CHARACTERIZING SOILS FOR

HAZARDOUS WASTE SITE ASSESSMENTS

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1. Introduction

The Regional Superfund Ground Water Forum is a group of ground-water scientists representing EPA's Regional Offices, organized to exchange up-to-date information related to ground-water remediation at hazardous waste sites. Soil characterization at hazardous waste sites is an issue identified by the forum as a concern of CERCLA decision-makers.

The identification and collection of soil characterization data types required for CERCLA decision making is an issue identified by the forum as a concern. This paper was prepared through support from EMSL-LV and RSKERL, under the direction of R. P. Breckenridge, with the support of the Superfund Technical Support Project. For further information contact Ken Brown, Center Director, at FTS 545-2270 or R. P. Breckenridge at FTS 583-0757.

Site investigation and remediation under the Superfund program is performed using the CERCLA remedial investigation/feasibility study (RI/FS) process. The goal of the RI/FS process is to reach a Record of Decision (ROD) in a timely manner. Soil characterization provides data types required for decision-making in three distinct RI/FS tasks:

1. Determination of the nature and extent of soil contamination.
2. Risk assessment, and determination of risk-based soil clean-up levels.
3. Determination of the potential effectiveness of soil remediation alternatives.

Identification of data types required for the first task, determination of the nature of extent of contamination, is relatively straightforward. The nature of contamination is related to the types of operations conducted at the site. Existing records, if available, and interviews with personnel familiar with the site history are good sources of information to help determine the types of contaminants potentially present. This information may be used to shorten the list of target analytes from the several hundred contaminants of concern on the Appendix IX list. Numerous guidance documents are available for planning all aspects of the subsequent sampling effort (US EPA, 1987a, 1988a, 1988b, and Jenkins et al., 1988).

The extent of contamination is also related to the types of operations conducted at the site. Existing records, if available, and interviews with personnel familiar with the site history are also good sources of information to help determine the extent of contamination potentially present. The extent of contamination is dependent on the nature of the contaminant source(s) and the extent of contaminant migration from the source(s). Migration routes may include air, via volatilization and fugitive dust emissions; overland flow; direct discharge; leachate migration to ground water and surface runoff and erosion. Preparation of a preliminary site conceptual model is therefore an important step in planning and directing the sampling effort. Use of the conceptual model helps to identify the most likely locations of contaminants in soil.

The data type requirements for tasks 2 and 3 are frequently less well understood. Tasks 2 and 3 require knowledge of both the nature and extent of contamination, the environmental fate and transport of the contaminants, and an appreciation of the need for quality data to select a viable remedial treatment technique.

Contaminant fate and transport estimation is usually performed by computer modeling. Site-specific information about the soils in which contamination occurs, migrates, and interacts with, is required as input to a model. The accuracy of the model output is no better than the accuracy of the input information.

The purpose of this paper is to provide guidance to Remedial Project Managers (RPM) and On-Scene Coordinators (OSC) concerning soil characterization data types required for decision-making in the CERCLA RI/FS process related to risk assessment and remedial alternative evaluation for contaminated soils. Many of the problems that arise are due to a lack of understanding the data types required for tasks 2 and 3 above. This paper describes the soil characterization data types required to conduct model based risk assessment for task 2 and the selection of remedial design for task 3. The information presented in this paper is a compilation of current information from the literature and from experience combined to meet the purpose of this paper.

EMSL-Las Vegas and RSKERL-Ada convened a technical committee of experts to examine the issue and provide technical guidance based on current scientific information. Members of the committee were Joe R. Williams, RSKERL-Ada; Robert G. Baca, Robert P. Breckenridge, Alan B. Crockett, and John F. Keck from the Idaho National Engineering Laboratory, Idaho Falls, ID; Gretchen L. Rupp, PE, University of Nevada-Las Vegas; and Ken Brown, EMSL-LV.

This document was compiled by the authors and edited by the members of the committee and a group of peer reviewers.

Characterization of a hazardous waste site requires an integrated investigative approach to determine quickly and cost effectively the potential health effects and appropriate response measures at a site. An integrated approach involves consideration of the different types and sources of contaminants, their fate as they are transported through and are partitioned, and their impact on different parts of the environment. In designing an integrated approach the (i.e. soils), vapor, and liquid phases (i.e. surface and ground water) of the site should be characterized. This paper focuses on characterizing a site relative to the movement and remediation of contaminants in the soil portion.

