Groundwater Monitoring&Remediation

Performance Assessment of Pump-and-Treat Systems

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Abstract

Pump-and-treat (P&T) is a widely applied remedy for groundwater remediation at many types of sites for multiple types of contaminants. Decisions regarding major changes in the remediation approach are an important element of environmental remediation management for a site using P&T. While existing guidance documents provide information on design, operation, and optimization for P&T systems, these documents do not provide specific technical guidance to support remedy decisions regarding when to transition to a new remedy or to initiate closure of the P&T remedy. A structured approach for P&T performance assessment was developed and is described herein, using analysis of three example P&T systems. These examples highlight key aspects of the performance assessment decision logic and represent assessment outcomes associated with optimizing the P&T system, transitioning from P&T to natural attenuation, and supplementing P&T with another technology to hasten transition to natural attenuation.

Introduction

Implementation of a pump-and-treat (P&T) groundwater remedy can be generalized into three categories based on the functional purpose of the system (Truex et al. 2015). Source control applications focus on eliminating or minimizing the flux of contaminants out of the contaminant source area and can be an important component of a remedy to diminish a downgradient plume. P&T is also commonly applied to contain a plume and prevent off-site migration and/or protect downgradient receptors. P&T is sometimes deployed for plume reduction, where the goal is to remove contaminant mass and collapse a plume. Though different in the specific details of their implementation, performance of all of these P&T systems can be assessed relative to the effect on the contaminant plume. The "pump" portion of P&T involves extraction of groundwater from an aquifer as a mechanism for both contaminant mass removal and hydraulic gradient manipulation. The aboveground "treat" portion of P&T generally involves routine engineering design to achieve a specified treatment goal. This manuscript focuses on the groundwater extraction and contaminant capture aspects of implementing a P&T system as a remedy.

Evaluation of remedy performance is an important aspect in assessing operation of a P&T system and considering the ability of the remedy to reach remedial action objectives (RAOs). Review of remedy performance and consideration of remedy closure or transition are consistent with the U.S. Environmental Protection Agency's (EPA) groundwater road map (EPA 2011a) and the EPA groundwater remedy completion strategy (EPA 2014a). In addition, a recent National Research Council study examining groundwater remediation for complex contaminated sites concluded that evaluating remedy performance and the potential need for transition to alternative approaches may be beneficial at these sites (NRC 2013). Existing guidance (e.g., EPA 1994, 1996, 1997, 1999a, 1999b, 2000, 2002a, 2007, 2008; USACE 1999, 2000) provides information on design, operation, and optimization for P&T systems. More recent P&T-related research has provided information about P&T configuration (Suthersan et al. 2015; Kahler and Kabala 2016) and design assessment through modeling of groundwater capture (Matott 2012; Liao et al. 2015). However, these documents and information do not provide specific technical guidance to support remedy decisions by site decision makers regarding P&T optimization, transition to a new remedy, or closure of the P&T remedy.

While P&T is a prevalent remedy, limitations in contaminant extraction effectiveness are often observed. Early efforts to evaluate P&T performance issues by EPA (1989)

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and Mackay and Cherry (1989) identified fundamental hydrologic (matrix diffusion) and contaminant-related properties (e.g., nonaqueous phase liquid [NAPL] and desorption) that hinder contaminant concentration reductions in situ in response to P&T operation. P&T is a mass transfer process involving bulk extraction of groundwater and associated dissolved contaminant mass, but treatment effectiveness is influenced by processes at a smaller scale, including mass transfer between hydrogeologic units (i.e., between low and high permeability units by advective or diffusive transport, for example, matrix diffusion issues as recently described by Hadley and Newell (2014)) and between phases (e.g., through desorption or dissolution processes). Therefore, the P&T contaminant mass removal rates over time can initially be high and then experience a decline in efficiency related to an increased influence of small-scale mass transfer limitations. This decline in performance, often termed "diminishing returns," may result in the need to examine P&T performance. If site RAOs have not yet been met, a performance assessment would need to determine whether to continue P&T, optimize the P&T system, or to transition to other approaches to reach RAOs.

Performance assessment can be facilitated by analyzing historical operational data (Brusseau 2013) and may consider elements such as evaluating plume persistence (Brusseau and Guo, 2014). Application of contaminant mass discharge (CMD) approaches (e.g., ITRC 2010; Brusseau et al. 2011) may also be important in predicting post-P&T downgradient contaminant behavior. To assist in the performance assessment process, a structured approach for P&T performance assessment was developed (Truex et al. 2015) and is described herein, using analysis of three example P&T systems to highlight key aspects of the associated decision logic, supporting calculations, and several potential outcomes of an assessment. The performance assessment and decision logic in Truex et al. (2015) could also be used prior to selection of a P&T remedy to establish a basis for P&T system objectives and to develop an exit strategy for transition to other elements of a multistep remedy. Case studies 2 and 3, in particular, highlight use of the approach to define an appropriate exit strategy for the P&T system with associated interim remedial objectives.

Performance Assessment Approach

A summary of the decision logic described by Truex et al. (2015) for the P&T performance assessment, incorporating the decision elements and the decision outcomes, is presented in Figure 1. After updating the conceptual site model (CSM) and assessing whether RAOs have been met, the decision logic consists of several primary assessments that distinguish between outcomes. The first assessment is based on whether the plume has declined during P&T operations. If the plume has declined, then an assessment of whether MNA is warranted is conducted. If MNA is not appropriate, then the logic points to evaluating continued/ optimized P&T. For plumes that have not declined during P&T or for situations where the plume has declined but RAOs cannot be practically reached with P&T or MNA, the decision logic points to evaluation of other approaches. In

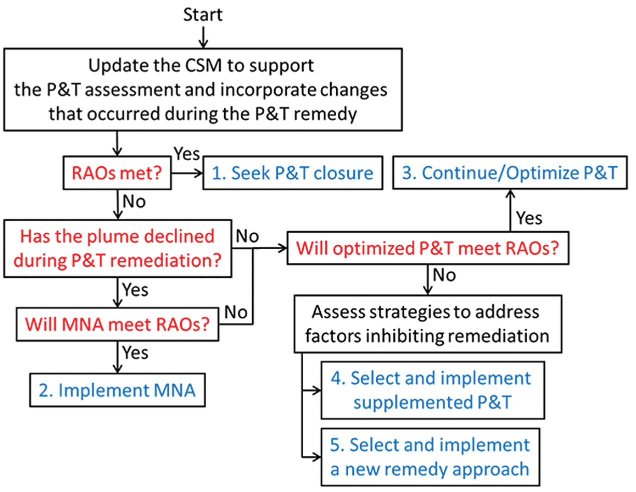

Figure 1. Primary elements of the decision logic used for the P&T assessment (after Truex et al. 2015). The blue numbered text is the potential decision outcomes of applying the logic. The full decision logic includes additional elements of the decision process which are omitted here for brevity.

this case, the decision logic specifies either evaluating technologies to supplement P&T or switching to a different remedy approach to address factors inhibiting remediation (e.g., matrix diffusion). Site decision makers may also consider ARAR waivers or revisiting RAOs (e.g., using approaches to define objectives, as described in the *Integrated DNAPL Site Strategy* document [ITRC 2011]), depending on the conditions driving the need for an alternative remedy approach to P&T. As described by Truex et al. (2015), evaluation of the above transitions includes assessment of remedy time and cost, and would need to be conducted consistently with the appropriate remedy decision documents for the site.

The performance assessment described in Truex et al. (2015) is essentially organized to use a set of *decision elements* to help decision makers distinguish between several categories of *decision outcomes* associated with optimization, transition, or closure of P&T systems.

The following categories of decision outcomes are included in the decision logic for the P&T performance assessment:

1. *Initiate P&T remedy closure*. If the site conditions meet RAOs, then an appropriate outcome of the analysis is to proceed with P&T remedy closure. Criteria used to evaluate whether RAOs have been met may have been established in site remedy decision documents. In some cases, a rebound study to assess concentration trends while the P&T system is off may be needed as part of assessing whether concentration goals have been met. EPA provides guidance (e.g., EPA 2011c, 2013, 2014b) for the remedy closure process.
2. *Transition P&T to MNA*. This outcome is for sites where P&T has changed plume conditions, and contaminant source discharge is low enough, such that RAOs can be met with MNA.
3. *Continue with existing or optimized P&T*. If P&T has diminished the plume, it may be appropriate to continue P&T or optimize the system and continue P&T. As time progresses, the P&T system may need to be reevaluated with respect to progress toward meeting the RAOs.

4. *Supplement P&T with other treatment technologies*. This outcome may be appropriate at sites where P&T has been inefficient or ineffective in progressing toward RAOs, but where a specific plume condition or feature can be addressed by a supplementary treatment (e.g., targeted treatment of a contaminant source) such that RAOs can then be met with this combined approach. At some sites, there may be site complexities that need to be considered in evaluating a supplemented P&T approach (NRC 2013; ITRC 2017). In this case, the site may need to consider adaptive remedy approaches and means to mitigate exposure while addressing contamination. It is also possible that, over time, the supplemented P&T system may need to be reevaluated with respect to progress toward meeting the RAOs.
5. *Transition to a new remedy approach*. At sites where P&T has been inefficient or ineffective in progressing toward RAOs, another remedy approach may be more cost effective in reaching RAOs. At some sites, there may be site complexities that need to be considered in selecting the new remedy approach (NRC 2013; ITRC 2017). In this case, the site may need to consider adaptive remedy approaches and means to mitigate exposure while addressing contamination.

