FINAL REPORT

Performance of Two Technologies to Control Difficult-to-Treat Matrix Diffusion Zones: Post-Bioremediation Sustained Treatment and MNA in Low Permeability Units

ESTCP Project ER-201429

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14. ABSTRACT
In-situ bioremediation (ISB) and monitored natural attenuation (MNA) are two widely used approaches to treat and control persistent matrix diffusion sources at chlorinated solvent sites. Such source zones represent a significant liability to the Department of Defense (DoD). Research has suggested that processes may be active at both ISB and MNA sites that could provide additional benefits to their application near or within low-permeability (low-K) matrix diffusion zones. The objectives of the project were: i) to develop new process knowledge on how to measure and demonstrate sustained treatment following application of ISB and ii) to evaluate and quantify MNA processes in low-K matrix diffusion zones. Data from field demonstrations and data mining of other sites indicated the occurrence of these processes and provided useful information on quantifying and assessing these processes. Fact Sheets are provided to allow cost effective application of these concepts at other sites using existing site data.

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FINAL REPORT

Project: ER-201429

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

ACRONYMS AND ABBREVIATIONS

Af	Aquifer
AFB	Air Force Base
AOC	Area of Concern
ASTP	Air Stripper Treatment Plant
At	Aquitard
BAK	Benzoalkonium Chloride
bgs	Below Ground Surface
BOD	Biological Oxygen Demand
BW	Biowall
C	Carbon
CBS	Comprehensive Background Study
CH_4	Methane
cis-DCE	cis-1,2-dichloroethene
cm/sec	Centimeters per Second
COD	Chemical Oxygen Demand
CSIA	Compound Specific Isotope Analysis
CVOC	Chlorinated Volatile Organic Compound
DNAPL	Dense Non-Aqueous Phase Liquid
DOD	Department of Defense
DG	Downgradient
DHC	Dehalococcoides spp.
DL	Detection Limit
DPT	Direct Push Technology
EBAC	Eubacteria
EOS	Emulsified Oil Substrate
ESTCP	Environmental Security Technology Certification Program
EVO	Emulsified Vegetable Oil
f_{oc}	Fraction of Organic Carbon
ft	Feet
gpm	Gallons per Minute
HCL	Hydrochloric Acid
HCO_3	Bicarbonate
High-K	High-Permeability
H_2SO_4	Sulfuric Acid
ISB	In-situ Bioremediation

Low-K	Low-Permeability
MCL	Maximum Contaminant Level
mg/kg	Milligrams per Kilogram
mg/L	Milligrams per Liter
MNA	Monitored Natural Attenuation
ND	Not Detected
NIT	North Interceptor Trench
NRC	National Research Council
NTC	Naval Training Center
OoM	Order of Magnitude
OU-2	Operable Unit 2 (Hill Air Force Base)
PBOC	Potentially Bioavailable Organic Carbon
PC	Polycarbonate Bottle
PCE	Tetrachloroethylene
PE	Polyethylene Bottle
psi	Pound per Square Inch
SA-17	Study Area 17
SRS	Source Recovery System
TCE	Trichloroethylene
TOC	Total Organic Carbon
TZ	Treatment Zone
UCS	Upgradient Control System
UG	Upgradient
ug/L	Micrograms per Liter
VC	Vinyl Chloride
VFAs	Volatile Fatty Acids
VOC	Volatile Organic Compound
V-TLS	Glass Vial with Teflon-Lined Septum
WMA	Waste Management Area
WMG	Wide Mouth Glass Jar
yr	Year

ACKNOWLEDGEMENTS

The authors would like to thank the Environmental Security Technology Certification Program (ESTCP) for funding this project and all ESTCP staff and support personnel who provided insightful and constructive feedback during the project. We would also like to thank the many site owners, remediation consultants, and regulators who provided site data for the project. A special thanks is owed to the remedial program managers who provided access to facilities and other assistance for the field demonstration work, including: Ms. Mary Bitney at Altus Air Force Base, Dr. Hunter Anderson with the Air Force Civil Engineer Center, Ms. Catherine Jerrard with the Air Force Civil Engineer Center, Ms. Sharon Stone with the Air Force Civil Engineer Center, Mr. Paul Carroll with the Air Force Civil Engineer Center, and Mr. Mike Singletary with NAVFAC. Many GSI staff members were involved in this project and we are grateful for their hard work and dedication to the success of the project.

ABSTRACT

INTRODUCTION AND OBJECTIVES

In-situ bioremediation (ISB) and monitored natural attenuation (MNA) are two widely used approaches to treat and control persistent matrix diffusion sources at chlorinated solvent sites. Such source zones represent a significant liability to the Department of Defense (DoD). Research has suggested that processes may be active at both ISB and MNA sites that could provide additional benefits to their application near or within low-permeability (low-K) matrix diffusion zones. The objectives of the project were: i) to develop new process knowledge on how to measure and demonstrate sustained treatment following application of ISB and ii) to evaluate and quantify MNA processes in low-K matrix diffusion zones.

TECHNOLOGY DESCRIPTION

Sustained treatment is a term used to describe the enhanced attenuation capacity within an ISB treatment zone that can prolong the benefits of ISB treatment after the depletion of the primary organic substrate. Post-ISB sustained treatment could be an important mechanism for controlling chlorinated solvent concentrations and preventing rebound, particularly at sites where matrix diffusion is expected. Low-K MNA is characterized by natural processes such as biodegradation and sorption that serve to control migration of chemicals that have diffused into a low permeability matrix. The extent to which these compounds undergo natural attenuation in the low-K zone is an emerging area of research and quantifying MNA process in the low-K zone is an integral component for the application of this approach as a management tool. To assess the occurrence and extent of these processes, data mining efforts and field demonstration studies were conducted. The results were analyzed to provide guidance on how to assess and quantify post-ISB sustained treatment and low-K MNA. Fact Sheets were prepared to help guide remedial site managers on the application of these tools at their sites.

PERFORMANCE AND COST ASSESSMENT

Post-ISB Sustained Treatment at Mulch Biowalls: Results demonstrate the ongoing and long-term efficacy of mulch biowalls 10 years after their installation. Given the sustained treatment, augmentation of the biowalls with supplemental substrate does not appear warranted. *Post-ISB Sustained Treatment at Substrate Injection Sites:* Parent CVOC concentration reductions following ISB at two sites indicated sustained concentration reductions without evidence of rebound 4 to 5 years after treatment. The data mining study, which included 34 sites with long post-treatment monitoring periods, indicated that sustained treatment of parent concentrations is observed at about 75% of sites. These results suggest that a generally well designed and implemented ISB project often will benefit from sustained treatment, at a minimum in terms of rebound suppression for 3 to more than 15 years. *Low-K MNA:* A lines-of-evidence approach was established to assess the occurrence of MNA in low-K zones, along with a data mining study to establish "benchmark" decay rates. High-resolution chemical profiling of CVOCs in the aquitard indicated that biodegradation daughter products were present at each site. Fraction organic carbon was found to be approximately 2.6 times higher in the low-K zone than the transmissive zone, with a median of 1.1% in the low-K zone. Fact Sheets are provided to allow cost effective application of these concepts at other sites using existing site data.

PUBLICATIONS

(Additional publications are in-preparation.)

Walker, K.L, T.M. McGuire, D.T. Adamson, and R.H. Anderson, 2020. "Long-Term Evaluation of Mulch Biowall Performance to Treat Chlorinated Solvents," *Groundwater Monitoring & Remediation*, 40(1), 35-46, doi: 10.1111/gwmr.12364

Battelle Conference 2016, 2018: Two platform presentations and two posters.

EXTENDED EXECUTIVE SUMMARY

INTRODUCTION

In-situ bioremediation (ISB) and monitored natural attenuation (MNA) are two widely used approaches to treat and control persistent matrix diffusion sources at chlorinated solvent sites. Such source zones represent a significant liability to the Department of Defense (DoD) and other parties responsible for their cleanup. Research has suggested that processes may be active at both ISB and MNA sites that could provide additional benefits to their application near or within low-permeability (low-K) matrix diffusion zones.

The DoD has recognized that chlorinated solvent source zones in complex hydrogeologic settings can cause difficult to treat, persistent groundwater plumes, with the potential to result in costly and incomplete treatment (Leeson and Stroo, 2011). Back diffusion from low-K zones can sustain plumes long after the source has been treated and the importance of these processes for site management has become more apparent in recent years (Stroo et al., 2012). Few remedial technologies can overcome the challenges associated with matrix diffusion, and those which have proven effective at some sites, such as in-situ thermal treatment or deep soil mixing, may not be cost effective in many situations.

Recognizing the challenges associated with matrix diffusion, it is important to identify and better understand remedial approaches and mechanisms that may provide residual, low-cost benefits at matrix diffusions sites. Sustained treatment following ISB and MNA in low-K zones are two remedial approaches that have the potential to provide such benefits. This project aimed to better quantify these processes and provide guidance to remedial project managers on how to evaluate their occurrence and incorporate the findings into site conceptual models and remediation planning.

OBJECTIVES

The objectives of the project were twofold:

1) to develop new process knowledge on how to measure and demonstrate sustained treatment following application of ISB; and
2) to evaluate and quantify MNA processes in low-K matrix diffusion zones.

Focused field studies were conducted at three ISB sites and three MNA sites to gather key site-specific data on the technologies. Data mining studies on sustained treatment occurrence and MNA decay rates were also conducted to complement information obtained through the field testing program.

TECHNOLOGY DESCRIPTION

<u>Sustained Treatment</u>

Sustained treatment is a term used to describe the enhanced attenuation capacity within an ISB treatment zone that can prolong the benefits of ISB treatment after the depletion of the primary organic substrate. A prior ESTCP project (ER-201120) demonstrated that at ISB sites with 3-12 years of post-ISB monitoring data (34 sites out of a total dataset of 118 sites), there was evidence for sustained treatment at most of these sites (McGuire et al., 2016a). Results from this data mining effort and a limited field study under ESTCP Project ER-201120 suggest that post-ISB sustained treatment could be an important mechanism for controlling chlorinated solvent concentrations and preventing rebound, particularly at sites where matrix diffusion is expected to result in long-term groundwater impacts (McGuire et al., 2016b). For this portion of the project, field demonstration activities were conducted at Altus Air Force Base, Kelly Air Force Base, and Naval Training Center Orlando.

Low-K MNA

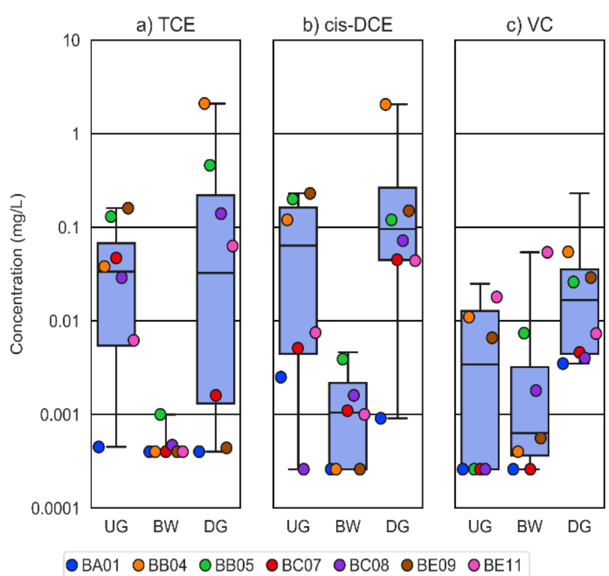
In this important new area in MNA, chlorinated solvents that have diffused into a low permeability matrix are subject to natural attenuation processes similar to those occurring in transmissive zones. The extent to which these compounds undergo natural attenuation in the low-K zone is an emerging area of research. Several recent studies have indicated that dechlorination can occur in low-K units (Takeuchi et al., 2011; Lima et al., 2012; Damgaard et al., 2012; Wanner et al., 2018), suggesting that a comprehensive analysis of MNA activity in these largely overlooked zones should be productive. Quantifying the rate and extent of natural attenuation in the low-K zone is likely to be an integral component of the groundwater management strategy at many sites as the impacts of matrix diffusion become more apparent. For this portion of the project, field demonstration activities were conducted at England Air Force Base, Hill Air Force Base, and Kelly Air Force Base.

PERFORMANCE ASSESSMENT

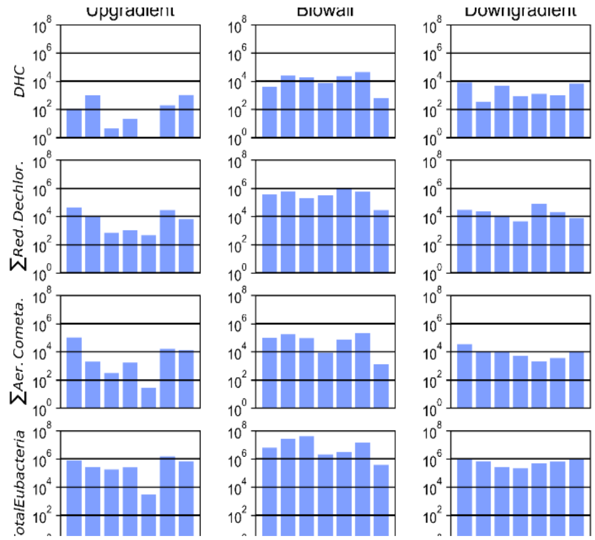
Sustained Treatment

At Altus AFB, field demonstration activities focused on assessing sustained treatment of more than 5,300 feet (approximately 25% of the total biowall length installed at DOD facilities) of mulch biowalls that were installed more than 10 years prior. Key findings included:

- As shown on the boxplot below, CVOC concentrations indicate ongoing degradation within the biowalls. TCE was not detected in five of seven groundwater samples collected from the biowall despite upgradient detections above MCLs. At the two locations with TCE detections, concentrations were below MCLs.

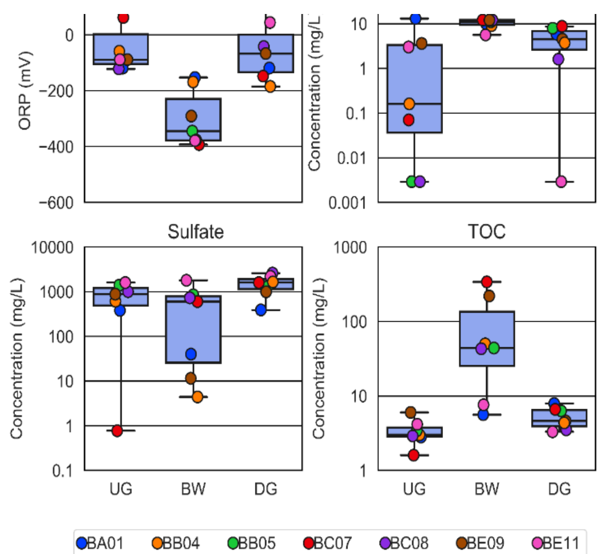


- Microbial sampling (see chart below) established the presence of key dechlorinating bacteria and the abundance of genes encoding specific enzymes for degradation, high methane concentrations, low sulfate concentrations, and negative oxidation-reduction potential, all indicative of highly reducing conditions within the biowalls and favorable conditions for CVOC destruction via microbial reductive dechlorination.



- High cellulose content (>79%) of the mulch, elevated total organic carbon (TOC) content in groundwater and elevated potentially bioavailable organic carbon (PBOC) measurements in soil samples further supports an ongoing, long-lived source of carbon. These results demonstrate the ongoing and long-term efficacy of the mulch biowalls at Altus AFB.

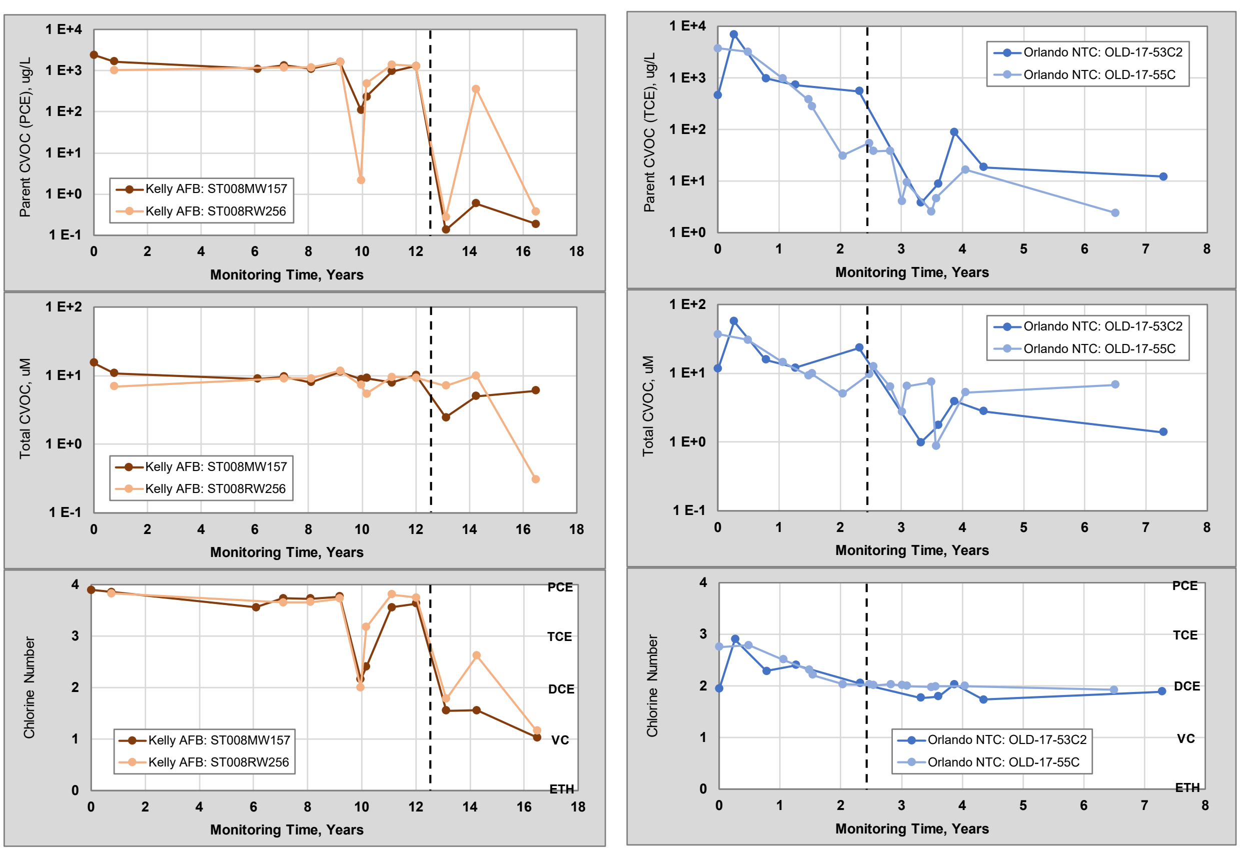
- Concentrations of bacteria, TOC, PBOC, and other geochemical parameters (see chart to the right) suggests a modest impact, or a "shadow" effect, of the biowalls downgradient. The continued presence of CVOCs downgradient may be attributable to back-diffusion from low-K shale. However, the biowalls continue to provide benefits by removing CVOCs in groundwater, thus reducing further CVOC loading to the downgradient, low-K strata.



- The ongoing efficacy of treatment within the biowalls, however, has helped to cut off downgradient loading to the low-permeability zone for an extended period, and downgradient CVOC concentrations should eventually decrease due to biotic and abiotic degradation, as well as flushing from treated water emanating from the biowalls. Consequently, an MNA approach may be appropriate for managing the downgradient groundwater.
- Given the ongoing performance as indicated by the lines-of-evidence assessment, augmentation of the biowalls with supplemental substrate does not appear warranted at this time, and we anticipate that the biowalls will continue to treat CVOCs effectively as they pass through the biowall, thus reducing the CVOC loading of downgradient low-K strata.

At Kelly AFB and NTC Orland, field demonstration activities focused on assessing sustained treatment approximately 4 to 5 years after the completion of ISB using emulsified vegetable oil substrate injections. Key findings included:

- Parent CVOC concentration reductions following ISB at these two sites indicates the bioremediation remedies have successfully reduced parent compound concentrations without evidence of significant rebound.
- At Kelly AFB (see chart below, left), parent CVOC concentrations at both wells included in the study have remained below MCLs; at NTC Orlando (char below, rightt) one well has attained a concentration below the MCL, with concentrations at the other well are slightly above the MCL (12.2 ug/L). These results further indicate better overall performance than most of the sites in the 117-site database (McGuire et al., 2016b), where only 21% of 710 monitoring wells achieved the MCL.



- The lines-of-evidence assessment indicates overall site conditions are conducive to ongoing sustained treatment.
- At Kelly AFB, PCE and TCE concentrations were below detection limits at the sampled wells despite an upgradient concentrations of 0.008 mg/L and 0.0146 mg/L, respectively. This is consistent with the high average DHC concentrations within the treatment zone, as well as elevated PBOC concentrations, even with relatively low TOC (2.15 mg/L). Results also show a continued decline in the chlorine number, indicating a continue progression in conversion of daughter products to lesser chlorinated compounds.
- At NTC Orlando, slight increases in TCE concentration have been observed in both wells; however, concentrations remain well below pre-treatment levels. DHC concentrations are measurable within the treatment zone, but well below the 10^4 cells/mL threshold generally considered to yield "useful" degradation rates (Lu et al., 2006). Other dechlorinating microbial indicators are present at concentrations on the order of 10^3 cells/mL. Borden et al. (2017) have indicated the low pH conditions and an underdosage of substrate and buffer are possible explanations for the observed performance at this site.
- The data mining study described in Appendix B, which includes a 34-site subset of the 117-site database with long post-treatment monitoring periods, indicates that sustained treatment of parent concentrations is observed at approximately three-quarters of sites. The comparable of these 2 sites with respect to the larger population of 117 sites suggests the results from these 2 sites and 34-site data mining study can likely be extended to most ISB sites. Site-specific hydrogeologic conditions, design considerations, and implementation effectiveness undoubtedly factor into the remedial outcome for any ISB application; however, these results suggest that a generally well designed and implemented ISB project more often than not will benefit from sustained treatment, at a minimum in terms of rebound suppression for the parent CVOC, for a period of at least 3 to more than 15 years after the end of treatment.
- Besides temporal concentration trends and decay rate analysis, the parameters appearing to be most indicative of sustained treatment potential were TOC, PBOC, and the microbial analyses from the QuantArray-Chlor suite. An attempt to use BOD as a cost-effective surrogate for PBOC proved unsuccessful due elevated detection limits for BOD.

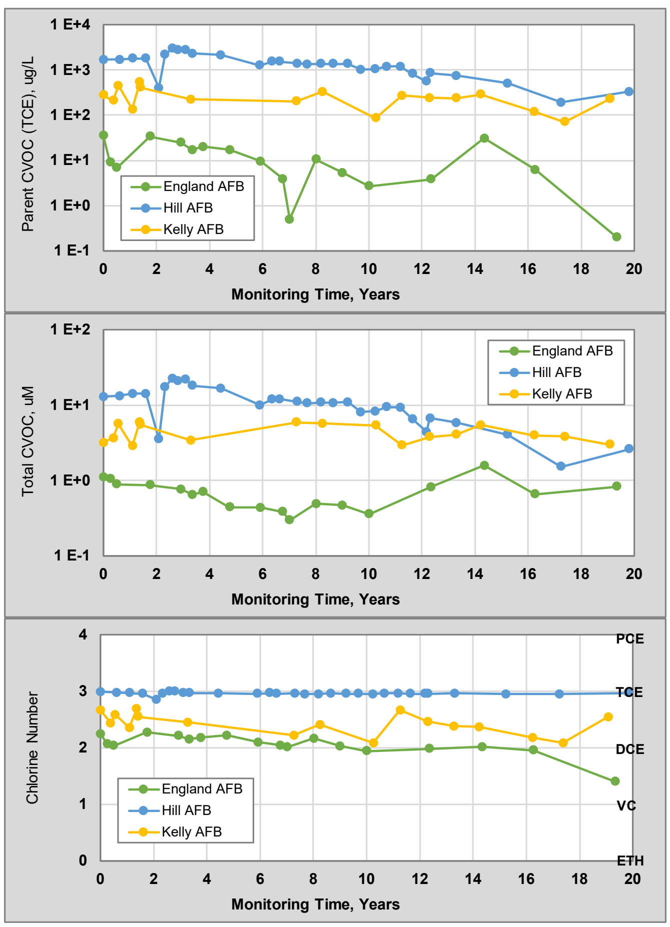
Low-K MNA

Field demonstration and data mining activities related to assessment of low-K MNA included the following key findings:

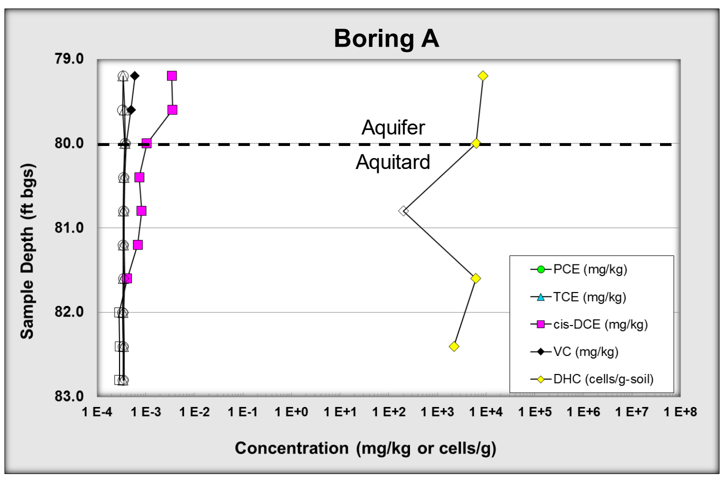
- An extensive data mining study was undertaken to establish "benchmark" decay rates for CVOCs, including an analysis of those sites likely affected by matrix diffusion. The benchmark decay rates were used for comparison of results from the current study, as well as to establish a range of potential values for use in modeling matrix diffusion. A summary of median decay rates from the data mining effort is provided on the table below. The decay rates corresponding to sites with a maximum concentration less than 50 ug/L are more likely to be more representative of the population of natural attenuation sites and those impacted by matrix diffusion effects.

Dataset	PCE	TCE	cis-DCE	VC
k (per year)				
All Wells	0.067	0.066	0.024	0.025
Max. Conc. <50 ug/L	0.048	0.045	0.020	0.021
Max. Conc. >50 ug/L	0.111	0.093	0.032	0.035
Half-life (years)				
All Wells	10.3	10.5	29	28
Max. Conc. <50 ug/L	14.5	15.3	35	33
Max. Conc. >50 ug/L	6.3	7.4	22	20

- A lines-of-evidence approach was established to assess the occurrence of MNA in low-K zones underlying the transmissive zone at these sites. To date, several research studies have detected the presence of key dechlorinating bacteria in low-K zones (Takeuchi et al., 2011; Lima et al., 2012; Damgaard et al., 2012), and more recent studies have begun to elucidate biodegradation mechanisms and quantify potential rates (Wanner et al., 2018). However, to our knowledge, this study represents the first comprehensive assessment of MNA potential in low-K zones, including analysis of microbial populations, geochemical conditions, sorption potential, organic carbon bioavailability, and high-resolution chemical profiling within the aquitard.



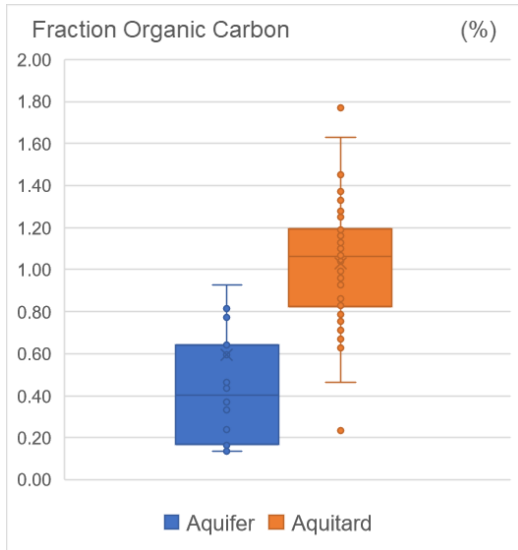
- As a precursor to evaluating the occurrence of MNA in the low-permeability zone at these sites, an analysis of MNA in the overlying aquifer was performed. All three sites have long monitoring periods with significant datasets. All wells at these sites exhibited “Decreasing” or “Probably Decreasing” Mann-Kendall trends for TCE (the parent CVOC), while Total CVOC concentrations exhibited “Decreasing,” “Probably Decreasing,” or “Stable” Mann-Kendall trends. Furthermore, first-order decay rates at these sites for the parent CVOC and total CVOCs were consistent with “benchmark” decay rates calculated as part of the data mining effort that included rate data from thousands of monitoring wells. First-order decay rates of the parent CVOC and total CVOCs in the wells sampled at these sites were consistent with median rates calculated from the data mining study for wells with maximum concentrations below 50 ug/L.
- High-resolution chemical profiling of CVOCs in the aquitard indicates that biodegradation daughter products are present within the low-K zone at each site. At two of the sites, England AFB and Hill AFB, these daughter product detections were coupled with the detection of DHC and other biomarkers indicative of potential for biological reductive dechlorination. At Kelly AFB, while DHC was not detected in the aquitard samples, another reductive dechlorinate biomarker was detected. On this basis, it is likely that microbial reactions are occurring in the aquitard at these sites.



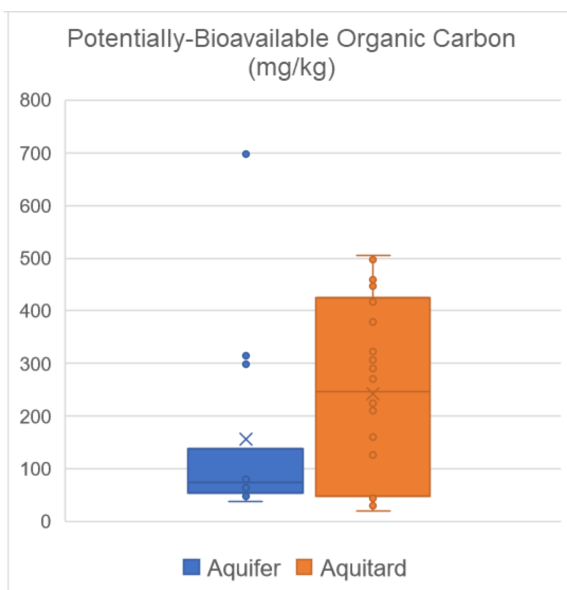
Open Symbol = Non-Detect

- Attempts to quantify the rates of biodegradation through compound specific isotope analysis (CSIA) were unsuccessful due to the inability for the commercial laboratory to achieve sufficiently low detection limits for the CVOCs in the aquitard soil samples. This limitation was identified early in the project (i.e., at the first site sampled), and therefore CSIA soil samples were not collected at the other two sites as a cost-saving measure.
- The Source History Tool, developed under a previous ESTCP project, was used to evaluate biodegradation rates within the aquitard based on the high-resolution CVOC data. As further described in Appendix D, rate calculation was possible at only one of four soil borings attempted (soil borings from the third site were not modeled due to the lack of parent CVOC and low concentrations of daughter products). The model indicated a potential slow biodegradation of TCE with a first-order rate constant on the order of 0.07 per year (half-life of 10 years) or more. This rate is generally consistent with a recent estimate of the upper end decay rate for TCE in the low-K zone of approximately 0.09 per year (half-life of 7.3 years) estimated using CSIA data (Wanner et al., 2018).

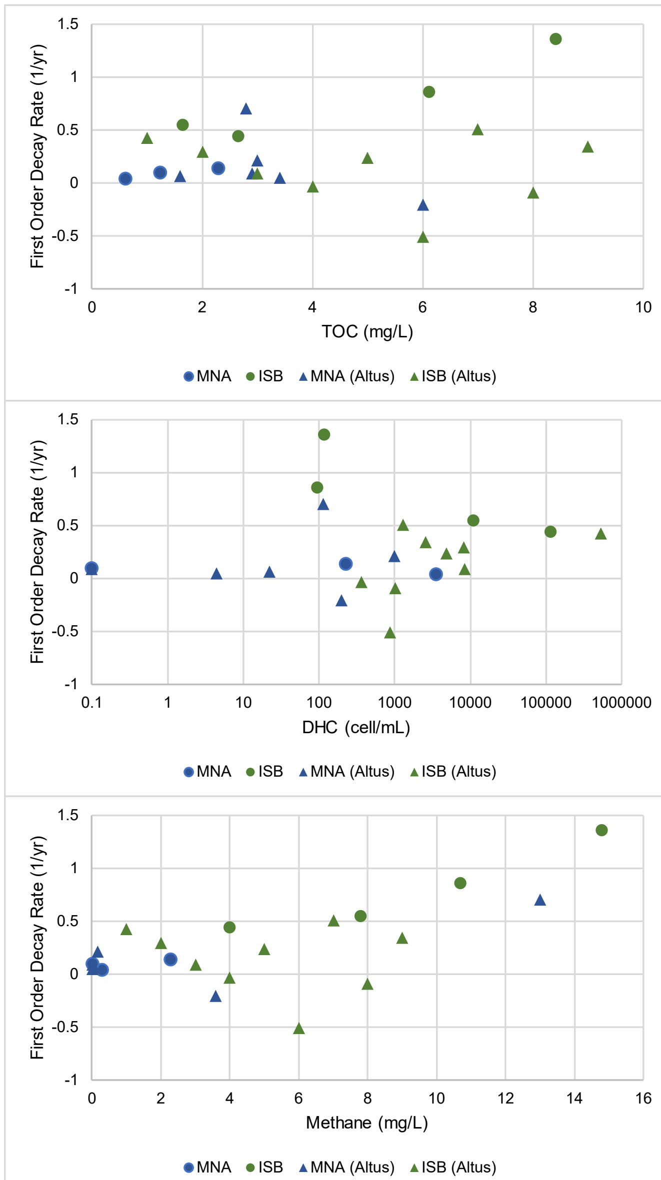
- Fraction organic carbon was analyzed in 48 aquitard samples and in 16 transmissive zone samples at the MNA sites. The distribution of f_{oc} is illustrated on the chart to the right and indicates that the aquitard samples have significantly higher f_{oc} concentrations than aquifer samples ($p<0.05$). This is an important finding that indicates a much higher sorption potential (approximately 2.6 times) within the aquitard compared to the aquifer.



- Potentially-bioavailable organic carbon (PBOC) was analyzed in 24 aquitard samples and in 12 transmissive zone samples at the MNA sites and untreated portions of the ISB sites. The distribution of PBOC is illustrated to the right. While the median PBOC in aquitard samples is approximately two times higher than the median of transmissive zone samples, the difference was not statistically significant at the 95% confidence level. Nonetheless, these data suggest the availability of potential carbon substrate within the aquitards.



- First-order decay rates calculated for the sustained treatment substrate injection sites, MNA sites, and the monitoring wells located outside the biowalls at Altus AFB were evaluated as a function of TOC, DHC, and methane. As shown on the chart to the left, relationships between these parameters were generally positive, but no strong correlations were found.
- A Fact Sheet on how the low-K MNA data can be used in matrix diffusion modeling using the REMChlor-MD computer model is provided as an appendix to the Final Report.
- A Fact Sheet on how to assess post-bioremediation Sustained Treatment is provided an appendix to the Final Report.



1.0 INTRODUCTION

In-situ bioremediation (ISB) and monitored natural attenuation (MNA) are two widely used approaches to treat and control persistent matrix diffusion sources at chlorinated solvent sites. Such source zones represent a significant liability to the Department of Defense (DoD) and other parties responsible for their cleanup. Research has suggested that processes may be active at both ISB and MNA sites that could provide additional benefits to their application near or within low-permeability (low-K) matrix diffusion zones.

At sites treated using ISB, these processes are referred to as sustained treatment, which is defined as an enhanced attenuation capacity within an ISB treatment zone that can prolong the benefits of remediation after depletion of the primary substrate (Adamson et al., 2011; Suthersan et al., 2013; McGuire et al., 2016). At MNA sites where matrix diffusion is present, attenuation processes such as biodegradation and sorption are likely occurring (Takeuchi et al., 2011; Lima et al., 2012; Damgaard et al., 2012) and quantifying these processes are important to more realistically and reliably demonstrate MNA.

1.1 BACKGROUND

The DoD has recognized that chlorinated solvent source zones in complex hydrogeologic settings can cause difficult to treat, persistent groundwater plumes, with the potential to result in costly and incomplete treatment (Leeson and Stroo, 2011). Back diffusion from low-K zones can sustain plumes long after the source has been treated and the importance of these processes for site management has become more apparent in recent years (Stroo et al., 2012). Few remedial technologies can overcome the challenges associated with matrix diffusion, and those which have proven effective at some sites, such as in-situ thermal treatment or deep soil mixing, may not be cost effective in many situations.

Recognizing the challenges associated with matrix diffusion, it is important to identify and better understand remedial approaches and mechanisms that may provide residual, low-cost benefits at matrix diffusions sites. Sustained treatment following ISB and MNA in low-K zones are two remedial approaches that have the potential to provide such benefits. This project aimed to better quantify these processes and provide guidance to remedial project managers on how to evaluate their occurrence and incorporate the findings into site conceptual models and remediation planning.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objectives of the project were twofold: 1) to develop new process knowledge on how to measure and maximize sustained treatment following application of ISB; and 2) to evaluate and quantify MNA processes in low-K matrix diffusion zones. Focused field studies were conducted at three ISB sites and three MNA sites to gather key site-specific data on the technologies. Data mining studies on sustained treatment occurrence and MNA decay rates were also conducted to complement information obtained through the field testing program.

1.3 REGULATORY DRIVERS

Transitioning sites from costly active remediation to more passive approaches is a key milestone for most groundwater cleanup sites. Such transitions typically require a rigorous demonstration that the passive approaches will achieve remedial objectives in a reasonable timeframe for regulatory approval. The National Research Council, in its 2012 report on management of complex sites stated, "The decision to switch from an aggressive remediation strategy to MNA is very dependent on a reliable estimate of post-remediation plume development, including how quickly the remaining source will attenuate and how the post-remediation plume will behave. Additional research is needed to develop strategies for long-term management that focus on plume zone processes that contribute to plume longevity." (NRC, 2012). Sustained treatment and MNA in low-K zones, as described herein, are anticipated to be critical components in justifying such transitions at many DoD sites.

2.0 TECHNOLOGIES

2.1 TECHNOLOGY DESCRIPTIONS

2.1.1 Sustained Treatment

Sustained treatment is a term used to describe the enhanced attenuation capacity within an ISB treatment zone that can prolong the benefits of ISB treatment after the depletion of the primary organic substrate. A prior ESTCP project (ER-201120) demonstrated that at ISB sites with 3-12 years of post-ISB monitoring data (34 sites out of a total dataset of 118 sites), there was evidence for sustained treatment at most of these sites (McGuire et al., 2016a). Results from this data mining effort and a limited field study under ESTCP Project ER-201120 suggest that post-ISB sustained treatment could be an important mechanism for controlling chlorinated solvent concentrations and preventing rebound, particularly at sites where matrix diffusion is expected to result in long-term groundwater impacts (McGuire et al., 2016b).

2.1.2 MNA in Low-K Zones

In this important new area in MNA, chlorinated solvents that have diffused into a low permeability matrix are subject to natural attenuation processes similar to those occurring in transmissive zones. The extent to which these compounds undergo natural attenuation in the low-K zone is an emerging area of research. Several recent studies have indicated that dechlorination can occur in low-K units (Takeuchi et al., 2011; Lima et al., 2012; Damgaard et al., 2012), suggesting that a rigorous search for this type of activity in these largely overlooked zones should be productive. Quantifying the rate and extent of natural attenuation in the low-K zone is likely to be an integral component of the groundwater management strategy at many sites as the impacts of matrix diffusion become more apparent.

2.2 TECHNOLOGY DEVELOPMENT

2.2.1 Sustained Treatment

The potential for sustained treatment occurrence at ISB sites was previously evaluated through a data mining study conducted under ESTCP project ER-201120. For that project, a database of groundwater concentration versus time records was compiled for 34 sites with at least 3 to 12 years of post-treatment monitoring data. No rebound was observed at 65% of these sites and Mann-Kendall trend analysis indicated that the concentration was stable or decreasing at 89% of the sites where a trend could be established (McGuire et al., 2016a). To date, the authors are aware of only one field testing program aimed at evaluating the occurrence of sustained treatment (McGuire et al., 2016b). In this focused field study, groundwater sampling was completed at the 3 sites where ISB had been completed 3 to 10 years prior. Two of the three sites showed strong evidence of sustained treatment based on statistical analyses, while the third site exhibited inconclusive results.

2.2.2 MNA in Low-K Zones

To date, only limited research on MNA processes in low-K zones has been performed and the majority of such research has focused on assessing the presence of dechlorinating bacteria in clay layers (Takeuchi et al., 2011; Lima et al., 2012; Damgaard et al., 2012). Critical data are needed to support the occurrence of MNA processes in low-K zones and to quantify key input parameters that can be used in emerging models that are being developed to predict future impacts on groundwater quality from matrix diffusion.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGIES

2.3.1 Sustained Treatment

The primary advantage of sustained treatment is that it prolongs the treatment effectiveness period beyond what would be anticipated based on traditional design criteria (i.e., a period of one to two years of effectiveness). The authors hypothesize that sustained treatment is a key mechanism accounting for lower rebound occurrence at ISB sites compared to non-biological remediation technologies, such as chemical oxidation (McGuire et al., 2006; 2016b). A further understanding of the key parameters that allow for successful sustained treatment may allow for tailored design of an enhanced bioremediation application with sustained treatment as an explicit design criterion. Furthermore, demonstrating that sustained treatment is taking place, or would be expected to take place, may allow for the closure of sites with persistent residual contamination or a shift in strategy to a more cost-effective monitored natural attenuation approach.

2.3.2 MNA in Low-K Zones

The primary advantage of natural attenuation processes is the passive reduction in contaminant mass and concentration that occurs due to biodegradation, sorption, diffusion, and dispersion. While recent investigations have identified MNA processes in the low-K zone, a better understanding of the rates and extent of these processes in low-K zones will allow for improved predictions of MNA efficacy. Additionally, further insights into matrix diffusion processes occurring at the interface of high-K and low-K zones will also assist in predicting cleanup trends and may allow for closure of such sites where natural attenuation processes are active and can be shown capable of mitigating the effects of matrix diffusion over the long-term.

3.0 PERFORMANCE OBJECTIVES

Performance objectives for the field demonstration are summarized on Table 3.1, with additional details of the quantitative objectives discussed below.

Table 3.1. Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
Collect data to evaluate long-term impacts following remediation by ISB and MNA in low permeability zones at field sites	• CVOC concentrations in saturated soil and groundwater • Geochemical concentrations in groundwater • Microbial and mineralogical parameters in soil and groundwater	• Sample collection at 100% of targeted areas
Evaluate long-term remediation impacts following ISB and MNA in low permeability zones at field sites	• Existing pre-treatment and post-treatment monitoring data, and new long-term post-treatment monitoring data to be collected as part of field demonstration	• Data are sufficient to evaluate long-term CVOC concentration trends and extent of degradation • Data are sufficient to evaluate long-term geochemical changes • Data are sufficient to evaluate microbial and mineralogical conditions

The performance objectives included in Table 1 are different than those for typical technology demonstrations because this project focused on evaluating occurrence of, and better characterizing, natural processes. As such, there is no anticipated "performance" that can be objectively evaluated for this project. Instead, the goal is to collect site-specific data to document the extent to which current conditions support sustained treatment and natural attenuation in low-K zones. Consequently, an evaluation of whether or not the project met its objectives cannot be solely based on the number of locations where these processes were confirmed.

Furthermore, the results of these characterization efforts will also be used to support site-specific remedial decision-making. Even if data show that post-ISB sustained treatment or natural attenuation in low-K units is not occurring, this is valuable information for updating conceptual site models and guiding near-term and long-term site management decisions.

3.1 DATA COLLECTION AND ANALYSIS OBJECTIVES

Evaluating long-term groundwater impacts following ISB or MNA of chlorinated volatile organic compounds (CVOCs) was the primary objective of the project. In addition to analysis of CVOC concentration trends, which are of primary concern and often the only parameters monitored following remediation, our study included geochemical parameters that may secondarily impact water quality, as well as microbial and mineralogic data. For sustained treatment, such data can provide useful information on decay rates, rebound suppression, and longevity of these benefits following an ISB remediation project. For MNA in low-K zones, these data can provide additional information on natural attenuation processes in low-permeability zones and future groundwater quality impacts resulting from back diffusion of CVOCs out of such zones.

3.1.1 Data Requirements and Uses

Data required for the evaluation of these processes included: i) CVOC concentrations in soil and groundwater from both transmissive and low-K zones; ii) geochemical parameter concentrations in groundwater; iii) microbial (e.g., biomarker) and mineralogic (e.g., magnetic susceptibility) parameters in soil and groundwater; and iv) fraction organic carbon (f_{oc}), as well as potentially-bioavailable organic carbon (PBOC) in the aquifer and low-K zones. For the single mulch biowall site, forage analysis was also performed to evaluate bioavailability of mulch substrate within the biowalls.

CVOC data were used to calculate long-term changes in groundwater concentrations at both MNA and ISB sites. These data were used to further evaluate occurrence of natural attenuation and sustained treatment at the interface of high and low permeability zones in the subsurface. The geochemical data were used to evaluate long-term changes in secondary water quality parameters. The microbial and mineralogical data were used to provide quantitative indicators for biotic and abiotic natural attenuation and sustained treatment processes. Organic carbon data (f_{oc} and PBOC) were used to quantify potential availability of carbon substrate to support biodegradation, as well as provide new key data on sorption potential in low-K zones.

4.0 SITE DESCRIPTIONS

4.1 SITE LOCATION AND HISTORY

4.1.1 Location and History of Sustained Treatment Sites

Altus AFB, Oklahoma: Mulch Biowalls

Altus Air Force Base (AFB) is located in southwestern Oklahoma. In May and June 2005, approximately 5,300 linear feet of mulch biowalls were installed to a depth of approximately 35 feet (ft) below ground surface (bgs) to treat chlorinated solvents in groundwater originating from spill sites SS-17, SS-18, and SS-23. The spill sites and mulch biowalls are shown on Figure 4.1.

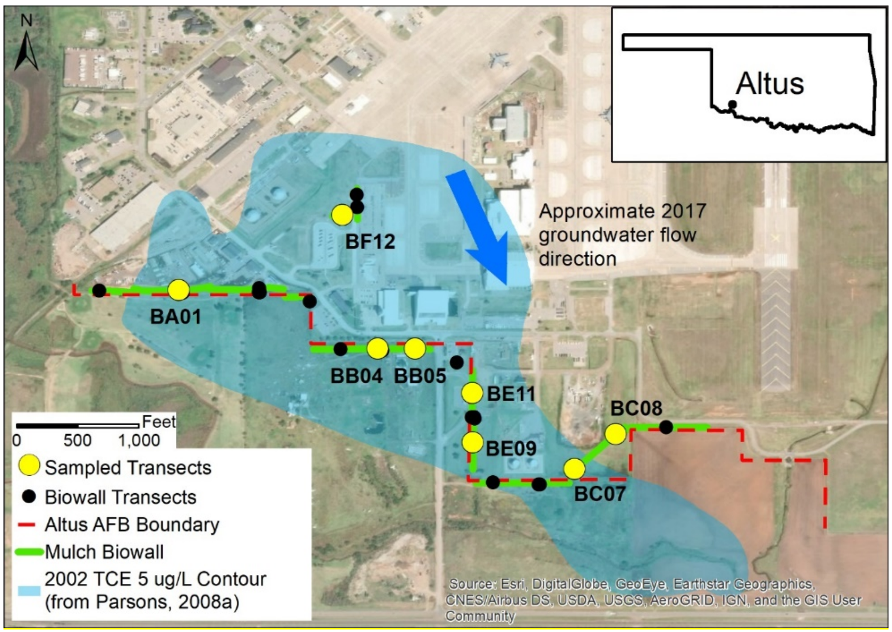


Figure 4.1. Altus AFB TCE Isoconcentration Map in 2002.

Sampled biowall transects are also shown. (Source: Figure 1, Walker et al., 2020)

Since 2005, there has been only minimal work performed at the site that focuses on the performance of the biowalls. In 2008, a supplemental remedial action was implemented to treat chlorinated solvents in the deeper Intermediate Flow Zone, from approximately 35-50 ft bgs, that were originating from Building 506, the presumed source of the SS-17 TCE plume (Parsons, 2009). This event involved injecting a carbon substrate through 16 injection wells upgradient of Section B of the 2005 biowall. Two locations at the SS-17 biowall (B04U-BB04W, B05U-BB05W) were included in the biogeochemical studies described by Whiting et al. (2014).

Kelly AFB, Texas: Emulsified Oil Injections

The former Kelly AFB was established in 1917 and utilized until closure in 2001. It is located on the edge of the Western Gulf Coastal Plains in Bexar County, Texas, approximately 7 miles southwest of downtown San Antonio. The 300 Area Waste Management Area (WMA) encompasses the majority of Zone 3 at Kelly AFB, which includes Building 331. Zone 3 was largely an industrial complex with numerous shops and facilities providing maintenance support, including automotive maintenance, a metal plating facility, a container storage area, solvents, aboveground storage tanks, and cleaning line operations. A comingled PCE and TCE plume is present within the 300 Area WMA. Extensive remediation has been conducted surrounding the various buildings within Zone 3, including an injection program implemented in May 2012 at Building 331.

In May 2012, emulsified vegetable oil (EVO) and a bioaugmentation culture (SDC-9) were injected into the saturated zone at Building 331 in a 25 ft by 25 ft grid pattern using direct push technology (DPT). The injection array was generally centered around well ST008MW157. Approximately 10,000 gallons of mixture were injected at an average rate of 13 gpm and an average pressure of 95 psi. Substrate volumes ranged between 140 gallons and 1,000 gallons at each injection point, with 500 gallons injected into 14 of the 19 locations.

