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Persistence of a Groundwater Contaminant Plume after Hydraulic Source Containment at a Chlorinated-Solvent Contaminated Site

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Abstract

The objective of this study was to characterize the behavior of a groundwater contaminant (trichloroethene) plume after implementation of a source-containment operation at a site in Arizona. The plume resides in a quasi three-layer system comprising a sand/gravel unit bounded on the top and bottom by relatively thick silty clayey layers. The system was monitored for 60 months beginning at start-up in 2007 to measure the change in contaminant concentrations within the plume, the change in plume area, the mass of contaminant removed, and the integrated contaminant mass discharge. Concentrations of trichloroethene in groundwater pumped from the plume extraction wells have declined significantly over the course of operation, as have concentrations for groundwater sampled from 40 monitoring wells located within the plume. The total contaminant mass discharge associated with operation of the plume extraction wells peaked at 0.23 kg/d, decreased significantly within one year, and thereafter began an asymptotic decline to a current value of approximately 0.03 kg/d. Despite an 87% reduction in contaminant mass and a comparable 87% reduction in contaminant mass discharge for the plume, the spatial area encompassed by the plume has decreased by only approximately 50%. This is much less than would be anticipated based on ideal flushing and mass-removal behavior. Simulations produced with a simplified 3-D numerical model matched reasonably well to the measured data. The results of the study suggest that permeability heterogeneity, back diffusion, hydraulic factors associated with the specific well field system, and residual discharge from the source zone are all contributing to the observed persistence of the plume, as well as the asymptotic behavior currently observed for mass removal and for the reduction in contaminant mass discharge.

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Keywords

DNAPL; contaminant plume; mass flux; back diffusion

INTRODUCTION

Contamination of groundwater by chlorinated solvents and other organic liquids is ubiquitous, and remains a significant human-health and water-resource sustainability issue. It is now recognized that typical chlorinated-solvent sites with large groundwater contaminant plumes will require many decades to remediate (e.g., NRC, 2013). Management of the source zones is a crucial component for successful remediation of these sites. There are many options available for source-zone remediation and management, with selection depending upon several factors including site conditions, remedial objectives, and land-use and other institutional factors. Hydraulic containment of source zones is often used when other options are impractical or not cost effective.

The primary objective for hydraulic containment is to establish containment of the source zone, thereby isolating it from the groundwater contaminant plume. This in turn is anticipated to reduce or eliminate the discharge of contaminant mass from the source to the plume. A critical issue associated with hydraulic source-containment systems and any other source-management approach is the response of the contaminant plume once the source has been contained or otherwise remediated. The disposition and persistence of the plume is a function of site conditions and various mass-transfer processes influencing contaminant transport and fate. The factors that may contribute to plume persistence have long been known, including impacts of dispersed mass storage (mass sorbed by sediment; aqueous mass in lower-permeability units), well-field hydraulics, and uncontrolled sources (e.g., Keely, 1989; Mackay and Cherry, 1989). However, only a few field-based studies have been reported wherein plume behavior in response to source containment was examined specifically.

Chapman and Parker (2005) conducted a study at a chlorinated-solvent contaminated site to investigate plume behavior after isolation of the source zone. Concentrations of trichloroethene in groundwater sampled from monitoring wells located more than 300 m downgradient of the isolated source declined from 5000–30,000 ug/L to between 200 and 3000 ug/L within approximately three years after isolation of the source zone. However, the plume was observed to persist for several years beyond the time estimated for removal via hydraulic flushing. The results of sediment coring and mathematical modeling indicated that diffusive mass transfer of contaminant (back diffusion) from a laterally extensive lower-permeability unit into the aquifer mediated long-term plume response. Parker et al (2008) investigated the impact of hydraulic source isolation on plume persistence for another trichloroethene-contaminated site. The results of mathematical modeling suggested that back diffusion from thin, but laterally extensive lower-permeability units into the aquifer caused the observed persistence of the plume.

