1776.7	-6.77E-03	8.972E-10	Yes	Yes
1995	7/1/1995	MW-70	6.150E-05	2222.8	-6.77E-03	1.786E-11	Yes	Yes
1995	7/1/1995	MW-72	6.046E-02	1647.8	-6.77E-03	8.618E-07	Yes	Yes
1995	7/1/1995	MW-74	2.583E-03	1690.8	-6.77E-03	2.752E-08	Yes	Yes
1995	7/1/1995	MW-76	2.093E-03	1985.3	-6.77E-03	3.037E-09	Yes	Yes
1995	7/1/1995	MW-88	8.494E-05	1575.6	-6.77E-03	1.974E-09	Yes	Yes
1995	7/1/1995	MW-89	4.948E-05	1743.4	-6.77E-03	3.693E-10	Yes	Yes

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1995	7/1/1995	MW-90	5.136E-03	1395.0	-6.77E-03	4.056E-07	Yes	Yes
1995	7/1/1995	MW-91	7.550E-04	1096.1	-6.77E-03	4.512E-07	Yes	Yes
1995	7/1/1995	MW-92	1.360E-04	966.2	-6.77E-03	1.959E-07	Yes	Yes
1997	7/1/1997	EW-73	9.730E-02	2000.5	-4.74E-03	7.409E-06	Yes	No
1997	7/1/1997	EW-83	1.770E-01	1952.5	-4.74E-03	1.692E-05	Yes	No
1997	7/1/1997	EW-84	1.600E-01	1702.5	-4.74E-03	5.002E-05	Yes	No
1997	7/1/1997	EW-85	5.880E-02	1407.1	-4.74E-03	7.457E-05	Yes	No
1997	7/1/1997	EW-86	7.750E-03	1361.4	-4.74E-03	1.221E-05	Yes	No
1997	7/1/1997	EW-87	2.200E-01	1650.4	-4.74E-03	8.804E-05	Yes	No
1997	7/1/1997	MW-10	1.430E-01	1626.1	-4.74E-03	6.421E-05	Yes	Yes
1997	7/1/1997	MW-1004	1.720E-04	2217.0	-4.74E-03	4.693E-09	Yes	Yes
1997	7/1/1997	MW-1064	6.520E-04	3878.2	-4.74E-03	6.764E-12	Yes	Yes
1997	7/1/1997	MW-1073	1.300E-04	3039.1	-4.74E-03	7.200E-11	Yes	Yes
1997	7/1/1997	MW-11	7.190E-02	2215.4	-4.74E-03	1.976E-06	Yes	Yes
1997	7/1/1997	MW-12	3.280E-01	2046.6	-4.74E-03	2.007E-05	Yes	Yes
1997	7/1/1997	MW-14	2.520E-02	1395.3	-4.74E-03	3.380E-05	Yes	Yes
1997	7/1/1997	MW-15	5.175E-02	1375.7	-4.74E-03	7.617E-05	Yes	Yes
1997	7/1/1997	MW-240	3.820E-03	1212.3	-4.74E-03	1.220E-05	Yes	Yes
1997	7/1/1997	MW-241	4.580E-02	1616.5	-4.74E-03	2.153E-05	Yes	Yes
1997	7/1/1997	MW-242	1.150E-02	1386.1	-4.74E-03	1.611E-05	Yes	Yes
1997	7/1/1997	MW-350	1.090E-03	327.6	-4.74E-03	2.307E-04	No	Yes
1997	7/1/1997	MW-351	2.570E-03	100.0	-4.74E-03	1.600E-03	No	Yes
1997	7/1/1997	MW-38D	1.620E-01	2032.3	-4.74E-03	1.061E-05	Yes	Yes
1997	7/1/1997	MW-412	2.563E-04	200.9	-4.74E-03	9.889E-05	Yes	Yes
1997	7/1/1997	MW-72	6.660E-02	1647.8	-4.74E-03	2.698E-05	Yes	Yes
1997	7/1/1997	MW-88	9.310E-02	1575.6	-4.74E-03	5.311E-05	Yes	Yes
1997	7/1/1997	MW-89	1.940E-04	1743.4	-4.74E-03	4.997E-08	Yes	Yes
1997	7/1/1997	MW-90	5.400E-03	1395.0	-4.74E-03	7.252E-06	Yes	Yes
1997	7/1/1997	MW-91	3.480E-04	1096.1	-4.74E-03	1.927E-06	Yes	Yes
1998	7/1/1998	EW-73	1.210E-01	2000.5	-3.84E-03	5.565E-05	Yes	No
1998	7/1/1998	EW-83	1.480E-01	1952.5	-3.84E-03	8.185E-05	Yes	No
1998	7/1/1998	EW-84	5.120E-02	1702.5	-3.84E-03	7.397E-05	Yes	No
1998	7/1/1998	EW-85	4.080E-02	1407.1	-3.84E-03	1.833E-04	Yes	No
1998	7/1/1998	EW-86	6.700E-03	1361.4	-3.84E-03	3.589E-05	Yes	No
1998	7/1/1998	EW-87	2.850E-01	1650.4	-3.84E-03	5.030E-04	No	No
1998	7/1/1998	MW-10	9.990E-02	1626.1	-3.84E-03	1.935E-04	Yes	Yes

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1998	7/1/1998	MW-11	8.695E-02	2215.4	-3.84E-03	1.751E-05	Yes	Yes
1998	7/1/1998	MW-12	2.405E-01	2046.6	-3.84E-03	9.266E-05	Yes	Yes
1998	7/1/1998	MW-14	3.905E-03	1395.3	-3.84E-03	1.836E-05	Yes	Yes
1998	7/1/1998	MW-15	6.195E-02	1375.7	-3.84E-03	3.141E-04	No	Yes
1998	7/1/1998	MW-240	9.050E-05	1212.3	-3.84E-03	8.594E-07	Yes	Yes
1998	7/1/1998	MW-241	7.670E-03	1616.5	-3.84E-03	1.542E-05	Yes	Yes
1998	7/1/1998	MW-242	1.290E-02	1386.1	-3.84E-03	6.283E-05	Yes	Yes
1998	7/1/1998	MW-350	1.000E-04	327.6	-3.84E-03	2.841E-05	Yes	Yes
1998	7/1/1998	MW-351	1.915E-03	100.0	-3.84E-03	1.304E-03	No	Yes
1998	7/1/1998	MW-38D	1.340E-01	2032.3	-3.84E-03	5.453E-05	Yes	Yes
1998	7/1/1998	MW-412	5.224E-04	200.9	-3.84E-03	2.414E-04	No	Yes
1998	7/1/1998	MW-52	5.400E-05	2282.6	-3.84E-03	8.403E-09	Yes	Yes
1998	7/1/1998	MW-53	3.845E-03	2099.3	-3.84E-03	1.210E-06	Yes	Yes
1998	7/1/1998	MW-55	3.580E-04	1776.7	-3.84E-03	3.889E-07	Yes	Yes
1998	7/1/1998	MW-72	4.630E-02	1647.8	-3.84E-03	8.253E-05	Yes	Yes
1998	7/1/1998	MW-88	9.050E-05	1575.6	-3.84E-03	2.129E-07	Yes	Yes
1998	7/1/1998	MW-89	9.050E-05	1743.4	-3.84E-03	1.117E-07	Yes	Yes
1998	7/1/1998	MW-92	7.853E-04	966.2	-3.84E-03	1.919E-05	Yes	Yes
1999	7/1/1999	EW-73	6.040E-02	2000.5	-4.75E-03	4.548E-06	Yes	No
1999	7/1/1999	EW-83	9.975E-02	1952.5	-4.75E-03	9.432E-06	Yes	No
1999	7/1/1999	EW-84	9.923E-03	1702.5	-4.75E-03	3.073E-06	Yes	No
1999	7/1/1999	EW-85	4.850E-02	1407.1	-4.75E-03	6.103E-05	Yes	No
1999	7/1/1999	EW-86	6.630E-03	1361.4	-4.75E-03	1.037E-05	Yes	No
1999	7/1/1999	EW-87	2.653E-01	1650.4	-4.75E-03	1.052E-04	Yes	No
1999	7/1/1999	MW-10	7.840E-02	1626.1	-4.75E-03	3.489E-05	Yes	Yes
1999	7/1/1999	MW-1004	1.095E-04	2217.0	-4.75E-03	2.951E-09	Yes	Yes
1999	7/1/1999	MW-1026	3.910E-03	2934.7	-4.75E-03	3.494E-09	Yes	Yes
1999	7/1/1999	MW-1073	4.330E-04	3039.1	-4.75E-03	2.358E-10	Yes	Yes
1999	7/1/1999	MW-11	3.475E-02	2215.4	-4.75E-03	9.433E-07	Yes	Yes
1999	7/1/1999	MW-12	8.290E-02	2046.6	-4.75E-03	5.015E-06	Yes	Yes
1999	7/1/1999	MW-14	4.990E-03	1395.3	-4.75E-03	6.640E-06	Yes	Yes
1999	7/1/1999	MW-15	7.890E-02	1375.7	-4.75E-03	1.152E-04	Yes	Yes
1999	7/1/1999	MW-237	4.840E-04	1412.7	-4.75E-03	5.930E-07	Yes	Yes
1999	7/1/1999	MW-240	4.645E-05	1212.3	-4.75E-03	1.473E-07	Yes	Yes
1999	7/1/1999	MW-241	1.030E-02	1616.5	-4.75E-03	4.798E-06	Yes	Yes
1999	7/1/1999	MW-242	5.680E-03	1386.1	-4.75E-03	7.895E-06	Yes	Yes

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

Sampling Event	Effective Date	Well	Observed Concentration (mg/L)	Distance Down Centerline (ft)	Regression Coefficient (1/ft)	Projected Concentration (mg/L)	Below Detection Limit?	Used in Analysis?
TRICHLOROETHYLENE (TCE)								
1999	7/1/1999	MW-350	1.095E-04	327.6	-4.75E-03	2.313E-05	Yes	Yes
1999	7/1/1999	MW-351	1.370E-02	100.0	-4.75E-03	8.523E-03	No	Yes
1999	7/1/1999	MW-38D	7.697E-02	2032.3	-4.75E-03	4.982E-06	Yes	Yes
1999	7/1/1999	MW-412	1.095E-04	200.9	-4.75E-03	4.220E-05	Yes	Yes
1999	7/1/1999	MW-458	1.202E-04	1094.3	-4.75E-03	6.675E-07	Yes	Yes
1999	7/1/1999	MW-52	1.095E-04	2282.6	-4.75E-03	2.161E-09	Yes	Yes
1999	7/1/1999	MW-53	4.420E-04	2099.3	-4.75E-03	2.082E-08	Yes	Yes
1999	7/1/1999	MW-55	1.730E-03	1776.7	-4.75E-03	3.767E-07	Yes	Yes
1999	7/1/1999	MW-70	1.095E-04	2222.8	-4.75E-03	2.870E-09	Yes	Yes
1999	7/1/1999	MW-72	2.770E-02	1647.8	-4.75E-03	1.112E-05	Yes	Yes
1999	7/1/1999	MW-74	1.610E-03	1690.8	-4.75E-03	5.270E-07	Yes	Yes
1999	7/1/1999	MW-76	5.430E-03	1985.3	-4.75E-03	4.395E-07	Yes	Yes
1999	7/1/1999	MW-88	1.095E-04	1575.6	-4.75E-03	6.192E-08	Yes	Yes
1999	7/1/1999	MW-89	1.095E-04	1743.4	-4.75E-03	2.793E-08	Yes	Yes
1999	7/1/1999	MW-90	1.095E-04	1395.0	-4.75E-03	1.459E-07	Yes	Yes
1999	7/1/1999	MW-91	3.970E-04	1096.1	-4.75E-03	2.185E-06	Yes	Yes
1999	7/1/1999	MW-92	1.095E-04	966.2	-4.75E-03	1.117E-06	Yes	Yes

Note: Projected Concentrations that are below the user-specified detection limit are indicated by a check mark to its right; for sampling events with less than 3 selected plume centerline wells, NO projected concentrations are calculated because no regression coefficient is available.

Regression of Plume Centerline Concentrations

Project: McClellan OUD ZoneA **User Name:** Meng

Location: McClellan AFB **State:** California

Groundwater Flow Direction: 280 degrees **Distance to Receptor:** 100 feet

From Period: 7/1/1995 **to** 7/1/2000

Selected Plume Centerline Wells:

Well	Distance to Receptor (feet)
MW-92	966.2
MW-91	1096.1
MW-72	1647.8
MW-11	2215.4

The distance is measured in the Groundwater Flow Angle from the well to the compliance boundary.

Sample Event	Effective Date	Number of Centerline Wells	Regression Coefficient (1/ft)	Confidence in Coefficient
TRICHLOROETHYLENE (TCE)				
1995	7/1/1995	4	-6.77E-03	99.2%
1996	7/1/1996	2	0.00E+00	0.0%
1997	7/1/1997	3	-4.74E-03	83.5%
1998	7/1/1998	3	-3.84E-03	88.9%
1999	7/1/1999	4	-4.75E-03	96.2%
2000	7/1/2000	2	0.00E+00	0.0%

Note: when the number of plume centerline wells is less than 3, no analysis is performed and all related values are set to ZERO; Confidence in Coefficient is the statistical confidence that the estimated coefficient is different from ZERO (for details, please refer to "Conference in Trend" in Linear Regression Analysis).

MAROS Mann-Kendall Statistics Summary

Project: McClellan Zone B OU D

User Name: Julia Aziz

Location: McClellan AFB

State: California

Time Period: 5/1/1990 **to** 12/31/2000
Consolidation Period: No Time Consolidation
Consolidation Type: Median
Duplicate Consolidation: Average
ND Values: Specified Detection Limit
J Flag Values : Actual Value

Well	Source/ Tail	Number of Samples	Number of Detects	Coefficient of Variation	Mann-Kendall Statistic	Confidence in Trend	All Samples "ND" ?	Concentration Trend
TRICHLOROETHYLENE (TCE)								
EW-83	S	16	16	0.30	22	82.5%	No	NT
EW-84	S	16	16	0.83	-105	100.0%	No	D
MW-54	S	10	8	1.46	28	99.4%	No	I
EW-85	S	16	16	0.79	-84	100.0%	No	D
EW-86	S	15	15	1.23	-53	99.6%	No	D
EW-87	S	15	15	0.68	60	99.9%	No	I
EW-73	S	15	15	0.92	-83	100.0%	No	D
MW-1028	T	10	2	0.61	-1	50.0%	No	S
MW-1001	T	10	1	0.03	-3	56.9%	No	S
MW-1003	T	11	3	0.30	-19	91.8%	No	PD
MW-1027	T	6	2	0.71	3	64.0%	No	NT
MW-59	T	12	2	0.31	-1	50.0%	No	S
MW-104	T	8	2	1.60	-7	76.4%	No	NT
MW-1043	T	6	1	0.09	5	76.5%	No	NT
MW-105	T	8	2	1.94	11	88.7%	No	NT
MW-19D	T	10	6	1.67	7	70.0%	No	NT
MW-51	T	8	1	0.18	-7	76.4%	No	S
MW-57	T	12	5	1.44	-3	55.4%	No	NT
MW-58	T	15	7	1.75	13	72.1%	No	NT
MW-1010	T	5	0	0.00	0	40.8%	Yes	S

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)- Due to insufficient Data (< 4 sampling events); Source/Tail (S/T)

The Number of Samples and Number of Detects shown above are post-consolidation values.

MAROS Linear Regression Statistics Summary

Project: McClellan Zone B OU D
User Name: Julia Aziz

Location: McClellan AFB
State: California

Time Period: 5/1/1990 **to** 12/31/2000
Consolidation Period: No Time Consolidation
Consolidation Type: Median
Duplicate Consolidation: Average
ND Values: Specified Detection Limit
J Flag Values : Actual Value

Well	Source/ Tail	Average Conc (mg/L)	Median Conc (mg/L)	Standard Deviation	All Samples "ND" ?	Ln Slope	Coefficient of Variation	Confidence in Trend	Concentration Trend
TRICHLOROETHYLENE (TCE)									
EW-83	S	1.0E-01	9.6E-02	3.1E-02	No	2.3E-05	0.30	60.7%	NT
EW-84	S	4.0E-01	2.5E-01	3.3E-01	No	-1.1E-03	0.83	100.0%	D
EW-85	S	1.9E-01	1.2E-01	1.5E-01	No	-6.6E-04	0.79	99.9%	D
EW-86	S	1.2E-02	7.7E-03	1.5E-02	No	-7.6E-04	1.23	99.6%	D
EW-87	S	1.2E-01	8.4E-02	8.2E-02	No	4.6E-04	0.68	99.9%	I
MW-54	S	1.7E-03	2.4E-04	2.5E-03	No	1.2E-03	1.46	99.9%	I
EW-73	S	2.6E-01	1.7E-01	2.4E-01	No	-7.2E-04	0.92	100.0%	D
MW-1027	T	1.5E-04	1.0E-04	1.0E-04	No	6.6E-05	0.71	60.4%	NT
MW-1001	T	9.9E-05	1.0E-04	2.6E-06	No	-3.9E-06	0.03	100.0%	D
MW-1010	T	1.0E-04	1.0E-04	0.0E+00	Yes	0.0E+00	0.00	100.0%	S
MW-59	T	1.0E-04	1.0E-04	3.2E-05	No	-2.9E-05	0.31	60.9%	S
MW-1028	T	1.3E-04	1.0E-04	7.8E-05	No	-1.1E-04	0.61	75.7%	S
MW-104	T	2.1E-04	1.0E-04	3.3E-04	No	-3.5E-04	1.60	83.6%	NT
MW-1043	T	1.0E-04	1.0E-04	9.4E-06	No	7.1E-05	0.09	85.4%	NT
MW-105	T	4.5E-04	1.0E-04	8.7E-04	No	6.3E-04	1.94	98.6%	I
MW-19D	T	5.1E-04	1.7E-04	8.5E-04	No	1.8E-04	1.67	67.4%	NT
MW-51	T	1.1E-04	1.0E-04	1.9E-05	No	-8.1E-05	0.18	92.4%	PD
MW-57	T	2.6E-04	1.0E-04	3.8E-04	No	3.4E-05	1.44	55.7%	NT
MW-58	T	3.0E-04	1.0E-04	5.3E-04	No	6.7E-05	1.75	62.3%	NT
MW-1003	T	1.1E-04	1.0E-04	3.3E-05	No	-1.1E-04	0.30	96.6%	D

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); COV = Coefficient of Variation

MAROS Statistical Trend Analysis Summary

Project: McClellan Zone B OU D

User Name: Julia Aziz

Location: McClellan AFB

State: California

Time Period: 5/1/1990 **to** 12/31/2000

Consolidation Period: No Time Consolidation

Consolidation Type: Median

Duplicate Consolidation: Average

ND Values: Specified Detection Limit

J Flag Values : Actual Value

Well	Source/ Tail	Number of Samples	Number of Detects	Average Conc. (mg/L)	Median Conc. (mg/L)	All Samples "ND" ?	Mann-Kendall Trend	Linear Regression Trend
TRICHLOROETHYLENE (TCE)								
EW-73	S	15	15	2.6E-01	1.7E-01	No	D	D
EW-83	S	16	16	1.0E-01	9.6E-02	No	NT	NT
EW-84	S	16	16	4.0E-01	2.5E-01	No	D	D
EW-85	S	16	16	1.9E-01	1.2E-01	No	D	D
EW-86	S	15	15	1.2E-02	7.7E-03	No	D	D
EW-87	S	15	15	1.2E-01	8.4E-02	No	I	I
MW-1001	T	10	1	9.9E-05	1.0E-04	No	S	D
MW-1003	T	11	3	1.1E-04	1.0E-04	No	PD	D
MW-1010	T	5	0	1.0E-04	1.0E-04	Yes	S	S
MW-1027	T	6	2	1.5E-04	1.0E-04	No	NT	NT
MW-1028	T	10	2	1.3E-04	1.0E-04	No	S	S
MW-104	T	8	2	2.1E-04	1.0E-04	No	NT	NT
MW-1043	T	6	1	1.0E-04	1.0E-04	No	NT	NT
MW-105	T	8	2	4.5E-04	1.0E-04	No	NT	I
MW-19D	T	10	6	5.1E-04	1.7E-04	No	NT	NT
MW-51	T	8	1	1.1E-04	1.0E-04	No	S	PD
MW-54	S	10	8	1.7E-03	2.4E-04	No	I	I
MW-57	T	12	5	2.6E-04	1.0E-04	No	NT	NT
MW-58	T	15	7	3.0E-04	1.0E-04	No	NT	NT
MW-59	T	12	2	1.0E-04	1.0E-04	No	S	S

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); No Detectable Concentration (NDC)

The Number of Samples and Number of Detects shown above are post-consolidation values.

MAROS Site Results

Project: McClellan Zone B OU D **User Name:** Julia Aziz

Location: McClellan AFB **State:** California

User Defined Site and Data Assumptions:

Hydrogeology and Plume Information:

Groundwater Seepage Velocity: 35 ft/yr

Current Plume Length: 1000 ft

Current Plume Width 600 ft

Number of Tail Wells: 13

Number of Source Wells: 7

Source Information:

Source Treatment: Pump and Treat

NAPL is not observed at this site.

Down-gradient Information:

Distance from Edge of Tail to Nearest:

Down-gradient receptor: 1000 ft

Down-gradient property: 10 ft

Distance from Source to Nearest:

Down-gradient receptor: 6000 ft

Down-gradient property: 10 ft

Data Consolidation Assumptions:

Time Period: 5/1/1990 **to** 12/31/2000

Consolidation Period: No Time Consolidation

Consolidation Type: Median

Duplicate Consolidation: Average

ND Values: Specified Detection Limit

J Flag Values : Actual Value

Plume Information Weighting Assumptions:

Consolidation Step 1. Weight Plume Information by Chemical

Summary Weighting: Weighting Applied to All Chemicals Equally

Consolidation Step 2. Weight Well Information by Chemical

Well Weighting: No Weighting of Wells was Applied.

Chemical Weighting: No Weighting of Chemicals was Applied.

Note: These assumptions were made when consolidating the historical montoring data and lumping the Wells and COCs.

1. Compliance Monitoring/Remediation Optimization Results:

Preliminary Monitoring System Optimization Results: Based on site classification, source treatment and Monitoring System Category the following suggestions are made for site Sampling Frequency, Duration of Sampling, and Well Density. These criteria take into consideration: Plume Stability, Type of Plume, and Groundwater Velocity.