The target injection interval was 19-29 feet bgs at Building 331. However, the mixture was applied as planned at only two locations in two five-foot intervals over the 10-foot target depth interval. At the remaining injection points, the volume was injected into one interval 5 feet or less into the saturated zone.

The specific area targeted for post-treatment ISB sampling and testing activities at Kelly AFB was monitoring wells ST008MW157 (within former treatment zone), ST008RW256 (within former treatment zone), and SS037MW307 (upgradient of former treatment zone), located within the Building 331 area (Figure 4.2).

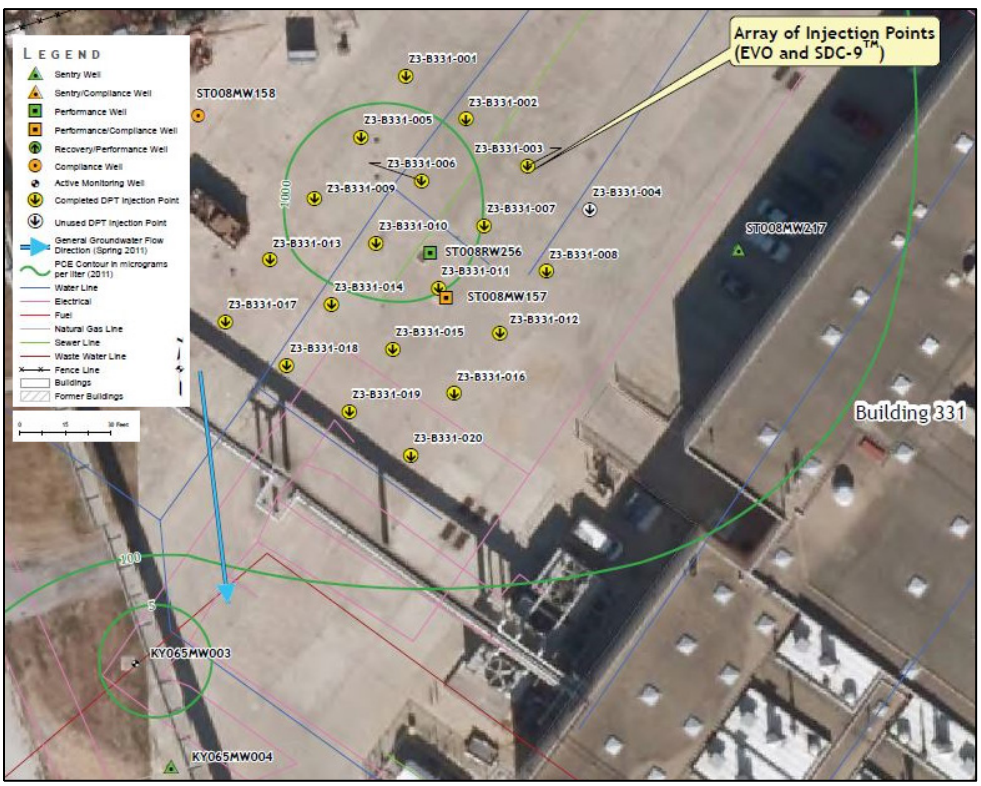


Figure 4.2. Kelly AFB Injection Point Locations at Building 331.

(Source: Figure 3-1 from Shaw, 2012. Final Construction Completion Report for In Situ Enhanced Bioremediation Injections at Site SS037 Zone 3 Groundwater (SWR No. 31750, Former Kelly Air Force Base, San Antonio, Texas. Contract No. FA8903-09-D-8580, Task Order No. 011, Report/Project No. 143253, Rev. 0, October)

NTC Orlando, Florida: Emulsified Oil Injections

Naval Training Center (NTC) Orlando was built in 1940 and is located in central Florida just north of the Orlando Executive Airport. It was initially established as Orlando Army Air Base and operated as an air force base until 1968 when it was re-designated as NTC Orlando. The site served as a training facility until the Fall of 1999 when it was sold to the City of Orlando and is currently owned by a private development company. The field demonstration was completed in study area 17 (SA-17). SA-17 occupies approximately 9 acres in the central part of the McCoy Annex at the former NTC Orlando. A shallow drainage ditch runs through the southern portion of the property. The site historically housed buildings used for motor pool storage and maintenance which included a wash rack with drainage to a former leach bed and a building used to store hazardous and flammable materials. Additionally, there was a drum and transformer storage area at the site.

Previous site activities related to the motor pool area were suspected to have contributed to subsurface soil and groundwater impacts by TCE. In 2006, an injection of an EVO substrate was conducted using a groundwater extraction and recirculation system to enhance the bioremediation of CVOCs. The injection layout consisted of six injection wells arranged in a circle around a central extraction well, and each injection well targeted two zones: Zone B (15-25 ft bgs) and Zone C (30-40 ft bgs). Approximately 2,410 gallons of an 8% dilution of concentrated EOS 598B42 (1,470 lbs) were injected into Zone B, followed by 30,500 gallons of chase water. Approximately 9,840 gallons of 8% dilution (6,090 lbs) were injected into Zone C, followed by 35,600 gallons of chase water. The EOS 598B42 mixture included 60% soybean oil, 4% soluble substrate, 10% emulsifiers, and vitamin B-12.

In 2008, a "polishing" injection of EVO was performed because of the continued elevated TCE concentrations. Approximately 140 gallons of 6% EOS 598B42 solution was injected via DPT at three locations near monitoring well OLD-17-55B and three locations near monitoring well OLD-17-56B. Post-injection monitoring revealed the polishing event had induced enhanced reductive dechlorination and increased the concentrations of daughter products cis-1,2-dichloroethene (cis-DCE) and vinyl chloride (VC). Note that these 2008 injections targeted the B horizon only.

In February 2012, an additional injection was conducted. Due to suboptimal pH levels, a buffered-EVO product was used to increase the pH of the aquifer (Solutions-IES, 2014). Injections were performed in five existing injection wells and one existing extraction well. A total of 1,680 lbs EOS 589B42 and 525 lbs of AquaBupH™ were distributed evenly between the six Zone B injection wells, with identical amounts injected into Zone C injection wells. Total fluid injection volumes were 47,330 gallons into Zone B and 63,185 gallons into Zone C. The AquaBupH™ contained 39% soybean oil, 4% soluble substrate, 7% emulsifiers, and 10% $Mg(OH)_2$.

The specific area targeted for post-treatment ISB sampling and testing activities at NTC Orlando was monitoring wells OLD-17-53C2 (within former treatment zone), OLD-17-55C (within former treatment zone), and OLD-17-10C (upgradient of former treatment zone), located within the SA-17 area (Figure 4.3).

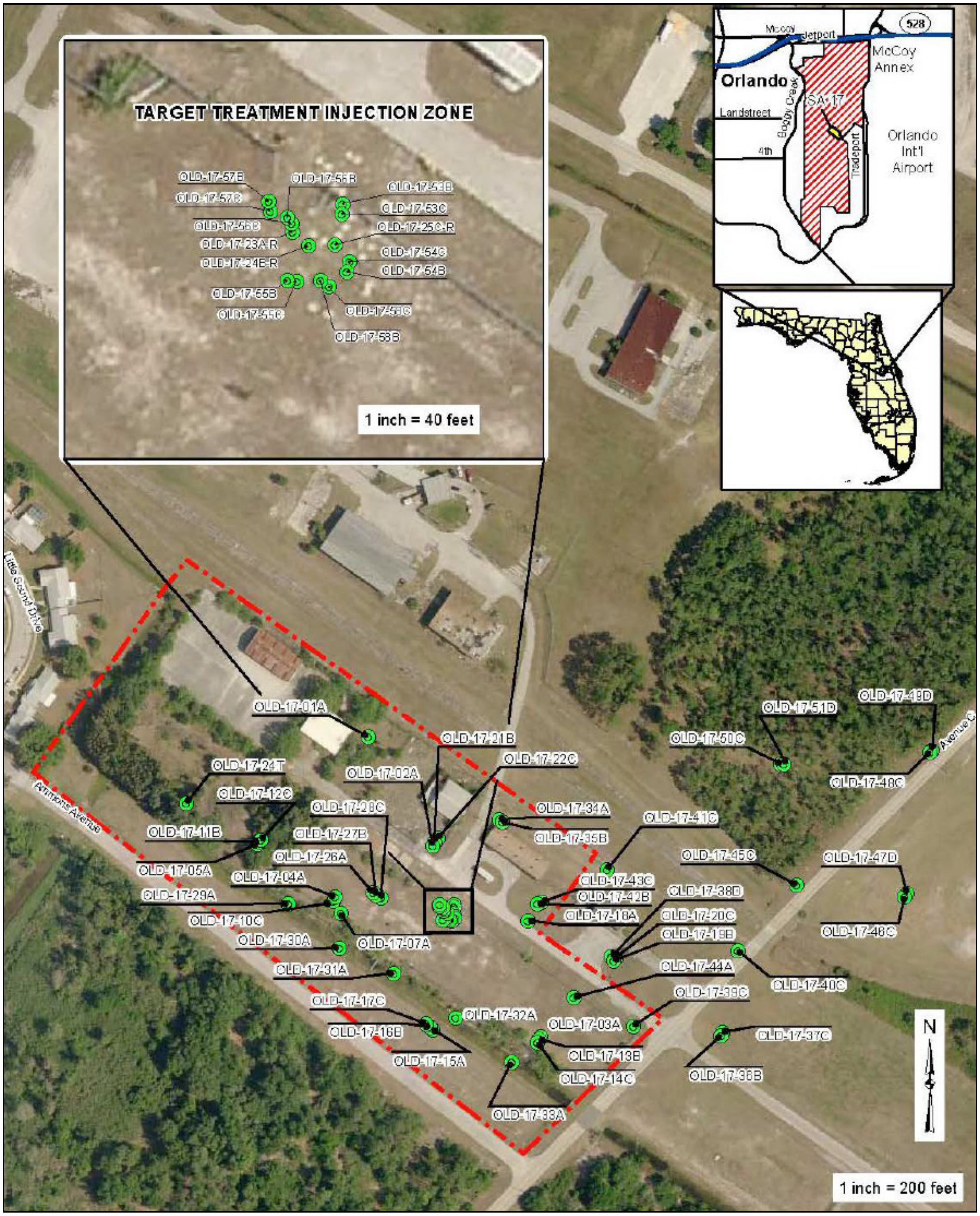


Figure 4.3. NTC Orlando SA-17.

(Source: Figure 2 from Borden, Robert C., 2017. Post-Remediation Evaluation of EVO Treatment – How Can We Improve Performance. ESTCP Project ER-201581, November)

4.1.2 Location and History of Low-K MNA Sites

England AFB

The former England AFB is located in Rapides Parish, in central Louisiana. Encompassing 2,604 acres, the former base lies approximately 5 miles west of the cities of Alexandria and Pineville and about 1 mile southwest of the Red River. Former England AFB was originally constructed as Alexandria Municipal Airport in 1942 and then leased to the Army Air Force by the City of Alexandria with national mobilization for World War II (CB&I, 2014b). Sampling and testing activities for this project were conducted at Site SS-45 as further discussed below.

Site SS-45 is located within the southeastern portion of the former England AFB property boundary and was initially identified as Area of Concern (AOC) 39 during the Comprehensive Background Study (CBS) completed in 1995. The AOC originated as a result of groundwater sampling data indicating that TCE was present above the Maximum Contaminant Level (MCL). Investigations indicate that Site SS-45 currently consists of an approximately 144-acre area of groundwater containing CVOCs (CB&I, 2014b). No active groundwater treatment has been performed in this area. The specific area targeted for MNA sampling and testing activities at England AFB was monitoring well A39L009PZ located within the SS-45 area (Figure 4.4).

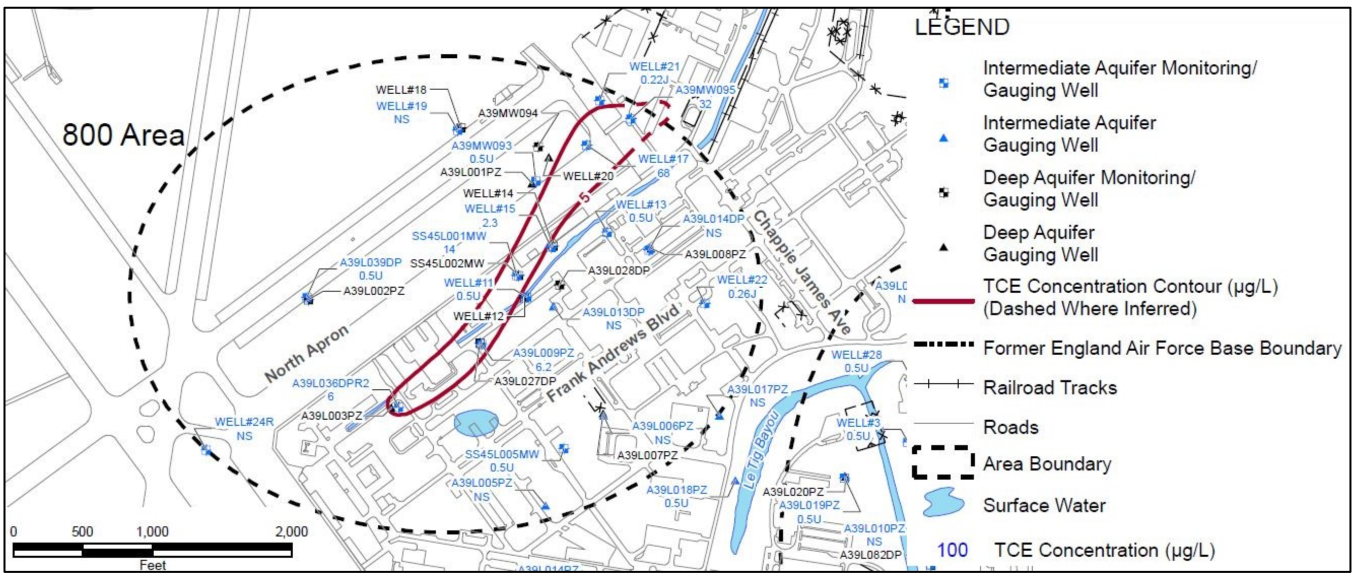


Figure 4.4. England AFB TCE Isoconcentration Map for Intermediate Groundwater Zone in October 2013.

(Source: Modified from Figure 5.3 from CB&I Federal Services LLC, 2014. Final 2013 Annual Monitoring Report, Spill Site SS-45 A(SWMU 332), Former England Air Force Base, Alexandria, Louisiana, Agency Interest No. 9029, South PBC-2, Contract No. FA8903-08-C-8000, August)

Hill AFB

Hill Air Force Base was built in 1939 in northern Utah, just south of the city of Ogden. Beginning in 1944, Hill field was utilized for the long-term storage of surplus aircraft and associated equipment that had been replaced by newer models. In the 1960s, Hill began to service and perform maintenance on jet warplanes to support the Vietnam War. Hill AFB continues to provide maintenance support for air combat systems to the present day. The field demonstration will be conducted in the off-base portion of Operable Unit 2 (OU-2).

OU-2 is located along the northeastern boundary of Hill AFB overlooking the Weber River Valley and is one of 13 Operable Units at Hill AFB in various stages of corrective action. OU-2 spans across the base boundary with the on-base portion located upon relatively flat ground, while the off-base portion consists of a steep, terraced, north-facing escarpment that is the south wall of the Weber River Valley, with the well of interest just beyond this escarpment on level ground. There is about 300 feet of relief between Hill AFB and the valley below. Parts of this hillside are unstable and are known as the Weber Landslide Complex. Numerous seeps and springs occur along the hillside (URS, 2003).

Records indicate that from 1967 to 1975, an estimated 45,000 to 50,000 gallons of spent chlorinated organic solvents from degreasing operations were disposed in trenches ("chemical pits") at the site. These compounds were placed into two unlined disposal trenches trending north northwest, which are estimated to have been approximately 6 to 9 feet deep, 10 feet wide, and approximately 50 to 100 feet long (URS, 2003). This resulted in a CVOC groundwater plume that extends approximately 1,500 feet downgradient of the former disposal trenches.

To address the groundwater impacts at OU-2, several remedial actions have been conducted. The remedial actions included conventional source recovery operations (pump-and-treat) and containment measures to impede off-site migration, as well as innovative treatability studies focused on enhanced DNAPL removal from the source area. The existing remedial systems located at OU-2 include the Source Recovery System (SRS), Containment Wall, Upgradient Control System (UCS), Air Stripper Treatment Plant (ASTP), Griffith Pool DNAPL Extraction System, North Interceptor Trench (NIT), Spring U2-326 Interceptor Trench, and Spring U2-304 Seep Interceptor Trench (ERB, 2009). Sampling and testing activities for this project were conducted approximately 750 feet downgradient of these source treatment zones in an area of the groundwater plume that has not been treated. The specific area targeted for MNA sampling and testing activities at Hill AFB was monitoring well U2-043 (Figure 4.5).

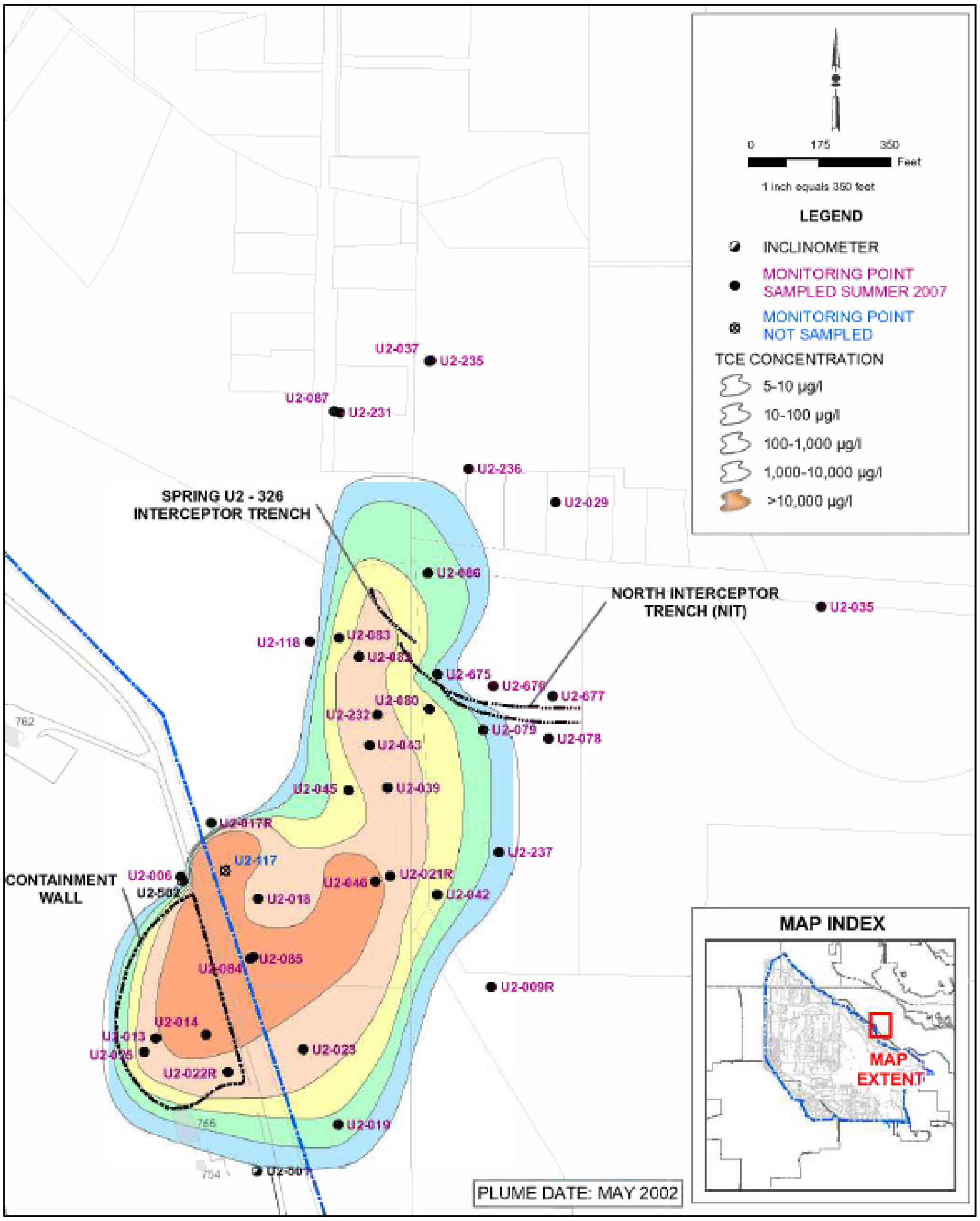


Figure 4.5. Hill AFB TCE Isoconcentration Map at OU-2 in May 2002.

(Source: Figure 2-1 from CH2MHill, 2007. Analytical Data Validation Report for the Summer 2007 Operable Unit 2 Groundwater Monitoring Point Sampling Round. Hill Air Force Base Long-Term Groundwater Monitoring Project, Hill Air Force Base, Contract No: F42650-03-D-0002, Task Order 0019, December.)

Kelly AFB

The former Kelly AFB was established in 1917 and utilized until closure in 2001. It is located on the edge of the Western Gulf Coastal Plains in Bexar County, Texas, approximately 7 miles southwest of downtown San Antonio. The geography around the former Kelly AFB consists of gently undulating prairie, generally sloping to the southeast toward the Gulf of Mexico.

The topography across the former Kelly AFB is generally flat. The former Kelly AFB is situated between a semi-arid area to the west and the coastal area of heavier precipitation to the east (HydroGeoLogic, 2010). Sampling and testing activities for this project were conducted at the 300 Area Waste Management Area (WMA), Building 348 in Zone 3, of the former Kelly AFB as further discussed below.

The 300 Area WMA encompasses the majority of Zone 3 at Kelly AFB, which includes Building 348. Zone 3 was largely an industrial complex with numerous shops and facilities providing maintenance support, including automotive maintenance, a metal plating facility, a container storage area, solvents, aboveground storage tanks, and cleaning line operations. A comingled PCE and TCE plume is present within the 300 Area WMA. Extensive remediation has been conducted surrounding the various buildings within Zone 3, however an untreated zone exists outside and downstream of Building 348. Building 348 was constructed in 1980 and served as a test center for engine fuel cells. The specific area targeted for MNA sampling and testing activities at Kelly AFB was monitoring well KY036MW026 located within the Building 348 area of the 300 Area WMA (Figure 4.6).

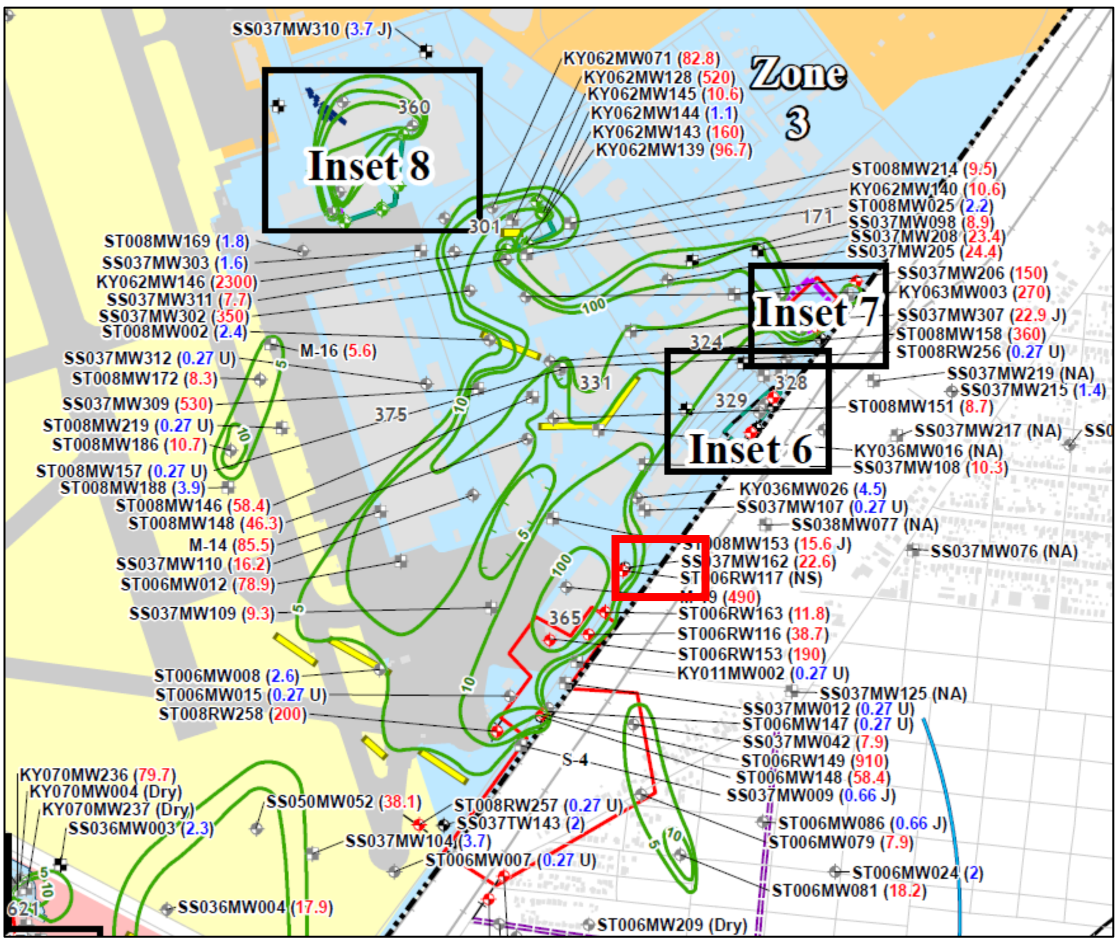


Figure 4.6. Kelly AFB PCE Isoconcentration Map for Zone 3 in 2013.

(Note: Building 348, where MNA activities were conducted, is identified in red outline) (Source: Figure C-2 from CB&I, 2014. Semiannual Compliance Plan Report, July through December 2013, Volume 1. Former Kelly Air Force Base, San Antonio, Texas. TCEQ SWR No. 31750, CN600919401, RN102338480, EPA ID No. TX2571724333. Contract No. FA8903-09-D-8580, Task Order No. 0011, Project No. 143253, Rev. 0, January)

4.2 SITE GEOLOGY/HYDROGEOLOGY

4.2.1 Site Geology/Hydrogeology at Sustained Treatment Sites

Altus AFB: Mulch Biowalls

Altus AFB is underlain primarily by the Hennessey Group of Permian age, which consists of reddish-brown shale with interbedded siltstone and sandstone; this unit ranges in thickness from 200 to 1,000 ft in southwest Oklahoma (Parsons, 2006; Parsons, 2009). The upper 40 ft of the subsurface is predominantly fill, weathered shale, and alluvium that becomes more competent with depth. Shallow groundwater primarily flows within two distinct zones: (1) a less consolidated weathered clay and alluvium material that extends to a depth of approximately 20 to 30 ft bgs, and (2) and an underlying layer of well cemented, better lithified shale that extends to a depth of approximately 40 to 50 ft bgs. The weathered shale has little intrinsic permeability but contains substantial quantities of soluble gypsum and anhydrite that has allowed secondary permeability to develop in dissolution cavities. The presence of the gypsum and anhydrite appears to accentuate flow along pre-existing fractures and bedding planes where high concentrations were present. Shallow groundwater is typically unconfined and flows generally to the southeast in the vicinity of SS-17, SS-18, and SS-23. A typical geologic cross-section of the shallow aquifer is provided in Figure 2.

Monitoring wells have been installed in the vicinity of the biowalls to target various intervals within the shallow groundwater zone. As shown on Figure 4.7, this includes "Upper" wells that focus on the unconsolidated clays and alluvium, "Lower" and "Intermediate" wells with screens that extend into the weathered shale, and "Deep" wells that are solely within the deeper shale. In addition, there are a series of Intermediate wells that are designated as either "Upper Intermediate Zone" or "Lower Intermediate Zone" wells. The "Upper" and "Lower" wells are screened within the same depth zone as the mulch biowalls, whereas the other wells are primarily screened at depths below the bottom of the mulch biowalls.

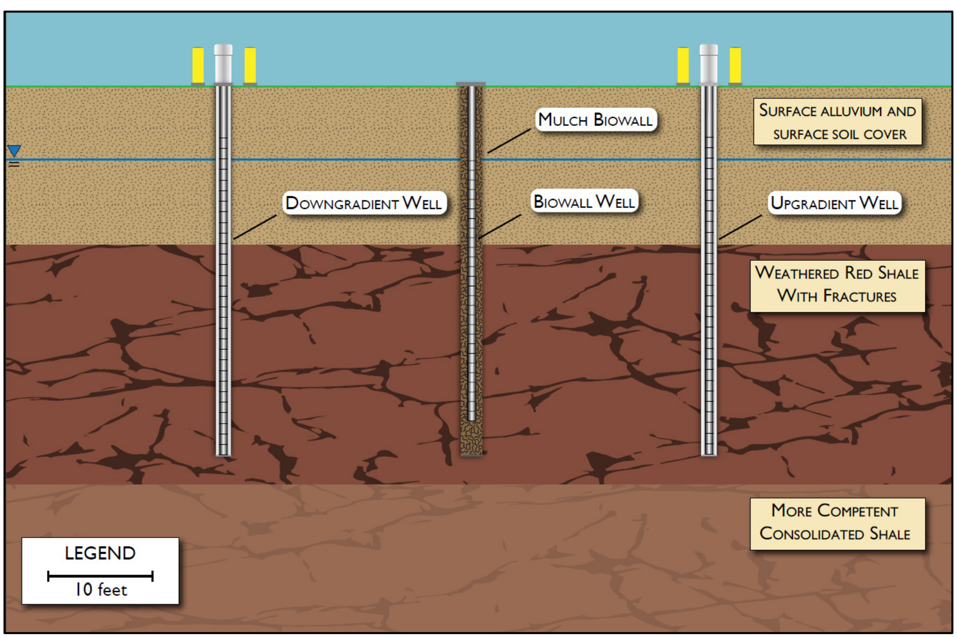


Figure 4.7. Conceptual Cross-Section for Altus AFB Biowalls and Monitoring Wells.

Kelly AFB: Emulsified Oil Injections

Two distinct aquifers underlie the former Kelly AFB: a shallow alluvial aquifer and the Edwards aquifer, a deep regional aquifer. Low permeability clay and limestone separate these aquifers by as much as 1,250 feet. Shallow groundwater is encountered within the basal gravel that lies directly atop the Navarro Clay. The Navarro Clay has a vertical hydraulic conductivity in the range of 5.2×10^{-7} to 1.5×10^{-9} centimeters per second (cm/sec) and acts as an aquitard separating the shallow aquifer from the underlying Edwards Aquifer. Sampling and testing activities targeted the alluvial aquifer zone and the underlying Navarro Clay layer.

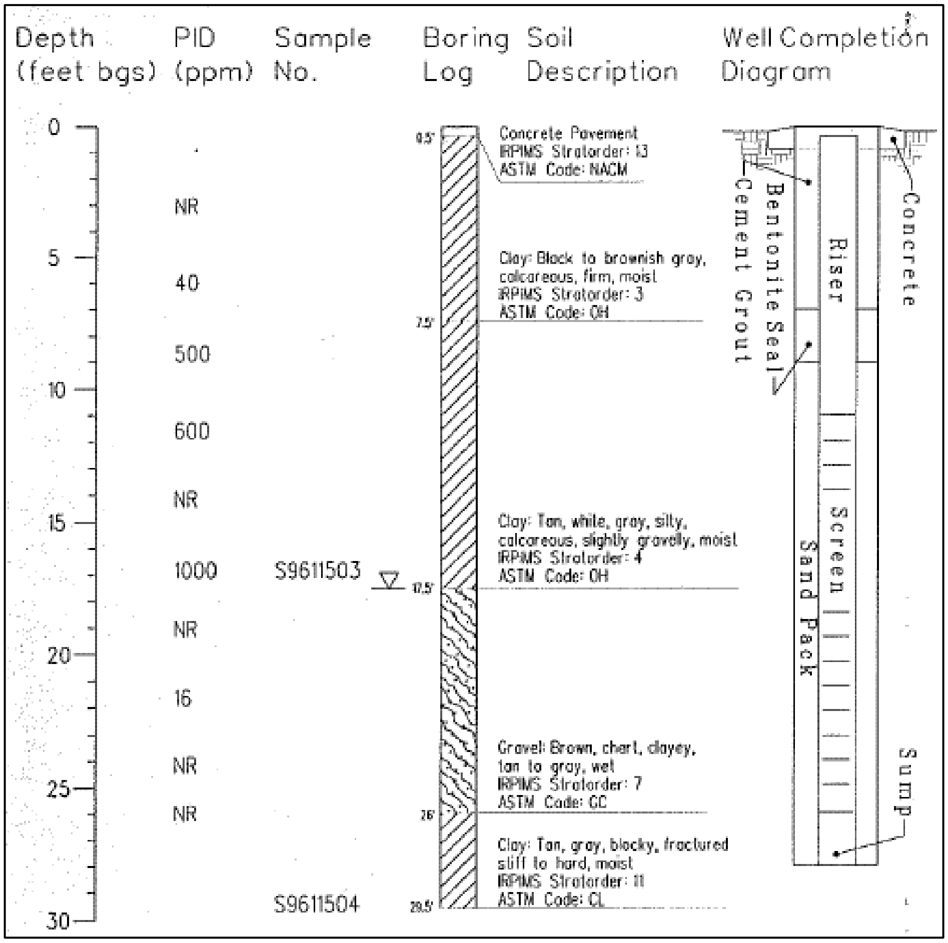


Figure 4.8. Monitoring Well Log for KY036MW026 at Kelly AFB.

NTC Orlando: Emulsified Oil Injections

The upper 30 feet of soils at SA-17 are typically fine-grained quartz sand except for two thin discontinuous layers of silty sand (approximately 5- to 10-feet thick). The upper layer of the silty sand lies at about 10 to 15 feet bgs and appears to dip to the east and northeast. The lower layer of silty sand lies at about 25 to 30 feet bgs and appears to be continuous across the site but thins slightly to the north and east in the area investigated. Groundwater analytical results suggest that these silty layers act as sorptive zones.

Below the lower layer of silty sand is an interval of fine- to coarse-grained sand that extends from about 30 to 50 feet bgs. This interval is underlain by another silty-sand layer that extends from 50 to 65 feet bgs, which is in turn underlain by approximately 10 feet of sandy, silty clay of the Hawthorn Group. This clay is considered an aquitard and represents the bottom of the surficial aquifer. The clay is underlain by fine- to coarse grained sand of the Hawthorn Group.

The groundwater flow direction in the deep portion of the aquifer, below the lower silty sand interval (30 to 50 feet bgs; Zone C wells), follows a more regional gradient toward the northeast suggesting that local recharge has little influence on this interval. Flow in this zone is to the east near the center of SA-17 and becomes northeast where it crosses the original SA-17 site boundary. Groundwater flow conditions indicate that groundwater moves downward through the surficial aquifer (Zones A through C) and becomes predominantly horizontal in Zone C Field demonstration activities for this project targeted the intermediate zone C and the underlying low-K layer.

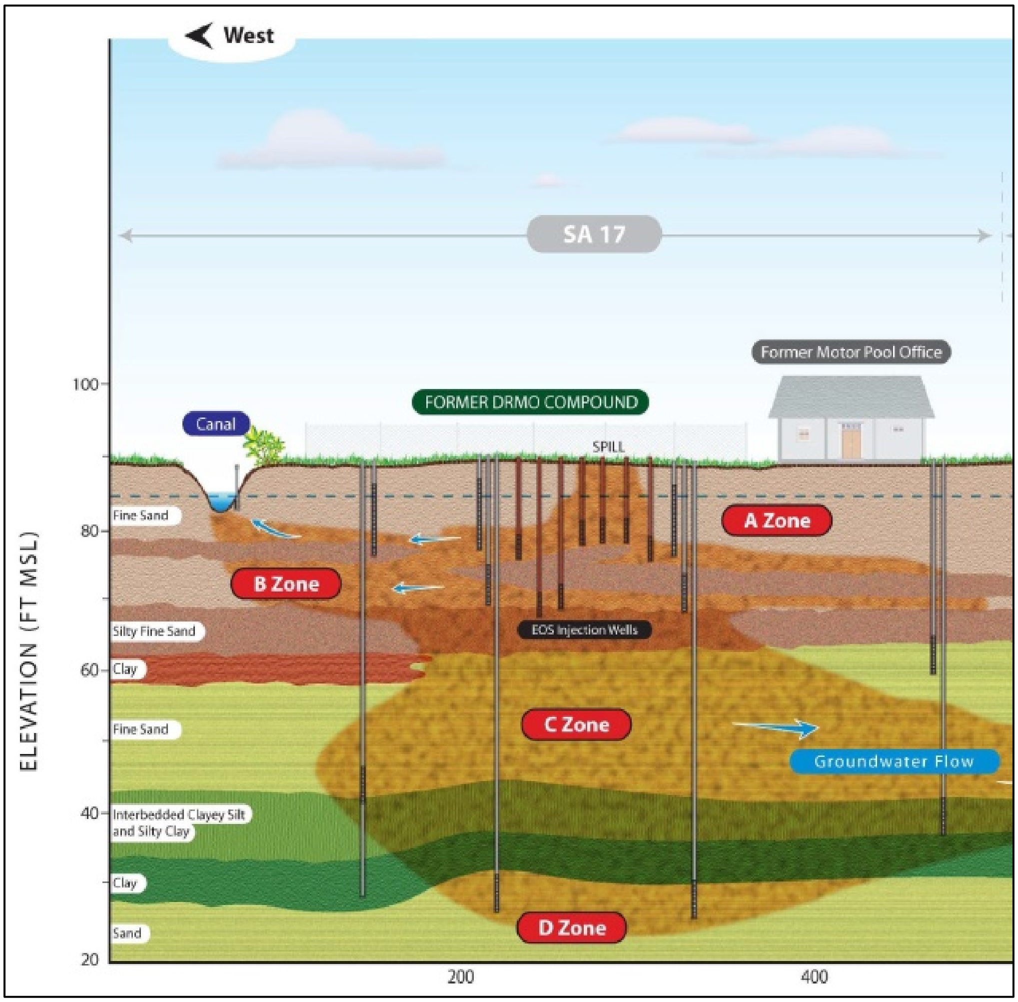


Figure 4.9. Cross-Section for NTC Orlando SA-17.

(Source: Figure 9 from Resolution Consultants, 2013. Long Term Monitoring Optimization Report for Study Area 17 (SA 17), Former NTC Orlando FL, N65928.PF.002905, NTC Orlando, 5090.3b, November 26)

4.2.2 Site Geology/Hydrogeology at Low-K MNA Sites

England AFB

The lithology if the SS-45 area consists of alluvium of the Red River Valley and the underlying Miocene deposits. The average thickness of the Red River alluvium is approximately 90 feet and consists of two main units: an upper zone with an average thickness of 40 feet and a lower zone occurring from 40 to 120 feet bgs. The upper zone is predominantly silts, clays, and sandy silts. The lower zone is comprised of an intermediate sand, intermediate clay, and deep sand. The intermediate sand occurs from 0 to 62 feet bgs with an average thickness of 37 feet. The intermediate sand is underlain by a distinctive but irregular intermediate clay with an average thickness of 11 feet. Groundwater occurs at shallow depths in the alluvium under both partially confined and unconfined conditions. (CB&I, 2014b). A hydrogeological cross-section through the 800 Area is shown on Figure 4.10. Field demonstration activities for this project targeted the intermediate sand and the underlying intermediate clay layer.

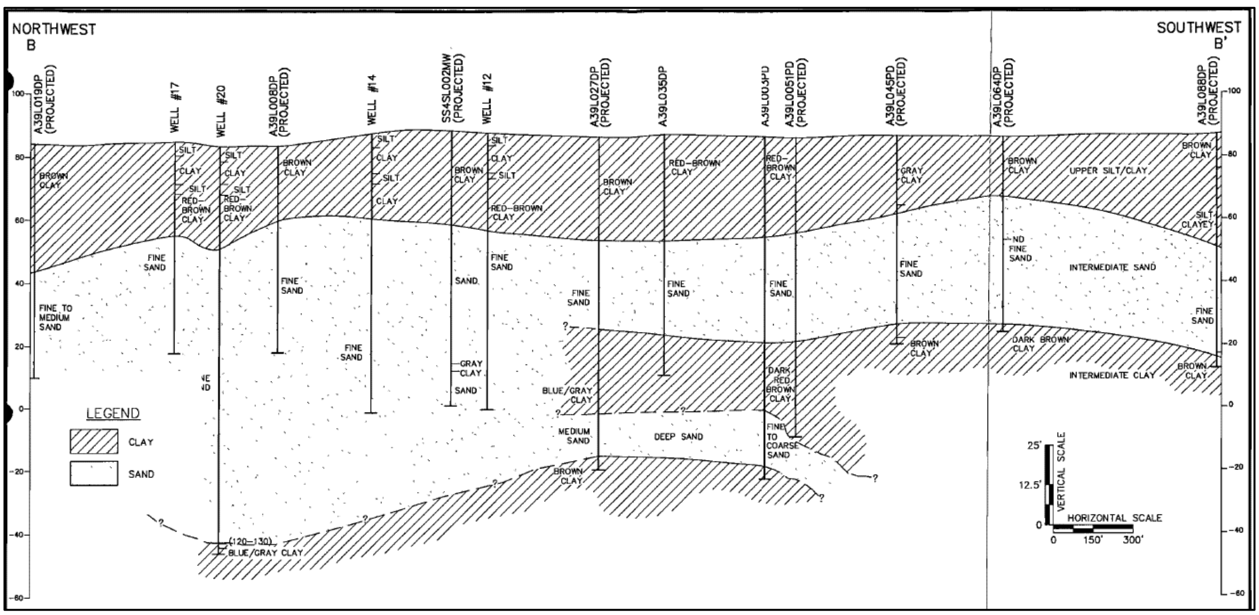


Figure 4.10. Cross-Section at SS-45 Area for England AFB.

(Source: Figure 3.4-3 from Parsons Engineering Science, Inc., 2000. Final Focused Corrective Measures Study for Groundwater at Site SS-45, England Air Force Base, Alexandria, Louisiana, Volume 1. February)

Hill AFB

Groundwater occurs in two aquifers beneath OU 2 at Hill AFB: in a shallow system, under confined and semiconfined conditions; and in the deep Delta aquifer which is the main water supply aquifer in the Ogden region. The Sunset aquifer, also an important regional water supply aquifer, occurs beneath the western and southwestern portions of Hill AFB, but is not present beneath OU 2. Groundwater contamination stemming from solvent disposal at OU 2 occurs only in the shallow groundwater system. Depth to groundwater in the shallow system is generally less than 10 feet below ground surface (bgs) in the off-base area and 20 feet bgs in the on-base area (URS, 2003).

The disposal area is underlain by an alluvial sand aquifer of the Provo formation that is composed of a heterogeneous mixture of sand and gravel contained in a narrow buried ancient river channel incised deeply into the underlying clay deposit. This clay deposit, known as the Alpine Formation, forms a barrier to the downward migration of DNAPL. The maximum observed horizontal conductivity of 0.69 cm/sec occurs in the gravelly sand, whereas the lower permeability clays and silts of the Alpine Formation exhibit conductivities of less than 7.1 x 10^{-8} cm/sec. The estimates of horizontal hydraulic conductivity in the discontinuous lower sand of the Provo Formation are highly variable, indicative of the heterogeneous character of this material type (URS, 2003). A generalized stratigraphic column for OU2 is included as Figure 4.11. Field demonstration activities for this project targeted the Provo alluvium and the underlying low-K layer of the Alpine formation.

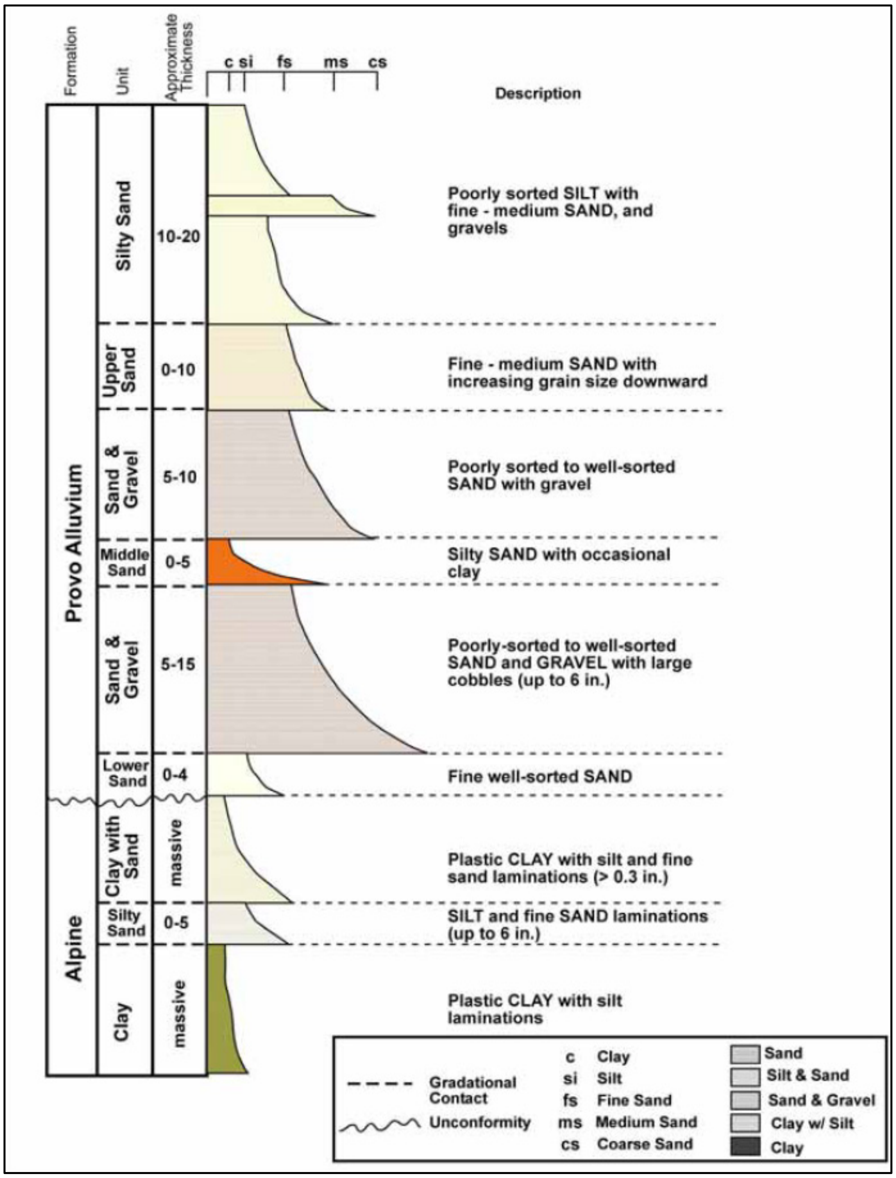


Figure 4.11. Generalized Stratigraphic Column for the OU-2 Source Zone at Hill AFB.

(Source: Figure 3-3 from URS & Intera, 2003. Conceptual Model Update for Operable Unit 2 Source Zone, Hill Air Force Base, Utah, September.)

Kelly AFB

Site geology/hydrogeology for the MNA sampling and testing activities was consistent with site conditions described above for the ISB sampling and testing activities.

4.3 CONTAMINANT DISTRIBUTION

4.3.1 Contaminant Distribution at Sustained Treatment Sites

Altus AFB: Mulch Biowalls

TCE is the primary CVOC within groundwater at Altus AFB spill sites SS-17, SS-18, and SS-23. The chlorinated solvent plume in SS-17 contains TCE, cis-DCE, and carbon tetrachloride, as well as associated degradation products VC, chloromethane, and chloroethane; the assumed source of this plume is Building 506. Another plume emanates from Facility 508 and contains both PCE and TCE. The SS-18 TCE plume originates in the vicinity of Building 394 and has migrated approximately 1,400 feet to the southeast across the southern boundary of Altus AFB and into the Elks Club Golf Course. A carbon tetrachloride plume also originates in the vicinity of Building 394 and extends 1,800 feet into the Elks Club Golf Course. The likely source area of SS-23 is near the southwest corner of Building 514. This plume commingles with the TCE plume associated with SS-22 and SS-17 to the west. Figure 4.1 above depicts the approximate extent of the CVOC plume exceeding MCLs at the site.

Kelly AFB: Emulsified Oil Injections

The primary constituents of concern for the Building 331 area at Kelly AFB are PCE (the parent compound), and daughter products TCE, cis-1,2-DCE, and VC. The plume is part of a large chlorinated solvent groundwater plume (a commingled PCE and TCE plume) that had several source areas within the 300 Area WMA. A PCE isoconcentration map for the 300 Area WMA in 2013 is provided in Figure 4.3 above.

