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Cost and Performance Report

(ER-201428)

Long-Term Performance Assessment at a Highly Characterized and Instrumented DNAPL Source Area Following Bioaugmentation

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14. ABSTRACT

The long-term behavior in chlorinated ethene DNAPL source areas following in situ bioaugmentation in heterogeneous media was investigated in this study. Monitoring was performed up to 3.7 years following active bioremediation using a high-density monitoring network. Soil sampling, passive flux meters, and push-pull tracer testing was performed. Results showed that, despite the absence of lactate, lactate fermentation transformation products, or hydrogen, biogeochemical conditions remained favorable for the reductive dechlorination of chlorinated ethenes. While ethene levels suggested relatively low dechlorination of the parent TCE and daughter products, CSIA showed that the extent of complete dechlorination was much greater than indicated by ethene generation. Results of the push-pull tracer testing confirmed that DNAPL remained in a portion of the source area, consistent with soil and groundwater data. Overall, study results suggest biological processes may persist to treat TCE years after cessation of active bioremediation, thereby serving as an important component of remedial design and long-term attenuation. Reliance on ethene generation alone as an indicator of complete dechlorination significantly underestimated the extent of complete dechlorination, as CSIA analysis provided a more reliable estimate; highlighting the importance of utilizing isotopic data to determine dechlorination rates in complex systems. Results also emphasize the need for high-resolution characterization and monitoring to facilitate improved design and performance monitoring to optimize resources to achieve remedial goals.

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ACRONYMS AND ABBREVIATIONS

µg/L	micrograms per liter
µM	micromolar
AFB	Air Force Base
bgs	below ground surface
CSIA	Compound Specific Isotope Analysis
DCE	*cis*-1,2-Dichloroethene
DHC	*Dehalococcoides* sp.
DNAPL	Dense Non-Aqueous Phase Liquid
DoD	U.S. Department of Defense
EST	Equilibrium Stream Tube
ESTCP	Environmental Security Technology Certification Program
Fe	Iron
FRTR	Federal Remediation Technologies Roundtable
ft	foot or feet
g	gram
HPT	Hydraulic Profiling Tool
IPR	In-Progress Review
kg	kilogram
L	liter
MCL	Maximum Contaminant Level
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MIP	Membrane Interface Probe
mL	milliliters
mL/min	milliliters per minute
MLS	Multi-Level Sampling
NPV	Net Present Value
O&M	Operation and Maintenance
PCE	Tetrachloroethene

PEW	Plume Extraction Well
PFM	Passive Flux Meter
PMLS	Plume Multi-Level Sampling
PTT	Partitioning Tracer Test
SERDP	Strategic Environmental Research and Development Program
SIW	Source Injection Well
SMLS	Source Multi-Level Sampling
TCE	Trichloroethene
USEPA/EPA	U.S. Environmental Protection Agency
VC	Vinyl Chloride
VFA	Volatile Fatty Acid
VOC	Volatile Organic Compound

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EXECUTIVE SUMMARY

Management of sites that are impacted by chlorinated solvent Dense Non-Aqueous Phase Liquids (DNAPLs) is a major challenge for the Department of Defense (DoD). There are many DoD facilities that have DNAPL source areas present in unconsolidated aquifers. Recently, several laboratory and field demonstrations have indicated that bioaugmentation is a viable remedial option for DNAPL source areas. The intensive DNAPL characterization and bioaugmentation field demonstration previously performed at Alameda Point, California, in cooperation with the Strategic Environmental Research and Development Program (SERDP) Project ER-1613, which utilized many advanced tools for assessing a DNAPL source area in overburden, provided an excellent opportunity to perform a detailed long-term performance assessment following bioaugmentation. This site was highly characterized and monitored both before and during bioaugmentation and remained instrumented to provide high-resolution groundwater monitoring data for the current demonstration. Performing such an assessment following bioaugmentation of a highly characterized DNAPL source area now provides the DoD with much needed information regarding the long-term effectiveness of bioaugmentation for DNAPL sources, and will facilitate improved design, implementation, monitoring, and management of DNAPL-impacted aquifers.

OBJECTIVES OF THE DEMONSTRATION

The overall objective of this project is to perform a long-term performance assessment at a site where bioaugmentation was used to treat a highly characterized overburden DNAPL source area. The long-term treatment impacts with respect to groundwater quality, DNAPL mass, contaminant flux, reductive dechlorination, geochemistry, and microbial structure were assessed. Specific objectives, which were all met during the demonstration, included (1) assess the effectiveness of DNAPL mass removal in low permeability materials using pre- and post- bioaugmentation sampling data and partitioning tracer data, (2) assess the long-term dechlorination activity (biotic/abiotic) following active remediation, (3) determine downgradient impacts using groundwater sampling data and contaminant mass flux measurements, and (4) identify characterization and monitoring tools that were most critical for designing and assessing treatment.

TECHNOLOGY DESCRIPTION

This demonstration took advantage of the highly characterized DNAPL demonstration site at Alameda to perform a long-term (starting at two years following cessation of active treatment and extending through almost four years post-treatment) detailed assessment of bioaugmentation performance. With the source area and downgradient Multi-Level Sampling (MLS) well transects still in place, there was a unique opportunity to perform an intensive long-term post treatment evaluation to assess contaminant rebound, extended treatment due to exogenous biomass decay, contaminant flux, geochemical conditions, and microbial communities within and downgradient of the source area. Three rounds of groundwater monitoring from up to 106 monitoring locations was performed during the 2-year monitoring period of this project, thereby allowing for observation in long-term trends following treatment with respect to dechlorination rates, geochemistry, groundwater quality, and microbial community. This assessment included monitoring at wells immediately downgradient of the treated DNAPL source area, which was used to assess treatment, biogeochemical impacts, Dehalococcoides (DHC) migration, and microbial community shifts on the near downgradient plume long term.

In addition, using the existing well network, Passive Flux Meters (PFMs) were deployed to measure flux both within and downgradient of the source area. PFM data collected prior to bioaugmentation (as part of SERDP Project ER-1613) was used to provide a direct measure of the contaminant flux reduction resulting from bioaugmentation treatment. Partitioning Tracer Testing (PTT) and soil sampling were also performed and compared to pre-treatment results (Wang et al., 2014) to determine the extent of DNAPL mass removal, and to further evaluate the relationship between DNAPL mass removal, groundwater quality in high and low permeability zones, and contaminant flux.

DEMONSTRATION RESULTS

Results showed that, despite the absence of lactate, lactate fermentation transformation products, or hydrogen, biogeochemical conditions remained favorable for the reductive dechlorination of chlorinated ethenes. In locations where soil data showed that Trichloroethene (TCE) DNAPL sources persisted, local contaminant rebound was observed in groundwater, whereas no rebound or continuous decreases in chlorinated ethenes were observed in locations where DNAPL sources were treated. While ethene levels measured 3.7 years after active treatment suggested relatively low (2 to 30%) dechlorination of the parent TCE and daughter products, Compound Specific Isotope Analysis (CSIA) for carbon showed that the extent of complete dechlorination was much greater than indicated by ethene generation, and that the estimated first-order rate constant describing the complete dechlorination of TCE at 3.7 years following active bioremediation was approximately 3.6 yr^{-1}.

Results of the push-pull tracer testing (using bromide and partitioning tracers) confirmed that DNAPL remained in a portion of the source area. The tracer testing was consistent with the results of the soil and groundwater data and showed that DNAPL removal in one portion of the site had been minimal (compared to another portion of the site where DNAPL had been effectively removed).

Overall, results of this study suggest that biological processes may persist to treat TCE for years after cessation of active bioremediation, thereby serving as an important component of remedial treatment design and long-term attenuation. Reliance on ethene generation alone as an indicator of complete dechlorination significantly underestimated the extent of complete dechlorination, as CSIA provided a more reliable estimate; this result highlights the importance of utilizing isotopic data to determine dechlorination rates in complex systems. Results of this study also emphasize the need for high-resolution characterization and monitoring to facilitate improved design and performance monitoring (short- and long-term) to optimize resources needed to achieve remedial goals.

IMPLEMENTATION ISSUES

PFM data interpretation must be carefully performed, as the Darcy velocity varied spatially and temporally, which had an impact on contaminant flux rates. Not surprisingly, biofouling of the injection wells previously utilized during the bioaugmentation activities was a challenge during this demonstration.

1.0 INTRODUCTION

1.1 BACKGROUND

Management of sites that are impacted by chlorinated solvent Dense Non-Aqueous Phase Liquids (DNAPLs), especially tetrachloroethene (PCE) or trichloroethene (TCE), is a major challenge for the Department of Defense (DoD). There are many DoD facilities that have DNAPL source areas present in unconsolidated aquifers, including Alameda Point, McGuire Air Force Base (AFB), Pease AFB, and the Cape Canaveral Air Force Station. Recently, several laboratory and field demonstrations have indicated that bioaugmentation is a viable remedial option for DNAPL source areas. Because DNAPL source areas result in high concentration and persistent plumes, and because treatment of these source areas requires a significant investment of project resources, a thorough long-term performance assessment following bioaugmentation in DNAPL source areas is needed to optimize treatment and mitigate costs needed to attain remedial goals.

The key to a proper bioaugmentation performance assessment in DNAPL source areas, both long and short term, is establishing a detailed understanding of the DNAPL distribution, DNAPL mass, flux, and flow field prior to implementing the remedial technology. High resolution and detailed evaluation during bioaugmentation implementation also is vital for proper long-term performance assessment. In most instances, characterization of DNAPL source zones fails to obtain the high-resolution spatial information that is needed to assess performance and fails to utilize advanced tools that can quantify DNAPL mass, flux, and the flow field. Understanding amendment distribution relative to the location of DNAPL sources and understanding how DNAPL mass and flux has changed in response to treatment, serves as a basis for assessing long-term bioremediation performance. Unfortunately, few sites have undergone the high level of characterization needed to facilitate a detailed assessment of remedial performance in DNAPL source areas, making it impossible to properly assess remedial performance and determine the limits of remedial effectiveness.

Long-term and detailed performance assessments using advanced tools within DNAPL source areas following bioaugmentation have, to the best of our knowledge, not been performed. Data collected during, or immediately after, active treatment while electron donor is still present and reductive dechlorination rates remain high, are typically not a good indication of remedial progress, as substantial rebound from DNAPL sources could occur as the reaction rates diminish. This lack of long-term performance assessment data has resulted in an insufficient understanding of many basic issues related to remedial implementation, design, and monitoring, both for the source area and the resultant downgradient plume. Key unknowns related to treatment effectiveness that require quantification include:

- Identification of the practical limits of treatment effectiveness (e.g., attainment of Maximum Contaminant Level (MCLs);
- Extent to which reductive dechlorination continues after active remediation;
- Extent to which remedial amendments migrate and treat the downgradient plume;
- Long-term geochemical and microbial community impacts; and
- Long-term impacts on contaminant flux.

The intensive DNAPL characterization and bioaugmentation field demonstration recently performed at Alameda Point in cooperation with the Strategic Environmental Research and Development Program (SERDP) Project ER-1613, which utilized many advanced tools for assessing a DNAPL source area in overburden, provided an excellent opportunity to perform a detailed long-term performance assessment following bioaugmentation. This site was highly characterized and monitored both before and during bioaugmentation and remains instrumented to provide high-resolution groundwater monitoring data. Performing such an assessment following bioaugmentation of a highly characterized DNAPL source area now provides the DoD with much needed information regarding the long-term effectiveness of bioaugmentation for DNAPL sources, and will facilitate improved design, implementation, monitoring, and management of DNAPL-impacted aquifers.

This demonstration was a collaborative effort between APTIM Federal Services, CDM Smith, and the University of Florida.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective of this project is to perform a long-term performance assessment at a site where bioaugmentation was used to treat a highly characterized overburden DNAPL source area. Specifically, the long-term treatment impacts with respect to groundwater quality, DNAPL mass, contaminant flux, reductive dechlorination, geochemistry, and microbial structure were assessed. Attainment of these objectives would provide for improved remedial selection, design, and management of DNAPL source areas, and ultimately will provide the information necessary to apply bioaugmentation more cost effectively. Our approach was to carry out a detailed and intensive performance assessment within a DNAPL source area that has been previously characterized using advanced tools and flux measurement techniques as part of SERDP Project ER-1613 and that has been carefully monitored during a recently completed bioaugmentation pilot test (performed by APTIM in conjunction with ER-1613). This assessment was initiated approximately two years following cessation of active treatment and employed multiple rounds of monitoring over the proposed 2-year demonstration period. The Plume 4-1 DNAPL source area at Alameda Point, CA, which is currently instrumented with several transects of multilevel samplers with highly discretized sampling intervals, was an ideal location for this intensive assessment to be performed and provided a unique opportunity to obtain a high-resolution, long-term, and detailed performance assessment following bioaugmentation.

