An Integrated Endpoint Approach for Complex Sites – 14599

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ABSTRACT

When a subsurface contamination site is complex, having properties that render remediation difficult, a sequence of progressive remediation endpoints may be an appropriate remedial approach. Progressive remediation steps would be adaptive to account for changing conditions and improved understanding as more data about the site are obtained through remedy implementation and associated monitoring. Given a progressive approach, initial remedy decisions would not necessarily need to select a remedy that will fully meet restoration goals. Rather, the remedy would outline an approach that maintains protectiveness (e.g., institutional controls, targeted actions for complete exposure pathways), makes appropriate progress toward reducing future risk, and provides information to evaluate subsequent remedy actions to reach restoration goals or consider appropriate alternative goals. A conceptual site model, with subsequent refinement as additional data are collected, is a key element for guiding the progression of remediation and the assessment of both risk reduction and restoration potential. Several categories of contaminant plume examples were developed to examine potential endpoint approaches and related data and decision support information that can be used to guide remedy implementation.

INTRODUCTION

Remediation of subsurface contamination, including remediation of groundwater to a condition allowing unlimited use/unrestricted exposure, remains a significant challenge facing the nation (EPA 2004). The National Research Council (NRC) recently completed a study examining technical and management issues for restoration of contaminated groundwater. The NRC examined Department of Defense and Department of Energy cleanup efforts, as well as cleanup programs under state purview, to identify trends and the magnitude of the remaining challenge. The NRC committee estimated that more than 126,000 facilities or contaminated sites with complex conditions remain and that remediation cost would be in the range of $110 to $127 billion (NRC 2013).

The National Contingency Plan and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA) statutes (as defined in the Code of Federal Regulations) provide the legal context for setting cleanup goals and define the basic elements of the process to determine appropriate responses to subsurface contamination (in addition to state regulations, where applicable). If the baseline risk assessment indicates the need for remediation, then the site must proceed with the remediation process and meet legal requirements for protection of receptors and restoration (e.g., meeting groundwater maximum contaminant level goals) except under specific conditions and with appropriate documentation (e.g., a technical impracticability waiver, EPA 1993). Remedy selection and implementation must consider site-specific conditions. Thus, there is flexibility in specific details of the remedy approach for each site, though the approach must be agreed to in remedy decision documentation using the associated processes provided under CERCLA and RCRA (and potentially state regulations).

Complex sites are those having properties that render remediation difficult. Technical issues can include difficult subsurface access, deep and/or thick zones of contamination, large areal extent, and subsurface heterogeneities that limit the uniformity of treatment operations. Sites are also complex because of significant uncertainty with respect to understanding contaminant behavior and estimating how the contamination will respond to a remedial action. Sites where long-term processes will be needed to address the contamination (e.g., due to presence of long-term sources or large size) are also challenging with respect to remedy selection and management.

For complex contaminated sites, sequences of remediation steps may be appropriate. The steps in the process can be adaptive to account for changing conditions and improved understanding as additional data about the site are obtained through remedy implementation and monitoring. With an adaptive approach, initial decisions do not necessarily need to result in selection of final remedies that fully meet restoration goals. To facilitate implementation of this type of approach, the concept of identifying and managing to intermediate *endpoints* during the course of remediation may be useful. In this context, remediation endpoints are risk-informed remediation goals or scenarios that facilitate management of an adaptive remedy path. An adaptive technical approach to regulatory processes established for remediation under CERCLA and RCRA is intended to facilitate remedy decisions and implementation at complex sites where restoration may be uncertain and require a long timeframes.