COC	Tail Stability	Source Stability	Level of Effort	Sampling Duration	Sampling Frequency	Sampling Density
TRICHLOROETHYLENE (TCE)	S	S	M	Remove treatment system if previously reducing concentation	No Recommendation	25

Note:

Plume Status: (I) Increasing; (PI)Probably Increasing; (S) Stable; (NT) No Trend; (PD) Probably Decreasing; (D) Decreasing

Design Categories: (E) Extensive; (M) Moderate; (L) Limited (N/A) Not Applicable, Insufficient Data Available

Level of Monitoring Effort Indicated by Analysi Moderate

2. Spatial Moment Analysis Results:

Moment Type	Consituent	Coefficient of Variation	Mann-Kendall S Statistic	Confidence in Trend	Moment Trend
Zeroth Moment: Mass					
	TRICHLOROETHYLENE (TCE)	1.32	-13	57.7%	NT
1st Moment: Distance to Source					
	TRICHLOROETHYLENE (TCE)	0.76	-50	93.0%	PD
2nd Moment: Sigma XX					
	TRICHLOROETHYLENE (TCE)	1.68	-50	93.0%	PD
2nd Moment: Sigma YY					
	TRICHLOROETHYLENE (TCE)	1.06	-56	95.1%	D

Note: The following assumptions were applied for the calculation of the Zeroth Moment:

Porosity: 0.30 **Saturated Thickness:** Uniform: 60 ft

Mann-Kendall Trend test performed on all sample events for each constituent. Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)-Due to insufficient Data (< 4 sampling events).

MAROS Zeroth Moment Analysis

Project: McClellan AFB Zone B OU D

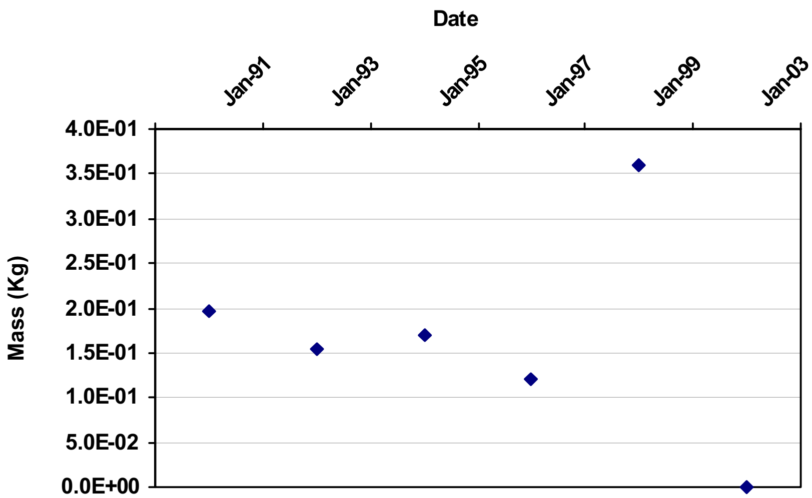
User Name: Julia Aziz

Location: McClellan AFB

State: California

COC: TRICHLOROETHYLENE (TCE)

Change in Dissolved Mass Over Time



Porosity: 0.30

Saturated Thickness:

Uniform: 60 ft

Mann Kendall S Statistic:

-5

Confidence in Trend:

76.5%

Coefficient of Variation:

0.70

Zeroth Moment Trend:

S

Data Table:

Effective Date	Constituent	Estimated Mass (Kg)	Number of Wells
1/1/1991	TRICHLOROETHYLENE (TCE)	2.0E-01	12
1/1/1993	TRICHLOROETHYLENE (TCE)	1.5E-01	12
1/1/1995	TRICHLOROETHYLENE (TCE)	1.7E-01	12
1/1/1997	TRICHLOROETHYLENE (TCE)	1.2E-01	7
1/1/1999	TRICHLOROETHYLENE (TCE)	3.6E-01	10
1/1/2001	TRICHLOROETHYLENE (TCE)	0.0E+00	3

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events); ND = Non-detect. Moments are not calculated for sample events with less than 6 wells.

MAROS First Moment Analysis

Project: McClellan AFB Zone B OU D

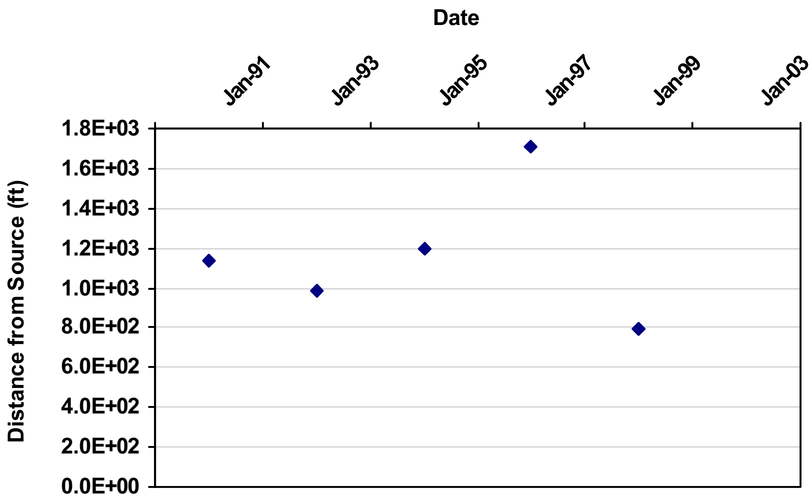
User Name: Julia Aziz

Location: McClellan AFB

State: California

COC: TRICHLOROETHYLENE (TCE)

Distance from Source to Center of Mass



Mann Kendall S Statistic:

0

Confidence in Trend:

40.8%

Coefficient of Variation:

0.29

First Moment Trend:

S

Data Table:

Effective Date	Constituent	Xc (ft)	Yc (ft)	Distance from Source (ft)	Number of Wells
1/1/1991	TRICHLOROETHYLENE (TCE)	2,167,260	367,204	1,138	12
1/1/1993	TRICHLOROETHYLENE (TCE)	2,167,260	367,030	986	12
1/1/1995	TRICHLOROETHYLENE (TCE)	2,167,280	367,265	1,201	12
1/1/1997	TRICHLOROETHYLENE (TCE)	2,167,915	367,431	1,709	7
1/1/1999	TRICHLOROETHYLENE (TCE)	2,167,287	366,773	799	10
1/1/2001	TRICHLOROETHYLENE (TCE)				3

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events). Moments are not calculated for sample events with less than 6 wells.

MAROS First Moment Analysis

Project: McClellan AFB Zone B OU D

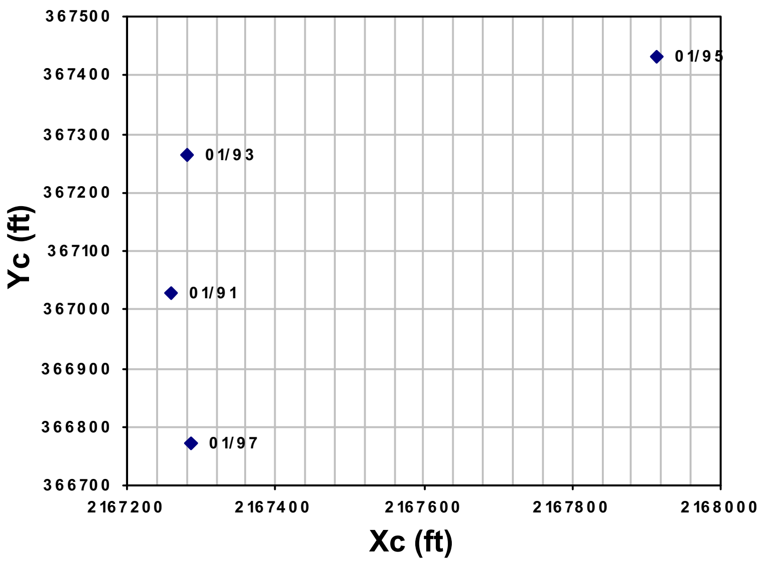
User Name: Julia Aziz

Location: McClellan AFB

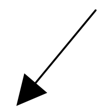
State: California

COC: TRICHLOROETHYLENE (TCE)

Change in Location of Center of Mass Over Time



Groundwater Flow Direction:



Source Coordinate:

X: 2,166,737

Y: 366,194

Effective Date	Constituent	Xc (ft)	Yc (ft)	Distance from Source (ft)	Number of Wells
1/1/1991	TRICHLOROETHYLENE (TCE)	2,167,260	367,204	1,138	12
1/1/1993	TRICHLOROETHYLENE (TCE)	2,167,260	367,030	986	12
1/1/1995	TRICHLOROETHYLENE (TCE)	2,167,280	367,265	1,201	12
1/1/1997	TRICHLOROETHYLENE (TCE)	2,167,915	367,431	1,709	7
1/1/1999	TRICHLOROETHYLENE (TCE)	2,167,287	366,773	799	10
1/1/2001	TRICHLOROETHYLENE (TCE)				3

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events). Moments are not calculated for sample events with less than 6 wells.

MAROS Second Moment Analysis

Project: McClellan AFB Zone B OU D

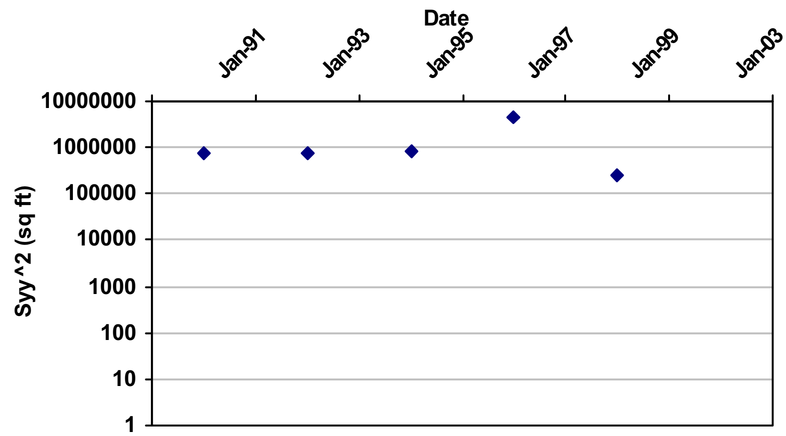
User Name: Julia Aziz

Location: McClellan AFB

State: California

COC: TRICHLOROETHYLENE (TCE)

Change in Plume Spread Over Time

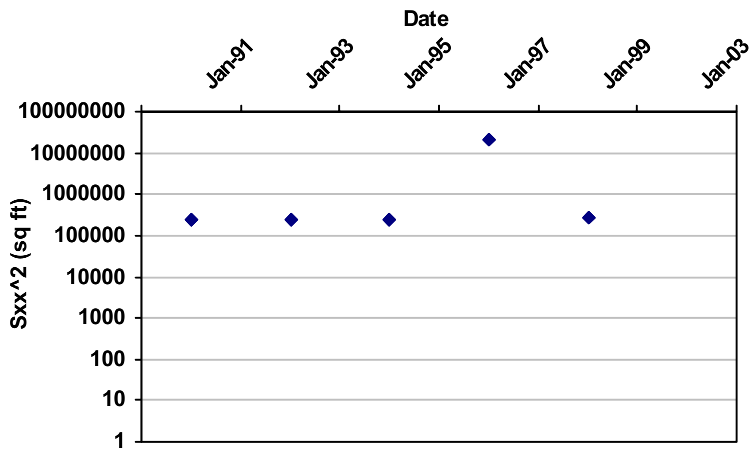


Mann Kendall S Statistic: 2

Confidence in Trend: 59.2%

Coefficient of Variation: 1.23

Second Moment Trend: NT



Mann Kendall S Statistic: 4

Confidence in Trend: 75.8%

Coefficient of Variation: 2.12

Second Moment Trend: NT

Data Table:

Effective Date	Constituent	Sigma XX (sq ft)	Sigma YY (sq ft)	Number of Wells
1/1/1991	TRICHLOROETHYLENE (TCE)	237,221	766,710	12
1/1/1993	TRICHLOROETHYLENE (TCE)	240,845	790,322	12
1/1/1995	TRICHLOROETHYLENE (TCE)	231,216	837,265	12
1/1/1997	TRICHLOROETHYLENE (TCE)	21,689,115	4,613,693	7
1/1/1999	TRICHLOROETHYLENE (TCE)	255,472	251,790	10
1/1/2001	TRICHLOROETHYLENE (TCE)			3

Note: Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A) - Due to insufficient Data (< 4 sampling events)

The Sigma XX and Sigma YY components are estimated using the given field coordinate system and then rotated to align with the estimated groundwater flow direction. Moments are not calculated for sample events with less than 6 wells.

MAROS Spatial Moment Analysis Summary

Project: McClellan AFB Zone B OU D

Location: McClellan AFB

User Name: Julia Aziz

State: California

	0th Moment	1st Moment (Center of Mass)			2nd Moment (Spread)		
Effective Date	**Estimated Mass (Kg)**	**Xc (ft)**	**Yc (ft)**	**Source Distance (ft)**	**Sigma XX (sq ft)**	**Sigma YY (sq ft)**	**Number of Wells**
TRICHLOROETHYLENE (TCE)							
1/1/1991	2.0E-01	2,167,260	367,204	1,138	237,221	766,710	12
1/1/1993	1.5E-01	2,167,260	367,030	986	240,845	790,322	12
1/1/1995	1.7E-01	2,167,280	367,265	1,201	231,216	837,265	12
1/1/1997	1.2E-01	2,167,915	367,431	1,709	21,689,115	4,613,693	7
1/1/1999	3.6E-01	2,167,287	366,773	799	255,472	251,790	10
1/1/2001	0.0E+00						3

Project: McClellan AFB Zone B OU D

Location: McClellan AFB

User Name: Julia Aziz

State: California

Moment Type	Consituent	Coefficient of Variation	Mann-Kendall S Statistic	Confidence in Trend	Moment Trend
Zeroth Moment: Mass					
	TRICHLOROETHYLENE (TCE)	0.70	-5	76.5%	S
1st Moment: Distance to Source					
	TRICHLOROETHYLENE (TCE)	0.29	0	40.8%	S
2nd Moment: Sigma XX					
	TRICHLOROETHYLENE (TCE)	2.12	4	75.8%	NT
2nd Moment: Sigma YY					
	TRICHLOROETHYLENE (TCE)	1.23	2	59.2%	NT

Note: The following assumptions were applied for the calculation of the Zeroth Moment:

Porosity: 0.30 **Saturated Thickness:** Uniform: 60 ft

Mann-Kendall Trend test performed on all sample events for each constituent. Increasing (I); Probably Increasing (PI); Stable (S); Probably Decreasing (PD); Decreasing (D); No Trend (NT); Not Applicable (N/A)-Due to insufficient Data (< 4 sampling events).

Note: The Sigma XX and Sigma YY components are estimated using the given field coordinate system and then rotated to align with the estimated groundwater flow direction. Moments are not calculated for sample events with less than 6 wells.

MAROS Sampling Location Optimization Results

Project: McClellan OUD ZoneB **User Name:** Meng

Location: McClellan AFB **State:** California

Sampling Events Analyzed: **From** 1995 **to** 2000

7/1/1995 7/1/2000

Parameters used:

Constituent	Inside SF	Hull SF	Area Ratio	Conc. Ratio
TRICHLOROETHYLENE (TCE)	0.1	0.01	0.95	0.95

Well	X (feet)	Y (feet)	Removable?	Average Slope Factor*	Minimum Slope Factor*	Maximum Slope Factor*	Eliminated?
TRICHLOROETHYLENE (TCE)							
MW-1001	2165839.75	366560.94	☑	0.574	0.262	0.949	☐
MW-1010	2165998.00	368273.56	☑	0.003	0.003	0.003	☐
MW-1027	2168527.25	367775.44	☑	0.262	0.000	0.481	☐
MW-104	2166810.00	367362.16	☑	0.712	0.534	0.925	☐
MW-1043	2165134.50	368138.75	☑	0.324	0.324	0.324	☐
MW-105	2168172.25	366814.81	☑	0.571	0.279	0.921	☐
MW-19D	2167162.75	365619.84	☑	0.156	0.084	0.242	☐
MW-51	2166767.25	366264.69	☑	0.642	0.390	0.944	☐
MW-54	2166658.50	366509.63	☑	0.556	0.292	0.873	☐
MW-57	2166663.50	365863.28	☑	0.257	0.098	0.447	☐
MW-58	2166656.25	366634.56	☑	0.329	0.048	0.665	☐
MW-59	2166608.50	365816.88	☑	0.377	0.025	0.799	☐

Note: The Slope Factor indicates the relative importance of a well in the monitoring network at a given sampling event; the larger the SF value of a well, the more important the well is and vice versa; the Average Slope Factor measures the overall well importance in the selected time period; the state coordinates system (i.e., X and Y refer to Easting and Northing respectively) or local coordinates systems may be used; wells that are NOT selected for analysis are not shown above.
* When the report is generated after running the Excel module, SF values will NOT be shown above.

MAROS Sampling Frequency Optimization Results

Project: McClellan OUD ZoneB **User Name:** Meng

Location: McClellan AFB **State:** California

The Overall Number of Sampling Events: 34

"Recent Period" defined by events: **From** 1995 1st Quarter 1/15/1995 **To** 2000 3rd Quarter 8/15/2000

"Rate of Change" parameters used:

Constituent	Cleanup Goal	Low Rate	Medium Rate	High Rate
TRICHLOROETHYLENE (TCE)	0.005	0.0025	0.005	0.01

Units: Cleanup Goal is in mg/L; all rate parameters are in mg/L/year.

Well	Recommended Sampling Frequency	Frequency Based on Recent Data	Frequency Based on Overall Data
TRICHLOROETHYLENE (TCE)			
EW-73	Annual	Annual	Annual
EW-83	Annual	Annual	Annual
EW-84	Annual	Annual	Annual
EW-85	Annual	Annual	Annual
EW-86	Annual	Annual	Annual
EW-87	Quarterly	Quarterly	Quarterly
MW-1001	Biennial	Annual	Annual
MW-1003	Biennial	Annual	Annual
MW-1010	Annual	Annual	Annual
MW-1027	Annual	Annual	Annual
MW-1028	Annual	Annual	Annual
MW-104	Annual	Annual	Annual
MW-1043	Annual	Annual	Annual
MW-105	Annual	Annual	Annual
MW-19D	Annual	Annual	Annual
MW-51	Biennial	Annual	Annual
MW-54	Annual	Annual	Annual
MW-57	Biennial	Annual	Annual
MW-58	Biennial	Annual	Annual
MW-59	Biennial	Annual	Annual

Note: Sampling frequency is determined considering both recent and overall concentration trends. Sampling Frequency is the final recommendation; Frequency Based on Recent Data is the frequency determined using recent (short) period of monitoring data; Frequency Based on Overall Data is the frequency determined using overall (long) period of monitoring data. If the "recent period" is defined using a different series of sampling events, the results could be different.

DRAFT FINAL

THREE-TIERED

GROUNDWATER MONITORING NETWORK

OPTIMIZATION EVALUATION

FOR

OPERABLE UNIT D

MCCLELLAN AIR FORCE BASE, CALIFORNIA

Prepared for

US Environmental Protection Agency

May 2003

PARSONS

Denver, Colorado

EXECUTIVE SUMMARY

This report presents a description and evaluation of the groundwater monitoring program associated with Operable Unit D (OU D) at McClellan Air Force Base (AFB), California. The monitoring program at this site was evaluated to identify potential opportunities to streamline monitoring activities while still maintaining an effective monitoring network. This evaluation is being conducted as part of an independent assessment of monitoring network optimization (MNO) methods by the US Environmental Protection Agency (USEPA) and the Air Force Center for Environmental Excellence (AFCEE).

Objectives

Groundwater monitoring programs have two primary objectives (USEPA, 1994b; Gibbons, 1994):

1. Evaluate long-term temporal trends in contaminant concentrations (*temporal objective*); and

2. Evaluate the extent to which contaminant migration is occurring (*spatial objective*).

The relative success of any remediation system (including the monitoring network) is judged based on the degree to which it achieves the stated objectives of the system. Designing an effective groundwater monitoring program involves locating monitoring points and developing a site-specific strategy for groundwater sampling and analysis that maximizes the amount of relevant information that can be obtained while minimizing incremental costs. The effectiveness of a monitoring network in achieving the two primary monitoring objectives can be evaluated quantitatively using statistical techniques. Qualitative evaluation also is important to allow consideration of such factors as hydrostratigraphy, locations of potential receptor exposure points with respect to a dissolved contaminant plume, and the direction(s) and rate(s) of contaminant migration.

The general objective of the project was to optimize the OU D LTM network by applying a three-tiered MNO approach to assess the degree to which the monitoring network addresses each of the two primary objectives of monitoring listed above and other important considerations. The three-tiered MNO evaluation described in this report examines the 51 wells (6 extraction wells and 45 monitoring wells) included in OU D monitoring network. The specific objectives of the project included:

- Apply a qualitative methodology that considers factors such as hydrostratigraphy, locations of potential receptors with respect to the dissolved plume, and the direction(s) and rate(s) of contaminant migration to establish the frequency at which monitoring should be conducted, and if each well should be retained in or removed from the monitoring program.

- Conduct a Mann-Kendall statistical analysis to determine the temporal trends of COCs over time, and apply an algorithm to determine the relevance of the trends within the monitoring network.

- Determine the relative amount of spatial information contributed by each monitoring well by performing a spatial statistical analysis utilizing kriging error predictions.

- Combine and evaluate the results of the three analyses to establish the frequency at which monitoring should be conducted, as well as the optimal number and locations of wells in the monitoring network.

Current Monitoring Program

Quarterly sampling of off-Base wells begin in 1984 as part of the Installation Restoration Program at McClellan AFB. In 1986, the Groundwater Sampling and Analysis Program was established to support ongoing remedial investigation/feasibility study activities. In 1996, the Groundwater Monitoring Plan (GWMP) for on- and off-Base wells was established under the Long-Term Monitoring Program to update the GSAP and to support groundwater operable unit (GWOU) activities associated with the Interim Record of Decision (IROD). Under the GWMP, groundwater samples are collected quarterly from selected wells across the entire Base and analyzed for contaminants of concern (COCs) associated with the respective plumes. Groundwater sampling data are used to monitor how plume sizes and shapes are changing in response to extraction well (EW) pumping to determine if remedial action objectives are being met.

In the OU D area, groundwater sampling is conducted primarily to monitor areas where dissolved VOC concentrations exceed MCLs (termed VOC target areas) in monitoring zones A and B (monitoring of deeper zones in the OU D area is not performed). In addition, selected wells that are more distant from the VOC target areas are monitored to confirm and demonstrate that significant concentrations of COCs are not present. The field sampling plan identifies the wells to be sampled in the area based on the rationale and decision logic presented in the GWMP (Radian, 1997). Based on the logic presented in the GWMP, the monitoring frequency and sampling rationale for each well are continually evaluated, and can change as new sampling data are obtained. Because the OU D plume is contained by the extraction system and the plume is well defined, all of the wells associated with the OU D plume are sampled relatively infrequently (annually or biennially). The *Monitoring and Extraction Well Baseline*

Sampling Frequency and Rationale (URS, 2002) identifies 6 extraction wells and 45 monitoring wells to be monitored in the vicinity of the OU D plume, based on groundwater-quality data collected through the first quarter of 2002.