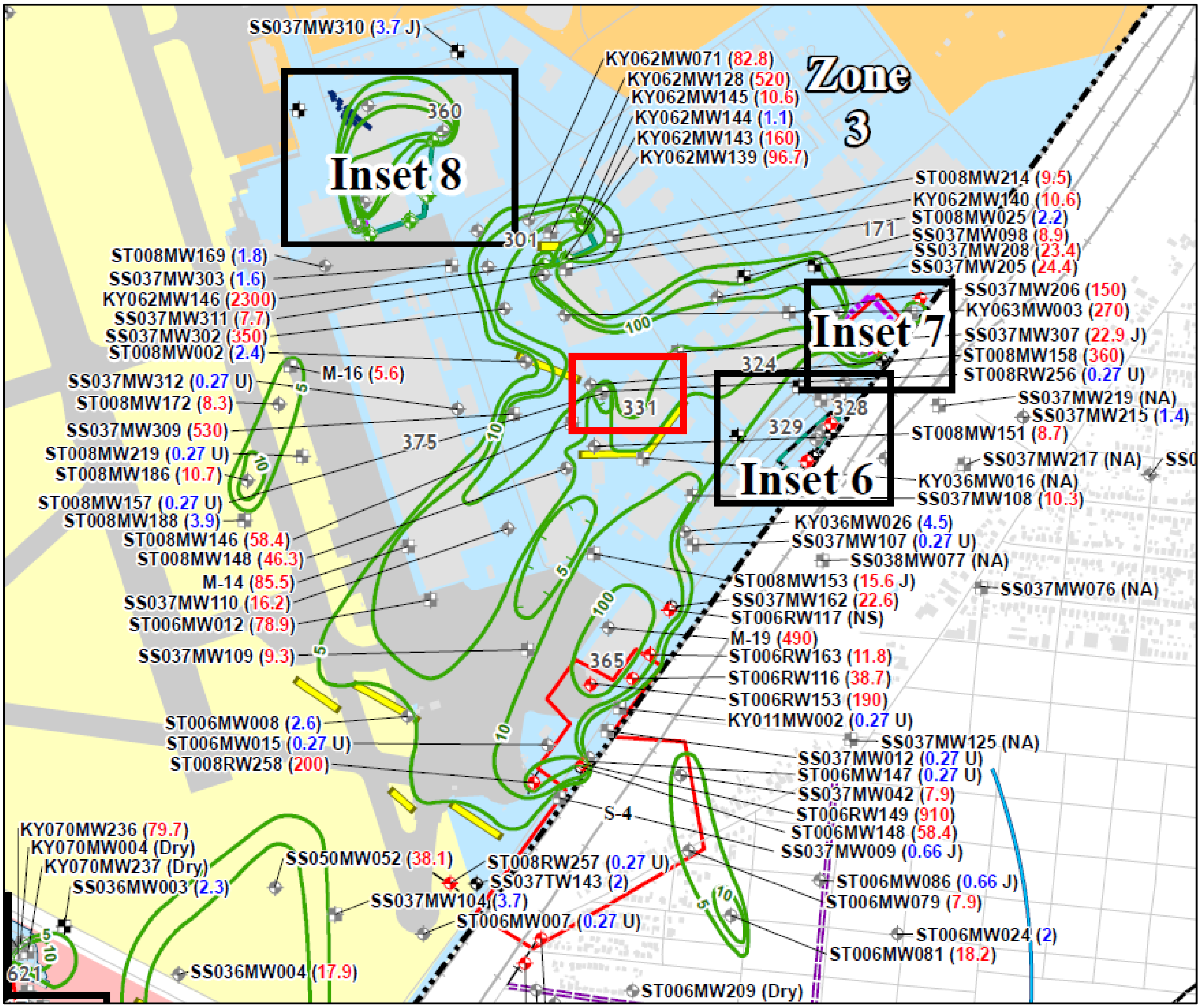


Figure 4.12. Kelly AFB PCE Isoconcentration Map for Zone 3 in 2013.

(Note: Building 331, where ISB activities were conducted, is identified in red outline)

NTC Orlando: Emulsified Oil Injections

In the western source area for SA-17, compounds detected at the highest concentrations were cis-DCE and VC. In the central portion, TCE was the dominant constituent detected, with reported concentrations up to 65,000 ug/L. The source of contamination has been attributed to spills and leaks from the former motor pool and wash rack operations at the site. The groundwater monitoring results from the October 2013 sampling event at SA-17 indicate significant concentrations of cis-DCE, TCE and VC.

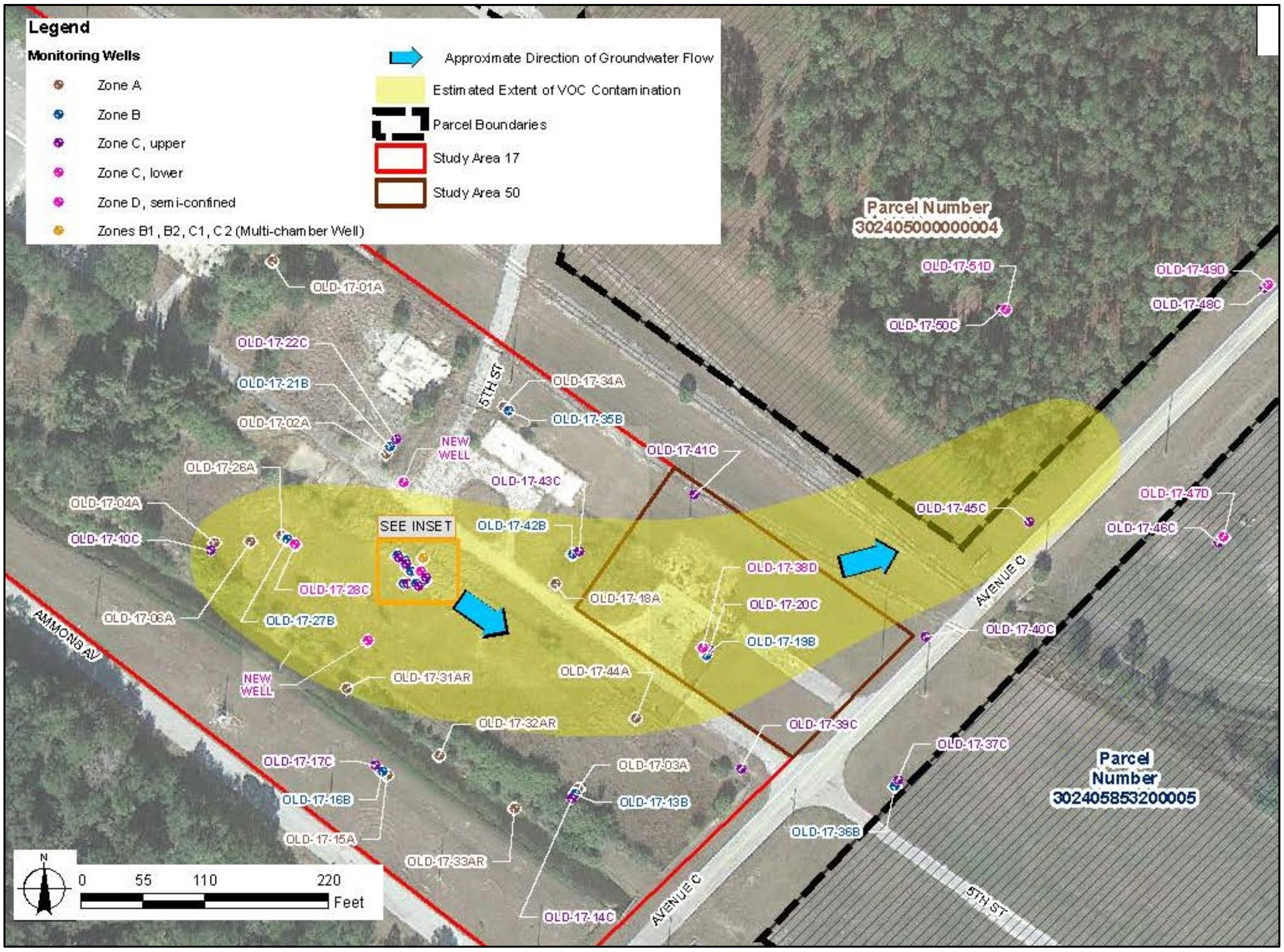


Figure 4.13. NTC Orlando SA-17 Estimated VOC Extent Map.

(Source: Figure 2-2 from Resolution Consultants, 2013. Long Term Monitoring Optimization Report for Study Area 17 (SA 17), Former NTC Orlando FL, N65928.PF.002905, NTC Orlando, 5090.3b, November 26)

4.3.2 Contaminant Distribution at Low-K MNA Sites

England AFB

Chlorinated solvent groundwater impacts are present within the Intermediate Sand (40 to 80 feet bgs) and the Deep Sand (90 to 120 feet bgs) units at SS-45. There have also been isolated historical chlorinated solvent detections in the shallow zone. The CVOCs in the SS-45 groundwater plume include, TCE, DCE, and VC. The plume now covers approximately 144 acres in the central portion of the Base. The groundwater plume at SS-45 is considered a single plume; however, the distribution of CVOCs and their concentrations vary in two distinct areas, called the "800 Area" and the "2500 Area" based on building numbers in the area of the impact. The 800 Area chosen for the demonstration is in the northwestern portion of the site near the North Apron where concentrations are reported above MCLs. The TCE concentration plume from 2013 in the 800 Area is shown on Figure 4.4 above.

Hill AFB

Disposal of the spent chlorinated solvents resulted in DNAPL impacts to the underlying shallow aquifer (the Provo Formation), predominantly as one or more pools above the clay (the Alpine Formation) and also as a "residual" phase held in the aquifer's pore spaces (the volume in between individual soil particles). The recovered DNAPL consists primarily of several chlorinated solvents (including PCE and TCE). Groundwater impacts are limited to the shallow, unconfined aquifer of the Provo Formation. The chlorinated solvent plume at OU-2 contains TCE as the primary parent compound (though lesser concentrations of PCE are also detected) and the associated degradation daughter products cis-DCE and VC. Figure 4.5 above shows the distribution of TCE at OU-2 in May 2002.

Kelly AFB

The primary constituents of concern for the Building 348 area at Kelly AFB are PCE (the parent compound), and daughter products TCE, cis-1,2-DCE, and VC. The plume is part of a large chlorinated solvent groundwater plume (a commingled PCE and TCE plume) that had several source areas within the 300 Area WMA. A PCE isoconcentration map for the 300 Area WMA in 2013 is provided in Figure 4.6 above. Extensive remediation has been conducted surrounding the various buildings within Zone 3; however an untreated groundwater zone exists outside and downstream of Building 348.

5.0 TECHNICAL APPROACH: ISB SUSTAINED TREATMENT

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The field demonstration design included sampling and testing of soil and groundwater at three sites where in-situ bioremediation was previously applied: Altus AFB, Kelly AFB, and NTC Orlando. The objective of the field demonstration was to evaluate long-term trends in remediation performance, as well as to assess the potential for sustained treatment to occur long after treatment. At each ISB site, samples were collected from within the former injection zone, as well as at a nearby upgradient monitoring well location, to analyze for geochemical or microbiological changes that potentially influence post-treatment CVOC concentration trends.

5.2 BASELINE CHARACTERIZATION

Baseline conditions, both chemical and hydrogeologic, have been previously defined through historical investigation and sampling events at each site. As such, baseline characterization was primarily limited to compilation and evaluation of historical data. However, sampling and testing activities at an untreated location upgradient of the treatment zone was conducted to provide data on untreated site conditions and water quality flowing into the treatment zone at each site.

5.3 DATA MINING ON THE OCCURRENCE OF SUSTAINED TREATMENT

As further described in Appendix B, a data mining study was performed to assess the occurrence of sustained treatment at a larger population of ISB sites having long post-treatment monitoring periods (i.e., greater than 3 years). The study was a continuation of the prior data mining efforts completed by the project team as part of former ESTCP project ER-201120. The prior study assessed sustained treatment at 34 ISB sites with 3 to 12 years of post-treatment monitoring. In the current study, original data sources were revisited for these 34 sites to determine if additional post-treatment monitoring had been conducted in the 5 years of elapsed time between the studies. 14 sites were identified with additional post-treatment data, which was appended to the existing data records. Analyses of concentration reductions and concentration trends were performed to determine the impact of the new data on the occurrence of sustained treatment versus rebound. Results from this larger population of sites from the data mining study were used to provide context and comparison of results from the field sites.

5.4 DESIGN AND LAYOUT OF FIELD TESTING

5.4.1 Biowall Site (Altus AFB)

At the Altus AFB SS-17/SS-18/SS-23 site, six mulch biowall segments were installed in 2005. During that time, 15 transects of three monitoring wells each were installed, with one well approximately 20 feet upgradient of the biowall, one well approximately 20 feet downgradient of the biowall, and one well within the biowall (see plan view of Figure 5.1).

Existing monitoring wells at eight transects were utilized for sampling groundwater within and surrounding the biowall treatment zones. At seven of the eight transects, a soil boring was advanced immediately adjacent to each of the three existing monitoring wells for collection of soil samples (note that all eight transects were initially planned for soil boring installation;

however one transect, BE11, soil sampling was not possible due to the presence of overhead electrical lines). Two soil samples were collected per boring at upgradient and downgradient locations and three soil samples were collected per boring within the mulch biowall (see section view of Figure 5.1). Table 5.1 lists the eight selected biowall transects and the rationale for their selection, and the locations of these transects are shown on Figure 4.1. No permanent groundwater monitoring wells were installed and soil borings were backfilled upon completion of sampling activities.

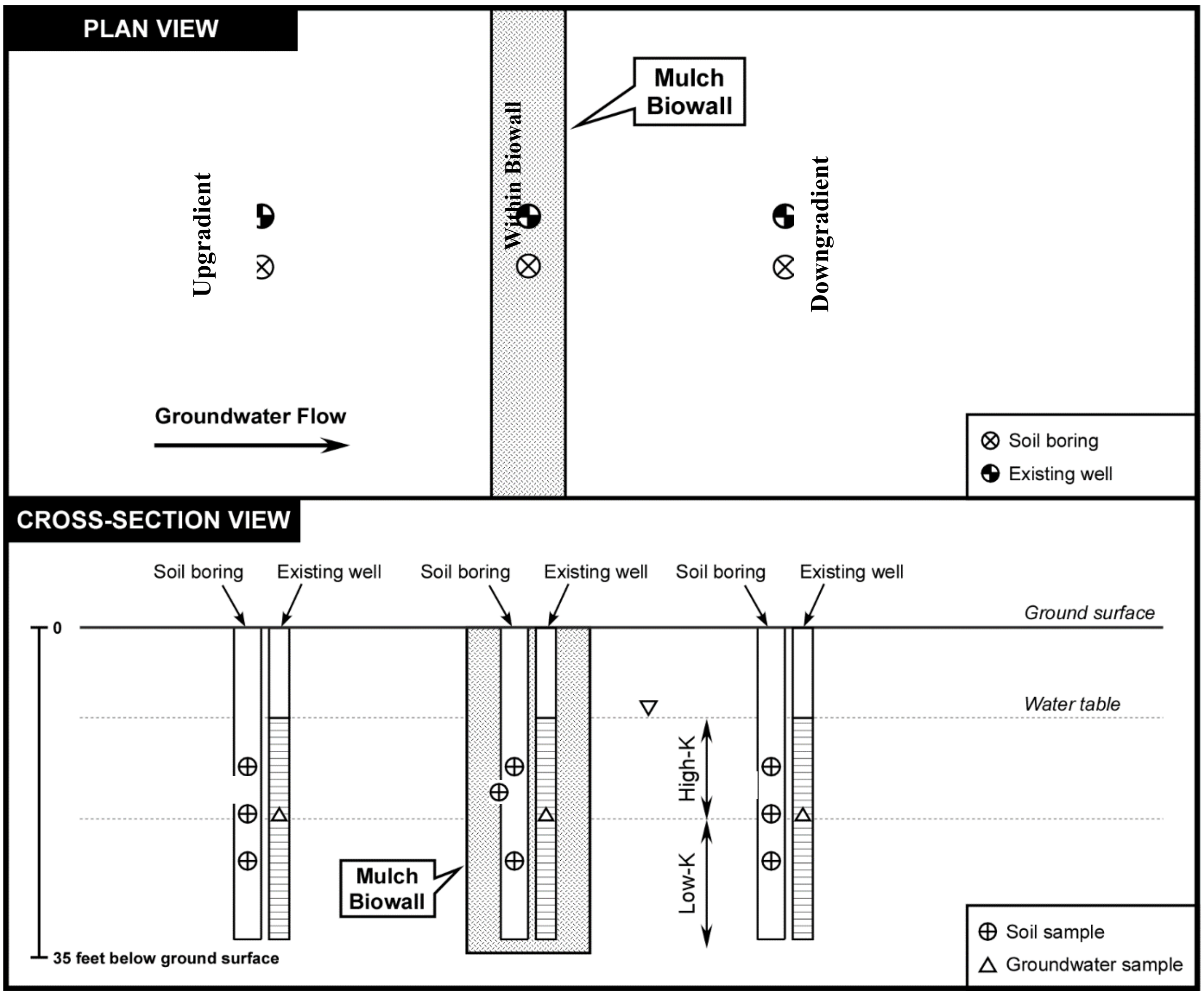


Figure 5.1. General Schematic of Sampling Locations for Each Biowall Transect Tested.

Table 5.1. Description of Biowall Well Transects Selected for Sampling Activities.

Transect	Rationale for Selection
BA01	Within the 2002 TCE plume in Section A, and the presence of both parent (i.e., TCE) and daughter (i.e., cis-1,2-DCE and vinyl chloride) products have been detected (transects BA02 AND BA13 show low parent and daughter concentrations).
BB04	Historically elevated parent and daughter concentrations, downgradient of the deeper Intermediate Flow Zone oil injections, has historically been studied, and has been sampled for abiotic degradation. Included in biogeochemical field study described in Whiting et al. (2014).
BB05	Historically elevated parent and daughter concentrations, downgradient of the deeper Intermediate Flow Zone oil injections, has historically been studied, and has been sampled for abiotic degradation. Included in biogeochemical field study described in Whiting et al. (2014).
BC07	Elevated concentrations of both parent and daughter products and has been sampled for abiotic degradation.
BC08	Elevated concentrations of both parent and daughter products. Near Section D, which is not being sampled.
BE09	Elevated concentrations of both parent and daughter products. Lower end of Section E. In the center of the 2002 TCE plume.
BE11	Elevated concentrations of both parent and daughter products. Upper end of Section E. (Unable to collect soil samples due to overhead utility obstruction)
BF12	Near the presumed source zone in Building 506, contains elevated concentrations of parent and daughter products, and has been sampled for abiotic degradation.

5.4.2 Substrate Injection Sites (Kelly AFB and NTC Orlando)

At substrate injection sites, two existing wells located within the footprint of the injection zone were selected for sampling and testing activities (see plan view in Figure 5.2). In addition to these treatment zone wells, an existing upgradient well was also included in sampling and testing activities for characterizing untreated condition upgradient of the treatment zone. Immediately adjacent to all three existing monitoring wells, a soil boring was advanced to the lower depth of the targeted treatment zone. Soil samples were collected from each of the three soil borings for analysis of target parameters (see section view in Figure 5.2). No permanent groundwater monitoring wells were installed and soil borings were backfilled upon completion of sampling activities.

At Kelly AFB, existing monitoring wells ST008MW157 and ST008RW256 were selected from within the former injection zone for sampling and testing activities. In addition to these wells, upgradient well SS037MW307 was utilized for characterizing untreated condition upgradient of the treatment zone. At NTC Orlando, existing monitoring wells OLD-17-53C2 and OLD-17-55C were selected from within the former injection zone and upgradient well OLD-17-10C was the upgradient well sampled. The “C” zone was target at NTC Orlando on the basis of site reports indicating that lower permeability of the shallower “B” zone did not allow adequate substrate distribution, and because the C zone is in closer proximity to the underlying clay stratum of the Hawthorn group.

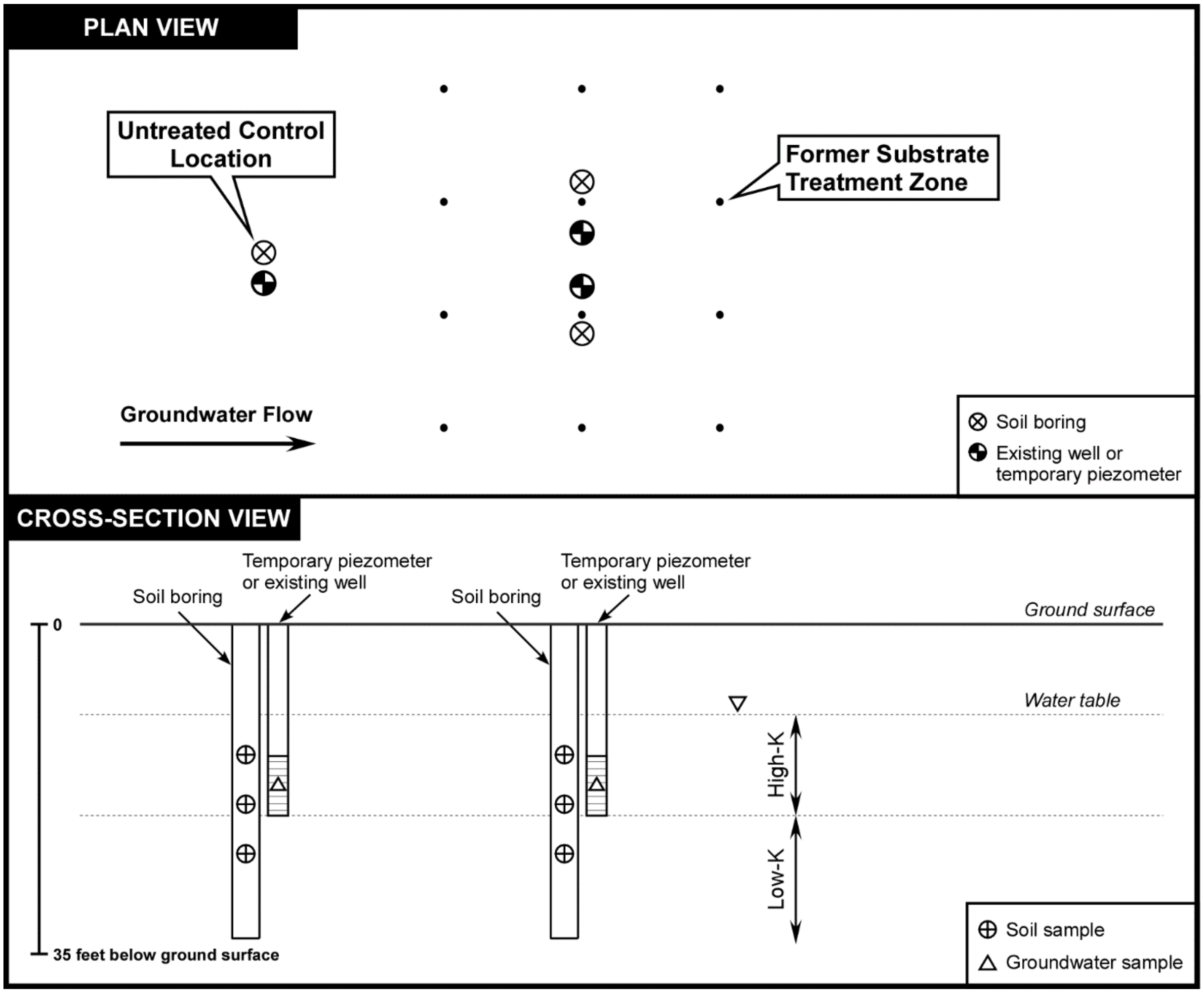


Figure 5.2. General Schematic of Sampling Locations for Substrate Injection Sites.

5.5 SAMPLING METHODS

Details of the sampling and testing methods for the ISB sites are provided below, with additional information, including numbers of samples, types of samples, and analytical methods, summarized in Tables 5.2 and 5.3. Note that data analysis was performed continually as work was completed at each site and the sampling plan was slightly modified when it was determined that a particular analysis was not providing useful results. Analytical testing for CVOC stable isotopes in soil samples was eliminated on this basis, as early results indicated the analytical sensitivity was inadequate to provide usable data.

5.5.1 Biowall Site

5.5.1.1 Soil Sampling and Testing

The primary objective of the soil boring installation program at Altus AFB was to characterize current contaminant, microbial, and geochemical conditions within and adjacent to the biowall treatment areas. In the upgradient and downgradient monitoring wells at each transect, two soil samples were collected from the within the transmissive zone intercepted by the biowalls.

This will include one sample from lower-permeability soils and one sample from higher-permeability soils, as determined from field inspection of the cores. Three "soil" samples were collected from within the mulch biowall at each of the sampled locations.

Soil samples were submitted to a commercial laboratory for testing of CVOCs, soil moisture content, and fraction organic carbon (f_{oc}). Soil samples were also submitted to specialized laboratories for analysis of PBOC and magnetic susceptibility. Soil samples were also analyzed for a suite of dechlorinating microorganisms and functional genes using microbiological tools at a commercial laboratory specializing in such analyses. The three samples collected from within the biowall were analyzed for forage analysis to quantify the fraction of bioavailable carbon substrate remaining in the mulch.

5.5.1.2 Groundwater Sampling and Testing

The primary objective of the groundwater sampling and testing program was to generate data for evaluation of long-term remediation performance of the biowalls. To accomplish this objective, groundwater samples were collected from within the mulch biowalls, as well as upgradient and downgradient of the biowalls. Samples were collected using low-flow sampling procedures, and general water quality parameters were measured during groundwater purging. Samples were collected for analysis of CVOCs and a variety of other geochemical and microbiological parameters by appropriate analytical methods (see Table 5.2). Samples collected for analysis of metals and major cations/anions will be field filtered using a 0.45-micron filter to minimize the impact of any sediment entrained in the samples. Compound specific isotope analysis (CSIA) of the CVOCs was also conducted for groundwater samples to estimate the extent of bioremediation.

5.5.2 Substrate Injection Sites (Kelly AFB and NTC Orlando)

5.5.2.1 Soil Sampling and Testing

The primary objective of the soil boring installation program at ISB sites was to characterize current contaminant, microbial, and geochemical conditions within former injection zones. In the upgradient and former injection zone monitoring, three soil samples were be collected from within the substrate injection depth interval.

Each soil sample was submitted to a commercial laboratory for testing of CVOCs, soil moisture content, and fraction organic carbon (f_{oc}). In addition, the soil sampling program will generate biogeochemical data to help quantify sustained treatment processes within the former treatment zones, if such processes are occurring. For this purpose, soil samples were also submitted to specialized laboratories for analysis of PBOC and magnetic susceptibility. Soil samples were also analyzed for a suite of dechlorinating microorganisms and functional genes using microbiological tools at a commercial laboratory specializing in such analyses.

5.5.2.2 Groundwater Sampling and Testing

The primary objective of the groundwater sampling and testing program at ISB sites was to generate data for evaluation of long-term remediation performance. To accomplish this objective, groundwater samples were collected from upgradient and within the former treatment zone.

Samples were collected using low-flow sampling procedures, and general water quality parameters were measured during groundwater purging. Samples were collected for analysis of CVOCs and a variety of other geochemical and microbiological parameters by appropriate analytical methods (see Tables 5.2 and 5.3). Samples collected for analysis of metals and major cations/anions were field filtered using a 0.45-micron filter to minimize the impact of any sediment entrained in the samples. CSIA of the CVOCs was also conducted for groundwater samples to estimate the extent of bioremediation.

Table 5.2. Total number and types of samples collected at ISB sites.

Matrix	Number of Samples at Mulch Biowall Site	Number of Samples at Substrate Injection Sites	Analyte
Soil: Standard lab measurements	56 samples	18 samples	CVOCs[1], fraction organic carbon (f_{oc}), and soil moisture content
Soil: Specialized lab measurements	56 samples	18 samples	PBOC, microbiological parameters[2], magnetic susceptibility, and forage analysis (biowall only)
Groundwater: Standard lab measurements	25; 24 samples plus 1 field duplicate	6 samples	CVOCs, metals[3], and geochemical parameters[4]
Groundwater: Specialized lab measurements	25; 24 samples plus 1 field duplicate	6 samples	Microbiological parameters[2] and compound-specific isotope analysis (CSIA)

1 CVOCs included PCE, TCE, cis-DCE, and VC

2 Microbiological parameters included standard QuantArray-Chlor analytes

3 Metals included dissolved (field filtered) calcium, iron, magnesium, potassium, sodium

4 Geochemical parameters included alkalinity, sulfate, nitrate, ferrous iron, chloride, total organic carbon, methane, ethane, ethene, acetate, biological oxygen demand, and chemical oxygen demand

Table 5.3. Analytical Methods for Sample Analysis at ISB Sites.

Matrix	Analyte	Method	Container[1]	Preservative[2]	Holding Time
Soil	CVOCs	Method 8260	2-oz. WMG	Ice	14 days
	Moisture Content / f_{oc}	2540G / ASTM D2974	4-oz. WMG	Ice	28 days
	Molecular Biological Tools	QuantArray-Chlor	8-oz. WMG	Ice	24-48 hours
	PBOC	Per Thomas et al., 2012	32-oz. WMG (or 2 x 16-oz. WMG)	None	N/A
	Forage Analysis	Per University of Wisconsin-Madison Soil Testing Laboratories[4]	Ziploc bag	None	None
	Magnetic Susceptibility	Per Microbial Insights laboratory protocol	2 x 8-oz. WMG	None	24-48 hours
Groundwater	CVOCs	Method 8260	3 x 40-mL V-TLS	Ice	7 days
	Total Organic Carbon	Method 9060A	250-mL Amber	HCl to pH<2	28 days
	Dissolved Gases (Methane, Ethane, Ethene)	RSK 175	3 x 40-mL V-TLS	Ice	7 days
	Major Cations	Method 6010	500-mL PE	HCO_3	165 days
	Alkalinity / Major Anions	Method 9056 / 2320B	500-mL PE	Ice	14 days
	CSIA (^{13}C)[3]	Internal CSIA Method	3 x 40-mL V-TLS	Only C	7 days
	Biological Oxygen Demand (BOD)	SM5210B	1L PE	Ice	48 hours
	Chemical Oxygen Demand (COD)	410.4	250-mL PE	H_2SO_4	28 days
	Molecular Biological Tools	QuantArray-Chlor	1L PC or Falcon tube with 1 or 2 filters	Ice	24 to 48 hours
	Acetate (volatile fatty acids)	IC	3 x 40-mL V-TLS	BAK	14 days

[1] WMG = wide mouth glass jar; V-TLS = glass vial with Teflon-lined septum; PE = polyethylene bottle; PC= polycarbonate bottle

[2] HCl = Hydrochloric acid; BAK = Benzalkonium Chloride; H_2SO_4 = sulfuric acid; HCO_3 = bicarbonate. All samples will be transported in cooler at 4 C

[3] C = Carbon

[4] Laboratory methods for forage analysis are available online at http://uwlab.soils.wisc.edu/lab-procedures/

5.6 SAMPLING RESULTS

Appendix E provides tabulated summaries of sampling and testing results for all new data collected for this project at ISB sites. Tables are separated by site and media. Key sampling and testing results for each site are summarized below.

5.6.1 Biowall Site Sampling Results (Altus AFB)

Key data generated from sampling and testing activities at the Altus AFB biowalls are summarized on the tables and figure below. Note that sampling results from the upgradient location at transect BF12 were not used in the analysis due to the presence of a nearby bioreactor that appeared to be influencing the results at this well location. Performance assessment results and key findings are discussed in Section 7.0 of this report.

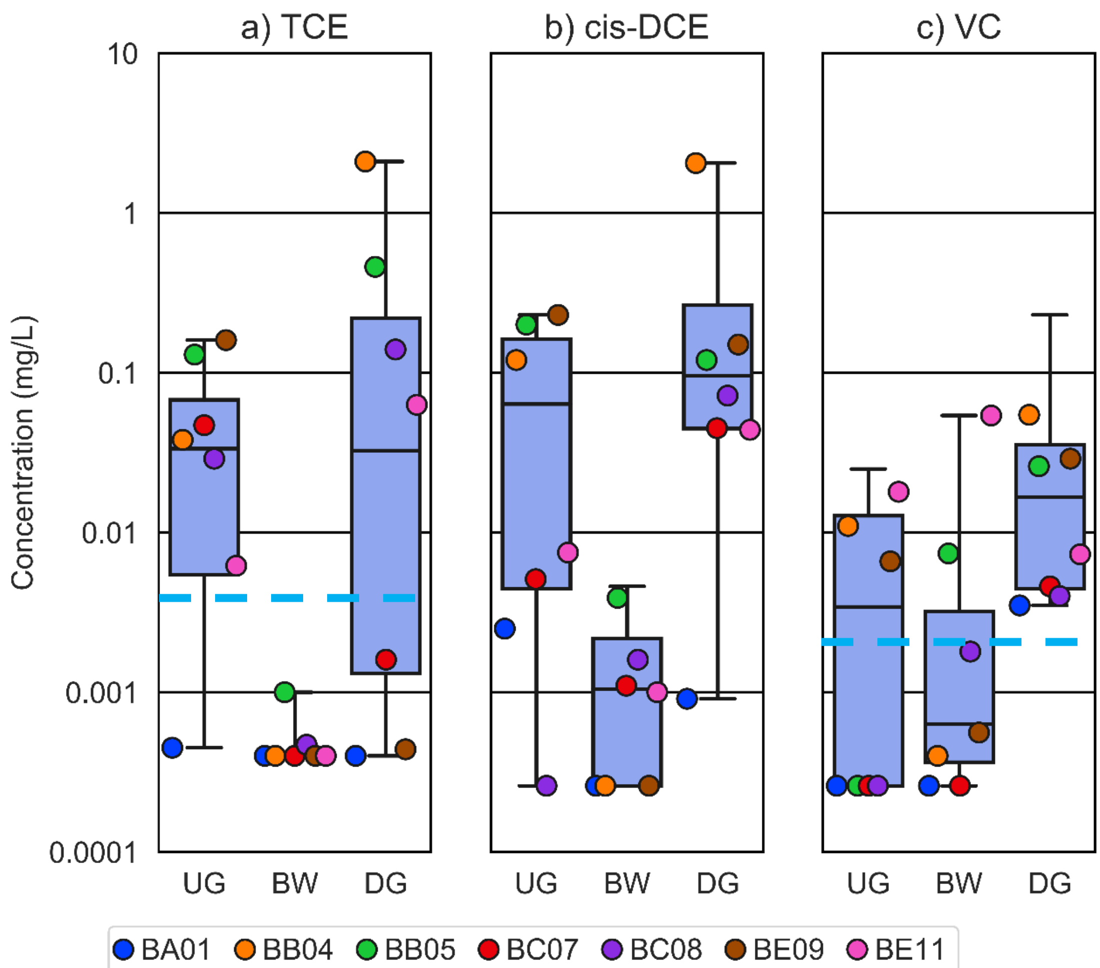


Figure 5.3. Distribution of CVOC Concentrations in Groundwater at the Biowall Site.

UG = upgradient, biowall BW = biowall, DG = downgradient. The dots are individual sampling results for the 7 transects. The box shows the 25th-75th percentile range, the whiskers represent maximum and minimum, and the horizontal line in the box is the median. Dashed horizontal line is the MCL.

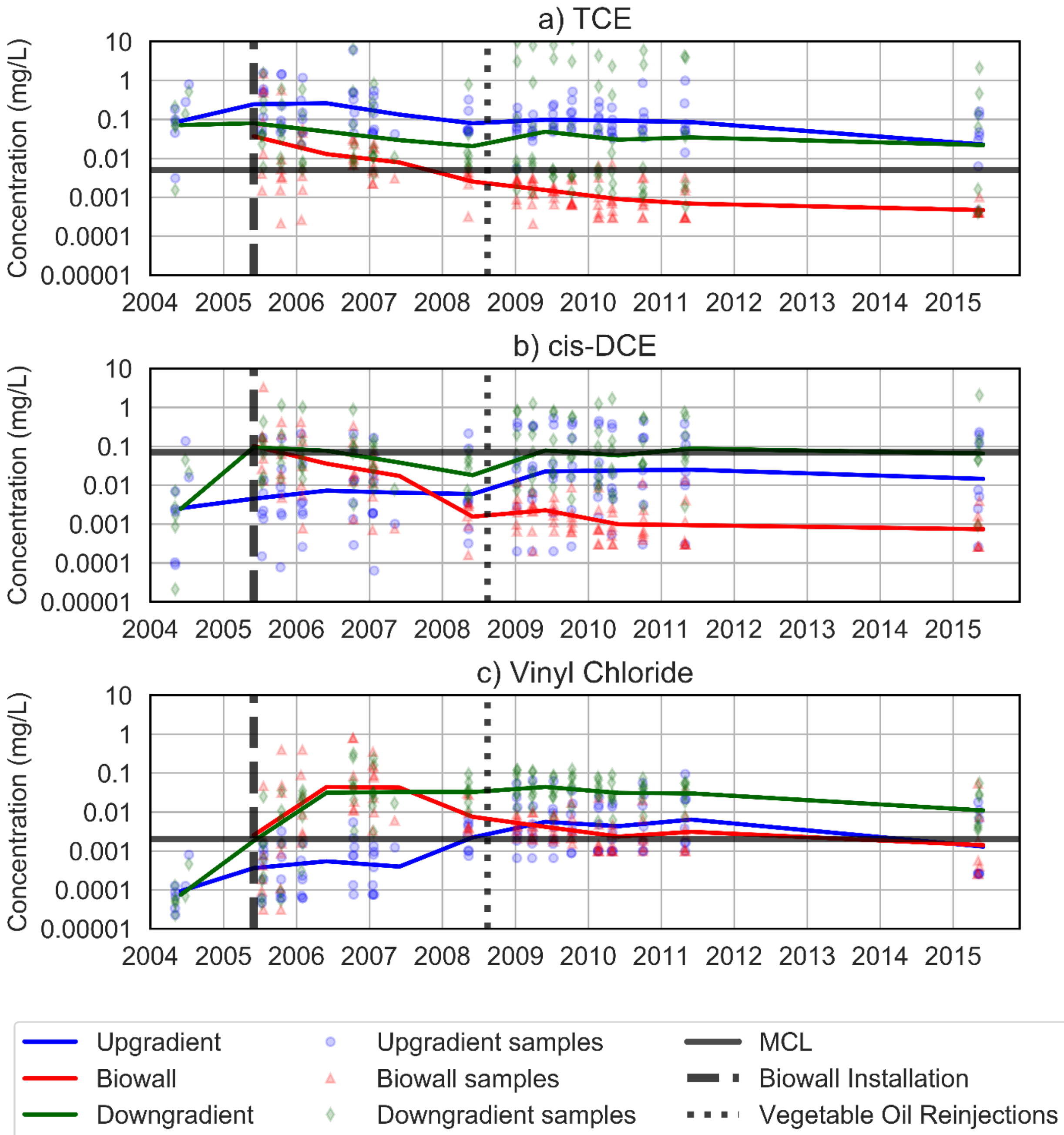


Figure 5.4. CVOC Concentrations over Time in Groundwater at the Biowall Site.

Solid lines represent the median annual concentration.

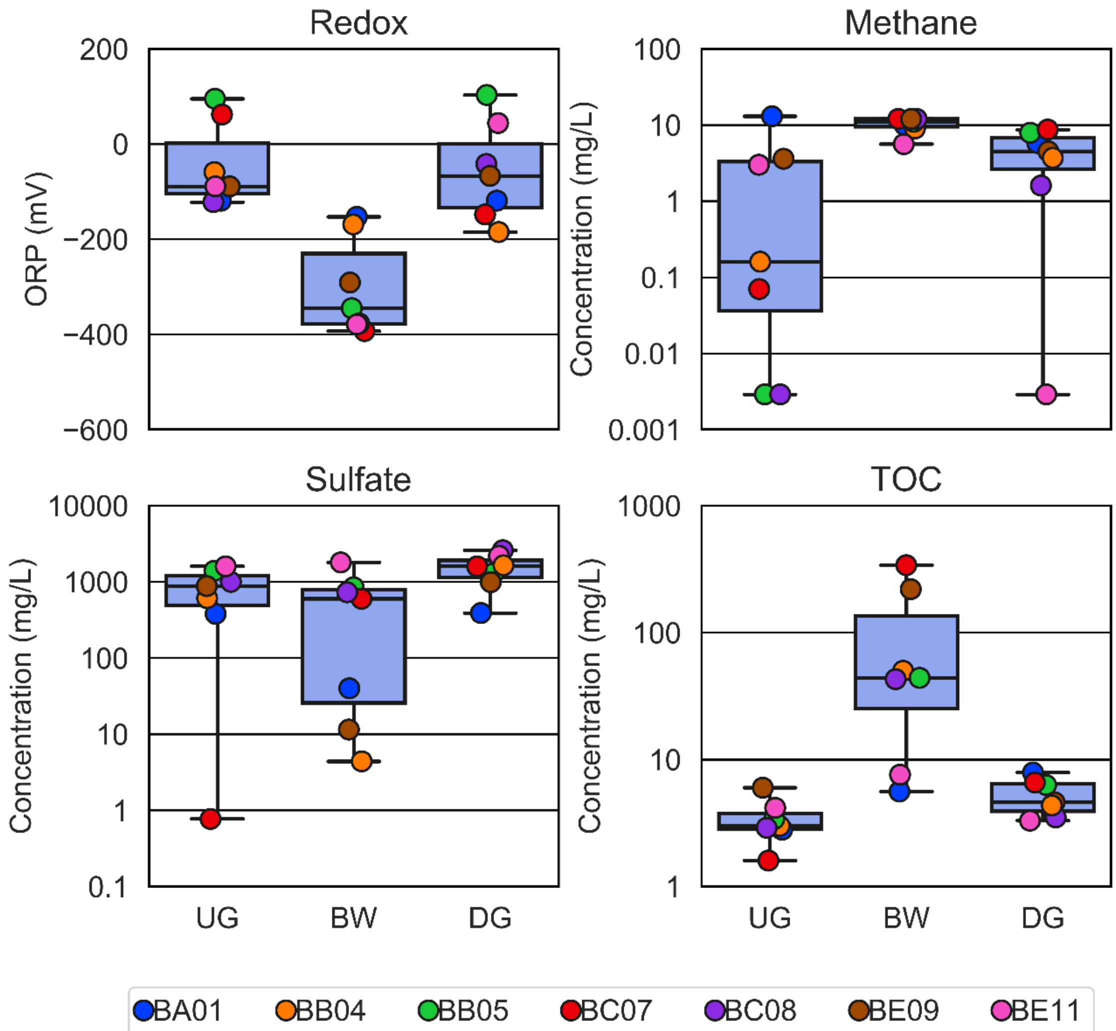


Figure 5.5. Distribution of Key Geochemical Parameters in Groundwater at the Biowall Site.

UG = upgradient, biowall BW = biowall, DG = downgradient. The dots show the individual sampling results for the 7 transects.

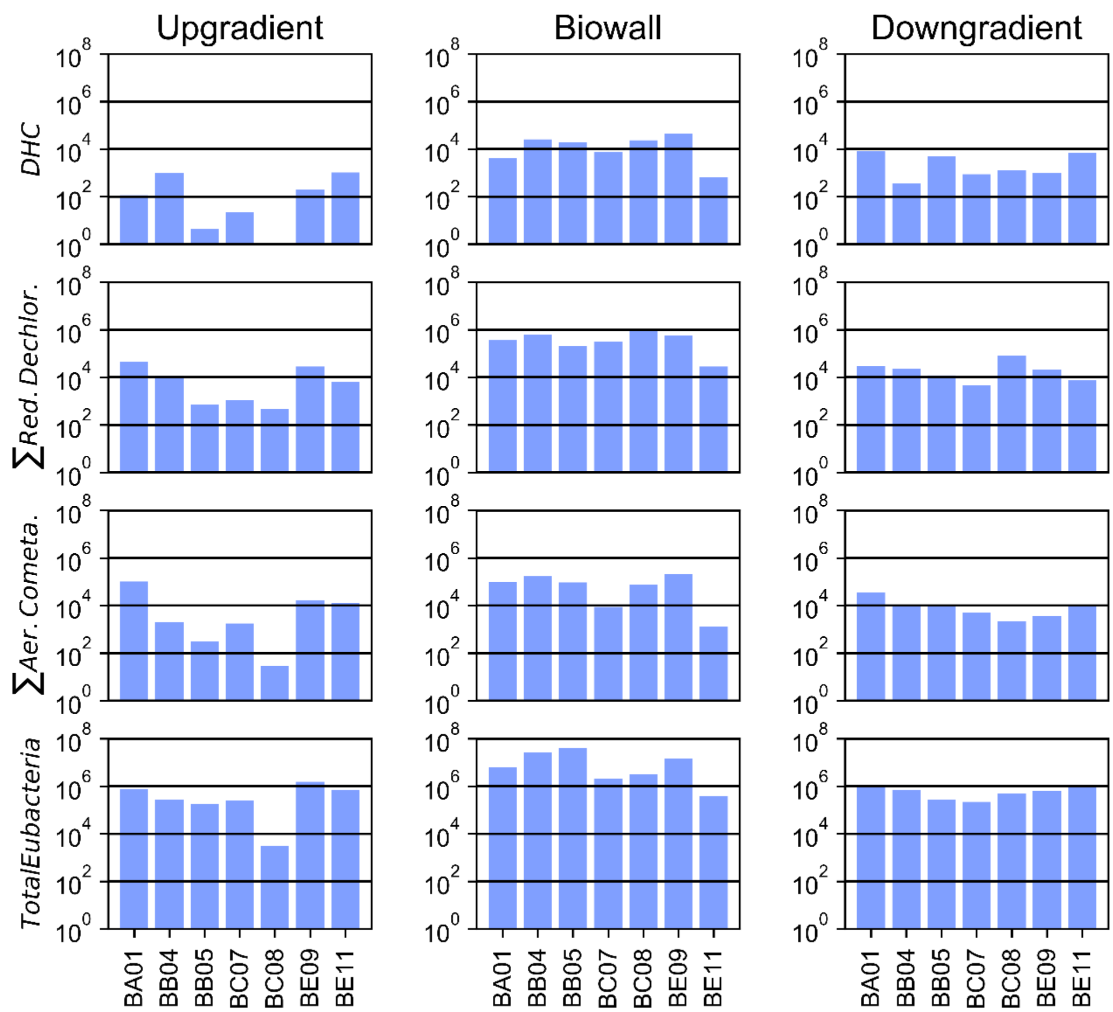


Figure 5.6. Microbial Parameters in Groundwater at the Biowall Site.

Concentrations are in cells/mL. Red. Dechlor. shows the sum concentration of microorganisms responsible for reductive dechlorination except DHC, which is shown separately. Aer. Cometa. shows the sum concentration of microorganisms responsible for aerobic co-metabolism. Non-detects were not used in sums.

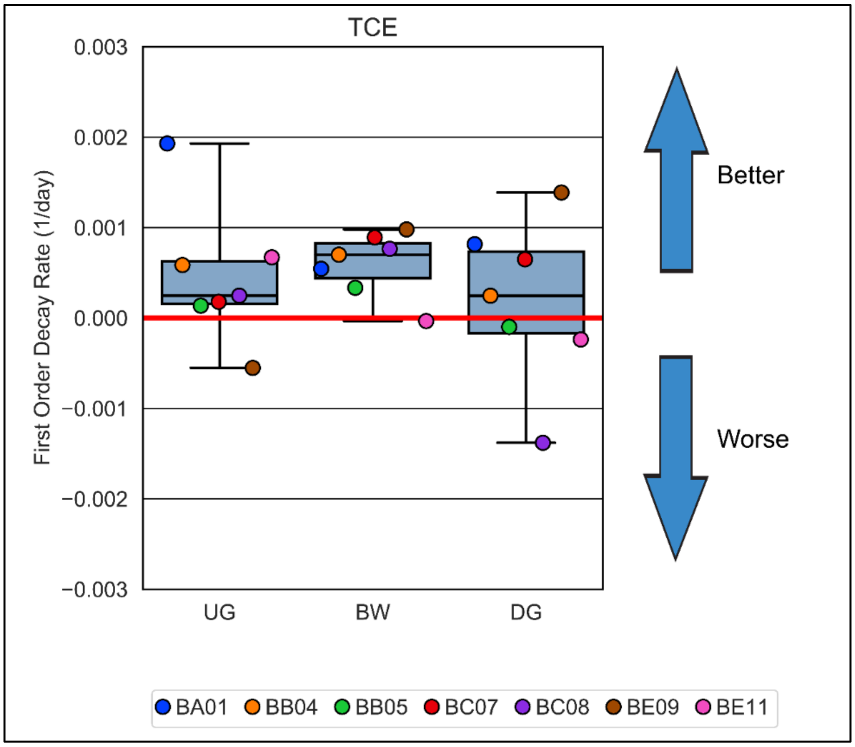


Figure 5.7. Distribution of First-order Decay Rates at Biowall Site.

UG = upgradient, biowall BW = biowall, DG = downgradient. The dots show the individual sampling results for the 7 transects.

Table 5.4. Summary of key ISB Parameters at Altus AFB Biowalls.

Parameter	Upgradient Wells	Biowall Wells	Downgradient Wells
PCE, mg/L	0.059	0.001	0.70
DCE+VC, mg/L	0.097	0.0098	0.62
Ethene, mg/L	0.0049	0.0046	0.016
Methane, mg/L	3.5	10.2	4.7
Σ VFAs, mg/L	2.0	17.3	2.0
BOD, mg/L	6.7	158	6.4
TOC, mg/L	4.9	91	5.6
D.O., mg/L	1.6	2.9	0.74
pH	7.1	7.1	6.9
DHC, cell/mL	3.9E+2	1.7E+4	3.5E+3
Σ Red.Dech., cell/mL	1.4E+4	4.2E+5	2.8E+4
EBAC, cell/mL	5.3E+5	1.2E+7	5.6E+5
^{13}C DCE, δ13C (‰)	-18.2	-6.7	-19.5
^{13}C VC, δ13C (‰)	-22.5	-3.3	-23.3
Mag. Susc., m3/kg	1.4E-07	8.9E-06	1.6E-07
f_{oc}, mg/kg	5,870	36,090	4,730
PBOC, mg/kg	40	2,380	96

Notes:

Non-detect values were calculated at the reported detection limit for CVOCs.

Non-detect values were not used when calculating the Σ VFAs and Σ Red. Dech.

Data from transect BF-12 at the upgradient well were not used due to the presence of an upgradient bioreactor.

5.6.2 Substrate Injection Site Sampling Results (Kelly AFB and NTC Orlando)

Key data generated from sampling and testing activities at the Kelly AFB and NTC Orlando ISB remediation areas are summarized on the tables and figure below. See Appendix E for complete sampling and testing results. Performance assessment results and key findings are discussed in Section 7.0 of this report.