Concerns

This paper was prepared to address two specific concerns related to soil characterization for CERCLA remedial response. The first concern is the applicability of traditional soil classification methods to CERCLA soil characterization. The second is the identification of soil characterization data types required for CERCLA risk assessment and analysis of remedial alternatives. These concerns are related, in that the Data Quality Objective (DQO) process addresses both. The DQO was developed in part to assist CERCLA decision-makers in identifying the data types, data quality, and data quantity required to support decisions that must be made during the RI/FS process. *Data Quality Objectives for Remedial Response Activities: Development Process* (US EPA, 1987b) is a guidebook on developing DQOs. This process as it relates to CERCLA soil characterization is discussed in the Data Quality Objective Section of this paper.

Data types required for soil characterization must be determined early in the RI/FS process, using the DQO process. Often, the first soil data types related to risk assessment and remedial alternative selection available during a CERCLA site investigation are soil textural descriptions from the borehole logs prepared by a geologist during investigations of the nature and extent of contamination. These boreholes might include installation of ground-water monitoring wells, or soil boreholes. Typically, borehole logs contain soil lithology and textural descriptions, based on visual analysis of drill cuttings.

These data are potentially valuable, and can provide modelers and engineers with preliminary data with which to begin preparation of the conceptual model and perform scoping calculations. Soil texture affects movement of air and water in soil, infiltration rate, porosity, water holding capacity, and other parameters. Changes in lithology identify heterogeneities in the subsurface (i.e., low permeability layers, etc.). Soil textural classification is therefore important to contaminant fate and transport modeling, and to screening and analysis of remedial alternatives. However, unless collected properly, soil textural descriptions are of limited value for the following reasons:

1. There are several different systems for classification of soil particles with respect to size. To address this problem it is important to identify which system has been or will be used to classify a soil so that data can be properly compared. Figure 1 can be used to compare the different systems (Gee and Bauder, 1986). *Keys to Soil Taxonomy* (Soil Survey Staff, 1990) provides details to one of the more useful systems that should be consulted prior to classifying a site's soils.

2. The accuracy of the field classification is dependent on the skill of the observer. To overcome this concern RPMs and OSCs should collect soil textural data that are quantitative rather than qualitative. Soil texture can be determined from a soil sample by sieve analysis or hydrometer. These data types are superior to qualitative description based on visual analysis and are more likely to meet DQOs.

3. Even if the field person accurately classifies a soil (e.g., as a silty sand or a sandy loam), textural descriptions do not afford accurate estimations of actual physical properties required for modeling and remedial alternative evaluation, such as hydraulic conductivity. For example, the hydraulic conductivity of silty-sand can range from 10^{-5} to 10^{-1} cm/sec (four orders of magnitude).

These ranges of values may be used for bounding calculations, or to assist in preparation of the preliminary conceptual model. These data may therefore meet DQOs for initial screening of remedial alternatives, for example, but will likely not meet DQOs for detailed analysis of alternatives.

The remainder of this paper will discuss how to identify soil characteristic data types that can be used to accurately model risk and select appropriate remedial treatment alternatives for a site.

Data Quality Objectives

EPA has developed the Data Quality Objective (DQO) process to guide CERCLA site characterization. The relationship between CERCLA RI/FS activities and the DQO process is shown in Figure 2 (US EPA, 1988c, 1987a). The DQO process occurs in three stages:

- **Stage 1.** Identify Decision Types. In this stage the types of decisions that must be made during the RI/FS are identified. The types of decisions vary throughout the RI/FS process, but in general they become increasingly quantitative as the process proceeds. During this stage it is important to identify and involve the data users (e.g., modelers, engineers, and scientists), evaluate available data, develop a conceptual site model, and specify objectives and decisions.

- **Stage 2.** Identify Data Uses/Needs. In this stage data uses are defined. This includes identification of the required data types, data quality and data quantity required to make decisions and meet project objectives. For CERCLA contaminated soils this includes:

  - Determine soil data types, data quality, and data quantity required to perform risk assessment

  - Determine soil data types, data quality, and data quantity required to perform contaminant fate and transport modeling

  - Determine soil data types, data quality, and data quantity required to identify and screen remedial alternatives

- **Stage 3.** Design Data Collection Program. After Stage 1 and 2 activities have been defined and reviewed, a data collection program addressing the data types, data quantity (number of samples) and data quality required to make these decisions is developed.

The remainder of this paper will discuss data types required for decision-making in the CERCLA RI/FS process related to soil contamination. References are provided relating to determining data quantity and data quality.

Data Types

Concerns related to data types arise when the OSC or RPM must determine which soil parameters are needed to make various RI/FS decisions. The types of decisions to be made therefore drive selection of data types. Data types required for RI/FS activities including risk assessment, contaminant fate and transport modeling and remedial alternative selection are discussed in Soil Characteristics Data Types Required for Modeling Section, and the Soil Characterization Data Type Required for Remedial Alternative Selection Section.