Optimization Findings

The OU D groundwater monitoring program was evaluated using results for sampling events performed from April 1990 through August 2001. The analytical database provided to Parsons contained from 5 to 18 sampling results for each of the 51 wells in the OU D monitoring program. The primary COCs identified for the OU D plume in the GWOU IROD are tricholoroethene (TCE), tetrachlroethene (PCE) , *cis*-1,2-dicholorethene, (DCE), and 1,2-dichloroethane (DCA); therefore, the MNO evaluation focused on these constituents. TCE is the COC with the highest concentrations and largest spatial extent in groundwater at McClellan AFB OU D; therefore TCE sampling results were the primary data used to conduct the three-tiered MNO.

Results from the three-tiered monitoring network optimization for OU D at McClellan AFB indicate that 30 of the 51 OU D area wells could be removed from the groundwater LTM program with little loss of information. A refined monitoring program consisting of 21 wells (13 to be sampled annually, and 8 to be sampled biennially) would be adequate to address the two primary objectives of monitoring. This refined monitoring network would result in an average of 17 sampling events per year, compared to 34 events per year in the current monitoring program. ***Implementing these recommendations for optimizing the LTM monitoring program at OU D at McClellan AFB could reduce current LTM annual monitoring events by 50 percent. Based on analytical costs alone, implementing these recommendations could save $2550 per year based on an estimate of $150 per sample analysis.*** The recommendations provided in this report for removal of off-Base monitoring wells from the LTM program were based largely on technical considerations, and should be evaluated in the light of relevant community relations concerns.

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ACRONYMS AND ABBREVIATIONS

1,2-DCA	dichloroethane
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
ASCE	American Society of Chemical Engineers
bgs	below ground surface
bmsl	below mean sea level
COC	contaminant of concern
DNAPL	dense nonaqueous-phase liquid
ESRI	Environmental Systems Research Institute, Inc.
ft/day	foot (feet) per day
ft/ft	foot per foot
GIS	geographical information system
GSAP	Groundwater Sampling and Analysis Program
GWMP	Groundwater Monitoring Plan
GWOU	Groundwater Operable Unit
IROD	Interim Record of Decision
IRP	Installation Restoration Program
LNAPL	light nonaqueous-phase liquid
LTM	long-term monitoring
LTMP	Long-Term Monitoring Program
µg/L	microgram(s) per liter
MCL	maximum contaminant level
MNO	monitoring network optimization
OU D	Operable Unit D
PCE	tetrachloroethene
PQL	practical quantitation limit
RAO	remedial action objective
TCA	trichloroethene
TCE	trichloroethene
USEPA	United States Environmental Protection Agency
VOC	volatile organic compound

SECTION 1

INTRODUCTION

Groundwater monitoring programs have two primary objectives (U.S. Environmental Protection Agency [USEPA], 1994b; Gibbons, 1994):

1. Evaluate long-term temporal trends in contaminant concentrations at one or more points within or outside of the remediation zone, as a means of monitoring the performance of the remedial measure (*temporal objective*); and

2. Evaluate the extent to which contaminant migration is occurring, particularly if a potential exposure point for a susceptible receptor exists (*spatial objective*).

The relative success of any remediation system and its components (including the monitoring network) must be judged based on the degree to which it achieves the stated objectives of the system. Designing an effective groundwater monitoring program involves locating monitoring points and developing a site-specific strategy for groundwater sampling and analysis so as to maximize the amount of relevant information that can be obtained while minimizing incremental costs. Relevant information is that required to effectively address the temporal and spatial objectives of monitoring. The effectiveness of a monitoring network in achieving these two primary objectives can be evaluated quantitatively using statistical techniques. In addition, there may be other important considerations associated with a particular monitoring network that are most appropriately addressed through a qualitative assessment of the network. The qualitative evaluation may consider such factors as hydrostratigraphy, locations of potential receptor exposure points with respect to a dissolved contaminant plume, and the direction(s) and rate(s) of contaminant migration.

This report presents a description and evaluation of the groundwater monitoring program associated with Operable Unit D (OU D) McClellan Air Force Base (AFB), California. The current monitoring program at this site was evaluated to identify potential opportunities to streamline monitoring activities while still maintaining an effective monitoring network. This evaluation is being conducted as part of an independent assessment of monitoring network optimization (MNO) methods by the USEPA and the Air Force Center for Environmental Excellence (AFCEE). A three-tiered approach, consisting of a qualitative evaluation, an evaluation of temporal trends in contaminant concentrations, and a statistical spatial analysis, was conducted to assess the degree to which the monitoring network addresses each of the two primary objectives of monitoring, and other important considerations. The results of the three evaluations were combined and used to assess the optimal frequency of monitoring and the spatial distribution of the components of the monitoring network. The results of the analysis were then used to develop recommendations for optimizing the monitoring program at OU D.

SECTION 2

SITE BACKGROUND INFORMATION

The location, operational history, geology, and hydrogeology of OU D at McClellan AFB are briefly described in the following subsections.

2.1 SITE DESCRIPTION

McClellan AFB is located approximately 7 miles northeast of downtown Sacramento, California. The installation comprises approximately 3,000 acres and is bounded by the city of Sacramento on the west and southwest, the unincorporated areas of Antelope on the north, Rio Linda on the northwest, and North Highlands on the east. OU D is located in the northwestern part of McClellan AFB, northwest of Building 1069 along Patrol Road, and occupies approximately 192 acres.

Through most of its operational history, McClellan AFB was engaged in a wide variety of military/industrial operations involving the use, storage, and disposal of hazardous materials, including industrial solvents, caustic cleaners, electroplating chemicals, metals, polychlorinated biphenyls, low-level radioactive wastes, and a variety of fuel oils and lubricants. Historical waste-disposal practices included the use of burial pits for the disposal and/or burning of these materials.

Fifteen sites that were formerly operated as waste pits are located at OU D. These waste pits were operational from the mid-1950s through the 1970s (CH2M Hill, 1994a). In 1956, the first burial pit was created for disposal of sodium valves from aircraft engines. Additional burial and burn pits were constructed throughout the 1960s and 1970s, and were used for the disposal of refuse, other solid waste, oil, various chemicals, and industrial sludges. From the late 1970s into the early 1980s, many of the burial and burn pits were closed and covered with soil. In 1985, the "Area D" cap was constructed over waste pits CS-1, CS-2, CS-3, CS-4, CS-5, CS-S, CS-A, and CS-T to reduce the infiltration of precipitation through the waste pits, thereby also reducing the formation and migration of leachate to groundwater at the site. Prior to 1985, waste pit CS-4 was excavated to remove the sludge waste, and pits CS-6 and CS-26 also were excavated and backfilled. The waste-disposal pits at OU D are no longer used for disposal of waste products (CH2M Hill, 1992).

Based on evidence of environmental contamination, McClellan AFB was included on the National Priorities List of Superfund sites in 1987. A single OU was established for groundwater at the Base, and an Interim Record of Decision (IROD) was signed for the Base-wide Groundwater OU (GWOU) in 1995 (CH2M Hill, 1995). The IROD specifies groundwater extraction and treatment as the interim remedy for groundwater at OU D, thereby endorsing the extraction well system that was installed in 1987 (see Section 2.5).

In 1995, McClellan AFB was recommended for closure under the Base Realignment and Closure Act (BRAC). The recommendation became effective on September 28, 1995, and the installation was closed in July, 2001. Ongoing environmental restoration activities are being directed by the Air Force Real Property Agency (formerly the Air Force Base Conversion Agency).

2.2 GEOLOGY AND HYDROGEOLOGY

2.2.1 Geology

The Central Valley is an elongate basin, bounded on the east and west by nearly-continuous mountain ranges. Sediments derived from the bordering mountain ranges have accumulated in the basin for millions of years, and now comprise a sequence of unconsolidated to partly consolidated deposits that, in places along the western side of the Valley, may be as much as 30,000 feet thick (Norris and Webb, 1990). The sediments that fill the Valley thin to the east, but the sequence is probably several thousand feet thick beneath the city of Sacramento.

The sediments in the upper few hundred feet of the subsurface beneath the Base consist of coalescing deposits laid down by fluvial systems of various sizes and competence that flowed generally from northeast to southwest or west. Soils are primarily sand, silt, and clay, generally poorly sorted, with localized occurrences of gravel, generally in the southern part of the Base. The nature of fluvial deposition, including stream meandering and abandonment/reoccupation of channels, produced morphologically irregular lenses and strata that are laterally and vertically discontinuous. The coalescing and intercalating nature of the sediments makes distinction among units, or stratigraphic correlation over distances greater than a few tens of feet, difficult (CH2M Hill, 1994a).

2.2.2 Local Hydrogeology

Although the stratigraphy of the sediments beneath McClellan AFB is complex, the juxtaposed and intercalated strata of sand, silt, clay, and gravel comprise a single groundwater system. The geologic and hydraulic properties of the upper water-bearing unit vary over short distances, and the more permeable intervals serve to establish hydraulic interconnection vertically and horizontally, so that in general, groundwater movement (and associated advective migration of contaminants) may occur throughout the groundwater system. The upper unit beneath McClellan AFB has been divided into the vadose (unsaturated) zone and five monitoring zones below the water table, distinguished on the basis of general hydraulic characteristics. From shallowest to deepest, the saturated zones are labeled A, B, C, D, and E (Radian, 1999a). The monitoring zones at McClellan AFB were designated primarily for the purpose of indicating the completion intervals of monitoring wells; all the monitoring zones are hydraulically connected to a greater or lesser degree, and groundwater can move between adjacent zones (CH2M Hill, 1994a). Generally, the zones dip to the west, and increase in thickness from east to west. In is entirely possible for two adjacent wells screened at different depth intervals to be completed within the same monitoring zone, or for two wells screened at similar depths to be completed in different monitoring zones. These local variations in the depths of monitoring zones are a consequence of the heterogeneity of the sediments beneath the Base, and the relative capacities of different deposits to transmit water.

The depth to the water table beneath McClellan AFB ranges between about 90 and 110 feet below ground surface (bgs) (CH2M Hill, 1994b and 1999). At OU D, the depth to shallow groundwater varies from approximately 99 to 102 feet bgs. As a consequence of the relatively deep water table, surface streams are not in direct hydraulic communication with the groundwater system beneath the Base (CH2M Hill, 1995). Water-table elevations have declined at rates ranging from 1 to 2 feet per year during the past 50 years. Groundwater levels are expected to continue to decline at a rate of about 2 feet per year as a consequence of large-scale groundwater production for industrial, irrigation, and municipal uses in the Sacramento area (CH2M Hill, 1994b).

The thickness of the A monitoring zone ranges from 9 to 50 feet, and groundwater in the A zone exists under unconfined conditions. The thickness of monitoring zone B ranges from 40 to 75 feet, and groundwater in this zone appears to exist under partially confined conditions. However, if the wells screened in the intermediate zone between the A and B monitoring zones are reassigned to either the A or B zones as described in Section 3.1, then the defined thickness of these two zones will increase. Monitoring wells at OU D have been constructed only in the A and B monitoring zones (Radian, 1999a); therefore, no information is available regarding the deeper monitoring zones at OU D.

Under natural conditions, prior to installation and operation of the OU D groundwater extraction system, groundwater typically moved from northeast to south or southwest in the A monitoring zone, and from north to south in the B monitoring zone (CH2M Hill, 1992). The local directions of groundwater movement beneath OU D currently are influenced by the groundwater extraction system operating at the site. Groundwater flow generally is directed radially inward toward the extraction wells (EWs).

Horizontal hydraulic gradients in the groundwater system at OU D range from 0.0008 foot per foot (ft/ft) to 0.0021 ft/ft, with the largest gradients occurring near active EWs.

Vertical hydraulic gradients have been calculated using pairs of adjacent monitoring wells that are completed in different monitoring zones. Vertical gradients calculated using well pairs within that part of the groundwater system influenced by active groundwater extraction at OU D are generally downward, similar to vertical gradients that exist between the A and B monitoring zones in other parts of the Base (Radian, 1999a). Downward gradients range in magnitude from about 0.003 ft/ft to 0.04 ft/ft, with the greatest vertical gradients occurring near active EWs. At distances greater than 1,000 feet from the extraction system, vertical gradients may be directed upward or downward, depending on local potentiometric conditions. The vertical gradients between monitoring zones A and B are usually upward in the winter and downward during the rest of the year.

Hydraulic conductivity is the property of a porous medium that describes the capacity of the medium to transmit water. The horizontal hydraulic conductivity of the sediments in monitoring zones A and B may range as high as 30 feet per day (ft/day); however, the weighted average hydraulic conductivity of the sediments in the two zones is somewhat lower (about 5.6 ft/day) (CH2M Hill, 1994a). The value of horizontal hydraulic conductivity is about 5 to 15 times greater than the vertical hydraulic conductivity (CH2M Hill, 1992), indicating that advective groundwater movement beneath OU D occurs primarily in the horizontal plane. Based on the weighted average of horizontal hydraulic conductivity for the A and B monitoring zones (5.6 ft/day), the range of horizontal hydraulic gradients within OU D (about 0.001 to 0.002 ft/ft), and an approximate effective porosity of 0.15 (a value consistent with the results of prior investigations at McClellan AFB [CH2M Hill, 1992]), the calculated horizontal advective velocity of groundwater movement in the A and B monitoring zones at OU D ranges between about 14 and 30 feet per year (ft/year) (Parsons, 2000).

2.3 NATURE AND EXTENT OF CONTAMINATION

The contaminants of concern (COCs) in groundwater at OU D are exclusively chlorinated aliphatic hydrocarbons (CAHs). Primary COCs include trichloroethene (TCE), tetrachloroethene (PCE), *cis*-1,2-dichloroethene (DCE), and 1,2-dichloroethane (DCA). These four compounds were identified in the GWOU IROD (CH2M Hill, 1995) as Base-wide groundwater COCs based on their frequency of detections, exceedance of regulatory maximum contaminant levels (MCLs), and health risks. However, a recent review of OU D-specific results suggests that additional volatile organic compounds (VOCs) may be COCs in groundwater directly beneath OU D (Parsons, 2000). For example, 1,1-DCA, 1,1-DCE, 1,1,1-trichloroethene (TCA), and vinyl chloride were detected in groundwater beneath OU D at frequencies greater than 5 percent, and at concentrations above their respective MCLs (Radian, 1999b).

A dissolved VOC plume in groundwater, consisting primarily of TCE at concentrations greater than the federal MCL of 5 micrograms per liter (µg/L), has been identified in the central and southwestern parts of OU D (CH2M Hill, 1999). Historically, low concentrations of VOCs also have been detected occasionally in groundwater samples collected from wells at distances up to approximately 500 feet off-Base to the northwest. No contaminants have been detected in groundwater samples from off-Base monitoring wells located west or northwest of OU D since 1995. However, the dissolved CAH plume sourced at the OU D waste pits has migrated with regional groundwater flow to the south and southwest, and historically extended off-Base, to the west of OU D (CH2M Hill, 1994a). The off-Base extension of the plume since has been hydraulically captured by the OU D groundwater extraction system (Radian, 1999b).

Groundwater "hot spots" at McClellan AFB are defined as areas where contaminants are present at concentrations greater than 100 times the applicable MCL. Such hot spots have been identified near the former waste pits at Sites CS-2, CS-3, CS-5, CS-A, CS-S, and CS-T, which are the sources of VOCs dissolved in groundwater. The CAHs detected most frequently at these hot spots include PCE, TCE, *cis*-1,2-DCE, and 1,2-DCA. Prior to the commencement of groundwater remediation, several VOCs were detected in groundwater hot spots at OU D at concentrations that occasionally represented appreciable fractions of the compounds' solubility in water. Although concentrations greater than 1 percent of solubility can be an indication of the presence of dense nonaqueous-phase liquid (DNAPL) (USEPA, 1994a), previous investigators had considered the likelihood of VOCs being present in the subsurface at OU D as a DNAPL to be low (CH2M Hill, 1997).

Parsons (2000) reevaluated the potential presence of DNAPL at OU D as part of a remedial process optimization (RPO) assessment. The elevated concentrations of VOCs detected in soil-vapor and groundwater samples collected during earlier phases of investigation and remediation activities at OU D were interpreted as evidence that CAHs likely were present as DNAPL in the vadose zone, and possibly below the water table, prior to implementation of interim remedial measures. Implementation of soil vapor extraction (SVE) has removed considerable VOC mass from the vadose zone during the past decade; however, because DNAPL is capable of migrating into "dead-end" soil-pore spaces that are inaccessible to through-flowing fluids (e.g., air or water) (Pankow and Cherry, 1996), it is likely that some CAH mass remains in the vadose zone as residual DNAPL.

In addition, increases in the concentrations of TCE and 1,1-DCE in extracted groundwater through time suggest that a free or residual DNAPL remains in the subsurface near or below the water table in the vicinities of wells EW83 and EW87. However, while the increased flow related to pumping may be enhancing the rate of dissolution of CAH from a local DNAPL source, the increases in dissolved CAH concentrations are not likely to be of sufficient magnitude to greatly affect the rate of mass removal. Therefore, residual DNAPL near or below the water table at OU D may persist as a continuing source of dissolved contaminants for an extended period of time.

Migration of the VOC plume has been halted as a result of the operation of the groundwater extraction and treatment system since its installation in 1987, and the OU D plume is currently regarded as being "fully contained" (Radian, 1999b). In general the concentrations of dissolved CAH in groundwater have decreased appreciably during the period of system operation. However, low concentrations of VOCs continue to be detected sporadically at locations distal from the hot spots, west and southwest of OU D (CH2M Hill, 1994a). According to the first quarter 2002 (1Q02) Groundwater

Monitoring Program Quarterly Report (URS, 2002), 15 years of groundwater remediation systems operation (1987 to 2002) have resulted in the following outcomes:

- The areal extent of the TCE plume has been reduced by 38.7 percent;
- Maximum TCE concentrations have been reduced below 100 µg/L; and
- The plume area defined by the 100-µg/L TCE isopleth has been essentially stable during the last 11.5 years of extraction system operation.

2.4 REMEDIAL SYSTEMS

The remediation systems currently operating at OU D include an SVE and treatment system, a groundwater extraction system, and associated monitoring networks. Pilot-scale testing of SVE at OU D began in March 1993, and continuous system operation was initiated in March 1994.

The primary objective of the groundwater extraction system at OU D is to prevent off-Base migration of CAH-contaminated groundwater, thereby eliminating potential exposure of off-Base receptors. A secondary objective of groundwater remediation, as expressed in the Base-wide GWOU IROD (CH2M Hill, 1995), is aggressive extraction and treatment of groundwater to remove contaminant mass.

Operation of the groundwater extraction system at OU D commenced in March 1987. The current groundwater extraction system in OU D consists of six EWs (EW-73 and EW-83 through EW-87), five of which are operational. Well EW-84 was removed from service in August 1997, because its continued operation was judged to be unnecessary in achieving the objective of plume containment (Radian, 1999a). Current plans call for well EW-84 to remain off-line indefinitely. All EWs were installed to a depth of about 160 feet bgs, and are fully screened across both the A and B monitoring zones. The design production rates for the individual wells in the current extraction system range from 10 gallons per minute (gpm) to 25 gpm; the actual production rates (0 to about 11 gpm) are generally somewhat lower than the design rates. Groundwater extracted at OU

D is conveyed via pipeline to a 1,500- gpm capacity groundwater treatment plant (GWTP), which is centrally located at McClellan AFB and treats water extracted from multiple OUs.

SECTION 3

LONG-TERM MONITORING PROGRAM AT OU D

The current groundwater monitoring program at OU D was examined to identify potential opportunities for streamlining monitoring activities while still maintaining an effective performance and compliance monitoring program. The current monitoring program at OU D is reviewed in the following subsections.

3.1 DESCRIPTION OF MONITORING PROGRAM

Quarterly sampling of off-Base wells begin in 1984 as part of the Installation Restoration Program (IRP) at McClellan AFB. In 1986, the Groundwater Sampling and Analysis Program (GSAP) was established to support ongoing remedial investigation/feasibility study activities. In 1996, the Groundwater Monitoring Plan (GWMP) for on- and off-Base wells was established under the Long-Term Monitoring Program (LTMP) to update the GSAP and to support GWOU IROD activities. Under the GWMP, groundwater samples are collected quarterly from selected wells across the entire Base and analyzed for COCs associated with the respective plumes. However, because groundwater sampling focus areas change from quarter to quarter, each areas of the Base are targeted for a detailed analysis of groundwater quality once each year. Groundwater sampling and analysis for wells in the OU D area occurs during the first quarter of each year (URS, 2001).

Groundwater sampling data are used to monitor how plume sizes and shapes are changing in response to EW pumping to determine if the following remedial action objectives (RAOs), as specified in the GWOU IROD (CH2M Hill, 1995) for McClellan AFB, are being met:

- Prevent contaminated groundwater from migrating off-Base;

- Contain hot spots; and

- Prevent downward migration of contamination.

As described in Section 2.4, groundwater sampling data also are used to evaluate contaminant mass removal rates.

In the OU D area, groundwater sampling is conducted to monitor areas where dissolved VOC concentrations exceed MCLs (termed VOC target areas) in monitoring zones A and B (there are no target areas in deeper monitoring zones in the OU D area). The field sampling plan (FSP) identifies the wells to be sampled in the area based on the rationale and decision logic presented in the GWMP (Radian, 1997). Based on the logic presented in the GWMP, the monitoring frequency and sampling rationale for each well are continually evaluated, and can change as new sampling data are obtained. Because the OU D plume is contained by the extraction system and the plume is well defined, all of the wells associated with the OU D plume are sampled relatively infrequently (annually or biennially). The *Monitoring and Extraction Well Baseline Sampling Frequency and Rationale* (URS, 2002) identifies 6 EWs and 45 monitoring wells to be monitored in the vicinity of the OU D plume, based on groundwater-quality data collected through 1Q02.