1.3 REGULATORY DRIVERS

TCE, along with its reductive dechlorination daughter products *cis*-1,2-dichloroethene (DCE), and vinyl chloride (VC), are regulated in drinking and ground water by both the U.S. Environmental Protection Agency (USEPA) and the state of California. USEPA MCLs for TCE, DCE, and VC are 5, 70, and 2 µg/L, respectively.

Prior to bioaugmentation, TCE concentrations in the treatment areas were up to four orders of magnitude above both state and federal regulatory levels. It is significant to note that partial dechlorination of TCE, resulting in near-stoichiometric accumulation of either DCE and/or VC, would result in regulatory exceedances of these compounds as well.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

2.1.1 DNAPL Source Area Characterization Tools

To assess the effectiveness (or, potential effectiveness) of *in situ* remedial technologies in source areas, several tools have been developed and utilized to attain improved insight into both the contaminant distribution and the flow field. High resolution vertical multi-level sampling wells have proven to be very useful for understanding amendment and mass distribution in heterogeneous systems (Smith et al., 1991). Collection of soil or rock cores, with subsequent high-density sampling to determine contaminant concentrations relative to lithology, also has been used to assess the potential for rebound and overall remedial effectiveness (Chapman and Parker, 2005).

Recently developed innovative approaches include the use of Passive Flux Meters (PFMs), which allow for a high resolution vertical profile of both the hydraulic and contaminant fluxes (Annable et al., 2005). PFMs can be placed in existing wells and can be used to determine, with high resolution (as low as one inch), both the flow field and the vertical dissolved contaminant concentration profile. Other useful tools, such as Membrane Interface Probes (MIPs), are able to provide a semi-quantitative high resolution (cm-scale) vertical profile of contaminant concentration. MIPs are particularly useful for isolating depth intervals where DNAPL sources may be present. The Hydraulic Profiling Tool (HPT) provides a semi-quantitative high resolution (cm scale) vertical profile of the permeability and is useful for identifying high and low-flow zones within a source area or contaminant plume. HPT provides a much-improved assessment of the flow field that typically can be determined via visual observation of collected soil cores, and with much improved resolution that can be obtained using slug or pump tests. Partitioning Tracer Testing (PTT), which has been demonstrated in several DNAPL source areas, is useful for locating and quantifying DNAPL sources (Annable et al., 1998; Hartog et al., 2010). Compound Specific Isotope Analysis (CSIA) has become a useful tool for evaluating treatment effectiveness and can also be used to identify DNAPL sources (Morrill et al., 2009; Hunkeler et al., 2011).

2.1.2 Background- Bioaugmentation for DNAPL Sources

For chlorinated ethenes, bioaugmentation typically involves the subsurface injection of *Dehalococcoides* sp. (DHC), or closely related strains, that are capable of completely dechlorinating PCE and TCE. Electron donor (e.g., lactate, vegetable oil) and nutrients are also generally added to support DHC growth. Bioaugmentation has been shown to enhance the rate of PCE DNAPL dissolution in sand columns and flow cells by factors ranging from approximately 1.1 to 21 (Glover et al., 2007; Amos et al., 2008; Amos et al., 2009). Our laboratory studies with PCE in bedrock fractures also indicated that bioaugmentation was effective for treating DNAPL sources (Schaefer et al., 2010). Studies have noted, however, that the elevated dissolved contaminant concentration inhibits the complete dechlorination of PCE to ethene, and that this complete dechlorination likely will occur either downgradient of the DNAPL sources or after dissolved concentrations diminish to do depletion of the DNAPL sources (Adamson et al., 2003).

Field scale applications of bioaugmentation or biostimulation to treat PCE or TCE DNAPL in unconsolidated materials have been performed (USEPA, 2004; ITRC, 2007; Hood et al., 2008).

Results generally have been consistent with the laboratory studies described in the previous paragraph. These results suggest that biostimulation/bioaugmentation can be effective for treating DNAPL sources in unconsolidated materials.

2.2 TECHNOLOGY DEVELOPMENT

2.2.1 Long Term and Detailed Assessment of Bioaugmentation for Treatment of DNAPL Sources

DNAPL source area bioaugmentation studies generally have not undergone any long-term and detailed performance assessments, thus the limits of remedial effectiveness and the extent to which dechlorination continues with time are unknown. In addition, the studies described above provide little insight into the efficacy of bioaugmentation for treating DNAPL sources that reside in low (or, lower) permeability materials. The one exception is a bioaugmentation demonstration performed at the Cape Canaveral Air Force station (USEPA, 2004; Hood et al., 2008), where limited groundwater sampling was performed 22 months following cessation of remedial activities. No rebound in TCE was observed (TCE remained at <50 µg/L), and substantial decreases in DCE, VC, and ethene were observed following active treatment. However, these data provide only limited insight with regard to long-term performance assessment because (1) only limited biogeochemical information was collected, (2) groundwater sampling was performed in wells with 10-ft screens, thus high resolution sampling information was not collected, (3) treatment was targeted in a permeable sandy zone where flow was likely controlled by thin zones of coarse shell fragments, and (4) the most substantial levels of TCE DNAPL were in an underlying zone of lower permeability (described as a silty/clayey sand), which was not targeted by this study. In addition, many of the advanced tools used for assessing DNAPL source areas, including high resolution groundwater sampling, PFMs, MIP, and PTT were not used in either the DNAPL characterization (pre-treatment) or in the post-treatment evaluation. Thus, a detailed long-term performance assessment at a well-characterized overburden DNAPL source area following bioaugmentation has not, to the best of our knowledge, been reported in the literature.

2.2.2 DNAPL Source Area Assessment and Bioaugmentation: Alameda Point, CA

Our initial field efforts for Plume 4-1 at Alameda Point, CA (in cooperation with SERDP Project ER-1613) focused on evaluating DNAPL architecture and dissolved flux from a DNAPL source area in overburden materials. Additional details of this effort are discussed in the Final Report. A layout of the demonstration plot is shown in Figure 2.1.

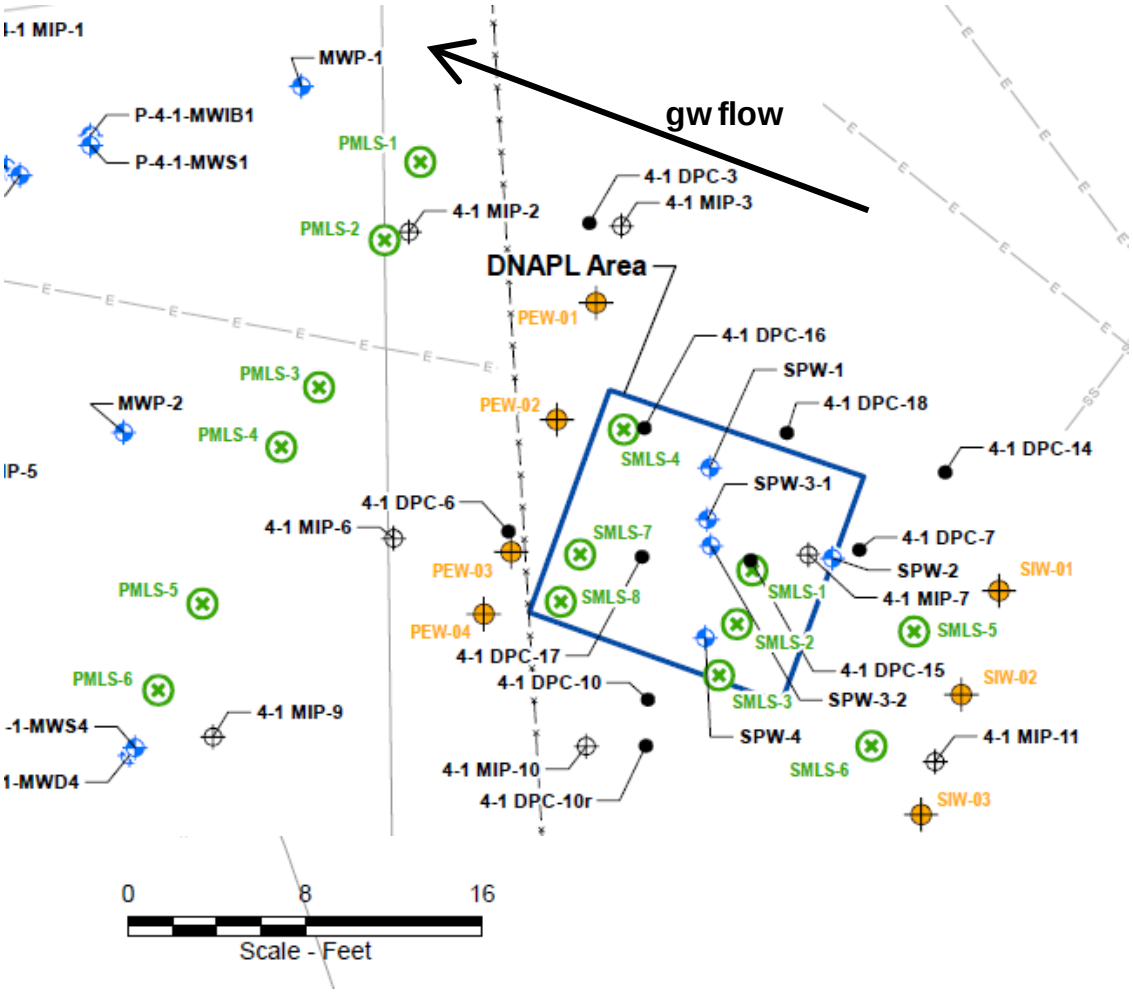

Figure 2.1. Site Layout for the DNAPL Source Area at Alameda Point

The blue box indicates the approximate location of the DNAPL sources. There are three transects of Source area Multi-Level Sampling (SMLS) wells, each well providing seven discrete sampling intervals. There is also one transect of Plume Multi-Level Sampling (PMLS) wells, each well also providing seven discrete sampling intervals, to monitor the downgradient plume. Source Injection Wells (SIW) and Plume Extraction Wells (PEW), with piping and other components connecting them, are used to facilitate tracer and dissolution testing.

PFM tests and PTTs were performed after the investigation and well installation described in the above paragraph was completed. PFM results showed that the TCE mass discharge emanating from the source area was 2.3 g/day. Partitioning tracer testing showed that the groundwater velocity through the lower permeability silty sand was approximately 3 to 4-times less than through the underlying sandy zone. In addition, substantial retardation of the hydrophobic tracers was observed in the silty sand zone where TCE DNAPL was present, consistent with the presence of residual TCE DNAPL in this zone. By comparison, much less hydrophobic tracer retardation was observed in the high permeability zone, suggesting DNAPL was absent or minimally present in this zone. The TCE DNAPL mass present in the high permeability zone prior to implementing bioaugmentation was approximately 15 kg, although another 58 to 150 kg of DNAPL may be present in the low permeability zone (Wang et al., 2014).

Following the DNAPL and flow field characterization, bioaugmentation, consisting of intermittent delivery of lactate and nutrients, was performed in the fall of 2012. Bioaugmentation was performed using APTIM's commercially-available bioaugmentation culture SDC-9, which contains DHC. Active remediation, during which groundwater was re-circulated and electron donor and nutrients were delivered, occurred for a period of nine weeks.

2.2.2.1 Questions Regarding Long-Term Treatment Effectiveness in the DNAPL Source Area

Several key questions remain regarding the long-term treatment effectiveness within the Plume 4-1 DNAPL source area. These key questions include:

- How effective was bioaugmentation for DNAPL in the lower permeability materials?
- What performance monitoring data during and immediately after active treatment are most useful for assessing long term behavior?
- What is the expected duration for which dechlorination will persist following active treatment, and how do they compare to rates observed during active treatment?
- What tools were most useful?
- What are the long-term geochemical and microbial impacts in a DNAPL source zone following bioaugmentation?
- What are the near downgradient impacts resulting from bioaugmentation in the source area?
- How did DNAPL mass removal and groundwater quality correlate, and what level of treatment (e.g., MCLs?) is attainable?

By obtaining an improved understanding of the fundamental processes that dictate the answers to these questions, the insight obtained from this highly characterized and instrumented site can be applied to other DNAPL source areas. To the best of our knowledge, such detailed characterization of a heterogeneous DNAPL source area before, during, and after bioaugmentation has not been performed.