In this paper, an integrated endpoint approach to complex sites is discussed using example contaminant plume scenarios. For complex subsurface contamination sites, there may be considerable uncertainty in the appropriate measures needed to meet restoration goals and selection of a suitable comprehensive remedy may be difficult. Thus, a progressive remediation approach using interim endpoint goals may be more appropriate. With an integrated endpoint approach, initial remedy actions would include measures necessary for protection of receptors (e.g., institutional controls, targeted actions for complete exposure pathways) to mitigate risk to human health and the environment while providing time for a progressive approach to cleanup. Additional initial actions would be designed to make progress toward cleanup goals and/or support collection of information to address site uncertainties (e.g., the extent to which natural attenuation can meet goals). This additional information from initial remedial actions would help guide and refine subsequent actions and remedy decisions with respect to the assessment of risk reduction and restoration potential. Considerations for implementing this type of endpoint approach are explored in the plume scenario examples, including use of quantitative conceptual models and integrated monitoring as part of the process.

EXAMPLE SCENARIOS

Illustrative plume examples were developed to examine potential endpoint approaches and how related data and decision support information can be used to guide progressive remedy implementation. The two example scenarios are introduced below and then discussed in terms of an endpoint remediation approach in the next section.

Plume Scenario 1: Vadose zone contaminant source

The first contaminant plume scenario considers a site with a thick vadose zone contaminated with inorganic, non-volatile compounds. In this scenario, the majority of the contamination currently resides in the vadose zone and has the potential to contaminate the groundwater in the future. Figure 1 shows a conceptual cross sectional diagram of the plume scenario. Remediation must consider meeting legal requirements for groundwater restoration goals and consider the potential exposure pathway to the hydraulically connected surface water or through other groundwater uses. For the example scenario, there are no nearby receptors (wells or facilities) and contamination must migrate over long distances/time before reaching a receptor. Thus, while a cleanup goal for the groundwater is relevant, there is no urgency to reach this goal within a short timeframe because institutional controls can be applied as the means to maintain protectiveness during the remediation period. The complexity of this scenario derives from the long-term source flux of contaminants from the vadose zone to the groundwater, the difficulty in directly measuring the extent and movement of the contaminant plume in the vadose zone, and the long duration timescale of transport and response to remedial actions. These complexities lead to uncertainties in understanding and estimating contaminant behavior and necessitate the use of predictive analyses for selecting a remedy.

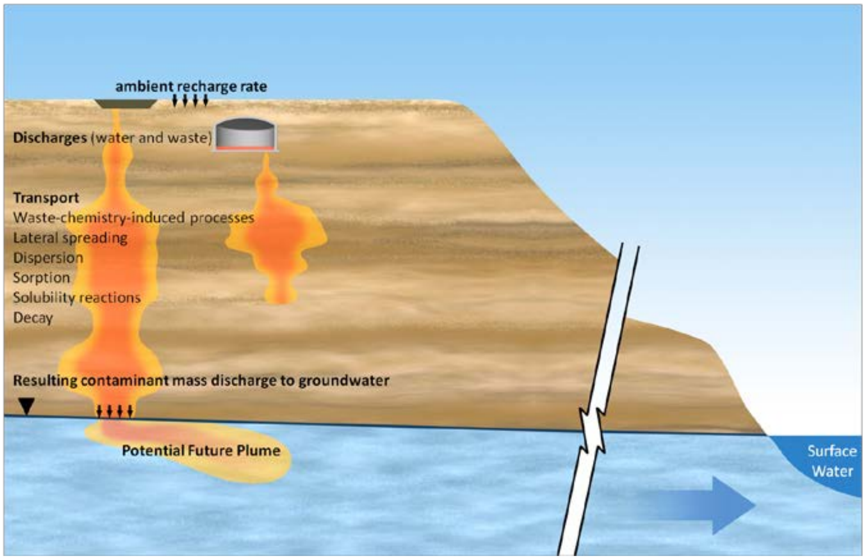

Figure 1. Example vadose zone contamination and associated processes.

Plume Scenario 2: Groundwater plume with a large, complex source area

This plume scenario considers groundwater contamination with a continuing source in the aquifer that is difficult to fully remove and is feeding a growing downgradient plume. Figure 2 depicts a conceptual groundwater plume and associated characteristic zones for this scenario. Sites with large groundwater plumes and difficult source areas (e.g., DNAPL, matrix diffusion, heterogeneous conditions) lead to complexities in remedy decisions due to the size, cost, and uncertainty in remedy performance.