Data Quality

Concerns related to data quality arise when the RPM or OSC must decide "How good does the data need to be in order for me to make a given decision?". EPA has assigned quality levels to different RI/FS activities as a guideline. *Data Quality Objectives for Remedial Response Activities* (US EPA, 1987a) offers guidance on this subject and contains many useful references.

Data Quantity

Concerns related to data quantity arise when the RPM or OSC must decide "How many samples do I need to determine the mean and standard deviation of a given parameter at a given site?", or "How does a given parameter vary spatially across the site?". Decisions of this type must be addressed by statistical design of the sampling effort. The *Soil Sampling Quality Assurance Guide* (Barth et al., 1989) and *Data Quality Objectives for Remedial Response* (US EPA, 1987a) offer guidance on this subject and contain many useful references.

Important Soil characteristics in Site Evaluation

Tables 1 and 2 identify methods for collecting and determining data types for soil characteristics either in the field, laboratory, or by calculation. Soil characteristics in Table 1 are considered the primary indicators that are needed to complete Phase I of the RI/FS process. This is a short, but concise list of soil data types that are needed to make CERCLA decisions and should be planned for and collected early in the sampling effort. These primary data types should allow for the initial screening of remedial

TABLE I . MEASUREMENT METHODS FOR PRIMARY SOIL CHARACTERISTICS NEEDED TO SUPPORT CERCLA DECISION-MAKING PROCESS

	Measurement Technique/Method (w/Reference)		
Soil Characteristic*	**Field**	**Laboratory**	**Calculation or Lookup Method**
Bulk density	Neutron probe (ASTM, 1985), Gamma radiation (Blake and Hartage, 1986, Blake, 1965).	Coring or excavation for lab analysis (Blake and Hartge, 1986).	Not applicable.
Soil pH	Measured in field in same manner as in laboratory.	Using a glass electrode in an aqueous slurry (ref. EPRI EN-6637) Analytical Method – Method 9045, SW-846, EPA.	Not applicable.
Texture	Collect composite sample for each soil type. No field methods are available, except through considerable experience of "feeling" the soil for an estimation of % sand, silt, and clay.	ASTM D 522-63 Method for Particle Analysis of Soils. Sieve analysis better at hazardous waste sites because organics can effect hydrometer analysis (Kluate, 1986).	Not applicable.
Depth to ground water	Ground-water monitoring wells or piezometers using EPA approved methods (EPA 1985a).	Not applicable.	Not applicable.
Horizons or stratigraphy	Soil pits dug with backhoe are best. If safety and cost are a concern, soil bores can be collected with either a thin wall sample driver and veilmayer tube (Brown et al., 1990).	Not applicable.	May be possible to obtain information from SCS soil survey for the site.
Hydraulic conductivity (saturated)	Auger-hole and piezometer methods (Amoozeger and Warrick, 1986) and Guelph permeameter (Reynolds & Elrick, 1985; Reynolds & Elrick, 1986).	Constant head and falling head methods (Amoozeger and Warrick, 1986).	Although there are tables available that list the values for the saturated hydraulic conductivity, it should be understood that the values are given for specific soil textures that may not be the same as those on the site.
Water retention (soil water characteristic curves)	Field methods require a considerable amount of time, effort, and equipment. For a good discussion of these methods refer to Bruce and Luxmoore (1986).	Obtained through wetting or drainage of core samples through a series of known pressure heads from low to high or high to low, respectively (Klute, 1986).	Some look-up and estimation methods are available, however, due to high spatial variabiltiy in this characteristic they are not generally recommended unless their use is justified.
Air permeability and water content relationships	None	Several methods have been used, however, all use disturbed soil samples. For field applications the structure of soils is very important. For more information refer to Corey (1986).	Estimation methods for air permeability exist that closely resemble the estimation methods for unsaturated hydraulic conductivity. Example models are those developed by Brooks and Corey (1964) and van Genuchten (1980).
Porosity (pore volume)		Gas pycnometer (Danielson and Sutherland, 1986).	Calcualted from particle and bulk densities (Danielson and Sutherland, 1986).
Climate	Precipitation measured using either Sacramento gauge for accumulated value or weighing gauge or tipping bucket gauge for continuous measurement (Finkelstein et al., 1983; Kite, 1979). Soil temperature measured using thermocouple.	Not applicable.	Data are provided in the Climatic Atlas of the Unbited States or are available from the National Climatic Data Center, Asheville, NC Telephone (704) 259-0682.

* Soil characteristics are discussed in general except where specific cases relate to different waste types (i.e., metals, hydrophobic organics or polar organics).