The decision elements supporting selection of a decision outcome are summarized below. Resources for each of these components are described by Truex et al. (2015). The concept of defining these decision elements is to focus characterization/evaluation efforts on elements needed to support decisions. In this way, the scope of characterization/evaluation efforts can be justified and managed. As part of applying the decision elements, the type of calculations described by Truex et al (2015) and highlighted in the Case Studies herein can also be used to define the necessary characterization/evaluation effort.

- *Contaminant concentrations and trends*. These data are used to evaluate whether the plume has declined during the P&T remedy and to provide input for use in the subsequent decision element assessments.
- *Contaminant mass discharge*. The CMD (mass/time) at a given location in a plume (or at the source) is an indication of the amount of contaminant mass migrating past that location over time. P&T system data can provide contaminant mass extracted over time, which is an indicator of extraction efficiency. With knowledge of the natural gradient at the site, the P&T data can be interpreted in terms of the CMD that would occur from the capture zone if P&T system operations were discontinued. This CMD information is useful when assessing performance and future plume behavior in comparison to factors that relate to the downgradient transport of the contaminants (e.g., the attenuation capacity [AC], as described below and shown conceptually in Figure 2). It is also important to consider the variation in contaminant concentrations within the plume or source at locations upgradient of the CMD measurement location. When there are steep concentration gradients or an order-of-magnitude variation in concentrations across the plume width, concentration-based approaches (e.g., a threshold concentration approach as discussed below) may be more appropriate than spatially averaged mass-based approaches in evaluating downgradient transport and attenuation. For example, it may be necessary to specifically assess what happens with a high concentration core of a plume (vs. lower concentrations further from the plume core) because that portion of the plume will likely drive the need for remediation.
- *AC of the Aquifer*. The AC (mass/time) is a way to quantify the ability of an aquifer (or portion of an aquifer) to decrease contaminant concentration over time without active remediation. There are multiple approaches to evaluate attenuation rates and mechanisms in the aquifer. These rates and mechanisms are important as part of assessing the role of natural attenuation during P&T or for transitioning P&T to MNA (or another remedy that includes the contribution of natural attenuation). The AC can be conceptually estimated as a decrease in contaminant mass over time within a given volume of the aquifer (shown in Figure 2) under natural-gradient conditions. Performance and future plume behavior can be assessed by comparing this AC to the CMD (described above). In some cases, especially when there is a higher concentration plume core, it may be more appropriate to represent the AC as an attenuation rate (change in concentration per time), using the threshold concentration approach (discussed below) for evaluating the concentration emanating from the source zone plume core.
- *Estimated future plume behavior and time to reach RAOs*. Like any remedy decision, a prediction of plume fate and transport and the time needed to reach the RAOs is an important part of P&T performance assessment. The plume behavior under continued P&T, MNA, or with application of other remedy components or alternative remedies needs to be estimated. Key components of this decision element include evaluating protectiveness (e.g., controlling exposure during remediation) and estimating the time to reach the RAOs. For the plume behavior estimate, it is also important to consider the controlling features at the site (e.g., matrix diffusion) or source conditions that may contribute to extending the remediation timeframe. It is also

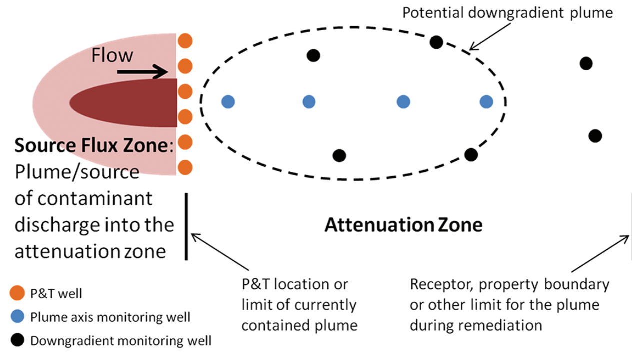

Figure 2. Conceptual depictions (after Truex et al. 2015) of the source flux zone being controlled by P&T and a downgradient attenuation zone, whose extent must be determined by the site decision makers. To support a decision to transition to an MNA remedy, the CMD from the source zone (or potentially an upgradient plume) must not be greater than the attenuation capacity in the attenuation zone under natural-gradient conditions. In this situation, the plume would stay within the limits defined by the site decision makers.

important to consider the uncertainty associated with estimating future plume behavior and time to reach RAOs when using these estimates to support a remedy decision.

- *P&T system design*, *operational*, *and cost information*. As part of the performance assessment, information about the P&T design, operation, and cost are important to consider for assessing whether optimization would help performance or for comparison of P&T to other remediation alternatives.

Case Study Sites

Case studies are used to highlight portions of the performance assessment approach for three of the decision outcomes associated with the decision logic: Case Study 1 shows how modeling and calculations can be applied to determine the plume conditions when it is appropriate to transition from P&T to MNA. Case Study 2 highlights how refining the CSM as part of the performance assessment may lead to P&T optimization as an appropriate outcome. Case Study 3 includes assessment of persistent sources and how the assessment can support selection of appropriate supplementary technologies for P&T and setting remediation objectives for transitioning to passive remediation in the future. These case studies are based on historical efforts which are interpreted within the framework of the recent P&T performance assessment approach (Truex et al. 2015). Background and context for the case studies is provided in this section, with the P&T assessments described in the Results section.

Case Studies 1 and 2: Joint Base Lewis McChord Logistics Center Plume

The Joint Base Lewis McChord (JBLM) Logistics Center trichloroethene (TCE) plume extends from a source area (containing dense nonaqueous phase liquid [DNAPL]) downgradient in an unconfined aquifer (the Vashon Aquifer). About 1.5 km downgradient, part of the plume passes through a "window" in the underlying aquitard and contaminates a nominally confined aquifer (the sea level aquifer [SLA]). The conceptual plume configuration and associated remedy components are shown in Figure 3. Three P&T systems are in place as part of the overall remedy for this plume. The Landfill 2 P&T system has a goal of source control to eliminate migration of additional contamination into the existing plume. Although source reduction by thermal treatment was applied in the most heavily contaminated zones, source zone containment is still required. The I-5 P&T system is located near the site boundary with a goal of containing the plume and preventing off-site migration in the Vashon Aquifer. The SLA P&T system is located in the middle of the SLA plume and works in conjunction with downgradient natural attenuation to prevent off-site migration. With effective performance of the Landfill 2 P&T system, the CMD into the downgradient I-5 and SLA P&T systems should diminish over time.

Case Study 1 examines the SLA P&T system. A relatively large, low concentration portion of the plume is present downgradient of the SLA P&T and is diminished by natural attenuation. The SLA P&T system was necessary because natural attenuation alone was not sufficient to attenuate the plume and prevent off-site migration (Fort Lewis 2007). The SLA P&T system was designed to contain the plume core within the SLA (i.e., stop the CMD feeding the downgradient SLA plume) so that, together with natural attenuation, RAOs could be met. For example, a P&T performance assessment was conducted to evaluate the future conditions for which the SLA P&T system can be terminated. This type of evaluation is the part of the decision logic (Figure 1) for transition of P&T to MNA, where the upgradient CMD is compared to the downgradient AC. The evaluation was conducted using the numerical fate and transport model developed for the site and used for a feasibility study in the SLA (Truex et al. 2006; Fort Lewis 2007) as one calculation tool. In addition, the supporting data used to configure the model (Truex et al. 2006; Fort Lewis 2007) and describe the plume and attenuation processes (Dinicola 2005) were also used to evaluate the CMD and AC to estimate a condition appropriate for transition.

Case Study 2 examines the Landfill 2 P&T system. As discussed above, the intent of this P&T system is to contain the contaminant source area. An initial P&T system was installed in 1995. This case study describes the P&T performance evaluation conducted in 2006 that led to optimization of the P&T system to improve its containment performance (which was still necessary after source reduction efforts had

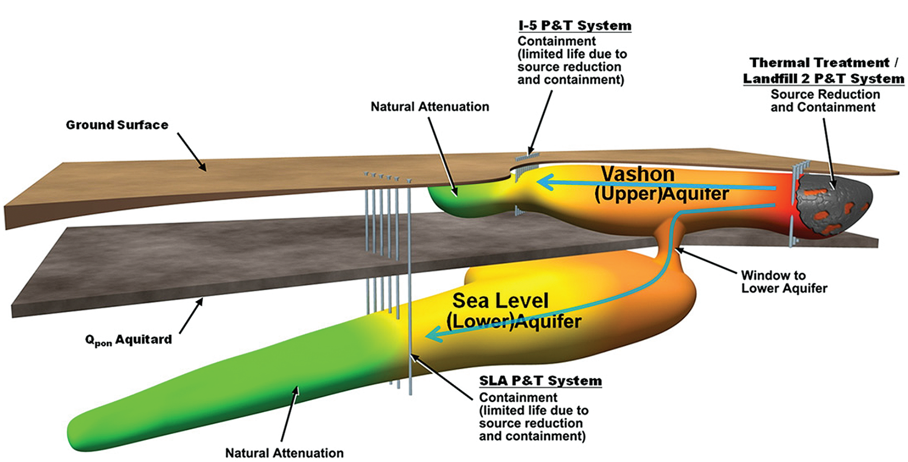

Figure 3. Conceptual depictions of the JBLM Logistics Center TCE plume and related remedy components.

been applied). This type of evaluation is the part of the decision logic (Figure 1) for plumes or source areas that are not declining and for which the ability of optimization to enable P&T to meet RAOs should be determined.