2.2.3 Overall Approach for the Long-Term Performance Assessment

With the source area and downgradient MLS transects still in place, there is a unique opportunity to perform an intensive long-term post treatment evaluation to assess contaminant rebound, extended treatment due to exogenous biomass decay, contaminant flux, geochemical conditions, and microbial communities within and downgradient of the source area. Three rounds of groundwater monitoring from up to 106 monitoring locations will be performed during the proposed 2-year duration of this project, thereby allowing for observation in long term trends following treatment with respect to dechlorination rates, geochemistry, groundwater quality, and microbial community. This assessment will include monitoring at wells immediately downgradient of the treated DNAPL source area, which will be used to assess treatment, biogeochemical impacts, DHC migration, and microbial community shifts on the near downgradient plume long term.

In addition, using the existing well network, PFMs will be deployed to measure flux both within and downgradient of the source area. PFM data collected prior to bioaugmentation (as part of SERDP Project ER-1613) will be used to provide a direct measure of the contaminant flux reduction resulting from bioaugmentation treatment. PTT and soil sampling also will be performed and compared to pre-treatment results (Wang et al., 2014) to determine the extent of DNAPL mass removal, and to further evaluate the relationship between DNAPL mass removal, groundwater quality in high and low permeability zones, and contaminant flux.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.3.1 Advantages

The primary advantages of performing the proposed long-term assessment approach are as follows:

1. The long-term performance of bioaugmentation in a DNAPL source area will be determined for a highly characterized site;
2. Processes contributing to the long-term dechlorination of TCE will be investigated;
3. Long-term impacts on groundwater biogeochemistry will be quantified; and
4. The characterization activities most crucial for project success will be identified.

In addition, by performing this demonstration at a site that has undergone extensive characterization (Wang et al., 2014), with a high density of multi-level sampling wells, we anticipate that very detailed insight into bioaugmentation and DNAPL dissolution processes will be attained.

2.3.2 Limitations

As with all technologies and assessment approaches, there are also limitations with the proposed approach:

1. The assessment is being performed at a single site. Although this site is highly characterized and well-instrumented, which is expected to provide unique and useful results, it is only one site;
2. The rate of change on groundwater biogeochemical properties, as well as chlorinated ethene concentrations, may be slow relatively to the proposed duration of this project. Options for extending the sampling timeframe for the project may need to be considered; and
3. Accumulated biomass from the bioaugmentation may interfere with the proposed partitioning tracer test, which will be used to estimate DNAPL mass. A column test will be performed prior to the field tracer test to assess this potential complication. In addition, alternative methods of estimating DNAPL mass (e.g., soil core collection) will be performed as a means to estimate DNAPL mass.

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3.0 PERFORMANCE OBJECTIVES

Performance objectives are summarized in Table 3.1, and details are provided in Sections 3.1 through 3.4.

Table 3.1. Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Assess effectiveness of DNAPL mass removal in low permeability materials	Groundwater TCE levels, soil samples (pre and post treatment), and partitioning tracer data	Groundwater TCE concentrations <1% solubility, TCE soil concentrations <100 µg/kg, and no measurable retardation during partitioning tracer test	DNAPL was removed in part of the source area, but not all.
Assess the long-term dechlorination activity (biotic/abiotic) following active remediation	Measured daughter products (DCE, VC, ethene/ethane/acetylene, chloride) and *Dehalococcoides* levels	Daughter product generation greater than baseline levels	Enhanced reductive dechlorination is continuing at the site
Determine downgradient impacts	Volatile Organic Compound (VOC), reduced gas, and biogeochemical parameters at downgradient transect from the treatment area. Also, contaminant mass flux from the source area.	>20% reduction in VOC concentrations downgradient, or >50% reduction in mass flux emanating from the source area.	Plume monitoring locations indicate >50% decrease
Qualitative Performance Objectives			
Identify characterization and monitoring tools that were most critical for designing and assessing treatment	Assess information from tracer tests, discrete interval sampling, MIP and soil investigations, hydraulic profiling tool	Determine how collected data contributed to conceptual model and performance assessment	Discrete interval sampling, MIP, and HPT were highly useful

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4.0 SITE DESCRIPTION

4.1 SITE LOCATION AND HISTORY

The Plume 4-1 DNAPL source area at Alameda Point is located on the northwestern tip of Alameda Island, which is along the eastern margin of the San Francisco Bay and south of the City of Oakland, California. Alameda Point was created by filling sub tidal areas, natural tidelands, marshlands, and sloughs with dredge spoils from the surrounding San Francisco Bay, Seaplane Lagoon, and Oakland Inner Harbor. Alameda Point is a roughly rectangular area approximately two miles wide from east to west and one mile from north to south, occupying approximately 1,734 acres of land.

4.2 SITE GEOLOGY AND HYDROGEOLOGY

The stratigraphy beneath Plume 4-1 consists of two geologic units: the Merritt Sand Formation and artificial fill (Tetra Tech Environmental Management, Inc., 1999). The Merritt Sand Formation extends from roughly 10 to 70 feet below ground surface (bgs).

It is composed of an orange-brown, fine-grained, silty sand and a fine-grained clayey sand. The top of the Merritt Sand is composed of a dense, well-consolidated, clayey sand, between one and five feet thick and has a low hydraulic conductivity. Additionally, a contact zone divides the Merritt Sand into an upper eolian and a lower alluvial section. The contact zone between the eolian sand and alluvial sand sections ranges from 5 to 15 feet thick, consisting of a dense to well-consolidated clayey sand.

Overlying the Merritt Sand Formation is the artificial fill that extends from the surface down to 10 feet bgs. The artificial fill consists of a light to dark brown, fine-grained, silty sand with trace amounts of gravel and brick fragments. The fill is composed of dredge spoils from the San Francisco Bay and the Oakland Inner Harbor.

Groundwater at Plume 4-1 is first encountered between two and eight feet bgs within the artificial fill. Unlike areas to the west, there is no intervening layer of Bay Sediment between the artificial fill and Merritt Sand beneath Plume 4-1; therefore, the first water-bearing zone behaves as a single hydro geologic unit. The groundwater flow directions are affected by local recharge from precipitation, seasonal variation in groundwater elevations, and tidal influences. For Alameda Point, the groundwater has been found to generally flow from southeast to northwest.

4.3 CONTAMINANT SOURCE AND DISTRIBUTION

Historic groundwater data for Plume 4-1 suggested that a chlorinated ethene source was present, as shown in Figure 2.1. Based on measured TCE concentrations well in excess of 1% of the aqueous solubility, there was a strong potential for the presence of TCE DNAPL. Initial characterization activities were performed (beginning in 2010) to determine the approximate location and extent of the potential DNAPL source area. Installation of transect of multi-level sampling wells was performed, as well as performance of a partitioning tracer test. This work, described in Wang et al. (2014), provided a detailed analysis of the DNAPL mass and distribution.

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5.0 TEST DESIGN

The following subsections provide detailed descriptions of the system design and testing conducted to address the performance objectives described in Section 3.0.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

This project focused on performing intensive groundwater and soil monitoring following previous bioaugmentation treatment of a TCE DNAPL source area. Monitoring activities included the following:

- Three rounds of groundwater sampling (including several MLS wells) over a 2-year period. VOCs, geochemical parameters, CSIA, and microbial parameters were all included in this monitoring program.
- Soil cores were collected within the DNAPL source area to determine the extent to which DNAPL sources had been treated.
- PFMs were used to determine the change in TCE flux before and after bioaugmentation treatment (PFMs were previously deployed at the site, prior to implementing bioaugmentation).
- A partitioning tracer test was performed at the end of the study to provide an estimate of the DNAPL mass remaining. The DNAPL mass estimate was then compared to the DNAPL mass estimate and partitioning tracer results attained prior to bioaugmentation (Wang et al., 2014).

5.2 BASELINE CHARACTERIZATION ACTIVITIES

Extensive characterization of the Plume 4-1 source area at Alameda had previously been performed. This characterization, and the conceptual model developed for the site, are presented in Wang et al. (2014) and summarized in Section 2.2.2. Additional baseline characterization activities were not planned for this project. However, as described in subsequent sections, intensive sampling, monitoring, and characterization activities were planned using the existing monitoring network. These activities were used to assess the long-term impacts, with respect to the treatment of DNAPL sources and groundwater biogeochemistry, following bioaugmentation.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The demonstration area for the proposed long-term performance assessment was previously instrumented with MLS wells and injection/extraction wells. The tanks, piping, and pumps that were used for the initial partitioning tracer testing (which employed groundwater recirculation within the DNAPL source area) had been previously dismantled but were re-installed for this demonstration.

5.4 FIELD TESTING

The demonstration field activities included (1) groundwater sampling, (2) PFM measurements (which coincided with two of the three groundwater sampling events), (3) soil sampling, and (4) performance of a partitioning tracer test (the final field activity of this demonstration). Activities occurred between March 2015 and January 2017.

5.4.1 Groundwater Sampling

Three rounds of groundwater sampling were performed. The objective of the groundwater sampling was to assess the long-term impacts of the previously performed bioaugmentation treatment on groundwater quality and biogeochemistry. Monitoring locations upgradient, within and downgradient of the DNAPL source area were evaluated. All monitoring locations are presented on Figure 5.1.

As will be discussed in Section 5.5.4, a full set of 106 sample intervals were monitored during the first sampling event, with each of the following two sampling events containing fewer monitoring intervals based on the results of the previous events.

Groundwater sampling included a wide range of parameters at select locations. A summary of the parameters and monitoring locations included during each of the three groundwater sampling events are provided in Sections 5.5.4.1 through 5.5.4.3.

While some parameters (e.g., VOCs) were monitored at all sampled locations for each of the three monitoring events, other analyses (e.g., CSIA, microbial community) were performed at select locations. In general, determination of these select locations was based in part on the history of the monitoring location. Representative locations with both elevated (i.e., indicative of DNAPL) and low TCE concentrations are included, and locations showing both substantial and limited dechlorination during active remediation were selected. These select locations were also based on location: upgradient, downgradient, low permeability zone, and high permeability zone.

5.4.2 Flux Measurements using Passive Flux Meters

PFMs were used to determine the change in TCE flux before and after bioaugmentation treatment; comparing data collected upon completion of the first and third groundwater sampling events to PFM data collected prior to implementing bioaugmentation at this site (performed by APTIM in conjunction with SERDP project ER-1613). PFMs were installed at select locations following both the first and third groundwater sampling events. The locations for PFM installation included PEW-01 through Plume Extraction Well (PEW)-04, and MWP-1 and MWP-2.

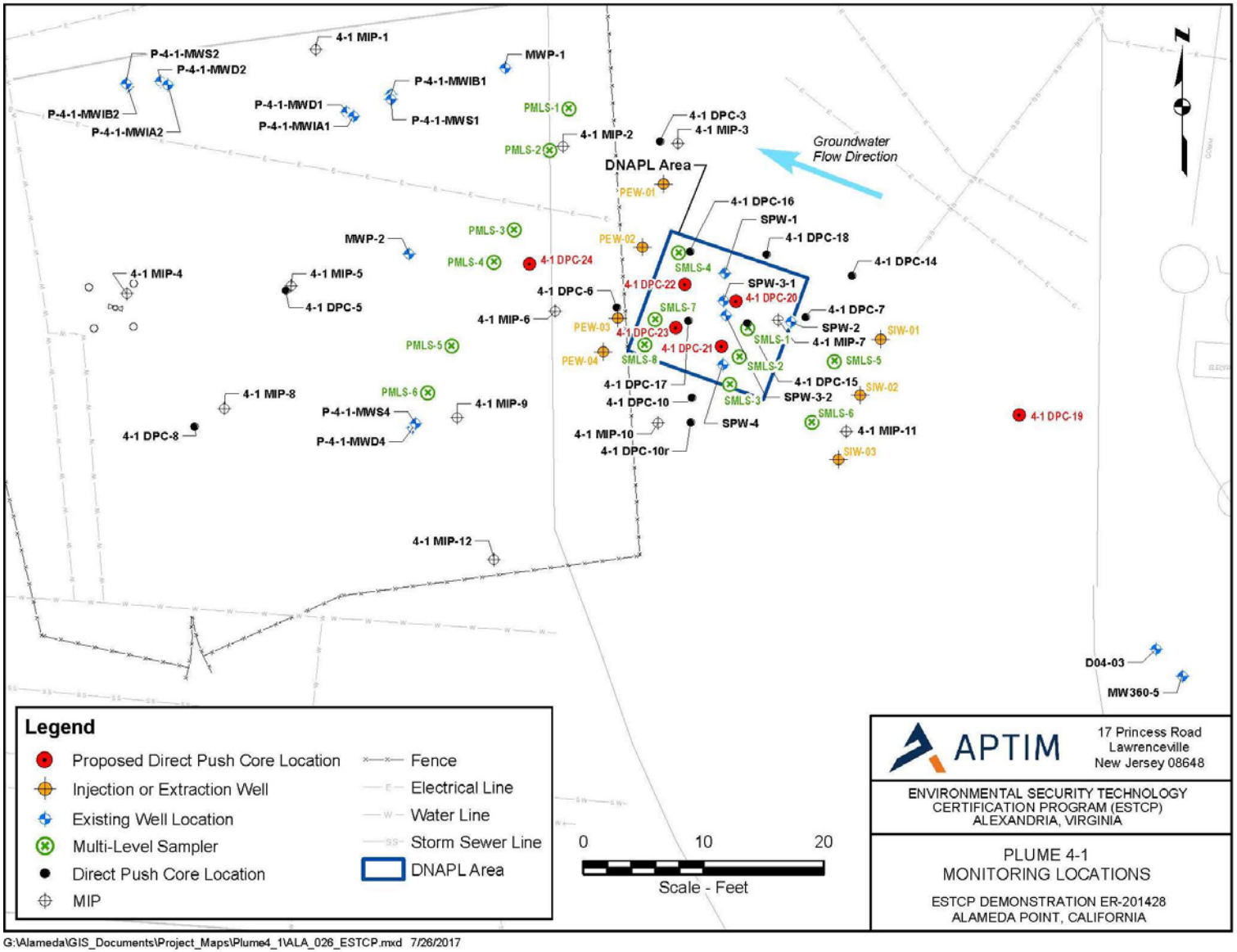

Figure 5.1. Plume 4-1 Monitoring Locations

5.4.3 Soil Investigation

One round of soil sampling was performed in the DNAPL source area on April 27 and 28, 2015. Soil core locations are shown in Figure 5.1.