TABLE II . MEASUREMENT METHODS FOR ANCILLARY SOIL PARAMETERS NEEDED TO SUPPORT CERCLA DECISION-MAKING PROCESS

	Measurement Technique/Method (w/Reference)		
Soil Characteristic*	**Field**	**Laboratory**	**Calculation or Lookup Method**
Organic carbon	Not applicable.	High temperature combustion (either wet or dry) and oxidation techniques (Powell et al., 1989) (Powell, 1990).	
Capacity Exchange Capacity (CEC)	See Rhoades for field methods.	(Rhoades, 1982).	
Erodibility			Estimated using standard equations and graphs (Israelsen et al., 1980) field data for slope, field length, and cover type required as input. Soils data can be obtained from the local Soil Conservation Service (SCS) office.
Water erosion Universal Soil Loss Equation (USLE) or Revised USLE (RUSLE)	Measurement/survey of slope (in ft rise/ft run or %), lenght of field, vegetative cover.		A modified universal soil loss equation (USLE) (Williams, 1975) presented in Mills et al., (1982) and US EPA (1988d) are sources for equations.
Wind erosion	Air monitoring for mass of contaminant. Field length along prevailing wind direction.		The SCS wind loss equation (Israelsen et al., 1980) must be adjusted (reduced) to account for suspended particles of diameter $\leq$10 µm Cowherd et al. (1985) for a rapid evaluation ($\leq$24 hr) of particle emission fro a Superfund site.
Vegetative cover	Visual observation and documented using map. USDA can aid in identification of unknown vegetation.	Not applicable.	
Soil structure	Classified into 10 standard kinds – see local SCS office for assistance (Soil Survey Staff, 1990) or Taylor and Ashcroft (1972), p. 310.		
Organic carbon partition cooefficient (K_{oc})	*In situ* tracer tests (Freeze and Cherry, 1979).	(ASTM E 1195-87, 1988)	Calculated from K_{ow}, water solubility (Mills et al., 1985; Sims et al., 1986).
Redox couple ratios of waste/soil system	Platium electrode used on lysimeter sample (ASTM, 1987).	Same as field.	Can be calculated from concentrations of redox pairs or 0_2 (Stumm and Morgan, 1981).
Linear soil/water partition coefficeint	*In situ* tracer tests (Freeze and Cherry, 1979)	Batch experiment (Ash et al., 1973); column tests (van Genuchten and Wierenga, 1986).	Mills et al., 1985.
Soil oxygen content (aeration)	O_2 by membrane electrode O_2 diffusion rate by Pt microelectrode (Phene, 1986). O_2 by field GC (Smith, 1983).	Same as field.	Calculated from pE (Stumm and Morgan, 1981) or from O_2 and soil-gas diffusion rate.
Soil temperature (as it affects volatilization)	Thermometry (Taylor and Jackson, 1986).	Same as field.	Brown and Associates (1980).

(Continued)

TABLE II. (CONTINUED)

Soil Characteristic*	Measurement Technique/Method (w/Reference) Field	Laboratory	Calculation or Lookup Method
Clay mineralogy	Parent material analysis.	X-ray diffraction (Whittig and Allardice, 1986).	
Unsaturated hydraulic conductivity	Unsteady drainage-flux (or instantaneous profile) method and simplified unsteady drainage flux method (Green et al., 1986).The instantaneous profile method was initially developed as a laboratory method (Watson, 1966), however it was adapted to the field (Hillel et al., 1972). Constant-head borehole infiltration (Amoozegar and Warrick, 1986).	Not usually done; results very difficult to obtain.	A number of estimation methods exist, each with its own set of assumptions and requirements. Reviews have been presented by Mualem (1986), and van Genuchten (in press).
Moisture content	Two types of techniques – indirect and direct. Direct methods (i.e., gravimetric sampling), considered the most accurate, with no calibration required. However, methods are destructive to field systems. Methods involve collecting samples, weighing, drying and re-weighing to determine field moisture. Indirect methods rely on calibration (Klute, 1986).		
Soil biota	No standard method exists (see model or remedial technology for input or remedial evaluation procedures).	No standard method exists; can use agar plate count using MOSA Method 99-3 p. 1462 (Klute, 1986).	
Visual textural classification	Visual observation used to assign to one of three primary groups: coarse-grained, fine-grained, or organic soils using ASTM D 2488-84 standard method for description of soils (Visual-Manual procedures) (EPA, 1987b).	Verify field assessment on selected samples using ASTM D 2487-85 and compare with results from texture analysis.	

* Soil characteristics are discussed in general except where specific cases relate to different waste types (i.e., metals, hydrophobic organics or polar organics).

treatment alternatives and preliminary modeling of the site for risk assessment. Many of these characteristics can be obtained relatively inexpensively during periods of early field work when the necessary drilling and sampling equipment are already on site. Investigators should plan to collect data for all the soil characteristics at the same locations and times boring is done to install monitoring wells and soil borings. Geophysical logging of the well should also be considered as a cost effective method for collecting lithologic information prior to casing the well. Data quality and quantity must also be considered before beginning collection of the appropriate data types.