Rivett et al. (2006) examined the behavior of a small, three-component (trichloromethane, trichloroethene, tetrachloroethene) groundwater contaminant plume after hydraulic isolation

of the source. They observed delayed contaminant removal, which was attributed primarily to the impact of inter-well stagnation zones. They concluded that back diffusion and nonideal desorption processes had minimal measurable impact on plume behavior, which is reasonable for this study due to a combination of a mildly heterogeneous field site (plume resident in shallow portion of aquifer with no contact with silt/clay zones) and the fact that the plume was freshly created for the study (resident for ~1 year). Rasa et al. (2011) concluded, based on mathematical modeling and analysis of field data, that back diffusion was the cause of a plume of tert-butyl alcohol (TBA) persisting for several years after source removal at a field site.

Long-term monitoring of plume behavior is often based on data collected from a few selected monitoring wells, for which issues of uncertainty are well known. For sites with operational pump-and-treat systems, integrated contaminant mass discharge data are available and the use of such data can supplement standard characterization efforts (Brusseau, 2013). The objective of this study was to characterize the behavior of a groundwater contaminant plume after implementation of a source-containment operation. The study site is located in Tucson, AZ, and is contaminated by trichloroethene. The system was monitored since start-up to measure the change in contaminant concentrations within the plume, the change in plume area, the mass of contaminant removed, and the integrated contaminant mass discharge.

MATERIALS AND METHODS

Study Site

The site that was the focus of the study is part of the Tucson International Airport Area (TIAA) federal Superfund complex in southern Arizona (Leake and Hanson, 1987). The TIAA complex was placed on the National Priorities List in August 1983 in response to the detection of trichloroethene (TCE) in groundwater from several potable water supply wells. A large, multiple-source plume of TCE exists in the upper portion of the regional aquifer. A single-source TCE plume also exists in a localized saturated zone located above the regional aquifer at the study site. Contaminants are believed to have entered the subsurface by seepage from unlined pits and other features used for disposal of organic solvents during the 1950's to mid-1970's. Administratively, the TIAA complex is separated into three major zones, the North, Central, and South sections.

Brusseau and colleagues have conducted an extensive study of source-zone remediation efforts and associated plume behavior for the South section of the TIAA site (Brusseau et al., 1999; Zhang and Brusseau, 1999; Brusseau et al., 2007, 2011a,b). Multiple methods, including contaminant elution tests, multiple-solute tracer tests, coring, analysis of historic pump-and-treat operations data, laboratory experiments, and mathematical modeling, were used to characterize the relative impacts of plume-scale back diffusion, plume-scale sorption/desorption, and dissolution of organic liquid trapped in the source zones on contaminant transport. The results indicated that all three mass-transfer processes were influencing plume removal and persistence, with source-zone mass discharge the primary factor to date. In addition, the results indicated that the plume would persist for many

decades even with isolation or remediation of the source zones, primarily due to back diffusion of contaminant associated with the lower-permeability units.

The site for the current study is located within the Central section of the TIAA site. The study site comprises a local saturated zone, referred to as the shallow groundwater zone, which exists as a persistent feature above the regional aquifer. The site comprises a small source zone (approximately 8400 m²) and a groundwater contaminant plume extending several hundred meters to the west (Figure 1). Trichloroethene is the primary groundwater contaminant, and aqueous concentrations upwards of 100 mg/L and greater have been observed for groundwater samples collected from monitoring wells located within the source zone. The source zone corresponds to a facility that was used in the past to clean aircraft parts and the external surfaces of military aircraft. TCE vapor degreasers, decarbonizers, and parts-cleaning tanks were located in several small buildings at the site. The activities at the site in conjunction with the high observed aqueous concentrations suggest that TCE as dense nonaqueous phase liquid (DNAPL) is likely present in the subsurface. A technical impracticability waiver was granted by the U.S. EPA for the source zone based on the degree of contamination and extensive lower-permeability materials present. Prior characterization efforts indicate that biotransformation processes are negligible at the site (Brusseau et al., 2007, 2011a,b).