Figure 3.1 shows the 51 wells currently monitored at OU D, and their monitoring frequency. Table 3.1 lists these wells along with their assigned monitoring zone, designated sampling frequency, and sampling rationale based on the information provided in the FSP for 1Q02, 2Q02, and 3Q02 (URS, 2002). Wells MW-1010 and MW-1042 are considered "cross-zone wells" (designated as "AB" in the "Original Zone" column in Table 3.1); these wells are screened across monitoring zones A and B. However, sampling results for these wells are assigned to a single monitoring zone based on water-level and lithologic data, contaminant concentrations, and well construction information for each cross-zone monitoring well compared to nearby single-zone monitoring wells. Analytical results for samples collected from well MW-1010 are assigned to zone B, and sampling results for MW-1042 are assigned to zone A. EWs at

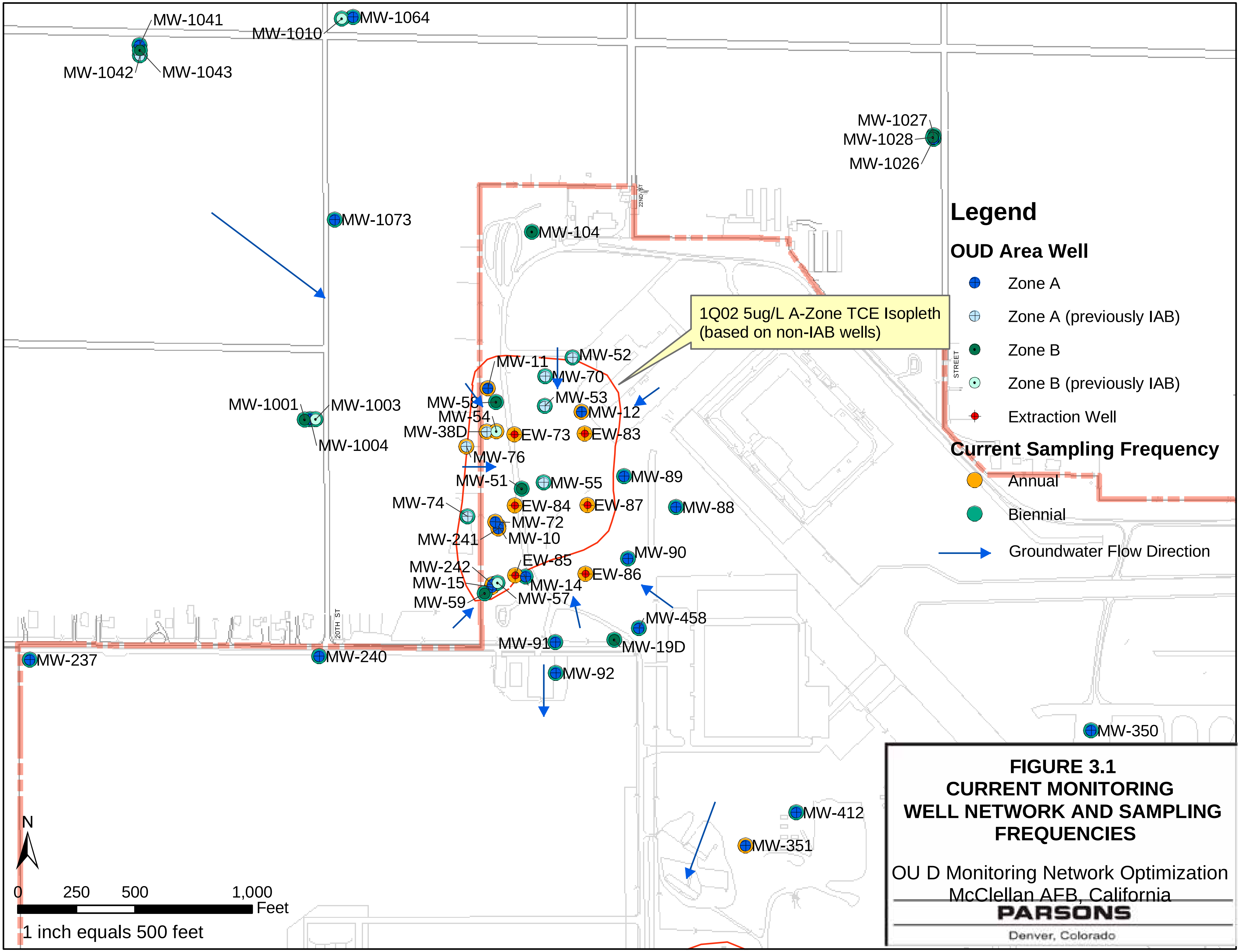


FIGURE 3.1
CURRENT MONITORING WELL NETWORK AND SAMPLING FREQUENCIES

OU D Monitoring Network Optimization
McClellan AFB, California

PARSONS
Denver, Colorado

TABLE 3.1
CURRENT GROUNDWATER MONITORING PROGRAM
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
McCLELLAN AFB, CALIFORNIA

Well ID	Screened Interval (ft msl) [a]	Original Zone	Zone	Sampling Frequency [b]
Extraction Wells				
EW-73	20.7 to -99.3	IAB	A/B	Annual
EW-83	24.22 to -95.78	IAB	A/B	Annual
EW-84	22.8 to -97.2	IAB	A/B	Annual
EW-85	22.9 to -97.1	IAB	A/B	Annual
EW-86	17.9 to -102.1	IAB	A/B	Annual
EW-87	18.1 to -101.9	IAB	A/B	Annual
Zone A Wells				
MW-10	-37.82 to -47.82	A	A	Annual
MW-11	-36.31 to -46.31	A	A	Annual
MW-12	-34.67 to -44.67	A	A	Annual
MW-14	-35.52 to -45.52	A	A	Biennial
MW-15	-41.48 to -46.48	A	A	Annual
MW-38D	-57.32 to -67.32	IAB	A* [c]	Annual
MW-52	-80.16 to -90.16	IAB	A*	Biennial
MW-53	-65.47 to -75.47	IAB	A*	Biennial
MW-55	-67.46 to -75.47	IAB	A*	Biennial
MW-70	- 66.77 to -76.77	IAB	A*	Biennial
MW-72	-58.45 to -68.45	A	A	Annual
MW-74	-71.39 to -81.39	IAB	A*	Biennial
MW-76	-80.23 to -90.23	IAB	A*	Annual
MW-88	-38.46 to -48.46	A	A	Biennial
MW-89	-38.89 to -48.89	A	A	Biennial
MW-90	-34.94 to -44.94	A	A	Biennial
MW-91	-35.85 to -45.85	A	A	Biennial
MW-92	-38.39 to 48.39	A	A	Biennial
MW-237	-41.55 to -61.55	A	A	Biennial
MW-240	-40.56 to -60.56	A	A	Biennial
MW-241	-49.24 to -69.24	A	A	Annual
MW-242	-52.25 to -67.25	A	A	Annual
MW-350	-32.92 to -52.92	A	A	Biennial
MW-351	-33.97 to -49.97	A	A	Annual
MW-412	-31.76 to -51.76	A	A	Biennial
MW-458	-40.81 to -60.81	A	A	Biennial
MW-1004	-30.88 to -40.88	A	A	Biennial
MW-1026	-31.93 to 41.93	A	A	Biennial
MW-1041	-52.87 to -62.87	A	A	Biennial
MW-1042	-80.18 to -90.18	AB	A*	Biennial
MW-1064	-30.96 to -50.96	A	A	Biennial
MW-1073	-52.6 to -62.6	A	A	Biennial
Zone B Wells				
MW-19D	-80.16 to -90.16	B	B	Biennial
MW-51	-112.96 to -127.96	B	B	Biennial
MW-54	-81.61 to -91.61	IAB	B*	Annual
MW-57	-80.38 to -90.38	IAB	B*	Biennial
MW-58	-112.63 to -122.63	B	B	Biennial
MW-59	-106.32 to -116.32	B	B	Biennial
MW-104	-113.78 to -123.78	B	B	Biennial
MW-1001	-105.25 to -115.25	B	B	Biennial
MW-1003	-77.72 to -87.72	IAB	B*	Biennial
MW-1010	-86.37 to -96.37	AB	B*	Biennial
MW-1027	-70.47 to -80.47	B	B	Biennial
MW-1028	-117 to -127	B	B	Biennial
MW-1043	-137.09 to -147.09	B	B	Biennial

[a] ft bmsl = feet relative to mean sea level.
[b] Sampling frequency based on 1st Quarter 2002 Groundwater Monitoring Program Quarterly Report (URS, 2002).
[c] * = Reassigned monitoring zone, per URS (2002).

OU D extract water from zones A and B, and analytical data for samples from these wells are used to characterize plumes in both zones. Ten of the monitoring wells are screened in intermediate zones between A and B monitoring zones (designated as "IAB" in the "Original Zone" column in Table 3.1), and concentrations from these wells have historically not been used for plume interpretation. However, these wells are sampled because the data may provide useful information about the effectiveness of the extraction system. For this MNO analysis, the IAB wells were assigned to either the A or B zones based on the recommendations listed in Table 3-3 of the 1Q02 Quarterly Monitoring Report (URS, 2002).

The six EWs are sampled annually. Of the 32 OU D wells that monitor zone A, 22 are sampled biennially and 10 are sampled annually. Twelve of the 13 zone B wells are sampled biennially, and the remaining well is sampled annually. All samples from the monitoring and extraction wells are analyzed for VOCs by USEPA Method SW8260B.

It should be noted that, in 2001, OU D wells were monitored using passive diffusion bag samplers (PDBSs); conventional-purge sampling was performed prior to and following the 2001 sampling event. Minor differences in analytical results may be attributable to use of the two types of sampling techniques. The three-tiered MNO evaluation described in this report examines the current monitoring network consisting of 51 wells (17 sampled annually and 34 biennially).

3.2 SUMMARY OF ANALYTICAL DATA

The OU D groundwater monitoring program was evaluated using results for sampling events performed from April 1990 through August 2001. These analytical data, along with water level and well location information was provided to Parsons by Ms. Diane Kiota, the Air Force groundwater program manager at McClellan. The database was processed to remove duplicate data measurements by retaining the maximum result of the duplicate samples. The analytical database provided to Parsons contained from 5 to 18 sampling results for each of the 51 wells in the OU D monitoring program. As discussed in Section 2.3, the primary COCs identified for the OU D plume in the GWOU

IROD are TCE, PCE, *cis*-1,2-DCE, and 1,2-DCA; therefore, the MNO evaluation focused on these constituents. Other VOCs of concern at the Base were not measured above their MCLs in the OU D area during recent sampling events (URS, 2002), and therefore were excluded from the MNO analysis.

Table 3.2 presents a summary of the occurrence of the four primary COCs in OU D groundwater based on the data collected from April 1990 through August 2001. As indicated in this table, TCE is the COC detected most frequently and at the greatest concentrations in groundwater at McClellan AFB OU D. TCE has been detected in approximately 63 percent of samples, and has exceeded its MCL of 5 μg/L in approximately 38 percent of the samples. TCE has been detected in 46 of the 51 wells in the monitoring program, and has exceeded the MCL in 26 of these wells. One of TCE's reductive dechlorination daughter products, *cis*-1,2-DCE, is the second-most prevalent compound, and has been detected in 36 percent of the collected samples. However, detected concentrations of *cis*-1,2-DCE have exceeded the MCL of 70 μg/L in less than 1 percent of samples. PCE and 1,2-DCA have been detected at OU D in approximately 24 percent and 32 percent of samples, respectively; these compounds have been detected within the footprint of the TCE plume. Detected concentrations of these COCs have exceeded their MCLs in approximately 5 percent and 14 percent of the samples, respectively.

TCE sampling results were the primary data used to conduct the three-tiered monitoring network optimization due to the magnitude and spatial extent of TCE concentrations in groundwater at OU D compared to the other detected compounds.

TABLE 3.2
SUMMARY OF OCCURRENCE OF GROUNDWATER CONTAMINANTS OF CONCERN
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
McCLELLAN AFB, CALIFORNIA

Parameter	Total Samples[a/]	Percentage of Detects	Range of Detects (µg/L)[b/]	MCL (µg/L)[c/]	Percentage of Samples with MCL Exceedances	Number of Wells with Results	Number of Wells with Detections	Number of Wells with MCL Exceedances
1,2-DCA	568	32.2%	0.0265-210	5	13.7%	51	38	13
cis-1,2-DCE	428	36.2%	0.0387-87.4	70	0.47%	51	27	2
PCE	569	23.6%	0.0294-770	5	5.4%	51	34	5
TCE	569	62.9%	0.0519-5000	5	38.3%	51	46	26

[a/] Analytical data analyzed includes sampling results from April 1990 through August 2001.

[b/] µg/L = micrograms per liter.

[c/] MCL = maximum contamiant level.

SECTION 4

QUALITATIVE MNO EVALUATION

An effective groundwater monitoring program will provide information regarding contaminant plume migration and changes in chemical concentrations through time at appropriate locations, enabling decision-makers to verify that contaminants are not endangering potential receptors, and that remediation is occurring at rates sufficient to achieve RAOs within a reasonable time frame. The design of the monitoring program should therefore include consideration of existing receptor exposure pathways, as well as exposure pathways arising from potential future use of the groundwater.

Performance monitoring wells located upgradient, within, and immediately downgradient from a plume provide a means of evaluating the effectiveness of a groundwater remedy relative to performance criteria. Long-term monitoring (LTM) of these wells also provides information about migration of the plume and temporal trends in chemical concentrations. Groundwater monitoring wells located downgradient from the leading edge of a plume (i.e., sentry wells) are used to evaluate possible changes in the extent of the plume and, if warranted, to trigger a contingency response action if contaminants are detected.

Primary factors to consider when developing a groundwater monitoring program include at a minimum:

- Aquifer heterogeneity,
- Types of contaminants,
- Distance to potential receptor exposure points,
- Groundwater seepage velocity,

- Potential surface-water impacts, and
- The effects of the remediation system.

These factors will influence the locations and spacing of monitoring points and the sampling frequency. Typically, the greater the seepage velocity and the shorter the distance to receptor exposure points, the more frequently groundwater sampling should be conducted.

One of the most important purposes of LTM is to confirm that the contaminant plume is behaving as predicted. Graphical and statistical tests can be used to evaluate plume stability. If a groundwater remediation system or strategy is effective, then over the long term, groundwater-monitoring data should demonstrate a clear and meaningful decreasing trend in concentrations at appropriate monitoring points. The current groundwater monitoring program at McClellan AFB OU D was evaluated to identify potential opportunities to LTM optimization.

4.1 METHODOLOGY FOR QUALITATIVE EVALUATION OF MONITORING NETWORK

The three-tiered MNO evaluation of the OU D groundwater LTM program considered information for 51 wells in the OU D study area that currently are included in the monitoring program. These wells, their respective monitoring zones, and their current monitoring frequency are listed in Table 3.1, and their locations are depicted on Figure 3.1.

Multiple factors were considered in developing recommendations for continuation or cessation of groundwater monitoring at each well. In some cases, a recommendation was made to continue monitoring a particular well, but at a reduced frequency. A recommendation to discontinue monitoring at a particular well based on the information reviewed does not necessarily constitute a recommendation to physically abandon the well. A change in site conditions might warrant resumption of monitoring at some time in the future at wells that are not currently recommended for continued sampling. Typical factors considered in developing recommendations to retain a well in, or remove a well from, the monitoring program are summarized in Table 4.1. Typical factors considered in developing recommendations for monitoring frequency are summarized in Table 4.2.

TABLE 4.1
MONITORING NETWORK OPTIMIZATION DECISION LOGIC
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
MCCLELLAN AFB, CALIFORNIA

Reasons for Retaining a Well in Monitoring Network	Reasons for Removing a Well From Monitoring Network
Well is needed to further characterize the site or monitor changes in contaminant concentrations through time	Well provides spatially redundant information with a neighboring well (e.g., same constituents, and/or short distance between wells)
Well is important for defining the lateral or vertical extent of contaminants	Well has been dry for more than 2 years[a/]
Well is needed to monitor water quality at compliance point or receptor exposure point (e.g., domestic well)	Contaminant concentrations are consistently below laboratory detection limits or cleanup goals
Well is important for defining background water quality	Well is completed in same water-bearing zone as nearby well(s)

a/ Water-level measurements in dry wells should continue, and groundwater sampling should be resumed if the well becomes re-wetted.

4.2 RESULTS OF QUALITATIVE MNO EVALUATION

The results of the qualitative evaluation of the 51 monitoring and EWs currently included in the LTM program at OU D included are summarized in Table 4.3, shown on Figure 4.1, and described in the following subsections. The table includes recommendations for retaining or deleting each existing monitoring well, and for changing the sampling frequency, and lists the rationale for the recommendations. Figure 4.1 shows the current and recommended revised sampling frequency for each well based on the qualitative evaluation.

TABLE 4.2
MONITORING FREQUENCY DECISION LOGIC
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
MCCLELLAN AFB, CALIFORNIA

Reasons for Increasing Sampling Frequency	Reasons for Decreasing Sampling Frequency
Groundwater velocity is high	Groundwater velocity is low
Change in contaminant concentration would significantly alter a decision or course of action	Change in contaminant concentration would not significantly alter a decision or course of action
Well is close to source area or operating remedial system	Well is distal from source area or remedial system
Cannot predict if concentrations will change significantly over time	Concentrations are not expected to change significantly over time, or contaminant levels have been below groundwater cleanup objectives for some prescribed period of time

4.2.1 Monitoring Network and Sampling Frequency

The current LTM plan for OU D specifies annual sampling of the six groundwater EWs, and annual or biennial sampling of 45 groundwater monitoring wells. These relatively infrequent sampling frequencies are appropriate given that:

1. The current plume is well-characterized and apparently decreasing in footprint and concentration as long as the groundwater extraction system continues to operate;

2. Available data indicate that the advective groundwater flow velocity is relatively slow (average of 14 and 30 feet per year in the A and B monitoring zones, as described in Section 2.2.2); and

3. Currently, there are no sensitive groundwater receptors near the plume.

TABLE 4.3

QUALITATIVE EVALUATION OF GROUNDWATER MONITORING NETWORK
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
McCLELLAN AFB, CALIFORNIA

Well ID	Zone	Current Sampling Frequency[a/]	Qualitative Analysis: Remove	Retain	Monitoring Frequency Recommendation	Rationale
Extraction Wells						
EW-73	A/B	Annual		√	Annual	Facilitates calculation of mass-removal rates, assessment of remedial progress, and remedial process optimization evaluations.
EW-83	A/B	Annual		√	Annual	Facilitates calculation of mass-removal rates, assessment of remedial progress, and remedial process optimization evaluations.
EW-84	A/B	Annual		√	Annual	Inactive well. Long screened interval (in zones A and B) hinders usefulness of monitoring data, but data are useful in assessing plume magnitude over time.
EW-85	A/B	Annual		√	Annual	Facilitates calculation of mass-removal rates, assessment of remedial progress, and remedial process optimization evaluations.
EW-86	A/B	Annual		√	Annual	Consider discontinuing pumping of this well as discussed in Section 4.2.1.1. It is located outside of the 5-ug/L TCE isopleth.
EW-87	A/B	Annual		√	Annual	Facilitates calculation of mass-removal rates, assessment of remedial progress, and remedial process optimization evaluations.
Zone A Wells						
MW-10	A	Annual		√	Annual	Monitors relatively elevated TCE concentrations in plume interior.
MW-11	A	Annual		√	Annual	Monitors TCE concentrations > MCL in plume interior.
MW-12	A	Annual		√	Annual	Monitors relatively elevated TCE concentrations in plume interior.
MW-14	A	Biennial		√	Biennial	Defines current boundary of TCE MCL target area. Relatively infrequent sampling justfied by low VOC concentrations.
MW-15	A	Annual		√	Annual	Monitors relatively elevated TCE concentrations in plume interior.
MW-38D	A*[b/]	Annual		√	Annual	Monitors historically elevated TCE concentrations, and effect of extraction system on IAB zone.
MW-52	A*	Biennial		√	Biennial	Defines current northern boundary of TCE MCL target area. Relatively infrequent sampling justfied by low to non-detect VOC concentrations.
MW-53	A*	Biennial	√			Consistently low (< MCL) concentrations of primary COCs; additional data not useful in assessing plume magnitude or vertical migration unless hydraulic controls are altered.
MW-55	A*	Biennial	√			Consistently low (< MCL) concentrations of primary COCs; additional data not useful in assessing plume magnitude or vertical migration unless hydraulic controls are altered.
MW-70	A*	Biennial	√			Historically non-detect for primary COCs; additional data not useful in defining plume magnitude. Located near upgradient edge of plume where vertical/horizontal plume expansion unlikely unless hydraulic controls are altered.
MW-72	A	Annual	√			Clustered well MW-10 monitors higher-concentration zone. However, this recommendation is conditional on having below MCL concentrations of COCs during three most recent consecutive monitoring events.
MW-74	A*	Biennial	√			Consistently low (< MCL) concentrations of primary COCs; additional data not useful in assessing plume magnitude or vertical migration unless hydraulic controls are altered.
MW-76	A*	Annual		√	Annual	Potential slight increasing trends in VOC concentrations.
MW-88	A	Biennial	√			MW-89 is screened in same interval and is located closer to estimated 5-ug/L TCE isopleth.
MW-89	A	Biennial		√	Biennial	Helps define location of 5-ug/L TCE isopleth over time and facilitates detection of any plume expansion.
MW-90	A	Biennial		√	Biennial	Helps define location of 5-ug/L TCE isopleth over time and facilitates detection of any plume expansion.
MW-91	A	Biennial	√			MW-14 is screened in same interval and is located closer to estimated 5-ug/L TCE isopleth.
MW-92	A	Biennial	√			MW-14 is screened in same interval and is located closer to estimated 5-ug/L TCE isopleth.
MW-237	A	Biennial	√			No MCL exceedances since monitoring began in 1993. Well is too far from plume (1900 ft) to provide useful information.
MW-240	A	Biennial	√			No MCL exceedances since monitoring began in 1993. Well is too far from plume (700 ft) to provide useful information.
MW-241	A	Annual	√			Clustered well MW-10 monitors higher-concentration zone. However, this recommendation is conditional on having below MCL concentrations of COCs during three most recent consecutive monitoring events.
MW-242	A	Annual	√			Paired A-zone well MW-15 monitors higher-concentration interval. However, this recommendation is conditional on having below MCL concentrations of COCs during three most recent consecutive monitoring events.
MW-350	A	Biennial	√			Well is too far from plume (2200 ft) to provide useful information.
MW-351	A	Annual	√			Well is too far from plume (1400 ft) to provide useful information.
MW-412	A	Biennial	√			Well is too far from plume (1400 ft) to provide useful information.
MW-458	A	Biennial	√			Well is too far from plume (400 ft) to provide useful information. Wells MW-90 and MW-14 provide definition of plume boundary in this area.
MW-1004	A	Biennial	√			Well is too far from plume (650 ft) to provide useful information.
MW-1026	A	Biennial	√			Hydraulically upgradient to cross-gradient, and too far from plume (1700 ft) to provide useful information. Last MCL exceedance was in 1992.
MW-1041	A	Biennial	√			Hydraulically up- to cross-gradient and too far from plume (1600 ft) to provide useful information. Only 1 trace-level detection of 1 primary COC from 1990 to 2001.
MW-1042	A*	Biennial	√			Hydraulically up- to cross-gradient and too far from plume (1600 ft) to provide useful information. Only infrequent trace-level detections of primary COCs from 1990 to 2001.
MW-1064	A	Biennial	√			Hydraulically upgradient and too far from plume (1200 ft) to provide useful information.
MW-1073	A	Biennial	√			Hydraulically upgradient and too far from plume (700 ft) to provide useful information. No MCL exceedances (for primary COCs) since monitoring began in 1993.
Zone B Wells						
MW-19D	B	Biennial		√	Biennial	Sentry well downgradient of plume area.