The soil characteristics in Table 2 are considered ancillary only because they are needed in the later stages and tasks of the DQO process and the RI/FS process. If the site budget allows, collection of these data types during early periods of field work will improve the database available to make decisions on remedial treatment selection and model-based risk assessments. Advanced planning and knowledge of the need for the ancillary soil characteristics should be factored into early site work to reduce overall costs and the time required to reach a ROD. A small additional investment to collect ancillary data during early site visits is almost always more cost effective than having to send crews back to the field to conduct additional soil sampling.

Further detailed descriptions of the soil characteristics in Tables 1 and 2 can be found in *Fundamentals of Soil Physics and Applications of Soil Physics* (Hillel, 1980) and in a series of articles by Dragun (1988, 1988a, 1988b). These references provide excellent discussions of these characteristics and their influence on water movement in soils as well as contaminant fate and transport.

Soil Characteristics Data Types Required For Modeling

The information presented here is not intended as a review of all data types required for all models, instead it presents a sampling of some of the more appropriate models used in risk assessment and remedial design.

Uses of Vadose Zone Models for CERCLA Remedial Response Activities

Models are used in CERCLA RIs and FSs to estimate contaminant fate and transport. These estimates of contaminant behavior in the environment are subsequently used for:

- **Risk assessment**. Risk assessment includes contaminant release assessment, exposure assessment, and determining risk-based clean-up levels. Each of these activities requires estimation of the rates and extents of contaminant movement in the vadose zone, and of transformation and degradation processes.

- **Effectiveness assessment of remedial alternatives**. This task may also require determination of the rates and extents of contaminant movement in the vadose zone, and of rates and extents of transformation and degradation processes. Technology-specific data requirements are cited in the Soil Characteization Data Type Required for Remedial Alternative Selection Section.

The types, quantities, and quality of site characterization data required for modeling should be carefully considered during RI/FS scoping. Several currently available vadose zone fate and transport models are listed in Table 3. Soil characterization data types required for each model are included in the table. Model documentation should be consulted for specific questions concerning uses and applications.

The Superfund Exposure Assessment Manual discusses various vadose zone models (US EPA, 1988e). This document should be consulted to select codes that are EPA-approved.

Data Types Required for Modeling

Soil characterization data types required for modeling are included in Tables 1 and 2. Most of these models are one- or two-dimensional solutions to the advection-dispersion equation, applied to unsaturated flow. Each is different in the extent to which transformation and degradation processes may be simulated; various contaminant release scenarios are accommodated; heterogeneous soils are accounted for; and other site-specific characteristics are accounted for. Each, therefore, has different data type input requirements.

All models require physicochemical data for the contaminants of concern. These data are available in the literature, and from EPA databases (US EPA, 1988c,d). The amount of physicochemical data required is generally related to the complexity of the model. These models that account for biodegradation of organics, vapor phase diffusion and other processes require more input data than the relatively simpler transport models.

Data Quality and Quantity Required for Modeling

DQOs for all RI/FS tasks should be defined during RI/FS scoping. The output of any computer model is only as valid as the quality of the input data and code itself. Variance may result from the data collection

TABLE III. SOIL CHARACTERISTICS REQUIRED FOR VADOSE ZONE MODELS

	Model Neme [Reference(s)]									
Properties and Parameters	**Help (A,B)**	**Sesoil (C,D)**	**Creams (E.F)**	**PRZM (G,H,I)**	**Vadoft (H,J)**	**Minteq (J)**	**Fowl™ (K)**	**Ritz (L)**	**Vip (M)**	**Chemflo (N)**
Soil bulk densities	◍	●	●	●	●	◍	●	●	●	●
Soil pH	○	●	◍	○	○	●	●	○	○	○
Soil texture	●	◍	●	●	●	◍	◍	●	●	◍
Depth to ground water	◍	●	◍	◍	●	◍	◍	◍	◍	◍
Horizons (soil layering)	●	●	●	●	●	◍	◍	◍	◍	◍
Saturated hydraulic conducitivity	●	●	●	●	●	◍	●	●	●	●
Water retention	●	●	●	●	●	◍	●	○	○	●
Air permeability	○	●	○	◍	◍	○	○	◍	●	○
Climate (precipitation)	●	●	●	●	◍	○	●	●	●	●
Soil porosity	●	●	●	●	●	◍	◍	●	●	◍
Soil organic content	○	●	●	●	●	●	◍	●	●	◍
Cation Exchange Capacity (CEC)	○	●	○	○	○	●	○	○	○	○
Degradation parameters	●	●	●	●	●	○	○	●	●	●
Soil grain size distribution	○	◍	◍	◍	◍	○	○	○	○	○
Soil redox potential	○	◍	◍	○	○	●	○	○	○	◍
Soil/water partition coefficients	○	●	●	●	●	●	●	●	●	●
Soil oxygen content	○	◍	○	○	○	◍	○	○	●	○
Soil temperature	◍	●	◍	●	●	●	◍	●	●	◍
Soil mineralogy	○	●	○	○	○	◍	○	○	○	○
Unsaturated hydraulic conductivity	●	●	●	●	●	◍	●	○	○	●
Saturated soil moisture content	●	●	●	●	●	◍	●	●	●	●
Microorganism population	○	◍	○	○	○	○	○	○	◍	○
Soil respiration	○	◍	○	○	○	○	○	○	◍	○
Evaporation	●	●	●	●	◍	○	○	●	●	●
Air/water contaminant densities	◍	◍	◍	◍	◍	○	●	●	●	◍
Air/water contaminant viscosities	◍	◍	◍	◍	◍	○	◍	◍	◍	◍

