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Use of Historical Pump-and-Treat Data to Enhance Site Characterization and Remediation Performance Assessment

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Abstract

Groundwater withdrawal and contaminant concentration data are routinely collected for pump-and-treat operations conducted at hazardous waste sites. These data sets can be mined to produce a wealth of information to support enhanced site characterization, optimization of remedial system operations, and improved decision making regarding long-term site management and closure. Methods that may be used to analyze and interpret pump-and-treat data to produce such assessments are presented, along with a brief illustration of their application to a site. The results presented herein illustrate that comprehensive analysis of pump-and-treat data is a powerful, cost-effective method for providing higher-resolution, value-added characterization of contaminated sites.

Keywords

DNAPL; Mass flux; Source depletion

1 Introduction

Pump and treat is currently the primary method used to contain and treat groundwater contaminant plumes at many hazardous waste sites. Groundwater withdrawal and contaminant concentration data are routinely collected under regulatory requirement for these pump-and-treat operations. However, these data are rarely used for purposes other than to monitor the mass of contaminant removed. These data sets constitute a source that can be mined to provide additional information to enhance site characterization activities and remediation performance assessments (Brusseau et al. 2007, 2011a, b).

Analysis of historical pump-and-treat data has the potential, for example, to provide the following information:

1. Estimates of initial contaminant mass
2. Time-continuous measurements of contaminant mass discharge
3. Time-continuous measurements of magnitudes and rates of mass removal
4. Characterization of the relationship between reductions in contaminant mass discharge and reductions in contaminant mass
5. Delineation of source-zone architecture

6. Delineation of contaminant mass-removal conditions
7. Assessment of contaminant persistence
8. Identification of specific mass-transfer processes and other factors influencing mass removal
9. Assessment of the impact of source-zone remedial actions on overall risk reduction

The information obtained from mining of the data can be used to update the site conceptual model, to revise the design and operation of the remediation systems, and to support decision making concerning remedy modification, long-term site management, and closure. The objective of this brief communication is to illustrate the types of data sets and associated evaluations that can be obtained from mining of pump-and-treat operations data.

2 Method Description

The basic approach of the characterization method involves the following components:

1. Tabulation and quality assurance evaluation of raw groundwater withdrawal and contaminant concentration data. This step entails collection of the raw data from the relevant sources and evaluation of various data quality aspects. For example, what is the frequency of data collection? For systems with multiple extraction wells, are data collected for individual wells, or only for the composite inflow into the treatment system? Periods of system shutdown should be noted and their impact on calculations accounted for in the analyses.
2. Calculation of contaminant mass discharge as a function of operational time. Contaminant mass-discharge values are calculated for each measurement period as the product of the extraction well pumpage and mean contaminant concentration. These values are equivalent to the magnitude of contaminant mass removed with the pump-and-treat system for the given measurement period. The data are typically converted to standard units such as kilogram per day.
3. Integration of the temporal mass-discharge data to determine time-continuous measurements of magnitudes and rates of mass removal. Stepwise integration of the contaminant mass-discharge data set provides magnitudes of contaminant mass removed as a function of operational time. Plots of cumulative contaminant mass removed are often constructed to help visualize mass-removal behavior. The contaminant mass-discharge data also provide the equivalent of mass-removal rates.
4. Application of mathematical models or functions to estimate the mass of contaminant that was present in the treatment zone at the start of remediation. The total contaminant mass initially present in the source area at a site is a critical variable that is unknown for most field sites. The standard method used to estimate initial mass, based on collection and analysis of sediment core samples, is expensive and typically influenced by a large degree of uncertainty. An alternative approach is based on fitting a source-depletion function to temporal concentration or contaminant mass-discharge data.

In general, a mechanistic-based reactive transport model can be calibrated to historical concentration data to solve the inverse problem for initial mass. However, the use of advanced transport models for field sites is typically constrained by a lack of information needed to parameterize the model. In lieu of this approach, simplified source-depletion functions can be fit to measured data to estimate initial mass. For example, simplified functions have been fit to temporal concentration

data collected from monitoring wells located within contaminant plumes to provide estimates of source mass (Butcher and Gauthier 1994; Basu et al. 2009). This approach has recently been applied to contaminant mass-discharge data obtained from analysis of pump-and-treat operation data (Brusseau et al. 2013).