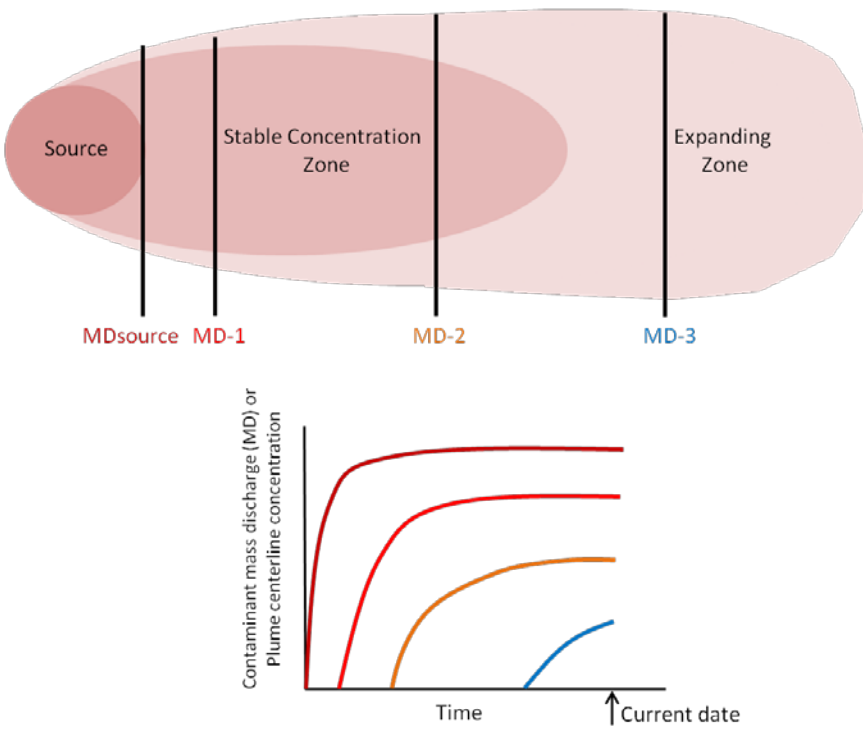

Figure 2. Example groundwater plume plan view and idealized data at selected locations for mass discharge cross sections or plume centerline concentrations.

DISCUSSION

Several key elements are used in applying an integrated endpoint approach for remediation. An initial foundation is a “systems-based” conceptual model of the site describing the associated “system” of features, events, and processes that collectively are important to plume behavior, remedy performance, and exposure pathways and control for these pathways. Quantitative assessment of the baseline plume behavior and the predicted response to candidate remedy actions is important information for evaluating remedy alternatives, appropriate performance metrics, and monitoring strategies. Obtaining insight into plume behavior by evaluating remedy actions as perturbations to the system is a fundamental aspect of an integrated endpoint approach. Based on the quantitative assessment, and with actions in place to protect potential receptors during the remedy process, an initial remedy action is selected along with the performance and monitoring goals that define the “endpoint” of this action. The endpoint provides a defined step in the progressive remedy where decisions about appropriate subsequent steps can be made. The example scenarios are discussed below using these elements as the framework of an integrated endpoint approach.

<u>Plume Scenario 1: Vadose zone contaminant source</u>

For the first plume scenario, non-volatile, inorganic contaminants in the vadose zone have an impact on groundwater based on the contaminant discharge over time. Contaminant discharge is the product of the water flux and contaminant concentration in the vadose zone integrated over the areal extent of the discharge zone from the vadose zone to the groundwater. When an aqueous waste is disposed to the surface and infiltrates through the vadose zone, unsaturated flow processes will spread some of the disposed water laterally, especially in arid environments and with certain types of subsurface heterogeneities. This lateral movement slows the vertical movement of the disposed water, causing vadose zone conditions to trend toward conditions where the water flux to the groundwater is controlled by the ambient recharge rate (i.e., is driven by ambient precipitation and the net water infiltration into the subsurface). Contaminant interactions such as sorption may further slow contaminant movement. In some cases, contaminant reactions, such as forming functionally immobile precipitates, may occur and limit the amount of mobile contaminants that will reach the groundwater. Thus, the nature and amount of waste disposed and the characteristics/thickness of the vadose zone are important information for evaluating the temporal profile of contaminant discharge into the groundwater and the associated potential risk for exposure.