A very simplified schematic of the stratigraphy for the shallow groundwater zone is presented in Figure 2, developed from well-log data collected for numerous boreholes. The subsurface consists of clay and silty clay units with localized and discontinuous intervals/lenses of silt, sand, and gravel. The clay is in some cases highly plastic, and is comprised primarily of muscovite, illite, and montmorillonite (Matthieu et al., 2013). A prominent feature is a sand and/or gravel unit of significant areal extent present between approximately 34 and 37 m below land surface (bls). A clay layer below the gravel unit separates the shallow groundwater zone from the regional aquifer. The potentiometric surface for the shallow groundwater zone is approximately 27–29 m bls in the vicinity of the source zone, and is strongly affected by the groundwater extraction system (Figure 3). The shallow groundwater zone merges with the regional aquifer at the western edge of the site, and thus the leading edge of the shallow-groundwater-zone contaminant plume is indeterminate at this transition zone (CRA, 2012).

A multi-element remediation project was initiated at the study site in the fall of 2007. The effort consists of three components: soil vapor extraction for the vadose-zone section of the source zone, hydraulic containment for the saturated-zone section of the source zone, and pump and treat for the groundwater-contaminant plume. Two extraction wells are used for source control (CRA-5 and DP-1), and currently four extraction wells (EW-1, EW-2R, EW-4, and EW-5) are operated within the plume (Figure 3). The extraction wells are screened at depth intervals of 35–38 m bls, corresponding to the gravel unit. The total extraction rate for the two source-control wells is approximately 75 m³/d, while the total for the plume wells is approximately 300 m³/d. A fifth extraction well (EW-3) was operated for the first 30 months and is no longer in operation. Four extraction wells are used for the soil vapor extraction system, which has a total discharge of approximately 20,000 m³/d. The vapor extraction wells are screened at two depth intervals, approximately 9 – 15 and 18 – 23

m bls. The source-zone groundwater extraction and soil vapor extraction systems have removed approximately 700 and >3000 kg of TCE, respectively, as of mid-2012. The impact of the remediation activities on mass removal within the source zone are discussed in Brusseau et al. (2013).

Assessment Methods

The behavior of the groundwater contaminant plume after source containment was characterized using multiple methods. Forty monitoring wells located within the plume area were sampled multiple times over several years prior to source containment, and semi-annually after source containment. Fifteen of the wells are screened in the gravel unit and twenty five are screened in the overlying clay unit. The screened intervals for the gravel-unit wells are ~2.6 m, and correspond approximately to the thickness of the unit. The mean location of the screened intervals for the clay-unit wells is 27–31 m bls (see Figure 2). This arrangement allowed monitoring of magnitudes and temporal variability of TCE concentrations separately within the two units. It is recognized that potential uncertainties associated with issues of sample representativeness exist for samples collected from monitoring wells screened in lower-permeability media. However, the data are used to examine general, long-term temporal trends observed for the system. Thus, while there may be uncertainty associated with the specific concentrations obtained, it is anticipated that viable comparative assessment can be based on samples collected from the same sets of wells over several years.

Data collected for the 40 wells and an additional approximately 20 wells located on the perimeter of the plume were used to develop contour maps of the groundwater contaminant plumes for the two units for each year. The spatial areas encompassed by the contaminant plumes were estimated using AutoCAD, with the 5 µg/L maximum contaminant level contour serving as the plume boundary. Note that all future references to plume areas refer to the 5-µg/L contour unless otherwise specified. It is recognized that these estimates may have significant uncertainty given the limited number of data points for the domain, as is typical for most field sites.

The use of contaminant-mass-discharge measurements to characterize site conditions and remediation performance is becoming more widespread (e.g., ITRC, 2010). Most applications conducted to date for remediation-performance assessment have been based on single measurements collected before and after a remedial action. While this approach provides useful information, additional insight can be gained by measuring time-continuous profiles of contaminant mass discharge (Brusseau et al., 2007; DiFilippo and Brusseau, 2008; Brusseau et al., 2013). Obtaining time-continuous data is generally expensive and/or impractical using standard characterization methods based upon downgradient control planes, such as flux fences or integral pumping tests. However, pump-and-treat operations data can be used to determine contaminant mass discharge, equivalent in this case to differential mass removed, with a high degree of temporal resolution. While this approach may not produce measures identical to those obtained with standard methods, they provide data useful for evaluating contaminant removal behavior. In this manner, contaminant mass discharge was determined as follows. Samples of extracted groundwater were collected