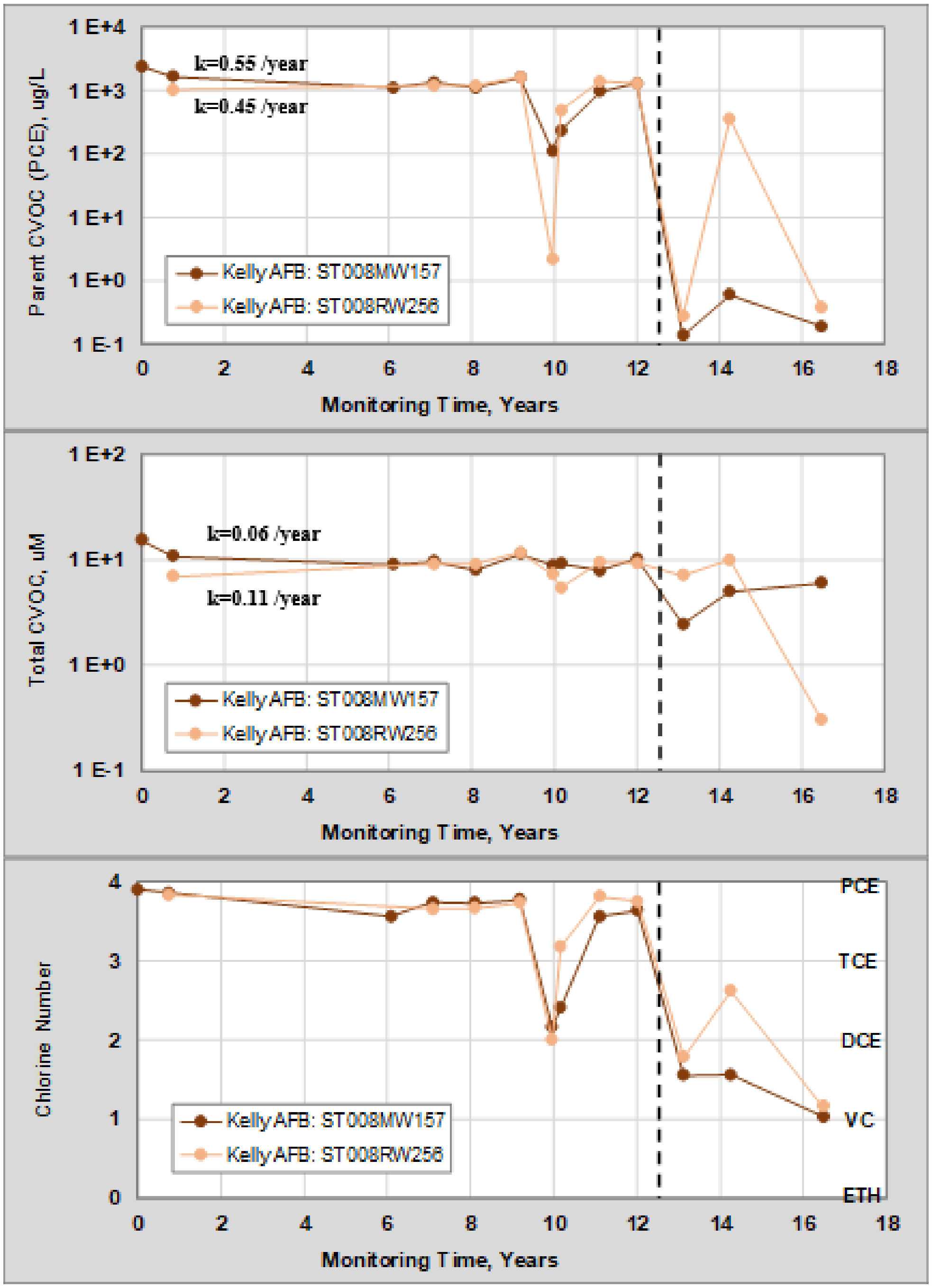


Figure 5.8. CVOC Concentrations Over Time in Groundwater at the Kelly AFB ISB Site.

Vertical dashed line represents the last substrate injection event.

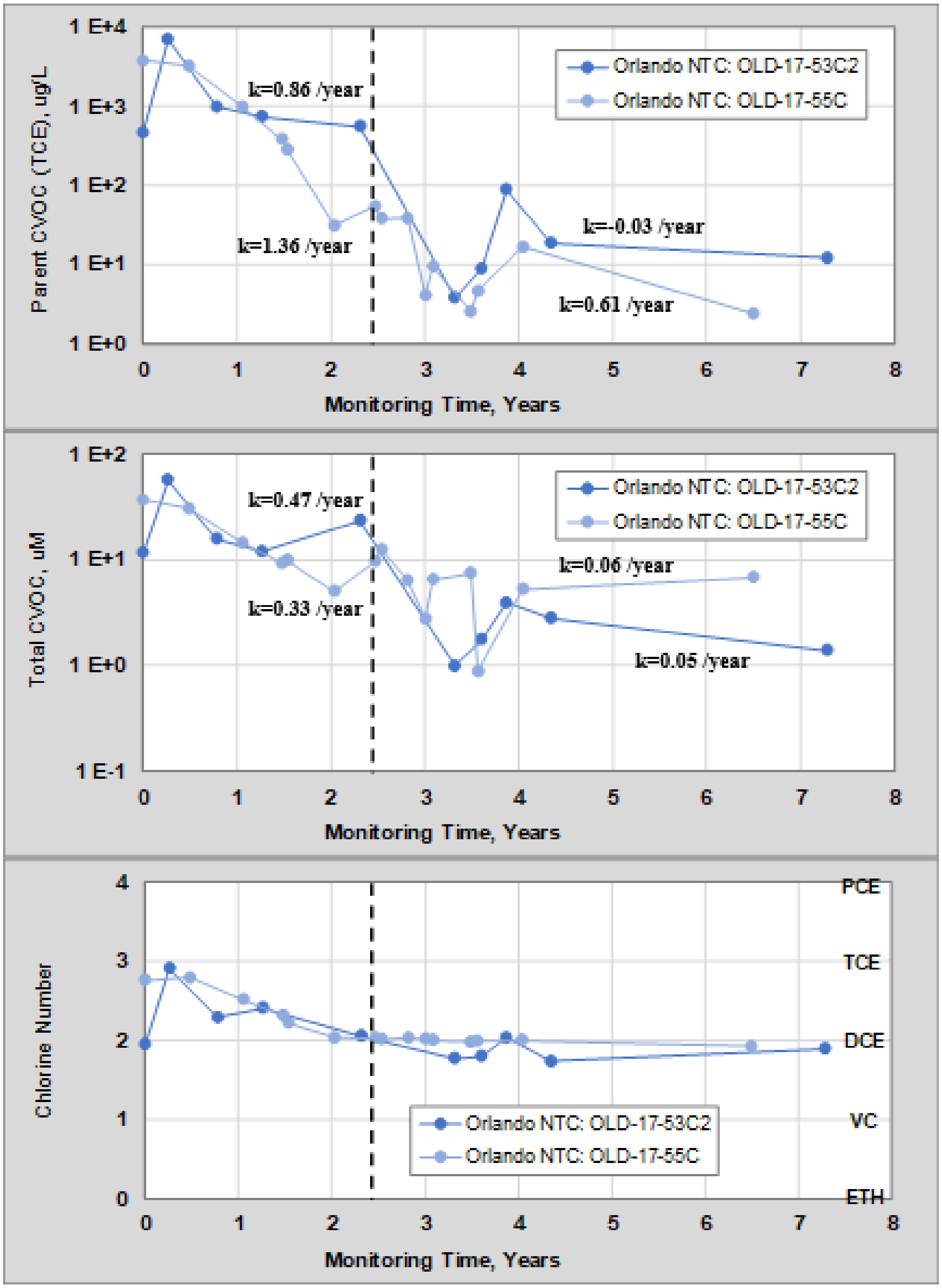


Figure 5.9. CVOC concentrations over time in groundwater at the NTC Orlando ISB site.

Vertical dashed line represents the last substrate injection event.

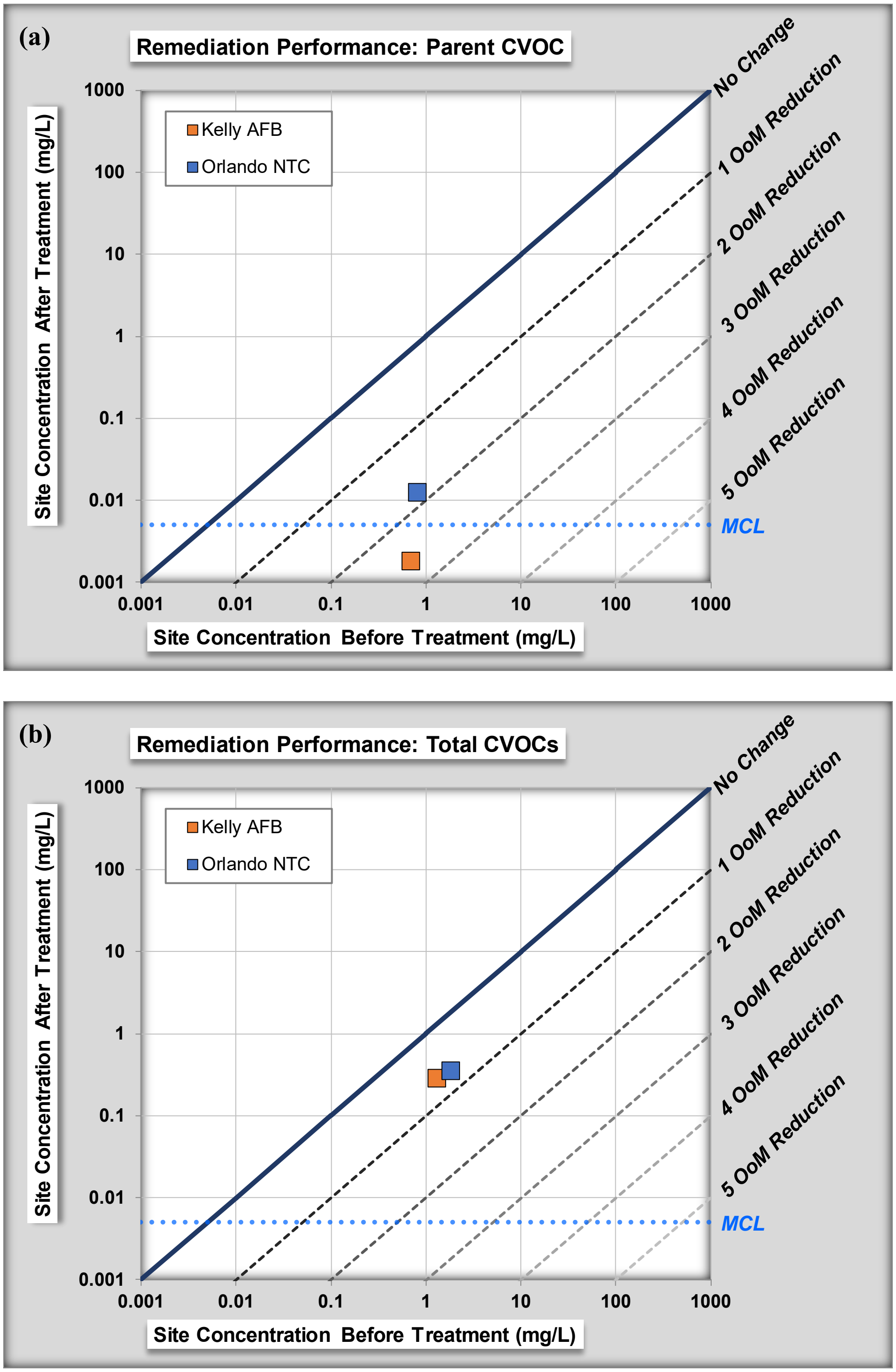


Figure 5.10. OoM Reductions in Parent CVOC (a) and Total CVOCs (b) for ISB Sites.

Diagonal lines represent the OoM Reduction achieved. MCL is for PCE or TCE.

Table 5.5. Summary of Key ISB Parameters at Kelly AFB.

Parameter	Upgradient Well	Treatment Zone Well #1	Treatment Zone Well #2	Average Treatment Zone
PCE, mg/L	0.0085	<0.000372	<0.000372	<0.000372
DCE+VC, mg/L	0.0822	0.385	0.020	0.202
Ethene, mg/L	<0.00426	0.08	0.014	0.047
Methane, mg/L	0.0083	7.78	3.99	5.89
Σ VFAs, mg/L	0.76	0.83	0.70	0.77
BOD, mg/L	<3.33	<3.33	<3.33	<3.33
TOC, mg/L	0.85	1.65	2.65	2.15
DHC, cell/mL	5	11,000	114,000	63,000
Σ Red.Dech., cell/mL	1,000	104,000	127,000	115,000
EBAC, cell/mL	190,000	479,000	1,250,000	865,000
^{13}C DCE, δ13C (‰)	-19.50	+38.70	+29.62	+34.16
^{13}C VC, δ13C (‰)	ND	-12.86	+7.39	-2.74
Mag. Susc., m3/kg	3.8 E-7	2.1 E-7	2.0 E-7	2.0 E-7
f_{oc}, mg/kg	6,350	2,260	3,690	2,980
PBOC, mg/kg	68	70	54	62

Notes:

Non-detect values were calculated at the reported detection limit for CVOCs.

Non-detect values were not used when calculating the Σ VFAs and Σ Red. Dech.

Table 5.6. Summary of key ISB parameters at NTC Orlando.

Parameter	Upgradient Well	Treatment Zone Well #1	Treatment Zone Well #2	Average Treatment Zone
TCE, mg/L	<0.000398	0.0122	0.00242	0.005
DCE+VC, mg/L	0.0011	0.12	0.64	0.38
Ethene, mg/L	<0.00426	<0.00426	0.0109	0.0076
Methane, mg/L	0.59	10.7	14.8	12.8
Σ VFAs, mg/L	1.32	0.47	ND	0.47
BOD, mg/L	7.8	9.3	16.5	12.9
TOC, mg/L	12.6	6.1 B	8.4	8.4
DHC, cell/mL	<25	95	116	106
Σ Red.Dech., cell/mL	380	970	5,660	3,310
EBAC, cell/mL	534,000	48,800	226,000	137,400
^{13}C DCE, δ13C (‰)	ND	-18.7	-20.2	-19.5
^{13}C VC, δ13C (‰)	ND	-19.6	-22.6	-21.1
Mag. Susc., m3/kg	8.6E-09	4.5E-09	3.5E-09	4.0E-09
f_{oc}, mg/kg	1,810	1,920	2,040	1,980
PBOC, mg/kg	440	530	540	530

Notes:

Non-detect values were calculated at the reported detection limit for CVOCs.

Non-detect values were not used when calculating the Σ VFAs and Σ Red. Dech.

ND = not detected

6.0 TECHNICAL APPROACH: MNA IN LOW-K ZONES

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

The field demonstration design included sampling and testing of soil and groundwater at three CVOC sites where no active groundwater remediation had previously been applied and where the impacted aquifer is underlain by, or interbedded with, low-permeability matrix diffusion strata. The objective of the field demonstration was to evaluate long-term trends in MNA performance, as well as to quantify key parameters that influence MNA feasibility at sites where matrix diffusion effects are likely to be important in the long-term management of the site. At each MNA site included in this project, groundwater samples and high-resolution soil samples were collected for analysis of chemical, geochemical, and microbiological parameters that potentially could influence natural attenuation processes in both the transmissive and low-K zones.

6.2 BASELINE CHARACTERIZATION

Baseline conditions, both chemical and hydrogeologic, have been previously defined through historical investigation and sampling events at each site. As such, baseline characterization was limited to compilation and evaluation of historical data.

6.3 DATA MINING TO ESTABLISH BENCHMARK DECAY RATES

An extensive data mining study was undertaken to establish "benchmark" decay rates for CVOCs, including an analysis of those sites likely affected by matrix diffusion. The benchmark decay rates were used for comparison of results from the current study, as well as to establish a range of potential values for use in modeling matrix diffusion. A summary of key findings from the decay rate data mining effort is provided on Table 6.1 and a complete description of the data mining methods and results is included in Appendix C.

Table 6.1. Median First-order Decay Rate and Half-life Calculated from Data Mining Study.

The number of wells in the analysis varied by CVOC ranging from 1,929 for VC to 6,265 for TCE.

Dataset	PCE	TCE	cis-DCE	VC
		k (per year)		
All Wells	0.067	0.066	0.024	0.025
Max. Conc. <50 ug/L	0.048	0.045	0.020	0.021
Max. Conc. >50 ug/L	0.111	0.093	0.032	0.035
		Half-life (years)		
All Wells	10.3	10.5	29	28
Max. Conc. <50 ug/L	14.5	15.3	35	33
Max. Conc. >50 ug/L	6.3	7.4	22	20

As further discussed in Appendix C, the decay rates corresponding to sites with a maximum concentration less than 50 ug/L are more likely to be more representative of the population of natural attenuation sites and those impacted by matrix diffusion effects.

6.4 DESIGN AND LAYOUT OF FIELD TESTING

At low-K MNA sites, an existing well located within the footprint of the groundwater plume was selected for sampling and testing activities (see plan view in Figure 6.1). Immediately adjacent to this existing monitoring well, two soil borings were advanced to a depth sufficient to penetrate approximately 1 meter into the low-K aquitard underlying the transmissive zone. High-resolution soil samples were collected at approximately 10-centimeter intervals, with 2 samples collected from within the transmissive zone and 8 samples collected from within the aquitard (see section view in Figure 6.1). At one of the soil borings, a temporary groundwater sampling point was installed at the base of the boring within the low-K zone to attempt groundwater sample collection. No permanent groundwater monitoring wells were installed, and soil borings were backfilled upon completion of sampling activities. At England AFB, existing monitoring well A39L009PZ was selected for sampling and testing activities. At Hill AFB, existing monitoring well U2-043 was targeted, and at Kelly AFB, existing monitoring well KY036MW026 was utilized. The rationale for selection of these wells is summarized in Table 6.1.

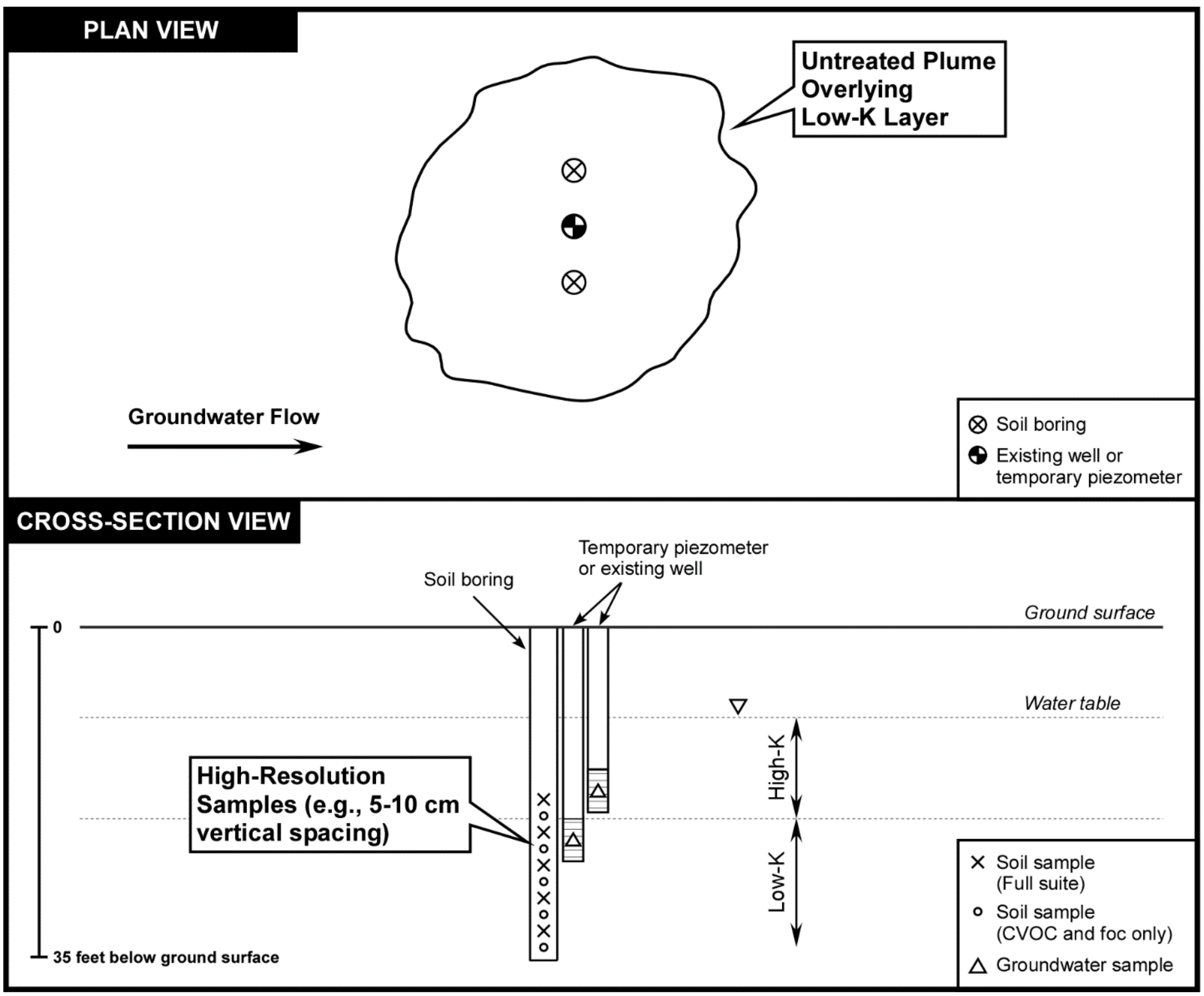


Figure 6.1. General Schematic of Sampling Locations for Low-K MNA Sites.

Table 6.2. Description of Biowall Well Transects Selected for Sampling Activities.

Site & Well ID	Rationale for Well Selection
England AFB A39L009PZ	A39L009PZ is located in SS-45, an untreated area with concentrations of TCE, cis-DCE, and VC. The intermediate clay is present near the location of this well at approximately 80 feet below ground surface (bgs).
Hill AFB U2-043	This well is downstream and outside the influence of remediation activities ongoing at OU2. The well is characterized by high concentrations of TCE, cis-DCE, and VC. Depth to the clay aquitard is approximately 80 feet bgs.
Kelly AFB KY036MW026	This well is also located in the 300 Area at Kelly but outside of the influence of former treatment activities but where concentrations of PCE/TCE and daughter products are still high. Depth to the transition into the Navarro Clay is approximately 20 to 25 feet bgs.

6.5 SAMPLING METHODS

Details of the sampling and testing methods for the MNA sites are provided below, with additional information, including numbers of samples, types of samples, and analytical methods, summarized in Tables 6.3 and 6.4. Note that data analysis was performed continually as work was completed at each site and the sampling plan was slightly modified when it was determined that a particular analysis was not providing useful results. Analytical testing for CVOC stable isotopes in soil samples was eliminated on this basis, as early results indicated the analytical sensitivity was inadequate to provide usable data.

Table 6.3. Total Number and Types of Samples Collected at Low-K MNA Sites.

Matrix	Number of Samples	Analyte
Soil: Standard lab measurements	60 samples	CVOCs[1], fraction organic carbon (f_{oc}), and soil moisture content
Soil: Specialized lab measurements	30 samples	PBOC, microbiological parameters[2], and magnetic susceptibility
Groundwater: Standard lab measurements	6 samples	CVOCs, metals[3], and geochemical parameters[4]
Groundwater: Specialized lab measurements	6 samples	Microbiological parameters[2] and compound-specific isotope analysis (CSIA)

[1] CVOCs included PCE, TCE, cis-DCE, and VC

[2] Microbiological parameters included standard QuantArray-Chlor analytes

[3] Metals included dissolved (field filtered) calcium, iron, magnesium, potassium, sodium

[4] Geochemical parameters included alkalinity, sulfate, nitrate, ferrous iron, chloride, total organic carbon, methane, ethane, ethene, acetate, biological oxygen demand, and chemical oxygen demand

Table 6.4. Analytical Methods for Sample Analysis at Low-K MNA Sites.

Matrix	Analyte	Method	Container[1]	Preservative[2]	Holding Time
Soil	CVOCs	Method 8260	2-oz. WMG	Ice	14 days
	Moisture Content / f_{oc}	2540G / ASTM D2974	4-oz. WMG	Ice	28 days
	Molecular Biological Tools	QuantArray-Chlor	8-oz. WMG	Ice	24-48 hours
	PBOC	Per Thomas et al., 2012	32-oz. WMG (or 2 x 16-oz. WMG)	None	N/A
	Magnetic Susceptibility	Per Microbial Insights laboratory protocol	2 x 8-oz. WMG	None	24-48 hours
Groundwater	CVOCs	Method 8260	3 x 40-mL V-TLS	Ice	7 days
	Total Organic Carbon	Method 9060A	250-mL Amber	HCl to pH<2	28 days
	Dissolved Gases (Methane, Ethane, Ethene)	RSK 175	3 x 40-mL V-TLS	Ice	7 days
	Major Cations	Method 6010	500-mL PE	HCO_3	165 days
	Alkalinity / Major Anions	Method 9056 / 2320B	500-mL PE	Ice	14 days
	CSIA (^{13}C)[3]	Internal CSIA Method	3 x 40-mL V-TLS	Only C	7 days
	Biological Oxygen Demand (BOD)	SM5210B	1L PE	Ice	48 hours
	Chemical Oxygen Demand (COD)	410.4	250-mL PE	H_2SO_4	28 days
	Molecular Biological Tools	QuantArray-Chlor	1L PC or Falcon tube with 1 or 2 filters	Ice	24 to 48 hours
	Acetate (volatile fatty acids)	IC	3 x 40-mL V-TLS	BAK	14 days

1 WMG = wide mouth glass jar; V-TLS = glass vial with Teflon-lined septum; PE = polyethylene bottle; PC= polycarbonate bottle

2 HCl = Hydrochloric acid; BAK = Benzalkonium Chloride; H_2SO_4 = sulfuric acid; HCO_3 = bicarbonate. All samples will be transported in cooler at 4 C

3 C = Carbon

6.6 SAMPLING RESULTS

Appendix F provides tabulated summaries of sampling and testing results for all new data collected for this project at the low-K MNA sites. Tables are separated by site and media. Key sampling and testing results for each site are summarized below. Performance assessment results and key findings are discussed in Section 7.0 of this report.

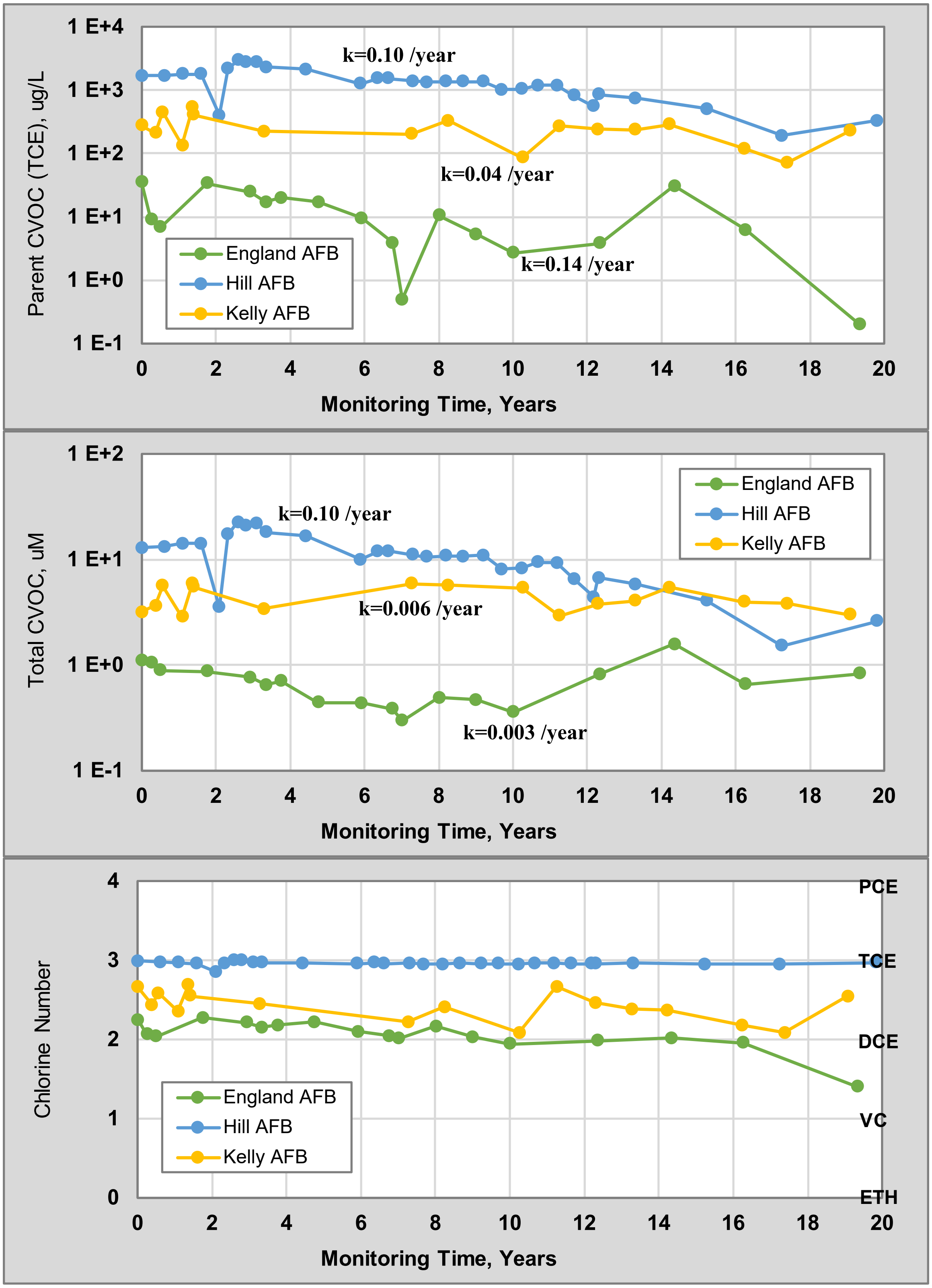


Figure 6.2. CVOC Concentrations Over Time at Low-K MNA Sites.

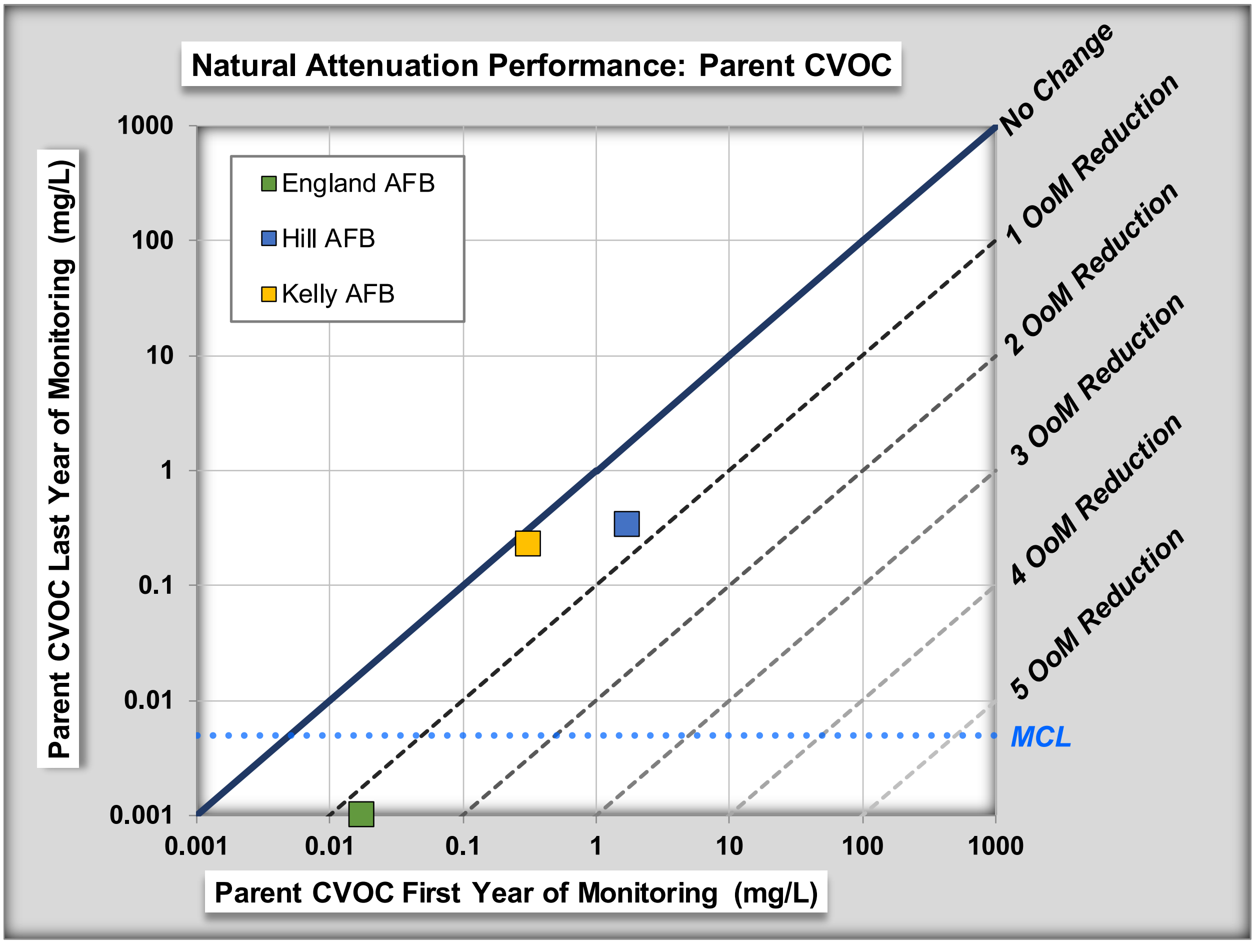


Figure 6.3. OoM Reduction in Parent CVOC in Groundwater for MNA Sites.

Diagonal lines represent the OoM Reduction achieved. MCL is for PCE or TCE.

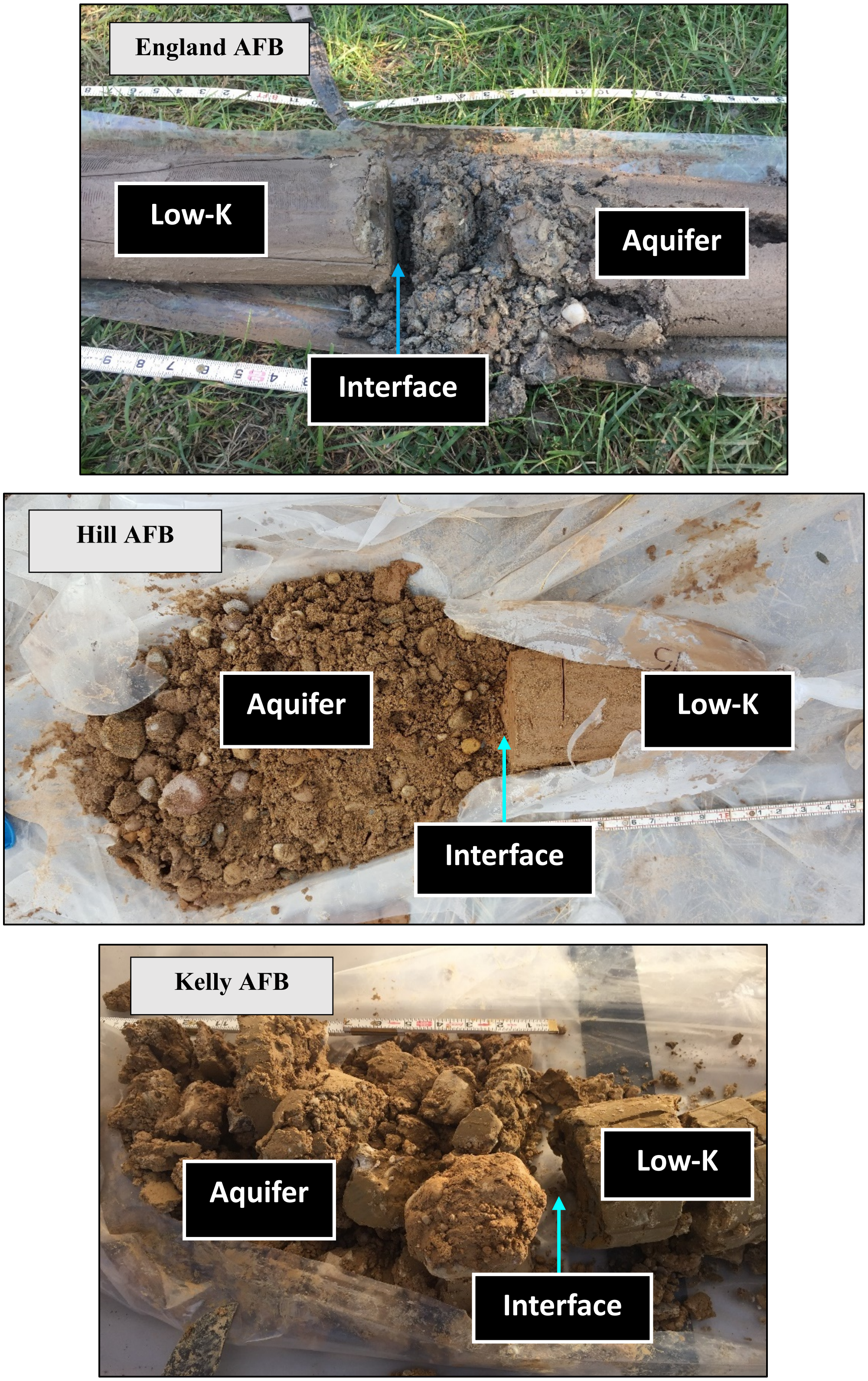


Figure 6.4. Photographs of Transmissive Zone and Aquitard at MNA Sites.

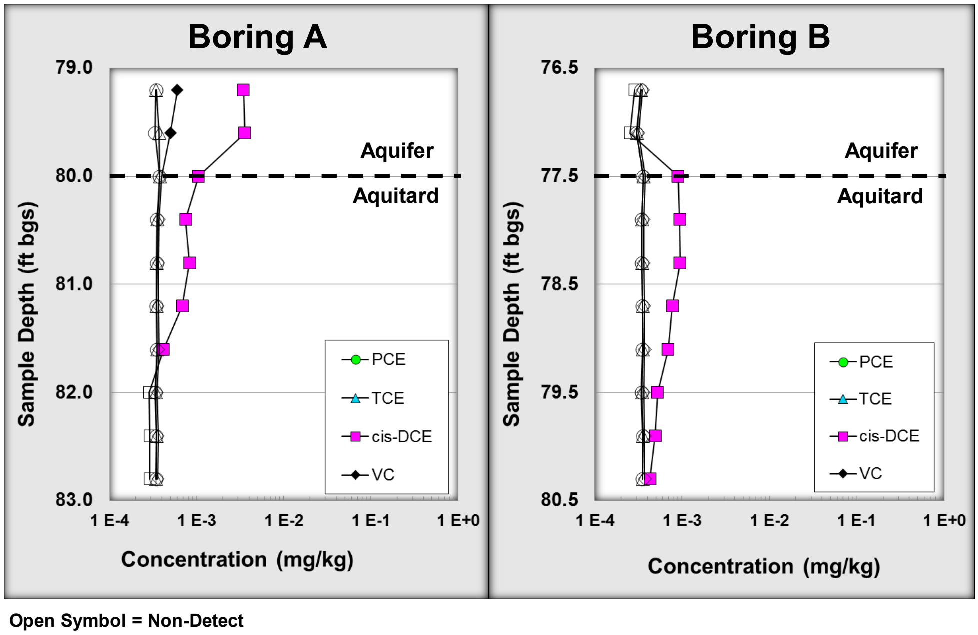


Figure 6.5. High-resolution Soil Sampling Results at England AFB.

At England AFB boring A, both VC and cis-DCE were detected in aquifer soil samples, but only cis-DCE was detected in the clay aquitard samples. At boring B, no CVOCs were detected in the aquifer, while cis-DCE was detected in each of the clay aquitard samples. These results suggest that the low-K aquitard is a reservoir for cis-DCE at the site.

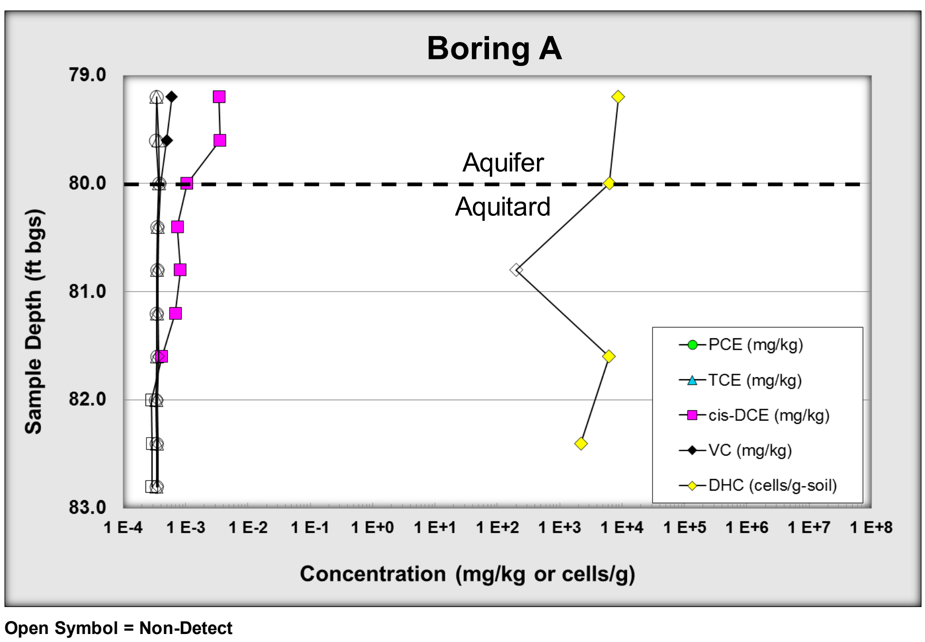


Figure 6.6. High-resolution Soil Sampling Results at England AFB, Including DHC.

At England AFB boring A, DHC was detected in four of five soil samples, including three samples in the clay aquitard. The presence of DHC could account for the lack of VC detections in the aquitard samples.

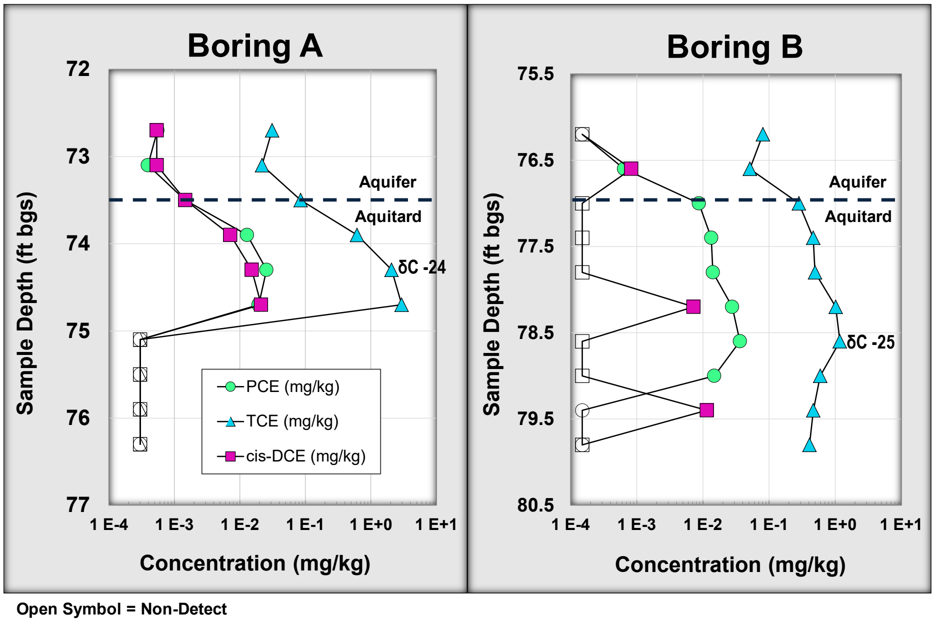


Figure 6.7. High-resolution Soil Sampling Results at Hill AFB.

At Hill AFB boring A, CVOCs exhibited a classic matrix diffusion pattern with a pronounced "shark fin" concentration increase and decline. At boring B, concentrations of PCE and TCE exhibited a similar though less pronounced pattern, while cis-DCE exhibited sporadic detections in both the aquifer and aquitard. These results suggest that the low-K aquitard is a reservoir for PCE and TCE at the site.

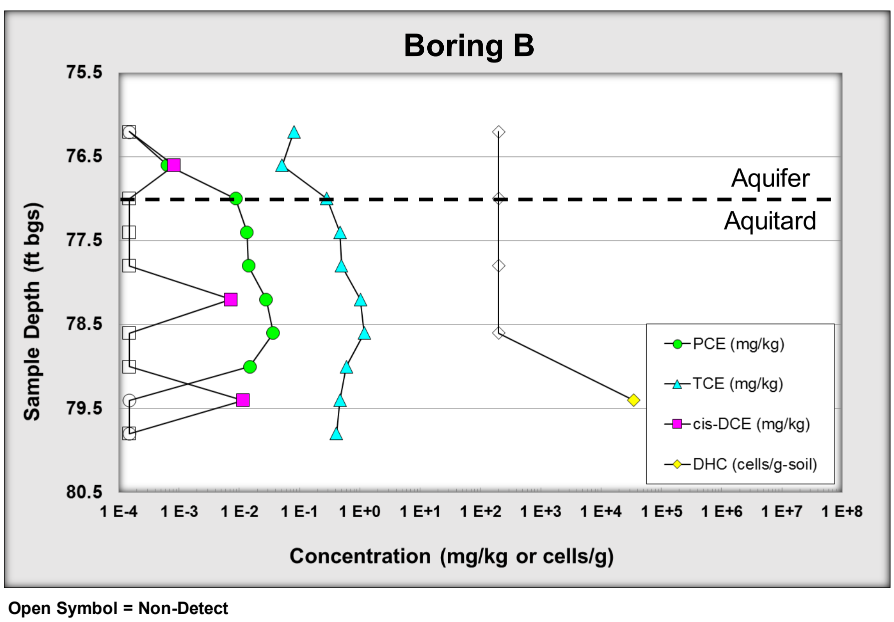


Figure 6.8. High-resolution Soil Sampling Results at Hill AFB, Including DHC.

At Hill AFB boring B, the cis-DCE detected at approximately 79.5 feet bgs was co-located with a reported detection of Dehalococcoides spp. (DHC), indicating the potential for production of cis-DCE within the clay aquitard.

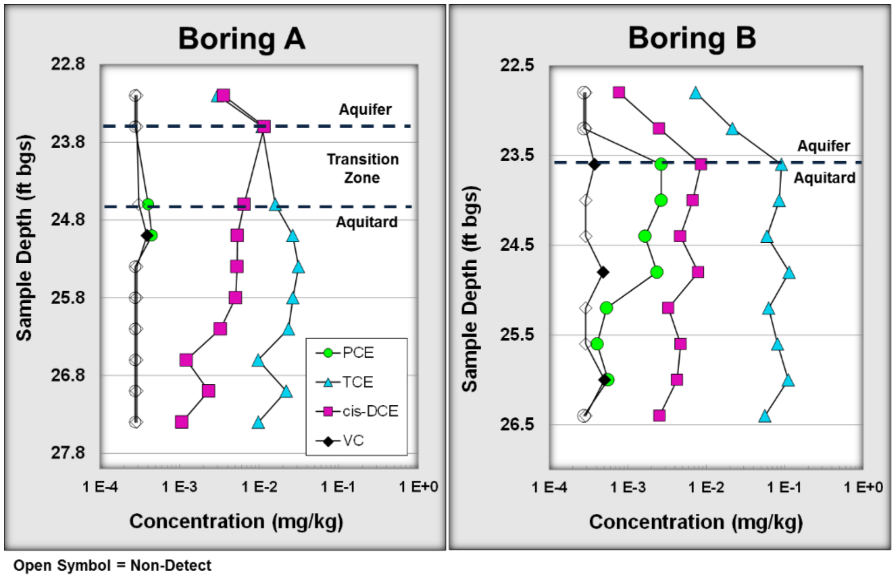


Figure 6.9. High-resolution Soil Sampling Results at Kelly AFB.

At Kelly AFB boring A, TCE and cis-DCE were present at each depth interval, with higher concentrations generally observed in the aquifer samples. A single detection of vinyl chloride was observed in the aquitard. At boring B, TCE and cis-DCE were also present at all depths, with generally higher concentrations observed in the low-K zone. VC was reported in three aquitard samples. The lack of VC detections in aquifer samples with four total detections in the aquitard indicates the possibility of VC generation within the aquitard. These results also suggest that the low-K aquitard is a reservoir for TCE and cis-DCE at the site.

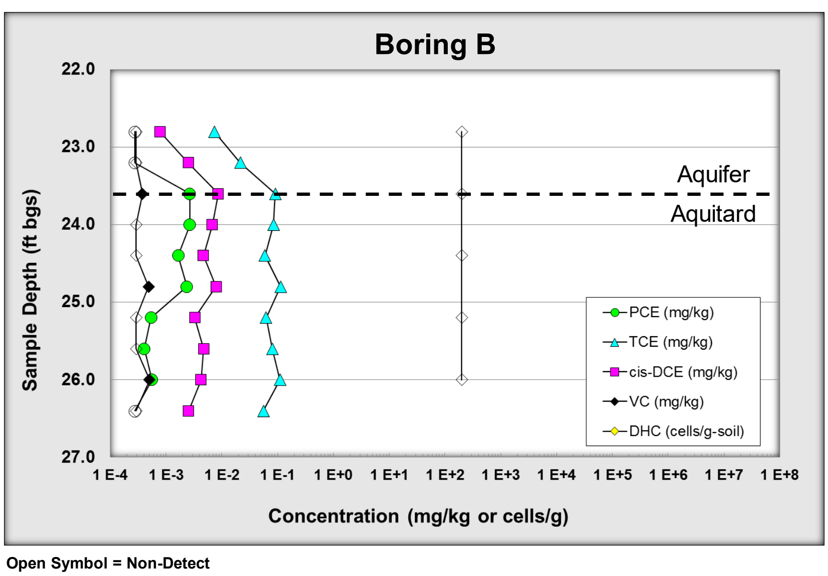


Figure 6.10. High-resolution Soil Sampling Results at Kelly AFB, Including DHC.