Figure 3 shows two primary categories of contaminant discharge plots for a vadose zone source. Figure 3A depicts the situation where a large volume of aqueous waste relative to the vadose zone thickness has been disposed and a portion of this contaminated water drains into the groundwater at a rate higher than the ambient recharge rate. In this case, a period of relatively high contaminant discharge occurs and then the higher water content conditions in the vadose zone caused by the waste disposal dissipate back to being controlled by the ambient recharge rate. At this time, contaminant discharge to the vadose zone is relatively constant associated with the ambient recharge conditions and the remaining pore-water contaminant concentrations. Eventually, the contaminant discharge declines as the mobile contaminant mass in the vadose zone is depleted. Figure 3B depicts the situation where a small volume of aqueous waste relative to the vadose zone thickness has been disposed and contaminant discharge to the groundwater rises only to a relatively constant value associated with the ambient recharge conditions and the pore-water contaminant concentrations. In this second case, lateral spreading dissipates the higher flux from added water to nominally background ambient recharge conditions before any of the contaminant reaches the groundwater.

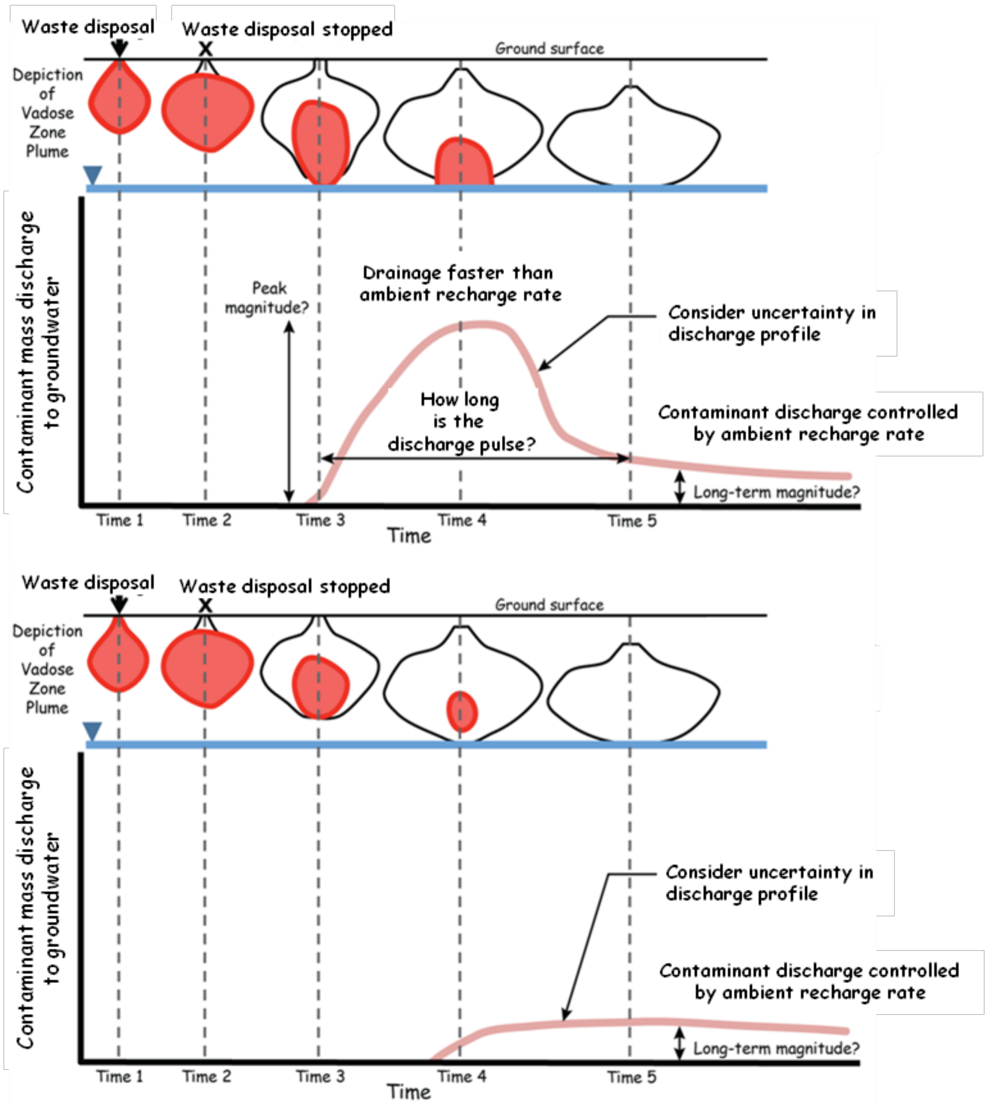

Figure 3. Conceptual depiction of a waste disposed to the vadose zone, resulting transport through the vadose zone, and profile of discharge to the groundwater. The red color represents zone that is draining faster than the ambient recharge rate. The black outlined zone represents lateral spread of the disposed waste that is moving downward at a rate approaching the ambient recharge rate. (after Truex and Carroll 2013)