5.4.4 Partitioning Tracer Test

A push-pull testing at SPW3-1 and SPW4 was conducted on December 5 through 8, 2016. Details of the push-pull testing are described in the Final Report.

5.5 SAMPLING METHODS

Groundwater and soil sampling was conducted to assess contaminant rebound, quantify the extent of any long-term dechlorination, and evaluate biogeochemical conditions.

5.5.1 Groundwater Sampling

Groundwater monitoring, extraction, and injection wells were sampled in accordance with the procedures described in the Final Report. The sampling method used was dependent on well construction with standard parameter measurements taken in conventional large diameter monitoring, extraction and injection wells. Modified sampling procedures were applied to MLS and small diameter conventional wells.

5.5.2 Decontamination

The portable bladder pumps were decontaminated before being inserted into each monitoring well. Sampling and measuring equipment were decontaminated prior to use.

5.5.3 Analytical and Sample Preservation for Groundwater Samples

The analytical methods and sample preservation used for the analyses that were part of this demonstration are summarized in the submitted Final Report.

5.5.4 Groundwater Sampling Locations and Frequency

A full set of 106 sample intervals were monitored during the first sampling event, with each of the following two sampling events containing fewer monitoring intervals based on the results of the previous events. The second groundwater sampling included the sampling of 66 monitoring intervals, based on the results from the first groundwater sampling event. The third groundwater sampling event included the sampling of 42 monitoring intervals, primarily based on the results from the first two groundwater sampling events.

5.5.5 Analytical and Sample Preservation for Soil Samples

The analytical methods and sample preservation used for the analyses that were part of this demonstration are summarized the Final Report.

5.5.6 Soil Sampling Locations and Frequency

As was discussed in Section 5.4.3, soils samples were collected at the six soil boring locations shown on Figure 5.1. The soil sampling event was conducted in the field on April 27 and 28, 2015.

5.6 SAMPLING RESULTS

5.6.1 Soil Core Results

Soil core results at each of the four source area locations (4-1 DPC-20 through 4-1 DPC-23, locations shown in Figure 5.1) showed that both TCE and DCE were observed at each location. However, only at location 4-1 DPC-20 were concentrations clearly indicative of residual TCE DNAPL present in the lower permeability material, indicating that TCE source remains in this portion of the source area. In contrast, in the vicinity of 4-1 DPC-23, substantial removal of DNAPL sources appears to have occurred following the dissolution and bioaugmentation testing.

5.6.2 Groundwater Monitoring Results

Tables containing all groundwater analytical results for the three sampling events performed during the demonstration are provided in the Final Report for this project.

5.6.2.1 Groundwater Biogeochemical Conditions

Groundwater monitoring results showed that Volatile Fatty Acids (VFAs) were below the analytical detection limit of 1 mg/L at all locations, indicating that the lactate and subsequent fermentation products present during active treatment were no longer present in the source area. Dissolved hydrogen levels also were below the analytical detection limit of 0.0084 µg/L.

Despite the absence of any measurable VFAs or dissolved hydrogen in the source area, other biogeochemical indicators suggest that conditions favorable to the biological reductive dechlorination of chlorinated ethenes persisted within the source area up to 3.7 years following active treatment. Comparison of methane, sulfate, and DHC levels measured 3.7 years after active treatment to those measured just prior to bioaugmentation suggest that biogeochemical impacts persist in the source area. The elevated methane levels suggest that methanogenic activity, especially in the low permeability materials, has been sustained 3.7 years following treatment using lactate as the electron donor. Previous studies (Sleep et al., 2005; Adamson and Newell, 2009) suggest that such persistence of reducing conditions in absence of amended electron donor is due to decay of endogenous bacteria that amassed during active treatment.

5.6.2.2 Groundwater Chlorinated Ethene and Ethene Concentrations

Results in this section focus on source area monitoring locations that were appreciably impacted with chlorinated solvents prior to bioaugmentation, and only the Plume Multi-Level Sampling (PMLS) wells that were in the core of the downgradient plume (the shallowest two intervals of PMLS 3 and 4). Groundwater chlorinated ethene and ethene results for Source Multi-Level Sampling (SMLS) locations screened within the lower permeability materials are shown in Figure 5.2. Consistent with the soil results, chlorinated ethene concentrations at SMLS 1-3 were elevated and consistent with the presence of nearby DNAPL sources.

SMLS locations in the adjacent intervals above, and approximately downgradient (SMLS 4 intervals) also show substantial rebound following bioaugmentation treatment; such rebound is not unexpected considering that nearby DNAPL sources persisted. In contrast, monitoring intervals at SMLS 7 showed an absence of contaminant rebound and/or continued decreases in VOC levels following bioaugmentation. This result also is consistent with the soil data which show an absence of DNAPL sources in the vicinity and upgradient of SMLS 7, thus the observed rebound appears to be related to the persistence of DNAPL sources.

Groundwater chlorinated ethene and ethene results for SMLS and extraction well locations screened within the higher permeability materials are shown in Figure 5.3. With respect to contaminant rebound, the trends for monitoring locations screened in the higher permeability materials are similar to those observed for those screened in the lower permeability materials, with locations near and downgradient of SMLS 1 showing rebound and/or contaminant concentrations similar to those observed prior to bioaugmentation. Monitoring locations not adjacent to or downgradient of SMLS 1 (SMLS 4 and PEW03) do not exhibit any measurable rebound and concentrations remain substantially lower than prior to bioaugmentation.

While the molar fraction of ethene compared to the other chlorinated ethenes present was small, both during and after bioaugmentation, the molar fraction of ethene remained 1 to 2 orders of magnitude greater than baseline (prior to bioaugmentation) at most monitoring locations. Thus, the complete reductive dechlorination of the chlorinated ethenes continued for 3.7 years following active treatment, although the typical molar fraction of ethene suggested that only 2 to 30% of the chlorinated ethene mass was being fully dechlorinated within the source area by the end of the rebound monitoring period. To verify that these ethene levels were due to ongoing generation, rather than slow release from the source area due to generation during active treatment only, groundwater in the three injection wells (Figure 5.1) was monitored. The injection wells were screened similarly to the extraction wells but located immediately upgradient of the source area.

The injection wells showed a substantial (>75%) loss of permeability presumably due to biofouling, as noted during the final stage of active treatment and during draw-down testing performed during this current study. While chlorinated ethene levels in the injection wells were all less than 1 µg/L in the 2 to 3.7 years following active treatment, strongly reducing conditions (as evidenced by sulfate reduction and elevated methane levels) persisted. However, ethene was below the analytical detection limit of 5 µg/L in all three injection wells, which was substantially less than the ~250 µg/L observed at the end of the active remediation phase. Thus, in the absence of chlorinated ethene sources and limited groundwater flow, ethene did not persist in the source area, thereby confirming that the ethene observed in the source area monitoring locations (Figure 5.1) likely was due to ongoing reductive dechlorination.

Potential abiotic dechlorination products acetylene and propane (He et al., 2015; Schaefer et al., 2015) were not detected in any of the groundwater samples.

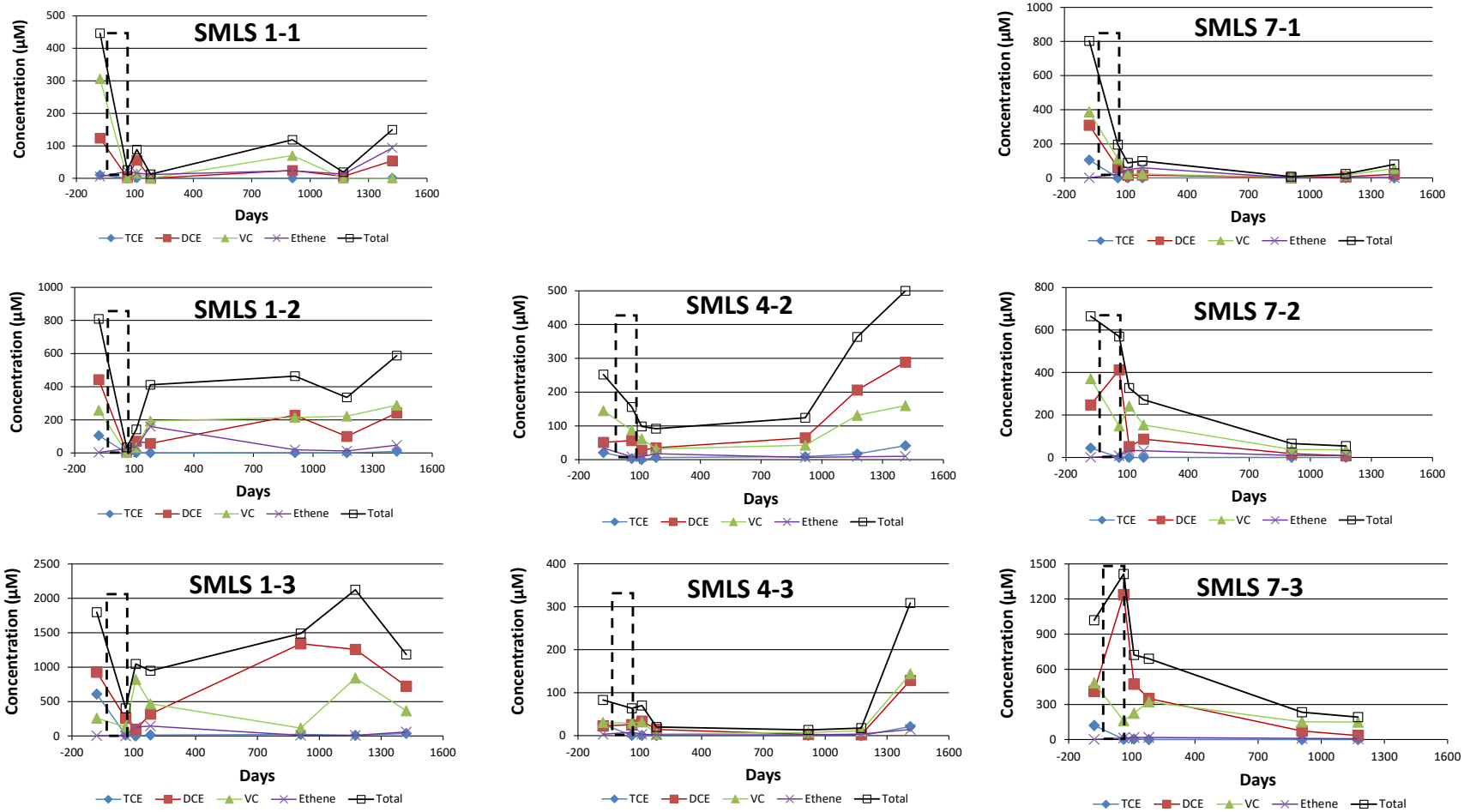

Figure 5.2. Groundwater Chlorinated Ethene and Ethene Results for SMLS Locations Screened within the Lower Permeability Materials

The dashed boxes represent the time intervals where active bioremediation occurred; the high density of data collected during active treatment was omitted for clarity.