5. Use of calculated initial mass and time-continuous mass-removal data to characterize the relationship between reductions in contaminant mass discharge (CMDR) and reductions in contaminant mass (MR). The CMDR–MR relationship is a defining characteristic of system behavior and is mediated by system properties and conditions such as permeability distribution, contaminant distribution, and mass-transfer processes. This relationship is useful for delineating mass-removal conditions of the system and thus has the potential to be a powerful tool for assessing the performance of remediation operations. Several prior CMDR–MR profiles have been reported based on laboratory experiments and mathematical modeling, while only a few have been reported for field sites (Brusseau et al. 2007, 2013; DiFilippo and Brusseau 2008).
6. Analysis of the processed data to evaluate contaminant mass-removal conditions, source-zone architecture, contaminant persistence, specific mass-transfer processes and other factors influencing mass removal, and the impact of source-zone remedial actions on overall risk reduction. This step employs the data produced in the prior steps, in combination with other site information such as contained within the site conceptual model, and can be enhanced by the application of mathematical modeling. The type of model used can range from simple ones that focus on a single transport process, such as diffusion models, or that employ a lumped mass-transfer term (e.g., source-depletion models) to complex transport and fate models that attempt to account explicitly for each relevant factor and process. The specific model used will depend on the availability of information and data required for model input, as well as the objectives of the effort. An example application of a complex model to a pump-and-treat system was reported by Zhang and Brusseau (1999), who characterized the relative impacts of plume-scale back diffusion, plume-scale sorption/desorption, and dissolution of organic liquid trapped in the source zones on performance of a pump-and-treat system for a site in Tucson, AZ, USA. It was shown that the asymptotic conditions observed for mass removal were caused primarily by the uncontrolled source zones. The results of additional modeling 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 (Brusseau et al. 2007).

While the use of advanced transport and fate models provides the most robust level of assessment, their application to field sites is typically constrained by a lack of information needed to parameterize the model. Thus, simplified approaches are often used. One example of a simplified approach is the use of source-depletion functions, which have recently received increased attention. This approach is often used when the specific processes and/or site conditions influencing contaminant transport are incompletely characterized, and thus, the use of process-specific models is problematic. An example of such a function is the first-order, exponential function, given as $CMD_t/CMD_0 = \exp(-kt)$ (e.g., Zhu and Sykes 2004; Falta et al. 2005), where CMD is contaminant mass discharge, t is time, k is the depletion coefficient, and subscripts t and 0 represent measured and initial values, respectively.

3 Case Study

Data collected from a federal Superfund site (i.e., listed on the Environmental Protection Agency, EPA, National Priorities List) located in Arizona are used herein to illustrate the methods. The site is contaminated by chlorinated-solvent compounds (primarily trichloroethene), and a large groundwater contaminant plume is present. A pump-and-treat system has been in operation at the site for approximately 18 years. The raw groundwater withdrawal and contaminant concentration data were graciously provided by the EPA project managers and subcontractors working with the EPA and the responsible parties.

The aquifer at the site comprises sand and gravel alluvium, with an ~20-m-thick silty clay unit in the middle that represents roughly less than one quarter of the total treatment-zone thickness. Solvent disposal occurred via injection into shallow dry wells. The pump-and-treat well field is designed such that there are no extraction wells located within the source area. A single extraction well is located approximately 100 m downgradient from the source zone, with all other extraction wells distributed further within the plume. These wells are grouped in two sets: one in relative close proximity to the source extraction well and the other at the downgradient margin of the plume, with the two sets approximately 1,500 m apart. Treated groundwater is reinjected into wells located far upgradient of the source zone.

4 Results and Discussion

The historical contaminant mass discharge (CMD) determined from analysis of the pump-and-treat data is presented in Fig. 1. The initial CMD was approximately 10 kg/day. This value is quite large in comparison to the range of values reported in a recent summary (ITRC 2010). This is reflective of the significant impact of the highly contaminated source zone, owing to the large quantities of solvent disposed of therein.

Interestingly, asymptotic behavior is observed for CMD in the later stage of operation. This may be attributed to the impact of constraints to mass transfer, such as poorly accessible contaminant mass associated with solvent in source zones as well as mass stored in lower-permeability units. Other factors, such as the impact of well-field hydraulics, may also influence the observed behavior.

To illustrate the application of a simplified transport model, a model employing a dual-porosity conceptualization of the system was used to simulate contaminant removal for the plume at the site. The model simulates rate-limited diffusion of contaminant from lower-permeability units (in which no advection is assumed to occur) into higher-permeability zones, in which advective transport occurs. Details of the model are presented in Brusseau (1991). The simulation provides a reasonable representation of the measured data (see Fig. 1), especially considering the simplifications employed (e.g., uniform pumping rate, uniform system thickness, uniform intra-unit permeabilities). The relatively good match may indicate that diffusion of contaminant from lower-permeability units (back diffusion) may be contributing to mass-removal constraints at the site. However, because of the simplified approach employed, the potential impact of other factors such as continued mass discharge from the source zone and well-field hydraulics cannot be ruled out, nor can the relative significance of the various factors be evaluated. The relative simplicity of using single- or lumped-process models for data analysis is an attractive advantage of this approach. However, it is imperative to remain cognizant of the uncertainty and limitations associated with the use of such models.

