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SITE CHARACTERIZATION METHODS FOR THE DESIGN OF IN-SITU ELECTRON DONOR DELIVERY SYSTEMS

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ABSTRACT: The Department of Energy and the U.S. Environmental Protection Agency have been involved in designing and evaluating a pilot field demonstration of reductive anaerobic biological in-situ treatment technologies (RABITT) for use as a standard remedial technology for chloroethene contamination. Innovative site characterization techniques have been utilized to identify the hydraulics of the site and in particular the vertical distribution of relative hydraulic conductivities. Direct extraction of intact frozen cores has been utilized to determine the vertical distribution of contaminants in the pore spaces and on the solid matrix of site material. The combination of these techniques along with standard site characterization methods has been used to develop a three-dimensional picture of the site with vertical resolutions down to 0.5 ft (15 cm). This information has then been used to evaluate different scenarios for nutrient/electron donor delivery at the site, and when used with appropriate transport and flow codes was used to exclude designs which did not allow for significant mixing of donor and contaminants, or which did not efficiently deliver nutrients/donors to all contaminated zones. It is felt that the use of site characterization data in this manner is critical to the effective and appropriate design and implementation of RABITT and other in-situ treatment technologies.

INTRODUCTION

Reductive anaerobic biological in-situ treatment technologies for the remediation of ground water contaminated with chloroethenes is a promising approach to an all too common environmental problem. The design of these treatment systems is a complex environmental engineering challenge requiring a clear understanding of the contaminant distribution, the hydrogeologic setting and the geochemistry. To an even greater extent than with pump-and-treat systems or aerobic-catabolic-bioremediation, the application of RABITT requires that this site conceptual model be a detailed three-dimensional representation, incorporating flow/time dynamics to ensure interaction of electron donor, contaminants and active microorganisms under appropriate conditions.

The Department of Energy, the U.S. Environmental Protection Agency, The State of Florida, and Industry Partners have been involved in the design and implementation of a pilot-scale field demonstration of RABITT to support the DOE's Innovative Treatment Remediation Demonstration (ITRD) Program. The study involves creation of an in-situ circulation cell and the injection of electron donor/nutrients to stimulate biological transformation processes. Constraints on system design included a potentially short half-life of the injected solutions and the need for controlled mixing of donor and contaminants. Travel time through the contaminated media was required to be no longer than approximately 100 days. Design of an effective and efficient system under such constraints requires three-dimensional characterization of contaminant distribution, hydrology, and geochemistry.

Detailed, three-dimensional site characterization is seldom performed due, in part, to a lack of appreciation of the potential effects of heterogeneity on remedial design and effectiveness. Estimates of bulk or "average" parameters obtained from traditional monitoring wells and aquifer tests generally have been used in design. Techniques for obtaining detailed hydraulic information, such as extensive laboratory permeameter testing and multi-level slug tests (Molz and others, 1990), have been available but are often costly, difficult to apply, and may not be representative at the field scale. Sensitive borehole flowmeters suitable for detailed characterization have only recently become commercially available. Despite availability, there still exists a general lack of recognition regarding uses for these tools and the value of detailed data in defining contaminant transport and fate processes/rates and in remedial design. The following case study illustrates the potential value of detailed hydraulic parameter and contaminant distribution data in cost-effective designs.

BACKGROUND

The site of the pilot study is located in central Florida and was used in the 1960's for disposal of drums of waste and construction debris. Subsurface contamination, as indicated by contaminant concentrations in ground-water samples from monitoring wells, is heterogeneously distributed in the shallow aquifer. Geology of the upper 30 ft (9.1 m) of the saturated zone is predominantly fine sands with varying fractions of silt and clay. Fill material, construction debris, and lagoon sediments are present in the upper few feet of the subsurface. The top of the Hawthorn Formation is encountered at a depth of about 30 ft (9.1 m) in this area and consists of clay and limestone.

