Remediation of a Fractured Rock Aquifer Containing Trichloroethylene Dense Nonaqueous Phase Liquid

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ABSTRACT

Extensive chlorinated solvent contamination, including trichloroethylene (TCE) dense nonaqueous phase liquid (DNAPL), was found in ground water at a Navy Installation Restoration Program site on a former Navy property in Pennsylvania. Ground water at the site is encountered in the Triassic age Stockton Formation, which consists of gently dipping, alternating sandstone and mudstone units. Ground-water flow is primarily through fractures in the coarser grained units, while the finer grained mudstones generally act as semi-confining units. An aggressive pump-and-treat remedy was selected for the site, with the goal of source area containment and mass removal. A municipal water supply well in operation approximately 2,000 feet downgradient from the site has been impacted by site-related and non site-related contamination. An air stripping unit on the municipal well is used to treat the water prior to public consumption. The remedial approach included the installation of extraction wells in the DNAPL zone. Extensive real-time hydraulic and water-quality testing and analysis and DNAPL screening procedures were employed through an iterative process during the installation of extraction wells to address the inherent uncertainties of fracture flow and minimize the potential for DNAPL migration. Measures were also taken to safeguard the municipal well against the possibility of contamination being released during the remedy implementation. A Technical Impracticability (TI) evaluation was also performed, and a TI Waiver subsequently was granted by EPA for the site to waive applicable or relevant and appropriate requirements (ARARs) in the DNAPL zone. Currently (2007), 12 extraction wells are in operation at the site. Contaminant concentration decreases since the startup of the extraction system are two to three orders of magnitude in both the source and downgradient areas. The project is an example of how an aggressive pump-and-treat approach can be successfully employed at a fractured rock DNAPL site in an area of high ground-water vulnerability.

Introduction

Ground-water investigations at contaminated sites are typically focused on determining the nature and extent of contamination both in the source (contaminant release) area and in downgradient areas. At sites where ground-water extraction and

315 to 327

treatment (pump and treat) is chosen as the remedial alternative, the design of an extraction system typically includes source area extraction wells to maximize contaminant mass removal and to gain hydraulic containment of the plume "hot spot." Additional extraction wells may also be installed further downgradient for containment and/or remediation of the remainder of the plume. Two factors that make implementation of the pump-and-treat approach more complex are fractured rock hydrogeologic conditions and the presence of dense nonaqueous phase liquid (DNAPL). A pump-and-treat approach that was successfully employed to address both the high spatial variability of water-yielding characteristics typical of fractured rock aquifers and the presence of DNAPL is described below.

Fractured Rock Aquifer Considerations

Several factors unique to fractured rock aquifers bear special consideration during the process of developing and implementing approaches to characterize and remediate contaminated ground water. These factors include:

- Heterogeneity - High spatial variability in the frequency and water-yielding characteristics of fracture zones are characteristic of fractured rock aquifers. Well yields range up to several orders of magnitude and generally cannot be reliably predicted on a well-specific basis.

- Low effective porosity - The bulk mass of most fractured rock aquifers have little or no water transmitting capacity at the time and distance scale that most environmental investigations are focused on. Ground water migration is primarily through interconnected fracture systems that typically account for less than 1 percent of the overall rock mass. As a result, migration pathways through fractured rock may be difficult to predict (especially on a local scale) and migration velocities can be highly variable. In addition, the short-term hydraulic impacts from intrusive activities such as drilling and pumping can be propagated at a much greater magnitude and more quickly than is typical of granular aquifers.

- Anisotropy - Fractured rock aquifers have a high degree of anisotropy, as ground-water and contaminant migration vectors are constrained on a local scale by the orientations of the water-transmitting fractures and bedding. This anisotropy adds significant uncertainty to the prediction of flow directions at on a local scale.

Dense Nonaqueous Phase Liquids

At sites where contaminants are known or suspected to be present in the form of DNAPL, there are significant concerns associated with the drilling and pumping of wells in the DNAPL area. These concerns are focused on the potential for disturbing and mobilizing DNAPL in the subsurface causing it to migrate to previously unimpacted zones in the aquifer and compounding the existing problem. As a result, the current approach to characterization and remediation of DNAPL sites typically is extremely cautious, especially in areas where ground water is used for water supply, and is focused on characterization and remediation around the fringe of the DNAPL zone rather than aggressively characterizing and remediating the DNAPL zone itself. For fractured rock sites, the attendant additional complexities and uncertainties regarding ground water occurrence and movement through the subsurface compounds the technical challenges to DNAPL site characterization and remediation.