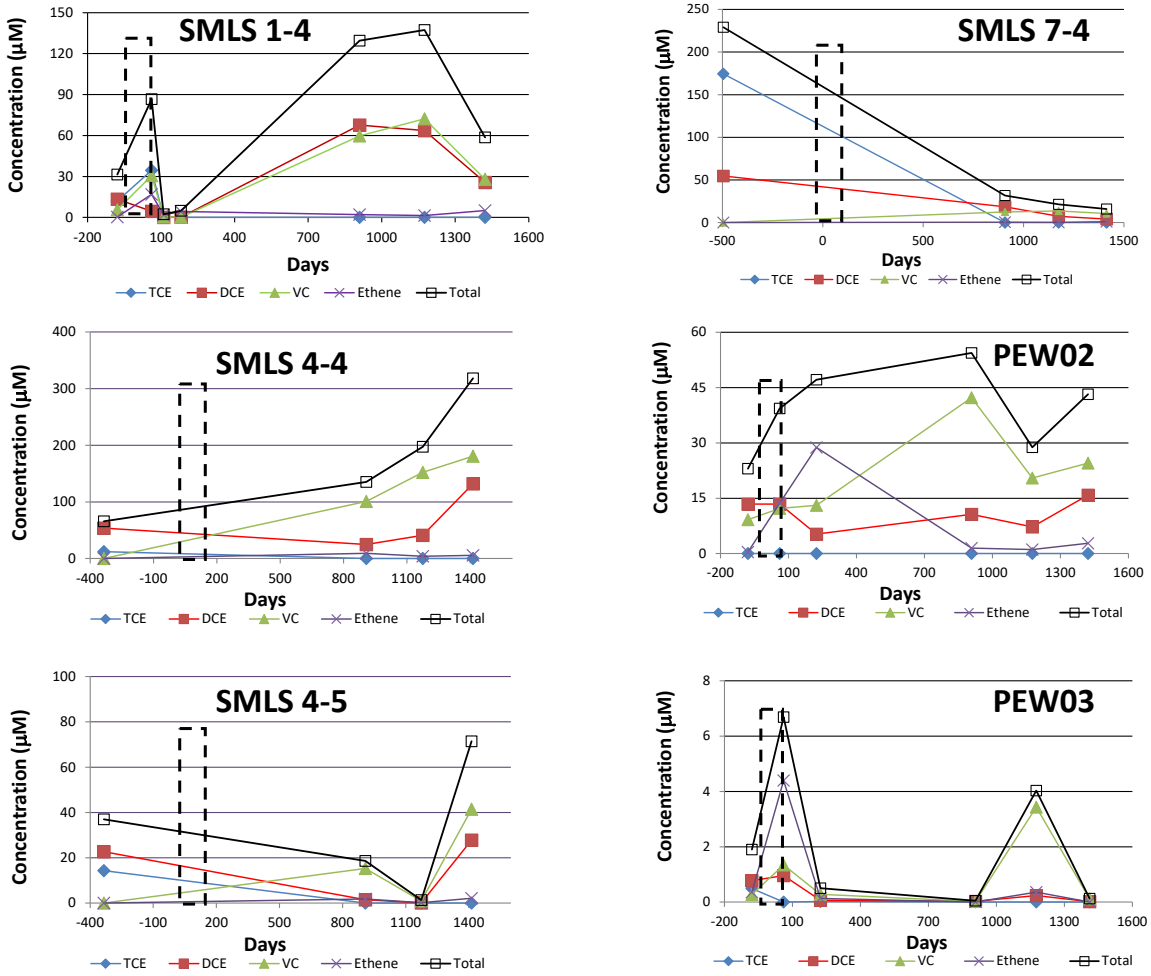

Figure 5.3. Groundwater Chlorinated Ethene and Ethene Results for SMLS and Extraction Well Locations Screened within the Higher Permeability Materials

The dashed boxes represent the time intervals where active bioremediation occurred; the high density of data collected during active treatment was omitted for clarity.

5.6.2.3 CSIA Assessment

To assess the extent to which complete dechlorination of TCE is occurring at the site, the net carbon isotopic enrichment for TCE, DCE, and VC is calculated as follows:

$$\delta^{13}C = (x_{TCE}\,\delta^{13}C_{TCE} + x_{DCE}\,\delta^{13}C_{DCE} + x_{VC}\,\delta^{13}C_{VC}) \qquad (1)$$

where $\delta^{13}C$ is the molar weighted isotopic carbon enrichment, x_i is the mole fraction of compound i, and δ^{13} is the ^{13}C isotopic level in either the TCE, DCE, or VC (‰). Figure 5.4(A) shows $\delta^{13}C$ as a function of total chlorinated ethene molar concentration emanating from the DNAPL sources in the lower permeability materials; Figure 5.4(B) shows the corresponding values for the underlying higher permeability material. In the higher permeability materials, chlorinated ethene enrichment and attenuation are clearly observed. The enrichment factor of - 1.87 observed in the higher permeability materials is less than enrichment factors observed for reductive chlorinated ethene biodegradation

(Bloom et al., 2000). The relative absence of enrichment and attenuation observed in the lower permeability materials likely is due to the fact that treated water has not yet fully migrated through the downgradient (PMLS) monitoring locations, so isotopic levels do not yet reflect changes due to bioremediation.

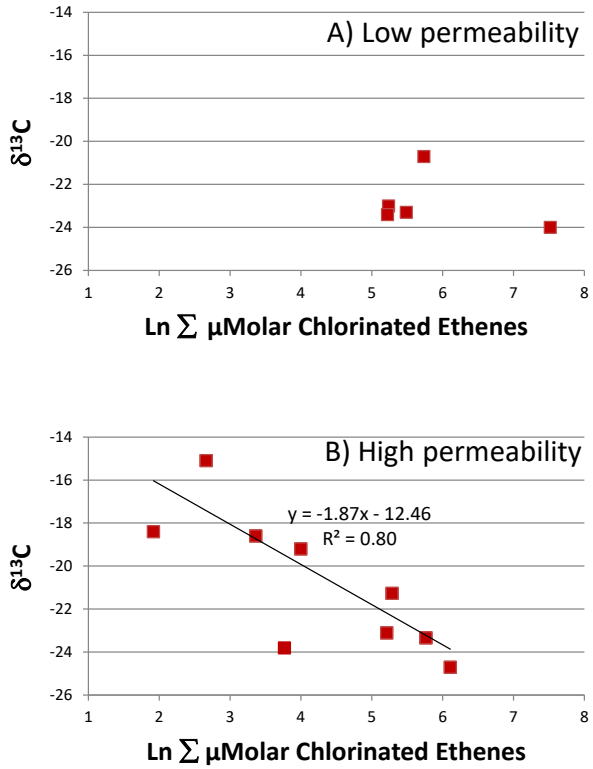

Figure 5.4. Carbon Isotopic Enrichment Measured as a Function of the Total Chlorinated Ethene Concentration in both the Low (top) and High (bottom) Permeability Materials Emanating from the Existing DNAPL Sources through the PMLS Wells

The visibly outlying data point in the bottom figure (3.8 on the x-axis) was not used in the linear regression.

The isotopic and concentration data in Figure 5.4(B) suggest that substantial complete dechlorination of TCE, DCE, and VC occurred, which is in apparent contradiction to the ethene data that showed ethene (the presumed complete dechlorination transformation product) represented only a small fraction of the molar chlorinated ethenes + ethene. Furthermore, the data in Figure 5.4(B) suggest that the complete dechlorination of chlorinated ethenes continued between the source area and the PMLS wells, despite the absence of any measurable ethene accumulation in this flow interval. While CSIA analysis was not performed on ethene, the low levels of ethene present likely would not have resolved the isotopic balance, as the ethene δ^{13} C required to complete the isotopic mass balance would be (based on inclusion of ethene in Eq. 1) approximately -400‰, which is not plausible. This apparent discrepancy suggests that ethene was further transformed, and/or that vinyl chloride transformation proceeded without formation of ethene. Only trace (approximately 10-times less than ethene) ethane was generated, so continued reduction of ethene to ethane cannot explain this discrepancy.

Previous studies have shown that trace levels of oxygen can result in the aerobic transformation of vinyl chloride and ethene (Abe et al., 2009; Gossett, 2010), with enrichment factors that are more in-line with (but still greater than) those observed in Figure 5.4(B). Others have shown that anaerobic oxidation of ethene can occur via sulfate as an electron acceptor (Fullerton et al., 2013). Either, or both, of these oxidative processes readily explains the observed chlorinated ethene fractionation in absence of appreciable stoichiometric quantities of ethene or ethane.

The CSIA data is used to estimate a first-order complete dechlorination rate constant (k), based on the overall dechlorination of the chlorinated ethenes, using the following expression (ITRC, 2013):

$$k = \frac{v(\delta^{13}C_0 - \delta^{13}C)}{\epsilon d} \quad (2)$$

where $\delta^{13}C_0$ refers to the initial (upgradient DNAPL source) isotopic enrichment (Eq. 1), v is the ambient superficial velocity through the higher permeability material (0.013 m/day), ε is the enrichment factor (slope is Figure 5.4(B)) and d is the distance (17.7 ft from the DNAPL source to the PMLS wells). For evaluation over this distance, a first order overall dechlorination rate constant of 0.01 day^{-1} is calculated. Assuming this rate constant has been maintained since the end of active treatment, and assuming a constant chlorinated ethene concentration (persistent DNAPL) near SMLS 1-3 of 1,600 µM, chlorinated ethene soil concentrations near SMLS 1-3 would have decreased by approximately 500 mg/kg since the end of active bioremediation. This decrease represents approximately 25% of the DNAPL levels currently near SMLS 1-3 and soil boring location DPC-20 and suggests that biotic dechlorination remains a significant attenuation mechanism for 3.7 years after active bioremediation.

5.6.3 Passive Flux Meters

The PFM results indicate that dissolved contaminant concentrations emanating from the source area have not been substantially reduced. These results are consistent with the groundwater data presented in Section 5.6.2.2. It is important to note that the molar flux at PEW02 is much greater than at the other three extractions wells, so the PFM data primarily reflect results at PEW02, which is downgradient of persistent DNAPL sources.

5.6.4 Push-Pull Partitioning Tracer Tests

While partitioning tracers were unable to identify the presence of DNAPL, application of the Equilibrium Stream Tube (EST) model proved useful for identifying DANPL sources. To assess the presence of DNAPL, the EST model was used to determine if DNAPL sources were present by comparing the recovery of TCE/DCE (after injecting VOC-free water) to that of bromide. This modeling showed that DNAPL sources in the immediate vicinity of SPW-4 were not present. However, application of the EST model to SPW-3-1 (where SPW-3-1 is in a region where, based on the soil and groundwater data, DNAPL sources are likely present) indicated that DNAPL source were located in the vicinity of this well. The DNAPL volume in the tested volume surrounding SPW-3-1 estimated by the EST model was 2.9 L, which is less than 0.1% of the interrogated pore volume during the push-pull test. Such low levels could not be identified using partition tracers but were identifiable by comparing the bromide and TCE/DCE recoveries and by applying the EST model. Results from both the push-pull test, soil core data, and groundwater data are qualitatively consistent.

6.0 PERFORMANCE ASSESSMENT

6.1 ASSESS EFFECTIVENESS OF DNAPL REMOVAL IN LOWER PERMEABILITY MATERIALS

As discussed in detail in Sections 5.6.1 and 5.6.2.2, DNAPL removal in the lower permeability material likely occurred in one portion of the site (near SMLS 7) but persisted in another portion of the site (near SMLS 1 and SPW3-1). The push-pull partitioning tracer testing performed at SPW3-1 also confirmed the presence of DNAPL. Thus, the combination of discrete monitoring intervals, soil sampling, and push-pull partitioning tracer testing served as useful tools for assessing treatment of DNAPL sources.

6.2 ASSESS LONG-TERM DECHLORINATION ACTIVITY

The complete dechlorination of TCE continued within the demonstration area based on groundwater monitoring data collected up to 3.7 years after cessation of active bioremediation. Continued dechlorination was evidenced by elevated (relative to pre-bioaugmentation) levels of ethene and based on the net carbon isotopic enrichment observed for the chlorinated ethenes as a function of concentration (discussed in Section 5.6.2.2). Thus, both ethene and CSIA data were critical for this assessment.