The water table at the site is located at depths of less than 10 ft (3 m) below land surface and varies seasonally. Ground-water flow at the site is strongly influenced by a ground-water extraction system that is currently in operation. Bulk hydraulic conductivity of aquifer materials was estimated using data from a 72-hour multi-well pumping test. Estimates of horizontal hydraulic conductivity clustered in a relatively narrow range from approximately 1 ft/d to 3 ft/d (0.3-0.9 m/d). Estimates of vertical hydraulic conductivity were less certain. The most reliable data set indicated that a horizontal to vertical anisotropy ratio of about 10:1 may be representative of bulk conditions in the shallow saturated zone of interest. Based on the potential for significant heterogeneity in hydraulic conductivity and contaminant distribution, detailed characterization of site conditions was undertaken.

MATERIALS AND METHODS

Borehole Flowmeter Description and Methodology. A sensitive electromagnetic borehole flowmeter was used to define the relative hydraulic conductivity distribution of aquifer materials screened by a test well. The study consisted of measuring the vertical component of ground-water flow at several depths in the well under undisturbed (ambient) conditions and during constant-rate ground-water extraction. Measurements made during constant-rate ground-water extraction or injection indicate the distribution of flow to the well and allow interpretation of the relative hydraulic conductivity distribution of materials within the screened interval (Molz and others, 1994).

Test well NEBIOTW-1 was installed in the vicinity of the proposed bioremediation pilot study site. The borehole was drilled using a wash rotary technique whereby a casing is driven in advance of the rotary bit and materials are washed from the hole. The objective of this technique was to minimize formation damage during drilling so that more representative data regarding hydraulic properties could be obtained. The well was installed using an approximately 1-inch (0.4 cm) thick artificial sand pack and screened from approximately 5 ft (1.5 m) below the water table (i.e., 9 ft or 0.7 m below land surface) to the top of the

Hawthorn Formation at approximately 30 ft (9.1 m) below land surface. Casing and screen were standard 2-inch Schedule 40 PVC materials. The investigation was performed using the following general protocol:

- Ambient vertical flowrates (undisturbed conditions) were measured from total depth to the top of the well screen at 1 ft intervals using the 0.5-inch (0.2 cm) ID probe.

- A peristaltic pump was used to stress the aquifer and establish a stable flow field under pumping conditions. Total flowrates were measured using graduated cylinders and a stop watch at routine intervals. Tests were performed at two different extraction rates (i.e., approximately 2.7 l/min and 4.8 l/min).

- After conditions in the well stabilized, the flowmeter was used with the 1.0-inch (1.54 cm) ID probe to measure vertical flowrates at each of the elevations occupied during the ambient flow profile. Measurements were also repeated at different times following the start of extraction to ensure a stable flow distribution was maintained.

Measurements of flowrates under ambient and constant-rate pumping conditions were analyzed using methods described by Molz and others (1994). Flow to the well from each interval is assumed to be horizontal and proportional to the transmissivity of the formation after an initial stabilization period. The relative hydraulic conductivity profile was estimated using Equation 1 developed by Molz and others (1990), which relates the dimensionless ratio K_i/K to the net induced flow from each interval, interval thickness, total flow from the well, and aquifer thickness influenced during the test.

$$\frac{K_i}{K} = \frac{(\Delta Q_i - \Delta q_i)/\Delta z_i}{Q_P/b} \quad ; \quad i = 1, 2, 3....n \qquad (1)$$

where:

K_i = horizontal hydraulic conductivity of interval i,
K = average hydraulic conductivity of screened materials,
Q_i = induced flow from interval i,
q_i = ambient flow from interval i,
z_i = interval i thickness,
Q_P = total extraction rate, and
b = aquifer thickness influenced by the test.

Determination of Contaminant Distribution. Three-dimensional characterization of contaminant distribution was also performed. Chemical analysis of monitoring well samples was used to identify the areal extent of contamination at the site and to identify an area for the pilot demonstration. However, greater vertical resolution of contaminant distribution was needed to refine the design of the delivery system to ensure appropriate mixing. Hollow-stem augers in combination with an impact driven core barrel were used to collect continuous sleeved cores of aquifer materials. The sleeved cores were sectioned, sealed, and frozen in the field for transport to the laboratory. Subsections of the frozen sleeved cores were obtained and used for various characterization studies. Subsections representing the combined pore water and soil matrix were analyzed by GC/Mass Spectrometry for types and relative concentrations of contaminants. Vertical resolutions of as little as 15 cm (0.5 ft) were achieved.