TABLE 4.3 (Continued)

QUALITATIVE EVALUATION OF GROUNDWATER MONITORING NETWORK
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
McCLELLAN AFB, CALIFORNIA

Well ID	Zone	Current Sampling Frequency[a/]	Qualitative Analysis: Remove	Retain	Monitoring Frequency Recommendation	Rationale
MW-51	B	Biennial		√	Biennial	Facilitates assessment of Zone B water quality over time. Lack of historic COC detections supports infrequent monitoring.
MW-54	B*	Annual		√	Annual	Monitors slight increasing trends in selected primary COCs.
MW-57	B*	Biennial	√			Monitoring of nearby Zone B well MW-59 sufficient to indicate Zone B water quality in this area.
MW-58	B	Biennial		√	Biennial	Facilitates assessment of Zone B water quality over time. Infrequent and low-level historic COC detections supports infrequent monitoring.
MW-59	B	Biennial		√	Biennial	Zone B sentry well near downgradient edge of plume area. Only two trace-level detections of primary COCs from 1990 to 2001, supporting infrequent monitoring.
MW-104	B	Biennial	√			Hydraulically upgradient and too far from plume (500 ft) to provide useful information Only 1 low-level detection of a single primary COC since 1990.
MW-1001	B	Biennial	√			Hydraulically cross-gradient and too far from plume (600 ft) to provide useful information No detections of primary COCs since 1995.
MW-1003	B*	Biennial	√			Hydraulically cross-gradient and too far from plume (600 ft) to provide useful information No detections of primary COCs since 1995.
MW-1010	B*	Biennial	√			Hydraulically upgradient and too far from plume (1600 ft) to provide useful information. No historic detections of primary COCs.
MW-1027	B	Biennial	√			Hydraulically cross-gradient and too far from plume (1700 ft) to provide useful information. No detections of primary COCs since 1994.
MW-1028	B	Biennial	√			Hydraulically upgradient to cross-gradient and too far from plume (1700 ft) to provide useful information. Only 1 trace detection of a single primary COC from 1990 to 2001.
MW-1043	B	Biennial	√			Hydraulically upgradient to cross-gradient and too far from plume (2000 ft) to provide useful information. Only 1 low-level detections of one primary COC from 1990 to 1995.

[a/] Sampling frequency based on 1st Quarter 2002 Groundwater Monitoring Program Quarterly Report (URS, 2002).

[b/] *= Well originally asigned to IAB or AB monitoring zone; reassigned per URS (2002).

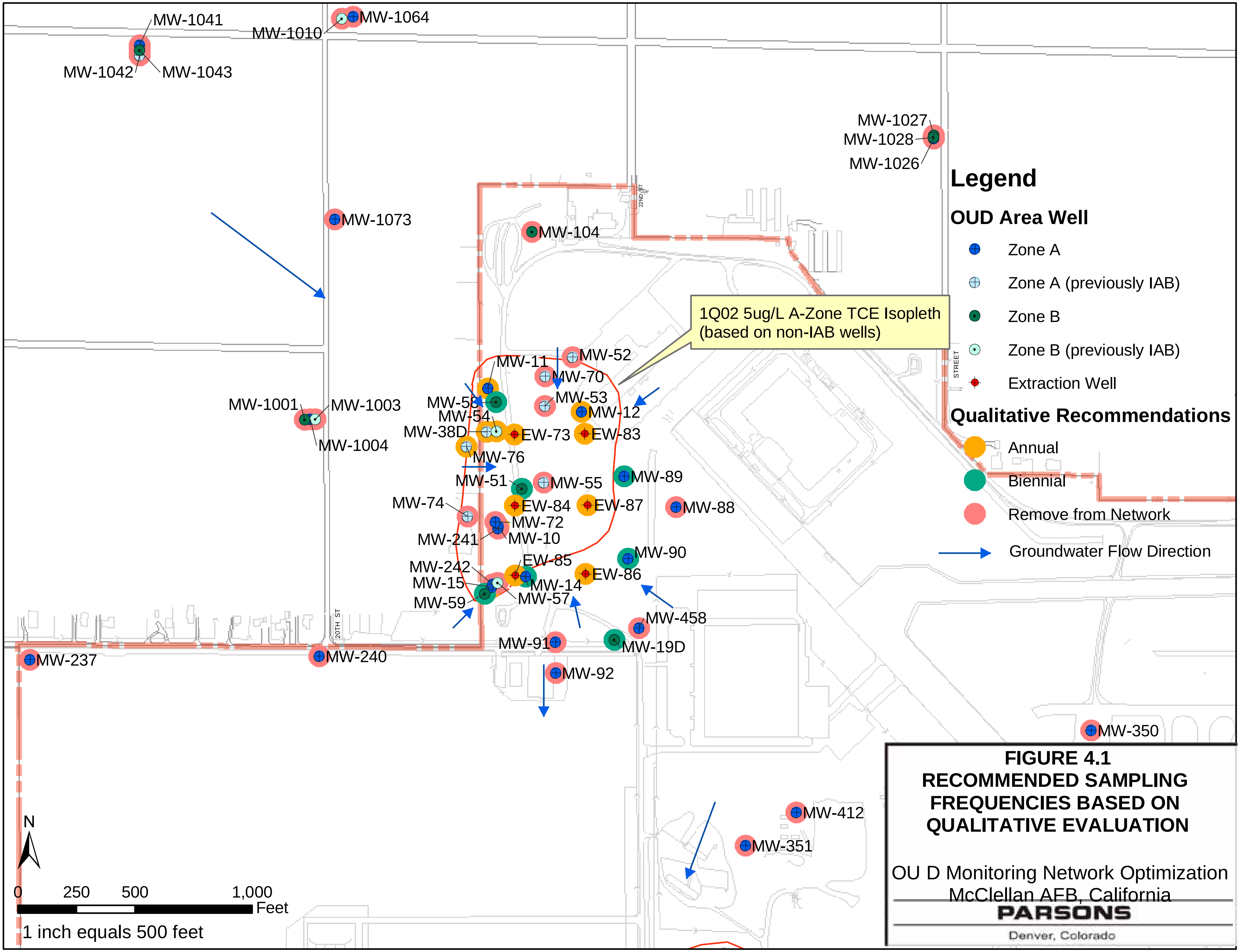


FIGURE 4.1
RECOMMENDED SAMPLING FREQUENCIES BASED ON QUALITATIVE EVALUATION

OU D Monitoring Network Optimization
McClellan AFB, California

PARSONS
Denver, Colorado

The LTM objectives for monitoring and extraction wells differ. Because EWs draw water from a larger (and sometimes unquantified) volume of the aquifer surrounding the well, the analytical data cannot be used for plume definition to the same extent as data from monitoring wells. However, data from EWs can be used to assess contaminant mass-removal rates and progress toward achieving RAOs, and to facilitate system optimization decision-making. Because the plume extent and magnitude are generally well-characterized both laterally and vertically, and because operation of the groundwater extraction system appears to be providing hydraulic control sufficient to cause reductions in the areal extent of and COC concentrations within the CAH plume , continued monitoring of a relatively small number of wells (i.e., fewer than the 51 wells currently included in the OU D LTM plan) should be sufficient to monitor changes in the plume extent and magnitude in the future.

4.2.1.1 Extraction Wells

The current operational status of extraction well EW-84 is not known. According to Parsons (2000), this well was deactivated and there were no plans to reactivate it in the foreseeable future. However, annual monitoring of this EW is continuing (URS, 2002). The long screened interval of this well (from 22.8 feet below mean sea level [bmsl] to -97.2 feet bmsl; see Table 3.1) hinders the usefulness of the analytical data obtained from this well (this issue also pertains to the other extraction wells) in that it cannot be confidently associated with either the A or B zones. However, groundwater samples from this well exhibit COC concentrations greater than MCLs that are likely present primarily in the uppermost part of the aquifer (i.e., the A monitoring zone) based on groundwater quality data from both A- and B-zone monitoring wells. Continued sampling of EW-84 will provide data useful for monitoring the magnitude of COC concentrations in the west-central plume area and the hydraulic effects of groundwater extraction. However, if this well remains inactive, its abandonment should be considered given that it may be acting as a conduit for downward migration of VOCs from the A to the B zone. As shown in Table 4.3, continued annual monitoring of the other five (active) EWs is recommended in order to permit periodic calculation of mass removal rates, and to facilitate assessment of remedial progress and system optimization. However, well EW-86 is currently outside of the 5-µg/L TCE isopleth, and consideration should be given to discontinuing pumping of this well unless it is required for hydraulic control of the plume.

4.2.1.2 A-Zone Monitoring Wells

Continued monitoring of only 8 of the 24 A-zone wells currently included in the LTM program is recommended (Table 4.3 and Figure 4.1). In addition, continued monitoring of only 2 of the 7 IAB wells reassigned to the A zone, as proposed by URS (2002), is recommended.

Nine of the A-zone wells (MW-1004, MW-1041, MW-1064, MW-1073, MW-1026, MW-237, MW-351, MW-412, and MW-350) and one of the IAB-zone wells (MW-1042) recommended for removal from the LTM program are distant (approximately 650 to 2,200 feet) from the location of the 5-µg/L TCE isopleth as estimated during the 1Q02 sampling event, and also are located hydraulically upgradient or crossgradient from the OU D plume area. These wells are too far from the plume to provide useful information on plume magnitude and extent given the localized and hydraulically contained distribution of elevated TCE concentrations. Well MW-240 also is 700 feet from the plume as defined by the 5-µg/L TCE isopleth, but is located downgradient from the OU D waste pits, based on a regional south to southwest groundwater flow direction (Section 2.2.2). Based on the decreasing trends exhibited by TCE concentrations at the downgradient (southern) edge of the A-zone plume (e.g., at wells MW-14, MW-15, and MW-242; see Section 5), plume expansion toward well MW-240 is not occurring, and continued monitoring of this well is not necessary unless hydraulic conditions change.

According to URS, the distant wells listed in the previous paragraph are sampled primarily for community relations purposes (i.e., to demonstrate that contaminant levels in these off-Base residential areas are remaining low and are not of concern from a human health point of view). The recommendation to discontinue monitoring of these wells is primarily technical and does not take into account political/community relations concerns. The recommendations should be evaluated with these other concerns in mind and followed as appropriate.

Cessation of monitoring at wells MW-88, MW-91, MW-92, and MW-458, which are located closer to, but still outside of, the 1Q02 5-µg/L TCE isopleth, also is recommended. Continued monitoring of these four wells is not recommended because monitoring of the plume, as defined by the 5-µg/L TCE isopleth, over time can be accomplished using sampling results from other wells located closer to the affected area (i.e., MW-89, MW-90, and MW-14; Figure 4.1). Concentrations of the four primary COCs (PCE, TCE, *cis*-1,2-DCE, and 1,2-DCA) detected in samples from well MW-89 have never exceeded MCLs, and concentrations detected in MW-90 and MW-14 have not exceeded MCLs since 1997.

Cessation of monitoring at wells MW-72, MW-241, and MW-242 is recommended because each of these wells is paired with another A-zone well that monitors a higher-concentration zone. For example, clustered wells MW-10, MW-72, and MW-241 are screened from -38 to -48 feet msl, -58 to -68 feet msl, and -49 to -69 feet msl, respectively. TCE concentrations in samples from MW-72 have decreased steadily from 440 µg/L in April 1990 to 2.95 µg/L in February 2001. Similarly, TCE concentrations in MW-241 have decreased from 210 µg/L in June 1993 to 2.53 µg/L in February 2001. During the period from 1990 to 2001, TCE concentrations at MW-10 have decreased from 1,100 µg/L to 50.9 µg/L. In this case, continued monitoring of MW-10 will allow assessment of how maximum COC concentrations at these plume-interior locations change over time. In the similar case of well pair MW-15/MW-242, continued monitoring of MW-15 will enable monitoring of maximum COC concentrations at this location.

The remaining four wells recommended for removal from the LTM program (wells MW-53, MW-55, MW-70, and MW-74) are IAB wells that are screened in intermediate zones between the A and B monitoring zones, and concentrations from these wells historically have not been used for plume interpretation. As described in Section 3.1, URS (2002) has proposed that these wells be reassigned to the A zone for monitoring and interpretive purposes (Table 3.1). These four wells have been included in the LTM program because the data may provide useful information about the effectiveness of the extraction system.

With the exception of one 6-µg/L concentration of TCE in the sample collected from MW-53 in February 1998, detected concentrations of the primary COCs in these four IAB wells have not exceeded MCLs. The maximum concentrations of the four primary COCs detected in MW-52, MW-55, and MW-74 since the 1990-1991 time frame have been 4.4 µg/L and 3.8 µg/L, respectively. The primary COCs have never been detected in MW-70. Given the relatively uncontaminated nature of the zones monitored by these wells, the data obtained from them does not provide very useful information about the effectiveness of the extraction system except that it may be limiting downward migration of dissolved contaminants from the A zone. However, water quality in the portions of the IAB zone monitored by these five wells has been well characterized, and appears to be stable over time. Therefore, continued monitoring is not necessary unless the hydraulic control exerted by the extraction system decreases.

The remaining 10 A-zone wells (MW-10 through MW-15, MW-38D, MW-52, MW-76, MW-89, MW-90) are recommended for continued sampling because they:

- Monitor relatively elevated COC concentrations within the plume interior, thereby allowing assessment of the plume magnitude and progress toward aquifer cleanup goals over time;
- Are useful in tracking plume stability or contraction through time (e.g., as defined by the 5-µg/L TCE isopleth); or
- Have exhibited increasing trends for one or more of the COCs that should be monitored over time to assess potential plume expansion either laterally or vertically.

4.2.1.3 B-Zone Monitoring Wells

The B-zone VOC plume is largely defined by EWs that are screened in both the A and B monitoring zones (i.e., the analytical results for these wells are assigned to both the A and B zones for data assessment and presentation purposes). Compared to the number of wells screened solely in the A zone, there are relatively few monitoring wells screened solely in the B zone beneath the A-zone plume (Table 3.1). Data from these B-zone monitoring wells indicate that COC concentrations in B-zone groundwater beneath the A-zone plume are relatively low (maximum detected CAH concentration of 6.45 µg/L [for TCE] from 1990 to 2001). Due to the relatively few B-zone wells, and the importance of documenting water quality in this zone over time, continued monitoring of four of the five B-zone wells located in the immediate vicinity of the plume area (wells MW-51, MW-54, MW-58, and MW-59) is recommended. Given the low magnitude of the COC concentrations, continued biennial monitoring is appropriate for three of these wells; annual sampling is recommended for well MW-54, where slight increasing trends for some COCs have been observed. Continued monitoring of IAB well MW-57 is not recommended due to its close proximity to B-zone well MW-59. Well MW-19D, located south of and potentially downgradient from the main plume area (Figure 4.1), near the estimated southern limit of the extraction system capture zone, serves as a sentry well, and continued biennial monitoring of this well is recommended.

Continued monitoring of B-zone wells located both distant and hydraulically up- or crossgradient from the plume area is not recommended. These wells, which include MW-1003, MW-1001, MW-1043, MW-1010, MW-104, MW-1027, and MW-1028 (Table 3.1 and Figure 4.1), do not provide useful information regarding plume magnitude and extent.

4.2.2 Laboratory Analytical Program

Groundwater samples from OU D wells are analyzed for VOCs using USEPA Method SW8260B. Because the characterization of conditions in the OU D groundwater plume has been largely completed, groundwater samples collected from monitoring wells could be analyzed for selected COCs using Method 8021B, rather than the currently-used Method 8260B. Method 8021B can be used to analyze for the primary COCs at the site, and could potentially result in a considerable reduction in analytical costs. Depending on the laboratory, the cost for analysis of a groundwater sample using Method 8021B (a gas-chromatographic [GC] method) can be substantially lower than the cost of analysis using Method 8260B (a gas-chromatographic/mass-spectrographic [GC/MS] method), especially if the target analyte list is reduced. USEPA Method 8260B should still be used to analyze samples from the few wells that contain substantially elevated CAH concentrations, in order to obtain appropriate analyte identifications.

4.2.3 LTM Program Flexibility

The LTM program recommendations made in Sections 4.2.1 are based on available data regarding current (and expected future) site conditions. Changing site conditions (e.g., lengthy malfunction or significant adjustment of the groundwater extraction system) could affect plume behavior. Therefore, the LTM program should be reviewed if hydraulic conditions change significantly, and revised as necessary to adequately track changes in plume magnitude and extent over time.

SECTION 5

TEMPORAL STATISTICAL EVALUATION

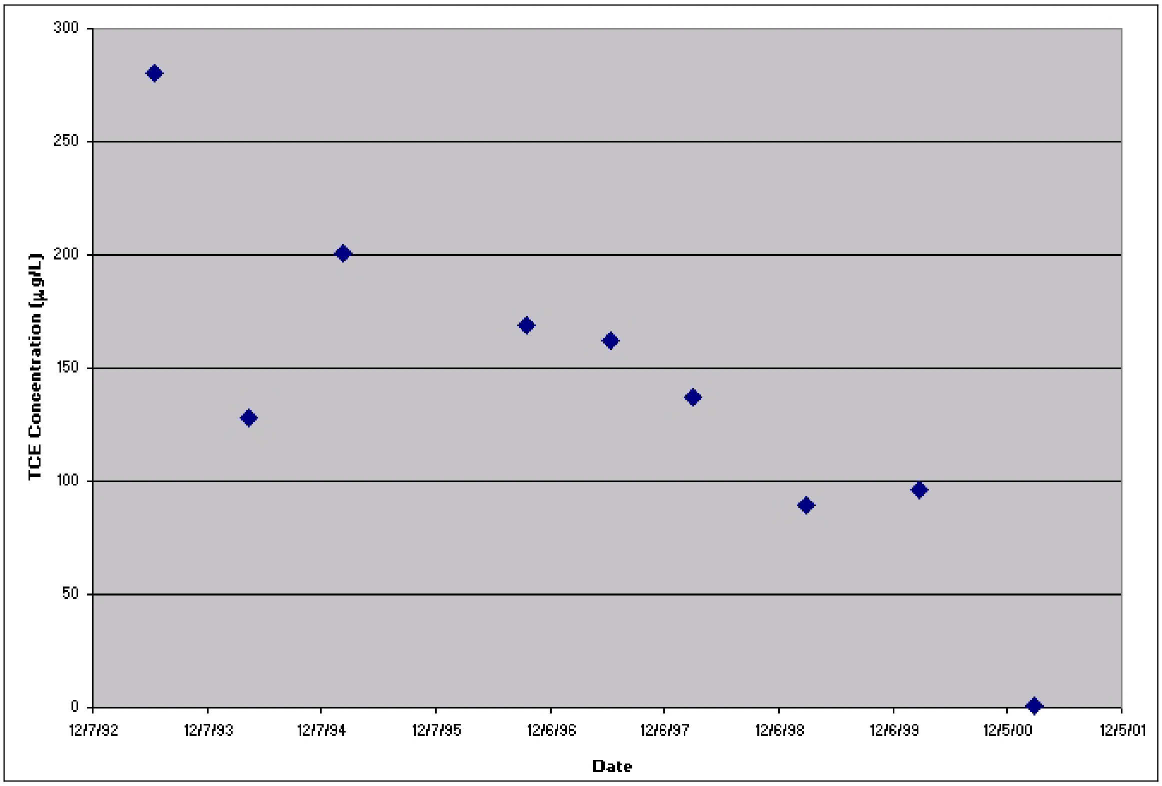
Temporal data (chemical concentrations measured at different points in time) can be examined graphically, or using statistical tests, to evaluate dissolved-contaminant plume stability. If removal of chemical mass is occurring in the subsurface as a consequence of attenuation processes or operation of a remediation system, mass removal will be apparent as a decrease in chemical concentrations through time at a particular sampling location, as a decrease in chemical concentrations with increasing distance from chemical source areas, and/or as a change in the suite of chemicals through time or with increasing migration distance.

5.1 METHODOLOGY FOR TEMPORAL TREND ANALYSIS OF CONTAMINANT CONCENTRATIONS

Temporal chemical-concentration data can be evaluated by plotting contaminant concentrations through time for individual monitoring wells (Figure 5.1), or by plotting contaminant concentrations versus downgradient distance from the contaminant source for several wells along the groundwater flowpath, over several monitoring events. Plotting temporal concentration data is recommended for any analysis of plume stability (Wiedemeier and Haas, 2000); however, visual identification of trends in plotted data may be a subjective process, particularly if (as is likely) the concentration data do not exhibit a uniform trend, but are variable through time (Figure 5.2).