6.3 DETERMINE DOWNGRADIENT IMPACTS

Monitoring performed at the downgradient PMLS wells (Figure 5.1) verified that chlorinated ethene concentrations decreased since initiation of active bioremediation and have continued to decrease during the post-treatment monitoring period. This decrease likely is due to both mass removal in the source area, and the continued biotic dechlorination that is occurring.

6.4 IDENTIFY THE CHARACTERIZATION AND MONITORING TOOLS THAT WERE MOST CRITICAL FOR PERFORMANCE ASSESSMENT

The ability to monitor discretely in both the lower and higher permeability materials provided key insight with respect to the site conceptual model, and on the nature of the residual DNAPL sources. In addition, the use of carbon isotopic analysis for the chlorinated ethenes was crucial for both verifying and quantifying the extent of dechlorination occurring at the site. Finally, use of both source area and nearby downgradient monitoring locations provided an opportunity to assess the rate of complete dechlorination occurring downgradient of the source area, and the overall impact on groundwater quality.

6.5 ASSESS OVERALL PERFORMANCE WITH RESPECT TO APPLICABILITY TO OTHER DNAPL SOURCE AREAS

An overview of the critical findings of this long-term monitoring study that can be applied to other DNAPL source areas is provided in Appendix B. This information is expected to provide guidance on how long-term monitoring should be applied, and how to utilize long-term dechlorination activity as part of the site remedy.

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7.0 COST ASSESSMENT

7.1 COST MODEL

To evaluate the cost of a potential full-scale bioremediation assessment program, costs associated with various aspects of the demonstration were tracked throughout the course of the project. Table 7.1 summarizes the various cost elements and total cost of the demonstration project. The costs have been grouped by categories as recommended in the Federal Remediation Technologies Roundtable (FRTR) Guide to Documenting and Managing Cost and Performance Information for Remediation Projects (FRTR, 1998). Many of the costs shown on this table are a product of the innovative and technology validation aspects of this project and would not be applicable to a typical site application. Therefore, a separate "discounted costs" column that excludes or appropriately discounts these costs has been included in Table 7.1 to provide a cost estimate for implementing this assessment approach at the same scale as the demonstration (i.e., pilot scale).

Costs associated with the long-term performance assessment following bioaugmentation demonstration were tracked from September 2014 to December 2017. The total cost of the demonstration was $649,977, which included $97,277 in capital costs, $338,125 in Operation and Maintenance (O&M) costs, and $214,576 in demonstration-specific costs (cost related to ESTCP requirements, site selection and characterization).

7.1.1 Capital Costs

Capital costs (primarily system design, fabrication, and installation) accounted for $97,277 (or 15 percent) of the total demonstration costs. As indicated in Table 7.1, these costs exceed what would be expected during a typical remediation project due partially to the ability to stream-line the system design and fabrication process for a more typical project of this scale.

7.1.2 O&M Costs

O&M costs accounted for $376,440 (or 58 percent) of the total demonstration cost. These costs consisted primarily of groundwater monitoring and soil sampling (including labor, materials, and analytical), PFM testing, the PTT, and data management and evaluation costs. Groundwater and soil sampling costs were $117,034, or 18 percent (%) of total demonstration costs, while the PFM testing costs were $28,338 (4.4% of total demonstration costs) and PTT costs were $35,224 (5.4% of total demonstration costs). Analytical costs during the demonstration totaled $120,545, or 18.5% of the total demonstration costs, due to the extensive performance monitoring activities conducted to effectively validate this technical approach.

Table 7.1. Demonstration Cost Components

Cost Element	Details	Tracked Demonstration Costs	Discounted Costs[1]
CAPITAL COSTS			
System Design	Labor	$12,480	$8,000
	Subcontractor (CDM Smith)	$3,725	$0
System Fabrication, Installation, and Demobilization	Labor & Travel	$52,459	$40,000
	Equipment & Materials	$28,613	$20,000
	Subtotal	**$97,277**	**$68,000**
OPERATION AND MAINTENANCE COSTS			
Groundwater and Soil Sampling	Labor	$73,948	$55,000
	Materials & Equipment	$25,300	$20,000
	Travel	$1,068	$0
	Subcontractor (CDM Smith)	$11,174	$0
	Subcontractor (driller)	$3,940	$0
	Subcontractor (utility clearance)	$1,605	$0
Passive Flux Meter Testing	Labor	$9,630	$5,000
	Subcontractor (Univ. of Florida)	$18,708	$15,000
Partitioning Tracer Testing	Labor	$9,630	$17,000
	Materials & Equipment	$3,179	$3,000
	Subcontractor (CDM Smith)	$7,449	$0
	Subcontractor (Univ. of Florida)	$14,966	$0
Analytical	In-House Labor	$47,180	$0
	Outside Labs	$73,366	$50,000
Data Management & Evaluation and Quarterly Reporting	Labor	$34,240	$15,000
	Subcontractor (CDM Smith)	$22,349	$0
	Subcontractor (Univ. of Florida)	$18,709	$0
	Subtotal	**$376,440**	**$180,000**
OTHER TECHNOLOGY-SPECIFIC COSTS			
Site Selection	Labor	$12,840	$0
Demonstration Plan/Work Plan	Labor	$26,750	$15,000
	Subcontractor (CDM Smith)	$7,449	$0
	Subcontractor (Univ. of Florida)	$3,742	$0
IPR Meetings	Labor	$3,210	$0
	Subcontractor (CDM Smith)	$3,726	$0
Project Management (financial/administrative)	Labor	$34,996	$15,000
Technology Transfer (conference and meeting presentations, published papers)	Labor	$5,350	$0
	Travel	$3,398	$0
	Subcontractor (CDM Smith)	$3,742	$0
	Subcontractor (Univ. of Florida)	$3,742	$0
Final Report and Final Cost and Perfromance Report	Labor	$37,450	$20,000
	Subcontractor (CDM Smith)	$14,899	$0
	Subcontractor (Univ. of Florida)	$14,966	$0
	Subtotal	**$176,260**	**$50,000**
	TOTAL COSTS	**$649,977**	**$298,000**

Notes:

[1]Discounted costs are defined as estimated costs to implement this technology at the same scale as the demonstration. These costs do not include the technology validation apects of this ESTCP demonstrations, such as site selection, treatability studies, ESTCP technical transfer requirements, ESTCP demonstration reporting and meeting (IPR) requirements, and preparation of technical and cost and performance reports.

7.1.3 Demonstration-Specific Costs

Other demonstration-specific costs (a portion of which are not expected to be incurred during non-research-oriented remediation projects for the most part) accounted for $176,260, or 27% of the total demonstration cost. These costs included site selection, preparation of the extensive technical demonstration plan, ESTCP technical transfer requirements (including presenting at technical conferences and publishing manuscripts), ESTCP demonstration reporting and meeting (IPR) requirements, preparation of extensive final technical and cost and performance reports, and financial and administrative project management tasks associated with required government cost reporting and billing.

7.2 COST DRIVERS

7.2.1 General Considerations

The expected cost drivers for the long-term performance assessment following bioaugmentation program, and those that will determine the cost/selection of this assessment technology include the following:

- Depth of the target contaminant zone below ground surface;
- Width, length, and thickness of the target contaminant zone;
- Aquifer lithology and hydrogeology;
- Monitoring well field density and the need to install additional monitoring points;
- Number of sample intervals and associated analytical costs; and
- PTT system O&M costs.

7.2.2 Competing Treatment Technologies

As this long-term performance assessment following bioaugmentation program is not a remediation technology, an assessment versus other treatment technologies is not applicable. Thus, no additional information is provided in this section of the report.

7.3 COST ANALYSIS

Though performing a thorough cost analysis of various competing technologies is not applicable for this demonstration, this section presents a cost estimate to implement a “typical” post-remediation performance assessment, and then quantifies the incremental cost associated with “up-grading” to the long-term performance assessment following bioaugmentation program at a typical site in which bioaugmentation had been applied in a source area.

7.3.1 Base Cost Template

The base case presented in Krug et al. (2009) is modified here as a template for the cost analysis of the assessment program. The base case presents a situation where a shallow, unconfined overburden aquifer is contaminated with residual TCE DNAPL in the source area.

The TCE source area extends to 30 feet bgs (saturated thickness is 20 feet), and is 45 feet long and 30 feet wide, perpendicular to groundwater flow (Figure 7.1). Figure 7.1 shows that eight monitoring wells were installed previously at the site during the site characterization phase and were sampled prior to and during the previously executed bioaugmentation activities. The site characteristics of the specific base case to be used to generate the cost estimate (Section 7.3.2), including aquifer characteristics, well points, and design parameters, are summarized in Table 7.2.

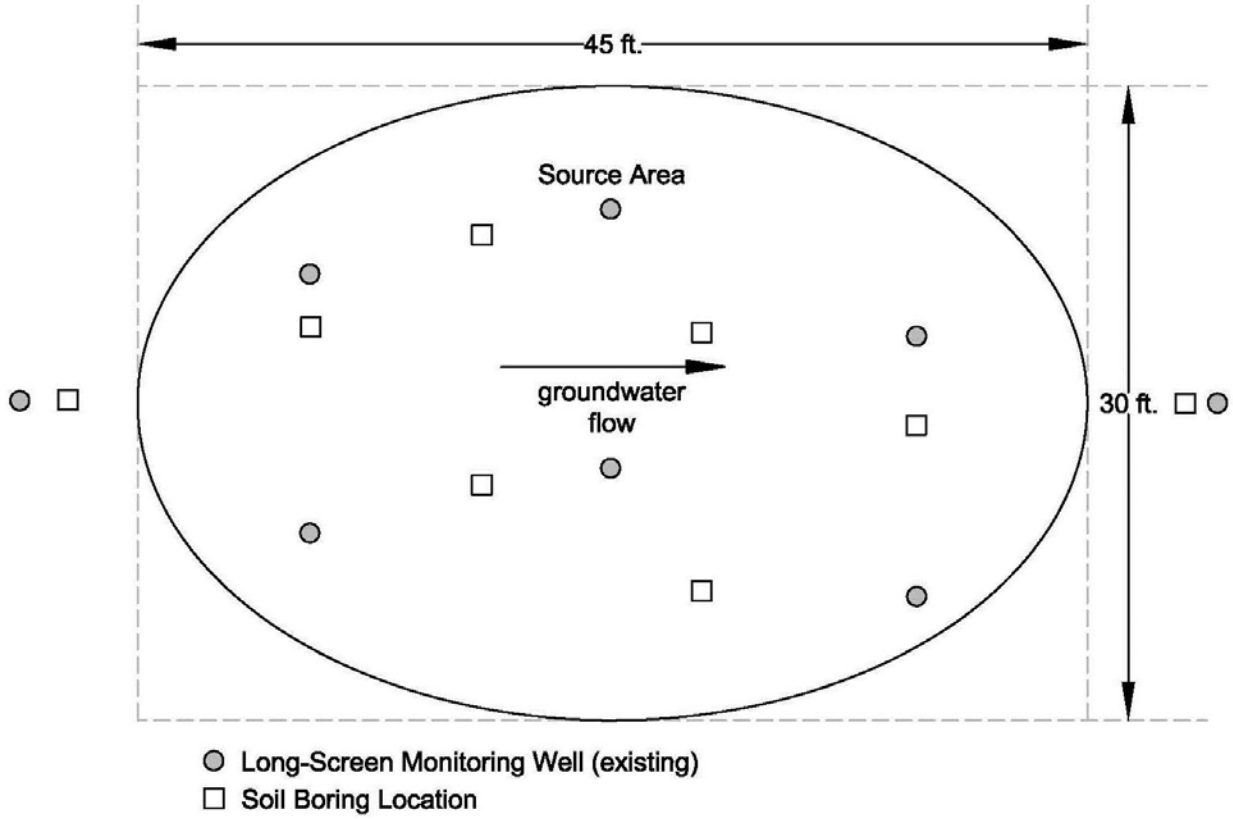

Figure 7.1. Base Plume Characteristics

The following subsection (Section 7.3.2) provides a cost estimate for the incremental cost of "up-grading" from a "typical" post-remediation monitoring program to the long-term performance assessment (similar to what was implemented for this ESTCP demonstration project) following bioaugmentation for the base case. The cost estimate provides insight into the incremental capital and O&M costs to better identify cost drivers for the more technical assessment approach. This will lead to an improved understanding of subsurface conditions, including a more precise picture of contaminant distribution, ultimately leading to potentially substantial remediation cost savings as the project progresses, as subsequent remedial efforts can focus on discrete areas. A second cost estimate is also included in Section 7.3.2, estimating a cost to perform the long-term performance assessment at a source area with twice the treatment area/volume, providing a comparison of the cost per unit volume for the two different sized source areas, showing economies of scale with the larger source area assessment.