If the timescale for the contaminant discharge in Figure 3 is long, such as for thick vadose zones in arid environments, and a groundwater plume has not occurred or is just beginning to occur, remedy decisions may need to be based on predicted future plume behavior. A conceptual site model with data on vadose zone moisture/contaminant distribution, recharge rate, and hydraulic properties can provide a basis for predictions of future contaminant discharge under baseline “no action” conditions (Truex and Carroll 2013). These data help distinguish between vadose zone conditions leading to a contaminant discharge profile similar to Figure 3A or 3B and can help answer key questions, as depicted on the figure, about the shape and magnitude of the expected contaminant discharge profile. A quantitative prediction can be used to evaluate the magnitude of the contaminant discharge profile and the resulting groundwater plume concentration and extent over time. This information is needed to evaluate contaminant transport for potential exposure pathways as part of assessing risks and defining monitoring and management strategies such as use of transition zones or defined points of compliance that allow for natural attenuation and maintain protectiveness with respect to exposure risk. As with any prediction, there will be some uncertainty in these estimates. Selection of a remedy approach will need to consider the predicted groundwater plume behavior over time in relation to the remediation goals.

Figure 4 depicts a hypothetical range of uncertainty in contaminant discharge profiles that may occur for either the scenario in Figure 3A or 3B. These uncertainties are shown in relation to a hypothetical contaminant discharge goal that would need to be estimated as the contaminant discharge at which the groundwater plume will meet the selected remediation goals. The goals may entail either meeting the contaminant MCLs, or could be based on a zone of natural attenuation acceptable for a period of time within the aquifer (e.g., establishing a transition zone or point of compliance during remediation). In either case, estimation of this contaminant discharge goal will also have some uncertainty.