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● Required ○ Not required ◍ Used indirectly*

* Used in the estimation of other required characteristics or the interpretation of the models, but not directly entered as input to models.

methodology or analytical process, or as a result of spatial variability in the soil characteristic being measured.

In general, the physical and chemical properties of soils vary spatially. This variation rarely follows well defined trends; rather it exhibits a stochastic (i.e., random) character. However, the stochastic character of many soil properties tends to follow classic statistical distributions. For example, properties such as bulk density and effective porosity of soils tend to be normally distributed (Campbell, 1985). Saturated hydraulic conductivity, in contrast, is often found to follow a log-normal distribution. Characterization of a site, therefore, should be performed in such a manner as to permit the determination of the statistical characteristics (i.e., mean and variance) and their spatial correlations.

Significant advances have been made in understanding and describing the spatial variability of soil properties (Neilsen and Bouma, 1985). Geostatistical methods and techniques (Clark, 1982; Davis, 1986) are available for statistically characterizing soil properties important to contaminant migration. Information gained from a geostatistical analysis of data can be used for three major purposes:

- Determining the heterogeneity and complexity of the site;

- Guiding the data collection and interpretation effort and thus identifying areas where additional sampling may be needed (to reduce uncertainty by estimating error); and

- Providing data for a stochastic model of fluid flow and contaminant migration.

Geostatistical tools can be used to help in the interpolation or mapping of a site using a technique referred to as kriging (Davis, 1986). General kriging computer codes are presently available. Application of this type of tool, however, requires an adequate sample size. As a rule of thumb, 50 or more data points are needed to construct the semivariogram required for use in kriging. The benefit of using kriging in site characterization is that it allows one to take point measurements and estimate soil characteristics at any point within the domain of interest, such as grid points, for a computer model.

Geostatistical packages are available from the US EPA, Geo-EAS and GEOPACK (Englund and Sparks, 1988 and Yates and Yates, 1990).

The use of stochastic models in hydrogeology has increased significantly in recent years. Two stochastic approaches that have been widely used are the first order uncertainty method (Dettinger and Wilson, 1981) and Monte Carlo methods (Clifton et al., 1985; Sagar et al., 1986; Eslinger and Sagar, 1988). Andersson and Shapiro (1983) have compared these two approaches for the case of steady-state unsaturated flow. TheMonte Carlo methods are more general and easier to implement than the first order uncertainty methods. However, the Monte Carlo method is more computationally intensive, particularly for multidimensional problems.

Application of stochastic models to Superfund sites has two main advantages. First, this approach provides a rigorous way to assess the uncertainty associated with the spatial variability of soil properties. Second, the approach produces model predictions in terms of the likelihood of outcomes, i.e., probability of exceeding water quality standards. The use of models at hazardous waste sites leads to a thoughtful and objective treatment of compliance issues and concerns.

In order to obtain accurate results with models, quality data types must be used. The issue of quality and confidence in data can be partially addressed by obtaining as representative data as possible. Good quality assurance and quality control plans must be in place for not only the acquisition of samples, but also for the application of the models (van der Heijde, et al., 1989).

Specific soil characteristics vary both laterally and vertically in an undisturbed soil profile. Different soil characteristics have different variances. As an example, the sample size required to have 95 percent probability of detecting a change of 20 percent in the mean bulk density at a specific site was 6; however, for saturated hydraulic conductivity the sample size would need to be 502 (Jury, 1986). A good understanding of site soil characteristics can help the investigators understand these variations. This is especially true for most hazardous waste sites because the soils have often been disturbed, which may cause even greater variability.