Total incremental cost to implement the demonstrated long-term assessment, beyond the cost of the "typical" post-remediation monitoring, was calculated. Net Present Value (NPV) of future costs was not calculated, as the assessment approach is short-term, with no longer term monitoring costs. Specifically excluded from consideration are the costs of pre-remediation site characterization activities, as well as implementation of the bioaugmentation remedy, assuming the costs for these activities would have already been born by the project site prior to implementation of the remedial monitoring approach.

Table 7.2. Summary of Base Case Site Characteristics and Design Parameters

Design Parameter	Units	Assessment Approach Alternative	
		"Typical" Post-Remediation Performance Assessment following Bioaugmentation	Demonstrated Long-Term Performance Assessment following Bioaugmentation
Width of Source Zone Assessment Area	feet	30	30
Length of Source Zone Assessment Area	feet	45	45
Area of Source Zone Assessment Area	square feet	1,350	1,350
Upper Depth of Source Zone Assessment Area	feet	10	10
Lower Depth of Source Zone Assessment Area	feet	30	30
Volume of Source Zone Assessment Area	cubic yards	1,000	1000
Number of Long-Screen Monitoring Wells	each	8	8
Number of Source MLS Monitoring Wells	each	0	3
Number of Plume MLS Monitoring Wells	each	0	1
Number of Sample Intervals per MLS Well	each	0	4
Total Number of Groundwater Monitoring Intervals	each	8	24
Total Number of Soil Boring Locations	each	8	8

7.3.2 Long-Term Performance Assessment following Bioaugmentation Program

The demonstrated long-term performance assessment following bioaugmentation program for the base case assumes that the project site will utilize existing and install additional wells (as shown on Figure 7.2), including three source area MLS wells and one plume MLS well. The existing upgradient and downgradient long-screen monitoring wells, as well as the source area long-screen monitoring wells, will remain as monitoring points for the long-term performance assessment program. One groundwater monitoring event would be conducted. Eight soil borings (one upgradient of the source area, six in the source area, and one downgradient of the source area) would be advanced at the locations shown on Figure 7.2 (note that these soil borings would be advanced during the "typical" post-remediation treatment approach, so no incremental cost will be incurred for this activity.

Upon completion of the groundwater monitoring event, push-pull tracer testing would be performed at six well locations, consisting of both long-screened wells and MLS well intervals. Groundwater will be used to mix the tracer solution to be injected (push) and the extracted water (pull) would be collected for off-site disposal.

As summarized in Table 7.3, the incremental estimated total cost to implement this approach beyond the "typical" approach over three years for the base case site is $51,160. A more detailed breakdown of the costs is included in the expanded table presented in Appendix E. The capital cost including the installation of source and plume MLS wells is approximately $24,800. The O&M costs of conducting the push-pull testing is estimated to be $15,420, while the cost of performing the groundwater sampling event (including sampling crew labor and laboratory analytical costs for analysis of VOCs, anions, dissolved metals, volatile fatty acids, and CSIA) is estimated to be $10,940. Based on a total assessment zone volume of 1,000 cubic yards (yd^3), the unit volume cost to implement this "upgraded" assessment is $51/$yd^3$.

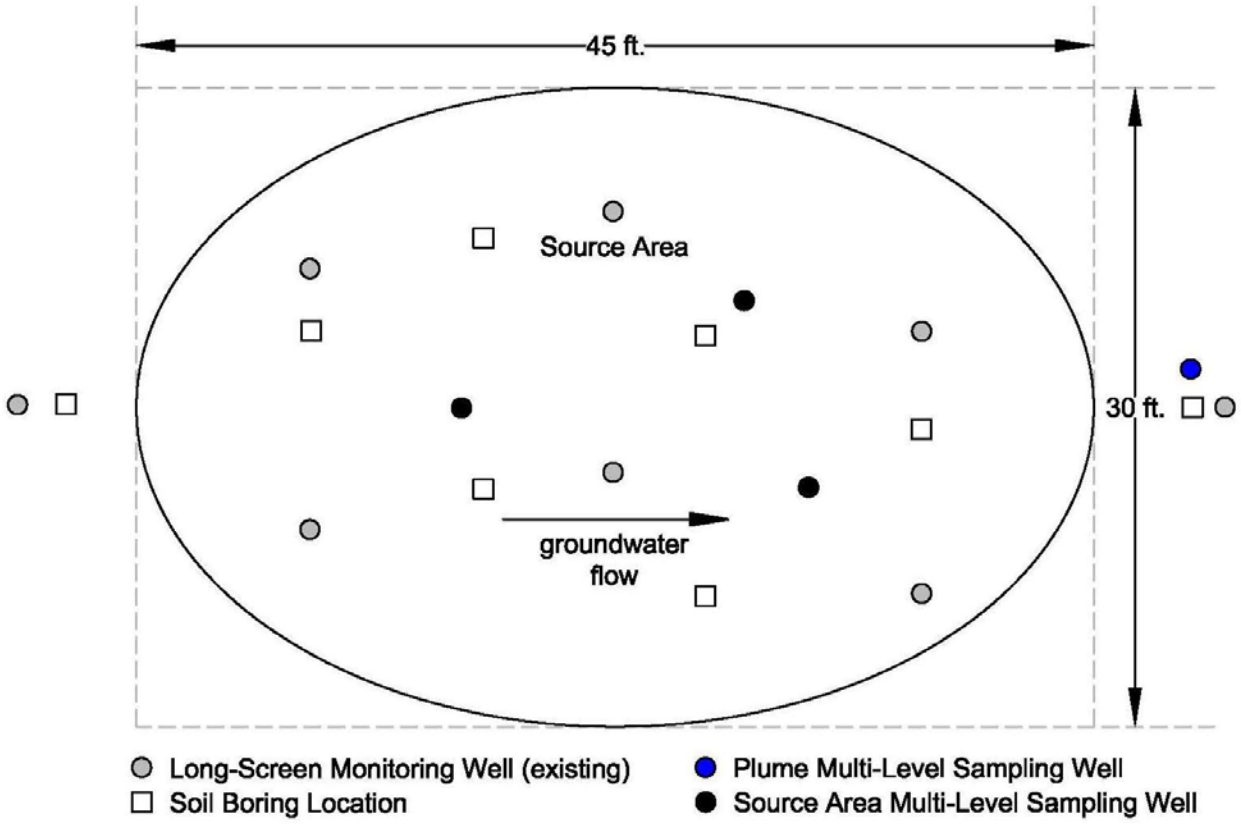

Figure 7.2. Long-Term Performance Assessment following Bioaugmentation

Table 7.3. Incremental Cost Estimate to "Up-Grade" to the Demonstrated Long-Term Performance Assessment following Bioaugmentation for Base Case

Capital Costs			***$24,800***
Well Installation			
	Mobilization	$3,000	
	Oversight Labor	$4,800	
	Subcontract Driller	$12,000	
	Subcontract Surveyor	$2,000	
	Materials/Consumables	$1,000	
	Utilities/Fuel	$500	
	Waste Disposal	$1,500	
Push-Pull Tracer Testing			***$15,420***
	Labor (Field Testing)	$7,680	
	Labor (Analytical)	$3,060	
	Labor (Data Management)	$680	
	Equipment/Parts	$1,000	
	Materials/Consumables	$1,000	
	Utilities/Fuel	$500	
	Waste Disposal	$1,500	
Groundwater Monitoring Costs			***$10,940***
	Labor (Sample Crew)	$3,200	
	Analytical	$7,540	
	Sampling Equipment	$200	
		TOTAL	***$51,160***

7.3.2.1 Assessment Size Implication on Unit Volume Cost

A second cost estimate was also generated for the performance of the long-term performance assessment at a source area with twice the treatment area/volume, to provide a comparison of the cost per unit volume for the two different sized source areas. Table 7.4 and associated Figure 7.3 present a case where the treatment volume has been doubled to 2,000 yd^3. In this case, two additional source area MLS wells were added.

Table 7.4. Summary of Expanded Zone Site Characteristics and Design Parameters

Design Parameter	Units	Demonstrated Long-Term Performance Assessment following Bioaugmentation (Assessment Volume = 2,000 yd^3)
Width of Source Zone Assessment Area	feet	45
Length of Source Zone Assessment Area	feet	60
Area of Source Zone Assessment Area	square feet	2,700
Upper Depth of Source Zone Assessment Area	feet	10
Lower Depth of Source Zone Assessment Area	feet	30
Volume of Source Zone Assessment Area	cubic yards	2,000
Number of Long-Screen Monitoring Wells	each	8
Number of Source MLS Monitoring Wells	each	5
Number of Plume MLS Monitoring Wells	each	1
Number of Sample Intervals per MLS Well	each	4
Total Number of Groundwater Monitoring Intervals	each	32
Total Number of Soil Boring Locations	each	8

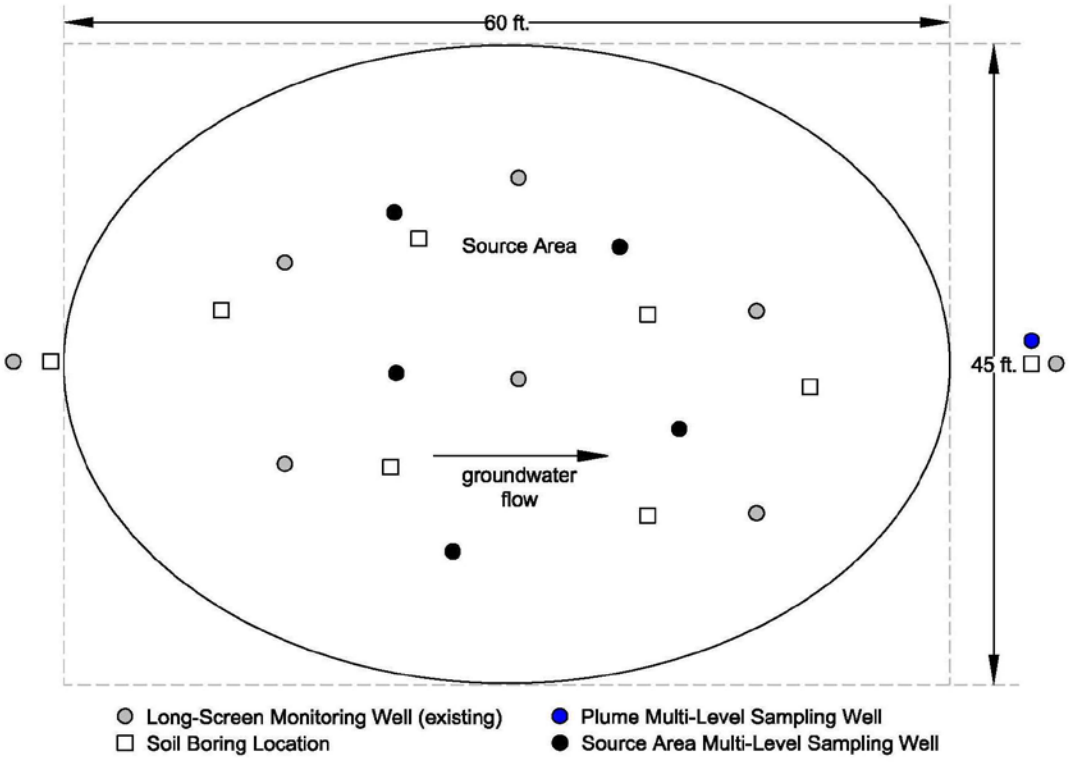

Figure 7.3. Expanded Zone Long-Term Performance Assessment following Bioaugmentation

As summarized in Table 7.5, the incremental estimated total cost to implement this approach beyond the "typical" approach for the case where the assessment zone is expanded to 2,000 yd^3 is $64,205. A more detailed breakdown of the costs is included in the expanded table presented in Appendix E. The capital cost including the installation of source and plume MLS wells is approximately $32,900. The O&M costs of conducting the push-pull testing is estimated to be $15,420, while the cost of performing the groundwater sampling event (including sampling crew labor and laboratory analytical costs for analysis of VOCs, anions, dissolved metals, volatile fatty acids, and CSIA) is estimated to be $15,885. Based on a total assessment zone volume of 2,000 cubic yards (yd^3), the unit volume cost to implement this "upgraded" assessment on the expanded assessment zone is $32/$yd^3$. Compared to the unit volume cost of $51/$yd^3$ for the base case, economies of scale are evident with significantly lower unit volume costs for the larger source area assessment.