At Kelly AFB, despite the observation of daughter products in the clay aquitard, DHC were below detection limits in the four clay soil samples tested.

Table 6.5. Summary of Key MNA Parameters at England AFB.

Parameter	Aquifer Samples	Aquitard Samples
TCE (parent), mg/L	<0.000398	<0.000398
DCE+VC, mg/L	0.063	0.016
Ethene, mg/L	0.0125 J	<0.00426
Methane, mg/L	2.29	3.16
Σ VFAs, mg/L	ND	ND
BOD, mg/L	<3.33	<3.33
TOC, mg/L	2.29	2.95
DHC, cell/mL	224	34.9
Σ Red.Dech., cell/mL	8,580	46
EBAC, cell/mL	662,000	4,510
^{13}C DCE, δ13C (‰)	-15.9	-15.1
^{13}C VC, δ13C (‰)	-19.9	-26.0
Mag. Susc., m3/kg	5.9E-08	1.3E-07
f_{oc}, mg/kg	5,380	12,180
PBOC, mg/kg	83	430

Notes:
ND = not detected

Table 6.6. Summary of key MNA Parameters at Hill AFB.

Parameter	Aquifer Samples	Aquitard Samples
PCE, mg/L	0.332	0.281
DCE+VC, mg/L	0.0084	0.0072
Ethene, mg/L	<0.0042	<0.0042
Methane, mg/L	<0.0029	0.047
Σ VFAs, mg/L	0.114	NM
BOD, mg/L	<3.33	NM
TOC, mg/L	1.24	NM
DHC, cell/mL	<0.1	<4
Σ Red.Dech., cell/mL	10.4	ND
EBAC, cell/mL	16,700	61,700
^{13}C DCE, δ13C (‰)	-28.02	-30.04
^{13}C VC, δ13C (‰)	ND	ND
Mag. Susc., m3/kg	2.3 E-07	1.2 E-07
f_{oc}, mg/kg	1,500 *	7,180
PBOC, mg/kg	60	260

Notes:
NM = not measured due to insufficient sample volume
ND = not detected

Table 6.7. Summary of Key MNA Parameters at Kelly AFB.

Parameter	Aquifer Samples	Aquitard Samples
PCE, mg/L	0.227	0.146
DCE+VC, mg/L	0.12	0.071
Ethene, mg/L	<0.00426	<0.00426
Methane, mg/L	0.294	0.154
Σ VFAs, mg/L	ND	0.29
BOD, mg/L	<3.33	<3.33
TOC, mg/L	0.61 J	1.27
DHC, cell/mL	3,500	2.4
Σ Red.Dech., cell/mL	32,300	94
EBAC, cell/mL	1.1 E+6	1.0 E+5
^{13}C DCE, δ13C (‰)	-24.51	NM
^{13}C VC, δ13C (‰)	-24.46	NM
Mag. Susc., m3/kg	1.2 E-07	7.3 E-08
f_{oc}, mg/kg	5,230	11,580
PBOC, mg/kg	43	39

Notes:

NM = not measured due to insufficient sample volume

ND = not detected

7.0 PERFORMANCE ASSESSMENT

7.1 SUSTAINED TREATMENT OF BIOWALLS

A summary of key performance results for evaluating the sustained treatment of the biowalls at Altus AFB using a lines-of-evidence approach is provided in Table 7.1 for samples collected within the biowalls, and in Table 7.2 for samples collected downgradient of the biowalls. Key findings from the assessment are as follow:

- Soil and groundwater sampling at the Altus AFB biowalls approximately ten years after installation demonstrated the ongoing degradation of CVOCs. TCE was not detected in five of seven groundwater samples collected from the biowall despite upgradient detections above MCLs. At the two locations with TCE detections, concentrations were below MCLs.

- Microbial sampling established the presence of key dechlorinating bacteria and the abundance of genes encoding specific enzymes for degradation, high methane concentrations, low sulfate concentrations, and negative oxidation-reduction potential, all indicative of highly reducing conditions within the biowalls and favorable conditions for CVOC destruction via microbial reductive dechlorination.

- High cellulose content (>79%) of the mulch, elevated total organic carbon (TOC) content in groundwater and elevated potentially bioavailable organic carbon (PBOC) measurements in soil samples further supports an ongoing, long-lived source of carbon. These results demonstrate the ongoing and long-term efficacy of the mulch biowalls at Altus AFB.

- Concentrations of bacteria, TOC, PBOC, and other geochemical parameters suggests a modest impact, or a “shadow” effect, of the biowalls downgradient. The continued presence of CVOCs downgradient may be attributable to back-diffusion from low-K shale. However, the biowalls continue to provide benefits by removing CVOCs in groundwater, thus reducing further CVOC loading to the downgradient, low-K strata.

- Based on our findings of microbial abundance and the patterns in daughter product formation, it appears that biodegradation is the dominant removal mechanism for TCE within the biowalls. This finding contrasts with a prior study (Whiting et al., 2014) suggesting 98-100% of VOC removal was due to abiotic processes. This discrepancy may be due to changing patterns of the fraction of biotic vs. abiotic degradation over time (prior study samples were collected in 2007-2008) or due to differences in methodology.

- Since the biowalls do not extend the full depth of the impacted groundwater-bearing unit, some impacted groundwater may be bypassing the biowall underneath the bottom of the biowalls via the fracture network. However, we believe that matrix diffusion of TCE and daughter products out of the low-K matrix into the higher-permeability zones at least partially explains the elevated downgradient CVOC concentrations relative to the biowall.

Table 7.1. Sustained Treatment Analysis within Biowalls 10 Years Post-Installation

Parameter / Line of Evidence	**Critical Value / Relationship**	**Average Sample Results**	**Data Support Evidence of Sustained Treatment?**
Concentration Change over Post-Treatment Monitoring Period	Significant decrease in CVOC conc. from early post-treatment monitoring vs. late post-treatment monitoring	CVOC concentrations decreased over post-treatment monitoring period	Yes
Concentration Trend (Parent compound and Daughter Products)	Trend from the recent monitoring period is same as (or better than) trend from early post-treatment monitoring	TCE trend better; Total CVOC trend better	Yes
TOC in Groundwater	TOC > 20 mg/L (USEPA, 1998)	91 mg/L	Yes
Dehalococcoides	> 10^4 cells/mL ("useful rate" Lu et al., 2006)	1.7 E+4	Yes
Sum of Reductive Dechlorinators	> 10^4 cells/mL	4.2 E+5	Yes
Magnetite + Concentration Trend for Daughter Products	Mag. Suscept. >4E-8 m3/kg (He et al., 2009) & daughter products decreasing or non-detect	8.9E-06 m3/kg & daughter products decreasing	Yes
^{13}C of CVOCs in Groundwater	Enrichment of ^{13}C signature within biowall relative to upgradient location	DCE = 11.5 (‰) inc. VC = 19 (‰) inc.	Yes
PBOC of Sediment Within Biowall	PBOC > 200 mg/kg (Chapelle et al., 2012)	2,380 mg/kg	Yes
Forage Analysis of Mulch	Cellulose + Hemicellulose to Lignin > 1 (Ahmad et al., 2007)	26.6	Yes

Table 7.2. Sustained Treatment Analysis for Zone Downgradient of Biowalls

Parameter / Line of Evidence	Critical Value / Relationship	Average Sample Results	Data Support Evidence of Sustained Treatment?
Concentration Change over Post-Treatment Monitoring Period	Significant decrease in concentration from early post-treatment monitoring vs. most recent post-treatment monitoring	TCE decreased; Daughter products generally the same	Yes
Concentration Trend (Parent compound and Daughter Products)	Trend from the recent monitoring period is same as (or better than) trend from early post-treatment monitoring	TCE trend the same; Total CVOC trend slightly better	Yes
TOC	TOC > 20 mg/L (USEPA, 1998)	5.6 mg/L	No, but higher than Upgradient
TOC	Downgradient (DG) > Upgradient (UG)	5.6 mg/L (DG) > 4.9 mg/L (UG)	Yes
Ethene	Downgradient (DG) > Upgradient (UG)	0.016 mg/L (DG) > 0.0049 mg/L (UG)	Yes
Methane	Downgradient (DG) > Upgradient (UG)	4.7 mg/L (DG) > 3.5 mg/L (UG)	Yes
Dehalococcoides	Downgradient (DG) > Upgradient (UG)	3,500 cells/mL (DG) > 390 cells/mL (UG)	Yes
Dehalococcoides	> 10^4 cells/mL ("useful rate" Lu et al., 2006)	3,500 cells/mL	No, but 1 OoM higher than Upgradient
Sum of Reductive Dechlorinators	> 10^4 cells/mL ("useful rate" Lu et al., 2006)	28,000 cells/mL	Yes
Magnetite + Concentration Trend for Daughter Products	Mag. Suscept. >4E-8 m3/kg (He et al., 2009) & daughter products decreasing or non-detect	1.6 E-7 & daughter products generally unchanged	Low potential for abiotic degradation
^{13}C of CVOCs in Groundwater	Enrichment of ^{13}C relative to upgradient location	No enrichment	No
PBOC in Aquifer Sediment	PBOC > 200 mg/kg (Chapelle et al., 2012)	96 mg/kg	No

- The ongoing efficacy of treatment within the biowalls, however, has helped to cut off downgradient loading to the low-permeability zone for an extended period, and downgradient CVOC concentrations should eventually decrease due to biotic and abiotic degradation, as well as flushing from treated water emanating from the biowalls. Consequently, an MNA approach may be appropriate for managing the downgradient groundwater.

- Given the ongoing performance as indicated by the lines-of-evidence assessment, augmentation of the biowalls with supplemental substrate (e.g., EVO) does not appear warranted at this time, and we anticipate that the biowalls will continue to treat CVOCs effectively as they pass through the biowall, thus reducing the CVOC loading of downgradient low-K strata. Furthermore, available evidence suggests that the biowalls contribute carbon and biogeochemical conditions downgradient that assist in degradation of remaining CVOCs in those low-K zones.

- The biowalls at Altus AFB total approximately 5,300 linear feet, representing approximately 25% of the total linear footage of biowalls that had been installed at DoD facilities as of 2015. The findings of this study should provide useful data to DoD site managers at biowall sites through: i) demonstration of biowall effectiveness more than 10 years after installation; and ii) identifying key guidelines for the most cost-effective assessment of biowall sustained treatment.

7.2 SUSTAINED TREATMENT AT SUBSTRATE INJECTION SITES

A summary of key performance results for evaluating the sustained treatment at the substrate injection sites using a lines-of-evidence approach is provided in Table 7.3 for Kelly AFB, and in Table 7.4 for NTC Orlando. Key findings from the assessment are as follow:

- Parent CVOC concentration reductions following ISB at these two sites indicates the bioremediation remedies have successfully reduced parent compound concentrations without evidence of significant rebound. As shown in Figure 7.1, OoM reductions achieved at these sites were generally better than results achieved at a majority of the 117 sites from the McGuire et al. (2016a) database.

- At Kelly AFB, parent CVOC concentrations at both wells included in the study have remained below MCLs; while at NTC Orlando one well has attained a concentration below the MCL, with concentrations at the other well are slightly above the MCL (12.2 ug/L). These results further indicate better overall performance than most of the sites in the 117-site database, where only 21% of 710 monitoring wells achieved the MCL.

- As shown in Figure 7.2, OoM reductions in Total CVOCs at both sites are lower than observed for the parent CVOC and are consistent with results from the 117-site database. This observation is common for ISB remedies where daughter products are generated as part of the bioremediation process.

Table 7.3. Sustained Treatment Analysis for ISB at Kelly AFB

Parameter / Line of Evidence	Critical Value / Relationship	Average Sample Results	Data Support Evidence of Sustained Treatment?
Concentration Change over Post-Treatment Monitoring Period	Significant decrease in CVOC conc. from early post-treatment monitoring vs. most recent post-treatment monitoring	TCE = ND; Total CVOC Increased post-treatment	Yes; Parent CVOC remains ND; Daughter trend indicates ongoing degradation
Concentration Trend (Parent compound and Daughter Products)	Trend from the recent monitoring period is same as (or better than) trend from early post-treatment monitoring	TCE = ND; Total CVOC not enough data to calculate trend	Yes; Parent CVOC remains ND
TOC	TOC > 20 mg/L (USEPA, 1998)	2.15 mg/L	No, but within 1 OoM
TOC	Treatment Zone (TZ) > Upgradient (UG)	2.15 mg/L (TZ) > 0.85 mg/L (UG)	Yes
Ethene	Treatment Zone (TZ) > Upgradient (UG)	0.047 (TZ) vs. <0.004 (UG)	Yes
Methane	Treatment Zone (TZ) > Upgradient (UG)	5.89 (TZ) vs. 0.008 (UG)	Yes
Dehalococcoides	Treatment Zone (TZ) > Upgradient (UG)	6.3E+4 (TZ) vs. 5.0E+1 (UG)	Yes
Dehalococcoides	> 10^4 cells/mL ("useful rate" Lu et al., 2006)	63,000	Yes
Sum of Reductive Dechlorinators	> 10^4 cells/mL	115,000	Yes
Magnetite + Concentration Trend for Daughter Products	Mag. Suscept. >4E-8 m3/kg (He et al., 2009) & daughter products decreasing or non-detect	2.0 E-7 m3/kg; Insufficient data for daughter trend calculation	Low potential for abiotic degradation
^{13}C of CVOCs in Groundwater	Enrichment of ^{13}C relative to upgradient location	DCE = 14.66 (‰) Inc. TCE & VC = ND upgradient	Yes
PBOC in Aquifer Sediment	PBOC > 200 mg/kg (Chapelle et al., 2012)	62	No, but within 1 OoM

Table 7.4. Sustained Treatment Analysis for ISB at NTC Orlando

Parameter / Line of Evidence	Critical Value / Relationship	Average Sample Results	Data Support Evidence of Sustained Treatment?
Concentration Change over Post-Treatment Monitoring Period	Significant decrease in CVOC conc. from early post-treatment monitoring vs. most recent post-treatment monitoring	TCE Increased post-treatment; Total CVOC Increased post-treatment	No; Total CVOC indicates ongoing degradation
Concentration Trend (Parent compound and Daughter Products)	Trend from the recent monitoring period is same as (or better than) trend from early post-treatment monitoring	TCE trend same or better; Total CVOC trend same or worse	Inconclusive; mixed trend results, but no statistically increasing trends
TOC	TOC > 20 mg/L (USEPA, 1998)	8.4	No, but within 1 OoM
TOC	Treatment Zone (TZ) > Upgradient (UG)	8.4 (TZ) vs. 12.6 (UG)	No
Ethene	Treatment Zone (TZ) > Upgradient (UG)	0.008 (TZ) vs. <0.004 (UG)	Yes
Methane	Treatment Zone (TZ) > Upgradient (UG)	12.8 (TZ) vs. 0.59 (UG)	Yes
Dehalococcoides	Treatment Zone (TZ) > Upgradient (UG)	106 (TZ) vs. <25 (UG)	Yes, but very low
Dehalococcoides	> 10^4 cells/mL ("useful rate" Lu et al., 2006)	106	No
Sum of Reductive Dechlorinators	> 10^4 cells/mL	3,310	No
Magnetite + Concentration Trend for Daughter Products	Mag. Suscept. >4E-8 m3/kg (He et al., 2009) & daughter products decreasing or non-detect	4.0 E-9 m3/kg	Not indicative of abiotic degradation
^{13}C of CVOCs in Groundwater	Enrichment of ^{13}C relative to upgradient location	CVOCs ND upgradient	Inconclusive; DCE and VC in TZ show general enrichment
PBOC in Aquifer Sediment	PBOC > 200 mg/kg (Chapelle et al., 2012)	530	Yes

- The lines-of-evidence assessment indicates overall site conditions are conducive to ongoing sustained treatment.

  - At Kelly AFB, PCE and TCE concentrations were below detection limits at the sampled wells despite an upgradient concentrations of 0.008 mg/L and 0.0146 mg/L, respectively. This is consistent with the high average DHC concentration within the treatment zone, as well as elevated PBOC concentrations, even with relatively low TOC (2.15 mg/L). Results also show a continued decline in the chlorine number, indicating a continue progression in conversion of daughter products to lesser chlorinated compounds.

  - At NTC Orlando, slight increases in TCE concentration have been observed in both wells; however, concentrations remain well below pre-treatment levels. DHC concentrations are measurable within the treatment zone, but well below the 10^4 cells/mL threshold generally considered to yield "useful" degradation rates (Lu et al., 2006). Other dechlorinating microbial indicators are present at concentrations on the order of 10^3 cells/mL. Borden et al. (2017) have indicated the low pH conditions and an underdosage of substrate and buffer are possible explanations for the observed performance at this site.

- While parent CVOC concentrations at both sites have been significantly reduced compared to pre-treatment levels, daughter product concentrations have increased correspondingly. Such pattern may lead to a conclusion of an unsuccessful remedy, but the conversion from TCE to cis-DCE and VC, while not only necessary to reach an innocuous endpoint for reductive dechlorination of TCE, likely represents a net benefit in terms of overall risk reduction when vapor intrusion is factored into the risk analysis. Reasons for lesser risk of cis-DCE and VC compared to TCE with respect to vapor intrusion are due to: i) a lower Henry's constant for DCE; and ii) a higher biodegradation rate of VC in the vadose zone (Patterson et al., 2013).

- The data mining study described in Appendix B, which includes a 34-site subset of the 117-site database with long post-treatment monitoring periods, indicates that sustained treatment of parent concentrations is observed at approximately three-quarters of sites. The comparable performance of these 2 sites with respect to the larger population of 117 sites suggests the results from these 2 sites and 34-site data mining study can likely be extended to most ISB sites. Site-specific hydrogeologic conditions, design considerations, and implementation effectiveness undoubtedly factor into the remedial outcome for any ISB application; however, these results suggest that a generally well designed and implemented ISB project more often than not will benefit from sustained treatment, at a minimum in terms of rebound suppression for the parent CVOC, for a period of at least 3 to more than 15 years after the end of treatment.

- Besides temporal concentration trends and decay rate analysis, the parameters appearing to be most indicative of sustained treatment potential were TOC, dissolved gasses, and the microbial analyses from the QuantArray-Chlor suite. An attempt to use BOD as a cost-effective surrogate for PBOC proved unsuccessful due elevated detection limits for BOD.

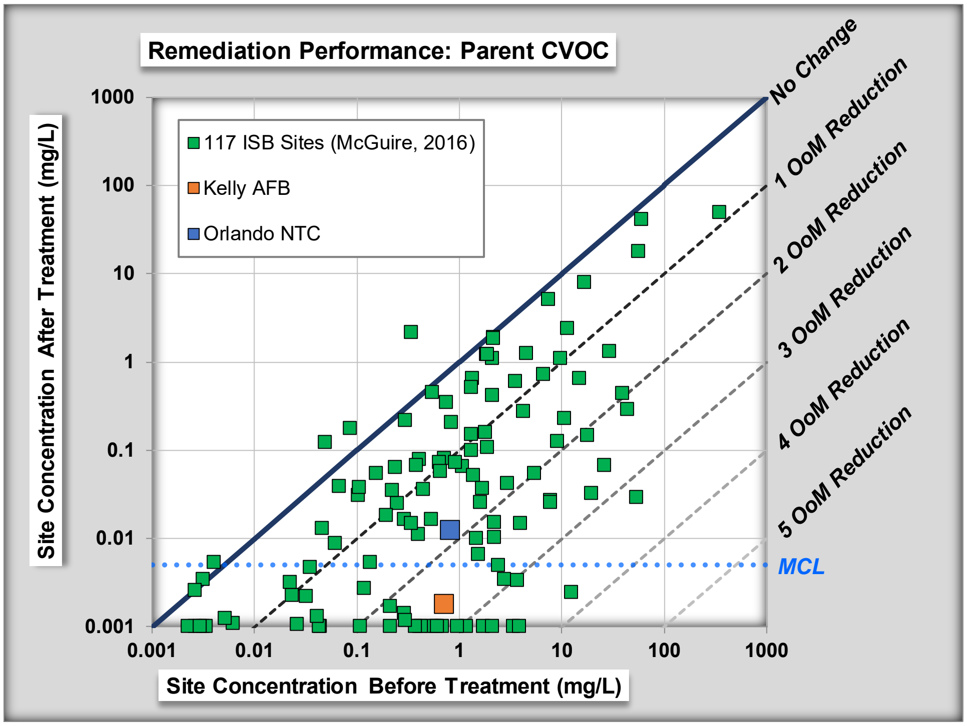


Figure 7.1. OoM Reduction in Parent CVOC Achieved by the 2 ISB Sites in this Study Compared to 117 ISB Sites from McGuire et al., 2016

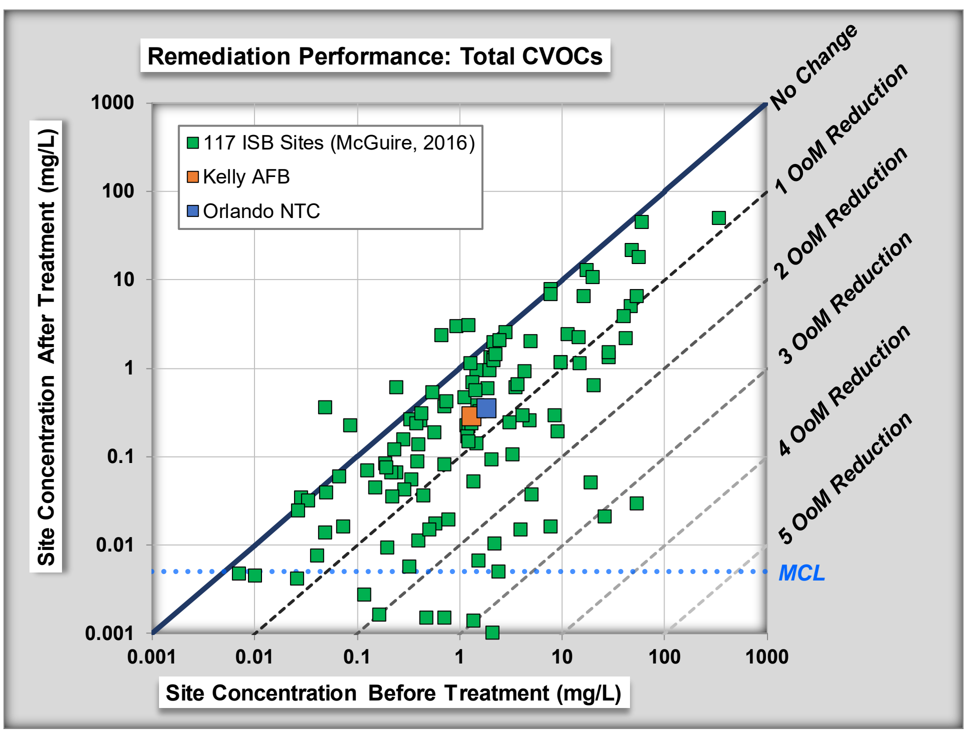


Figure 7.2. OoM Reduction in Total CVOC Achieved by the 2 ISB Sites in this Study Compared to 117 ISB Sites from McGuire et al., 2016

7.3 LOW-K MNA

A summary of key performance results for evaluating the occurrence of low-K MNA using a lines-of-evidence approach is provided in Table 7.5, 7.6, and 7.7 for England AFB, Hill AFB, and Kelly AFB, respectively. Key findings from the assessment are as follow:

- A lines-of-evidence approach was established to assess the occurrence of MNA in low-K zones underlying the transmissive zone at these sites. To date, several research studies have detected the presence of key dechlorinating bacteria in low-K zones (Takeuchi et al., 2011; Lima et al., 2012; Damgaard et al., 2012), and more recent studies have begun to elucidate biodegradation mechanisms and quantify potential rates (Wanner et al., 2018). However, to our knowledge, this study represents the first comprehensive assessment of MNA potential in low-K zones, including analysis of microbial populations, geochemical conditions, sorption potential, organic carbon bioavailability, and high-resolution chemical profiling within the aquitard.
- As a precursor to evaluating the occurrence of MNA in the low-permeability zone at these sites, an analysis of MNA in the overlying aquifer was performed. All three sites have long monitoring periods with significant datasets. All wells at these sites exhibited "Decreasing" or "Probably Decreasing" Mann-Kendall trends for TCE (the parent CVOC), while Total CVOC concentrations exhibited "Decreasing," "Probably Decreasing," or "Stable" Mann-Kendall trends. Furthermore, first-order decay rates at these sites for the parent CVOC and total CVOCs were consistent with "benchmark" decay rates calculated as part of the data mining effort that included rate data from thousands of monitoring wells.
- As shown on Figure 7.3, groundwater MNA performance at these sites, in terms of parent CVOC concentration reduction observed over the entire monitoring period, was consistent with a database of 45 MNA sites developed as part of a prior ESTCP project (ER-201120, McGuire et al., 2016a). England AFB represents one of few sites where parent CVOC concentrations have naturally declined below the MCL (recognizing that each "site" in this study only analyzed data from a single well since evaluation of MNA in the low-K zone was the primary objective).
- High-resolution chemical profiling of CVOCs in the aquitard indicates that biodegradation daughter products are present within the low-K zone at each site. At two of the sites, England AFB and Hill AFB, these daughter product detections were coupled with the detection of DHC and other biomarkers indicative of potential for biological reductive dechlorination. At Kelly AFB, while DHC was not detected in the aquitard samples, another reductive dechlorinate biomarker was detected. On this basis, it is likely that microbial reactions are occurring in the aquitard at these sites.

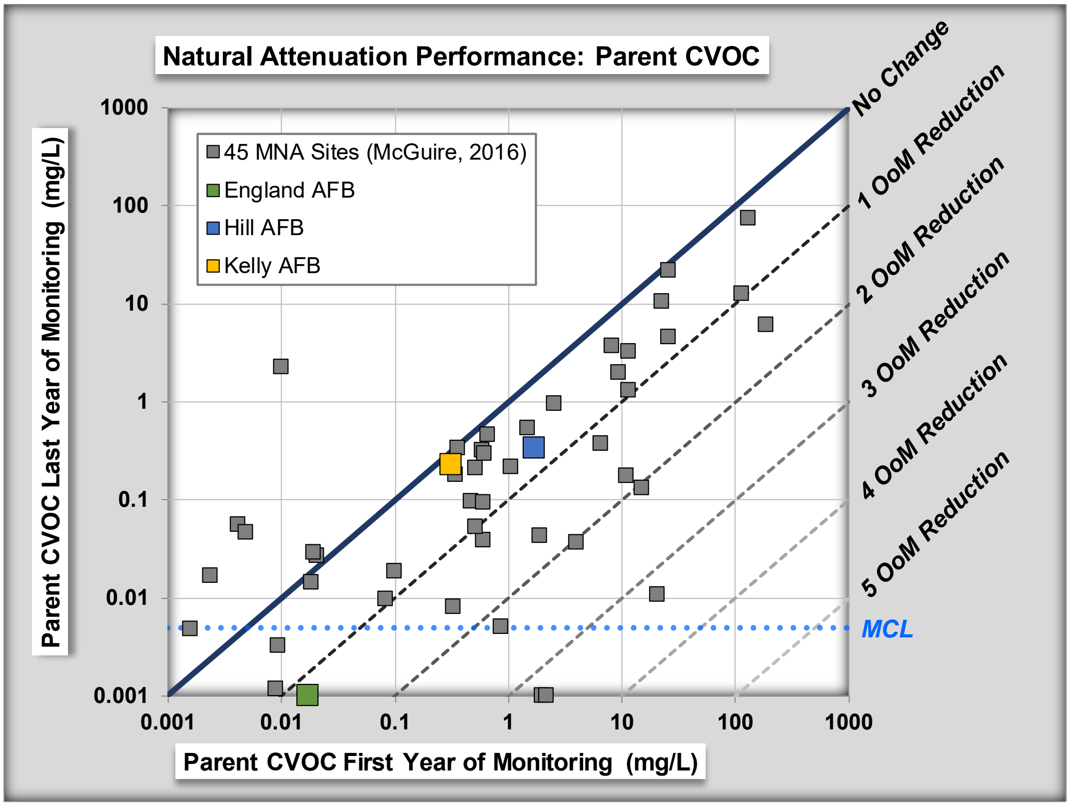


Figure 7.3. OoM Reduction in Parent CVOC Achieved by the 3 MNA Sites in this Study Compared to 45 MNA Sites from McGuire et al., 2016

- Attempts to quantify the rates of biodegradation through compound specific isotope analysis (CSIA) were unsuccessful due to the inability for the commercial laboratory to achieve sufficiently low detection limits for the CVOCs in the aquitard soil samples. This limitation was identified early in the project (i.e., at the first site sampled), and therefore CSIA soil samples were not collected at the other two sites as a cost-saving measure.

- The Source History Tool, developed under a previous ESTCP project, was used to evaluate biodegradation rates within the aquitard based on the high-resolution CVOC data. As further described in Appendix D, rate calculation was possible at only one of four soil borings attempted (soil borings from the third site were not modeled due to the lack of parent CVOC and low concentrations of daughter products). The model indicated a potential slow biodegradation of TCE with a first-order rate constant on the order of 0.07 per year (half-life of 10 years) or more. This rate is generally consistent with a recent estimate of the upper end decay rate for TCE in the low-K zone of approximately 0.09 per year (half-life of 7.3 years) estimated using CSIA data (Wanner et al., 2018).

Table 7.5. Low-K MNA Analysis at England AFB

Parameter / Line of Evidence	Critical Value / Relationship	Average Sample Results	Data Support Evidence of Low-K MNA?
Mann-Kendall Concentration Trend over MNA Monitoring Period for Parent CVOC	Stable or decreasing concentration trend in groundwater	Parent CVOC trend is Decreasing	Yes
Mann-Kendall Concentration Trend over MNA Monitoring Period for Total CVOCs	Stable or decreasing concentration trend in groundwater	Total CVOC trend is Probably Decreasing	Yes
First-Order Decay Rate of Parent CVOC	Rate consistent with data mining study for All Sites <50 ug/L (0.045 /yr; $t_{1/2}$ = 15 yr)	0.14 /yr $t_{1/2}$ = 5 yr	Yes
Geochemistry in Aquitard Groundwater Indicative of Reducing Conditions	TOC > DL CH4 > DL	TOC = 2.95 mg/L CH4 = 3.16 mg/L	Yes
Presence of Ethene or Ethane in Aquitard Groundwater	Ethene > DL Ethane > DL	ND	No
PBOC in Aquitard	PBOC > 200 mg/kg (Chapelle et al., 2012)	430 mg/kg	Yes
Fraction organic carbon (f_{oc})	f_{oc} in Aquitard (At) > f_{oc} in Aquifer (Af)	12,180 (At) > 5,380 (Af)	Yes
Dehalococcoides or Other Relevant Biomarkers Detected in Low-K Zone + Presence of Daughter Products in Low-K Zone	Presence of DHC & daughter products in aquitard soil samples	Yes	Yes
Magnetite + Concentration Trend for Daughter Products	Mag. Suscept. >4E-8 m3/kg (He et al., 2009) & daughter products decreasing or non-detect	1.3 E-7; Daughter product trends are stable	Low potential for abiotic degradation

Table 7.6. Low-K MNA Analysis at Hill AFB

Parameter / Line of Evidence	Critical Value / Relationship	Average Sample Results	Data Support Evidence of Low-K MNA?
Mann-Kendall Concentration Trend over MNA Monitoring Period for Parent CVOC	Stable or decreasing concentration trend in groundwater	Parent CVOC trend is Decreasing	Yes
Mann-Kendall Concentration Trend over MNA Monitoring Period for Total CVOCs	Stable or decreasing concentration trend in groundwater	Total CVOC trend is Decreasing	Yes
First-Order Decay Rate of Parent CVOC	Rate consistent with data mining study for All Sites <50 ug/L (0.045 /yr; $t_{1/2}$ = 15 yr)	0.10 /yr $t_{1/2}$ = 7 yr	Yes
Geochemistry in Aquitard Groundwater Indicative of Reducing Conditions	TOC > DL CH_4 > DL	TOC = insuff. vol. CH_4 = 0.047 mg/L	Yes
Presence of Ethene or Ethane in Aquitard Groundwater	Ethene > DL Ethane > DL	Ethane = 0.008 J	Yes
PBOC in Aquitard	PBOC > 200 mg/kg (Chapelle et al., 2012)	260 mg/kg	Yes
Fraction organic carbon (f_{oc})	f_{oc} in Aquitard (At) > f_{oc} in Aquifer (Af)	7,180 (At) > 1,500 (Af)	Yes
Dehalococcoides or Other Relevant Biomarkers Detected in Low-K Zone + Presence of Daughter Products in Low-K Zone	Presence of DHC & daughter products in aquitard soil samples	Yes	Yes
Magnetite + Concentration Trend for Daughter Products	Mag. Suscept. >4E-8 m3/kg (He et al., 2009) & daughter products decreasing or non-detect	1.2 E-7; Daughter product trends are stable	Low potential for abiotic degradation

Table 7.7. Low-K MNA Analysis at Kelly AFB

Parameter / Line of Evidence	Critical Value / Relationship	Average Sample Results	Data Support Evidence of Low-K MNA?
Mann-Kendall Concentration Trend over MNA Monitoring Period for Parent CVOC	Stable or decreasing concentration trend in groundwater	Parent CVOC trend is Probably Decreasing	Yes
Mann-Kendall Concentration Trend over MNA Monitoring Period for Total CVOCs	Stable or decreasing concentration trend in groundwater	Total CVOC trend is Stable	Yes
First-Order Decay Rate of Parent CVOC	Rate consistent with data mining study for All Sites <50 ug/L (0.045 /yr; $t_{1/2}$ = 15 yr)	0.039 /yr $t_{1/2}$ = 18 yr	Yes
Geochemistry in Aquitard Groundwater Indicative of Reducing Conditions	TOC > DL CH4 > DL	TOC = 1.27 mg/L CH4 = 0.154 mg/L	Yes
Presence of Ethene or Ethane in Aquitard Groundwater	Ethene > DL Ethane > DL	Ethane = 0.005 J	Yes
PBOC in Aquitard	PBOC > 200 mg/kg (Chapelle et al., 2012)	39 mg/kg	Yes
Fraction organic carbon (f_{oc})	f_{oc} in Aquitard (At) > f_{oc} in Aquifer (Af)	11,580 (At) > 5,230 (Af)	Yes
Dehalococcoides or Other Relevant Biomarkers Detected in Low-K Zone + Presence of Daughter Products in Low-K Zone	Presence of DHC & daughter products in aquitard soil samples	No DHC detected	Inconclusive; Daughter products present, but no DHC detected
Magnetite + Concentration Trend for Daughter Products	Mag. Suscept. >4E-8 m3/kg (He et al., 2009) & daughter products decreasing or non-detect	7.3 E-8; Daughter product trends are stable	Low potential for abiotic degradation

- Fraction organic carbon was analyzed in 48 aquitard samples and in 16 transmissive zone samples at the MNA sites. The distribution of f_{oc} is illustrated on Figure 7.4 and indicates that the aquitard samples have significantly higher f_{oc} concentrations than aquifer samples ($p<0.05$). This is an important finding that indicates a much higher sorption potential (approximately 2.6 times) within the aquitard compared to the aquifer.

- Potentially-bioavailable organic carbon (PBOC) was analyzed in 24 aquitard samples and in 12 transmissive zone samples at the MNA sites and untreated portions of the ISB sites. The distribution of PBOC is also illustrated on Figure 7.4. While the median PBOC in aquitard samples is approximately two times higher than the median of transmissive zone samples, the difference was not statistically significant at the 95% confidence level. Nonetheless, these data suggest the availability of potential carbon substrate within the aquitards.

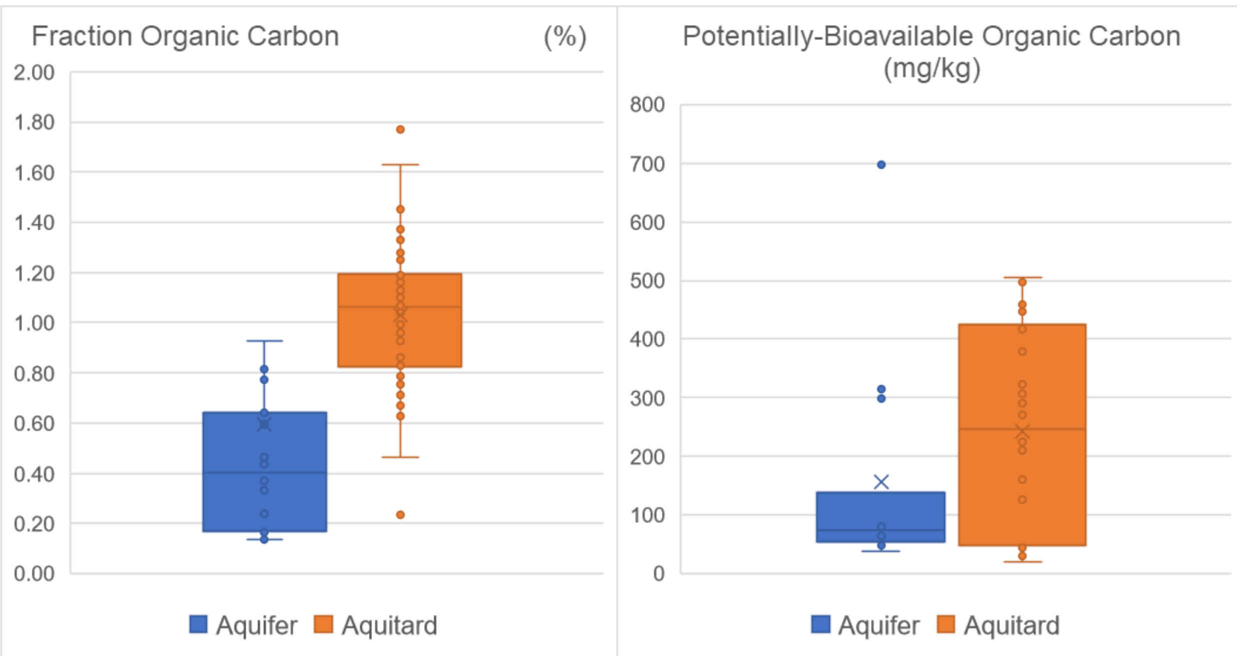


Figure 7.4. Distribution of f_{oc} and PBOC in Aquifer and Aquitard Samples.

7.4 FIRST-ORDER DECAY RATE CORRELATION ANALYSES

First-order decay rates calculated for the sustained treatment substrate injection sites, MNA sites, and the monitoring wells located outside the biowalls at Altus AFB were evaluate as a function of TOC, DHC, and methane. As shown on Figure 7.5, relationships between these parameters were generally positive, but no strong correlations were found. The Altus data points identified as "MNA" are from wells upgradient of the biowalls, while the Altus data points identified as "ISB" are from wells located downgradient of the biowalls.

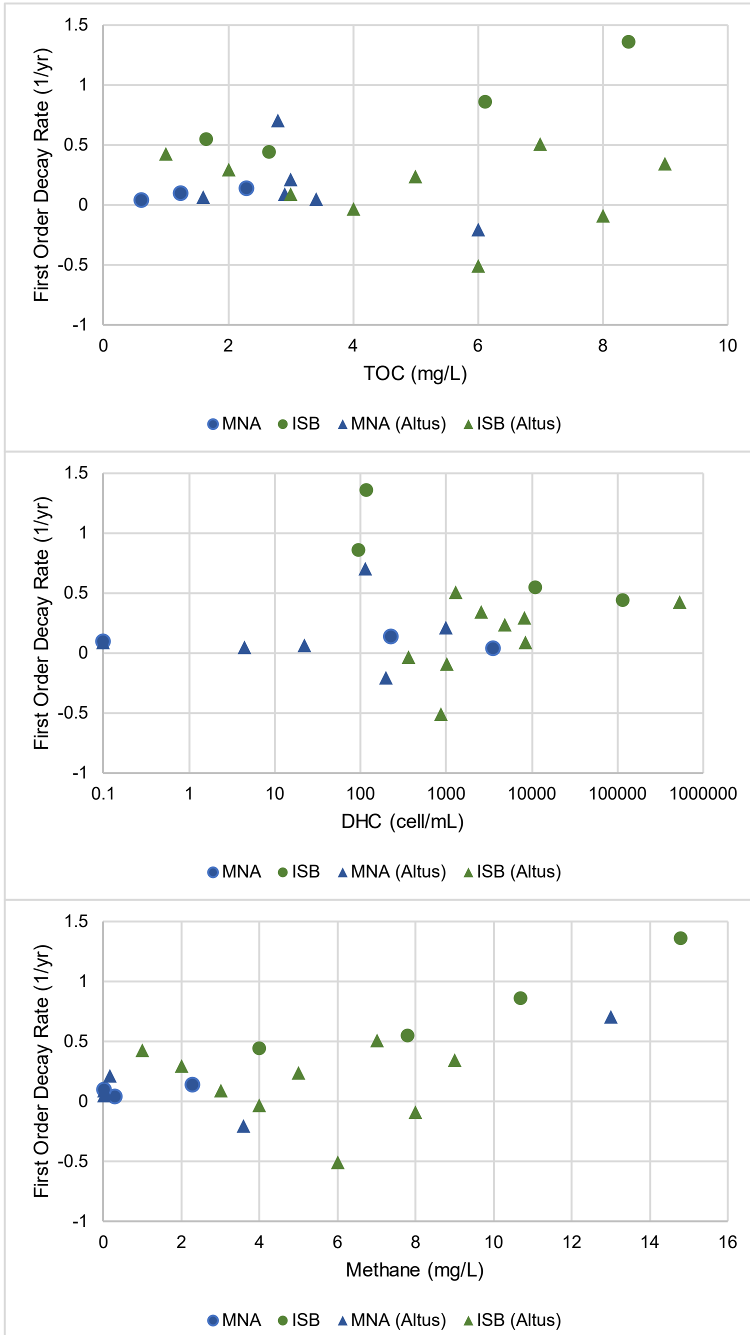


Figure 7.5. Scatterplots of Selected Groundwater Parameters and First-order Decay Rates.

7.5 FACT SHEETS

Key deliverables for this project include Fact Sheets to assist end-users in the application of this dataset to their sites. Appendix G contains the Fact Sheet on how the low-K MNA data can be used in matrix diffusion modeling using the REMChlor-MD computer model. Appendix H contains the Fact Sheet on application of the Sustained Treatment findings.

8.0 COST ANALYSIS

Assessing post-ISB sustained treatment and low-K MNA at other sites should be feasible using data that is already available, or readily attainable using existing monitoring wells. If warranted, additional data to support a more detailed lines-of-evidence evaluation can be collected through the installation of an additional soil boring and temporary groundwater monitoring point. Analytical costs on a per-sample basis for the suite of monitoring parameters utilized in this study are summarized on Table 8.1 below (note that analytical costs may vary based on total number of samples).

Table 8.1. Summary of Analytical Costs.

Matrix	Analyte	Method	Laboratory (Phone)	Cost per Sample
Aquifer / Aquitard Sediment	CVOCs (Parent & Daughters)	Method 8260 / 5035	Pace National (800-767-5859)	$60 (incl. core kits)
	Fraction Organic Carbon (f_{oc})	ASTM D2974	Pace National (800-767-5859)	$25
	Molecular Biological Tools	QuantArray-Chlor	Microbial Insights (865-573-8188)	$750
	PBOC	Per Thomas et al., 2012	Virginia Tech, Dr. Mark Widdowson (540-231-7153)	$300
	Magnetic Susceptibility	Per laboratory protocol	Microbial Insights (865-573-8188)	$75
Mulch Sediment	Forage Analysis	Per laboratory protocol	Univ. of Wisconsin, Soil & Forage Lab. (715-387-2523)	$72
Groundwater	CVOCs (Parent & Daughters)	Method 8260	Pace National (800-767-5859)	$60
	Total Organic Carbon	Method 9060A	Pace National (800-767-5859)	$25
	Methane, Ethane, Ethene	RSK 175	Pace National (800-767-5859)	$55
	Major Cations, Alk. and Anions	Method 6010, 9056, 2320B	Pace National (800-767-5859)	$90
	CSIA (^{13}C)	Internal CSIA Method	Pace National (800-767-5859)	$525
	Molecular Biological Tools	QuantArray-Chlor	Microbial Insights (865-573-8188)	$750

For assessing low-K MNA, a soil boring advanced into the low-permeability zone can be particularly useful if existing information is unavailable. High-resolution sampling as conducted in this study may be cost prohibitive, and in such cases, we recommend at least one sample be collected for analysis of CVOCs and foc. If budget allows, collection of a sample for Molecular Biological Tools and Magnetic Susceptibility can be particularly useful. Analysis of PBOC generally requires multiple samples and therefore may be cost prohibitive; an attempt to correlate BOD to PBOC as a low-cost substitution was included in this study but was found to be unsuitable due to elevated BOD detection limits relative to organic content of the soils. Similarly, detection limits for compound-specific isotope analysis (CSIA) were found to be elevated relative to CVOC concentrations in the low-K zones. On this basis, CSIA samples from the low-K zone are not recommended (note that detection limits may improve over time).

If a soil boring is installed into the low-K zone, consideration should also be given to attempting collection of a groundwater sample from the low-K zone. This can often be accomplished using a temporary monitoring point provided by the drilling subcontractor, as was done in this study. Beyond the analytical program, total costs for a soil boring and temporary groundwater monitoring point should consider the drilling subcontractor and field staff labor, as well as costs for coordinating site access, implementing a health and safety plan, and managing investigation derived waste. Field work can typically be completed in one to two days, depending on site-specific hydrogeologic conditions.

For assessing post-bioremediation sustained treatment, data from existing monitoring wells can generally be utilized without the need for installing additional soil borings or groundwater monitoring points. A key data need, however, is groundwater characterization from outside the treatment zone, preferably from a monitoring point located upgradient of the treatment zone. Therefore, if no such monitoring point exists, then installation of a temporary groundwater monitoring point may be necessary. Beyond the analytical program, total costs for a soil boring and temporary groundwater monitoring point should consider the drilling subcontractor and field staff labor, as well as costs for coordinating site access, implementing a health and safety plan, and managing investigation derived waste. Field work can typically be completed in one to two days, depending on site-specific hydrogeologic conditions.

Data analysis costs for both technologies can generally be completed within one to two weeks of receiving all applicable analytical data. Based on our experience, data analysis and reporting labor associated with assessing these technologies typically requires approximately 60 to 100 person-hours per site, but this estimate could vary considerably based on familiarity with the site and data analysis tools such as Mann-Kendall statistical trend analysis and the REMChlor-MD model. Assuming an average consultant rate of approximately $150 per person-hour, the total cost for data analysis is estimated to be in the range of approximately $10,000 to $15,000 per site area assessed.

9.0 REFERENCES

Adamson, D.T., T.M. McGuire, C.J. Newell, and H. Stroo, 2011. Sustained Treatment: Implications for Treatment Timescales Associated with Source-Depletion Technologies. *Remediation* 21, no. 2: 27-50. DOI: 10.1002/rem.20280.

Adamson, D.T., R.H. Anderson, S. Mahendra, and C.J. Newell, 2015. Evidence of 1,4-Dioxane Attenuation at Groundwater Sites Contaminated with Chlorinated Solvents and 1,4-Dioxane. Environmental Science & Technology, 49: 6510-6518. DOI: 10.1021/acs/est/5b00964.

Adamson, D.T., S. Mahendra, K.L. Walker, S.R. Rauch, S. Sengupta, and C.J. Newell. A Multisite Survey to Identify the Scale of the 1,4-Dioxane Problem at Contaminated Groundwater Sites. Environmental Science & Technology Letters, 1 (5): 254-258. DOI: 10.1021/ez500092u.

Ahmad, F., T.M. McGuire, R.S. Lee, and E. Becvar, 2007. Considerations for the Design of Organic Mulch Permeable Reactive Barriers, *Remediation,* 18(1), 59-72.

Borden, Robert C., 2017. Post-Remediation Evaluation of EVO Treatment – How Can We Improve Performance. ESTCP Project ER-201581, November 2017.

CB&I, 2014a. Semiannual Compliance Plan Report, July through December 2013, Volume 1. Former Kelly Air Force Base, San Antonio, Texas. TCEQ SWR No. 31750, CN600919401, RN102338480, EPA ID No. TX2571724333. Contract No. FA8903-09-D-8580, Task Order No. 0011, Project No. 143253, Rev. 0, January.

CB&I Federal Services LLC, 2014b. Final 2013 Annual Monitoring Report, Spill Site SS-45 A(SWMU 332), Former England Air Force Base, Alexandria, Louisiana, Agency Interest No. 9029, South PBC-2, Contract No. FA8903-08-C-8000, August.

Chapelle, F.H., L.K. Thomas, P.M. Bradley, H.V. Rectanus, and M.A. Widdowson. 2012. Threshold amounts of organic carbon needed to initiate reductive dechlorination in ground-water systems. *Remediation Journal*. 22(3): 19-28.

CH2MHill, 2007. Analytical Data Validation Report for the Summer 2007 Operable Unit 2 Groundwater Monitoring Point Sampling Round. Hill Air Force Base Long-Term Groundwater Monitoring Project, Hill Air Force Base, Contract No: F42650-03-D-0002, Task Order 0019, December.

Connor, J.A., S.K. Farhat, and M. Vanderford. 2014. GSI Mann-Kendall Toolkit for Quantitative Analysis of Plume Concentration Trends. *Groundwater* 56, no. 6: 819-820. DOI: 10.1111/gwat.12277.