Case Study 3: Commencement Bay–South Tacoma Channel Superfund Site (Time-Oil Site)

The Time-Oil site is located in Tacoma, Washington approximately 4 miles southwest of the southernmost tip of Commencement Bay. Contamination was introduced to a heterogeneous glacial sediment aquifer from approximately 1924 to 1976 during operation of paint and lacquer manufacturing, oil recycling, and oil canning businesses that released petroleum hydrocarbons and chlorinated solvents as NAPLs. The site encompasses the source of contamination at the property of the former Time-Oil company and the dissolved-phase groundwater plume that impacts the city of Tacoma drinking water well, well 12A (Figure 4). The contaminants of concern at the site are tetrachloroethene (PCE), TCE, *cis*-1,2dichloroethene (cDCE), *trans*-1,2-dichloroethene (tDCE), vinyl chloride (VC), and 1,1,2,2-tetrachloroethane (TeCA), with TCE being the most prevalent contaminant. DNAPL has been identified in some portions of the aquifer. These DNAPL zones and a silt layer within the glacial outwash/till hydrogeology of the subsurface act as continuing sources for the dissolved-phase plume traveling downgradient in the gravel-dominated zones of the aquifer. These persistent sources are spread over an area of about 16,500 m^2.

The original 1983 Record of Decision (ROD) involved installation of an air stripping system to treat contaminated groundwater for well 12A. A ROD amendment in 1985 included excavation of contaminated soils at the site, installation of a P&T system near the source area, excavation of about 3800 m^3 of disposed filter cake, and installation of a SVE system for a portion of the source zone in unsaturated soils. The SVE system removed approximately 24,600 kg of VOCs over 2 years of operations. During a P&T operational period of over 20 years, the system extracted approximately 3.25 billion liters of groundwater and removed approximately 8600 kg of VOCs. While P&T partially contained the source area plume, the extent of the plume had not been

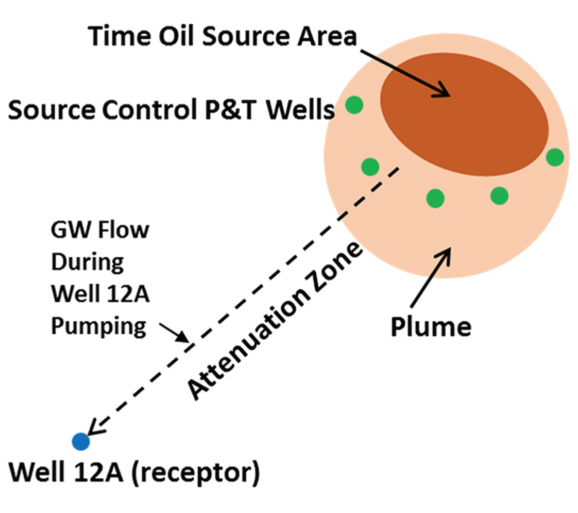

Figure 4. Conceptual depiction of the Time-Oil site source, plume, P&T wells, and receptor.

significantly diminished, and source depletion, while occurring, was slow and would likely not meet RAOs. Therefore, the site reevaluated alternatives for additional source treatment to augment the P&T-based remedy.

A 2009 ROD Amendment for the Time-Oil site selected an amended remedy and developed interim RAOs to improve remedy performance compared to the existing P&T remedy. The amended remedy included soil excavation and use of thermal treatment and bioremediation in the groundwater to diminish the source of contaminants impacting groundwater. The interim RAO is to reduce the source CMD sufficiently to allow transition from the active remedy (including the P&T system) to passive long-term monitoring. An interim source-reduction target, expressed as a CMD objective, was included in the ROD. The required reduction in CMD from the Time-Oil source area was based on: (1) predicted chlorinated chemical attenuation within the anaerobic and aerobic portions of the plume; (2) concentration reduction to EPA drinking water standards before reaching the receptor (the well 12A municipal water supply); and (3) the achievable reductions based on available remedial technology. The source strength and contaminant fate, and transport in the source area and within the downgradient plume were evaluated to establish the CMD objective. The existing P&T system provides the means to measure CMD.

The source reduction effort was implemented using targeted actions selected, as appropriate, for the different source conditions present at the site. For zones with more saturated NAPL, which is responsible for the majority of contamination discharged to the P&T system, in situ thermal treatment was applied to volatilize and extract the NAPL. For the remainder of the anaerobic source zone (discrete residual NAPL hot spots and contaminant mass in an extensive silt zone, which act as secondary sources of aquifer contamination), bioremediation using a substrate combining vegetable oil, ethyl lactate, and sodium bicarbonate was applied. Shear-thinning fluid was also used to improve distribution of the substrate to the silt zone. At two localized DNAPL hot spots within the bioremediation treatment area, a low-energy thermal system was used to accelerate the DNAPL treatment rates. Once the CMD goal is achieved, shut-down of the active treatment phase (including P&T system operation) and transition to passive remediation can be considered.

The conceptual source remedy described in the Time-Oil site ROD amendment was based on a set of assumptions developed with the best available information. To address uncertainty in this basis, an adaptive remedial action approach was implemented that includes: (1) a robust and “living” CSM that is updated through all phases of the remedial action implementation and is based on high-resolution characterization data to understand contaminant mass distribution and transport in a heterogeneous aquifer; (2) performance goals that are SMART (specific, measureable, achievable, relevant, and time-bound [ITRC 2011]) for site conditions and based on the best use of available remediation technologies; and (3) a flexible implementation approach which relies on an engaged project team to make course corrections based on new information. This approach has facilitated a dynamic remedial action implementation to address additional contaminant sources, complex groundwater hydraulics and aquifer heterogeneities, and changing demands for the municipal well field, as required, to advance towards achieving the remedial objectives.

Results

The following results describe calculations and evaluations that address specific decision elements of the P&T performance assessment decision logic shown in Figure 1.

Case Study 1: SLA P&T System—Transition to MNA

Previous efforts used numerical simulations and field data to evaluate AC of the SLA downgradient of the P&T system. Numerical simulations for design of the SLA P&T system performance predicted that the downgradient SLA plume would diminish over time and would meet the site RAOs (Fort Lewis 2007) as shown in Figure 5. Based on isotopic tracer data (Dinicola 2005), natural attenuation of the downgradient plume is driven primarily by dispersion and dilution due to inflow of water to the SLA from the Vashon Aquifer beneath American Lake. Beneath American Lake, the confining-unit aquitard (Q_{pon}, Figure 3) is apparently less competent than in the surrounding area (e.g., similar to the conditions at the "window" where TCE enters the SLA). The inflow of water into the SLA diverts groundwater flow in the SLA to the south and results in mixing of water from beneath American Lake and SLA water from near the southern end of American Lake (Figure 6). Dinicola (2005) interpreted this mixing based on oxygen and hydrogen isotopic tracer data in well samples showing younger water with an isotopic signature more similar to the signature for American Lake water mixing with older SLA groundwater. These mixing data were used as input to adjust the inflow of Vashon Aquifer water in this area in the site numerical model by calculating mixing ratios for water entering the mixing zone (Figure 6) at 4 wells, and adjusting model parameters to best match these values (Truex et al. 2006). In this way, the AC of this dilution process was incorporated into the model along with attenuation due to lateral and transverse dispersion.

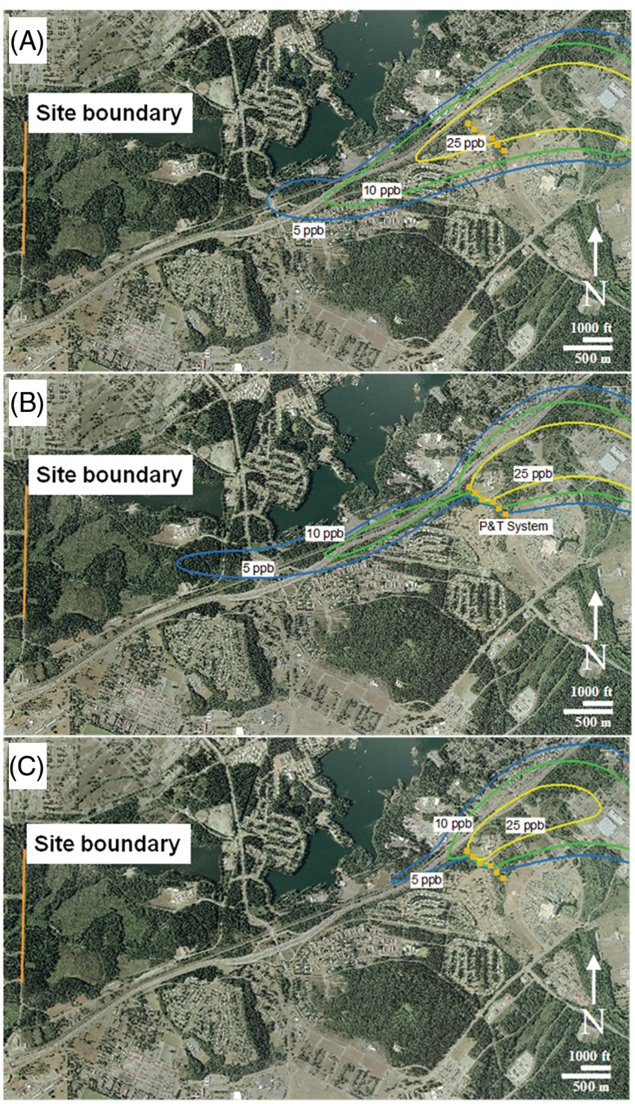

Figure 5. Simulated TCE plume (adapted from Fort Lewis 2007): (A) just prior to P&T operation, (B) after 10 years of P&T operation, and (C) after 20 years of P&T operation.