The potential benefits of extracting contaminants in the dissolved and/or nonaqueous phase from the DNAPL zone can be considerable and should be weighed against the attendant risks. These benefits include:

- Maximizing the efficiency and effectiveness of contaminant mass removal
- Maximizing the source depletion rate
- Minimizing the area and magnitude of long-term ground-water impacts by providing hydraulic containment from within the source area
- Minimizing migration of high concentrations of contaminants out of the source area

This paper presents an aggressive investigation and remediation approach that was successfully applied at a fractured rock DNAPL site in a suburban area that relies exclusively on ground water for water supply. The approach provides useful guidance that may be applicable to other sites with similar issues. Specific objectives of this paper are to:

- Provide general guidance on investigating fractured rock sites, especially when the presence of DNAPL is known or suspected
- Provide guidance on addressing the inherent variability of well yields in fractured rock aquifers during extraction well installation
- Provide general guidance on taking protective measures when drilling in fractured rock in or near a suspected DNAPL area.

General Characteristics of Fractured Rock Aquifers

It is important to have a sound understanding of the mechanisms and processes governing ground-water migration through fractured rock in order to effectively design and implement site characterization and/or remediation programs in this type of hydrogeologic setting. In most bedrock ground-water-flow systems, ground-water flow and contaminant migration is primarily through interconnected fracture systems, with possible minor flow through the rock matrix. The amount of flow through the rock matrix depends primarily on the rock type and degree of cementation. Contaminant migration into and out of the rock matrix is typically diffusion-controlled, and the rock matrix may act as a long term, low concentration residual source after contaminants in fractures are flushed out.

Fracture patterns can often be identified and predicted on a large-scale basis; however, the level of uncertainty regarding specific fracture locations, depths, and interconnections on a local scale is much higher. The degree of fracturing is also a function of the amount of deformation (folding and faulting) that the rock unit has undergone. Water-transmitting characteristics of individual fractures are related to aperture size, openness, and interconnections with other fractures. Fractures in soft, relatively ductile rocks, such as mudstones, generally tend to be less open and transmissive than those in harder, more brittle rocks. Fractures in soluble rocks, such as carbonates, may be enlarged by solution.

Ground-water flow through discrete, planar fractures with a high degree of variability in o permeability can result in a wide range of velocities within a given rock mass. The more open, permeable fracture networks serve as primary conduits for large-scale ground-water and contaminant migration. Due to fracture control over ground-water-flow directions, anisotropic behavior of ground-water flow is predominant on a local scale; as the scale increases, overall flow patterns generally (but not always) become more predictable. The sloping planar surfaces of fractures and bedding planes provide conduits for gravity-driven migration of DNAPL.

Site Description

The site is a former Naval Air Warfare Center located in a suburban area north of Philadelphia, Pennsylvania. The base has been closed by the Navy in accordance with the Defense Base Realignment and Closure (BRAC) Act by the 1995 BRAC Commission (BRAC IV). The former base is underlain by the Triassic age Stockton Formation, which consists of gently dipping arkosic sandstone units alternating with finer grained mudstone units. The Stockton includes alluvial fan, fluvial, lacustrine, and near-shore lacustrine depositional environments. Thick, poorly defined, upward fining cycles possibly were deposited by large, perennial, meandering rivers. Thus, Stockton lithology is diverse, and the rocks differ widely in bedding, texture, and color (Sloto et al. 1996).

Ground-water flow in the Stockton Formation is primarily through fractures in the more brittle, coarser grained units, with the softer mudstones acting as semi-confining units. Fine-grained lithologic units are not laterally persistent on a regional scale, but are generally persistent over the area of investigation. Coarse-grained units interbedded within the larger depositional sequences often pinch out over distances of several hundred feet. Bedrock units strike N72°E and dip approximately 6-7° to the northwest (Figure 1). Ground-water flow is generally sub-parallel to the dip direction to the north-northwest (Figure 2). A 250 gallon per minute (gpm) municipal water supply well is located approximately 2,000 feet north of the source area.