The fit of the exponential source-depletion function to the measured CMD data is presented in Fig. 1. The coefficients obtained from the fit of the source-depletion function are used to estimate an initial mass of approximately 29,000 kg (see Fig. 1 caption for explanation).

This compares to a value of approximately 20,000 kg of contaminant mass that has been recovered to date from the pump-and-treat operation. The determination of an estimate of initial contaminant mass allows quantitative assessment of remediation performance and evaluation of time scales for operation. The results of such assessments must be evaluated with due consideration of uncertainties associated with the estimates produced with the method.

The CMDR–MR profile determined for the site is presented in Fig. 2, along with three reference profiles. It is observed that the profile for the measured data resides primarily above the one-to-one line. The nature of the profile is indicative that a substantial amount of contaminant mass remains at the site that is poorly accessible to groundwater flushing associated with the pump-and-treat system (e.g., Jawitz et al. 2005; Brusseau et al. 2008, 2013; DiFilippo et al. 2010; Christ et al. 2010). The removal of this mass is thus constrained by mass-transfer processes, which likely is at least partially responsible for the asymptotic behavior observed for the temporal CMD profile (Fig. 1). The CMDR–MR relationship can be plotted in equivalent log form to better visualize behavior under asymptotic conditions (see Fig. 3).

5 Summary

The ultimate goal of remedial actions is to reduce overall risk posed by the site, which is typically mediated by the groundwater contaminant plume. The standard method for assessing remediation performance is based on analysis of changes in contaminant concentrations for groundwater samples collected from monitoring wells located within the treatment zone. It is advantageous to employ time-continuous contaminant mass-discharge data obtained from analysis of pump-and-treat operation data to enhance these assessments. An example of such an application is presented in Fig. 4, wherein the impacts of two major source-zone remediation efforts (soil vapor extraction and in situ chemical oxidation) are evaluated using historical pump-and-treat data collected for a site in Tucson, AZ, USA (Brusseau et al. 2011b).

Collection and analysis of data for individual wells for systems with multiple extraction wells provides an opportunity to characterize spatial variability of properties, conditions, and behavior in the areal plane. However, standard extraction wells for pump-and-treat systems are designed (e.g., large screened intervals) such that the flow and contaminant concentration data collected represent composite, vertically averaged values. It is proposed that modifying fully screened extraction wells to collect vertically discrete flow and contaminant concentration data would produce significant benefit by providing vertical resolution of contaminant distributions, mass discharge, and mass removal. A major advantage of this proposed modification is that the vertically discrete monitoring of extraction wells in conjunction with the use of multiple extraction wells provides a three-dimensional characterization of the treatment zone.

The results presented herein illustrate that comprehensive analysis of historical pump-and-treat data is a powerful, cost-effective method for providing higher-resolution, value-added characterization of contaminated sites. Advantages of the method include the following: (a) use of data that typically exist for operating sites, thus minimizing data collection costs; (b) no disruption of the operating remediation system; and (c) ability to update the analysis at any time, providing a means to periodically revise the site conceptual model and optimize the operation of the remediation system. It should be noted that this method can also be used for soil vapor extraction systems (Brusseau et al. 2010). It is anticipated that implementation of this approach will enhance decision making concerning remedy modification, long-term site management, and closure.

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Fig. 1.

Contaminant mass discharge profile obtained from analysis of pump-and-treat data for the selected site. A simulation (model sim) produced with a dual-porosity mathematical model (described in the text) is also presented. The fit of a first-order exponential source-depletion (S-D) function is also presented ($CMD_t/CMD_0 = \exp(-0.14 t)$; $r^2=0.80$). Initial mass is determined as $M_0 = CMD_0/k$, with $CMD_0 = 11 \text{ kg/d}$

Fig. 2. Plot of the relationship between the reduction in CMD and the reduction in contaminant mass. Also shown are three reference profiles

Fig. 3.

Plot of the relationship between the reduction in CMD and the reduction in contaminant mass-log version. Also shown are three reference profiles

Composite CMD- Historical

Fig. 4.

Impact of source-zone remediation on composite CMD measured at the groundwater contaminant plume scale for a site in Tucson, AZ, USA. Soil vapor extraction (SVE) was stopped in year 17, and in situ chemical oxidation (ISCO) was stopped past year 19. The figure was adapted from Brusseau et al. (2011b)