MNA may be a viable post-P&T remedy if there is a specified zone of the aquifer where, in conjunction with site-specific institutional controls, MNA can be allowed to occur to reduce plume concentrations to meet RAOs in a reasonable time. The MNA evaluation needs to be conducted in the context of the MNA OSWER directive (EPA 1999c) as well as existing guidance and protocols for chlorinated solvent MNA remedy evaluation (e.g., EPA 1998, 2002b, 2003, 2004, 2011b; ITRC 1999a, 1999b, 2008; USGS 2003). However, in the situation where P&T has already been applied at a site, the evaluation of transition to MNA after P&T is terminated, or reduced, must consider different lines of evidence than can be applied for a site where active remedies have not been applied. For instance, evaluation of whether a plume is stable, shrinking, or expanding is not relevant because the plume conditions have been affected by P&T and will change again when P&T is terminated. Thus, for a transition of P&T to MNA, an analysis could be conducted by determining when the CMD from the portion of the plume contained by the P&T system has been reduced sufficiently and can be balanced by the AC of the downgradient aquifer in the attenuation zone and meet the RAOs for the site. This situation is the analysis conceptually depicted in Figure 2.

One approach to evaluate the balance between P&T zone CMD and the available AC is to use estimates of the attenuation rate and calculate the threshold concentration below which attenuation will reduce concentrations (i.e., along a downgradient flow path) sufficiently to meet RAOs. That is, concentrations within the portion of the plume previously controlled by the P&T system need to be low enough that they can decline to the RAO concentration limit before the plume migrates beyond a defined footprint or specified downgradient location. Computing a concentration-based attenuation rate for the downgradient plume is a key step for using the threshold concentration approach. EPA (2002b) provides information on calculating attenuation rates (e.g., mg/L/d) using data from wells along the plume migration axis (Attenuation $\text{rate}|_{\text{plume axis}}$), considering plume migration conditions that may affect the calculation. Using the estimated attenuation rate and the computed contaminant transport velocity ($v_{\text{contaminant}}$), a threshold concentration at the upgradient location of the P&T system can be calculated whereby the RAO

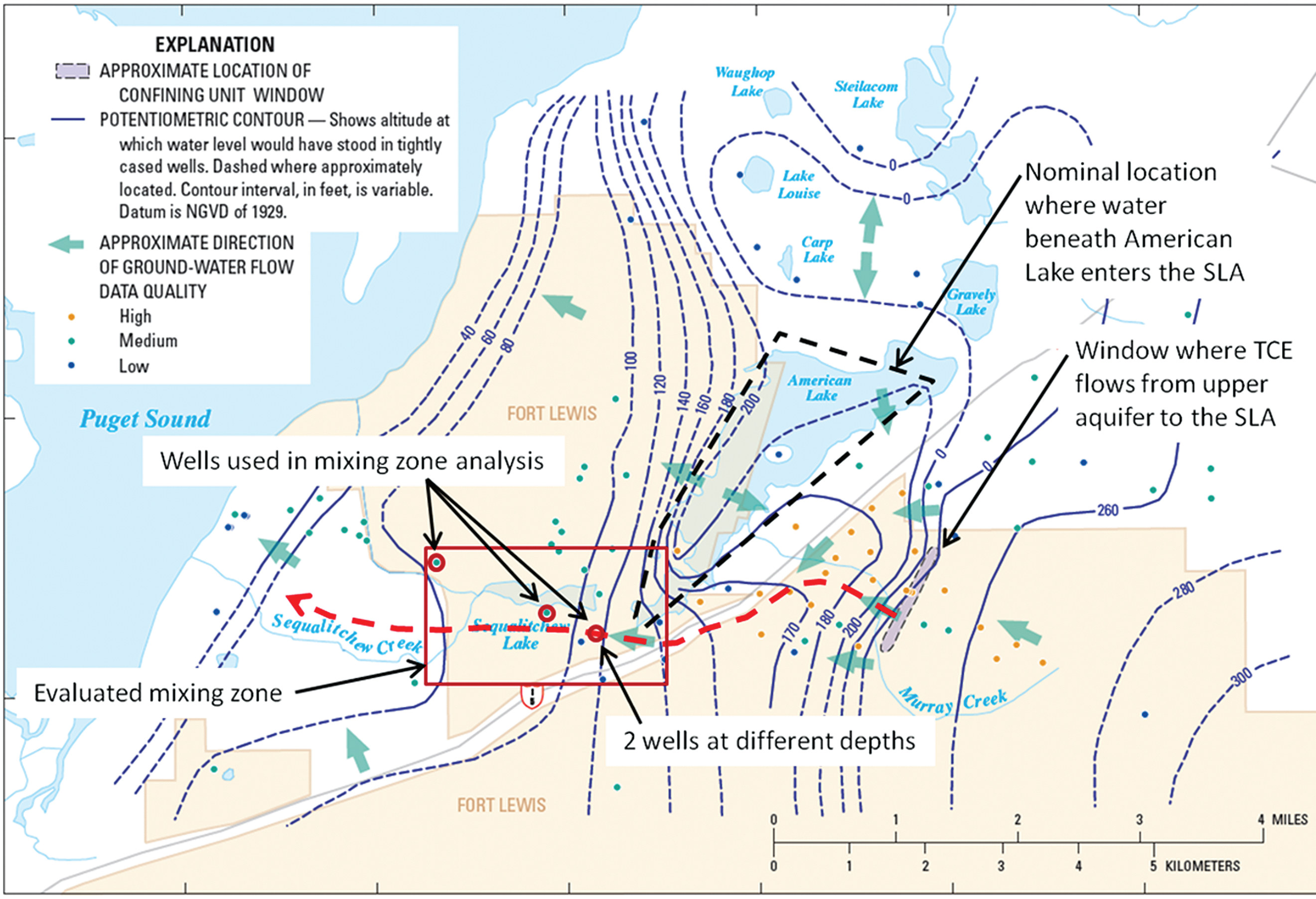

Figure 6. General flow path (red dashed arrow) of contamination in the SLA from the location where it enters via the "window" from the upper Vashon Aquifer along the path toward Puget Sound. Contour lines are hydraulic head under natural-gradient conditions (adapted from Truex et al. 2006; Dinicola 2005). The mixing zone and wells used for calibrating the numerical model to the observed mixing ratios of SLA water and water from beneath American Lake are also shown.

concentration goal (C_{RAO}) is reached at a selected downgradient plume migration distance. For a first-order attenuation rate (k), Equation 1 can be used to compute the threshold concentration. This threshold concentration can then be compared to concentrations within the upgradient plume or to a concentration measured during a rebound test.

$$\text{Threshold concentration} = C_{RAO}/[\exp(-k \times t)] \quad (1)$$

where k is the first-order attenuation rate coefficient (year^{-1}) and t is the travel time (years) from the P&T system to the end of the zone acceptable for MNA. The attenuation rate (k) can be estimated as described by EPA (2002b) using historical data and Equation 1, where the threshold concentration is a known upgradient concentration and C_{RAO} is a known downgradient concentration. The travel time (t) can be estimated from Equation 2 as follows:

$$t = \text{distance}/v_{contaminant} \quad (2)$$

where distance is the distance from the P&T system to the end of the zone acceptable for MNA,

$$v_{contaminant} = (q_{natural}/n)/R_{contaminant},$$

where $q_{natural}$ is the Darcy flux under natural (nonpumped) conditions, n is the effective porosity, and $R_{contaminant}$ is the contaminant-specific retardation factor resulting from adsorption.

For the case study site, previous work by Dinicola (2005) examined TCE data in the SLA plume and estimated a value for k of 0.1 year^{-1} for TCE based on temporal data at multiple well pairs along the plume flow path in zones downgradient of the P&T system where Dinicola (2005) suggests that the estimates are not impacted by transient plume conditions. Dinicola (2005) also estimated the travel time from well LC-74D (near the location of the SLA P&T system) to an off-site water well (located about 300-m downgradient of the site boundary and considered a potential receptor for the plume) to be 13.6 years. This travel time estimate was for nominal hydraulic gradient conditions with the SLA P&T wells not pumping, but with the off-site well pumping at its nominal production rate. Using these parameter values and a value of 5 µg/L for C_{RAO}, with the threshold calculation approach presented herein, the computed threshold concentration at the SLA P&T system is 19.5 µg/L. Historically, the concentration at well LC-74D was approximately 65 µg/L, consistent with the feasibility study conclusion that MNA would not be sufficient to meet the site RAOs.

In the previous SLA feasibility study (Fort Lewis 2007), the site numerical model was used to evaluate remedial alternatives and was then used to design the SLA P&T system so that the plume would not reach the site boundary (Figure 5). This model was applied in the feasibility study to investigate plume migration over different P&T operational durations.