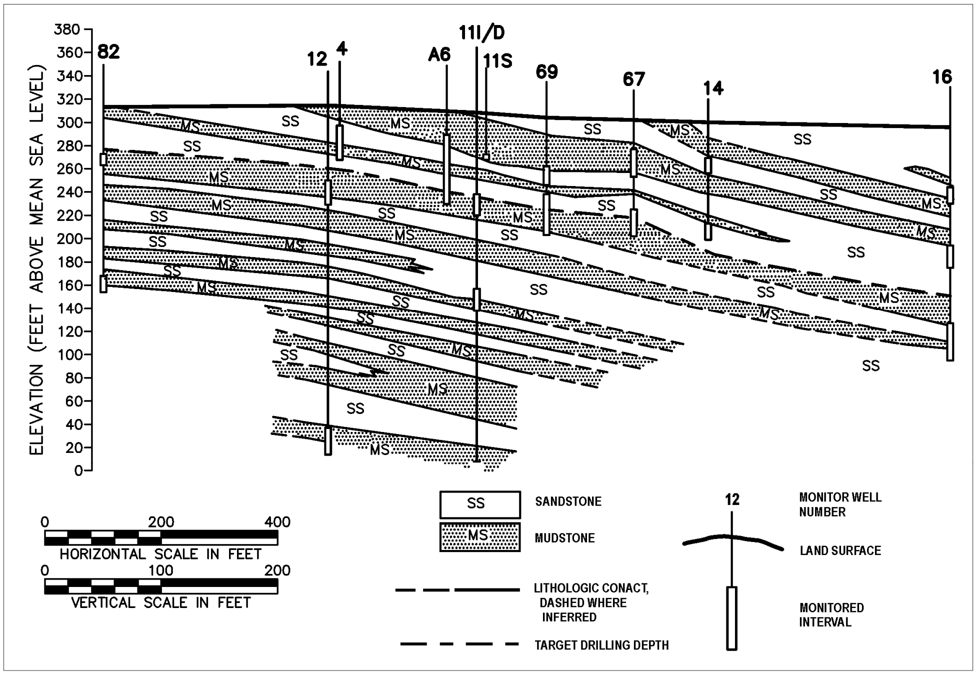

Figure 1. Geologic cross-section.

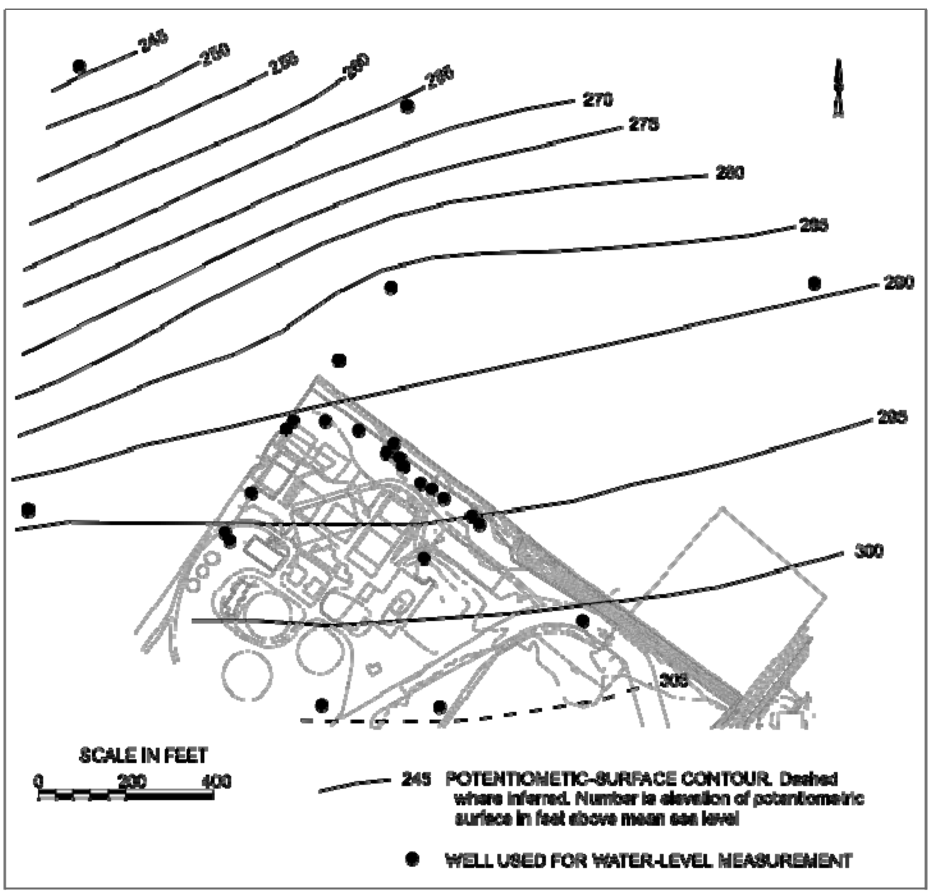

Figure 2. Potentiometric surface under non-pumping conditions.

Historic operations at the facility included the use of chlorinated solvents for various industrial activities. Disposal of chlorinated solvent-containing wastes occurred in the northwestern corner of the facility; over time, leaching of contaminants from these wastes impacted ground water. As part of the Installation Restoration Program, the Navy excavated and disposed of residual waste and impacted soils from the site; however, elevated concentrations of contaminants were found in ground water within and downgradient of the former disposal area. The highest contaminant concentrations were found near the bottom of a sandstone unit that crops out in the source area. This sandstone unit is immediately above a laterally persistent mudstone unit that acts as a confining unit to ground-water flow (Tetra Tech NUS, 200a).