Table 7.5. Incremental Cost Estimate to "Up-Grade" to the Demonstrated Long-Term Performance Assessment following Bioaugmentation for Expanded Zone Case

Capital Costs			***$32,900***
Well Installation			
	Mobilization	$3,000	
	Oversight Labor	$6,400	
	Subcontract Driller	$18,000	
	Subcontract Surveyor	$2,000	
	Materials/Consumables	$1,000	
	Utilities/Fuel	$500	
	Waste Disposal	$2,000	
Push-Pull Tracer Testing			***$15,420***
	Labor (System Operation)	$7,680	
	Labor (Analytical)	$3,060	
	Labor (Data Management)	$680	
	Equipment/Parts	$1,000	
	Materials/Consumables	$1,000	
	Utilities/Fuel	$500	
	Waste Disposal	$1,500	
Groundwater Monitoring Costs			***$15,885***
	Labor (Sample Crew)	$4,800	
	Analytical	$10,785	
	Sampling Equipment	$300	
		TOTAL	***$64,205***

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8.0 IMPLEMENTATION ISSUES

The primary issues related to implementation of the long-term performance assessment at a site (Alameda Point) where bioaugmentation was used to treat a highly characterized overburden DNAPL source area were:

- ***PFM Data Interpretation***. PFM data interpretation must be carefully performed, as the Darcy velocity varied spatially and temporally, which had an impact on contaminant flux rates. Contaminant fluxes must be normalized to the groundwater flux to assess changes in contaminant mass discharge due to source removal.

- ***Biofouling within injection wells***. Biofouling has often been an issue for active bioremediation systems. Not surprisingly, biofouling of the previously utilized injection wells during the bioaugmentation activities was a challenge in this demonstration. As discussed in Section 5.4.4, upon initial water testing of the recirculation system components, it was discovered that the yield of the injection wells was very low (approximately 0.04 gal/min); too low for implementation of the recirculation PTT. Because all the underground and well connection piping (constructed as part of SERDP Project ER-1613) was glued, the costs to excavate, disconnect, and reconstruct this piping to access the wells for rehabilitation were too great and beyond the scope of this current project. Approaches using automated or periodic biocide treatment to limit microbial biomass accumulation within injection wells is likely needed to mitigate this issue in future bioremediation applications. Construction of the injection and extraction well heads should be done in such a manner that the piping can be easily removed for periodic well rehabilitation efforts, if/when needed.

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APPENDIX B BIOAUGMENTATION FOR TREATMENT OF DNAPL SOURCES: INSIGHTS FROM ALAMEDA POINT PLUME 4-1

Bioaugmentation for Treatment of DNAPL Sources:

Insights from Alameda Point Plume 4-1

The following questions were addressed as part of the long-term post-bioaugmentation evaluation in the DNAPL source area within Plume 4-1 at Alameda Point, CA as part of ESTCP Project ER-201428.

I. What tools were most useful for treatment design?

Characterization of the DNAPL source area, as well as performance monitoring (verification of amendment delivery, determination of transformation products and dechlorination rates), was highly dependent upon determining the location of the DNAPL sources relative to the flow field. For initial screening of potential locations of DNAPL, use of a membrane interface probe (MIP) was extremely useful. Soil core screening using a hand-held photoionization detector, followed by selective soil sampling for chlorinated ethene analysis, served as an effective approach for further identifying and characterizing DNAPL sources. Use of a hydraulic profiling tool (HPT) to determine (semi-quantitatively) the permeability/flow field also served to help develop a conceptual site model for the source area.

The information described above provided the information needed to install the appropriate monitoring locations within the source area. Discretely-screened multi-level sampling (MLS) wells proved very useful for assessing both short- and long-term remedial performance. It is recommended that such discrete monitoring be used within the specific location where DNAPL source reside, especially if the DNAPL sources are in lower permeability materials.

II. What monitoring should be performed to ensure treatment effectiveness?

The use of MLS wells, particularly those located adjacent to DNAPL sources, were useful for confirming proper distribution of amendment and evaluating dissolution/dechlorination. Specific monitoring/testing that was performed at these MLS wells that were useful in assessing treatment effectiveness included:

- Contaminant rebound monitoring (both short-term and long-term)
- Compound specific isotopic analysis (CSIA) for carbon. This information was used to confirm complete dechlorination in the absence of appreciable ethene/ethane.
- Partitioning tracer testing (PTT). PTT, whether in the form of forced gradient tracer or push-pull tests, served as a means to confirm and quantify DNAPL both before and after treatment.

III. What are the expected DNAPL dissolution and dechlorination rates

While the DNAPL dissolution rates during the active bioaugmentation treatment that was performed at Alameda Point Plume 4-1 source area were not readily determined, groundwater monitoring of chlorinated ethene levels coupled with carbon CSIA analyses performed during the long-term dissolution provided an estimate of the overall DNAPL dissolution and dechlorination rate. The observed overall dechlorination rate constant measured during the long-term evaluation (3.5 years following active bioremediation) was 0.01 day^{-1}. With both *Dehalococcoides sp*. and ethene levels several times higher during active bioremediation than at the end of the long-term rebound monitoring, it is likely that the DNAPL dissolution/dechlorination rate constant during active treatment was greater than that measured during this long-term rebound study.

IV. What groundwater remedial levels are attainable?

At locations where measureable DNAPL residual was still present (based on soil core data and/or PTT), bioaugmentation had only marginal impacts on groundwater quality with respect to removal of chlorinated ethenes (sum of TCE + DCE + VC). However, in locations where residual DNAPL sources had been removed (via bioremediation and the preceding enhanced flushing), total chlorinated ethene concentrations decreased by approximately 1 order of magnitude in groundwater. Despite this decrease, chlorinated ethene levels were orders of magnitude above regulatory levels.

This order of magnitude decrease was attained with only 4 months of active (electron donor addition while recirculating groundwater), followed by 3.5 years of post-treatment natural attenuation. It is likely that the extent of chlorinated ethene decrease in groundwater would have been greater if a longer active bioremediation timeframe was employed.

V. What are reasonable expectations with respect to decrease in contaminant mass discharge from the source area?

Chlorinated ethene mass discharge echoed the changes observed in groundwater chlorinated ethene concentrations, where approximately a 1 order of magnitude decrease was observed where residual DNAPL had been removed, while little to no decreases were observed where residual DNAPL sources remained.

VI. How can treatment scale and timeframe be more effectively designed considering downgradient amendment migration and/or post-treatment reductive dechlorination?

Long-term (post active treatment) groundwater monitoring results showed that complete dechlorination of the chlorinated ethenes was occurring along the flow path from the source area to monitoring locations located approximately 10 feet downgradient of where bioremediation was performed. This result suggests that a treatment “halo” of at least 10 feet was attained, and that this additional reaction residence time can be used to determine the expected contaminant mass discharge emanating from the treatment zone.

Perhaps more importantly, the long-term groundwater monitoring showed that active dechlorination continued, with an observed overall dechlorination rate constant of 0.01 day^{-1}, maintained for up to 3.5 years. Assuming that this rate constant has been maintained since the end of active treatment, and assuming a constant chlorinated ethene concentration (maintained by the presence of DNAPL) near SMLS 1-3 of 1,600 µM, chlorinated ethene soil concentrations near SMLS 1-3 would have decreased by approximately 500 mg/kg since the end of active bioremediation. This decrease represents approximately 25% of the DNAPL levels currently near SMLS 1-3 and soil boring location DPC-20. Accounting for this, post-treatment attenuation and DNAPL removal would allow for a reduction in the time and resources needed for active treatment.

VII. To what extent is long-term monitoring required to properly assess treatment of DNAPL sources in unconsolidated media?

Monitoring results performed within several months of the cessation of active bioremediation were, for monitoring locations screened adjacent to remaining residual DNAPL sources, consistent with monitoring results attained 3.5 years following treatment with respect to chlorinated ethene levels. Thus, discrete monitoring locations located adjacent to DNAPL sources provide relatively rapid feedback with respect to untreated sources and contaminant rebound.

However, at monitoring locations not located and discretely screened in remaining DNAPL sources, results between the short term (several months) and long-term (3.5 years) rebound monitoring were not always consistent. Rebound was not observed until years after cessation of active treatment at some locations, likely due to the time needed for contaminants to migrate within the source area and/or decreases in microbial dechlorination activity. Thus, caution must be taken when relying solely on short-term rebound data for overall remedial assessment, especially if discretely screening monitoring locations located in DNAPL source areas are not available.

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APPENDIX C COST ESTIMATE DETAILS: INCREMENTAL COST ESTIMATE TO "UP-GRADE" TO THE DEMONSTRATED LONG-TERM PERFORMANCE ASSESSMENT FOLLOWING BIOAUGMENTATION

Incremental Cost Estimate to "Up-Grade" to the Demonstrated Long-Term Performance Assessment following Bioaugmentation (3-Year Program) for Base Case Site

Capital Costs		***$123,500***				
System Design / Workplan (additional)	$10,000					
Site Planning/Permitting	$2,500					
Well Installation			10 MLS wells, 3 long-screen wells			
Mobilization	$3,000					
Oversight Labor	$15,000		50hrs/wk*3 weeks*100/hr			
Subcontract Driller	$39,000		13 wells @ 3,000/well			
Subcontract Surveyor	$2,500					
Materials/Consumables	$2,000					
Utilities/Fuel	$1,000					
Waste Disposal	$2,500					
System Installation						
Oversight Labor	$14,000		10hrs/day*7 days*100/hr*2 people			
Equipment/Parts	$15,000					
Materials/Consumables	$2,000					
Utilities/Fuel	$1,000					
System Start-Up Testing	$4,000		10hrs/day*2days*100/hr*2 people			
Data Evaluation/Final Report (additional)	$10,000					
PTT Operation and Maintenance Costs		***$18,500***				
Labor (System Operation)	$6,000		60hrs/wk*1 week*100/hr			
Labor (Analytical)	$4,000		40hrs/wk*1 week*100/hr			
Labor (Data Management)	$4,000		10hrs/wk*4 weeks*100/hr			
Equipment/Parts	$1,000					
Materials/Consumables	$2,000					
Utilities/Fuel	$1,000					
Waste Disposal	$500					
Groundwater Monitoring Costs (Event 1)		***$60,425***				
Labor (Sample Crew)	$12,000		10hrs/day*6 days*2 persons*100/hr			
Analytical - VOCs	$4,505		$85	per x	53	samples
Analytical - Reduced Gases	$4,505		$85	per x	53	samples
Analytical - Anions	$3,180		$60	per x	53	samples
Analytical - Dissolved Metals	$1,325		$25	per x	53	samples
Analytical - VFAs	$4,505		$85	per x	53	samples
Analytical - Dissolved Hydrogen	$3,975		$75	per x	53	samples
Analytical - TOC	$3,180		$60	per x	53	samples
Analytical - Microbial Community	$4,500		$750	per x	6	samples
Analytical - CSIA	$3,150		$525	per x	6	samples
Sampling Equipment	$600		$100/day*6 days			
PFM Testing	$15,000					
Groundwater Monitoring Costs (Event 2)		***$53,250***				
Labor (Sample Crew)	$10,000		10hrs/day*5 days*2 persons*100/hr			
Analytical - VOCs	$3,825		$85	per x	45	samples
Analytical - Reduced Gases	$3,825		$85	per x	45	samples
Analytical - Anions	$2,700		$60	per x	45	samples
Analytical - Dissolved Metals	$1,125		$25	per x	45	samples
Analytical - VFAs	$3,825		$85	per x	45	samples
Analytical - Dissolved Hydrogen	$3,375		$75	per x	45	samples
Analytical - TOC	$2,700		$60	per x	45	samples
Analytical - Microbial Community	$3,750		$750	per x	5	samples
Analytical - CSIA	$2,625		$525	per x	5	samples
Sampling Equipment	$500		$100/day*5 days			
PFM Testing	$15,000					

Groundwater Monitoring Costs (Event 3)		***$46,550***			
Labor (Sample Crew)	$8,000	10hrs/day*4 days*2 persons*100/hr			
Analytical - VOCs	$3,230	$85	per x	38	samples
Analytical - Reduced Gases	$3,230	$85	per x	38	samples
Analytical - Anions	$2,280	$60	per x	38	samples
Analytical - Dissolved Metals	$950	$25	per x	38	samples
Analytical - VFAs	$3,230	$85	per x	38	samples
Analytical - Dissolved Hydrogen	$2,850	$75	per x	38	samples
Analytical - TOC	$2,280	$60	per x	38	samples
Analytical - Microbial Community	$3,000	$750	per x	4	samples
Analytical - CSIA	$2,100	$525	per x	4	samples
Sampling Equipment	$400	$100/day*4 days			
PFM Testing	$15,000				
	TOTAL	***$302,225***			

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