The results were interpreted in terms of when the plume upgradient of the SLA P&T system had diminished sufficiently that MNA would meet the site RAOs in the downgradient contaminant plume. The site RAO is prevention of TCE contaminant concentrations greater than 5 µg/L migrating past the site boundary (e.g., as shown in Figure 5). The numerical model, in effect, calculates the balance between the CMD at the P&T system and the downgradient AC. Example simulation results are shown in Figures 7 and 8 where MNA cannot meet the RAOs if the P&T system is terminated after 23 years of total operation (Figure 7), but can meet the RAOs if P&T is terminated after 28 years of operation (Figure 8). As shown in Figure 8, the plume concentrations upgradient of the P&T system for the case that will meet the RAO with MNA are in the order of 20 µg/L, close to the threshold concentration value calculated above with the parameters from Dinicola (2005). Note also from Figure 8 that the total time to reach RAOs is a little more than 50 years from initiation of the P&T remedy.

These previous and new (threshold) calculations define the conditions under which the SLA P&T can be terminated and natural attenuation will effectively meet the RAO of preventing off-site plume migration. At JBLM, the extracted water from the P&T system is being used for beneficial use in building a cooling system. Thus, the P&T system will likely not be shut off. However, once the P&T system is not strictly needed for meeting RAOs, building managers will have more flexibility in setting pumping rates that meet their cooling needs rather than having the pumping rates set based on plume capture requirements.

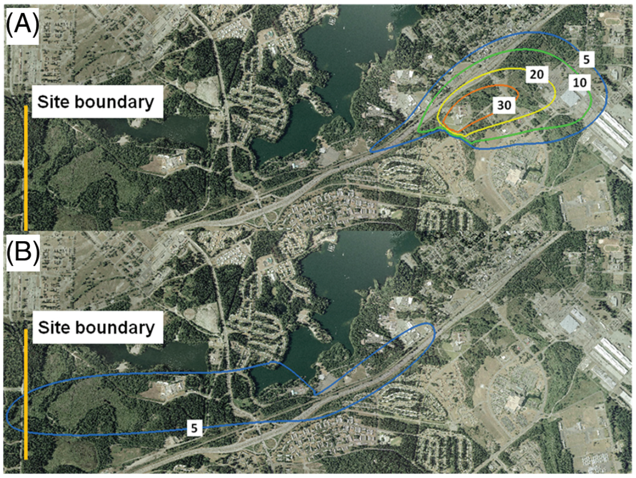

Figure 7. SLA TCE concentration contours (µg/L): (A) after 23 years of P&T and (B) 27.5 years after termination of P&T (at which time contamination is predicted to have crossed the site boundary) (adapted from Fort Lewis 2007).

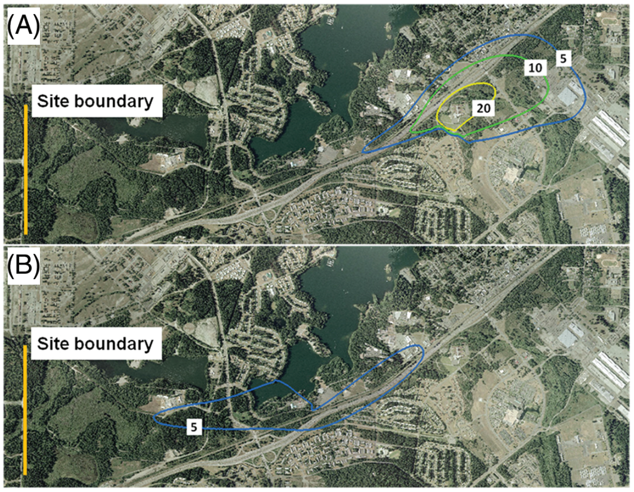

Figure 8. SLA TCE concentration contours (µg/L): (A) after 28 years of P&T and (B) 22.5 years after termination of P&T (maximum extent of contamination) (adapted from Fort Lewis 2007).

Case Study 2: JBLM Landfill 2 P&T System—Optimization

Groundwater monitoring conducted by JBLM after installation of the initial Landfill 2 P&T system showed that the source was still discharging contaminants to the downgradient plume and that the plume was not declining. The initial P&T design was based on a CSM with the hydraulic gradient parallel to the downgradient plume migration axis (Figure 9). Previous investigations of the source area (USACE 2002) were conducted to support remedy decisions associated with application of source reduction treatment at Landfill 2. These investigations revealed that the hydraulic gradient across the source area was complex and had flow components both directly along the plume axis and laterally, with the fraction of flow along these flow paths varying seasonally and related to variation in drainage to an adjacent creek (USACE 2002; Truex et al. 2003). JBLM used the additional information from the remedial investigation and the operational history of the P&T system to refine the CSM, in particular, to account for these groundwater flow patterns.

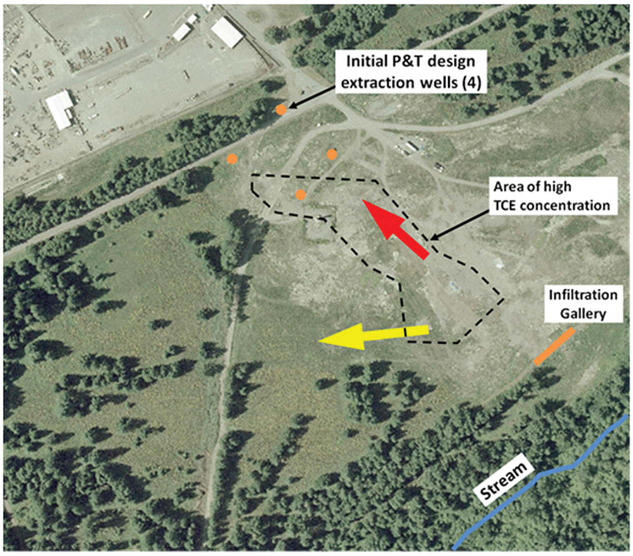

Figure 9. Initial Landfill 2 P&T system design. The red arrow represents the plume axis direction and direction of the hydraulic gradient in the initial CSM. The yellow arrow shows the lateral hydraulic gradient component (caused by seasonal drainage to the adjacent stream) that was revealed in the refined CSM. This lateral hydraulic gradient component caused poor contaminant capture with the initial P&T design.

P&T containment of the source was still needed after the source reduction (i.e., thermal treatment) actions. Therefore, a P&T performance assessment was conducted by JBLM to evaluate P&T optimization in light of the refined CSM. Two elements of the P&T system could be changed while retaining the same aboveground treatment system. Individual extraction well locations and flow rates could be varied (though the total flow was constrained by the aboveground treatment capacity) and the location of treated water infiltration could be changed (within surface feature constraints). The JBLM effort used a numerical model to evaluate source area capture within the identified constraints of the design (Truex et al. 2003, 2006; Fort Lewis 2006). These simulations demonstrated that a "v"-shaped configuration of extraction wells and a new location for the treated water infiltration would effectively capture the source area (Figure 10). Data collected by JBLM over the first 5 years of P&T operation show that the downgradient plume is beginning to diminish with the new P&T configuration (Figure 11). This case study example highlights the importance of refining the CSM and evaluating P&T optimization options as part of the P&T performance assessment decision logic.

Case Study 3: Time-Oil Site P&T System—Supplement and Transition to Passive Remediation

Numerous investigations and remedial actions, including excavation, soil vapor extraction, and operation of the source area P&T system occurred between 1985 and 2009 to address a chlorinated solvent source area impacting a municipal supply well (well 12A). Due to inefficient mass removal and lack of progress towards achieving groundwater remedial objectives, the remedy was revised to implement interim thermal and bioremediation source reduction technologies to supplement the P&T system, reduce the persistent sources, and potentially enable termination of the P&T system in the

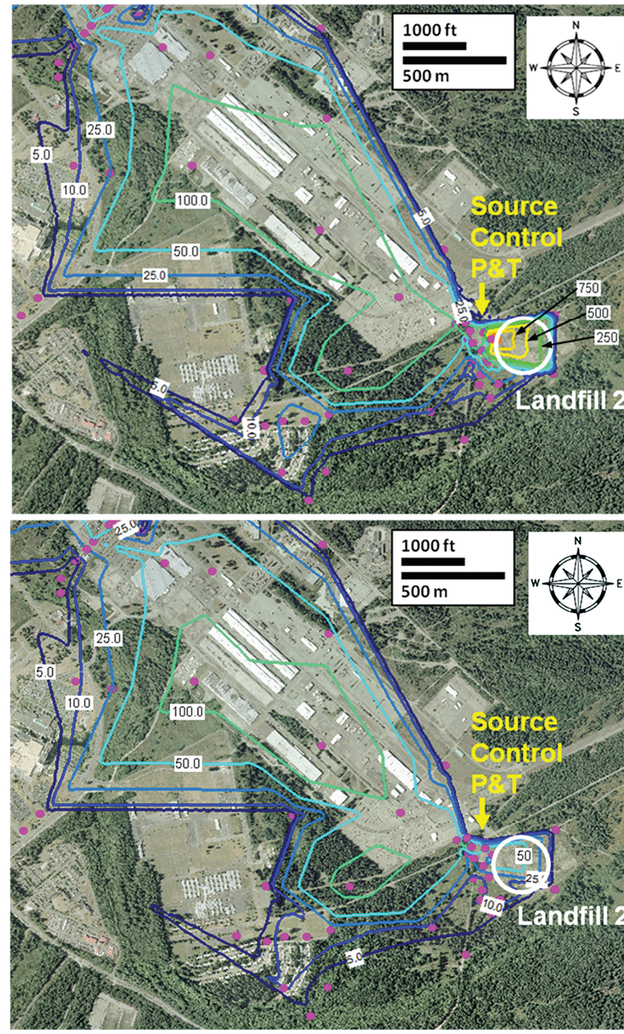

Figure 11. Interpolation of TCE concentration data (μg/L) in the Vashon Aquifer at JBLM for 2007 (top) and 2012 (bottom) (adapted from Truex and Johnson 2013). Source control P&T at Landfill 2 was initiated in 2006.