Remedy Description

A pump-and-treat remedy was selected for ground-water remediation at the site. The objectives of the remedy were source area containment and contaminant mass removal. Downgradient parts of the plume are within the capture zone of the municipal well, which has an air stripper to remove contamination from the pumped water. Along with the pump-and-treat remedy, a Technical Impracticability (TI) Waiver was obtained for source area ground water due to the presence of trichloroethylene (TCE) DNAPL in the fractured rock aquifer (Tetra Tech NUS, 2000b).

Two key issues faced during the remedy implementation were:

- The high variability in water-yielding characteristics from well to well because of the heterogeneity of the ground-water fracture-flow system, and

- The presence of DNAPL and its potential for mobilization, particularly during extraction well drilling.

Initially, a conceptual design for an extraction system was developed using aquifer-test data from tests performed in nearby areas, along with site-specific ground-water flow and contaminant distribution data. An equivalent porous media (EPM) approach was employed in the design process, as aquifer-test data indicated that on a large scale the ground-water-flow system could be reasonably approximated in this manner. The design called for 9 extraction wells pumping at 6 gpm each, for a combined extraction rate of 54 gpm. Due to the geometry of the source area and it's close proximity to the adjacent property, the wells were positioned to span the width of the source area approximately perpendicular to the ground-water-flow direction. An air stripping and carbon polishing treatment system was constructed to treat the contaminated ground water.

Technical Approach

Prior to source area extraction well drilling, several safeguards were implemented to protect the downgradient area (including the municipal water well) from the potential release of highly contaminated ground water that might result from disturbance of the DNAPL zone. The capacity of the existing air stripper on the municipal well was upgraded to handle higher levels of contamination. An additional monitor well that could also serve as a potential extraction well was installed downgradient of the source area and the necessary hardware (pump, piping, electrical service) set up so that the well could be pumped on short notice. A monitoring program was developed for the project that addressed pre-drilling, drilling and testing, and post-drilling monitoring activities (Brown and Root, 1997; Foster Wheeler, 1998 and 1999). The program included establishing a mobile laboratory at the site. The pre-drilling part of the plan established baseline conditions in and downgradient of the source area, so that subsequent changes in ground-water quality could be quickly identified. A daily sampling schedule was incorporated into the plan for monitoring nearby wells during drilling and testing in the DNAPL zone, and an every other day sampling schedule was incorporated into the plan during drilling and testing outside the DNAPL zone. Nearby wells were also checked daily for DNAPL. The monitoring program was gradually tailed off over a period of several weeks after source area drilling and testing activities were completed.

Extraction Well Drilling and Testing Program

To address the issue of highly variable well yields in fractured rock settings, a flexible, iterative approach was employed for the extraction well drilling program to allow for real-time modifications in response to the well-specific conditions encountered. The approach called for the drilling of an extraction well, followed by an 8-hour yield test to estimate the sustainable yield (defined as the yield at 1/3 the maximum available drawdown) and evaluate the drawdown pattern around the extraction well. The data were evaluated in the field, and a decision was made regarding the spacing and location of the next extraction well following a brief consultation among hydrogeologists representing the Navy, EPA, and USGS. Well spacings were adjusted to ensure overlap of capture zones while at the same time minimizing well interference. To expedite the process and minimize delays, drilling was initiated from the center of the source area, so that the initial well test would allow for selection of two locations, one to either side of the first well drilled. From that point on, drilling moved steadily outward from the center, moving sequentially from one end to the other. With this approach, there was always a location available for drilling while decisions were made from testing done at the preceding location. Keys to the successful implementation of this approach were well-established lines of communication among decision-makers and the quick dissemination and evaluation of test data.

Because of the nature of the drilling operations (air hammer drilling), it was not possible to generate a detailed log of the borehole lithology during drilling. Geophysical logs were collected to obtain detailed information about borehole conditions and to correlate lithologies from borehold to borehole. On a larger scale, the geophysical logs were critical to correlating major lithologic sequences (and ground water flow units) across the area of investigation. The following logs were collected in each extraction well borehole:

- Natural gamma (borehole lithology)
- Single-point resistance (borehole lithology)

- Caliper (fracture locations)
- Fluid resistivity and temperature (zones of water production/movement)
- Heatpulse flowmeter (identify and quantify vertical borehole flow)

The geophysical data were combined with the geologists boring log to fully characterize borehole conditions and make final determinations regarding the extraction well construction.