The possibility of arriving at incorrect conclusions regarding plume stability on the basis of visual examination of temporal concentration data can be reduced by examining temporal trends in chemical concentrations using various statistical procedures, including

FIGURE 5.1
TCE CONCENTRATIONS THROUGH TIME
AT WELL MW-38D
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
MCCLELLAN AFB, CALIFORNIA



regression analyses and the Mann-Kendall test for trends. The Mann-Kendall nonparametric test (Gibbons, 1994) is well-suited for evaluation of environmental data because the sample size can be small (as few as four data points), no assumptions are made regarding the underlying statistical distribution of the data, and the test can be adapted to account for seasonal variations in the data. The Mann-Kendall test statistic can be calculated at a specified level of confidence to evaluate whether a temporal trend is exhibited by contaminant concentrations detected through time in samples from an individual well. If a trend is identified, a nonparametric slope of the trend line (change in concentration per unit time) also can be estimated using the test procedure. A negative slope (indicating decreasing contaminant concentrations through time) or a positive slope

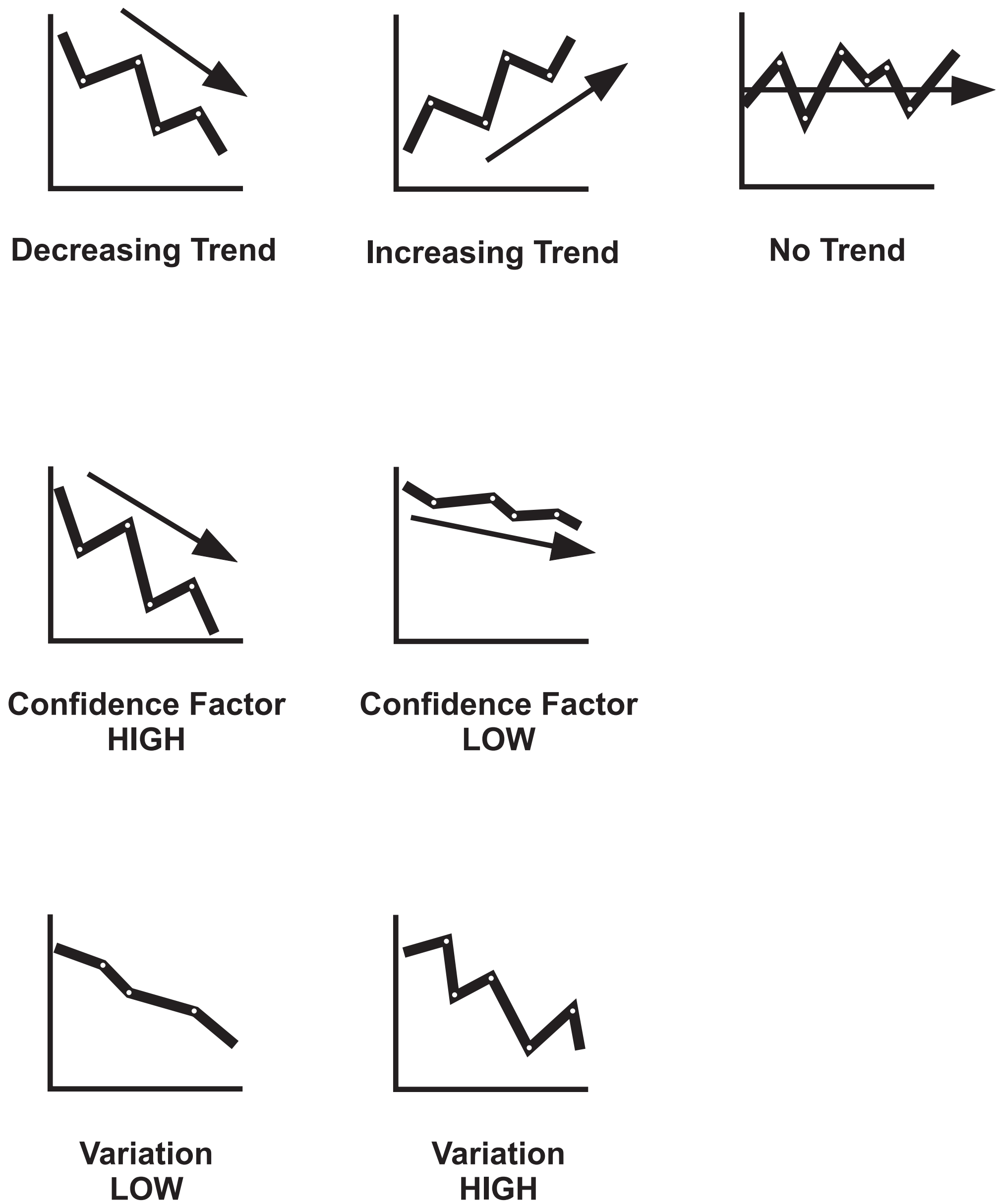


FIGURE 5.2

CONCEPTUAL REPRESENTATION OF TEMPORAL TRENDS AND TEMPORAL VARIATIONS IN CONCENTRATIONS

OU D Monitoring Network Optimization
McClellan AFB, California

(increasing concentrations through time) provides statistical confirmation of temporal trends that may have been identified visually from plotted data (Figure 5.2).

The relative value of information obtained from periodic monitoring at a particular monitoring well can be evaluated by considering the location of the well with respect to the dissolved contaminant plume and potential receptor exposure points, and the presence or absence of temporal trends in contaminant concentrations in samples collected from the well. The degree to which the amount and quality of information that can be obtained at a particular monitoring point serve the two primary (i.e., temporal and spatial) objectives of monitoring must be considered in this evaluation. For example, the continued non-detection of a target contaminant in groundwater at a particular monitoring location provides no information about temporal trends in contaminant concentrations at that location, or about the extent to which contaminant migration is occurring, unless the monitoring location lies along a groundwater flowpath between a contaminant source and a potential receptor exposure point. Therefore, a monitoring well having a history of contaminant concentrations below detection limits may be providing little or no useful information, depending on its location.

A trend of increasing contaminant concentrations in groundwater at a location between a contaminant source and a potential receptor exposure point may represent information critical in evaluating whether contaminants are migrating to the exposure point, thereby completing an exposure pathway. Identification of a trend of decreasing contaminant concentrations at the same location may be useful in evaluating decreases in the areal extent of dissolved contaminants, but does not represent information that is critical to the protection of a potential receptor. Similarly, a trend of decreasing contaminant concentrations in groundwater near a contaminant source may represent important information regarding the progress of remediation near, and downgradient from the source, while identification of a trend of increasing contaminant concentrations at the same location does not provide as much useful information regarding contaminant conditions. By contrast, the absence of a temporal trend in contaminant concentrations at a particular location within or downgradient from a plume indicates that virtually no additional information can be obtained by continued monitoring of groundwater at that location, in that the results of continued monitoring through time are likely to fall within the historic range of concentrations that have already been detected (Figure 5.3). Continued monitoring at locations where no temporal trend in contaminant concentrations is present serves merely to confirm the results of previous monitoring activities at that location. The relative amounts of information generated by the results of temporal-trend evaluation at monitoring points near, upgradient from, and downgradient from contaminant sources are presented schematically as follow:

Monitoring Point Near Contaminant Source

Relatively less information	Nondetect or no trend
↓	Increasing trend in concentrations
Relatively more information	Decreasing trend in concentrations

Monitoring Point Upgradient from Contaminant Source

Relatively less information	Nondetect or no trend
↓	Decreasing trend in concentrations
Relatively more information	Increasing trend in concentrations

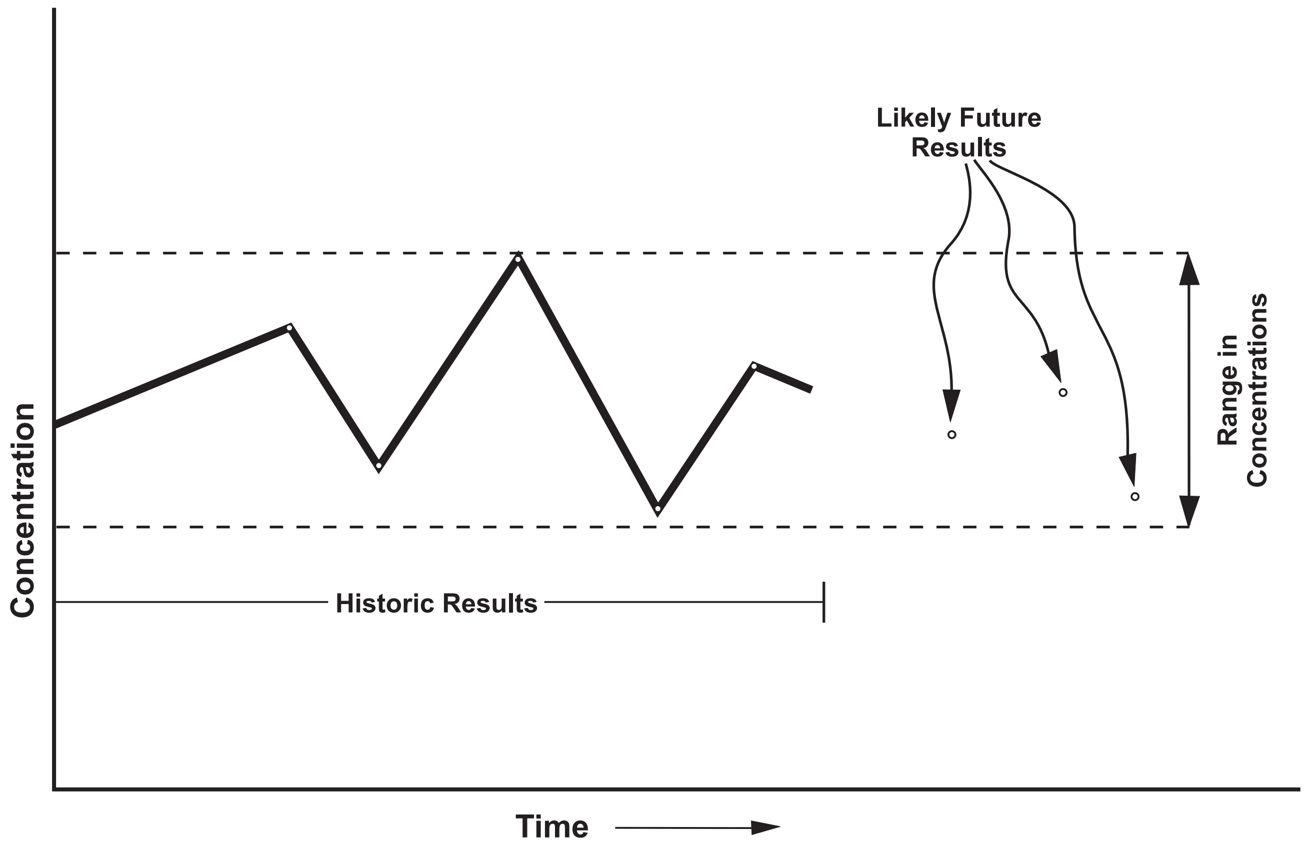


FIGURE 5.3
CONCEPTUAL REPRESENTATION OF CONTINUED MONITORING AT LOCATION WHERE NO TEMPORAL TREND IN CONCENTRATIONS IS PRESENT
OU D Monitoring Network Optimization
McClellan AFB, California

Monitoring Point Downgradient from Contaminant Source

Relatively less information	Decreasing trend in concentrations
↓	
	Nondetect or no trend
Relatively more information	Increasing trend in concentrations

5.2 TEMPORAL EVALUATION RESULTS

The analytical data for groundwater samples collected from the 51 wells in OU D LTM program from April 1990 through August 2001 were examined for temporal trends using the Mann-Kendall test. The objective of the evaluation was to identify those wells having increasing or decreasing concentration trends for each COC, and to consider the quality of information represented by the existence or absence of concentration trends in terms of the location of each monitoring point.

Summary results of Mann-Kendall temporal trend analyses for COCs in groundwater samples from wells in the TCE plume area are presented in Table 5.1. As implemented, the algorithm used to evaluate concentration trends assigned a value of “ND” (not detected) to those wells with sampling results that were consistently below analytical detection limits through time, rather than assigning a surrogate value corresponding to the detection limit – a procedure that could generate potentially misleading and anomalous “trends” in concentrations. In addition, a value of “<PQL” was assigned to those constituents for which no values were measured above the practical quantitation limit. For example, TCE results for groundwater samples from well MW-412 include four trace detections that were less than the PQLs, and five measurements in which TCE was not detected during the sampling events from 1997 to 2001. In the absence of the “<PQL” classification category, the results of trend analysis would indicate no trend for TCE in

these samples, which is primarily an artifact of the analytical procedures, and could generate false conclusions regarding concentration trends. The color-coding of the Table 5.1 entries denotes the presence/absence of temporal trends, and allows those monitoring points having nondetectable concentrations, concentrations below PQLs, decreasing or increasing concentrations, or no discernible trend in concentrations to be readily identified. Figure 5.4 thematically displays the Mann-Kendall results for TCE by well and hydraulic unit; the analytical results for TCE in 2000 and 2001 are also presented. Several of the wells were only sampled once, and EW-85 and MW-1043 were not sampled during either of the events in the 2-year period.

The basis of the decision to remove or retain a well in the monitoring program based on the value of its temporal information is described in the "Rationale" column of Table 5.1. In general, monitoring wells at which detected chemical concentrations display no discernible temporal trend (e.g., wells MW-53, MW-59 MW-90, MW-237, and MW-1064) represent points generating the least amount of useful information, and can be recommended for removal from the monitoring network. Monitoring wells upgradient from the source or crossgradient from the plume (e.g., wells MW-1010, MW-1027, MW-1041, MW-458) for which concentrations of chemicals consistently have been non-detected or <PQL through time, and downgradient wells with decreasing trends (e.g., wells MW-91 and MW-350) also may provide relatively little information. Conversely, monitoring wells (e.g., MW-10 through MW-12, MW-38B, MW-72) that have decreasing temporal trends in a source area are valuable and should be retained because they provide information on the effectiveness of source-area remediation. A flow chart of the decision logic applied to the temporal trend analysis results is presented in Figure 5.5.

Table 5.1 summarizes recommendations to retain 12 of the 45 monitoring wells and 5 of the 6 EWs in a revised monitoring program for the McClellan OU D plume. Note that the recommendations provided in Table 5.1 are based on the evaluation of temporal statistical results only, and must be used in conjunction with the results of the qualitative and spatial evaluations to generate final recommendations regarding retention of monitoring points in the LTM program, and the frequency of monitoring at particular locations at OU D.

TABLE 5.1
RESULTS OF TEMPORAL TREND ANALYSIS OF GROUNDWATER MONITORING RESULTS
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
McCLELLAN AFB, CALIFORNIA

Well ID	Zone	TCE	PCE	cis-1,2-DCE	1,2-DCA	Remove	Retain	Rationale
Extraction Wells								
EW-73	A/B	Decreasing	Decreasing	Decreasing	Decreasing		√	Decreasing in source area, measures remedy and mass removal.
EW-83	A/B	No Trend	No Trend	Increasing	No Trend	√		cis-1,2DCE < 3μg/L; limited temporal information
EW-84	A/B	Decreasing	No Trend	Decreasing	Decreasing		√	Decreasing in source area, measures remedy and mass removal.
EW-85	A/B	Decreasing	ND	No Trend	No Trend		√	Decreasing in source area, measures remedy and mass removal.
EW-86	A/B	Decreasing	ND	No Trend	No Trend		√	Decreasing in source area, measures remedy and mass removal.
EW-87	A/B	Increasing	No Trend	No Trend	Increasing		√	Increasing TCE at hotspot.
Zone A Wells								
MW-10	A	Decreasing	No Trend	No Trend	Decreasing		√	Decreasing trend measures remedy in source area.
MW-11	A	Decreasing	No Trend	Decreasing	No Trend		√	Decreasing trend measures remedy in source area.
MW-12	A	Decreasing	Decreasing	<PQL	ND		√	Decreasing trend measures remedy in source area.
MW-14	A	Decreasing	No Trend	Decreasing	No Trend		√	Decreasing trend measures remedy in source area.
MW-15	A	Decreasing	No Trend	<PQL	No Trend		√	Decreasing trend measures remedy in source area.
MW-38D	A*[a/]	Decreasing	Decreasing	Decreasing	Decreasing		√	Decreasing trend measures remedy in source area.
MW-52	A*	Decreasing	Decreasing	ND	NT (<5)	√		TCE and PCE trace or not detected since 1990. Trends no longer valuable.
MW-53	A*	No Trend	No Trend	ND	No Trend	√		No trend in upgradient. Very low concentrations of TCE.
MW-55	A*	No Trend	Decreasing	No Trend	<PQL	√		No trend upgradient area. Trace PCE concentrations, decreasing trends no longer valuable
MW-70	A*	ND	ND	ND	ND	√		Concentrations not detected in sampling history.
MW-72	A	Decreasing	<PQL	No Trend	Decreasing		√	Decreasing trend measures remedy in source area.
MW-74	A*	Decreasing	ND	<PQL	No Trend	√		Decreasing trend, TCE < MCL, limited temporal information.
MW-76	A*	Increasing	No Trend	Increasing	Increasing		√	Increasing trend on outer edge of plume
MW-88	A	No Trend	No Trend	ND	ND	√		No trend down/cross-gradient. Not detected since 1997.
MW-89	A	No Trend	ND	ND	ND	√		No trend down/cross-gradient. TCE < 0.2μg/L, limited temporal information.
MW-90	A	No Trend	No Trend	No Trend	No Trend	√		No trend down/cross-gradient.
MW-91	A	Decreasing	No Trend	No Trend	No Trend	√		Decreasing downgradient of extraction wells.
MW-92	A	Decreasing	ND	ND	ND	√		Decreasing downgradient; TCE < MCL since 1996, limited temporal information.
MW-237	A	No Trend	No Trend	ND	ND	√		No trend cross-gradient of plume.
MW-240	A	No Trend	No Trend	ND	ND	√		No trend cross-gradient of plume.
MW-241	A	Decreasing	No Trend	Decreasing	Decreasing		√	Decreasing trend measures remedy in source area.
MW-242	A	Decreasing	No Trend	Decreasing	No Trend		√	Decreasing trend measures remedy in source area.
MW-350	A	Decreasing	Decreasing	No Trend	ND	√		Decreasing downgradient. TCE not detected since 1997, trends no longer valuable.
MW-351	A	No Trend	No Trend	No Trend	ND	√		No temporal trends distant from OU D plume.
MW-412	A	<PQL	ND	ND	ND	√		VOCs not detected or detected at less than PQLs distant from OU D plume.

TABLE 5.1 (Continued)
RESULTS OF TEMPORAL TREND ANALYSIS OF GROUNDWATER MONITORING RESULTS
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
McCLELLAN AFB, CALIFORNIA

Well ID	Zone	TCE	PCE	cis-1,2-DCE	1,2-DCA	Remove	Retain	Rationale
MW-458	A	<PQL	ND	ND	ND	√		Low concentrations over 500 ft from TCE 5µg/L isopleth
MW-1004	A	Decreasing	No Trend	ND	ND	√		Decreasing cross-gradient. TCE non-detect or <1µg/L, trends not valuable.
MW-1026	A	No Trend	No Trend	<PQL	ND	√		No trend upgradient area.TCE concentrations <MCL since 1993.
MW-1041	A	ND	ND	ND	No Trend	√		Non-detect upgradient. One detect <MCL of 1,2DCA in 1995.
MW-1042	A*	No Trend	No Trend	ND	No Trend	√		No trend upgradient. TCE not detected since 1993.
MW-1064	A	No Trend	No Trend	No Trend	No Trend	√		No trend upgradient.
MW-1073	A	Decreasing	Decreasing	No Trend	Decreasing	√		Decreasing trend upgradient. Trace or non-detects since 1996, trends no longer valuable.
Zone B Wells								
MW-19D	B	No Trend	No Trend	ND	No Trend		√	No trend downgradient. Sentry well.
MW-51	B	Decreasing	ND	ND	ND	√		Non-detect since 1991.
MW-54	B*	Increasing	No Trend	Increasing	Increasing		√	Increasing in source area, but "downgradient" of MW-38D.
MW-57	B*	No Trend	Decreasing	ND	No Trend	√		No trend in source area. PCE not detected since 1990, trends no longer valuable.
MW-58	B	No Trend	Decreasing	ND	No Trend	√		Non-detect in source area. PCE not detected since 1990, trends no longer valuable.
MW-59	B	No Trend	ND	ND	No Trend	√		No trend in source area. TCE non-detect or <1µg/L throughout monitoring history.
MW-104	B	Decreasing	ND	ND	No Trend	√		Decreasing trend upgradient. TCE not detected since 1990.
MW-1001	B	ND	ND	ND	No Trend	√		Non-detect/no trend cross-gradient from plume.
MW-1003	B*	Decreasing	ND	ND	ND	√		TCE non-detect since 1991, trends no longer valuable.
MW-1010	B*	ND	ND	ND	ND	√		Non-detect upgradient.
MW-1027	B	ND	ND	ND	ND	√		Non-detect upgradient.
MW-1028	B	No Trend	ND	ND	ND	√		TCE non-detect or <1µg/L. No trend/non-detect upgradient.
MW-1043	B	ND	ND	ND	No Trend	√		Non-detect/no trend upgradient.

ND	= Constituent has not been detected during history of monitoring at inidcated well.
No Trend	= No statistically significant temporal trend in concentrations.
Increasing	= Statistically significant increasing trend in concentrations.
Decreasing	= Statistically significant decreasing trend in concentrations.
<PQL	= Concentrations consistently below practical quantitation limit.