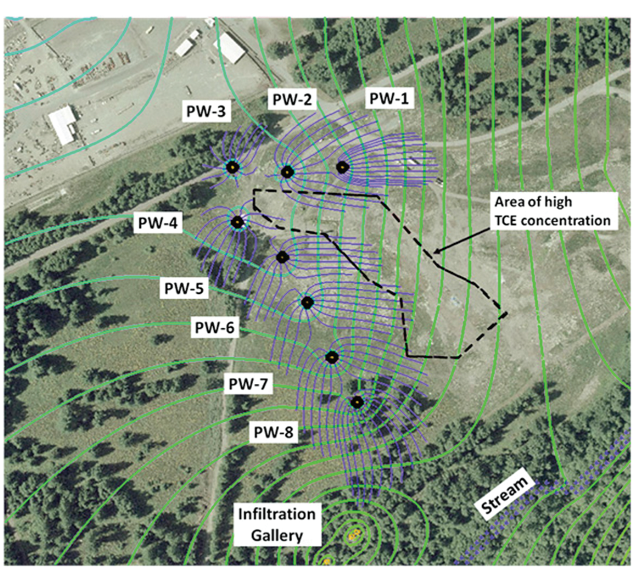

Figure 10. Optimized Landfill 2 P&T system design (the PW-# wells and the revised infiltration gallery location) and predicted groundwater capture path lines relative to the contaminant source and in the context of the hydraulic head contours (adapted from Fort Lewis 2006).

future. Calculations used by the site to support the selection and design of this approach evaluated the amount of source CMD reduction that would enable the downgradient AC to meet the site RAOs. Data were compiled to: (1) evaluate the source strength; and (2) support evaluation of the natural AC of the aquifer. This information was used in conjunction with a modeling analysis to develop a realistic, and protective, CMD goal for the interim groundwater remedy and to support transition to passive remediation.

Source Strength

A three-dimensional (3D) visualization model built in the Environmental Visualization System software (C Tech Development Corp, Osprey, Florida) was used to evaluate available soil (Figure 12) and groundwater data, with Kriging interpolation used to estimate the extent of contamination (Camp, Dresser, and McKee [CDM] 2009). TCE was used as the primary indicator chemical of concern due to its persistence and the large TCE groundwater plume, which had previously impacted the well 12A receptor. TCE concentration contours were generated in the 3D model and were

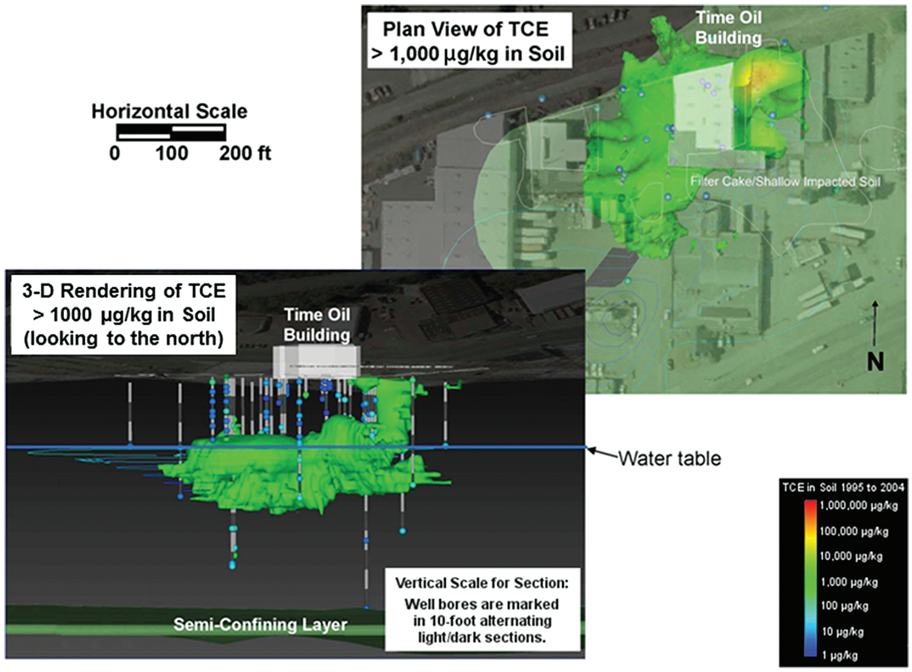

Figure 12. Modeled TCE contamination extent in soil at the Time-Oil source zone (adapted from CDM 2009).

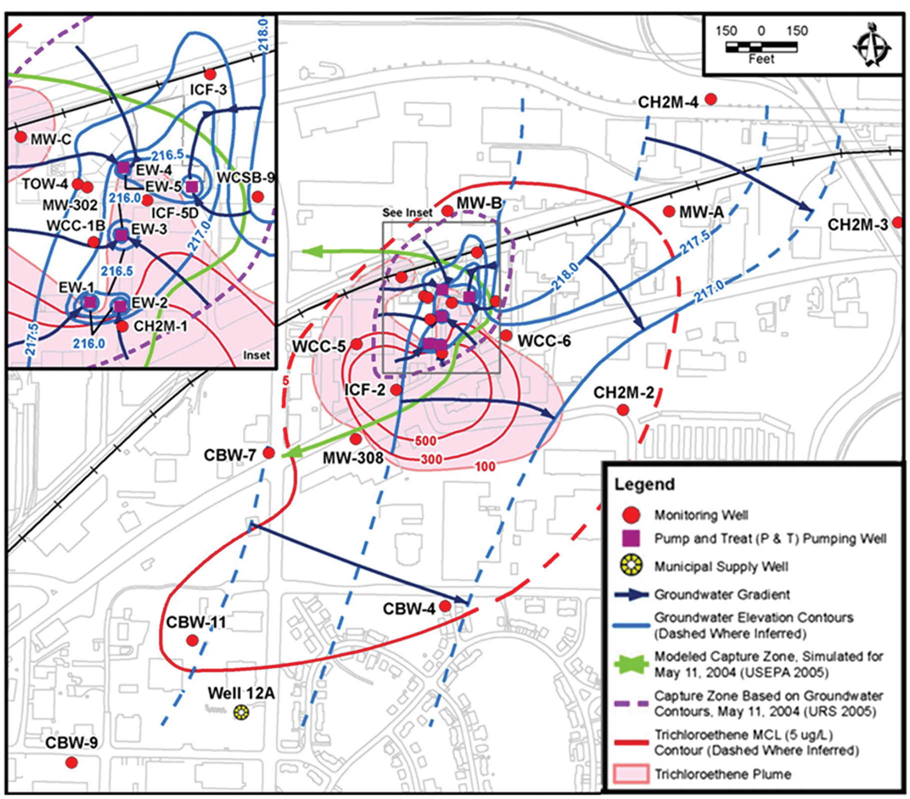

Figure 13. Hydraulic head contours (with well 12A not pumping), TCE concentration contours, and the interpreted P&T capture zones (adapted from CDM 2009).

used to evaluate the extent of the high concentration source term around the Time-Oil property, to refine the volume of the source in a numerical fate and transport model, and to define the downgradient TCE plume (Figure 13). Figure 13 also depicts the ambient gradient (i.e., without well 12A pumping) and the capture zone of the Time-Oil P&T system.

Source strength dynamics were estimated based on solute transport parameters and the TCE distribution in groundwater to provide an estimate of the source area CMD. The site used a steady-state numerical model (URS Corporation 2005; CDM 2009) as the basis for evaluating contaminant transport and the pumping of both well 12A and the P&T

system. Site-measured values for parameters such as effective porosity, hydraulic conductivity, and contaminant concentrations were used for the modeling (URS Corporation 2005). The numerical model included two zones of distinct hydraulic characteristics within the source area and the plume. One zone had a bulk horizontal hydraulic conductivity of 12 m/d (40 ft/d) and the other represented a high permeability zone with a horizontal hydraulic conductivity of 120 m/d (400 ft/d). The natural groundwater gradient from the Time-Oil source is due east. When well 12A is pumping, the gradient shifts towards the southwest. In addition, model calibration had to account for high permeability preferential paths connecting the Time-Oil source to well 12A.

The plume natural AC was evaluated by first assessing the biodegradation potential for chlorinated chemicals of concern based on geochemical conditions and observed biodegradation products in groundwater (Attenuation Capacity section). This information provided the technical defensibility to estimate a biodegradation-based attenuation rate (Attenuation Capacity section) and apply a modeling assessment to estimate necessary reductions in source area CMD to set interim source reduction goals (Modeling Assessment section).

Attenuation Capacity

This section presents the site's technical basis for biological attenuation mechanisms at the site followed by estimation of the attenuation rate. For the Time-Oil source area, mixed petroleum hydrocarbons drive geochemical conditions anaerobic and facilitate anaerobic biodegradation of PCE, TCE, and TeCA to primarily cDCE and tDCE, VC, ethene, and ethane. For chlorinated ethenes, the primary degradation pathway is transformation via reductive dechlorination (Vogel et al. 1987; Truex et al. 2007). For TeCA, the anaerobic biodegradation pathway includes TeCA dichloroelimination to cDCE and tDCE, followed by reductive dechlorination (Chen et al., 1996). In addition, reductive dechlorination can also occur with TeCA (Vogel et al. 1987; Truex et al. 2007), but this latter pathway was determined to be insignificant at the site based on very low concentrations of the less-chlorinated ethanes. Because the predominant pathway for TCE reduction is through cDCE, it is likely that the majority of tDCE generated at the Time-Oil site comes from TeCA and not from TCE. TeCA can also undergo an abiotic hydrolysis where it is converted to TCE (Truex et al. 2007). Hydrolysis rates can be significant (with a half-life in the order of days to weeks), though the rates are a function of temperature and pH (Jeffers et al., 1989). Therefore, TCE is a parent compound, but also a daughter product of TeCA hydrolysis.