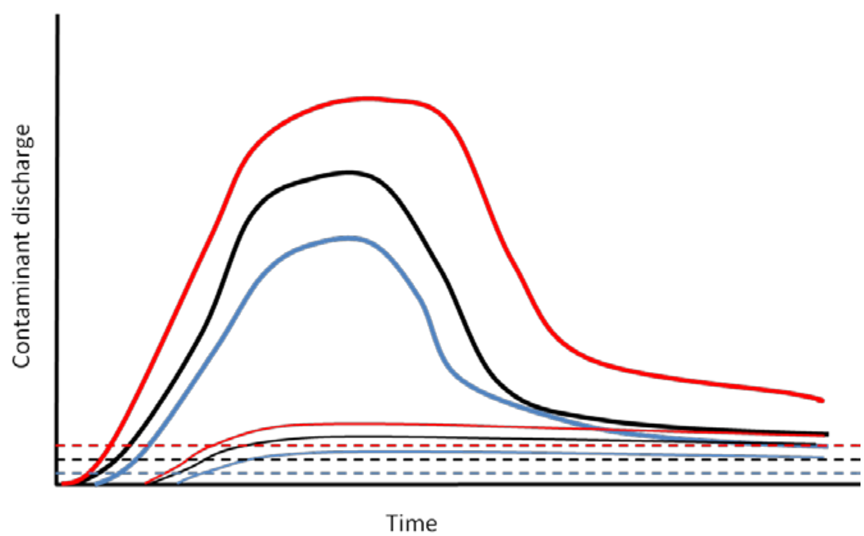

Figure 4. Conceptual contaminant discharge profiles and uncertainty bounds related to the conditions described in Figure 3A (heavy solid lines) and Figure 3B (light solid lines). Dashed lines are hypothetical contaminant discharge goals associated with meeting groundwater remediation goals. Black, blue, and red lines represent nominal, higher bound, and lower bound estimates, respectively.

The concept of an integrated endpoint approach would consider the context of the plume in terms of first ensuring protection of receptors (e.g., institutional controls, targeted actions for complete exposure pathways) and then evaluating appropriate actions to address reduction of future risk and progression toward cleanup goals, i.e., a deliberately adaptive approach. In evaluating cleanup actions, it is also important to recognize that important information to reduce uncertainties in plume behavior evolve over time with monitoring data and through observed responses to initial actions. These data an observations need to be interpreted through refinement of the conceptual model with respect to impact on contaminant fate and transport and in the context of exposure pathways. Thus, a progressive approach, when appropriate in the context of maintaining protectiveness, entails refining the conceptual model and, as necessary, refining the remedy over time. In the vadose zone plume scenario example, an initial action may be to use a surface barrier or moderate vadose zone treatment designed to address the lower bound of estimated contaminant discharge profile (blue estimated contaminant discharge lines on Figure 4) and higher bound of the contaminant discharge goal (red contaminant discharge goal lines on Figure 4). This initial action would use an interim endpoint goal associated with selected vadose zone measurements that indicate conditions consistent with meeting contaminant discharge goals (e.g., moisture content profiles and other indicators based on predicted vadose zone responses to the initial action). The initial action would also define threshold groundwater concentrations at the area of discharge that are consistent with the predicted concentrations that will meet the overall groundwater goals. Monitoring data would be used to evaluate the response for the initial action in the context of these endpoint goals to determine if additional actions are needed and to inform the nature and extent of these additional actions.

A key element of the above approach is defining endpoints and appropriate metrics to integrate performance assessment and a refined conceptual site model into the initial action as a means to manage a progressive remedy approach. This approach recognizes the uncertainty in plume behavior and provides a mechanism to manage use of incremental actions with specified interim performance goals if complementary steps are in place to protect potential receptors during the remedy and there is time and adequate distance available to manage the cleanup before potential impact to receptors (e.g., wells or surface water discharge). Taking a series of steps may be more appropriate for complex sites where determining a suitable comprehensive remedy is difficult. The series of endpoint steps and information gathered during the course of these steps as part of refining the site conceptual model can also assist in providing the means to develop and technically justify an appropriate exit strategy for the remediation process.

Plume Scenario 2: Groundwater plume with a large, complex source area

An integrated endpoint approach such as described for the vadose zone plume scenario may also be appropriate for a groundwater plume with a large complex source. For this scenario, where a continuing source within the groundwater would be difficult to fully remove, incremental actions may provide information to help guide source reduction or containment goals in conjunction with downgradient remediation strategies. Here, remedial actions that are perturbations to the current plume status can be informative for subsequent steps. Key to implementing remediation is establishing protection for any exposure (e.g., surface water, wells, or vapor intrusion) so that there is time to progressively address clean up goals. Any incremental actions would also need to consider the impact of allowing the contaminant source flux to continue for an additional period of time if only incremental steps are taken. For instance, the site should consider whether letting the plume temporarily grow or have downgradient concentrations increase to a finite extent is acceptable and will not impact protectiveness or the hinder future efforts to reach cleanup goals.