DNAPL Screening

One of the key concerns with the extraction well drilling and yield-testing program was the potential for encountering and mobilizing DNAPL. A detailed approach to monitoring each borehole during drilling was developed and employed. This approach included the initial step of using a photoionization detector (PID) for continuous monitoring of the drill cuttings and borehole during drilling. A PID is a field instrument that measures volatile organic vapor concentrations. In situations where PID readings exceeded 20 parts per million (ppm), or if a sheen was noted on the water discharged from the borehole, a DNAPL detection process was initiated, including testing of the drill cuttings and water for DNAPL presence using a combination of ultraviolet (UV) fluorescence and hydrophobic dye testing, along with onsite laboratory analysis of a water sample collected from the bottom of the borehole. Oil Red O, the hydrophobic dye used, is a powder that remains in a granular state when in water but dissolves in contact with hydrocarbon non-aqueous phase liquids, including chlorinated solvents, giving them a distinct deep red color. A flowchart of the DNAPL monitoring process is shown on Figure 3. If DNAPL was confirmed, drilling was stopped, and DNAPL recovery operations were initiated. If no evidence of DNAPL was found, drilling continued to the target completion depth (top of the mudstone confining unit).

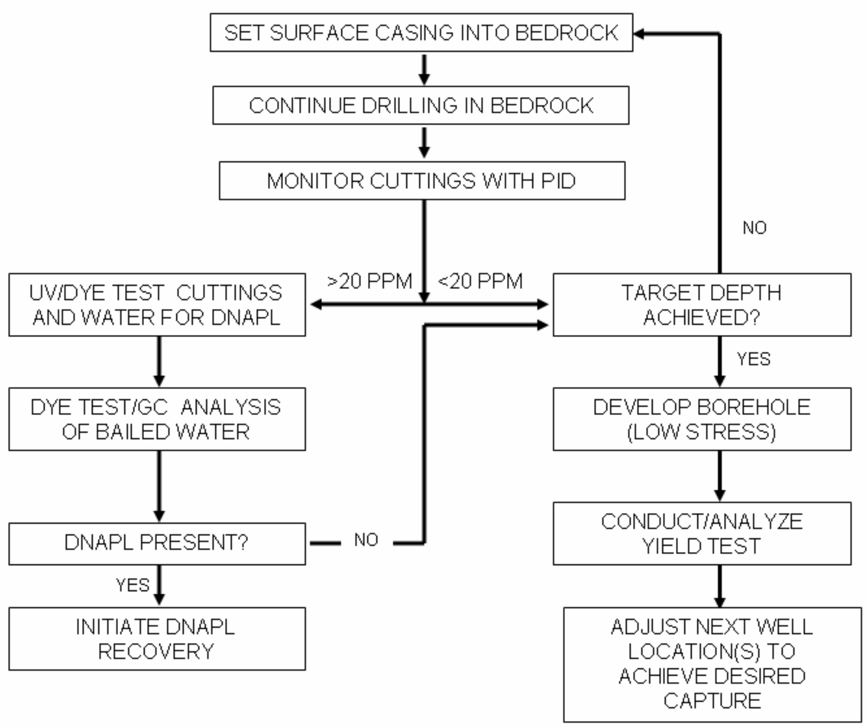

Figure 3. Flow chart for the DNAPL monitoring process used during drilling of extraction wells.

Final Extraction System Configuration

The final configuration of the extraction system included 12 operating extraction wells with long-term pumping rates ranging from less than 1 gpm to approximately 7 gpm; the sustainable yields estimated for the extraction wells ranged from less than 1 to 15 gpm. The distance between extraction wells ranges from less than 15 feet to more than 90 feet, depending on the yield of each well. The aggregate pumping rate for the extraction system (currently about 50 gpm) compares favorably with the design rate of 54 gpm. The extraction system capture zone encompasses the entire source area and is similar in overall geometry to that predicted in the design process using the EPM approach, verifying the assumption that the fracture rock flow system could be approximated as an EPM at a site scale.

One important observation regarding the extraction wells is that the two lowest yielding wells in the DNAPL zone were also the most contaminated wells and have continued to have higher TCE concentrations than adjacent higher-yielding wells. This indicates that DNAPL is persistent in tight fractures in the source area and suggests that ignoring low-yielding wells as potential extraction wells in a source area may be counter-productive in terms of achieving the optimum contaminant mass removal efficiency.

Extraction System Performance To Date

Since the startup of the extraction system in mid-1999, contaminant concentrations have declined considerably in both the source area and downgradient of the source area (ECOR, 2007). TCE concentrations in the area immediately downgradient of the extraction system capture zone have declined over two orders of magnitude and are currently at concentrations slightly above the maximum contaminant level (MCL) (Figure 4). Within the source area, concentration decreases are more variable; however, TCE concentrations in the most highly contaminated wells have decreased by approximately two orders of magnitude (Figure 5). Capture zone evaluations based on water-level data confirm that containment of source area ground water is being maintained through the operation of the extraction system (Figure 6) (Tetra Tech NUS, 2000c). Further downgradient, more gradual concentration decreases are observed that are not nearly as pronounced as those in the area immediately downgradient of the extraction system. The presence of other (off-site) contributing source(s) co-mingling with the plume in the downgradient area is strongly suspected based on the investigations and monitoring performed to date, and several potential off-site sources are currently under investigation. TCE concentration declines in the municipal well (Figure 7) illustrate the more gradual decline typical of the far downgradient area.