approximately once per month from the manifold leading to the treatment plant. The contaminant concentrations for these samples represent composite values for the zone of influence associated with the wells. Thus, analysis of these data provides a means by which to assess the integrated contaminant mass discharge for the entire plume area. The groundwater samples were analyzed using primarily by GC/MS supplemented by GC-ECD, with detection limits of 0.5 µg/L. Total extraction flow rates were monitored continuously. Contaminant mass discharge was calculated as the product of TCE concentrations and flow rates.

Numerical Simulation

Operation of the pump-and-treat system was simulated using numerical modeling to help evaluate observed behavior. Groundwater flow was simulated with MODFLOW, the three-dimensional finite-difference numerical model developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988). Solute transport was simulated with the three-dimensional code MT3D (Zheng, 1990). Groundwater Vista (Rumbaugh and Rumbaugh, 2007) was used as the graphical user interface. Parameters used for input were determined from information collected at the site, generated from geologic borehole-logs, pumping tests, and other prior characterization activities. The model domain was 1000 (L) by 600 (W) by 19 (H) m, and encompassed the source zone and the plume. Grid spacing and time step were selected to ensure robust simulations, based on the standard grid-Peclet number and Courant number criteria, respectively. Specified head boundaries were used along the east and west borders of the domain, and specified flow boundaries were used along the north and south boundaries. A natural gradient of 0.004 was imposed, with groundwater flow from the east to west.

Subsurface stratigraphy was represented with a simplified, three-layer system, with upper and lower lower-permeability layers (each 7-m thick) sandwiching the higher-permeability sand/gravel unit (5-m thick). Areal (x-y) spatial variability of hydraulic conductivity (K) was represented for the middle layer, based on measured data, by dividing the unit into multiple uniform-K zones. The specific locations of the zone borders were adjusted to improve the simulation of the groundwater TCE concentrations measured for the individual extraction wells. Hydraulic conductivity was uniform in the x-y plane for the lower-permeability layers. The geometric mean of K for the middle layer (6.6 m/d) was approximately 25 times the K for the upper and lower layers (0.26 m/d). Longitudinal, transverse, and vertical dispersivities were set to 5, 0.5, and 0.075 m, respectively. Porosities of 0.25 and 0.37 were used for the gravel and lower-permeability units, respectively. A distribution coefficient of 0.04 cm³/g was used for sorption of TCE, and the aqueous diffusion coefficient was 7.6×10^{-5} m²/d (Zhang and Brusseau, 1999).

The initial concentrations were set according to data collected from the monitoring well network. The two source control wells and the five plume extraction wells were represented with screened intervals only in the middle layer. The measured pumping rates for each well were used as input. Concentrations were reported for each extraction well with time. The simulated time continuous profile of contaminant mass discharge was determined as the product of the pumping rate and the simulated concentration.

RESULTS AND DISCUSSION

Concentration Data

The composite concentrations of TCE in groundwater extracted with the contaminant-plume extraction wells are presented in Figure 4. The concentrations are observed to increase during the first six months of operation, after which they peak at approximately 950 µg/L. The delay in attaining the peak reflects stabilization of the flow and concentration fields. The concentrations decrease relatively rapidly during the following year, and begin to exhibit asymptotic behavior approximately 20 months after system startup.

The volume of groundwater pumped for the plume extraction wells is presented in Figure 4. Rates of extraction increased gradually for the first 30 months of operation, and have been relatively constant thereafter. The gradual increase is related to optimization efforts implemented for the system. A total of approximately 430,000 m³ of groundwater had been removed with the plume extraction wells at the time of data analysis. This corresponds to the equivalent of more than three pore volumes of flushing, or 0.06 pore volumes per month, based on the estimated pore volume of the gravel unit (incorporating unit thickness and estimated plume areal extent).