An important aspect of site characterization data and models is that the modeling process is dynamic, i.e., as an increasing number of "simplifying" assumptions are needed, the complexity of the models must increase to adequately simulate the additional processes that must be included. Such simplifying assumptions might include an isotropic homogeneous medium or the presence of only one mobile phase (Weaver, et al., 1989). In order to decrease the number of assumptions required, there is usually a need to increase the number of site-specific soil characteristic data types in a model (see Table 2); thus providing greater confidence in the values produced. For complex sites, an iterative process of initial data collection and evaluation leading to more data collection and evaluation until an acceptable level of confidence in the evaluation can be reached.

Table 3 identifies selected unsaturated zone models and their soil characteristic needs. For specific questions regarding use and application of the model, the reader should refer to their associated manuals. Some of these models are also reviewed by Donigan and Rao (1986) and van der Heijde et al. (1988).

Soil Characteristics Data Types Required For Remedial Alternative Selection

Remedial Alternative Selection Procedure

The CERCLA process involves the identification, screening and analysis of remedial alternatives at uncontrolled hazardous waste sites (US EPA, 1988c). During screening and analysis, decision values for process-limiting characteristics for a given remedial alternative are compared to site-specific values of those characteristics. If site-specific values are outside the range required for effective use of a particular alternative, that alternative is less likely to be selected. Site soil conditions are critical process-limiting characteristics.

Process-Limiting Characteristics

Process-limiting characteristics are site- and waste-specific data types that are critical to effectiveness and ability to implement remedial processes. Often, process-limiting characteristics are descriptors of rate-limiting steps in the overall remedial process. In some cases, limitations imposed by process-limiting characteristics can be overcome by adjustment of soil characteristics such as pH, soil moisture content, temperature and others. In other cases, the level of effort required to overcome these limitations will preclude use of the remedial process.

Decision values for process limiting characteristics are increasingly available in the literature, and may be calculated for processes where design equations are known. Process-limiting characteristics are identified and decision values are given for several vadose zone remedial alternatives in Table 4. For waste/site characterization, process-limiting characteristics may be broadly grouped in four categories:

1. Mass transport characteristics
2. Soil reaction characteristics
3. Contaminant properties
4. Engineering characteristics

Thorough soil characterization is required to determine site-specific values for process-limiting characteristics. Most remedial alternatives will have process-limiting characteristics in more than one category.

Mass Transport Characteristics

Mass transport is the bulk flow, or advection of fluids through soil. Mass transport characteristics are used to calculate potential rates of movement of liquids or gases through soil and include:

Soil texture

Unsaturated hydraulic conductivity

Dispersivity

Moisture content vs. soil moisture tension

Bulk density

Porosity

Permeability

Infiltration rate, stratigraphy and others.

TABLE IV. SOIL CHARACTERIZATION CHARACTERISTICS REQUIRED FOR REMEDIAL TECHNOLOGY EVALUATION, (US EPA, 1988e,f; 1989a,b; 1990; Sims et al., 1986; Sims, 1990; Towers et al., 1989)

Technology	Process Limiting Characteristics	Site Data Required
Pretreatment/ materials handling	Large particles interfere Clayey soils or hardpan difficult to handle	Particle size distribution
	Wet soils difficult to handle	Soil moisture content
Soil vapor extraction	Applicable only to volatile organics w/significant vapor pressure >1 mm Hg	Contaminants present
	Low soil permeability inhibits air movement	Air permeability
	Soil hydraulic conductivity >1E-8 cm/sec required	Hydraulic conductivity
	Depth to ground water >20 ft recommended	Depth to ground water
	High moisture content inhibits air movement	Soil moisture content
	High organic matter content inhibits contaminant removal	Organic matter content
In situ enhanced bioremediation	Applicable only to specific organics	Contaminants present
	Hydraulic conductivity >1E-4 cm/sec preferred to transport nutrients	Hydraulic conductivity
	Stratification should be minimal	Soil stratigraphy
	Lower permeability layers difficult to remediate	Soil stratigraphy
	Temperature 15-45°C required	Soil temperature
	Moisture content 40-80% of that at -1/3 bars tension preferred	Soil moisture characteristic curves
	pH 4.5-8.5 required	Soil pH
	Presence of microbes required	Plate count
	Minimum 10% air-filled porosity required for aeration	Porosity and soil moisture content
Thermal treatment	Applicable only to organics	Contaminants present
	Soil moisture content affects handling and heating requirements	Soil moisture content
Thermal treatment (continued)	Particle size affects feeding and residuals	Particle size distribution
	pH <5 and >11 causes corrosion	pH
Solidification/ stabilization	Not equally effective for all contaminants	Contaminants present
	Fine particles < No. 200 mesh may interfere	Particle size distribution
	Oil and grease >10% may interfere	Oil and grease
Chemical extraction (slurry reactors)	Not equally effective for all contaminants	Contaminants present
	Particle size <0.25 in.	Particle size distribution
	pH <10	pH
Soil washing	Not equally effective for all contaminants	Contaminants present
	Silt and clay difficult to remove from wash fluid	Particle size distribution
Soil flushing	Not equally effective for all contaminants	Contaminants present
	Required number of pore volumes	Infiltration rate and porosity
Glycolate dechlorination	Not equally effective for all contaminants	Contaminants present
	Moisture content <20%	Moisture content
	Low organic matter content required	Organic carbon
Chemical oxidation/ reduction (slurry reactor)	Not equally effective for all contaminants	Contaminants present
	Oxidizable organics interfere	Organic carbon
	pH <2 interferes	pH
In situ vitrification	Maximum moisture content of 25% by weight	Moisture content
	Particle size <4 inches	Particle size distribution
	Requires soil hydraulic conductivity <1E-5 cm/sec	Hydraulic conductivity