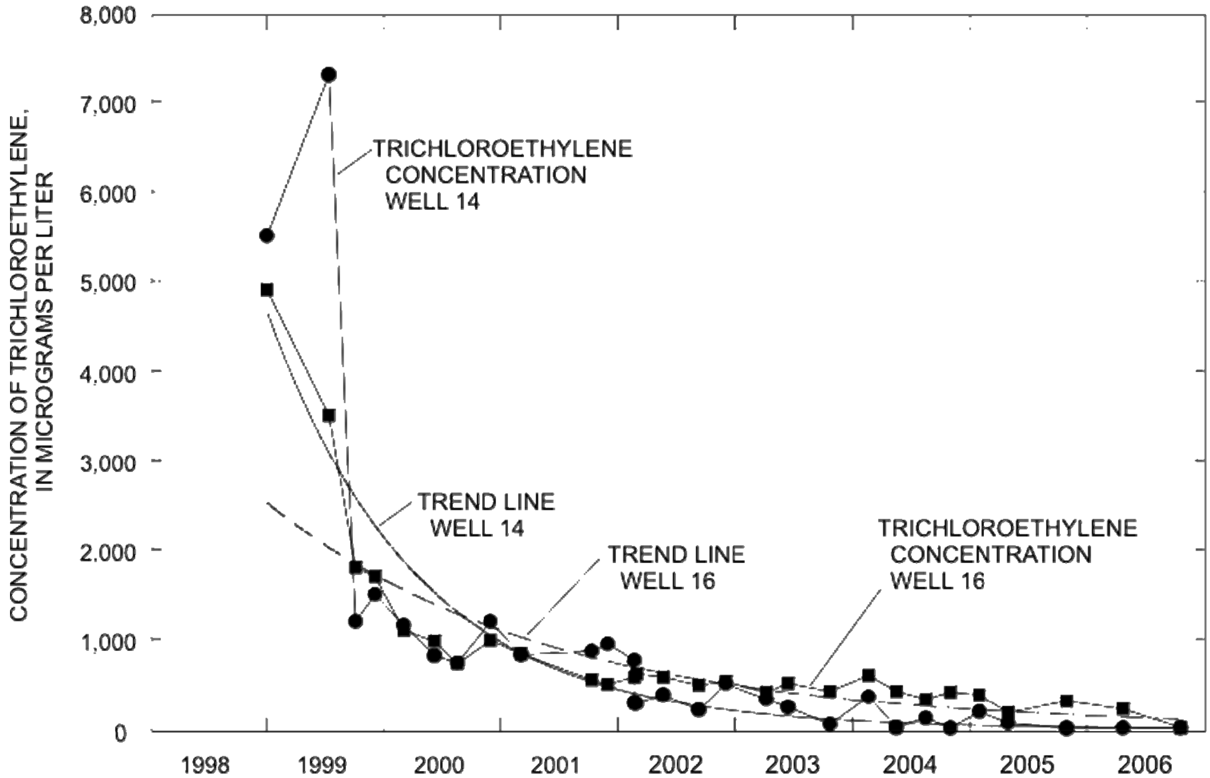

Figure 4. Concentration of trichloroethylene in water samples from downgradient monitor wells, 1998-2006.