Forty groundwater monitoring wells located within the plume area were sampled periodically. Data were collected separately for wells screened in the gravel unit and wells screened in the overlying clay unit. The mean baseline concentrations of TCE prior to system start-up were 794 (ranging from 1 to 7850) and 62 (ranging from 1 to 330) µg/L for groundwater sampled from the gravel and clay units, respectively. The mean TCE concentrations for the August 2012 sampling event were 56 and 34 µg/L, respectively. These data reflect concentration reductions of 93 and 46% for the gravel unit and clay unit, respectively, after 60 months of system operation. The temporal changes in mean relative concentrations are presented in Figure 5. The relative concentration is observed to decrease more rapidly for the wells screened in the gravel unit. It is important to note that these data represent mean concentrations for all wells sampled, and that the two sets of wells screened in the gravel and clay units are not co-located. Furthermore, the screened intervals for the clay unit are approximately three meters from the clay-gravel interface (recognizing that the interface is actually ill-defined and of variable depth). Thus, the mean values cannot be used to assess the direction of the concentration gradient between the two layers. One monitoring well, S-26 (located in the downgradient zone of the plume) is screened at the clay-gravel interface. The TCE concentrations for this well decreased from 140 to 85 µg/L since the start of pump and treat. This 40% reduction is consistent with that observed for the mean of all clay-unit wells.

The spatial areas encompassed by the contaminant plumes for the gravel and clay units were approximately 200,000 m² and 245,000 m², respectively, in 2007 (prior to system startup). It is assumed that quasi steady state conditions had developed with respect to plume size by this point, given that the plume has existed at the site for several decades, the presence of the flow-control boundary on the western (downgradient) edge of the plume, and the presence of the uncontrolled source on the eastern edge. Evidence of steady state conditions is presented by examination of TCE concentration data collected from 1997 to 2007 for a well

located at the downgradient edge of the plume and screened in the gravel unit (S-21B, located adjacent to S-21 shown in Figure 1). The mean concentration is 334 $\mu\text{g/L}$, with a coefficient of variation of 13%, the latter indicating small temporal variability. Under such conditions, the sizes of the plumes in the adjacent units would be expected to be similar. The plumes for the two units differ by approximately 20%, which is considered reasonable similarity given the uncertainty associated with the estimation method.

The plume areas in August 2012 were approximately 87,000 m^2 and 130,000 m^2 , for the gravel and clay units, respectively. The relative decrease in plume areas was 53% for the gravel unit and 43% for the clay unit. A significant decrease in area associated with TCE concentrations greater than 100 $\mu\text{g/L}$ was observed for both units. The temporal changes in relative plume area are presented in Figure 6. The maximum reduction in area observed for the plume in the gravel unit occurred essentially within the first year. Conversely, the reduction in area occurred more gradually for the clay-unit plume. This is consistent with the data presented in Figure 5.

Contaminant Mass Removal and Mass Discharge

A total of approximately 140 kg of TCE has been removed with the plume extraction wells as of mid-2012, based on integration of the concentration and pumpage data. The rate of mass removal began to decrease greatly after approximately 10 months, and attained asymptotic conditions after approximately 20 months (data not shown). An estimate of the mass of TCE currently present within the plume can be obtained using the estimated pore volume, the mean TCE concentration for the plume, and an assumption that sorption contributes an additional approximately 15% to the total mass (Zhang and Brusseau, 1999; Brusseau et al., 2007). This produces an estimated mass of approximately 20 kg, which translates to an initial mass of 160 kg and an associated mass reduction of approximately 87%. It is emphasized that the mass extracted was directly removed from the gravel unit, given that the extraction wells are screened in that unit. However, it is expected that some of the removed mass represents contaminant that transferred from the clay units by diffusive mass transfer during the operation. Based on the TCE concentration data presented in Figure 5, it is estimated that a greater fraction of contaminant was removed from the gravel unit such that a larger proportion of contaminant currently resides in the clay units than did at the start of pump and treat.