[a/] *= Well screened interval orginally designated as monitoring zone IAB or AB; reassigned per URS (2002)

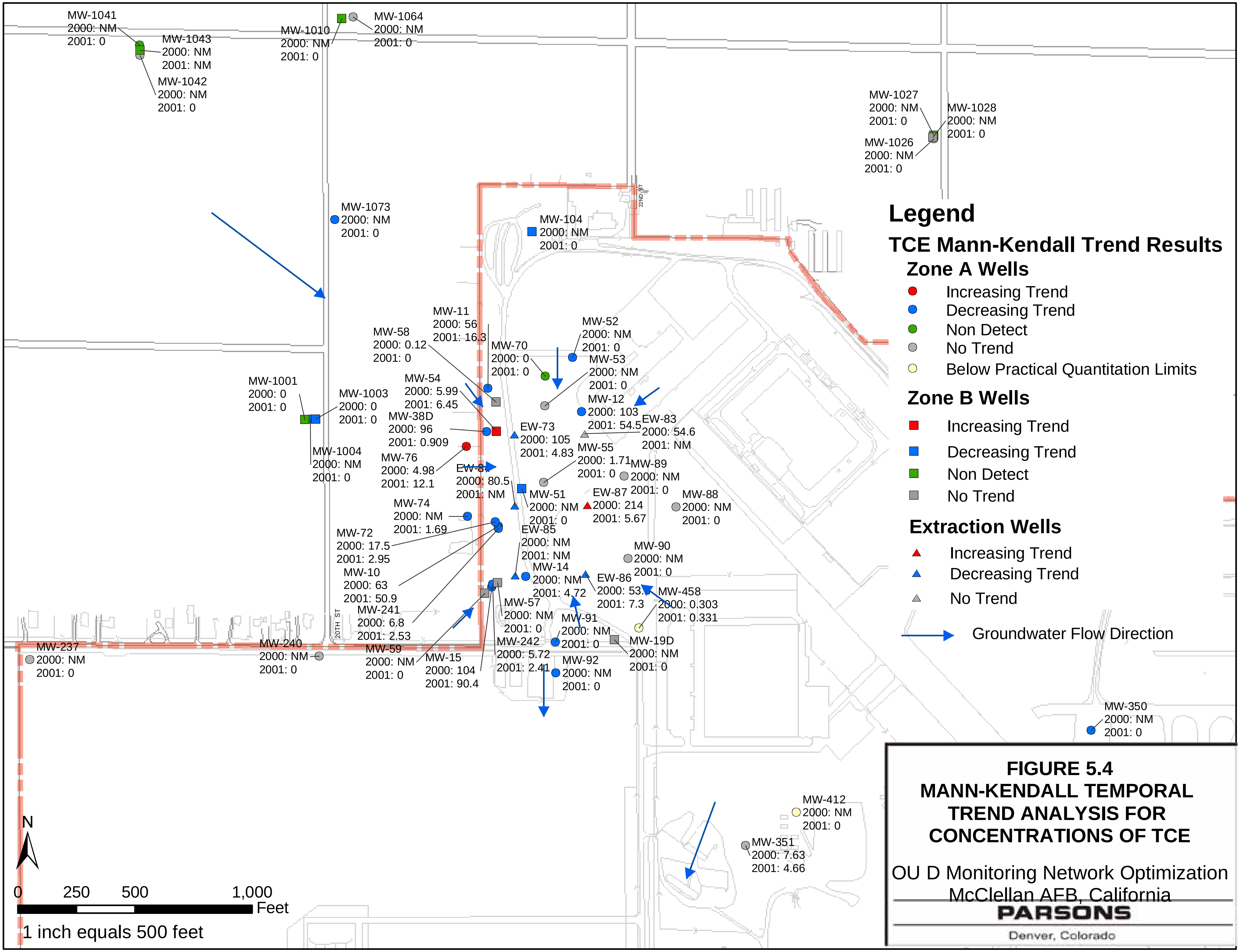


FIGURE 5.4
MANN-KENDALL TEMPORAL TREND ANALYSIS FOR CONCENTRATIONS OF TCE

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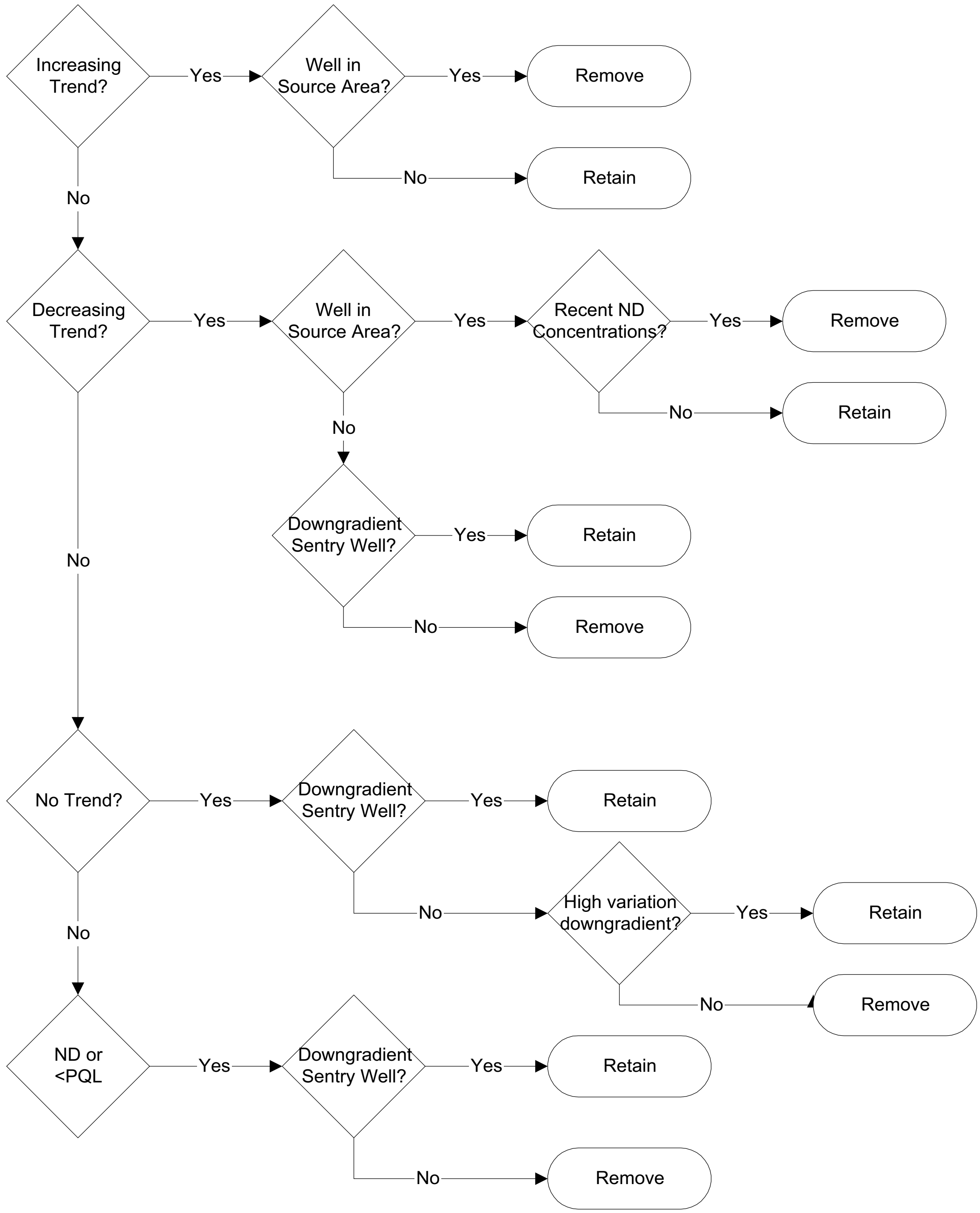

FIGURE 5.5
TEMPORAL TREND DECISION RATIONALE FLOW CHART

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SECTION 6

SPATIAL STATISTICAL EVALUATION

Spatial statistical techniques also can be applied to the design and evaluation of groundwater monitoring programs to assess the quality of information generated during monitoring, and to evaluate monitoring networks. *Geostatistics*, or the Theory of Regionalized Variables (Clark, 1987; Rock 1988; American Society of Civil Engineers [ASCE] Task Committee on Geostatistical Techniques in Hydrology, 1990a and 1990b), is concerned with variables having values dependent on location, and which are continuous in space, but which vary in a manner too complex for simple mathematical description. Geostatistics is based on the premise that the differences in values of a spatial variable depend only on the distances between sampling locations, and the relative orientations of sampling locations -- that is, the values of a variable (e.g., chemical concentrations) measured at two locations that are spatially "close together" will be more similar than values of that variable measured at two locations that are "far apart".

6.1 GEOSTATISTICAL METHODS FOR EVALUATING MONITORING NETWORKS

Ideally, application of geostatistical methods to the results of the groundwater monitoring program at OU D could be used to estimate COC concentrations at every point within the dissolved contaminant plume, and also could be used to generate estimates of the "error," or uncertainty, associated with each estimated concentration value. Thus, the monitoring program could be "optimized" by using available information to identify those areas having the greatest uncertainty associated with the estimated plume extent and configuration. Conversely, sampling points could be successively eliminated from simulations, and the resulting uncertainty examined, to evaluate if significant loss of information (represented by increasing error or uncertainty in estimated chemical concentrations) occurs as the number of sampling locations is reduced. Repeated application of geostatistical estimating techniques, using tentatively identified sampling locations, then could be used to generate a sampling program that would provide an acceptable level of uncertainty regarding the distribution of COCs with the minimum possible number of samples collected. Furthermore, application of geostatistical methods can provide unbiased representations of the distribution of COCs at different locations in the subsurface, enabling the extent of COCs to be evaluated more precisely.

Fundamental to geostatistics is the concept of semivariance [$\gamma(h)$], which is a measure of the spatial dependence between samples (e.g., chemical concentrations) in a specified direction. Semivariance is defined for a constant spacing between samples (***h***) by:

$$\gamma(h) = \frac{1}{2n} \sum [g(x) - g(x + h)]^2 \qquad \textit{Equation 6-1}$$

Where:

$\gamma(h)$ = semivariance calculated for all samples at a distance ***h*** from each other;

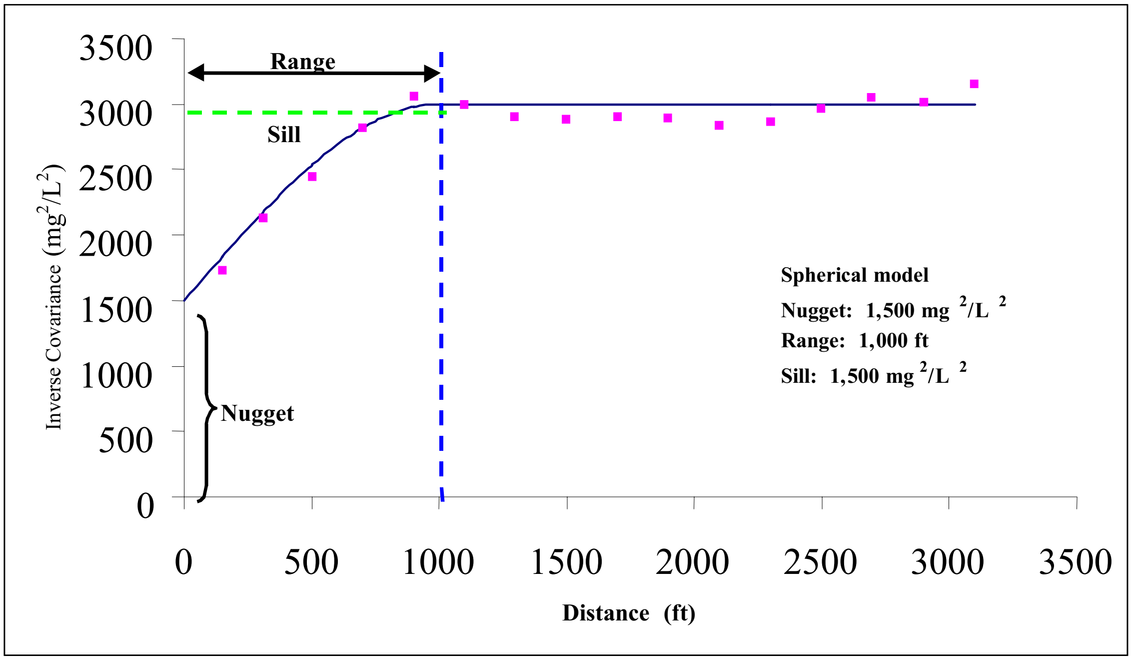
$g(x)$ = value of the variable in sample at location ***x***;

$g(x + h)$ = value of the variable in sample at a distance ***h*** from sample at location ***x***; and

n = number of samples in which the variable has been determined.

Semivariograms (plots of $\gamma(h)$ versus ***h***) are a means of depicting graphically the range of distances over which, and the degree to which, sample values at a given point are related to sample values at adjacent, or nearby, points, and conversely, indicate how close together sample points must be for a value determined at one point to be useful in predicting unknown values at other points. For $h = 0$, for example, a sample is being compared with itself, so normally $\gamma(0) = 0$ (the semivariance at a spacing of zero, is zero), except where a so-called nugget effect is present (Figure 6.1), which implies that

FIGURE 6.1
IDEALIZED SEMVARIOGRAM MODEL
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
MCCLELLAN AIR FORCE BASE, CALIFORNIA



sample values are highly variable at distances less than the sampling interval. As the distance between samples increases, sample values become less and less closely related, and the semivariance, therefore, increases, until a sill is eventually reached, where $\gamma(h)$ equals the overall variance (i.e., the variance around the average value). The sill is reached at a sample spacing called the range of influence, beyond which sample values are not related. Only values between points at spacings less than the range of influence can be predicted; but within that distance, the semivariogram provides the proper weightings, which apply to sample values separated by different distances.

When a semivariogram is calculated for a variable over an area (e.g., concentrations of TCE in the groundwater plume at OU D), an irregular spread of points across the semivariogram plot is the usual result (Rock, 1988). One of the most subjective tasks of geostatistical analysis is to identify a continuous, theoretical semivariogram model that most closely follows the real data. Fitting a theoretical model to calculated semivariance points is accomplished by trial-and-error, rather than by a formal statistical procedure (Davis, 1986; Clark, 1987; Rock, 1988). If a "good" model fit results, then $\gamma(h)$ (the semivariance) can be confidently estimated for any value of ***h***, and not only at the sampled points.

6.2 SPATIAL EVALUATION OF MONITORING NETWORK AT OU D

TCE was used as the indicator chemical for the spatial evaluation of the groundwater monitoring network at OU D because this COC has the largest detection percentage and spatial distribution of measurements that exceeded groundwater MCLs. Although the A and B zones are hydraulically connected, the A-zone wells were considered separately from the B-zone wells for the spatial analysis because the A and B zone wells are generally screened in shallower and deeper portions of the aquifer, respectively, and have historically have been used to create different plume distribution maps.

A kriging analysis was not conducted for the wells because this zone contains too few wells for a valuable spatial analysis. The monitoring network includes a total of 32 designated A-zone monitoring wells (Table 3.1). Additionally, although the EWs have historically been used to define the plume extent in both the A and B zones, data from active EWs are not appropriate for use in a kriging analysis because they represent COC concentrations averaged over the area within the well's capture zone, and thus are not point specific, nor temporally discrete; the EWs are also screened across both Zones A and B. Therefore, the active EWs were excluded from the spatial analysis. The most recent validated analytical data available at the start of this MNO evaluation (February 2000 or March 2001) were used in the kriging evaluation because a spatial "snapshot" is required in order to conduct the geospatial statistical analysis. Thus, 2000 and 2001 TCE measurements from the 32 A-Zone monitoring wells were used to develop the semivariogram model. The commercially available geostatistical software package Geostatistical Analyst™ (an extension to the ArcView® geographic information system

[GIS] software package) (Environmental Systems Research Institute, Inc. [ESRI], 2001) was used to develop a semivariogram model depicting the spatial variation in TCE concentrations in groundwater for the 32 wells completed in the A zone in the OU D area.

As semivariogram models were calculated for TCE (Equation 6-1), considerable scatter of the data was apparent during fitting of the models. Several data transformations (including a log transformation) were attempted to obtain a representative semivariogram model. Ultimately, the concentration data were transformed to "rank statistics," in which the 32 wells were ranked according to their 2000 or 2001 TCE concentration from 1 to 32 (tie values were assigned the median rank of the set). Transformations of this type can be less sensitive to outliers, skewed distributions, or clustered data than semivariograms based on raw concentration values, and thus may enable recognition and description of the underlying spatial structure of the data in cases where ordinary data are too "noisy".

The TCE rank statistics were used to develop a semivariogram that most accurately modeled the spatial distribution of the data. Figure 6.2 shows the semivariogram model in comparison to the site data. The best-fit semivariogram had the following parameters:

- Spherical Model
- Range: 600 feet
- Sill: 70
- Nugget: 10

After this semivariogram model had been developed, it was used in the kriging system implemented by the Geostatistical Analyst™ software package (ESRI, 2001) to develop kriging realizations (estimates of the spatial distribution of TCE in groundwater at OU D), and to calculate the associated kriging prediction standard errors. The median kriging standard deviation was obtained from the standard errors calculated using the entire 32-well A-zone monitoring network for OU D. Next, each of the 32 wells was sequentially

FIGURE 6.2
TCE A-ZONE SEMVARIOGRAM MODEL
THREE-TIERED MONITORING NETWORK OPTIMIZATION
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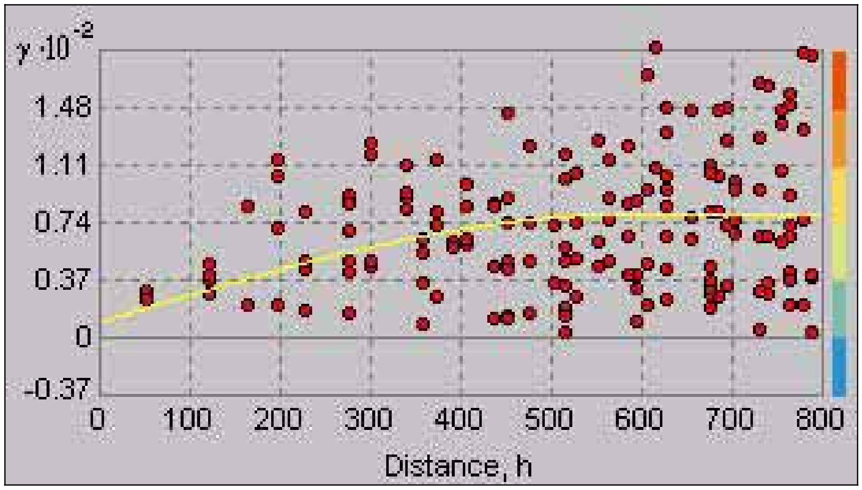
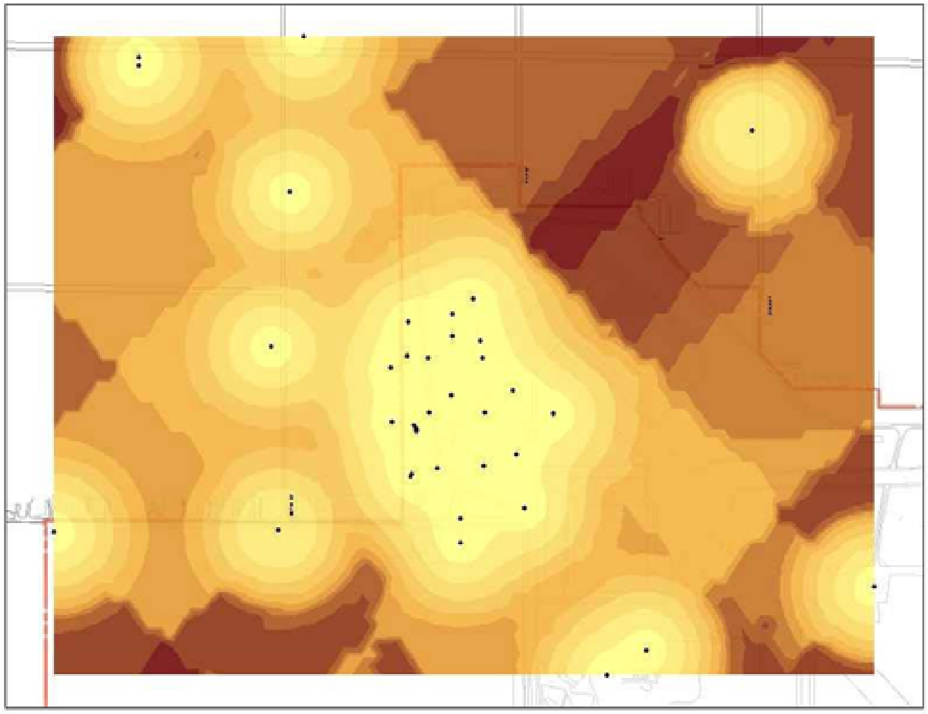
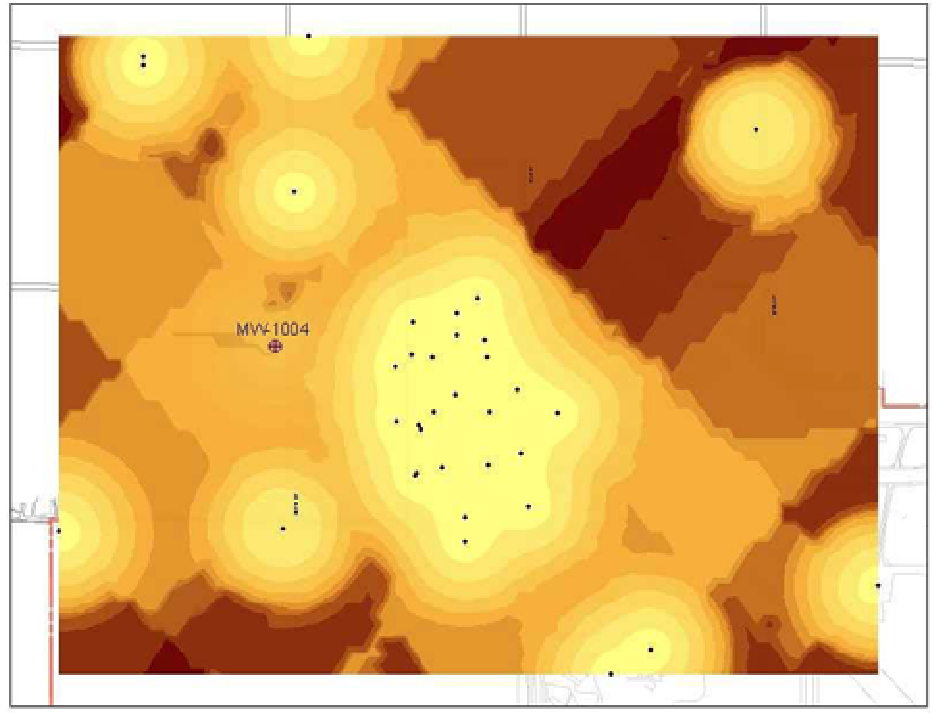


removed from the network, and for each resulting well network configuration, a kriging realization was completed using the TCE concentration rankings from the remaining 31 wells. The "missing-well" monitoring network realizations were used to calculate prediction standard errors, and the median kriging standard deviations were obtained for each "missing-well" realization and compared with the median kriging standard deviation for the "base-case" realization (obtained using the complete 32-well monitoring network), as a means of evaluating the amount of information loss (as indicated by increases in kriging error) resulting from the use of fewer monitoring points.

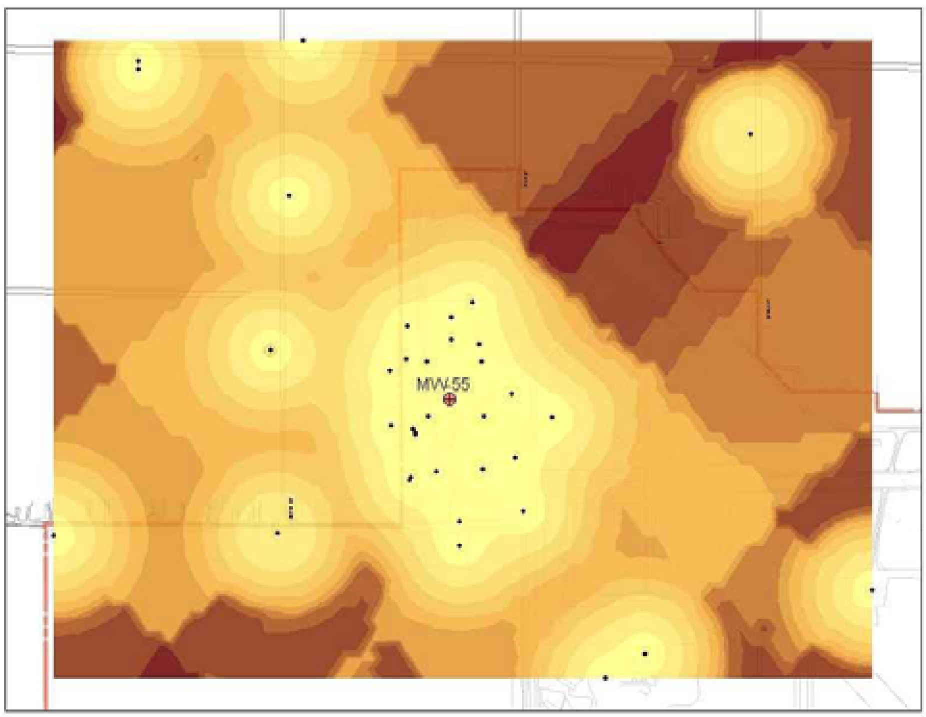
Figure 6.3 illustrates the spatial-evaluation procedure by showing kriging prediction standard-error maps for three kriging realizations. Each map shows the predicted standard error associated with a given group of wells based on the semivariogram parameters discussed above. Lighter colors represent areas with lower spatial uncertainty, and darker colors represent areas with higher uncertainty; regions in the vicinity of wells (i.e., data points) have the lowest associated uncertainty. Map A on Figure 6.3 shows the predicted standard error map for the "base-case" realization in



A) Base-case (All wells)



B) "Missing" Well MW-1004



C) "Missing" Well MW-55

Legend

Well missing from kriging realization

Prediction Standard Error Map

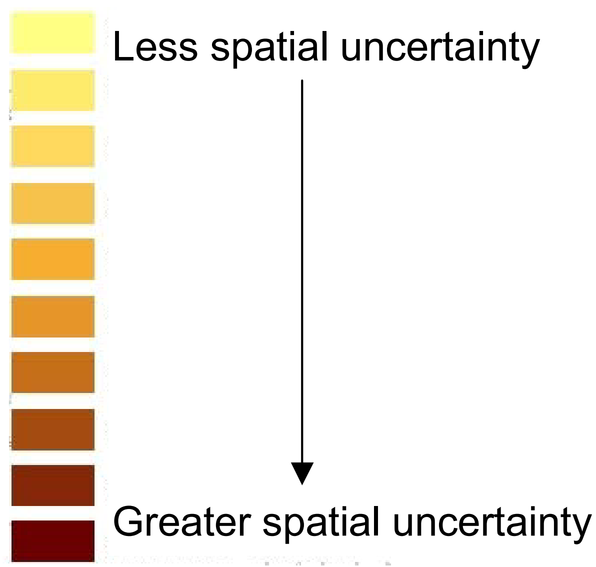


FIGURE 6.3
IMPACT OF MISSING WELLS ON PREDICTED STANDARD ERROR

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which all A-zone wells are included. Map B shows the realization in which well MW-1004 was removed from the monitoring network, and Map C shows the realization in which well MW-55 was removed. Figure 6.3 shows that when a well is removed from the network, the predicted standard error in the vicinity of the missing well increases (as indicated by a darkening of the shading in the vicinity of that well). If a "removed" (missing) well is in an area with several other wells (e.g., well MW-55; Map C on Figure 6.3), the predicted standard error may not increase as much as if a well (e.g., MW-1004; Map B) is missing from an area with fewer surrounding wells.