Damgaard, I., Bjerg, P. L., Jacobsen, C. S., Tsitonaki, A., Kerrn-Jespersen, H. and Broholm, M. M., 2013, Performance of Full-Scale Enhanced Reductive Dechlorination in Clay Till. Groundwater Monitoring & Remediation, 33: 48–61.

Environmental Restoration Branch, 2009. Final Explanation of Significant Differences for Operable Unit 2, Hill Air Force Base, Utah. September.

Farhat, S.K., P.C. de Blanc, C.J. Newell, and D.T. Adamson, 2013. Source History Tool, developed for the Environmental Security Technology Certification Program (ESTCP) by GSI Environmental Inc., Houston, Texas.

He, Y., C. Su, J. Wilson, R. Wilkin, C. Adair, T. Lee, P. Bradley, M. Ferrey, 2009. *Identification and Characterization Methods for Reactive Minerals Responsible for Natural Attenuation of Chlorinated Organic Compounds in Ground Water*, US Environmental Protection Agency, EPA 600/R-09/115.

HydroGeoLogic, 2010. Final Operating Properly and Successful Determination Report for Waste Management Areas in Zone 3, Former Kelly AFB, San Antonio, Texas. Contract No. FA8903-0-D-8772-0024, CDRL No. A001b, Project No. MBPB20097602. September.

Kulkarni, P.R., D.C. King, T.E. McHugh, D.T. Adamson, C.J. Newell, 2017. Impact of Temperature on Groundwater Source Attenuation Rates at Hydrocarbon Sites. Groundwater Monitoring & Remediation, 37 (3): 82-93. DOI: 10.1111/gwmr.12226.

Leeson, A, and H. Stroo, 2011. Workshop Report: SERDP and ESTCP Workshop on Investment Strategies to Optimize Research and Demonstration Impacts in Support of DoD Restoration Goals. SERDP/ESTCP, Oct. 2011.

Lima, G., B. Parker, and J. Meyer, 2012. Dechlorinating Microorganisms in a Sedimentary Rock Matrix Contaminated with a Mixture of VOCs, Environmental Science & Technology, 46 (11), 5756-5763.

Lu, X., J.T. Wilson, and D.H. Kampbell, 2006. Relationship between Dehalococcoides DNA in groundwater and rates of reductive dechlorination at field scale. *Water Research*, 40, no. 16: 3131-3140. https://doi.org/10.1016.j.watres.2006.05.030.

McGuire, T.M., D.T. Adamson, M.S. Burcham, P.B. Bedient, and C.J. Newell, 2016a. Evaluation of Long-Term Performance and Sustained Treatment at Enhanced Anaerobic Bioremediation Sites. Groundwater Monitoring & Remediation, 36 (2): 32-44. DOI: 10.1111/gwmr.12151.

McGuire, T.M, D.T. Adamson, C.J. Newell, and P.R. Kulkarni, 2016b. Final Report: Development of an Expanded, High-Reliability Cost and Performance Database for In-Situ Remediation Technologies. ESTCP Project ER-201120. March.

McHugh, T.E., P.R. Kulkarni, C.J. Newell, J.A. Connor, and S. Garg, 2014. Progress in Remediation of Groundwater at Petroleum Sites in California. Groundwater, November-December: 898-907. Doi: 10.1111/gwat.12136.

National Research Council (NRC), 2012. Alternatives for Managing the Nation's Complex Contaminated Groundwater Sites. National Academies Press, Washington, DC, USA.

Newell, C.J., H.S. Rifai, J.T. Wilson, J.A. Connor, J.A. Aziz, and M.P. Suarez, 2002. Calculation and Use of First-Order Rate Constants for Monitored Natural Attenuation Studies. United States Environmental Protection Agency Ground Water Issue, EPA/540/S-02/500, November.

Parsons Engineering Science, Inc., 2000. Final Focused Corrective Measures Study for Groundwater at Site SS-45, England Air Force Base, Alexandria, Louisiana, Volume 1. February.

Parsons, 2006. Final Construction Closeout Report: Bark Mulch Trench Interim Corrective Action for In-Situ Anaerobic Bioremediation of Chlorinated Solvents in Groundwater, Altus Air Force Base, Oklahoma. Prepared for Altus AFB Air Education Training Command and the Air Force Center for Environmental Excellence, Contract No. F41624-01-D-8544, Delivery Order No. 0025, May.

Patterson, B.M., R. Aravena, G.B. Davis, A.J. Furness, T.P. Bastow, and D. Bouchard, 2013. Multiple lines of evidence to demonstrate vinyl chloride aerobic biodegradation in the vadose zone, and factors controlling rates. Journal of Contaminant Hydrology, 153: 69-77. Doi: 10.1016/j.jconhyd.2013.07.008.

Resolution Consultants, 2013. Long Term Monitoring Optimization Report for Study Area 17 (SA 17), Former NTC Orlando FL, N65928.PF.002905, NTC Orlando, 5090.3b, November 26.

Shaw, 2012. Final Construction Completion Report for In Situ Enhanced Bioremediation Injections at Site SS037 Zone 3 Groundwater (SWR No. 31750, Former Kelly Air Force Base, San Antonio, Texas. Contract No. FA8903-09-D-8580, Task Order No. 011, Report/Project No. 143253, Rev. 0, October

Stroo, H.F., A. Leeson, J.A. Marqusee, P.C. Johnson, C.H. Ward, M.C. Kavanaugh, T.C. Sale, C.J. Newell, K.D. Penell, C.A. Lebron, and M. Unger, 2012. Chlorinated Ethene Source Remediation: Lessons Learned, Environmental Science & Technology, 46, 6438-6447.

Suthersan, S., D. Nelson, M. Schnobrich, E. Kalve, and M. McCaughey, 2013. Role of Biomass Recycling in the Successful Completion of Enhanced Reductive Dechlorination (ERD) Systems. Groundwater Monitoring & Remediation 33 (1): 31-36.

Suthersan, S., M. Gentile, C. Bell, J. Quinnan, and J. Horst, 2016. Big Data and Environmental Remediation: Gaining Predictive Insights. Groundwater Monitoring & Remediation 36 (2): 21-31.

State Water Resources Control Board (SWRCB), 2016. GeoTracker. March. Viewed online on 9 March 2020: https://www.waterboards.ca.gov/water_issues/programs/gama/docs/geotracker_factsheet.pdf.

Takeuchi M., Y. Kawabe, E. Watanabe, T. Oiwa, M. Takahashi, K. Nanba, Y. Kamagata, S. Hanada, Y. Ohko, T. Komai, 2011. Comparative study of microbial dechlorination of chlorinated ethenes in an aquifer and a clayey aquitard, Journal of Contaminant Hydrology, Volume 124, Issues 1–4, Pages 14-24.

Thomas, L.K, M.A. Widdowson, J.T. Novak, F.H. Chappelle, R. Benner, and K. Kaiser, 2012. Potentially Bioavailable Natural Organic Carbon and Hydrolyzable Amino Acids in Aquifer Sediments, *Groundwater Monitoring and Remediation*, 32, no. 4: 92-95.

URS & Intera, 2003. Conceptual Model Update for Operable Unit 2 Source Zone, Hill Air Force Base, Utah, September.

USEPA, 2009. *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater*. US Environmental Protection Agency, EPA/600/R-98/128 September 1998.

Walker, K.L., T.M. McGuire, D.T. Adamson, and R.H. Anderson, 2020. Long-Term Evaluation of Mulch Biowall Performance to Treat Chlorinated Solvents. Groundwater Monitoring & Remediation, 40 (1): 35-46. Doi: 10.1111/gwmr.12364.

Whiting, K., P.J. Evans, C. Lebrón, B. Henry, J.T. Wilson, and E. Becvar, 2014. Factors Controlling In Situ Biogeochemical Transformation of Trichloroethene: Field Survey. *Groundwater Monitoring and Remediation*, 34, no. 3: 79-94.

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APPENDIX B DATA MINING ON THE OCCURRENCE OF SUSTAINED TREATMENT AT ISB SITES

INTRODUCTION

As part of ESTCP Project ER-201120, McGuire et al. (2016a; 2016b) evaluated 34 sites where an in-situ bioremediation (ISB) remediation treatment had been performed to treat chlorinated solvents in groundwater. Whereas the results of the original study were based on between 3 and 12 years of post-treatment data, this study evaluated insights from an additional 5 years of monitoring data at these same sites where additional monitoring had been performed since the initial data mining study. The extended data mining analysis was performed to evaluate whether sustained treatment processes continue to help prevent concentration rebound, even with five additional years of monitoring data post-treatment.

The database of 34 ISB sites with long post-treatment monitoring periods was updated with additional data from the California GeoTracker database, Florida's OCULUS document management system, and the New Hampshire OneStop database. The new data mining effort added between 1 and 6 years of additional post-treatment monitoring data for 14 of the original 34 sites and extended the overall range of post-treatment monitoring within the dataset to 16 years (from a maximum of 12 years in the original study).

METHODS

Two primary data analyses were performed:

1) Calculation of the OoM reduction from before treatment to the first year of post-treatment monitoring data and the OoM reduction from before treatment to the last year of post-treatment monitoring data, where:

   OoM reduction is calculated as the negative logarithm of the geometric mean concentration in the post-treatment period of interest (i.e., either the first or last year of monitoring) divided by the geometric mean concentration before treatment; and

2) Mann-Kendall non-parametric temporal trend analyses, as performed with the GSI Mann-Kendall Toolkit (Connor et al., 2014).

RESULTS

Table C.1 summarizes the updated Mann-Kendall concentration trend results for each of the 14 sites with new post-treatment monitoring data. Key results are:

- 6 sites (highlighted in green in Table C.1) showed evidence of improved or sustained treatment between the original study and updated study;

- 1 site (highlighted in red in Table C.1) showed evidence of decreased performance over time, although shifting from a "decreasing" trend condition to a "probably decreasing" trend; and

- 7 sites (no highlighting in Table C.1) showed no difference in trends between the original study and updated study.

Table C-1. Mann-Kendall Trend Test Results for the 14 Sites with Additional Post-Treatment Monitoring Data.

Sites in green demonstrate evidence of improved or sustained treatment. Sites in red showed evidence of decreased performance over time. Sites with no highlighting showed no differences in trend.

Site No.	Post-Treatment Mann-Kendall Trend for the Site (Original Study)	Post-Treatment Mann-Kendall Trend for the Site (Updated Study)	Years of Additional Monitoring Data
2	Stable	Prob. Decreasing	2
4	Stable	Stable	1
7	Prob. Increasing	Prob. Increasing	4
9	Prob. Decreasing	Decreasing	6
11	Increasing	No Trend	3
13	No Trend	Prob. Decreasing	4
14	Decreasing	Prob. Decreasing	5
15	Stable	Stable	6
18	No Trend	Stable	4
19	Decreasing	Decreasing	6
20	Decreasing	Decreasing	6
25	No Trend	Stable	6
31	Prob. Decreasing	Prob. Decreasing	2
33	Prob. Increasing	Stable	2

When comparing the change in final concentrations between the original monitoring record and the updated monitoring record, 11 of the 14 sites (79%) showed additional decreases in parent concentrations (see Figure C.1). Concentrations at most sites remained within 1 OoM of the original study, with minor rebound at only three sites.

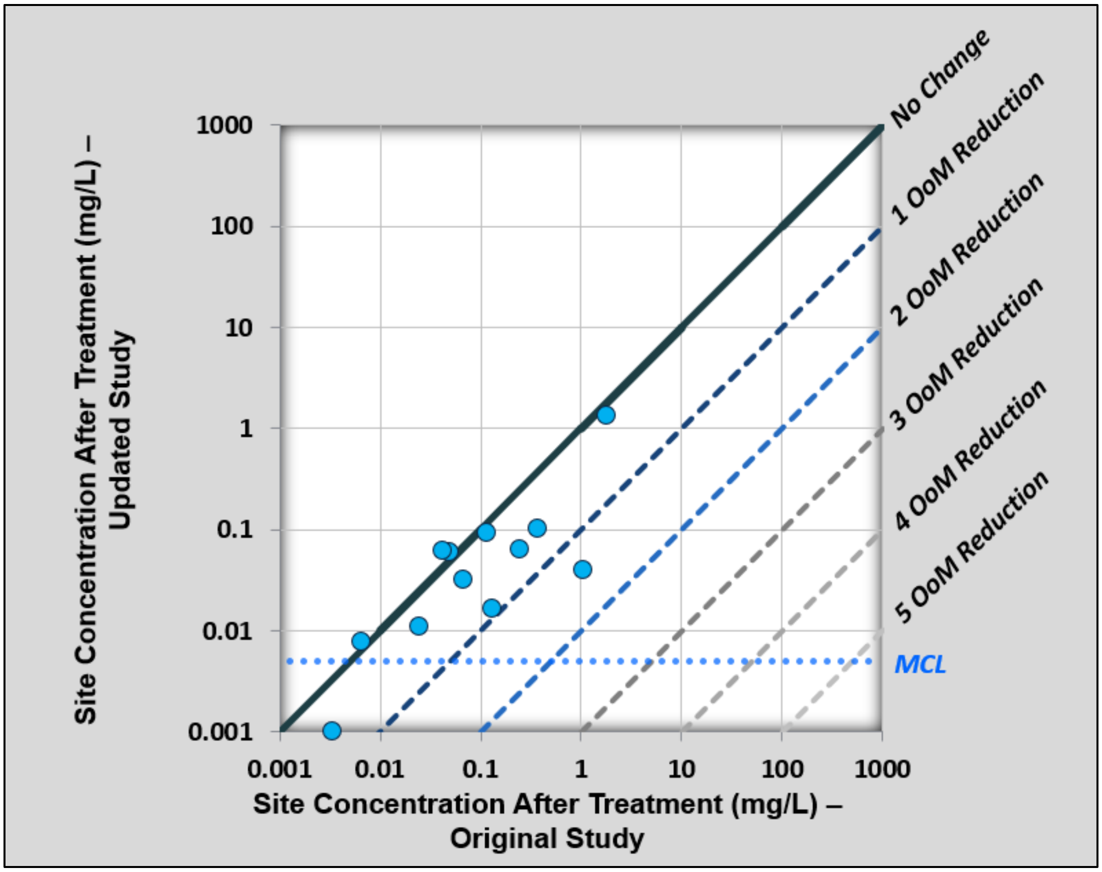


Figure C.1. Comparison of the Change in Final Concentration Between the Original Monitoring Record Compared to the Updated Monitoring Record for 14 Sites.

On average, 4 additional years of monitoring data were available for the 14 sites.

A detailed Mann-Kendall analysis of the updated post-treatment monitoring period was performed at each of the 34 sites, as well as for the 106 monitoring wells at these sites. Figure D.2 illustrates the number of sites falling within each Mann-Kendall trend category for the updated data set, and Figure D.3 shows the Mann-Kendall trend results for 106 monitoring wells at these sites. Key findings of the trend analyses include:

- The most common trend over the post-treatment monitoring period indicated stable conditions at 59% of the sites and 52% of the groundwater monitoring wells that were evaluated;
- The majority of sites (93%) and groundwater monitoring wells (93%) showed evidence of sustained treatment, defined as a stable, no trend, probably decreasing, or decreasing trend over the post-treatment monitoring period;
- Only a small handful of sites (3%) and wells (7%) exhibited rebound (increasing or probably increasing trend); and
- Sites (15%) and wells (29%) exhibiting higher variability and thus no apparent trend make evaluation of sustained treatment difficult at these sites.

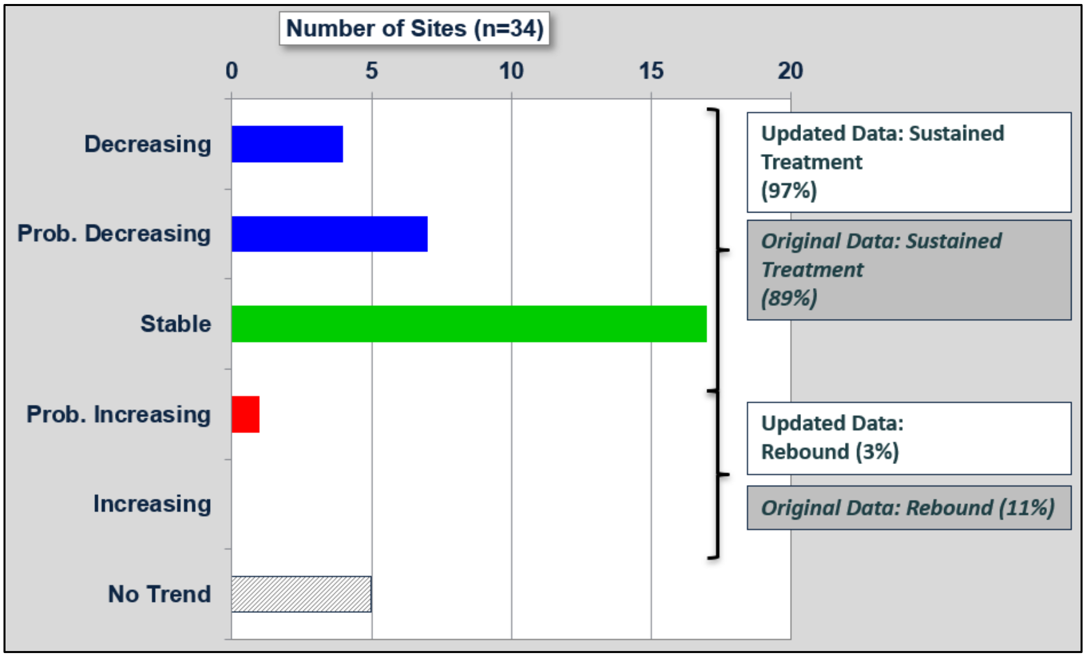


Figure D.2. Mann-Kendall Trend Analyses for Post-treatment Period for 34 ISB Sites.

Site-wide Mann-Kendall trends calculated using the GSI Mann-Kendall Toolkit.

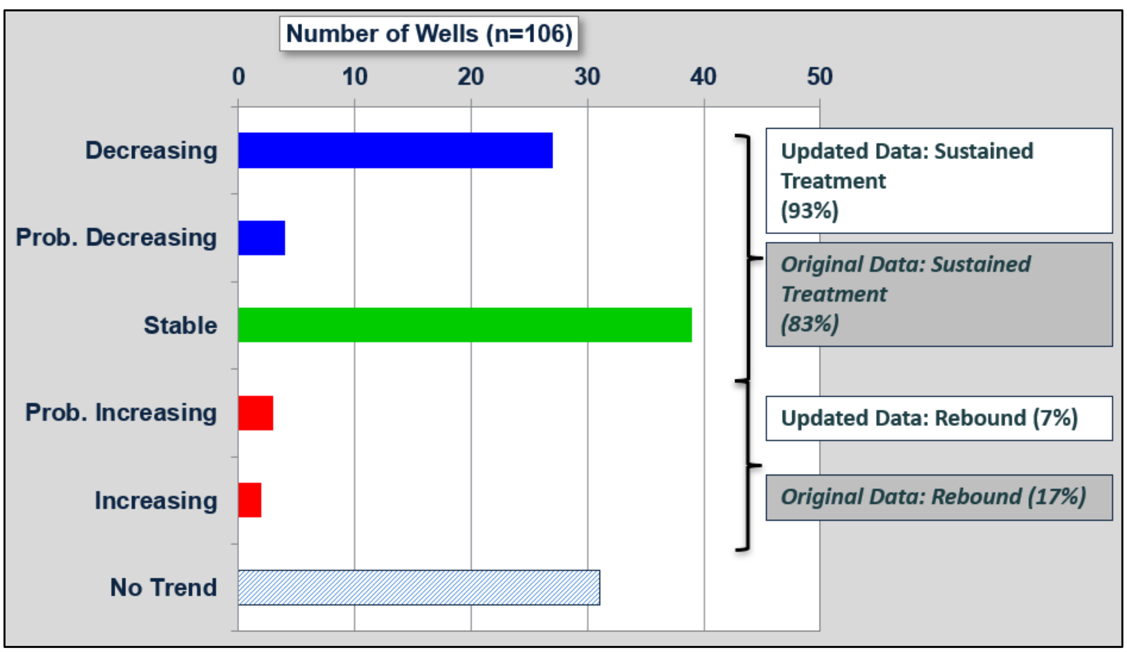


Figure D.3. Mann-Kendall Trend Analyses for Post-treatment Period for 106 Monitoring Wells at the 34 ISB Sites.

Mann-Kendall trends calculated using the GSI Mann-Kendall Toolkit.

Figure D.4 shows the OoM reductions for each of the 34 ISB sites during post-treatment monitoring. Whereas the original dataset demonstrated sustained treatment at 65% of the sites, the additional data suggests that sustained treatment has been observed at 74% of the sites, with concentration rebound occurring at only 26% of the sites. In fact, three sites showed greater than a 1 OoM reduction between the first year and last year of monitoring, and only one site with greater than 2 OoM reductions initially showed rebound.

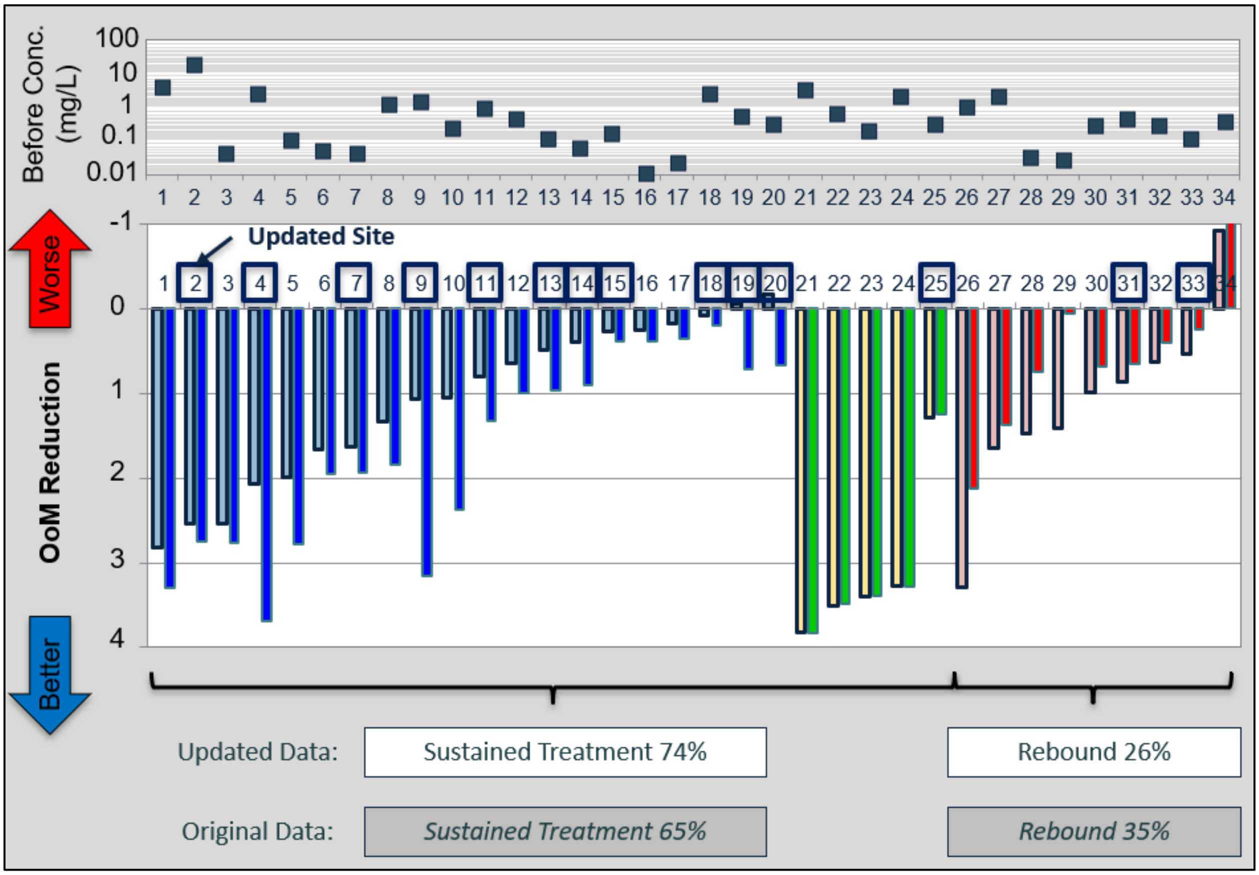


Figure D.4. OoM Reductions Achieved for Each of 34 ISB Sites During Post-treatment Monitoring Periods.

For each site, the lighter colored bar on the left represents OoM reduction from before treatment to first year of post-treatment monitoring, and the darker color on the right represents OoM reduction from before treatment to final year of post-treatment monitoring. The average time between first year and last year of post-treatment monitoring is approximately 8 years for this set of sites (i.e., an average post-treatment monitoring period of 9 years overall).

Figure D.5 compares OoM reductions achieved for all 34 ISB sites during the first year of post-treatment monitoring compared to the final year of the post-treatment monitoring period. There is no statistically significant relationship in OoM reductions between the first year and last year of post-treatment monitoring, suggesting that sustained treatment processes are providing some benefit in preventing concentration rebound. With the additional data collected as part of this study, the average post-treatment monitoring period is 9 years, and the median percent reduction is approximately 0.3 OoM lower (i.e., better performance) with the additional monitoring data.

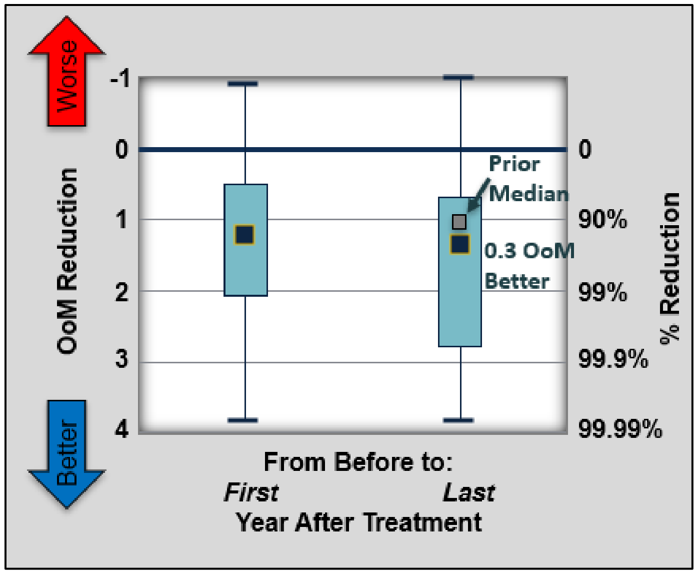


Figure D.5. Comparison of OoM Reductions Achieved for All 34 ISB Sites During First Year of Post-treatment Monitoring Period vs. Final Year of Post-treatment Monitoring Period.

Figure D.6 compares OoM reductions at 84 sites with short-post-treatment monitoring periods of less than 3 years with the 34 sites with longer post-treatment monitoring records (3-16 years). The additional data showed a 0.3 OoM increase in concentration reduction (i.e., better performance) compared to the original dataset. No statistically significant relationship in OoM reductions was observed between sites with less than 3 years of monitoring and sites with 3-16 years post-monitoring data. This finding suggests that long-term post-treatment monitoring may not be necessary at the majority of sites.

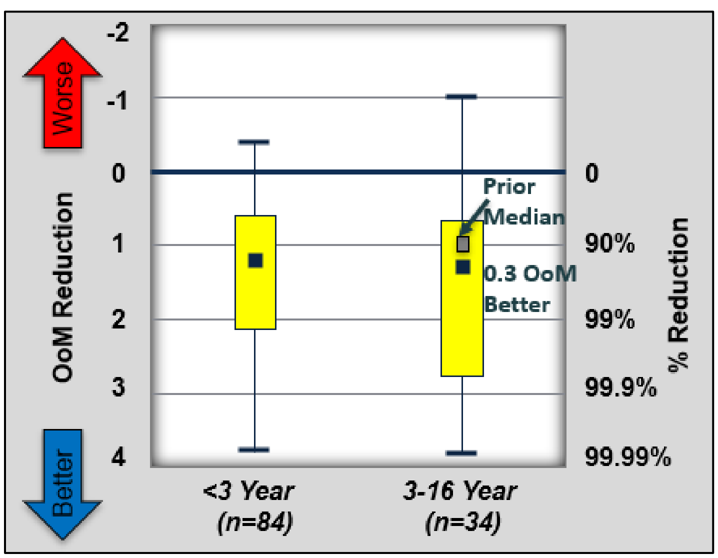


Figure D.6. Comparison of OoM Reductions Achieved for ISB Sites with Short Post-Treatment Monitoring Records (n=84) vs. ISB Sites with Long Post-treatment Monitoring Records (n=34).

APPENDIX C DATA MINING TO ESTABLISH BENCHMARK DECAY RATES

INTRODUCTION

Over the past 10 years, the concept of "big data" has been proposed to help develop and validate benchmarks (e.g., Suthersan et al., 2016). While successes and failures occur at the level of an individual site, aggregating performance across numerous sites can provide key insights into the relative strengths and weaknesses of various technologies, site conditions, and the fate and transport of individual constituents of concern. In addition, Suthersan et al. (2016) advocated for using "big data" to develop and validate benchmarks. In this study, California's GeoTracker database was used to develop benchmark decay rates for four CVOCs: PCE, TCE, cis-DCE, and VC. These decay rates may be useful for comparison to field data, as well as to provide insights into best practices for model development when simulating the effects of matrix diffusion at a groundwater cleanup site.

Several studies have utilized California's GeoTracker to provide information on petroleum hydrocarbons (McHugh et al., 2014; Kulkarni et al., 2017), 1,4-dioxane (Adamson et al., 2015; Adamson et al., 2016), and the long-term performance of in-situ bioremediation (ISB) at chlorinated solvent sites (McGuire et al., 2016).

METHODS

The California State Water Resources Control Board (SWRCB) maintains the GeoTracker database, which is a data management system for sites that require remedial activities (SWRCB, 2016). The GeoTracker Electronic Submission of Information (ESI) program handles several hundreds of thousands of transactions per year from over four thousand businesses that are required to upload electronic data to fulfill regulatory directives and requirements, making GeoTracker the largest system for analytical and field data across the United States (SWRCB, 2016). The "Cleanup Sites" database within GeoTracker contains a list of regulatory activities for cleanup sites, a status history for those sites, an electronic document repository, and a database of chemical testing results for each site.

Chemical data for four chlorinated volatile organic compounds (CVOCs) (i.e., tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cis-DCE) and vinyl chloride (VC)) were downloaded from the GeoTracker website and loaded into an Access database for further processing. Data from the time period 2001 through 2017 were included in the analysis described herein.

Figure C.1 shows the number of sites in GeoTracker where the 4 CVOCs of interest to our study were sampled, as well as the number of sites with detections of these CVOCs. As shown on Figure C.1, between 2004 and 2005 there was a sharp increase in the number of sites reporting CVOC data to GeoTracker. Prior to 2004, only leaking underground storage tank (LUST) sites were required to provide electronic data to GeoTracker. In 2004, the California SWRCB expanded the types of sites requiring submittal of electronic data to GeoTracker.

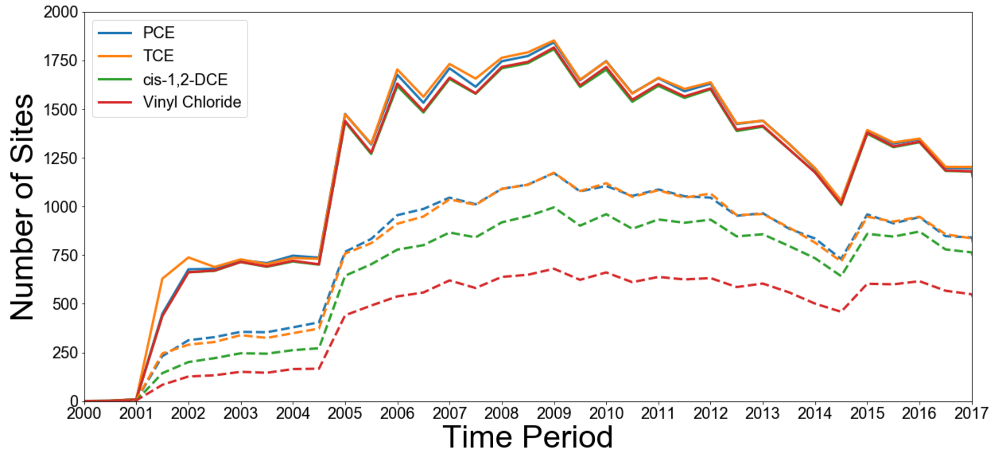


Figure C.1. Number of Sites with CVOC Sampling Results in the GeoTracker Database.

Solid lines are sampled. Dashed lines are detected.

The geographic distribution of sites with detections of the four CVOCs is depicted on Figure C.2 and presumed dry cleaner and DOD facilities (discussed later) is shown on Figure C.3.

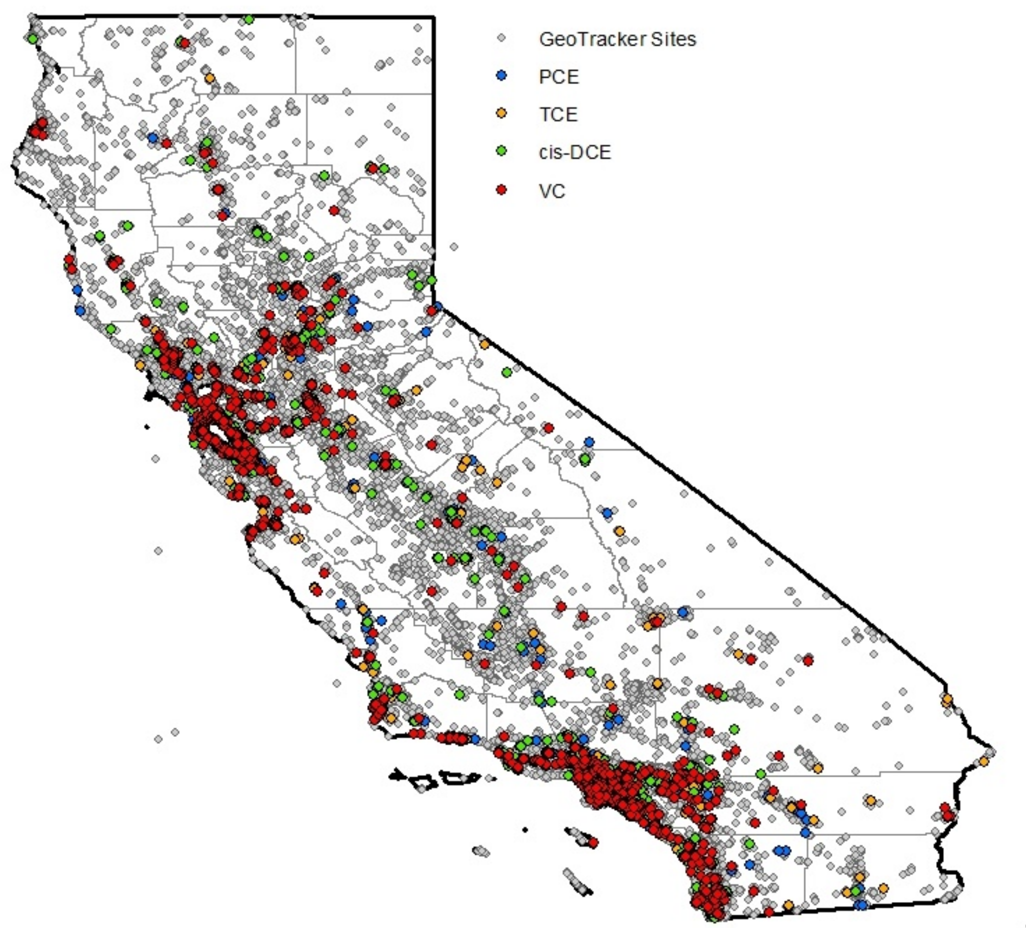


Figure C.2. Locations of Sites with Detected Concentrations of Each CVOC.

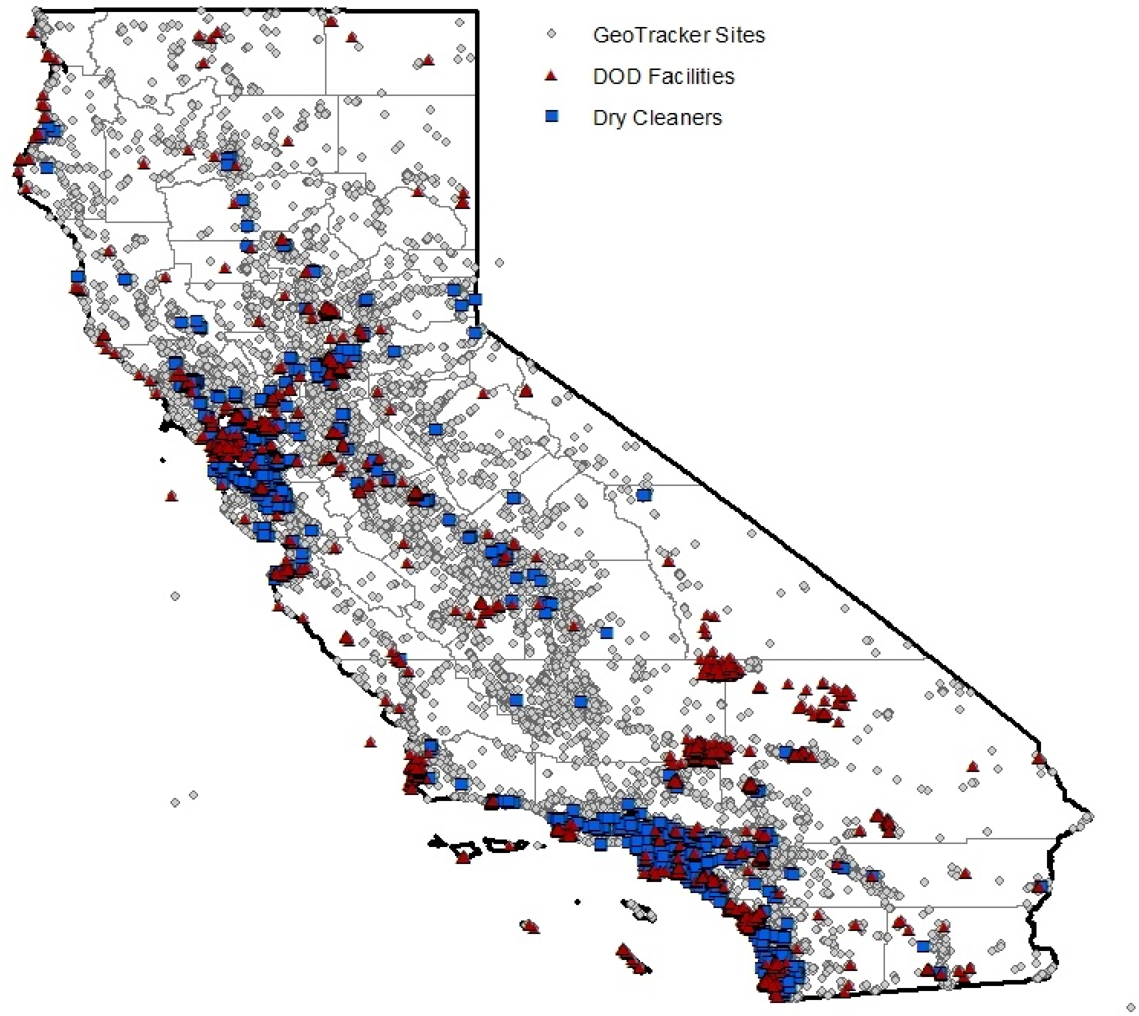


Figure C.3. Locations of Presumed Dry Cleaner Locations and DOD Facilities.

Site Screening

The following inclusion criteria were applied to include sites and individual monitoring wells with sufficient data to develop a representative dataset:

- At least 5 years of monitoring data; and
- At least 4 monitoring points.

In addition, when evaluating individual monitoring wells, wells were retained when less than 75% of the dataset was non-detect in order to remove those wells with only sporadic detections.

To evaluate the impact of the assumed parent compound (i.e., PCE vs. TCE) on the calculated decay rates, the sites were subdivided into the following two subgroups to see if the parent compound provided a meaningful effect:

- *Dry Cleaners:* to analyze sites with an assumed PCE source, presumed dry cleaner sites were selected by identifying business names that contained "clean", "laundry", or "martinizing". To reduce the selection of potential non-dry cleaners, if "cleanup" was present in the business name, the site was excluded as a dry cleaner site.

- *DOD Facilities:* to analyze sites with an assumed TCE source, DOD sites were selected by identifying those that contained "DOD" in the GeoTracker global site ID or contained a GeoTracker case type of "Military Cleanup Site", "Military UST Site", or "Military Privatized Site."

Sites were further divided into two groups based on whether the maximum detected concentration at the site (for source zones) or in individual monitoring wells was below or exceeded 50 µg/L. 50 µg/L was selected because it represents 1 order-of-magnitude (OoM) above the United States Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) of 5 µg/L for both PCE and TCE.

For source zones or individual monitoring wells with maximum detected concentrations below 50 µg/L, we hypothesize that the first-order decay rates at these lower concentrations are representative of natural attenuation processes because it is unlikely that active site remediation activities would have been undertaken for these lower concentrations. Furthermore, we hypothesize that matrix diffusion is likely a meaningful process, and that the calculated first-order decay rates also represent the influence of matrix diffusion on the contaminant trends.

Table C.1 provides details on the number of sites within GeoTracker and those that were retained for calculation of first-order decay rates based on the various inclusion criteria described above. Table C.2 provides these same details for individual monitoring wells.

Table C.1. Number of Sites Analyzed and Used to Compute First-order Decay Rates.

Dataset	PCE	TCE	cis-DCE	VC
Number of Sites with CVOC Sample Data	7,176	7,320	7,052	7,075
Number of Sites with CVOC Detections	2,922	2,848	2,377	1,362
Sites Meeting Inclusion Criteria				
All	1,413	1,413	1,229	854
Site Maximum < 50 µg/L	792	761	635	553
Site Maximum >= 50 µg/L	621	652	594	301
Presumed PCE Source (Dry Cleaners)				
All	128	115	109	66
Site Maximum < 50 µg/L	11	49	34	31
Site Maximum >= 50 µg/L	117	66	75	35
Presumed TCE Source (DOD Facilities)				
All	46	59	47	34
Site Maximum < 50 µg/L	31	27	25	22
Site Maximum >= 50 µg/L	15	32	22	12

Note: Inclusion criteria were sites with more than five years of monitoring data and at least four data points per site.

Table C.2. Number of Wells Analyzed and Used to Compute First-order Decay Rates.

Dataset	PCE	TCE	cis-DCE	VC
Number of Wells with CVOC Sample Data	37,966	38,066	37,642	37,241
Number of Wells with CVOC detections	27,125	32,609	25,564	11,151
Wells Meeting Inclusion Criteria				
All	4,801	6,265	4,980	1,929
Well Maximum < 50 µg/L	3,050	3,513	3,075	1,260
Well Maximum >= 50 µg/L	1,751	2,752	1,905	669
Presumed PCE Source (Dry Cleaners)				
All	519	338	282	96
Well Maximum < 50 µg/L	211	216	141	52
Well Maximum >= 50 µg/L	308	122	141	44
Presumed TCE Source (DOD Facilities)				
All	363	662	420	180
Well Maximum < 50 µg/L	337	446	307	141
Well Maximum >= 50 µg/L	26	216	113	39

Note: Inclusion criteria were wells with more than five years of monitoring data, at least four data points per well, and less than 75% non-detect analytical results.

Data Consolidation

For time-series analyses, the monitoring record was divided into six-month periods (i.e., January through June, July through December). For each six-month period, the maximum detected concentration was selected as the representative concentration for each CVOC at each monitoring well. Furthermore, we defined the maximum "source" concentration at each site by selecting the maximum site-wide concentration for each six-month period; note that the maximum "source" concentration can be from different monitoring wells over time at that site.

Calculation of First-order decay rates

First-order decay rates were calculated in the presumed source zone at each site (k_{source}) with at least five years of monitoring data for each constituent as the negative slope of the best-fit line on the natural log of concentration vs. time plot (Newell et al., 2002). First-order decay rates at individual monitoring well locations (k_{point}) with at least five years of monitoring data for each constituent were calculated as the negative slope of the best-fit line on the natural log of concentration vs. time plot (Newell et al., 2002). These decay rates can be translated to half-lives by dividing 0.693 by the k_{point} rate constant.

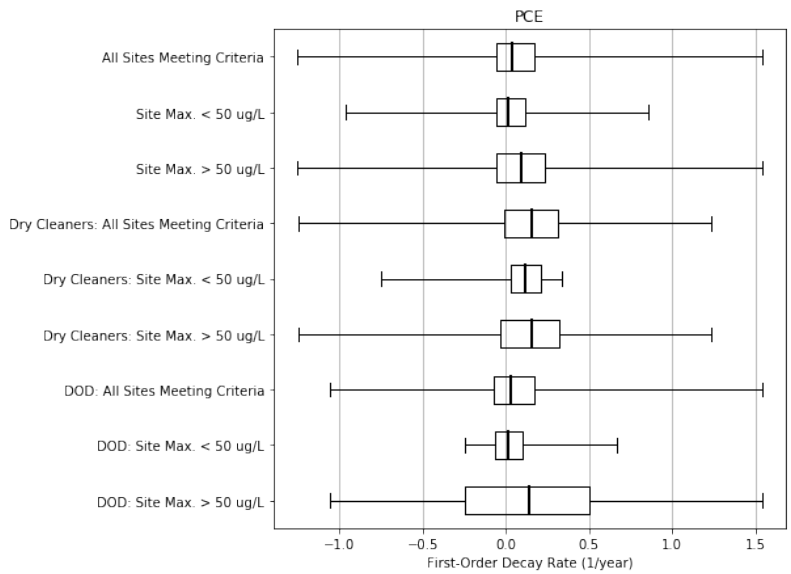
Given the size of the datasets, no attempts were made to statistically verify the applicability of first-order decay. However, use of first-order decay rate assumption is common practice for groundwater datasets, and in aggregate, the use of statistical distributions of first-order rate constants should provide meaningful information across the range of sites. It is also important to recognize that these decay rates may represent the influence of active treatment technologies at some sites (i.e., the implementation of active remediation was not a screening criterion for the analysis).

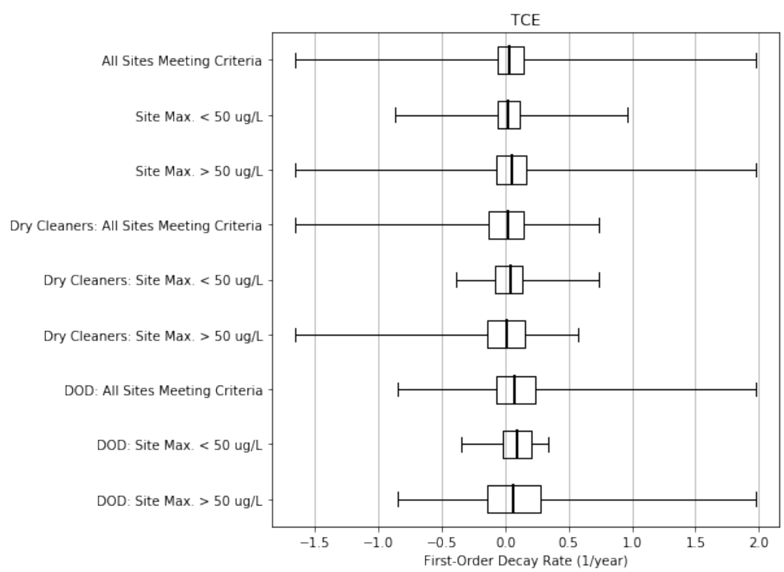
RESULTS

Table C.3 summarizes median first-order decay rates for the source area (k_{source}) and the equivalent half-lives for the first-order decay rates that show decreasing concentrations. Table C.4 summarizes median first-order decay rates for individual monitoring wells (k_{point}) meeting the selection criteria described above and the equivalent half-lives for the first-order decay rates that show decreasing concentrations.

Table C.3. Median k_{source} and equivalent half-life within the presumed source location.

Dataset	PCE	TCE	cis-DCE	VC
k_{source} (1/years)				
All Sites Meeting Criteria				
All	0.040	0.035	0.006	-0.001
Site Maximum < 50 µg/L	0.018	0.021	0.008	0.002
Site Maximum >= 50 µg/L	0.095	0.052	0.005	-0.058
Presumed PCE Source (Dry Cleaners)				
All	0.155	0.020	-0.067	-0.143
Site Maximum < 50 µg/L	0.117	0.041	-0.073	0.013
Site Maximum >= 50 µg/L	0.158	0.008	-0.045	-0.489
Presumed TCE Source (DOD Facilities)				
All	0.032	0.074	-0.049	-0.065
Site Maximum < 50 µg/L	0.018	0.091	0.026	0.008
Site Maximum >= 50 µg/L	0.142	0.060	-0.119	-0.339
Half-Life (years)				
All Sites Meeting Criteria				
All	17.2	20.0	118.7	Increasing
Site Maximum < 50 µg/L	38.0	32.9	91.1	368.5
Site Maximum >= 50 µg/L	7.3	13.2	143.9	Increasing
Presumed PCE Source (Dry Cleaners)				
All	4.5	35.0	Increasing	Increasing
Site Maximum < 50 µg/L	5.9	17.1	Increasing	53.1
Site Maximum >= 50 µg/L	4.4	87.6	Increasing	Increasing
Presumed TCE Source (DOD Facilities)				
All	21.4	9.4	Increasing	Increasing
Site Maximum < 50 µg/L	39.1	7.6	26.4	83.9
Site Maximum >= 50 µg/L	4.9	11.6	Increasing	Increasing





Key points:

- Median half-lives for source zones with maximum historical concentrations > 50 ug/L are approximately 7 years for PCE (median k_{source} = 0.095) and 13 years for TCE (median k_{source} = 0.052).
- Regardless of scenario, half-lives for cis-DCE and VC are much higher than PCE/TCE half-lives or demonstrate an increasing trend, which fits a conceptual model that these constituents are formed as daughter products from the reductive dechlorination of PCE and TCE.
- At presumed PCE source areas (i.e., dry cleaner sites), the median half-life of PCE at low concentration sites (maximum <50 ug/L) is greater than that at higher concentration sites (maximum >50 ug/L), potentially reflecting the influence of matrix diffusion or active remediation technologies. TCE half-lives are much higher at the higher concentration sites (approximately 88 years) when compared to low concentration sites (approximately 17 years), likely reflecting the formation of TCE from PCE via reductive dechlorination.