The total contaminant mass discharge (CMD) associated with operation of the plume extraction wells is presented in Figure 7. The discharge peaked at 0.23 kg/d approximately 6 months after system start up. The delay in attaining the peak reflects the behavior observed for the concentration data. The mass discharge decreased significantly during the next year of operation, and thereafter began an asymptotic decline to a current value of approximately 0.03 kg/d . This represents an approximate 87% reduction in mass discharge (from the peak value) since the initiation of the plume pump-and-treat system. This reduction is a function of the reduction in TCE concentrations observed for the extraction wells (Figure 4), given that the system flow rate increased over the first half of the operations period and thereafter has remained relatively constant (Figure 4). This then suggests that the reduction in mass

discharge is associated with contaminant mass removal as opposed to other factors, such as changes in hydraulic conditions.

Evaluating the response of contaminant mass discharge to mass removal or reduction efforts is facilitated by determining the relationship between reductions in contaminant mass discharge and reductions in contaminant mass (e.g., Rao et al., 2002; Brusseau et al., 2007; DiFilippo and Brusseau, 2008). The relationship was determined using the data collected for the plume, and is presented in Figure 8. It is observed that the data exhibit a muted sigmoidal profile that is centered approximately about the one-to-one relationship between reductions in contaminant mass discharge associated with pump-and-treat remediation of the plume and reductions in contaminant mass within the plume. Such behavior is often considered to reflect the existence of poorly accessible mass that constrains the overall mass-removal rate (e.g., Jawitz et al., 2005; Brusseau et al., 2008; DiFilippo and Brusseau, 2008; Christ et al., 2010; DiFilippo et al., 2010; Brusseau et al., 2013).

Numerical Simulations

The simulated CMD obtained from the numerical modeling is presented in Figure 7. The simulation provides a reasonable representation of the measured data, especially considering the simplifications used for developing the K field. In addition, the simulated mean TCE concentrations for the gravel unit compares well to the measured data (Figure 5). Analysis of the simulation results suggests that K heterogeneity, back diffusion, hydraulic factors associated with the specific well field system, and residual discharge from the source zone are all contributing to the observed temporal CMD behavior.

Plume Persistence

Plume migration at the site is considered to be driven by longitudinal advective transport in the gravel unit, with such transport in the clay units adjacent to the gravel considered to be insignificant. This hypothesis is supported by the TCE-concentration data collected for the groundwater monitoring wells. As reported above, the mean concentration of TCE within the plume was more than ten-times higher in the gravel compared to the clay prior to system startup. Conversely, the mean concentrations of TCE in the source zone prior to system start-up were 12,320 and 16,300 µg/L for monitoring wells screened in the gravel and clay, respectively. The concentrations are comparable for the two units in the source zone as would be expected for the extant contamination scenario, which involved surface disposal of waste. In contrast, the order-of-magnitude disparity observed for the plume data is consistent with advective transport in the gravel unit serving as the primary control on plume migration, with diffusive mass transfer serving as the transport vector for contaminant delivery to the clay units adjacent to the gravel.

Inspection of Figure 4 shows that the integrated TCE concentrations (and the associated CMD, Figure 7) decreased rapidly from the peak, attaining asymptotic conditions within 20 months of operation. This time period corresponds to the equivalent of roughly one pore volume of groundwater removal (with pore volume based on the gravel unit). This observation is consistent with the behavior expected for ideal hydraulic flushing. These observations suggest that the mass removed prior to the start of asymptotic conditions

represents primarily contaminant present in the advective (e.g., higher-permeability) domain, namely the gravel unit, which is consistent with the observed changes in TCE concentration and mass distributions reported above for the gravel versus clay units. This supports the contention that the gravel unit is the primary domain for plume migration and removal.

The equivalent of an additional approximately 2.5 pore volumes of groundwater have been flushed through the contaminated zone since the start of asymptotic conditions. However, the spatial area encompassed by the plume has decreased by only approximately 50% since containment of the source. In addition, the rate of decrease in contaminant mass discharge is significantly lower after asymptotic conditions were attained (Figure 7). These observations indicate a significant decrease in mass-removal effectiveness. The potential causes of this behavior are of interest in assessing and predicting long-term response of the plume. The observed differential rates of concentration reduction discussed above, supported by the numerical-modeling results, suggest that the clay units are serving as an extensive, distributed source of TCE to the gravel unit via back diffusion. However, as noted, other factors such as residual source-zone discharge and well-field hydrodynamics may also be influencing observed behavior.