Downgradient of the Time-Oil source area, geochemical conditions transition from anaerobic to predominantly aerobic, as indicated by a transition from near-zero dissolved-oxygen concentrations to dissolved-oxygen concentrations generally greater than 3 mg/L. Anaerobic and aerobic groundwater mixing zones can support a variety of biodegradation processes. Chlorinated chemicals discharging from the anaerobic source to the zone of aerobic conditions are subject to aerobic biodegradation processes, which include oxidation of cDCE and tDCE, DCA, chloroethane, and VC to carbon dioxide and water. Under conditions where chemicals are being oxidized, a complete mass balance to innocuous end products cannot be assessed with standard groundwater chemistry parameters. Concomitant with transition to aerobic conditions, concentrations of the less-chlorinated chemicals are quickly reduced downgradient from the Time-Oil source area. However, TCE downgradient of the source area was significantly more recalcitrant to biodegradation reactions, as was reflected in the much larger extent of the TCE plume compared to the other chemicals. Therefore, a more detailed evaluation of TCE attenuation under aerobic conditions was conducted. The only known aerobic degradation pathway for TCE is aerobic cometabolism, which occurs when organisms generate nonspecific enzymes capable of fortuitously transforming TCE to innocuous products. A variety of bacteria generate enzymes capable of cometabolic TCE degradation, including bacteria that use ammonia, methane, benzene, propane, or toluene as natural growth (i.e., "primary") substrates. The presence of both petroleum hydrocarbons and low levels of methane as potential inducing substrates supported the potential for cometabolic activity at this site.

The site used molecular diagnostic tools to assess groundwater samples collected from four locations within the aerobic portion of the dissolved phase plume to determine if microorganisms capable of aerobic TCE biodegradation were present and active. Enzyme activity probes (EAP) and DNA analysis (results in Table 1) were used by the site to assess the presence and activity of cometabolic enzymes known to

Table 1

Result of Molecular Analysis of Aerobic TCE Plume Groundwater for Case Study 3 (Adapted from CDM 2009)

					Enzyme Activity Probes						
	Detection of Functional Gene DNA				Toluene Probe—PA		Toluene Probe—3HPA		Toluene Probe—CINN		sMMO
Monitoring Well	sMMO	PHE	TOD	RMO	Cells/mL	Standard Deviation	Cells/mL	Standard Deviation	Cells/mL	Standard Deviation	Coumarin
CH_2M3	+	+	−	+	6.11E+04	9.39E+03	7.37E+04	5.81E+04	3.33E+04	4.45E+03	+
CH_2M4	+	+	+	+	1.26E+05	3.18E+03	1.26E+05	4.14E+03	8.90E+04	3.98E+03	+
CBW4	+	+	+	+	5.87E+04	6.05E+03	9.98E+04	7.95E+02	1.65E+04	2.39E+03	+
WCC6	+	+	+	+	1.91E+04	3.18E+02	4.96E+04	3.98E+03	2.26E+04	4.30E+03	+

A plus (+) sign indicates the positive response for the DNA probes or the sMMO EAP probe.
3HPA, 3-hydroxy-phenylacetylene; CINN, cinnamonitrile; PA, phenylacetylene; PHE, toluene 2,3,4-monooxygenase; RMO, toluene 3,4-monooxygenase; sMMO, soluble methane monooxygenase; TOD, toluene/xylene monooxygenase.

degrade TCE, including toluene 2,3-dioxygenase (TOD), toluene 2-monooxygenase (T2MO), toluene 3-monooxygenase (T3MO) (Keener et al. 1998, 2001; Lee et al. 2008), and the soluble methane monooxygenase (sMMO) (Kauffman et al. 2003; Clingenpeel et al. 2005; Wymore et al. 2007; Lee et al. 2008). Positive responses for all the DNA targets were observed, except one location where TOD was negative, suggesting that the DNA coding for these enzymes was present within the plume. Activity from cometabolic enzyme sMMO and toluene was also observed at all of the sampled wells. These data suggest that multiple aerobic cometabolic pathways are present and active within the aerobic TCE plume.

Once aerobic and anaerobic biodegradation mechanisms were identified for the site, the site estimated aerobic biodegradation rates using a steady-state transport solution along the centerline of a plume (Domenico 1987; Aziz et al., 2000) to evaluate concentration reduction estimates to achieve the maximum contaminant level (MCL) of 5 μg/L for TCE at two proposed compliance points. The groundwater plume was divided into two areas, the source area/anaerobic zone (out to ~300 μg/L TCE contour) and the downgradient aerobic plume (Figure 13). Transport of TCE was evaluated to two monitoring wells, considered "compliance points," with one approximately 160-m (520 ft) east (in the direction of the ambient groundwater gradient) and one approximately 350-m (1140 ft) south (in the direction of the groundwater gradient when well 12A is operating). The actual receptor (and compliance point), well 12A, is approximately 380-m (1250 ft) south from the boundary (Figure 13). Plume concentration and geometry were based on the 3D modeling, and transport property values were based on site data. The model assumed first-order degradation and was calibrated to concentrations observed at the two monitoring wells (~21 and 160 μg/L, respectively), resulting in estimated biodegradation half-lives of 8.25 and 1.5 years within the aerobic plume, respectively. These values are consistent with other field-scale estimates for aerobic TCE degradation half-life of 5 to 30 years (e.g., Sorenson et al. 2000; Wymore et al. 2007; Lee et al. 2008). The higher estimated rate to the south/southwest was attributed to different hydrogeological characteristics between the east and south-southwest areas of the aquifer.

Modeling Assessment

Using the estimated biodegradation rates, the site estimated the concentration reduction needed at the source/plume boundary to achieve MCLs at the two compliance locations (i.e., the threshold concentration approach as was conducted for Case Study 1). The analysis suggested that concentrations discharging from the anaerobic source area need to decrease by 50 and 80% in the south and east sides of the site, respectively, for the TCE concentrations to be less than 5 μg/L at the compliance points, although the uncertainty in this estimate, due to site heterogeneities and variable values, was acknowledged. Therefore, a 90% reduction in CMD from the source, assuming the hydraulic parameters were consistent, was selected as the interim goal for the source treatment remedy. This was considered achievable with available source-treatment technologies (McDade et al. 2005; McGuire et al. 2006).

Detailed hydraulic and capture zone assessment of the P&T system led to operational modifications such that the system could be used to measure CMD for evaluating compliance of the ROD-specified interim goal. The P&T system was used as an integrated measure of concentrations discharging from the anaerobic source zone. A method was developed that: (1) used the P&T system to achieve the hydraulic capture of the anaerobic source area, as shown in Figure 14; (2) collected influent P&T system discharge samples, representing the groundwater concentrations in the capture zone; and (3) collected replicate measurements to address the intrinsic variability in the sampling, analysis, and operation of the P&T system. Details of the method development are provided by USACE (2013).

Using the P&T system, target extraction rates were chosen by the site to represent the source area chlorinated chemical concentration after approximately 3 months of system operations based on travel times from the edge of the capture zone to the extraction wells (Figure 14). Therefore, the P&T system extraction rates determined both the capture zone and the duration that the system has to be operated to obtain integrated measurements of chlorinated chemical concentrations. Each individual well was operated as close as possible (within 10%) to the target extraction rates. The intrinsic variability in sampling was also quantified using nearly 4 years of P&T system operations and maintenance data (USACE 2013) to establish a tolerance criterion for variability in sample results. Based on this assessment, intrinsic variability of 18.5% was established and used as the acceptable variability in replicate samples used for the baseline CMD measurement.

During the baseline CMD assessment, chlorinated chemical concentrations within the P&T system influent line were evaluated by the site over approximately 175 days of operation, as shown in Figure 15. Eight samples were collected in this baseline assessment, during which time the P&T system was operated at the target extraction rates. The last three samples show reasonably stable chlorinated chemical concentrations and extraction rate (Figures 5 and 6). The total VOC concentration (sum of TeCA, PCE, TCE, cDCE and tDCE, and VC) for the three measurements collected at the end of operations were 592, 613, and 629 μg/L, respectively, with a relative percent difference between values of less than about 6%, well within the expected intrinsic variability of the system. Therefore, these measurements were accepted as reasonable values for use in the baseline mass discharge calculation. The average of these last three total VOC concentration values was used to determine the baseline CMD to be about 400 g/d total VOC. Therefore, the source treatment goal is to achieve CMD of approximately 40 g/d (90% reduction) (Figure 16).