RESULTS AND DISCUSSION

Flowmeter Results. The majority of the induced flow entered the well in two zones located near the middle and bottom of the screened interval. Approximately 25% of the flow entered the well within the bottom 0.5 foot (15 cm) of the well screen. This indicates that the top of the Hawthorn Formation is much more conductive in this area than originally conceptualized, resulting in a significant flow contribution from depths below this interval. Therefore, the value of hydraulic conductivity estimated for this zone is considered relatively uncertain.

The hydraulic conductivity profile (Figure 1), estimated from this study and the results of the previous multiwell pumping test, indicates that a stratified hydraulic structure exists. A zone of relatively high conductivity exists between approximately 15 ft and 22 ft (4.6-6.7 m) below TOC. This interval is bounded by zones of lower hydraulic conductivity. Aquifer materials in this zone are as much as approximately one-half order of magnitude more conductive than the bulk hydraulic conductivity in the screened interval. Hydraulic conductivity estimated for aquifer materials near the well screen ranged from less than 0.1 ft/d to approximately 9 ft/d (0.03-30 m/d), spanning two orders of magnitude.

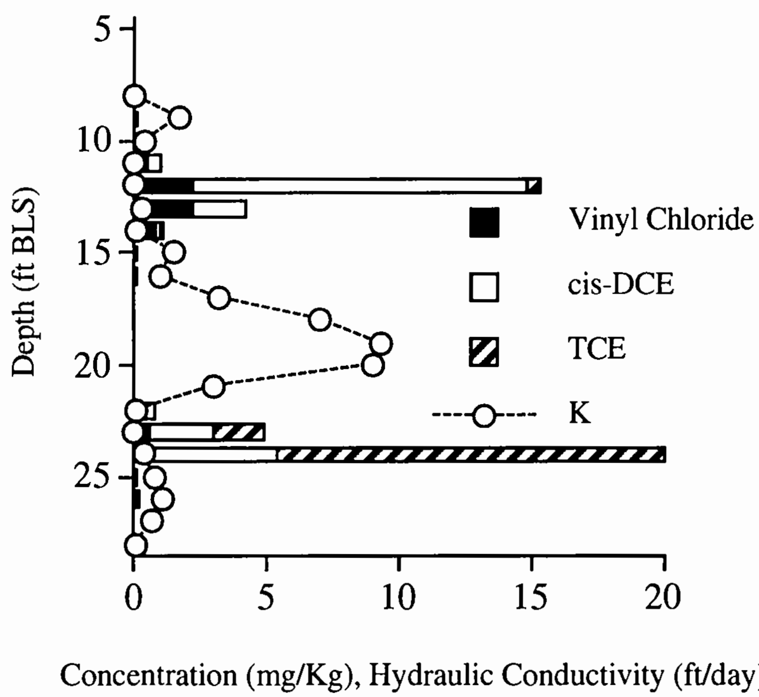

FIGURE 1. Absolute hydraulic conductivity of each measured flow interval estimated using a bulk hydraulic conductivity of 2 ft/d obtained near well NEBIOTW-1, and organic contaminant concentrations in soil/pore water samples from composite site cores (PS1 and PS2), vs depth. Depth is relative to top of casing which is approximately land surface.

Contaminant Distribution. Results of analyses from initial cores (Figure 1) indicate contaminants at these locations were heterogeneously distributed and predominantly associated with materials of lower hydraulic conductivity identified in the flowmeter survey. The profile of the contaminants detected in the core material suggests that reductive biotransformations are occurring in-situ and that the potential for augmenting those transformations, with the addition of exogenous electron donor, is high. It is also felt that recoveries of vinyl chloride in the mg/kg range argue that the sample collection and handling procedures are robust and appropriate for the characterization activities.

System Design. Detailed, three-dimensional characterization data combined with more conventional information were used to define the conceptual model for contaminant distribution and transport at this site. A site specific three-dimensional ground-water flow model was developed with these data and used to screen various injection and extraction scenarios. Scenarios were evaluated with respect to well configurations for delivery of these solutions and potential travel times of injected solutions through contaminated zones. Potential designs that did not provide sufficient transport of injected solutions through target zones, which included materials with relatively low hydraulic conductivity, in approximately a 100 day time frame were excluded from consideration.