One factor that has not yet been discussed is the potential impact of sorption and retardation. The low-permeability sediments comprise a high percentage of clay minerals, including smectitic clays (Matthieu et al., 2013). The results of studies conducted with sediments from the site indicate that TCE can be intercalated within the interlayer spaces of clay minerals associated with the site sediments (Matthieu et al., 2013). This intercalation may contribute to recalcitrance and plume persistence by constraining desorption. The results of prior experiments conducted using sediment collected from the TIAA site indicate that sorption/desorption of TCE is rate limited (Johnson et al., 2003, 2009). In addition, the results of prior experiments show that sorption of TCE by the site sediments is nonlinear, which can also influence rates of mass removal. However, given that sorption of TCE by the site sediments is quite low, with retardation factors less than 1.2, it is anticipated that the impact of sorption/desorption associated factors may be relatively minor compared to that of diffusive mass transfer associated with the extensive clayey units. This is supported by the results of the numerical modeling.

SUMMARY

The results of this study indicate that operation of the plume-scale pump-and-treat system has resulted in a significant reduction in contaminant mass, mass discharge, and areal extent for the plume. For example, concentrations of TCE within the gravel unit decreased by 90% after implementation of source containment. In addition, the mass of TCE and the contaminant mass discharge associated with the plume have both decreased by approximately 87%.

However, TCE concentrations and associated mass discharge began to exhibit an asymptotic decline after the equivalent of approximately one pore volume of groundwater removal. In addition, the areal extent of the plume has decreased by only 50% despite the flushing of the

equivalent of more than three pore volumes of groundwater. The results of the study suggest that permeability heterogeneity, back diffusion, hydraulic factors associated with the specific well field system, and residual discharge from the source zone are all contributing to the observed persistence of the plume, as well as the asymptotic behavior currently observed for mass removal and for the reduction in contaminant mass discharge. Simulations produced with the numerical model indicate that it may take several decades of pump and treat to attain a mean TCE concentration of 5 µg/L within the gravel unit.

The use of pump-and-treat operations data to supplement characterization based on monitoring-well information was illustrated to enhance the analysis. The operations data provide an integrated measure of plume behavior that can support a more comprehensive assessment of the system. For example, the data were used herein to determine the relationship between reductions in contaminant mass discharge and reductions in contaminant mass for the plume. To our knowledge, this represents the first such measurement for an isolated contaminant plume.

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Figure 1.

Map of the site and the TCE plume. The extraction wells and selected monitoring wells are shown.

Figure 2.
Simplified schematic of local stratigraphy for the site (from Brusseau et al., 2013)

Figure 3.

Map of groundwater elevations in the gravel unit (GSU). Scale is the same as for Figure 1.

Figure 4.

Concentrations of trichloroethene (TCE) in groundwater extracted with extraction wells located within the contaminant plume. Also included is total pumpage rate for all extraction wells. Zero time corresponds to system startup in fall 2007.

Figure 5.

Change in mean relative TCE concentrations for groundwater sampled from monitoring wells screened separately in the gravel and clay units. The concentrations are the mean for data collected for 15 and 25 wells, respectively. Also shown is the simulated mean TCE concentration for the gravel unit obtained from the mathematical modeling. Zero time corresponds to system startup in fall 2007.

Figure 6.

Change in relative areas of the TCE plume (defined by the 5 ug/L contour) for data collected from monitoring wells screened separately in the gravel and clay units. Zero time corresponds to system startup in fall 2007.

Figure 7.

Total contaminant mass discharge for the groundwater contaminant plume extraction-well system. Also shown is the simulated data obtained from the mathematical modeling. Zero time corresponds to system startup in fall 2007. The inset above the x-axis presents the approximate number of pore volumes flushed (based on gravel layer resident pore volume).

Figure 8.

Relationship between reductions in contaminant mass discharge and reductions in contaminant mass for the plume after source containment. The data points associated with the pre-peak CMD data are not shown.