As shown in Figure 2, the conceptual model for the example groundwater plume indicates that it has existed long enough to have a stable concentration zone downgradient of the source, and is still expanding at the distal end of the plume. In this example, some natural attenuation is occurring based on the difference in contaminant discharge at MDsource, MD-1, and MD-2. Although these discharge values could be difficult to directly measure at a complex site, developing a conceptual model of the plume behavior and quantitative estimates of plume transport can provide important information for assessing remedial actions and determining appropriate targeted performance metrics that relate to the overall plume behavior. With an integrated endpoint approach, estimates can be made of the magnitude of source zone or stable concentration zone actions that are expected to stabilize or shrink the plume. These estimates would consider the uncertainty in plume behavior and expected response to the perturbation caused by the remedial action in selecting an initial approach that could achieve a measureable interim goal while providing additional information about the plume behavior and subsequent actions that may be needed. The endpoint approach would provide a means to implement a managed stepwise remedy where focused performance metrics with associated monitoring would be used to support remedy decisions and validate predicted plume behavior while minimizing cost. Again, integration of monitoring and predictive analysis is important for this progressive endpoint approach.

An example initial action could be a source reduction or containment action where the impact on the downgradient plume can be evaluated with respect to determining the need for and magnitude of additional action to create a shrinking plume condition; for instance, evaluating how source flux reduction can help enable downgradient natural attenuation to meet remediation goals. There will be a time lag in observing the response to these actions that must be considered in the overall remediation plan. Candidate initial actions could range from a source area biological treatment to a PRB downgradient of a portion of the source. Selection of the initial action would depend on the relative cost and benefit of the action in making a step toward plume cleanup goals, meeting the interim endpoint goal, and providing appropriate information to guide subsequent steps. For these types of plumes it may also be important to consider whether it is appropriate to designate that a zone of groundwater at the source and for some distance downgradient can have contaminant concentrations above the concentration goals (e.g., use of a transition zone or point of compliance approach). This approach enables source reduction efforts to target attaining a residual source flux that can be attenuated to reach downgradient concentration goals within a defined distance of the source. With the information collected as part of implementing and achieving endpoints, technical justification is made available to define completion of the remediation process.

CONCLUSIONS

Complex sites present challenges for remediation due to properties that affect the technical aspects of implementing remediation (e.g., subsurface access, depth, size, heterogeneities). Another challenge is the uncertainty in plume behavior and response of the plume to a remedial action. The integrated endpoint approach addresses this latter challenge through an approach where progressive actions are applied to enhance understanding of plume behavior and make progress toward cleanup goals. Plume behavior and responses to remedial actions evolve over time and the progressive approach allows time to monitor and incorporate information into refinements of the conceptual model and the remediation approach. Elements of this approach include the need for a quantitative conceptual model of the plume as a foundation for selecting an appropriate initial action. The conceptual model also provides a basis to design monitoring to evaluate the impact of the action on reaching goals and support selection of subsequent actions, as needed. In defining an appropriate initial remedial action, the approach considers the uncertainty that is inherent in complex sites with respect to plume behavior and level of reduction needed to meet goals. The progressive approach is intended to provide additional information through implementation of the initial remediation actions to reduce these uncertainties and to help develop appropriate remediation exit strategies.

In evaluating use of an endpoint approach, the lifecycle cost of a progressive approach and associated monitoring should be considered in relation to the cost for more aggressive remedies. To help minimize cost, progressive actions and monitoring approaches need to be designed to use focused performance metrics that provide input to remedy decisions by validating predicted plume behavior and responses to actions. Thus, integration of monitoring as feedback to evaluate predictions is important for a progressive endpoint approach.

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