The site plans to conduct postremedial action mass discharge measurement with the same type of approach as for the baseline measurement. Of particular importance will be tracking the percentages of chlorinated constituents as concentrations of parent and daughter compounds change. Due to the impacts of the source-area bioremediation, the postremedial action measurement will likely include much higher relative percentages of lower chlorinated compounds such as cDCE and tDCE. Therefore, assessment of

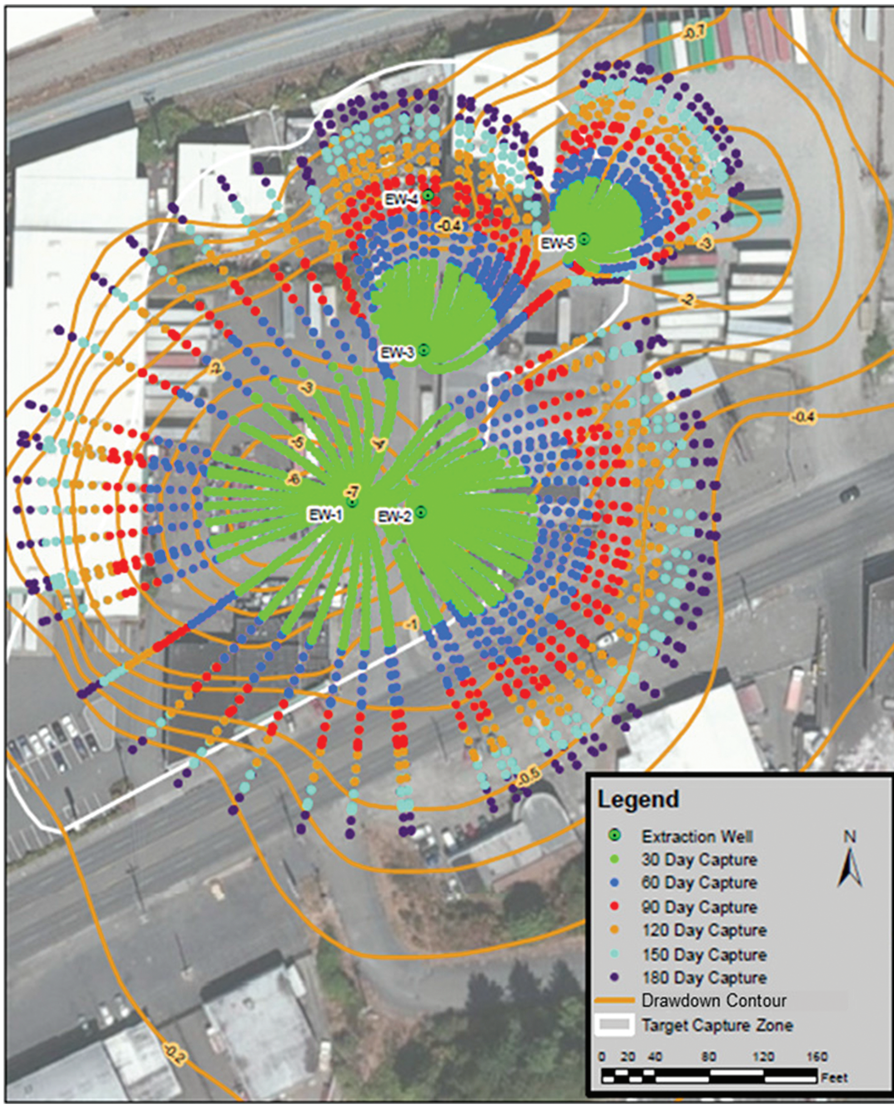

Figure 14. Particle capture tracking model of P&T extraction wells (EW-1, EW-2, EW-3, and EW-5) that are operated at target flow rates (adapted from USACE 2013).

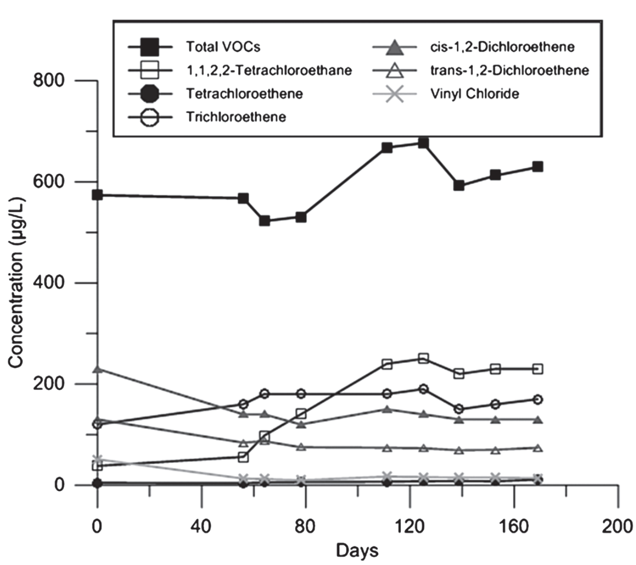

Figure 15. Trends in chemical concentrations for the Time-Oil P&T system during the baseline remedial action compliance measurement (adapted from USACE 2013).

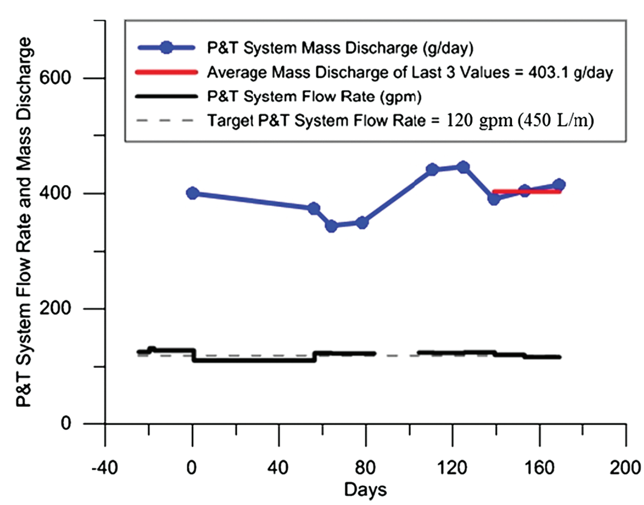

Figure 16. Trends in CMD for the Time-Oil P&T system during the baseline remedial action compliance measurement (adapted from USACE 2013).

the mass discharge measurement will also need to evaluate individual compounds as well as total VOC to provide input to fate and transport analysis when evaluating postremedial action performance. In addition, the measurement will need to account for sampling and analysis variability at the much lower concentrations anticipated coming into the P&T system.

As demonstrated in this case study, a mass discharge-based interim compliance metric measured using a P&T system allowed for development of realistic performance goals for active treatment of a DNAPL site, compatible with the overall remedy management approach to protect the receptor. In addition, monitoring during and after the source reduction effort will be used to verify assumptions of the aquifer AC and aerobic plume response to source treatment as part of a decision to transition to passive remediation.

Conclusions

A structured approach to assess P&T performance provides a means to support decision makers in determining appropriate next steps for remediation at sites where P&T has been operating. At some sites, the plume or source may have diminished sufficiently that P&T can be transitioned to a natural attenuation approach. However, evidence must be provided to demonstrate that natural attenuation processes are predicted to meet the site RAOs. The calculation approaches demonstrated in Case Study 1 can provide this type of information. These types of approaches for considering natural attenuation are needed because a traditional evaluation of plume stability is not possible for sites where P&T has altered the plume and the aquifer hydraulic conditions will change if the P&T is terminated. Site decision makers will need to assess the site complexity and select the level of detail needed to support the prediction of natural attenuation performance in meeting the site RAOs.

When assessing P&T system performance at sites where the plume is not declining or is otherwise not responding as expected to the P&T system, it is important to review the CSM and identify factors that may be contributing to the observed performance. As shown in Case Study 2, an updated CSM (from new characterization data or incorporating data collected during the P&T operational period) may lead to an improved understanding of the aquifer system. It is useful in these situations to examine the viability of optimizing the P&T system to effectively meet site RAOs. For Case Study 2, optimization of the P&T system enabled use of existing P&T infrastructure with a new well configuration that provided more effective source control. At the Case Study 2 site, cutting off the CMD from the source area was an important piece of the overall remedy to limit the duration of the downgradient remedy components.

At sites where the plume is not declining or otherwise responding as expected to the P&T system, P&T may be an inherently inefficient method to meet the site RAOs due to the characteristics of the site and contamination. These sites may benefit from an overall reassessment of the remedy approach considering the factors inhibiting remediation (e.g., matrix diffusion). Depending on the nature of these factors, other technologies (e.g., focused source treatment) or adaptive site management (ITRC 2017) may be most appropriate for these sites. Case Study 3 shows an example of a site where persistent sources of contaminants were expected to result in long-term P&T operation. Evaluation of remedial technology options identified a suitable approach to supplement the P&T system in the near term and reduce the persistent sources enough so that termination of the P&T system could be considered in the future. Calculations to support the selection and design of this approach evaluated the amount of source CMD reduction that would enable the downgradient AC to meet the site RAOs. Consistent with the decision logic provided in Figure 1, the site considered the factors inhibiting remediation in evaluating an appropriate transition to this new approach. For this case study site, the calculations based on CMD and AC provided a useful basis to update the site RAOs and to identify an effective metric for the remedies applied to supplement the P&T system. Furthermore, the P&T system can be used as part of the monitoring approach to verify when the site has met this metric.

While each site is unique, there are common decision elements that can be used in assessing P&T performance (e.g., Truex et al. 2015). Thus, decision logic, supported by appropriate calculation approaches and assessment tools can be applied within the context of site-specific conditions to support a P&T performance assessment. The above case studies provide examples of P&T performance assessment in support of three types of outcomes for the assessment: transition of P&T to MNA, optimization of the P&T system, and transition of P&T to an approach incorporating other remedy technologies to address factors inhibiting remediation (e.g., supplementing P&T with another type of remedy).

Acknowledgments

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