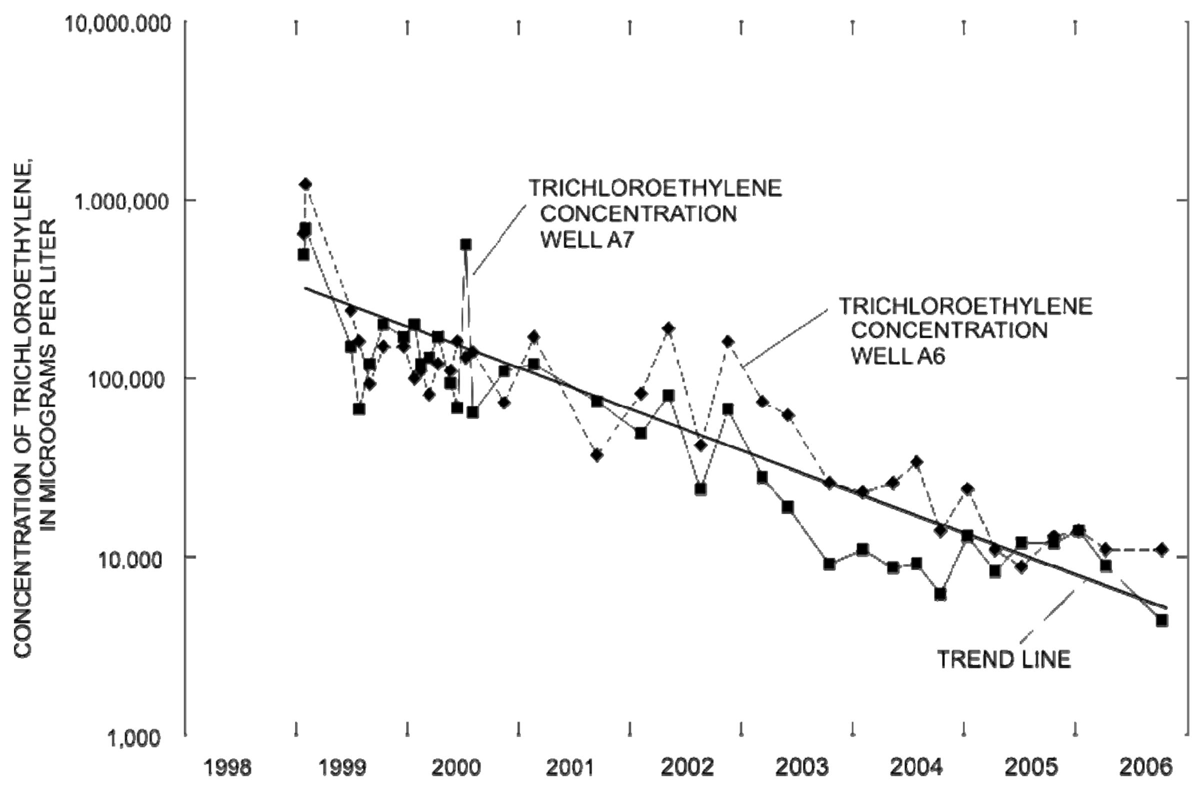

Figure 5. Concentration of trichloroethylene in water samples from extraction wells in the DNAPL zone, 1998-2006.

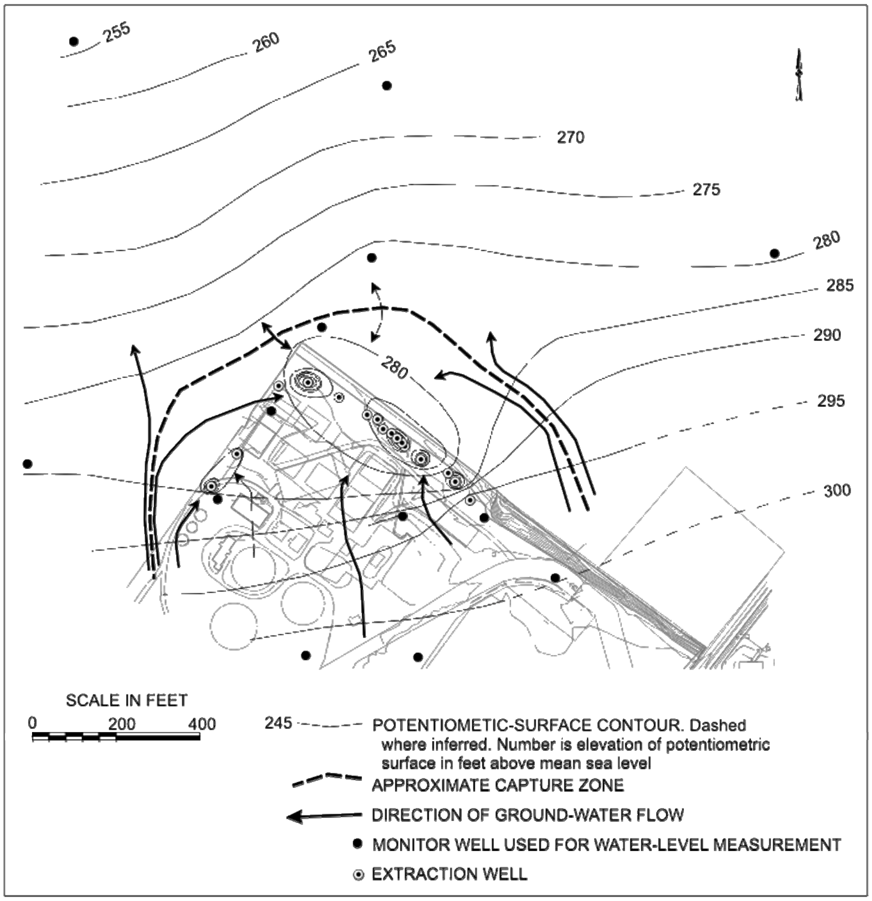

Figure 6. Potentiometric surface with the extraction wells pumping.