If removal of a particular well from the monitoring network caused very little change in the resulting median kriging standard deviation (less than about 1 percent), that well was regarded as contributing only a limited amount of information to the LTM program. Likewise, if removal of a well from the monitoring network produced larger increases in the kriging standard deviation, this was regarded as an indication that the well contributes a relatively greater amount of information, and is relatively more important to the monitoring network. At the conclusion of the kriging realizations, each well was ranked from 1 (providing the least information) to 32 (providing the most information), based on the amount of information (as measured by changes in median kriging standard deviation) the well contributed toward describing the spatial distribution of TCE, as shown in Table 6.1. Wells providing the least amount of information represent possible candidates for removal from the monitoring network at the OU D.

6.3 SPATIAL STATISTICAL EVALUATION RESULTS

6.3.1 Kriging Ranking Results

Figure 6.4 and Table 6.1 present the ranking of monitoring locations based on the relative value of recent TCE information provided by each well, as calculated based on the kriging realizations. Examination of these results indicate that monitoring wells in close proximity to several other monitoring wells (e.g., red and yellow color coding on Figure 6.4) generally provide relatively lesser amounts of information than do wells at greater distances from other wells, or wells located in areas having limited numbers of

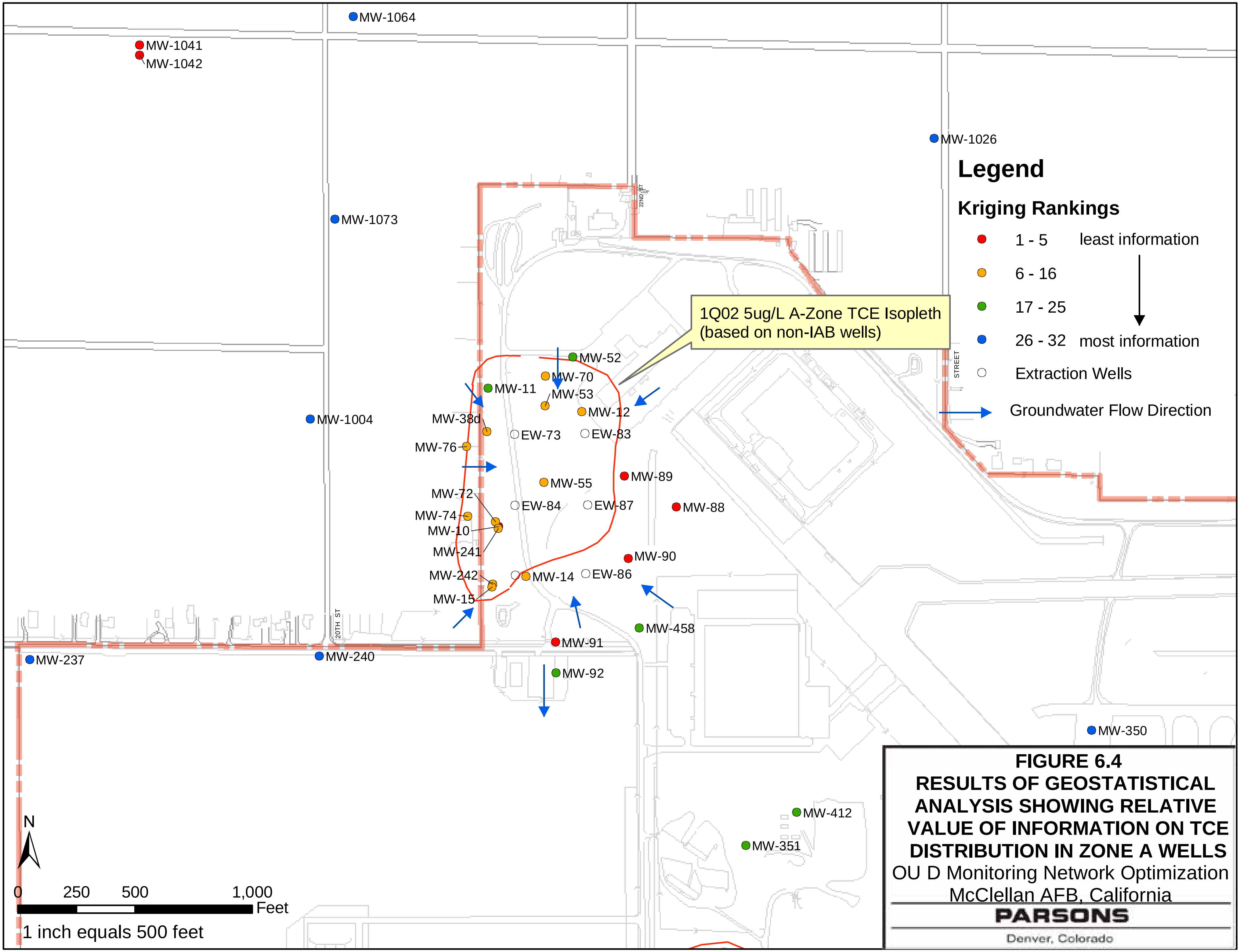

FIGURE 6.4
RESULTS OF GEOSTATISTICAL ANALYSIS SHOWING RELATIVE VALUE OF INFORMATION ON TCE DISTRIBUTION IN ZONE A WELLS
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TABLE 6.1
RESULTS OF GEOSTATISTICAL EVALUATION RANKING OF ZONE A WELLS BY RELATIVE VALUE OF TCE INFORMATION
OPERABLE UNIT D
THREE-TIERED MONITORING NETWORK OPTIMIZATION
McCLELLAN AFB, CALIFORNIA

All Zone A Wells	
Well ID	**Kriging Ranking [a/]**
MW-10	1
MW-88	2
MW-91	5[c/]
MW-90	5
MW-89	5
MW-1042	5
MW-1041	5
MW-76	13.5
MW-74	13.5
MW-72	13.5
MW-70	13.5
MW-55	13.5
MW-53	13.5
MW-38d	13.5
MW-242	13.5
MW-241	13.5
MW-15	13.5
MW-14	13.5
MW-12	13.5
MW-92	21.5
MW-52	21.5
MW-351	21.5
MW-11	21.5
MW-458	24
MW-412	25
MW-1004	26
MW-1064	27
MW-350	29.5
MW-237	29.5
MW-1073	29.5
MW-1026	29.5
MW-240	32

OU D TCE Plume Area Zone A Wells			
Well Id	**Kriging Ranking [b/]**	**Remove**	**Retain**
MW-92	1	√	
MW-74	3.5	√	
MW-72	3.5	√	
MW-241	3.5	√	
MW-10	3.5	√	
MW-76	8	--[d/]	--
MW-70	8	--	--
MW-53	8	--	--
MW-38d	8	--	--
MW-242	8	--	--
MW-52	11.5	--	--
MW-11	11.5	--	--
MW-458	13	--	--
MW-14	14.5	--	--
MW-12	14.5	--	--
MW-88	16	--	--
MW-91	17	--	--
MW-90	18.5		√
MW-55	18.5		√
MW-89	20		√
MW-15	21		√

[a/] 1= least relative amount of information; 32= most relative amount of information.

[b/] 1= least relative amount of information; 21= most relative amount of information.

[c/] Tie values receive the median ranking of the set.

[d/] Wells in the "intermediate" range and receive no recommendation for removal or retention.

monitoring points (e.g., blue color coding on Figure 6.4). This is intuitively obvious, but the analysis allows the most valuable and least valuable wells to be identified quantitatively. In this analysis, the A-zone wells distant from the TCE plume, as defined by the 5-µg/L concentration isopleth (MW-1004, MW-1064, MW-350, MW-237, MW-1073, and MW-240) were identified as providing the greatest relative amount of spatial information. However, as discussed in Section 4.2.1.2, these wells are located approximately 650 to 2,200 feet from the 5-µg/L TCE isopleth (Figure 6.4), and most also are located hydraulically up- or crossgradient from the plume sources (i.e., the OU D waste pits); they are too far from the plume to provide useful information on plume magnitude and extent given the very localized and contained nature of dissolved COC present at concentrations above the respective MCLs. Thus, although these wells provide spatial information, they not in the region of interest for the OU D plume.

Therefore, a revised kriging analysis was conducted only for those monitoring wells within 500 feet of the OU D plume, as defined by the 5-µg/L TCE isopleth. Although the EWs are in this region, they were excluded from the analysis because their screened intervals span both the A and B zones, and monitor water drawn from the respective EW capture zones, while the monitoring well provide "point" data representative of water flowing past the well. Thus, the revised analysis examined the relative spatial information provided by the 21 monitoring wells in the vicinity of the OU D plume using the same procedure described in Section 6.2. The best-fit semivariogram for the revised 21-well network had the following parameters:

- Circular Model
- Range: 600 feet
- Sill: 20
- Nugget: 19

Figure 6.5 and Table 6.1 present the ranking of monitoring locations based on the relative value of TCE information provided by each well, as calculated based on the kriging realizations for the select group of zone A wells. For example, Table 6.1

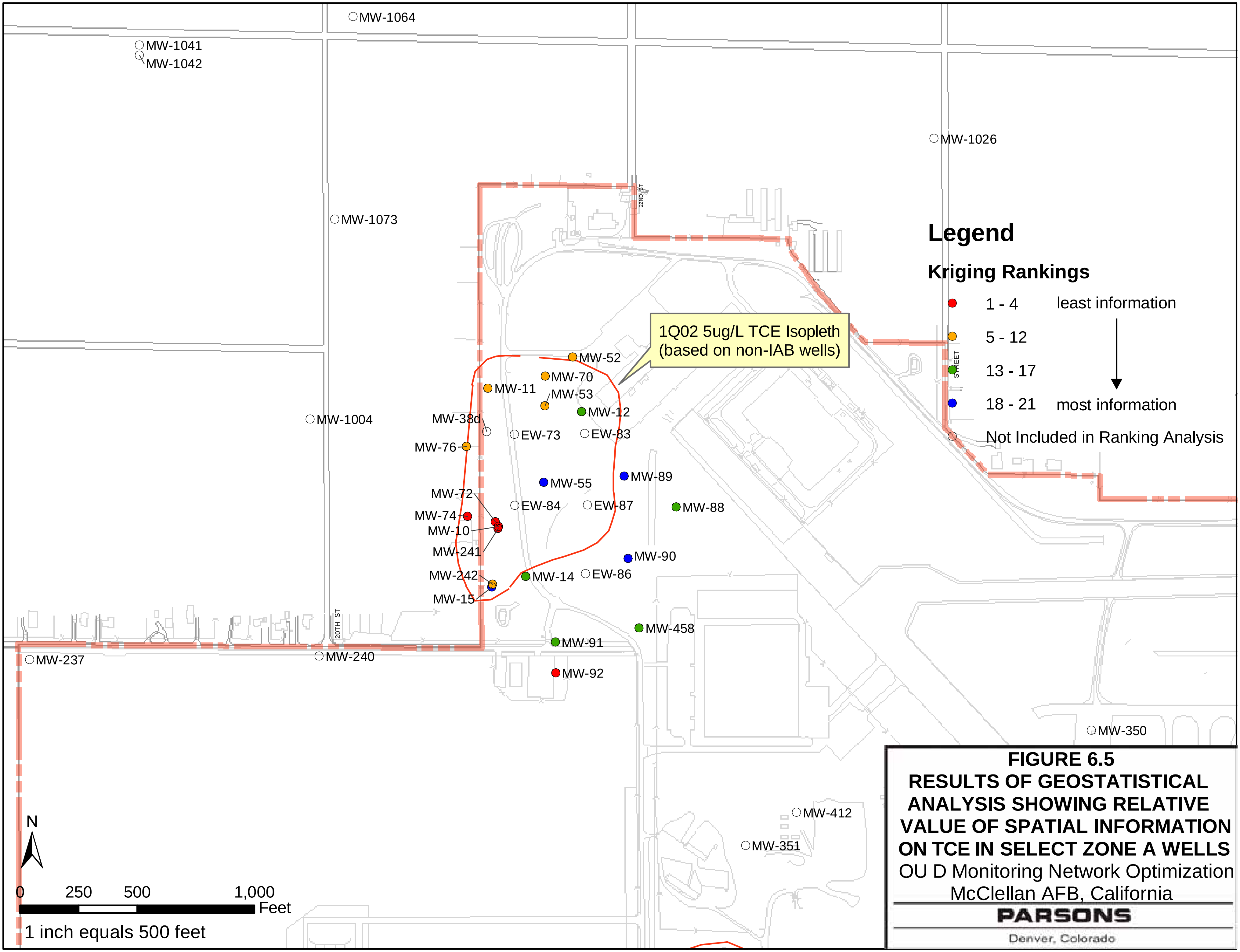

FIGURE 6.5

RESULTS OF GEOSTATISTICAL ANALYSIS SHOWING RELATIVE VALUE OF SPATIAL INFORMATION ON TCE IN SELECT ZONE A WELLS

OU D Monitoring Network Optimization
McClellan AFB, California

PARSONS
Denver, Colorado

identifies the five wells ranked at or below 3.5 (wells MW-10, MW-241, MW-92, MW-74, and MW-72) that provide the relative least amount of information, and the four wells ranked at or above 18.5 (wells MW-15, MW-55, MW-89, MW-90) that provide the greatest amount of information regarding the occurrence and distribution of TCE in groundwater in the zone A wells in the region of interest surrounding the OU D TCE plume. The five lowest-ranked wells are potential candidates for removal from the OU D groundwater monitoring program, and the four highest-ranked wells are candidates for retention in the monitoring program, intermediate ranked wells receive no recommendation for removal or retention in the monitoring program based on the spatial analysis.

SECTION 7

SUMMARY OF THREE-TIERED MONITORING NETWORK EVALUATION

The 51 wells included in the groundwater monitoring program at OU D were evaluated using qualitative hydrogeologic and extraction-system information, temporal statistical techniques, and spatial statistics. At each tier of the evaluation, monitoring points that provide relatively greater amounts of information regarding the occurrence and distribution of COCs in groundwater were identified, and were distinguished from those monitoring points that provide relatively lesser amounts of information. In this section, the results of the evaluations are combined to generate a refined monitoring program that potentially could provide information sufficient to address the primary objectives of monitoring, at reduced cost. Monitoring wells not retained in the refined monitoring network could be removed from the monitoring program with relatively little loss of information. The results of the evaluations were combined and summarized in accordance with the following decision logic:

1. Each well retained in the monitoring network on the basis of the qualitative hydrogeologic evaluation is recommended to be retained in the refined monitoring program.

2. Those wells recommended for removal from the monitoring program on the basis of all three evaluations, or on the basis of the qualitative and temporal evaluations (with no recommendation resulting from the spatial evaluation) should be removed from the monitoring program.

3. If a well is recommended for removal based on the qualitative evaluation and recommended for retention based on the temporal or spatial evaluation, the final recommendation is based on a case-by-case review of well information.

The results of the qualitative, temporal, and spatial evaluations are summarized in Table 7.1. These results indicate that 30 of the 51 monitoring wells could be removed from the groundwater LTM program with little loss of information. The justifications for the recommendations for the four wells that fall into case 3 of the decision logic are as follow:

- Well MW-55 should be retained in the monitoring program based on its contribution to spatial plume-definition information.

- Wells MW-72 and MW-241 are recommended for removal from the monitoring network based on the qualitative and spatial evaluations, and for retention based on the temporal evaluation. They should be removed from the monitoring network because they are monitoring lower concentration portions of the A zone than clustered well MW-10. However, this recommendation is conditional on having below MCL concentrations of COCs during three most recent consecutive monitoring events.

- Well MW-242 is recommended for removal from the monitoring network based on the qualitative and spatial evaluations, and for retention based on the temporal evaluation. It should be removed from the monitoring network because it is monitoring lower concentration portions of the A zone than clustered well MW-15. However, this recommendation is conditional on having below MCL concentrations of COCs during three most recent consecutive monitoring events.

A refined monitoring program, consisting of 21 wells (13 to be sampled annually, and 8 to be sampled biennially) would be adequate to address the two primary objectives of monitoring. This refined monitoring network would result in an average of 17 sampling events per year, compared to 34 events per year in the current monitoring program.

TABLE 7.1
SUMMARY OF EVALUATION OF CURRENT GROUNDWATER MONITORING PROGRAM
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
McCLELLAN AFB, CALIFORNIA

Well ID	Zone	Current Sampling Frequency[a/]	Qualitative Evaluation		Temporal Evaluation		Spatial Evaluation		Summary		
			Remove	Retain	Remove	Retain	Remove	Retain	Remove	Retain	Recommended Monitoring Frequency
Extraction Wells											
EW-73	A/B	Annual		√		√	NI			√	Annual
EW-83	A/B	Annual		√	√		NI			√	Annual
EW-84	A/B	Annual		√		√	NI			√	Annual
EW-85	A/B	Annual		√		√	NI			√	Annual
EW-86	A/B	Annual		√		√	NI			√	Annual
EW-87	A/B	Annual		√		√	NI			√	Annual
Zone A Wells											
MW-10	A	Annual		√		√	√			√	Annual
MW-11	A	Annual		√		√				√	Annual
MW-12	A	Annual		√		√				√	Annual
MW-14	A	Biennial		√		√				√	Biennial
MW-15	A	Annual		√		√		√		√	Annual
MW-38D	A*[b/]	Annual		√		√				√	Annual
MW-52	A*	Biennial	√		√				√		--
MW-53	A*	Biennial	√		√				√		--
MW-55	A*	Biennial	√		√			√		√	Biennial
MW-70	A*	Biennial	√		√				√		--
MW-72	A	Annual	√			√	√		√		--
MW-74	A*	Biennial	√		√		√		√		--
MW-76	A*	Annual		√		√				√	Annual
MW-88	A	Biennial	√		√				√		--
MW-89	A	Biennial		√	√			√		√	Biennial
MW-90	A	Biennial		√	√			√		√	Biennial
MW-91	A	Biennial	√		√				√		--
MW-92	A	Biennial	√		√		√		√		--
MW-237	A	Biennial	√		√		NI		√		--
MW-240	A	Biennial	√		√		NI		√		--
MW-241	A	Annual	√			√	√		√		--
MW-242	A	Annual	√			√			√		--
MW-350	A	Biennial	√		√		NI		√		--
MW-351	A	Annual	√		√		NI		√		--
MW-412	A	Biennial	√		√		NI		√		--
MW-458	A	Biennial	√		√				√		--
MW-1004	A	Biennial	√		√		NI		√		--

TABLE 7.1 (Continued)
SUMMARY OF EVALUATION OF CURRENT GROUNDWATER MONITORING PROGRAM
THREE-TIERED MONITORING NETWORK OPTIMIZATION
OPERABLE UNIT D
McCLELLAN AFB, CALIFORNIA

			Qualitative Evaluation		Temporal Evaluation		Spatial Evaluation		Summary		
Well ID	Zone	Current Sampling Frequency[a/]	Remove	Retain	Remove	Retain	Remove	Retain	Remove	Retain	Recommended Monitoring Frequency
MW-1026	A	Biennial	√		√		NI		√		--
MW-1041	A	Biennial	√		√		NI		√		--
MW-1042	A*	Biennial	√		√		NI		√		--
MW-1064	A	Biennial	√		√		NI		√		--
MW-1073	A	Biennial	√		√		NI		√		--
Zone B Wells											
MW-19D	B	Biennial		√		√	NI			√	Biennial
MW-51	B	Biennial		√	√		NI			√	Biennial
MW-54	B*	Annual		√		√	NI			√	Annual
MW-57	B*	Biennial	√		√		NI		√		--
MW-58	B	Biennial		√	√		NI			√	Biennial
MW-59	B	Biennial		√	√		NI			√	Biennial
MW-104	B	Biennial	√		√		NI		√		--
MW-1001	B	Biennial	√		√		NI		√		--
MW-1003	B*	Biennial	√		√		NI		√		--
MW-1010	B*	Biennial	√		√		NI		√		--
MW-1027	B	Biennial	√		√		NI		√		--
MW-1028	B	Biennial	√		√		NI		√		--
MW-1043	B	Biennial	√		√		NI		√		--

[a/] Sampling frequency based on 1st Quarter 2002 Groundwater Monitoring Program Quarterly Report (URS, 2002).
[b/] *= Well screened interval orginally designated as monitoring zone IAB or AB; reassigned per URS (2002).

Implementing these recommendations for optimizing the LTM monitoring program at OU D at McClellan AFB could reduce current LTM annual monitoring costs events by 50 percent. Based on analytical costs alone, implementing these recommendations could save $2550 per year based on an estimate of $150 per sample analysis. Additional cost savings could be realized if groundwater samples collected from select wells (e.g., wells along the lateral and upgradient plume margins) were analyzed for a short list of halogenated VOCs using USEPA Method SW8021B instead of USEPA Method SW8260B.

SECTION 8

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