Detailed design considerations such as these would not have been possible without the three-dimensional characterization data to identify contaminated zones and the hydraulic conductivity distribution. The design chosen for the pilot study (Figure 2) incorporates infiltration galleries and horizontal wells for fluid circulation which may be scaled up in a cost-effective manner.

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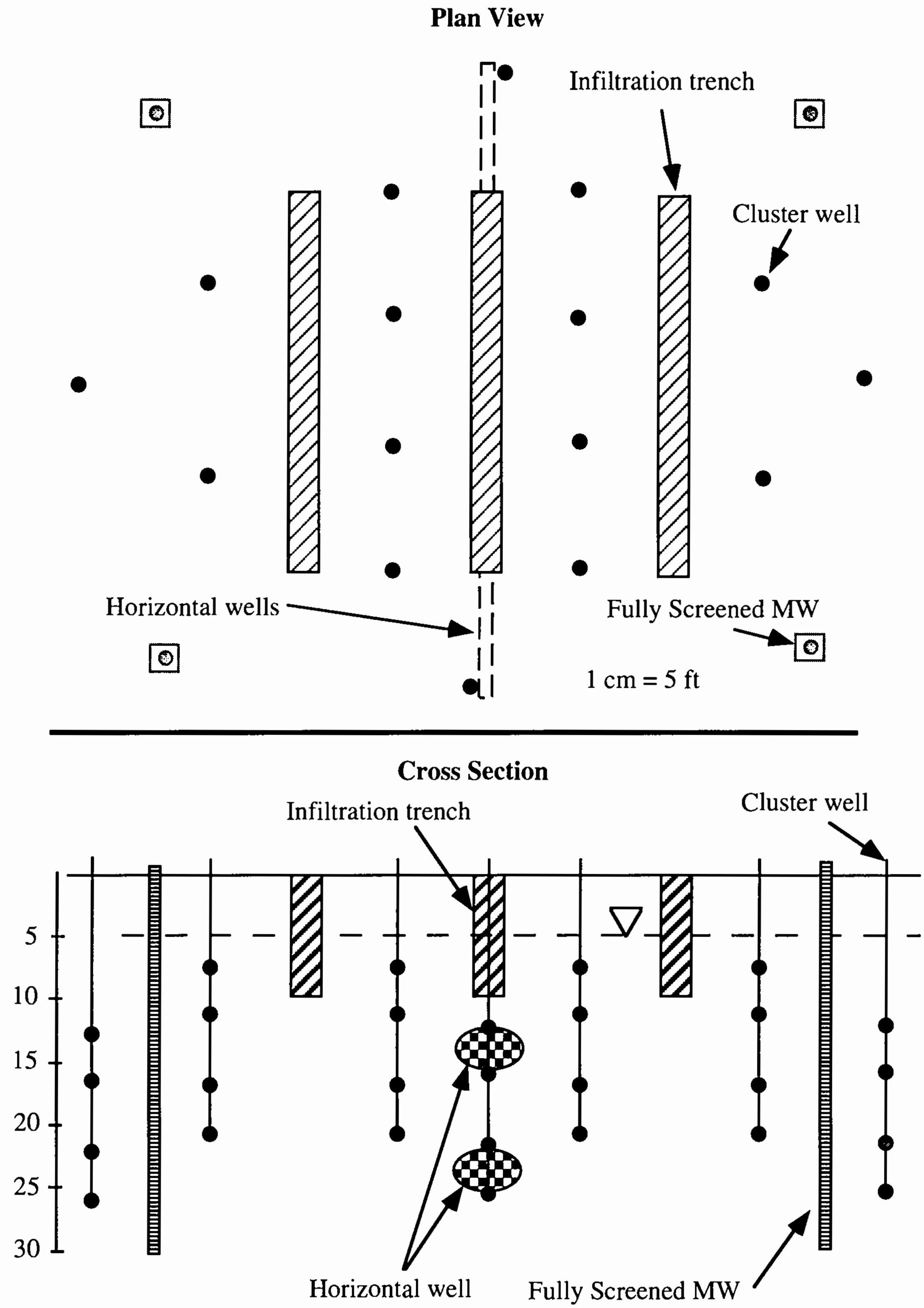

FIGURE 2. Schematic of pilot biotreatment system design using infiltration galleries and horizontal wells for extraction/injection, and monitoring system.

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