Table C.4. Median k_{point} (1/year) and Equivalent Half-lives for Individual Monitoring Wells Meeting Selection Criteria.

Dataset	PCE	TCE	cis-DCE	VC
k_{point} (1/years)				
All Sites Meeting Criteria				
All	0.067	0.066	0.024	0.025
Well Maximum < 50 µg/L	0.048	0.045	0.020	0.021
Well Maximum >= 50 µg/L	0.111	0.093	0.032	0.035
Presumed PCE Source (Dry Cleaners)				
All	0.141	0.057	0.005	-0.155
Well Maximum < 50 µg/L	0.096	0.052	0.034	-0.155
Well Maximum >= 50 µg/L	0.180	0.099	-0.004	-0.125
Presumed TCE Source (DOD Facilities)				
All	0.062	0.072	0.030	-0.086
Well Maximum < 50 µg/L	0.054	0.046	0.050	-0.065
Well Maximum >= 50 µg/L	0.302	0.140	-0.006	-0.198
Half-Life (years)				
All Sites Meeting Criteria				
All	10.3	10.5	29.1	27.8
Well Maximum < 50 µg/L	14.5	15.3	35.1	32.9
Well Maximum >= 50 µg/L	6.3	7.4	21.8	19.8
Presumed PCE Source (Dry Cleaners)				
All	4.9	12.1	139.1	Increasing
Well Maximum < 50 µg/L	7.2	13.4	20.6	Increasing
Well Maximum >= 50 µg/L	3.9	7.0	Increasing	Increasing
Presumed TCE Source (DOD Facilities)				
All	11.1	9.7	22.9	Increasing
Well Maximum < 50 µg/L	12.8	15.0	13.8	Increasing
Well Maximum >= 50 µg/L	2.3	4.9	Increasing	Increasing

Key points:

- Median half-lives for individual monitoring wells with maximum historical concentrations > 50 ug/L are approximately 6 years for PCE (median k_{point} = 0.11) and 7 years for TCE (median k_{point} = 0.093).
- Half-lives for cis-DCE and VC are generally greater than approximately 20 years or demonstrate increasing trends, which fits a conceptual model that these constituents are formed as daughter products from the reductive dechlorination of PCE and TCE.

APPENDIX D MODELING ASSESSMENT OF LOW-K BIODEGRADATION AT MNA SITES

EXECUTIVE SUMMARY

The objective of this study was to analyze soil concentration vs penetration depth data in low permeability ("low-k") units collected at four different sites to determine if biodegradation rates within these low-k zones, in the form of first order decay coefficients, could be ascertained. The Source History Tool (Farhat et al., 2013) was used to analyze the occurrence and magnitude of natural attenuation processes within the low-k clay stratum at two sites at Hill Air Force Base (AFB) and two sites at Kelly AFB. Data from England AFB was not utilized in this analysis due to the high frequency of non-detects for the parent compound.

High-resolution low-k zone soil data comprised of closely spaced samples collected vertically within the low-k units were used for this analysis. A reconstruction of the source history based on trichloroethene (TCE) soil concentrations in the low-k zone, indicated slow biodegradation was occurring with a half-life of >10 years within the low-k unit at Location B of Hill AFB. At Location A at Hill AFB and both locations at Kelly AFB, it was not possible to distinguish between a half-life of 2 years and a scenario with no biodegradation. This was not an unexpected outcome of this analysis due to the noise in the sampling data and other factors that increase the uncertainty in the modeling.

GROUNDWATER MODEL DESCRIPTION

The Source History Tool (Farhat et al., 2013) (Toolkit) is a screening level tool, developed for the Environmental Security Technology Certification Program (ESTCP) of the U.S. Department of Defense. The Toolkit can assist site personnel reconstruct an estimate of the long-term source concentration profile over time, i.e., a "source history", that can be used as a line of evidence for occurrence of natural attenuation. A long-term source history, from the beginning of releases at a site to present time, would help confirm a site conceptual model that shows attenuation is a significant process for both the source and the plume, and generate data that are well-suited for use in predicting future concentration and attenuation trends (Farhat et al., 2013).

INPUT DATA AND METHODOLOGY

The Toolkit was used to reconstruct the source history based on high-resolution TCE soil concentrations collect from the low-k zone at Hill AFB (Location A and Location B) and Kelly AFB (Location A and Location B). Toolkit default values were used as input parameters where necessary. Input data for the sampling locations are shown in Tables D.1 through D.4 and Figures D.1 through D.4.

To run the model, hydrogeological data were entered in Section 1, transport parameters in Section 2, general information in Section 3, high-resolution core data in Section 4, and data for matching in Section 6.0. The Toolkit was applied as follows:

- Step 1: Initial values of all parameters, site-specific or Toolkit default parameters, were entered into the model.

- Step 2. Toolkit simulated concentrations in the low-k unit were compared to observed TCE soil concentrations at the high-resolution sampling locations. The TCE soil concentrations represented concentration vs. penetration depth from the transmissive zone/low-k unit interface into the low-k zones. Typically, seven (7) to eight (8) soils were collected with the 3-foot interval below the interface.

- Step 3. Input parameters were then adjusted, as needed, to improve the comparison of simulated and observed TCE concentrations. For this purpose, the initial source concentration, the concentration versus time decay pattern, and the groundwater concentrations at the transmissive zone/low-k zone interface were varied until a reasonable comparison between simulated and observed low-k zone concentrations was obtained assuming no biodegradation.

- Step 4. Finally, a biodegradation half-life in the low-k zone was entered into the model to see if a better calibration (based on the Root Mean Square (RMS) and Relative errors) of the simulated and observed low-k zone concentrations could be obtained compared to the no-biodegradation scenario of Step 3.

The Toolkit input and output screens are shown on Figures D.1 through D.4.

Table D.1. Input Data for Hill AFB Location A

Data Type	Parameter	Value	Source of Data
Hydrogeology	• Low-k zone material: • Low-k zone porosity: • Transport type:	Clay 0.47 (-) Diffusion only	• Site information • Literature (Toolkit default) • Site information
Transport	• Key constituent: • Molecular diffusion coefficient in free water: • Low-k. zone apparent tortuosity factor exponent: • Low-k zone bulk density: • Low-k. zone fraction organic carbon: • Organic carbon partitioning coefficient: • Constituent half-life in low-k zone:	TCE 9.1E-10 (m^2/sec) 1.1 (-) 1.5 (g/mL) 0.0082 (-) 93.33 (L/kg) No Biodegradation: 10,000 (yr) Biodegradation (calibrated): 2 (yr)	• Site information • Literature (Toolkit default) • Literature (Toolkit default) • Literature (Toolkit default) • Site information • Literature (Toolkit default) • Calibration
General	• Year core sample collected: • Source concentration:	2015 Initial: 100 (mg/L) Calibrated: 10 (mg/L	• Site information • Initial: Toolkit suggestion of 10% TCE solubility
Match Data	• Source loading starts in year: • Source decay method:	1970 Linear decay	• Site information • Calibration
High-Resolution Core Data Collected at U2-043-SB-A (Location A)			

Depth (ft)	0	0.4	0.8	1.2	1.6	2.0	2.4	2.8
TCE Conc (mg/kg)	0.085	0.62	2.07	2.96	0.0053	0.0062	0.0052	0.0003

Table D.2. Input data for Hill AFB Location B

Data Type	Parameter	Value	Source of Data
Hydrogeology	• Low-k zone material: • Low-k zone porosity: • Transport type:	Clay 0.47 (-) Diffusion only	• Site information • Literature (Toolkit default) • Site information
Transport	• Key constituent: • Molecular diffusion coefficient in free water: • Low-k. zone apparent tortuosity factor exponent: • Low-k zone bulk density: • Low-k. zone fraction organic carbon: • Organic carbon partitioning coefficient: • Constituent half-life in low-k zone:	TCE 9.1E-10 (m^2/sec) 1.1 (-) 1.5 (g/mL) 0.0062 (-) 93.33 (L/kg) No Biodegradation: 10000 (yr) Biodegradation (calibrated): >10 (yr)	• Site information • Literature (Toolkit default) • Literature (Toolkit default) • Literature (Toolkit default) • Site information • Literature (Toolkit default) • Calibration
General	• Year core sample collected: • Source concentration:	2015 Initial: 100 (mg/L) Calibrated: 10 (mg/L	• Site information • Initial: Toolkit suggestion of 10% TCE solubility
Match Data	• Source loading starts in year: • Source decay method:	1970 Linear decay	• Site information • Calibration

High-Resolution Core Data Collected at U2-043-SB-B (Location B)

Depth (ft)	0	0.4	0.8	1.2	1.6	2.0	2.4	2.8
TCE Conc (mg/kg)	0.28	0.47	0.50	1.02	1.18	0.56	0.45	0.41

Table D.3: Input data for Kelly AFB Location A

Data Type	Parameter	Value	Source of Data
Hydrogeology	• Low-k zone material: • Low-k zone porosity: • Transport type:	Clay 0.47 (-) Diffusion only	• Site information • Literature (Toolkit default) • Site information
Transport	• Key constituent: • Molecular diffusion coefficient in free water: • Low-k. zone apparent tortuosity factor exponent: • Low-k zone bulk density: • Low-k. zone fraction organic carbon: • Organic carbon partitioning coefficient: • Constituent half-life in low-k zone:	TCE 9.1E-10 (m^2/sec) 1.1 (-) 1.5 (g/mL) 0.012 (-) 93.33 (L/kg) No Biodegradation: 10000 (yr) Biodegradation (calibrated): 2 (yr)	• Site information • Literature (Toolkit default) • Literature (Toolkit default) • Literature (Toolkit default) • Site information • Literature (Toolkit default) • Calibration
General	• Year core sample collected: • Source concentration:	2016 Initial: 100 (mg/L) Calibrated: 1 (mg/L	• Site information • Initial: Toolkit suggestion of 10% TCE solubility
Match Data	• Source loading starts in year: • Source decay method:	1960 Linear decay	• Site information • Calibration

High-Resolution Core Data Collected at KY036MW026-SB-A (Location A)

Depth (ft)	0	0.4	0.8	1.2	1.6	2.0	2.4
TCE Conc (mg/kg)	0.026	0.031	0.027	0.023	0.0097	0.022	0.0098

Table D.4. Input Data for Kelly AFB Location B

Data Type	Parameter	Value	Source of Data
Hydrogeology	• Low-k zone material: • Low-k zone porosity: • Transport type:	Clay 0.47 (-) Diffusion only	• Site information • Literature (Toolkit default) • Site information
Transport	• Key constituent: • Molecular diffusion coefficient in free water: • Low-k. zone apparent tortuosity factor exponent: • Low-k zone bulk density: • Low-k. zone fraction organic carbon: • Organic carbon partitioning coefficient: • Constituent half-life in low-k zone:	TCE 9.1E-10 (m^2/sec) 1.1 (-) 1.5 (g/mL) 0.011 (-) 93.33 (L/kg) No Biodegradation: 10000 (yr) Biodegradation (calibrated): 2 (yr)	• Site information • Literature (Toolkit default) • Literature (Toolkit default) • Literature (Toolkit default) • Site information • Literature (Toolkit default) • Calibration
General	• Year core sample collected: • Source concentration:	2016 Initial: 100 (mg/L) Calibrated: 1 (mg/L	• Site information • Initial: Toolkit suggestion of 10% TCE solubility
Match Data	• Source loading starts in year: • Source decay method:	1960 Linear decay	• Site information • Calibration
High-Resolution Core Data Collected at KY036MW026-SB-B (Location B)			

Depth (ft)	0	0.4	0.8	1.2	1.6	2.0	2.4	2.8
TCE Conc (mg/kg)	0.091	0.085	0.059	0.11	0.062	0.081	0.11	0.056

MODELING RESULTS

As shown on Figures D.1 through D.4, the Toolkit was able to reproduce observed low-k zone concentrations reasonably well at all locations. As summarized on Table D.5, the highest RMS error and relative error were observed at Location A of Hill AFB (i.e., this was the location where the model match to the field data was the worst of the four locations).

Table D.5. Summary of RMS and Relative Errors

Data Type	Hill AFB Location A	Hill AFB Location B	Kelly AFB Location A	Kelly AFB Location B
RMS Error (mg/L)				
No Biodegradation	0.667	0.215	0.005	0.021
With Biodegradation	0.668	0.217	0.004	0.021
Relative Error				
No Biodegradation	24.275	0.289	0.294	0.309
With Biodegradation	22.940	0.288	0.345	0.292

A constant initial source concentration was unable to reproduce the observed concentrations in the low-k zone. This source configuration is expected near on-going strong, high mass DNAPL sources.

A better comparison between simulated and observed concentrations was obtained by decreasing the source concentration over time, varying the concentrations in the histogram, and using the linear decay pattern. This type of decreasing source concentration occurs when a weak, sparse DNAPL source slowly decays over time.

Note that although for this evaluation, only the source concentration, histogram concentrations, and the decay pattern were used as calibration parameters, there could be other combinations of input parameters that could be adjusted to yield similar or better results.

Based on the Source History Tool modeling, a viable biodegradation signal from within the low-k zone was detected at one location:

- Hill AFB Location B: modeling indicates a potential slow biodegradation occurring with a TCE half-life of >10 years.

Based on the Source History Tool modeling, no clear biodegradation signal from within the low-k zone was detected at the other three locations:

- Hill AFB Location A: there is no significant difference between a TCE half-life of two years and the occurrence of no TCE biodegradation.
- Kelly AFB Location A: there is no significant difference between a TCE half-life of two years and the occurrence of no TCE biodegradation.
- Kelly AFB Location B: there is no significant difference between a TCE half-life of two years and the occurrence of no TCE biodegradation.

At these three sites, either no biodegradation was occurring in the low-k zones, or alternatively, the model was not able to distinguish between the signal from the sampling noise and model uncertainties.

MODEL LIMITATIONS

The Source History Tool has the following key assumptions and limitations (Farhat et al., 2013):

- Assumes the presence of low permeability strata within or downgradient of the source zone.
- Assumes diffusion occurs only in the water phase.
- Requires presence and delineation of interface between two geologic strata with contrasting permeabilities.
- Presence of multiple sources and/or commingled plumes can complicate analysis.
- Occurrence of reactions (abiotic or biotic), non-linear sorption, etc. within the low-k zones can complicate analysis.

REFERENCES

Farhat, S.K., P.C. de Blanc, C.J. Newell, and D.T. Adamson, 2013. Source History Tool, developed for the Environmental Security Technology Certification Program (ESTCP) by GSI Environmental Inc., Houston, Texas.

Figure D.1A. Model Input and Output for Hill AFB Location A: No Biodegradation

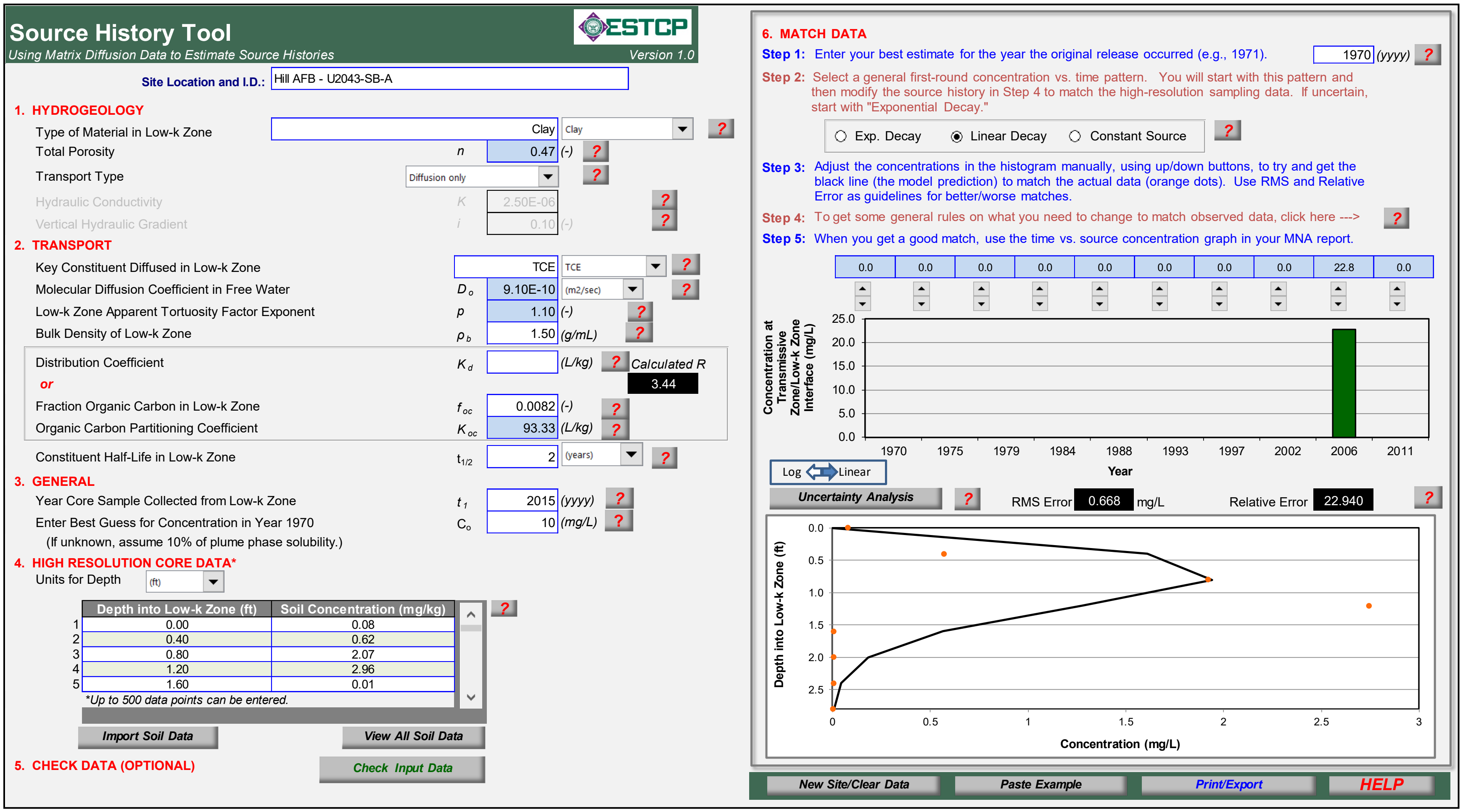


Figure D.1B. Model Input and Output for Hill AFB Location A: With Biodegradation

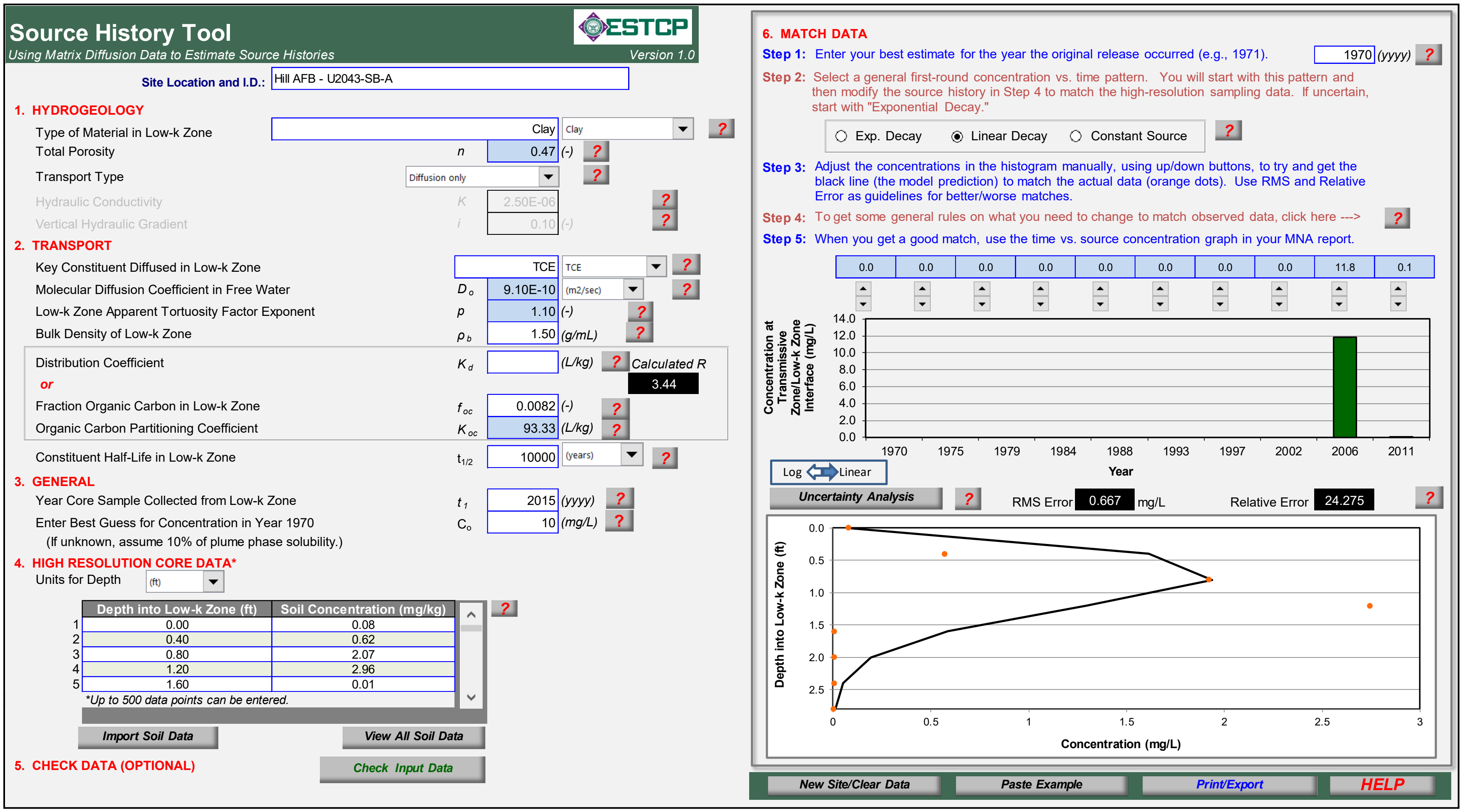


Figure D.2A. Model Input and Output for Hill AFB Location B: No Biodegradation

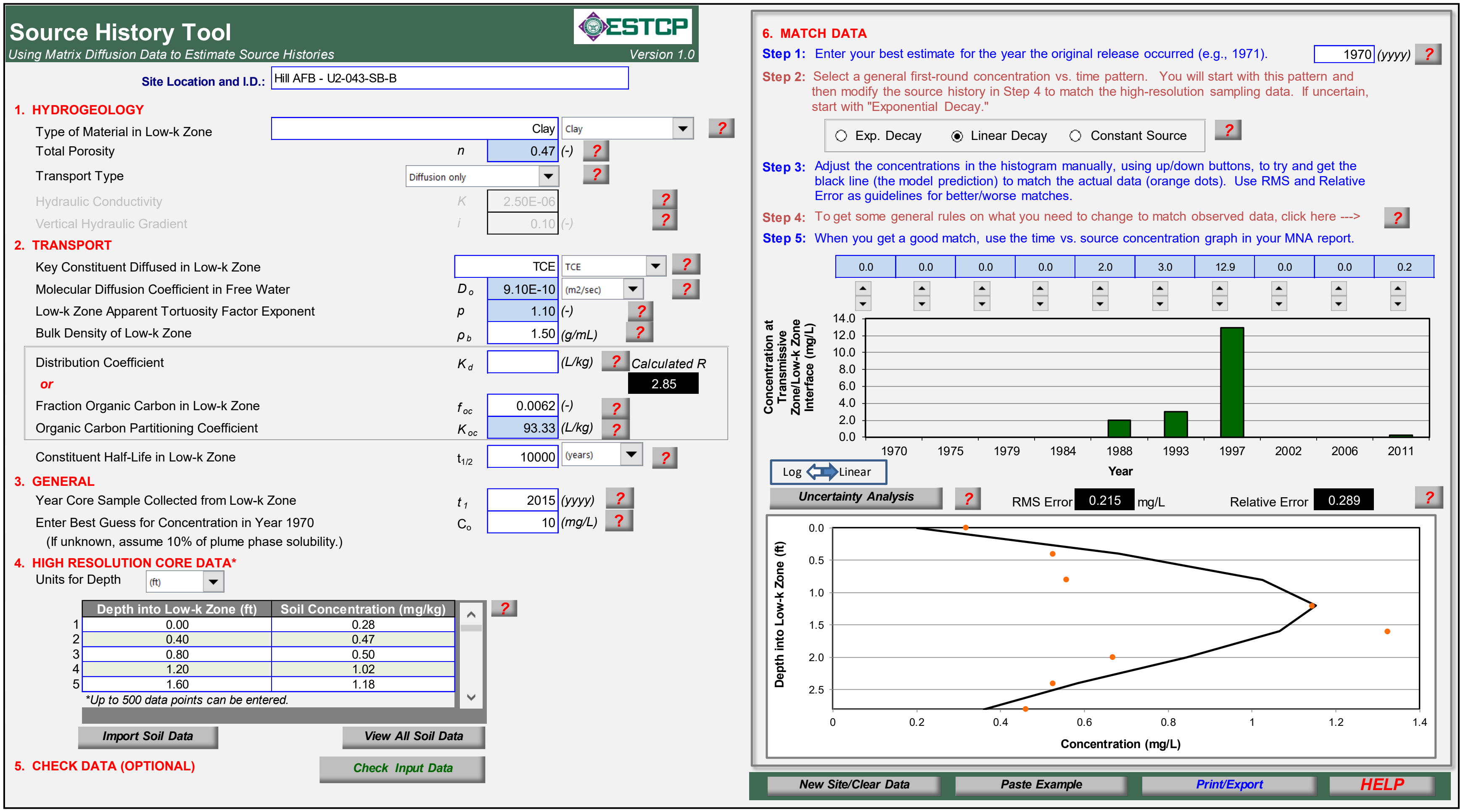


Figure D.2B. Model Input and Output for Hill AFB Location B: With Biodegradation

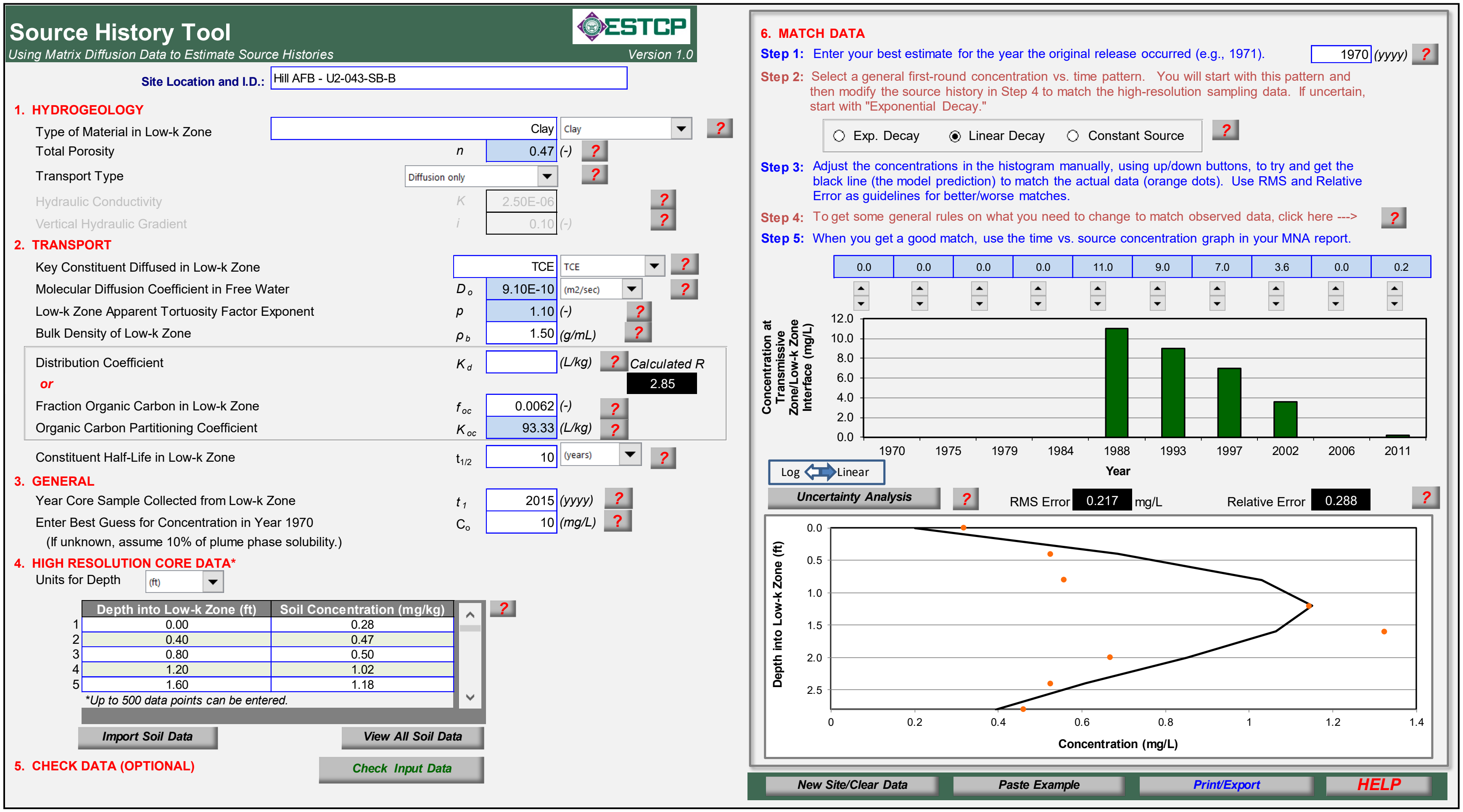


Figure D.3A. Model Input and Output for Kelly AFB Location A: No Biodegradation

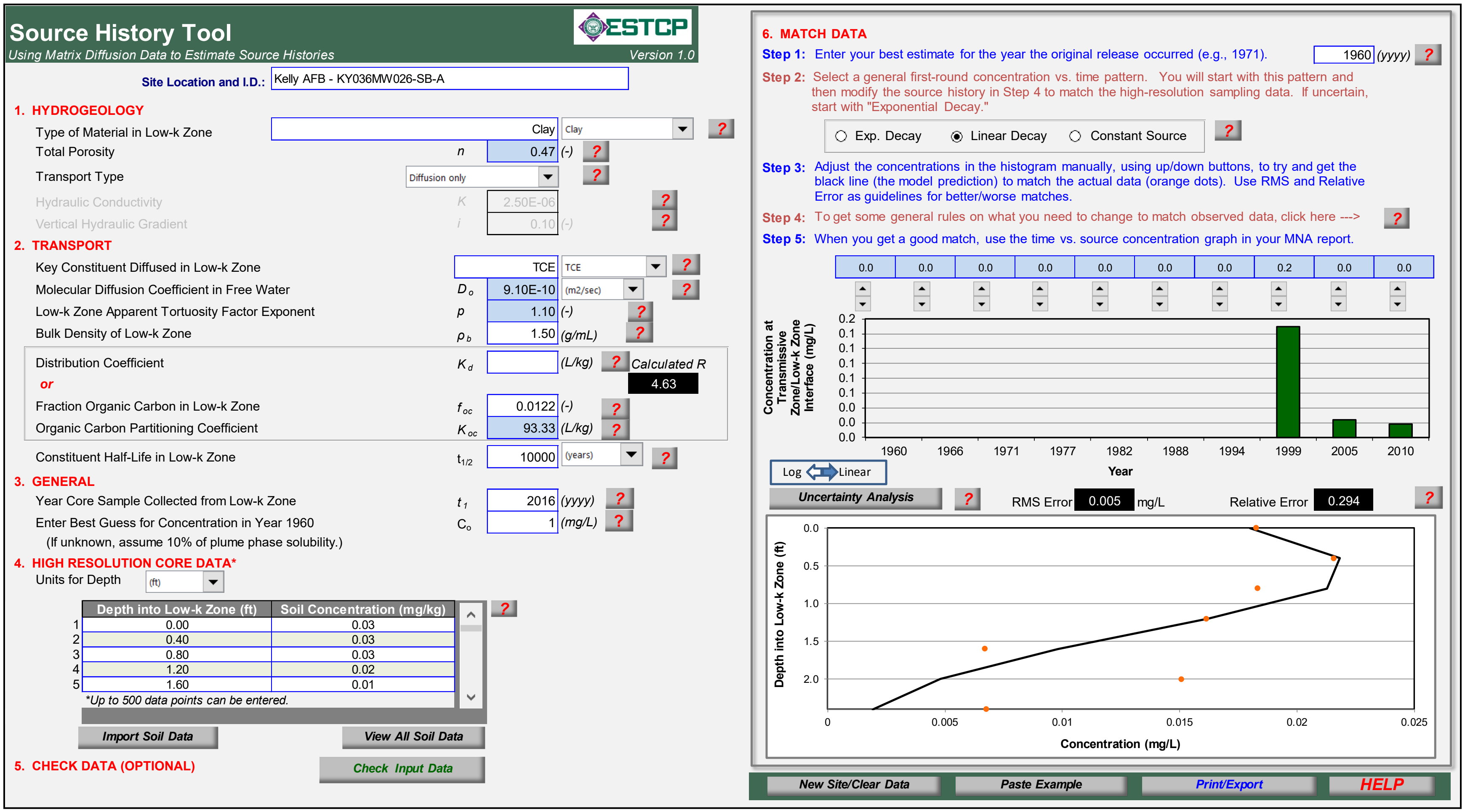


Figure D.3B. Model Input and Output for Kelly AFB Location A: With Biodegradation

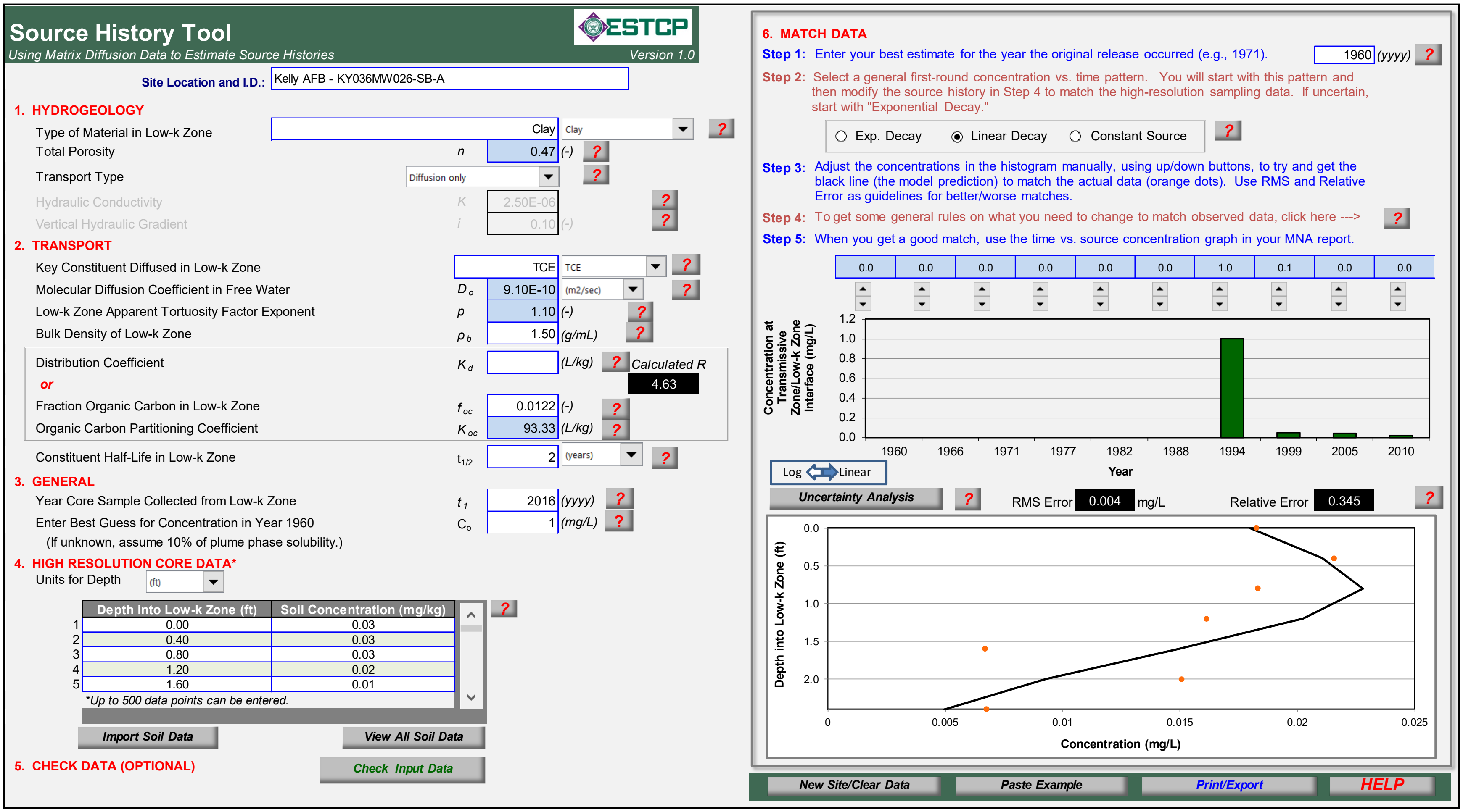


Figure D.4A. Model Input and Output for Kelly AFB Location B: No Biodegradation

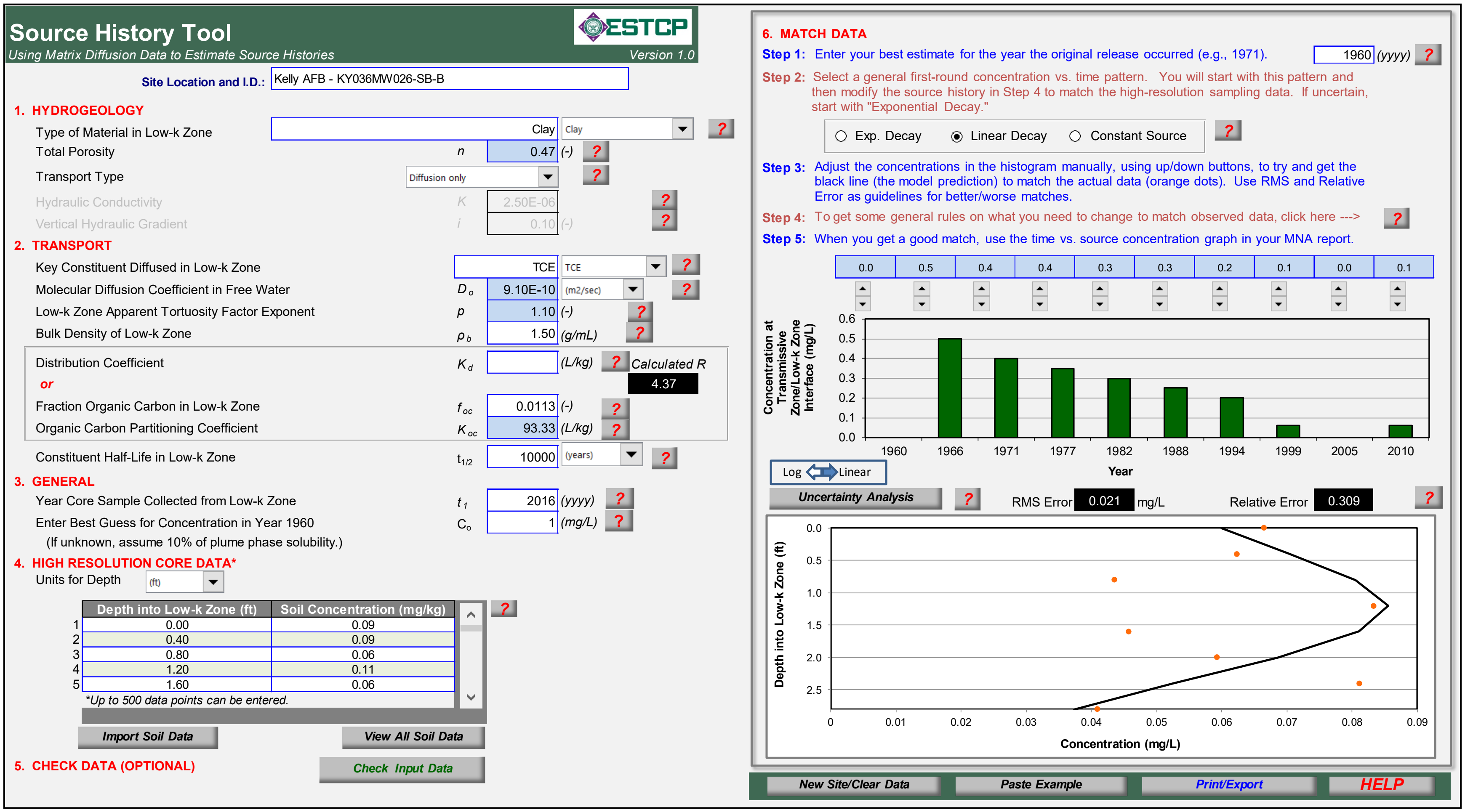
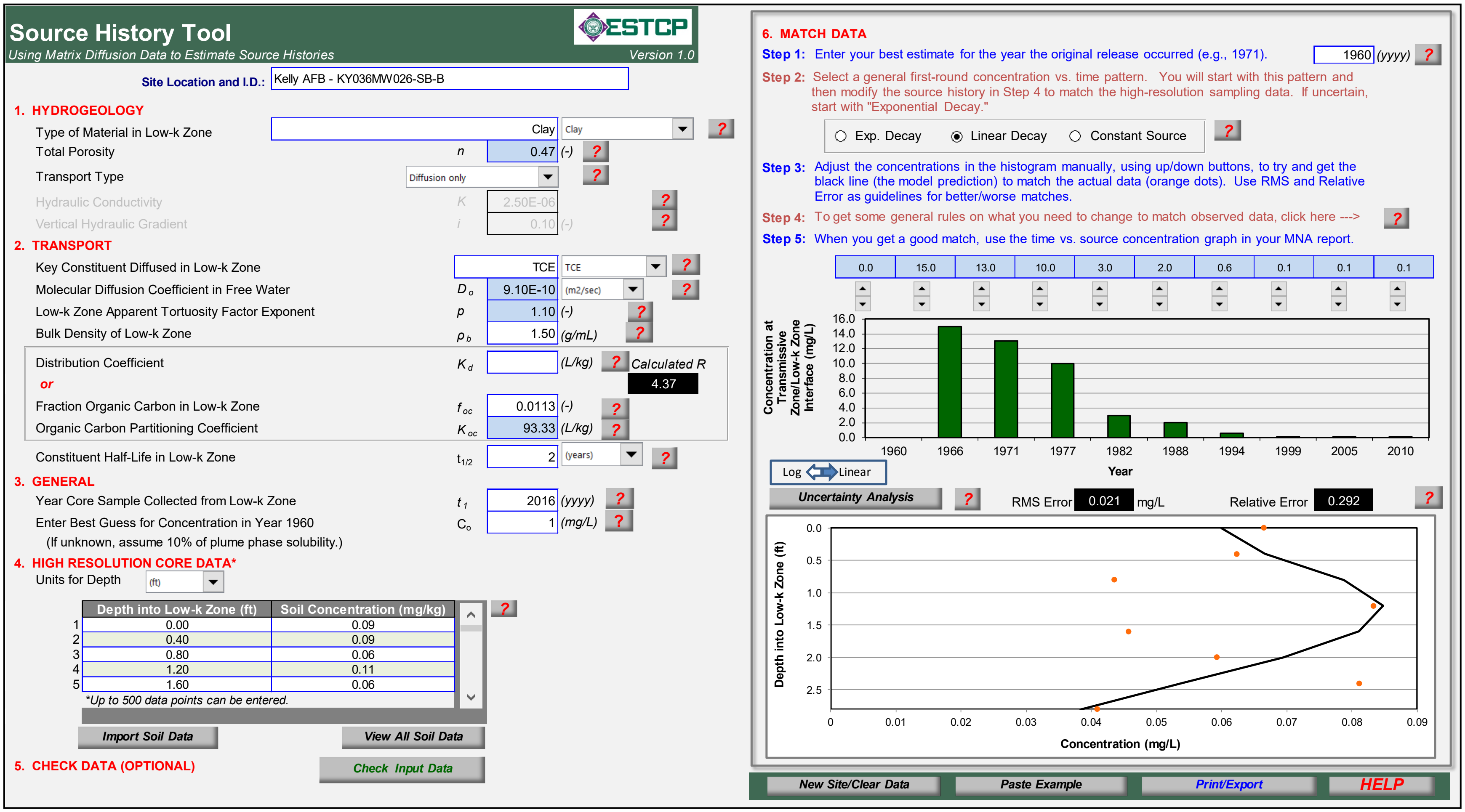


Figure D.4B. Model Input and Output for Kelly AFB Location B: With Biodegradation