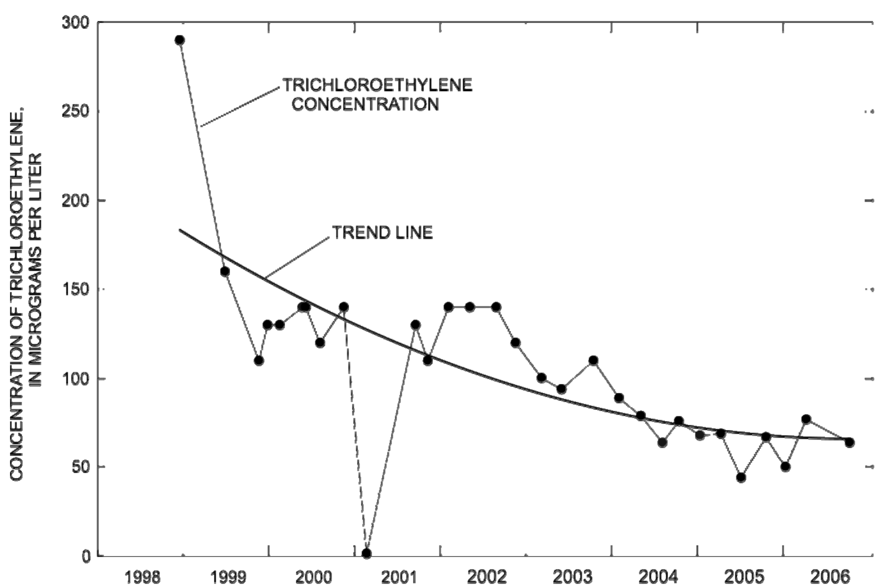

Figure 7. Concentration of trichloroethylene in untreated water samples from the municipal supply well, 1998-2006.

Conclusions

An aggressive pump-and-treat approach can be employed at a fractured rock DNAPL site with proper planning and execution, even in particularly sensitive areas. Key points for consideration include:

- Flexibility in implementation is important to adjust for fracture flow system variability. An iterative drilling, testing, and design modification process addressed the uncertainties inherent in fracture flow systems.

- Low-yielding wells in the source area had the highest contaminant concentrations. [The wells are not sources of contamination and we don't know for sure if the low yielding fractures in the other wells supply high TCE water]

- A combination of geologic and geophysical logging maximized subsurface characterization of borehole-specific geologic and hydrogeologic properties. Geophysical logs in particular were key in correlating major lithologies/flow units across the area of investigation.

- Multiple, overlapping safeguards allowed for an aggressive approach to DNAPL zone remediation.

- Ground-water extraction from the DNAPL source zone has maximized mass removal and helped to hydraulically isolate d the source area.

The techniques employed at this site for the implementation of the ground-water extraction and treatment remedy can be applied to other fractured rock sites, including ones with and without DNAPL. Site-specific conditions may dictate modifications to the approach outlined herein; however, the general principles are expected to be valid for most fractured rock sites.

References:

Brown and Root. 1997. Extraction Well and Observation Well Drilling Procedures for Area A, Naval Air Warfare Center, Warminster, Pennsylvania. Pittsburgh, Pennsylvania.

ECOR, 2007. Long Term Groundwater Monitoring Data, Operable Unit 1A. West Chester, Pennsylvania.

Foster Wheeler. 1999. Installation/Testing of Groundwater Extraction Wells at Naval Air Warfare Center, Warminster, Pennsylvania. Langhorne, Pennsylvania.

Foster Wheeler. 1998. Addendum No. 4 to the Work Plan for Various Source Removal Sites at Naval Air Warfare Center, Warminster, Pennsylvania. Langhorne, Pennsylvania.

Sloto, R.A., Macchiaroli, Paola, and Towle, M.T., 1996, Geohydrology of the Stockton Formation and cross-contamination through open boreholes, Hatboro Borough and Warminster Township, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 96-4047, 49 p.

Tetra Tech NUS. 2000a. Remedial Investigation/Feasibility Study for Area A Groundwater, Naval Air Warfare Center, Warminster, Pennsylvania. King of Prussia, Pennsylvania.

Tetra Tech NUS. 2000b. Evaluation of the Technical Impracticability of Groundwater Restoration, Area A, Former NAWC Warminster, Pennsylvania. King of Prussia, Pennsylvania.

Tetra Tech NUS. 2000c. Operating Properly and Successfully Demonstration, Operable Unit-1A. Pittsburgh, Pennsylvania.

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Ron Sloto is a hydrologist with U.S. Geological Survey in Exton, Pennsylvania. During the past 32 years he has worked on a wide variety of water resource issues in Pennsylvania and the surrounding states. His experience includes ground water and surface water modeling, hydraulic characterization of hazardous waste sites, application of borehole geophysics to hydrologic investigations, basin-scale ground water availability, radionuclides in ground water, and development of computer programs for hydrologic analysis. He has authored numerous technical publications characterizing ground-water movement through fractured rocks.