Mass transport processes are often process-limiting for both *in situ* and extract-and-treat vadose zone remedial alternatives (Table 4). *In situ* alternatives frequently use a gas or liquid mobile phase to move reactants or nutrients through contaminated soil. Alternatively, extract-and-treat processes such as soil vapor extraction (SVE) or soil flushing use a gas or liquid mobile phase to move contaminants to a surface treatment site. For either type of process to be effective, mass transport rates must be large enough to clean up a site within a reasonable time frame.

Soil Reaction Characteristics

Soil reaction characteristics describe contaminant-soil interactions. Soil reactions include bio- and physicochemical reactions that occur between the contaminants and the site soil. Rates of reactions such as biodegradation, hydrolysis, sorption/desorption, precipitation/dissolution, redox reactions, acid-base reactions, and others are process-limiting characteristics for many remedial alternatives (Table 4). Soil reaction characteristics include:

- K_d, specific to the site soils and contaminants
- Cation exchange capacity (CEC)
- Eh
- pH
- Soil biota
- Soil nutrient content
- Contaminant abiotic/biological degradation rates
- Soil mineralogy
- Contaminant properties, described below, and others.

Soil reaction characteristics determine the effectiveness of many remedial alternatives. For example, the ability of a soil to attenuate metals (typically described by K_d) may determine the effectiveness of an alternative that relies on capping and natural attenuation to immobilize contaminants.

Soil Contaminant Properties

Contaminant properties are critical to contaminant-soil interactions, contaminant mobility, and to the ability of treatment technologies to remove, destroy or immobilize contaminants. Important contaminant properties include:

- Water solubility
- Dielectric constant
- Diffusion coefficient
- K_{oc}
- K_d
- K_H
- Molecular weight
- Vapor pressure
- Density
- Aqueous solution chemistry, and others.

Soil contaminant properties will determine the effectiveness of many treatment techniques. For example, the aqueous solution chemistry of metal contaminants often dictates the potential effectiveness of stabilization/solidification alternatives.

Soil Engineering Characteristics and Properties

Engineering characteristics and properties of the soil relate both to implementability and effectiveness of the remedial action. Examples include the ability of the treatment method to remove, destroy or immobilize contaminants; the costs and difficulties in installing slurry walls and other containment options at depths greater than 60 feet; the ability of the site to withstand vehicle traffic (trafficability); costs and difficulties in deep excavation of contaminated soil; the ability of soil to be worked for implementation of *in situ* treatment technologies (tilth); and others. Knowledge of site-specific engineering characteristics and properties is therefore required for analysis of effectiveness and implementability of remedial alternatives. Engineering characteristics and properties include, but are not limited to:

Trafficability

Erodibility

Tilth

Depth to ground water

Thickness of saturated zone

Depth and total volume of contaminated soil

Bearing capacity, and others.

Summary and Conclusions

The goal of the CERCLA RI/FS process is to reach a ROD in a timely manner. Soil characterization is critical to this goal. Soil characterization provides information for RI/FS tasks including determination of the nature and extent of contamination, risk assessment, and selection of remedial techniques.

This paper is intended to inform investigators of the types, quality, and quantity of data required for RI/FS tasks, so that data may be collected as quickly, efficiently, and cost effectively as possible. This knowledge should improve the consistency of site evaluations, improve the ability of OSCs and RPMs to communicate data needs to site contractors, and aid in the overall goal of reaching a ROD in a timely manner.

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Fig. 1. Particle-size limits according to several current classification schemes (Gee and Bauder, 1986).

Fig. 2. Phase RI/FS approach and the DQO process (EPA, 1987a).