APPENDIX E SAMPLING AND TESTING RESULTS FOR ISB SITES

Altus AFB Sampling and Testing Results

Kelly AFB (Building 331) Sampling and Testing Results

NTC Orlando Sampling and Testing Results

TABLE 1
SOIL CONSTITUENTS
Altus Air Force Base, Altus, Oklahoma

Transect	Location ID	Location in Transect	Sample Interval (ft bgs)	Relative K Zone	Sample ID	Sample Date	Tetrachloroethene (mg/kg)	Trichloroethene (mg/kg)	cis-1,2-Dichloroethene (mg/kg)	Vinyl chloride (mg/kg)	Fractional Organic Carbon (g C/g soil)	Fractional Organic Matter (%)	Magnetic Susceptibility (Avg) (m3/kg)	Magnetic Susceptibility (St Dev) (m3/kg)
BA01	GSI-SB-BA01U	Upgradient	30-31	High K	GSI-SB-BA01U-1	5/18/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0051	0.89	2.01E-07	5.13E-08
	GSI-SB-BA01U	Upgradient	31-32	Low K	GSI-SB-BA01U-2	5/18/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0039	0.68	1.22E-07	1.66E-09
	GSI-SB-BA01W	Biowall	18-19	High K	GSI-SB-BA01W-1	5/18/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.045	7.7	7.43E-07	4.38E-07
	GSI-SB-BA01W	Biowall	26-27	High K	GSI-SB-BA01W-2	5/18/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.031	5.3	6.15E-07	4.57E-07
	GSI-SB-BA01W	Biowall	28-29	High K	GSI-SB-BA01W-3	5/18/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.044	7.6	9.40E-07	7.84E-07
	GSI-SB-BA01D	Downgradient	30-31.5	High K	GSI-SB-BA01D-1	5/18/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0044	0.76	2.61E-07	2.60E-08
	GSI-SB-BA01D	Downgradient	31.5-32.5	Low K	GSI-SB-BA01D-2	5/18/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.00469	0.808	1.36E-07	2.61E-09
BB04	GSI-SB-BB04U	Upgradient	26-26.25	High K	GSI-SB-BB04U-1	5/30/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0075	1.3	1.39E-07	2.77E-09
	GSI-SB-BB04U	Upgradient	26.25-28	Low K	GSI-SB-BB04U-2	5/30/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0077	1.3	1.33E-07	4.55E-09
	GSI-SB-BB04W	Biowall	26-27	High K	GSI-SB-BB04W-1	5/31/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.038	6.6	4.47E-05	1.84E-06
	GSI-SB-BB04W	Biowall	29-30	High K	GSI-SB-BB04W-2	5/31/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.03	5.1	6.86E-05	2.19E-05
	GSI-SB-BB04W	Biowall	30-31	High K	GSI-SB-BB04W-3	5/31/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.03	5.1	6.86E-05	2.21E-05
	GSI-SB-BB04D	Downgradient	26.5-26.5	High K	GSI-SB-BB04D-1	5/30/2015	<0.0014	**0.0042 J**	**0.0025 J**	<0.0014	0.0074	1.3	3.70E-07	3.77E-07
	GSI-SB-BB04D	Downgradient	27-28	Low K	GSI-SB-BB04D-2	5/30/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0078	1.3	1.35E-07	2.58E-09
BB05	GSI-SB-BB05U	Upgradient	28.5-29.5	Low K	GSI-SB-BB05U-2	5/29/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0074	1.3	1.32E-07	5.16E-09
	GSI-SB-BB05U	Upgradient	29.5-29.7	High K	GSI-SB-BB05U-1	5/29/2015	<0.0014	**0.046**	**0.024**	<0.0014	0.00692	1.19	1.77E-07	3.13E-08
	GSI-SB-BB05W	Biowall	20.5-21.5	High K	GSI-SB-BB05W-1	5/31/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.025	4.3	1.50E-07	2.57E-08
	GSI-SB-BB05W	Biowall	29-30	High K	GSI-SB-BB05W-2	5/31/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.026	4.5	3.92E-07	4.74E-07
	GSI-SB-BB05W	Biowall	30.5-31.5	High K	GSI-SB-BB05W-3	5/31/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.08	14	6.22E-07	4.48E-07
	GSI-SB-BB05D	Downgradient	29.75-31	High K	GSI-SB-BB05D-1	5/29/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0033	0.57	2.52E-07	7.55E-08
	GSI-SB-BB05D	Downgradient	31-32	Low K	GSI-SB-BB05D-2	5/29/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0034	0.58	1.33E-07	1.99E-09
BC07	GSI-SB-BC07U	Upgradient	23-23.5	High K	GSI-SB-BC07U-1	6/1/2015	<0.0014	**0.0044 J**	<0.0012	<0.0014	0.00648	1.12	1.41E-07	1.63E-09
	GSI-SB-BC07U	Upgradient	23.5-24.5	Low K	GSI-SB-BC07U-2	6/1/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0068	1.2	1.18E-07	2.80E-09
	GSI-SB-BC07W	Biowall	23-25	High K	GSI-SB-BC07W-3	5/17/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.026	4.6	5.99E-08	2.20E-08
	GSI-SB-BC07W	Biowall	25-27	High K	GSI-SB-BC07W-2	5/17/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.022	3.9	2.57E-07	2.28E-07
	GSI-SB-BC07W	Biowall	27-29	High K	GSI-SB-BC07W-1	5/17/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0263	4.54	6.19E-08	2.71E-08
	GSI-SB-BC07D	Downgradient	30-31.5	High K	GSI-SB-BC07D-1	5/17/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0053	0.91	1.16E-07	1.26E-08
	GSI-SB-BC07D	Downgradient	31.5-33	Low K	GSI-SB-BC07D-2	5/17/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0044	0.76	1.21E-07	7.32E-09
BC08	GSI-SB-BC08U	Upgradient	23.5-24	High K	GSI-SB-BC08U-1	6/1/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0058	1	1.24E-07	1.67E-09
	GSI-SB-BC08U	Upgradient	24-25	Low K	GSI-SB-BC08U-2	6/1/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.00718	1.24	1.26E-07	1.47E-09
	GSI-SB-BC08W	Biowall	15-20	High K	GSI-SB-BC08W-1	5/17/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.047	8.1	7.07E-08	4.41E-09
	GSI-SB-BC08W	Biowall	30-31	High K	GSI-SB-BC08W-2	5/17/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.14	24	1.57E-07	1.22E-09
	GSI-SB-BC08W	Biowall	31-32	High K	GSI-SB-BC08W-3	5/17/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0055	0.94	1.48E-07	4.19E-08
	GSI-SB-BC08D	Downgradient	20-21	High K	GSI-SB-BC08D-1	5/17/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0044	0.76	1.18E-07	1.59E-08
	GSI-SB-BC08D	Downgradient	21-22.5	Low K	GSI-SB-BC08D-2	5/17/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0038	0.65	1.12E-07	2.74E-09
BE09	GSI-SB-BE09U	Upgradient	25.5-26.5	High K	GSI-SB-BE09U-1	5/27/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0037	0.64	1.41E-07	1.06E-09
	GSI-SB-BE09U	Upgradient	26.5-28	Low K	GSI-SB-BE09U-2	5/27/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0035	0.6	1.36E-07	2.08E-09
	GSI-SB-BE09W	Biowall	15-17	High K	GSI-SB-BE09W-1	5/28/2015	<0.0014	**0.0027 J**	<0.0012	<0.0014	0.03	5.2	3.56E-07	5.33E-08
	GSI-SB-BE09W	Biowall	17-19	High K	GSI-SB-BE09W-2	5/28/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.019	3.2	3.38E-07	3.21E-08
	GSI-SB-BE09W	Biowall	23.5-26	High K	GSI-SB-BE09W-3	5/28/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.035	6	1.78E-07	2.66E-08
	GSI-SB-BE09D	Downgradient	23-24	High K	GSI-SB-BE09D-1	5/28/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0033	0.57	1.27E-07	4.87E-09
	GSI-SB-BE09D	Downgradient	25-27	Low K	GSI-SB-BE09D-2	5/28/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.00351	0.605	1.35E-07	2.35E-09
BF12	GSI-SB-BF12U	Upgradient	35-36.5	High K	GSI-SB-BF12U-1	5/16/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0051	0.88	1.53E-07	9.46E-09
	GSI-SB-BF12U	Upgradient	36.5-38	Low K	GSI-SB-BF12U-2	5/16/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.00505	0.87	1.21E-07	1.10E-09
	GSI-SB-BF12W	Biowall	20-23	High K	GSI-SB-BF12W-1	5/16/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.033	5.7	1.17E-07	4.70E-08
	GSI-SB-BF12W	Biowall	25-27	High K	GSI-SB-BF12W-2	5/16/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.01	1.7	1.81E-07	6.14E-08
	GSI-SB-BF12W	Biowall	29-31	High K	GSI-SB-BF12W-3	5/16/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.015	2.6	5.68E-07	6.10E-07
	GSI-SB-BF12D	Downgradient	30-31.5	High K	GSI-SB-BF12D-1	5/15/2015	<0.0014	**0.0049 J**	**0.0024 J**	<0.0014	0.0076	1.3	1.45E-07	1.82E-09
	GSI-SB-BF12D	Downgradient	31.5-32.5	Low K	GSI-SB-BF12D-2	5/15/2015	<0.0014	<0.0014	<0.0012	<0.0014	0.0029	0.5	1.21E-07	4.82E-09

Notes:
Analytes analyzed by ESC Lab Sciences, Mount Juliet, TN
Shaded, bold cells are detected concentrations.
bgs = below ground surface
ft = feet
J = estimated concentration between the method detection limit and laboratory reporting limit
K = hydraulic conductivity
mg/kg = milligrams per kilogram
< = concentration less than the specified method detection limit

GSI ENVIRONMENTAL

TABLE 2
MICROBIOLOGICAL PARAMETERS IN SOIL
Altus Air Force Base, Altus, Oklahoma

Location in Transect	Upgradient													
Transect	BA01	BA01	BB04	BB04	BB05	BB05	BC07	BC07	BC08	BC08	BE09	BE09	BF12	BF12
Sample ID	GSI-SB-BA01U-1	GSI-SB-BA01U-2	GSI-SB-BB04U-1	GSI-SB-BB04U-2	GSI-SB-BB05U-2	GSI-SB-BB05U-1	GSI-SB-BC07U-1	GSI-SB-BC07U-2	GSI-SB-BC08U-1	GSI-SB-BC08U-2	GSI-SB-BE09U-1	GSI-SB-BE09U-2	GSI-SB-BF12U-1	GSI-SB-BF12U-2
Sample Interval (ft bgs)	30-31	31-32	26-26.25	26.25-28	28.5-29.5	29.5-29.7	23-23.5	23.5-24.5	23.5-24	24-25	25.5-26.5	26.5-28	35-36.5	36.5-38
Sample Date	5/18/2015	5/18/2015	5/30/2015	5/30/2015	5/29/2015	5/29/2015	6/1/2015	6/1/2015	6/1/2015	6/1/2015	5/27/2015	5/27/2015	5/16/2015	5/16/2015
K Zone	High K	Low K	High K	Low K	Low K	High K	High K	Low K	High K	Low K	High K	Low K	High K	Low K
Reductive Dechlorination (cells/mL)														
Dehalococcoides spp. (DHC)	<200	--	<200	<200	<200	<200	**4.88E+4**	<200	<200	<200	<200	<200	**2.65E+5**	--
tceA Reductase (TCE)	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	**4.36E+4**	<200
BAV1 Vinyl Chloride Reductase (BVC)	<200	--	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	--
Vinyl Chloride Reductase (VCR)	<200	--	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	**1.45E+4**	--
Dehalobacter spp. (DHBt)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Dehalobacter DCM (DCM)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Dehalogenimonas spp. (DHG)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Desulfitobacterium spp. (DSB)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Dehalobium chlorocoercia (DECO)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Desulfuromonas spp. (DSM)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Chloroform reductase (CFR)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
1,1 DCA Reductase (DCA)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
1,2 DCA Reductase (DCAR)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Aerobic (Co)Metabolic (cells/mL)														
Soluble Methane Monooxygenase (SMMO)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	**8.19E+5**	--
Particulate Methane Monooxygenase (PMMO)	<200	--	<200	--	--	**2.34E+5**	**1.13E+3**	--	**2.31E+4**	--	**1.81E+4**	--	<200	--
Toluene Dioxygenase (TOD)	**9.96E+3 J**	--	<200	--	--	<200	<200	--	<200	--	<200	--	**6.54E+4**	--
Phenol Hydroxylase (PHE)	<200	--	<200	--	--	**3.52E+3 J**	**1.81E+3**	--	**7.57E+3**	--	<200	--	**1.13E+3 J**	--
Trichlorobenzene Dioxygenase (TCBO)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Toluene Monooxygenase 2 (RDEG)	<200	--	**1.79E+4**	--	--	**5.41E+4**	<200	--	<200	--	<200	--	<200	--
Toluene Monooxygenase (RMO)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Ethene Monooxygenase (EtnC)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Epoxyalkane transferase (EtnE)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Dichloromethane dehalogenase (DCMA)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	<200	--
Other (cells/mL)														
Total Eubacteria (EBAC)	**1.02E+10**	--	**1.07E+9**	--	--	**2.33E+9**	**1.47E+9**	--	**2.18E+7**	--	**1.18E+7**	--	**3.09E+8**	--
Sulfate Reducing Bacteria (APS)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	**1.10E+7**	--
Methanogens (MGN)	<200	--	<200	--	--	<200	<200	--	<200	--	<200	--	**1.29E+6**	--

>10 E+5
>10 E+4
>10 E+3
>10 E+2
>DL to 10 E+2

Notes:
Analytes analyzed by Microbial Insights, Knoxville, TN
Bold cells are detected concentrations.
cells/mL = cells per milliliter
< = concentration less than the specified method detection limit

GSI ENVIRONMENTAL

TABLE 2
MICROBIOLOGICAL PARAMETERS IN SOIL
ALTUS AIR FORCE BASE, ALTUS, OK

Location in Transect	Biowall																				
Transect	BA01	BA01	BA01	BB04	BB04	BB04	BB05	BB05	BB05	BC07	BC07	BC07	BC08	BC08	BC08	BE09	BE09	BE09	BF12	BF12	BF12
Sample ID	GSI-SB-BA01W-1	GSI-SB-BA01W-2	GSI-SB-BA01W-3	GSI-SB-BB04W-1	GSI-SB-BB04W-2	GSI-SB-BB04W-3	GSI-SB-BB05W-1	GSI-SB-BB05W-2	GSI-SB-BB05W-3	GSI-SB-BC07W-3	GSI-SB-BC07W-2	GSI-SB-BC07W-1	GSI-SB-BC08W-1	GSI-SB-BC08W-2	GSI-SB-BC08W-3	GSI-SB-BE09W-1	GSI-SB-BE09W-2	GSI-SB-BE09W-3	GSI-SB-BF12W-1	GSI-SB-BF12W-2	GSI-SB-BF12W-3
Sample Interval (ft bgs)	18-19	26-27	28-29	26-27	29-30	30-31	20.5-21.5	29-30	30.5-31.5	23-25	25-27	27-29	15-20	30-31	31-32	15-17	17-19	23.5-26	23-25	25-27	29-31
Sample Date	5/18/2015	5/18/2015	5/18/2015	5/31/2015	5/31/2015	5/31/2015	5/31/2015	5/31/2015	5/31/2015	5/17/2015	5/17/2015	5/17/2015	5/17/2015	5/17/2015	5/17/2015	5/28/2015	5/28/2015	5/28/2015	5/16/2015	5/16/2015	5/16/2015
K Zone	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K	High K
Reductive Dechlorination (cells/mL)																					
Dehalococcoides spp. (DHC)	--	--	1.39E+6	7.11E+5	7.27E+5	8.82E+5	1.22E+6	1.26E+6	4.82E+5	--	9.65E+5	--	2.14E+6	--	--	5.61E+5	3.94E+5	8.64E+5	2.77E+6	--	--
tceA Reductase (TCE)	4.06E+4	2.83E+3	<200	1.40E+3	1.72E+3	1.28E+4	8.26E+4	864 J	1.55E+3	3.65E+3	1.25E+3	<200	1.53E+3	3.34E+3	3.64E+3	<200	<200	2.56E+3	1.40E+5	1.93E+5	2.28E+5
BAV1 Vinyl Chloride Reductase (BVC)	--	--	<200	<200	<200	<200	<200	<200	<200	--	<200	--	<200	--	--	<200	<200	<200	<200	--	--
Vinyl Chloride Reductase (VCR)	--	--	2.94E+2 J	<200	<200	1.76E+3	1.57E+4	<200	<200	--	<200	--	<200	--	--	<200	<200	4.72E+2 J	7.35E+4	--	--
Dehalobacter spp. (DHBt)	--	--	5.59E+5	7.33E+5	--	--	--	--	1.03E+6	--	2.05E+6	--	1.02E+6	--	--	--	6.73E+5	--	3.75E+5	--	--
Dehalobacter DCM (DCM)	--	--	<200	5.16E+4	--	--	--	--	<200	--	<200	--	9.89E+5	--	--	--	<200	--	<200	--	--
Dehalogenimonas spp. (DHG)	--	--	5.40E+7	3.21E+7	--	--	--	--	5.61E+7	--	4.37E+7	--	5.44E+7	--	--	--	2.61E+7	--	3.48E+7	--	--
Desulfitobacterium spp. (DSB)	--	--	7.94E+6	5.09E+5	--	--	--	--	7.33E+5	--	5.52E+6	--	1.01E+7	--	--	--	2.19E+5	--	4.69E+5	--	--
Dehalobium chlorocoercia (DECO)	--	--	<200	<200	--	--	--	--	<200	--	<200	--	<200	--	--	--	<200	--	<200	--	--
Desulfuromonas spp. (DSM)	--	--	8.12E+4	5.28E+5	--	--	--	--	<200	--	1.23E+6	--	<200	--	--	--	2.68E+5	--	1.38E+5	--	--
Chloroform reductase (CFR)	--	--	<200	<200	--	--	--	--	<200	--	<200	--	<200	--	--	--	<200	--	<200	--	--
1,1 DCA Reductase (DCA)	--	--	<200	<200	--	--	--	--	<200	--	<200	--	<200	--	--	--	<200	--	<200	--	--
1,2 DCA Reductase (DCAR)	--	--	<200	<200	--	--	--	--	<200	--	<200	--	5.44E+2 J	--	--	--	<200	--	<200	--	--
Aerobic (Co)Metabolic (cells/mL)																					
Soluble Methane Monooxygenase (SMMO)	--	--	9.52E+6	1.78E+6	--	--	--	--	3.39E+6	--	3.28E+7	--	2.52E+7	--	--	--	2.74E+6	--	2.43E+7	--	--
Particulate Methane Monooxygenase (PMMO)	--	--	3.29E+7	1.72E+7	--	--	--	--	8.90E+6	--	7.06E+6	--	2.05E+7	--	--	--	2.75E+6	--	9.52E+7	--	--
Toluene Dioxygenase (TOD)	--	--	6.61E+5	7.34E+5	--	--	--	--	7.87E+5	--	2.00E+6	--	2.24E+6	--	--	--	8.32E+5	--	1.02E+6	--	--
Phenol Hydroxylase (PHE)	--	--	7.66E+5	8.09E+5	--	--	--	--	3.39E+5	--	5.91E+5	--	3.10E+5	--	--	--	8.76E+5	--	7.30E+5	--	--
Trichlorobenzene Dioxygenase (TCBO)	--	--	<200	<200	--	--	--	--	<200	--	<200	--	<200	--	--	--	<200	--	<200	--	--
Toluene Monooxygenase 2 (RDEG)	--	--	1.53E+5	<200	--	--	--	--	<200	--	6.48E+4	--	<200	--	--	--	8.41E+4	--	<200	--	--
Toluene Monooxygenase (RMO)	--	--	1.70E+4	<200	--	--	--	--	<200	--	<200	--	<200	--	--	--	<200	--	<200	--	--
Ethene Monooxygenase (EtnC)	--	--	<200	<200	--	--	--	--	<200	--	<200	--	<200	--	--	--	<200	--	<200	--	--
Epoxyalkane transferase (EtnE)	--	--	<200	<200	--	--	--	--	<200	--	<200	--	<200	--	--	--	<200	--	<200	--	--
Dichloromethane dehalogenase (DCMA)	--	--	<200	<200	--	--	--	--	<200	--	<200	--	<200	--	--	--	<200	--	<200	--	--
Other (cells/mL)																					
Total Eubacteria (EBAC)	--	--	3.98E+9	4.24E+9	--	--	--	--	4.00E+9	--	1.76E+10	--	2.00E+10	--	--	--	1.51E+9	--	1.16E+10	--	--
Sulfate Reducing Bacteria (APS)	--	--	1.66E+6	8.80E+3	--	--	--	--	6.12E+4	--	9.82E+8	--	4.99E+8	--	--	--	7.18E+4	--	1.78E+8	--	--
Methanogens (MGN)	--	--	4.78E+7	2.17E+7	--	--	--	--	9.81E+7	--	1.31E+7	--	2.56E+7	--	--	--	3.43E+7	--	1.75E+8	--	--

>10 E+5
>10 E+4
>10 E+3
>10 E+2
>DL to 10 E+2

Notes:
Analytes analyzed by Microbial Insights, Knoxville, TN
Bold cells are detected concentrations.
cells/mL = cells per milliliter
< = concentration less than the specified method detection limit

GSI ENVIRONMENTAL

TABLE 2
MICROBIOLOGICAL PARAMETERS IN SOIL
ALTUS AIR FORCE BASE, ALTUS, OK

Location in Transect	Downgradient													
Transect	BA01	BA01	BB04	BB04	BB05	BB05	BC07	BC07	BC08	BC08	BE09	BE09	BF12	BF12
Sample ID	GSI-SB-BA01D-1	GSI-SB-BA01D-2	GSI-SB-BB04D-1	GSI-SB-BB04D-2	GSI-SB-BB05D-1	GSI-SB-BB05D-2	GSI-SB-BC07D-1	GSI-SB-BC07D-2	GSI-SB-BC08D-1	GSI-SB-BC08D-2	GSI-SB-BE09D-1	GSI-SB-BE09D-2	GSI-SB-BF12D-1	GSI-SB-BF12D-2
Sample Interval (ft bgs)	30-31.5	31.5-32.5	26.5-26.5	27-28	29.75-31	31-32	30-31.5	31.5-33	20-21	21-22.5	23-24	25-27	30-31.5	31.5-32.5
Sample Date	5/18/2015	5/18/2015	5/30/2015	5/30/2015	5/29/2015	5/29/2015	5/17/2015	5/17/2015	5/17/2015	5/17/2015	5/28/2015	5/28/2015	5/15/2015	5/15/2015
K Zone	High K	Low K	High K	Low K	High K	Low K	High K	Low K	High K	Low K	High K	Low K	High K	Low K
Reductive Dechlorination (cells/mL)														
Dehalococcoides spp. (DHC)	**2.16E+4**	--	<200	<200	<200	<200	<200	--	**3.35E+4**	--	<200	<200	<200	--
tceA Reductase (TCE)	**1.81E+3**	<200	<200	<200	<200	<200	<200	<200	**2.47E+3**	<200	<200	<200	<200	<200
BAV1 Vinyl Chloride Reductase (BVC)	<200	--	<200	<200	<200	<200	<200	--	<200	--	<200	<200	<200	--
Vinyl Chloride Reductase (VCR)	<200	--	<200	<200	<200	<200	<200	--	<200	--	<200	<200	<200	--
Dehalobacter spp. (DHBt)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Dehalobacter DCM (DCM)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Dehalogenimonas spp. (DHG)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Desulfitobacterium spp. (DSB)	**1.22E+4**	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Dehalobium chlorocoercia (DECO)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Desulfuromonas spp. (DSM)	**3.34E+4**	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Chloroform reductase (CFR)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
1,1 DCA Reductase (DCA)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
1,2 DCA Reductase (DCAR)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Aerobic (Co)Metabolic (cells/mL)														
Soluble Methane Monooxygenase (SMMO)	**5.05E+5**	--	<200	--	<200	--	<200	--	**1.56E+6**	--	<200	--	<200	--
Particulate Methane Monooxygenase (PMMO)	**3.98E+3**	--	**7.51E+3**	--	**2.16E+5**	--	<200	--	<200	--	**1.85E+4**	--	<200	--
Toluene Dioxygenase (TOD)	**9.12E+4**	--	**3.75E+3 J**	--	<200	--	**1.16E+3 J**	--	**1.37E+5**	--	<200	--	**5.02E+3 J**	--
Phenol Hydroxylase (PHE)	**1.66E+4**	--	<200	--	<200	--	**2.06E+4**	--	**9.16E+3 J**	--	<200	--	<200	--
Trichlorobenzene Dioxygenase (TCBO)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Toluene Monooxygenase 2 (RDEG)	**8.89E+4**	--	**5.22E+4**	--	<200	--	**2.65E+3 J**	--	<200	--	<200	--	<200	--
Toluene Monooxygenase (RMO)	**2.18E+3**	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Ethene Monooxygenase (EtnC)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Epoxyalkane transferase (EtnE)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Dichloromethane dehalogenase (DCMA)	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Other (cells/mL)														
Total Eubacteria (EBAC)	**3.67E+8**	--	**1.09E+9**	--	**1.88E+7**	--	**6.64E+7**	--	**1.56E+9**	--	**1.97E+6**	--	**5.68E+8**	--
Sulfate Reducing Bacteria (APS)	**6.22E+6**	--	<200	--	<200	--	<200	--	<200	--	<200	--	<200	--
Methanogens (MGN)	**1.43E+4**	--	**3.24E+2 J**	--	<200	--	<200	--	**1.92E+5**	--	<200	--	<200	--

>10 E+5
>10 E+4
>10 E+3
>10 E+2
>DL to 10 E+2

Notes:
Analytes analyzed by Microbial Insights, Knoxville, TN
Bold cells are detected concentrations.
cells/mL = cells per milliliter
< = concentration less than the specified method detection limit

GSI ENVIRONMENTAL

TABLE 3
GROUNDWATER CONSTITUENTS
Altus Air Force Base, Altus, Oklahoma

Transect	BA01			BB04				BB05			BC07			BC08			BE09			BE11			BF12		
Location in Transect	Upgrad.	Biowall	Downgrad.	Upgrad.	Biowall	Downgrad.	Downgrad.	Upgrad.	Biowall	Downgrad.	Upgrad.	Biowall	Downgrad.	Upgrad.	Biowall	Downgrad.	Upgrad.	Biowall	Downgrad.	Upgrad.	Biowall	Downgrad.	Upgrad.	Biowall	Downgrad.
Sample ID	BA01U	BA01W	BA01D	BB04U	BB04W	BB04D	Dup 1	BB05U	BB05W	BB05D	BC07U	BC07W	BC07D	BC08U	BC08W	BC08D	BE09U	BE09W	BE09D	BE11U	BE11W	BE11D	BF12UL	BF12W	BF12DL
Sample Date	5/5/2015	5/5/2015	5/5/2015	5/12/2015	5/13/2015	5/13/2015	5/13/2015	5/12/2015	5/13/2015	5/12/2015	5/12/2015	5/6/2015	5/6/2015	5/6/2015	5/6/2015	5/6/2015	5/12/2015	5/7/2015	5/12/2015	5/7/2015	5/6/2015	5/7/2015	5/5/2015	5/5/2015	5/5/2015
Sample Type	N	N	N	N	N	N	Dup	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Volatile Organic Compounds (mg/L)																									
Trichloroethene	0.00045 J	<0.0004	<0.0004	0.038	<0.0004	2.3	1.9	0.13	0.001	0.46	0.047	<0.0004	0.0016	0.029	0.00047 J	0.14	0.16	<0.0004	0.00044 J	0.0062	<0.0004	0.063	0.0031	<0.0004	0.0022
cis-1,2-Dichloroethene	0.0025	<0.00026	0.00091 J	0.12	<0.00026	2.2	1.9	0.2	0.0039	0.12	0.0051	0.0011	0.045	<0.00026	0.0016	0.072	0.23	<0.00026	0.15	0.0075	0.001	0.044	0.15	0.0046	0.61
trans-1,2-Dichloroethene	0.0021	<0.0004	0.003	0.0074	<0.0004	0.015	0.015	0.0078	0.011	0.0064	<0.0004	0.00062 J	0.0046	<0.0004	0.0021	0.002	0.0014	0.00054 J	0.0017	0.0052	0.0058	0.0057	0.00065 J	<0.0004	0.0016
Vinyl chloride	<0.00026	<0.00026	0.0035	0.011	0.0004 J	0.055	0.054	<0.00026	0.0074	0.026	<0.00026	<0.00026	0.0046	<0.00026	0.0018	0.004	0.0066	0.00056 J	0.029	0.018	0.054	0.0073	0.025	0.0007 J	0.23
Dissolved Gases (mg/L)																									
Ethane	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	0.0048 J	<0.0041	0.0098 J
Ethene	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	0.036	0.041	<0.0043	0.0063 J	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	0.0091 J	<0.0043	0.044
Methane	13	10	5.8	0.16	9	3.7	3.7	<0.0029	11	7.9	0.07	12	8.7	<0.0029	12	1.6	3.6	12	4.5	3	5.6	<0.0029	8.3	10	6.4
Volatile Fatty Acids (mg/L)																									
Acetic Acid	0.046 J	0.65	0.0084 J	0.46 Jd	2.3	0.43 Jd	0.47 Jd	0.43 Jd	33	0.42 Jd	0.48 Jd	2.2	<0.08	<0.08	83	0.97	0.44 Jd	0.49 Jd	0.47 Jd	0.43 Jd	<0.08	0.43 Jd	<0.08	<0.08	<0.08
Butyric Acid	<0.007	0.01 J	0.012 J	0.72	0.78	0.73	0.72	0.73	0.93	0.72	0.73	<0.07	<0.07	<0.07	1.1	<0.07	0.72	0.72	0.72	0.72	<0.07	0.72	<0.07	0.71	<0.07
Formic Acid	0.037 JB	0.063 JB	0.093 JB	0.51 Jd	0.57 Jd	0.49 Jd	0.5 Jd	0.49 Jd	0.84 Jd	0.49 Jd	0.51 Jd	0.28 JBd	0.32 JBd	0.29 JBd	0.47 JBd	0.3 JBd	0.5 Jd	0.51 Jd	0.48 Jd	0.54 Jd	0.32 JBd	0.51 Jd	0.3 JBd	0.31 JBd	0.31 JBd
Hexanoic Acid	<0.12	<0.12	<0.12	<0.08	0.92 Jd	<0.08	<0.08	<0.08	1.1 Jd	<0.08	<0.08	<1.2	<1.2	<1.2	<1.2	<1.2	<0.08	<0.08	0.9 Jd	<0.08	<1.2	<0.08	<1.2	<1.2	<1.2
i-Hexanoic Acid	<0.1	<0.1	<0.1	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<1	<1	<1	<1	<1	<0.08	<0.08	<0.08	<0.08	<1	<0.08	<1	<1	<1
i-Pentanoic Acid	<0.008	<0.008	<0.008	<0.03	<0.03	<0.03	<0.03	<0.03	0.99 Jd	<0.03	<0.03	<0.08	<0.08	<0.08	0.39 Jd	<0.08	<0.03	<0.03	<0.03	<0.03	<0.08	<0.03	<0.08	<0.08	<0.08
Lactic Acid	<0.012	<0.012	0.023 J	0.74 Jd	0.72 Jd	0.68 Jd	0.7 Jd	0.75 Jd	<0.02	0.77 Jd	0.72 Jd	0.16 Jd	0.16 Jd	0.4 Jd	0.15 Jd	0.16 Jd	0.83 Jd	0.72 Jd	0.75 Jd	0.68 Jd	0.25 Jd	0.74 Jd	0.18 Jd	0.2 Jd	0.15 Jd
Pentanoic Acid	<0.014	<0.014	<0.014	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.14	<0.14	<0.14	<0.14	<0.14	<0.04	<0.04	<0.04	<0.04	<0.14	<0.04	<0.14	<0.14	<0.14
Propionic Acid	<0.011	<0.011	0.066	0.46 Jd	0.56	0.46 Jd	0.46 Jd	0.46 Jd	0.71	0.46 Jd	0.46 Jd	<0.11	<0.11	<0.11	0.9	<0.11	0.46 Jd	0.47 Jd	0.46 Jd	0.46 Jd	<0.11	0.46 Jd	<0.11	<0.11	<0.11
Pyruvic Acid	<0.009	<0.009	<0.009	<0.02	<0.02	<0.02	<0.02	<0.02	0.9 Jd	<0.02	<0.02	<0.09	<0.09	<0.09	0.39 Jd	<0.09	<0.02	<0.02	<0.02	<0.02	<0.09	<0.02	<0.09	<0.09	<0.09
TOTAL VOLATILE FATTY ACIDS	0.083	0.723	0.2024	2.89	5.85	2.79	2.85	2.86	38.47	2.86	2.9	2.64	0.48	0.69	86.4	1.43	2.95	2.91	3.78	2.83	0.57	2.86	0.48	1.22	0.46
Oxygen Demand and Total Organic Carbon (mg/L)																									
BOD	15	13	<5	<5	460	<5	<5	<5	340	15	<5	150	6.5	<5	200	<5	5.7	17	<5	<5	63	<5	8.2	20	6
COD	<3	36	17	<3	930	12	21	13	760	22	26	430	36	110	420	74	14	180	29	41.7	190	20	44	28	24
TOC (1)	2.8	5.6	7.9	3	50	4.4	4.3	3.4	44	6.3	1.6	340	6.6	2.9	43	3.5	6	220	4.6	4.16	7.6	3.3	15	18	9.2
Dissolved Ions (mg/L) (1)																									
Sodium	240	110	490	350	530	710	680	530	540	600	780	670	940	410	570	1100	420	990	550	880	830	860	720	540	800
Potassium	2	1.4	4.4	1.5	36	7.4	7.2	2.3	6.1	6.1	6.7	8.3	6.6	4.1	15	15	4.4	19	2.5	6.9	7.4	7.2	4	5.9	5
Calcium	88	91	120	98	320	340	330	250	290	340	430	400	370	220	480	620	210	590	310	340	360	360	220	120	290
Magnesium	42	33	66	56	96	130	130	160	170	170	160	120	160	90	110	220	76	190	150	150	150	150	110	62	140
Iron	0.54	0.16	1.8	0.077 J	16	0.56	0.46	<0.014	0.023 J	<0.014	<0.014	0.021 J, B	0.51	<0.014	0.029 J, B	0.1	2.1	0.13	1.2	1.6	<0.014	0.032 J	0.084 J, B	1.3	1.9
Chloride	24	8	77	130	220	610	640	450	530	690	680	520	710	250	400	1600	460	1280	570	650	460	450	460	220	430
Sulfate	380	40	390	610	4.4 J	1600	1700	1400	850	1300	<0.77	600	1600	1000	730	2600	880	11	990	1600	1800	2200	<0.077	150	<0.077
Nitrate	0.062 J	0.046 J	<0.023	<0.023	0.22	0.2	0.4	0.37	<0.023	0.5	0.48	<0.023	5.1	7.6	0.22	0.17	<0.023	0.046	0.097 J	3.6	0.91	0.076	<0.023	0.62	<0.023
Alkalinity	460	540	1000	470	1900	460	470	390	960	660	280	1400	690	350	1300	290	380	2400	890	760	730	300	1300	1300	760
Field Parameters																									
Temperature (Deg F)	63.8	65.3	65.2	65.8	65.1	65.0	65.0	66.9	65.0	66.4	64.5	67.1	72.1	65.8	66.2	65.8	67.2	66.8	68.7	66.7	73.7	65.5	66.7	66.7	67.4
pH (s.u.)	7.27	6.89	7.21	7.24	7.03	6.81	6.81	7.00	7.59	6.67	7.01	6.85	6.81	7.38	7.25	7.09	7.07	7.18	6.67	7.12	7.01	7.02	6.93	7.17	7.17
Specific Conductivity (mS/cm)	1.37	0.968	2.36	2.31	3.93	5.18	5.18	4.2	4.31	5.02	5.94	4.83	5.99	3.06	4.63	8.33	3.21	7.31	4.19	5.53	5.2	5.51	4.36	2.94	4.94
Turbidity (NTU)	23.1	21.5	22	36.9	2.13	5.3	5.3	<0.1	204	<0.1	25.6	28.4	42.5	<0.1	55.5	<0.1	34.6	57.6	<0.1	0.1	0.1	22.4	78.9	0.3	2.0
Dissolved Oxygen (mg/L)	0.78	3.66	0.6	0.62	3.19	0.71	0.71	0.75	4.12	0.62	4.44	3.06	0.74	3.22	2.76	0.74	0.67	2.3	0.8	1.13	3.08	1.01	0.82	0.88	0.72
Redox (mV)	-119	-153	-119	-59	-169	-185	-185	95	-345	103	62	-393	-148	-122	-377	-42	-89	-291	-67	-89	-379	44	-115	-133	-133
Ferrous Iron (mg/L)	0.66	0.08	1.41	0.34	2.65	0.61	0.61	0.09	0.41	0.01	0.1	<0.01	0.56	<0.01	<0.01	<0.01	2.47	0.16	1.27	1.49	0.1	0.06	0.26	1.33	1.87

Notes:
(1) Field filtered with a 0.45 micron filter.
Analytes analyzed by ESC Lab Sciences, Mount Juliet, TN. Volatile Fatty Acids analyzed by Microseeps/Pace Analytical Services LLC, Pittsburgh, PA.
Shaded cells are exceedances of applicable United States Environmental Protection Agency Maximum Contaminant Levels
Bold cells are detected concentrations of chemical analytes
B = analyte detected in associated method blank as well as the laboratory sample
BOD = biological oxygen demand
COD = chemical oxygen demand
d = the analyte concentration was determined from a dilution
Downgrad. = downgradient
Dup = field duplicate
F = fahrenheit
J = estimated concentration between the method detection limit and laboratory reporting limit
mg/L = milligrams per liter
mS/cm = microSiemens per centimeter
mV = millivolts
N = normal
NTU = nephelometric turbidity units
ORP = oxidation-reduction potential
s.u. = standard units
TOC = total organic carbon
Upgrad. = upgradient
< = concentration less than the specified method detection limit

GSI ENVIRONMENTAL

TABLE 4
MICROBIOLOGICAL PARAMETERS IN GROUNDWATER
Altus Air Force Base, Altus, Oklahoma

Transect	BA01	BB04	BB05	BC07	BC08	BE09	BE11	BF12	BA01	BB04	BB05	BC07	BC08	BE09	BE11	BF12	BA01	BB04	BB05	BC07	BC08	BE09	BE11	BF12
Location in Transect	Upgradient								Within Biowall								Downgradient							
Reductive Dechlorination (cells/mL)																								
Dehalococcoides spp. (DHC)	1.14E+2	9.80E+2	4.40E+0	2.20E+1	<0.1	1.98E+2	1.04E+3	5.32E+5	4.23E+3	2.58E+4	1.88E+4	7.56E+3	2.36E+4	4.56E+4	6.28E+2	8.58E+3	8.21E+3	8.44E+3	3.61E+2	4.88E+3	8.66E+2	1.30E+3	1.01E+3	2.56E+3
tceA Reductase (TCE)	5.20E+0	1.19E+2	1.00E+0	3.70E+0	<0.1	3.16E+1	1.25E+1	1.88E+4	4.30E+0	1.91E+2	3.98E+3	4.05E+1	1.54E+2	7.10E+2	4.80E+0	3.55E+2	6.16E+2	7.19E+2	2.29E+1	3.14E+2	4.44E+1	6.79E+1	1.57E+1	1.74E+2
BAV1 Vinyl Chloride Reductase (BVC)	2.40E+0	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	4.39E+1	<0.3	<0.3	<0.6	<0.4	<0.5	<0.7	<0.1	8.80E+0	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.33E+1	2.40E+0
Vinyl Chloride Reductase (VCR)	<0.1	3.82E+1	2.00E-1	1.70E+0	<0.1	1.51E+1	<0.1	4.60E+4	<0.3	7.35E+1	8.59E+2	1.75E+1	9.89E+1	4.91E+2	<0.1	2.78E+2	1.00E-1	1.07E+3	1.80E+0	2.56E+1	3.00E-1	3.79E+1	7.00E-1	3.58E+1
Dehalobacter spp. (DHBt)	<0.1	<0.1	6.00E-1	<0.1	<0.1	1.53E+2	1.80E+1	<0.1	1.16E+2	2.69E+2	5.00E+1	8.78E+1	1.10E+1	5.19E+1	<0.1	<0.1	1.86E+2	8.08E+1	1.69E+1	3.48E+1	<0.1	5.75E+1	2.15E+1	<0.1
Dehalobacter DCM (DCM)	<0.1	<0.1	<0.1	<0.1	<0.1	1.18E+2	<0.1	<0.1	8.60E+1	<0.3	1.77E+3	<0.4	<0.5	<0.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	8.20E+0	<0.1
Dehalogenimonas spp. (DHG)	4.56E+4	4.39E+3	6.54E+2	9.45E+2	4.79E+2	1.86E+3	6.51E+3	6.24E+4	3.61E+5	6.10E+5	2.13E+5	3.14E+5	1.00E+6	5.76E+5	2.83E+4	6.30E+4	2.94E+4	1.38E+4	1.12E+4	3.19E+3	8.21E+4	1.99E+4	7.30E+3	3.07E+3
Desulfitobacterium spp. (DSB)	2.80E+1	<0.1	4.21E+1	8.04E+1	<0.1	9.80E+0	4.66E+1	6.28E+1	9.12E+2	6.00E+1	<0.6	<0.4	5.55E+1	7.44E+3	1.88E+1	1.34E+1	7.47E+1	1.83E+3	6.49E+2	2.00E-1	2.20E+0	6.01E+2	<0.1	2.5 J
Dehalobium chlorocoercia (DECO)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.3	<0.3	<0.6	<0.4	<0.5	<0.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Desulfuromonas spp. (DSM)	<0.1	7.39E+3	1.28E+1	6.81E+1	<0.1	2.65E+4	3.36E+1	<0.1	<0.3	<0.3	<0.6	2.78E+2	<0.5	4.43E+3	<0.1	1.34E+2	<0.1	1.77E+4	1.66E+2	1.44E+3	<0.1	7.00E+1	3.27E+1	<0.1
Chloroform reductase (CFR)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.3	<0.3	<0.6	<0.4	<0.5	<0.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1,1 DCA Reductase (DCA)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.3	<0.3	<0.6	<0.4	<0.5	<0.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1,2 DCA Reductase (DCAR)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	8.00E-1	<0.3	<0.6	9.00E-1	4.60E+0	<0.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Aerobic (Co)Metabolic (cells/mL)																								
Soluble Methane Monooxygenase (SMMO)	4.66E+4	1.31E+3	2.21E+2	1.31E+3	2.32E+1	6.77E+3	9.38E+3	1.19E+4	8.37E+4	1.59E+5	8.68E+4	8.03E+3	7.10E+4	2.01E+5	6.67E+2	2.11E+3	1.54E+4	1.30E+4	8.40E+3	8.65E+2	4.83E+2	1.82E+3	6.09E+3	1.67E+2
Particulate Methane Monooxygenase (PMMO)	5.16E+4	6.90E+2	2.99E+1	3.94E+2	1.90E+0	7.80E+3	2.85E+3	4.96E+1	5.74E+2	7.62E+2	2.24E+3	2.90E+2	4.74E+2	1.11E+3	5.66E+1	2.11E+2	1.72E+4	4.19E+3	2.00E+3	3.41E+3	1.26E+3	1.50E+3	1.05E+3	7.57E+2
Toluene Dioxygenase (TOD)	6.05E+2	3.69E+1	1.91E+1	2.02E+1	3.00E+0	6.85E+2	4.72E+2	6.17E+2	1.45E+4	1.30E+4	5.24E+3	4.07E+2	4.59E+3	1.36E+4	6.26E+2	6.59E+2	1.18E+3	6.84E+2	4.78E+2	5.60E+2	4.03E+2	3.68E+2	5.76E+2	1.42E+1
Phenol Hydroxylase (PHE)	1.23E+3	<0.1	4.70E+1	3.59E+1	<0.1	1.05E+3	<0.1	1.78E+1	9.90E+0	<0.3	<0.6	<0.4	1.70E+0	<0.7	8.00E-1	2.37E+1	5.21E+2	7.13E+1	1.55E+1	1.62E+2	3.30E+0	6.26E+1	1.07E+3	1.33E+1
Trichlorobenzene Dioxygenase (TCBO)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.3	<0.3	<0.6	<0.4	<0.5	<0.7	<0.1	<0.1	4.90E+0	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Toluene Monooxygenase 2 (RDEG)	7.12E+2	2.60E+1	<0.1	7.90E+0	<0.1	4.33E+2	<0.1	<0.1	1.28E+2	1.76E+2	6.44E+2	<0.4	<0.5	<0.7	<0.1	5.57E+1	2.97E+2	3.39E+1	2.17E+1	<0.1	1.70E+1	<0.1	1.47E+3	1.92E+1
Toluene Monooxygenase (RMO)	1.39E+3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	4.39E+2	<0.3	<0.3	<0.6	<0.4	<0.5	2.92E+2	<0.1	1.28E+1	1.71E+3	<0.1	<0.1	<0.1	<0.1	7.10E+0	<0.1	<0.1
Ethene Monooxygenase (EtnC)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.3	<0.3	<0.6	<0.4	<0.5	<0.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Epoxyalkane transferase (EtnE)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.3	<0.3	<0.6	<0.4	<0.5	<0.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dichloromethane dehalogenase (DCMA)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.3	<0.3	<0.6	<0.4	<0.5	<0.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Other (cells/mL)																								
Total Eubacteria (EBAC)	7.60E+5	2.66E+5	1.84E+5	2.48E+5	3.12E+3	1.55E+6	7.10E+5	8.08E+5	6.38E+6	2.68E+7	4.12E+7	2.06E+6	3.19E+6	1.48E+7	3.79E+5	5.00E+5	1.01E+6	1.01E+6	7.25E+5	2.75E+5	2.21E+5	5.12E+5	6.55E+5	9.61E+4
Sulfate Reducing Bacteria (APS)	4.99E+5	9.23E+4	2.12E+1	3.66E+4	<0.1	1.04E+5	1.51E+5	1.00E+6	1.68E+6	3.18E+5	3.99E+6	1.06E+6	1.53E+6	1.32E+6	2.48E+5	2.84E+5	6.03E+5	8.71E+4	2.21E+5	1.66E+5	1.06E+5	3.77E+5	1.15E+5	1.74E+4
Methanogens (MGN)	1.88E+3	1.89E+2	9.10E+0	5.60E+1	4.50E+0	1.03E+3	1.58E+3	1.90E+3	1.20E+6	2.45E+6	4.15E+5	5.50E+5	5.24E+5	1.49E+6	1.34E+4	2.07E+4	3.75E+3	4.15E+3	3.79E+3	3.02E+2	2.15E+2	1.55E+4	1.32E+2	3.90E+2

>10 E+5
>10 E+4
>10 E+3
>10 E+2
>DL to 10 E+2

Notes:
Analytes analyzed by Microbial Insights, Knoxville, TN
Bold cells are detected concentrations.
cells/mL = cells per milliliter
< = concentration less than the specified method detection limit

TABLE 5
ISOTOPE RESULTS IN GROUNDWATER
Altus Air Force Base, Altus, Oklahoma

Transect	Location in Transect	Location ID	TCE	cis-1,2-DCE	Vinyl Chloride
BA01	Upgradient	BA01U	-13.11	-14.28	--
	Biowall	BA01W	--	--	--
	Downgradient	BA01D	--	-25.36	-18.62
BB04	Upgradient	BB04U	-19.96	-21.02	-28.52
	Biowall	BB04W	--	--	-19.03
	Downgradient	BB04D	-22.735	-22.755	-26.38
BB05	Upgradient	BB05U	-20.075	-20.7	-28.58
	Biowall	BB05W	-6.78	8.71	-5.2
	Downgradient	BB05D	-22.63	-19.5	-17.65
BC07	Upgradient	BC07U	-24.17	-24.64	--
	Biowall	BC07W	--	-19.13	--
	Downgradient	BC07D	-14.53	-19.08	-26.17
BC08	Upgradient	BC08U	-24.13	--	--
	Biowall	BC08W	-14.15	-10.3	33.23
	Downgradient	BC08D	-22.27	-21.31	-29.71
BE09	Upgradient	BE09U	-22.22	-22.8	-27.29
	Biowall	BE09W	--	--	6.6
	Downgradient	BE09D	-19.84	-18.455	-27.945
BE11	Upgradient	BE11U	-20.19	-18.28	-8.89
	Biowall	BE11W	--	-7.77	-15.9
	Downgradient	BE11D	-20.375	-22.75	-19.275
BF12	Upgradient	BF12UL	-9.35	-5.33	-19.34
	Biowall	BF12W	--	-5.18	-19.59
	Downgradient	BF12DL	-11.01	-6.66	-20.27

Notes:
CSIA analyzed by Microseeps/Pace Analytical Services LLC, Pittsburgh, PA.
-- = no result reported because analyte was not detected in the sample
Units are δ (‰)

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TABLE 6
BIOWALL MULCH ANALYSES
Altus Air Force Base, Altus, Oklahoma

Transect	BA01			BB04			BB05			BC07			BC08			BE09			BF12		
Location ID	GSI-SB-BA01W	GSI-SB-BA01W	GSI-SB-BA01W	GSI-SB-BB04W	GSI-SB-BB04W	GSI-SB-BB04W	GSI-SB-BB05W	GSI-SB-BB05W	GSI-SB-BB05W	GSI-SB-BC07W	GSI-SB-BC07W	GSI-SB-BC07W	GSI-SB-BC08W	GSI-SB-BC08W	GSI-SB-BC08W	GSI-SB-BE09W	GSI-SB-BE09W	GSI-SB-BE09W	GSI-SB-BF12W	GSI-SB-BF12W	GSI-SB-BF12W
Depth Top (ft)	18	26	28	26	29	30	20.5	29	30.5	23	25	27	15	30	31	15	17	23.5	20	23	27
Depth Bottom (ft)	19	27	29	27	30	31	21.5	30	31.5	25	27	29	20	31	32	17	19	26	23	25	31
Sample ID	BA01W-1	BA01W-2	BA01W-3	BB04W-1	BB04W-2	BB04W-3	BB05W-1	BB05W-2	BB05W-3	BC07W-3	BC07W-2	BC07W-1	BC08W-1	BC08W-2	BC08W-3	BE09W-1	BE09W-2	BE09W-3	BF12W-1	BF12W-2	BF12W-3
Sample Date	5/18/2015	5/18/2015	5/18/2015	5/31/2015	5/31/2015	5/31/2015	5/31/2015	5/31/2015	5/31/2015	5/17/2015	5/17/2015	5/17/2015	5/17/2015	5/17/2015	5/17/2015	5/28/2015	5/28/2015	5/28/2015	5/16/2015	5/16/2015	5/16/2015
Sample Type	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
pH (s.u.)	6.9	6.9	7	8	8.6	8.6	8	8.6	8.4	8	8	8.1	7.8	7.8	8	7.8	7.9	8.2	8.4	8.4	8.5
Moisture (%)	18.4	22.4	20.1	32.4	32.4	34.1	31.6	33.3	34.6	37.2	23.1	23.9	27.8	37.6	23.9	24.1	26.3	21.5	23.7	21.2	22.0
DM (%)	81.6	77.6	79.9	67.6	67.6	65.9	68.4	66.7	65.4	62.8	76.9	76.1	72.2	62.4	76.1	75.9	73.7	78.5	76.3	78.8	78.0
NDF (% of DM)	94.6	95.1	95.1	95.1	92.9	93.4	92.9	92.6	91.7	93.8	95.2	94.0	83.8	96.3	95.0	78.7	77.0	83.6	92.7	91.7	96.5
ADF (% of DM)	93.4	93.4	91.5	90.2	93.7	93.2	91.9	93.6	94.3	92.8	95.0	94.5	84.1	94.8	94.9	81.5	83.9	87.2	94.2	93.6	94.4
Hemicellulose (% of DM)	1.2	1.71	3.62	4.83	0	0.2	1.01	0	0	1	0.2	0	0	1.51	0.1	0	0	0	0	0	2.11
Cellulose (% of DM)	89.9	89.3	88.0	84.4	89.9	89.6	87.7	90.2	90.5	87.8	92.0	91.3	80.0	89.9	92.8	79.5	81.5	84.8	90.4	90.2	92.0
Lignin (% of DM)	3.52	4.12	3.52	5.83	3.81	3.61	4.21	3.41	3.81	4.93	3.01	3.21	4.13	4.82	2.1	2.02	2.32	2.41	3.71	3.41	2.41
Silica Ash (% of DM)	89.1	88.0	87.7	81.0	88.3	89.4	87.1	91.0	91.1	85.3	92.2	90.9	78.5	85.8	92.0	82.1	80.0	83.8	89.3	89.4	92.1
Total Carbon (% of DM)	5.39	4.71	3.92	5.86	5.36	4.15	4.55	4.56	5.04	6.03	2.59	3.18	5.02	6.6	2.82	2.53	3.61	4.24	4.35	4.98	2.5
Total Nitrogen (% of DM)	0.13	0.17	0.17	0.15	0.16	0.13	0.13	0.17	0.16	0.22	0.17	0.16	0.16	0.19	0.09	0.04	0.07	0.09	0.13	0.11	0.09
Total Phosphorus (% of DM)	0.05	0.04	0.05	0.07	0.08	0.04	0.05	0.05	0.08	0.03	0.05	0.03	0.06	0.04	0.03	0.07	0.05	0.05	0.03	0.03	0.02
Total Potassium (% of DM)	0.09	0.11	0.13	0.21	0.17	0.1	0.12	0.13	0.13	0.08	0.08	0.07	0.24	0.08	0.06	0.3	0.21	0.15	0.11	0.09	0.09
Sulfur (% of DM)	0.1	0.08	0.09	0.12	0.1	0.09	0.12	0.09	0.11	0.1	0.09	0.09	0.19	0.1	0.08	0.18	0.19	0.11	0.08	0.08	0.09
NH4-N (% of DM)	0.01	0.01	0.01	0.05	0.03	0.03	0.02	0.04	0.04	0.1	0.07	0.07	0.08	0.07	0.12	0.01	0.01	0.01	0.08	0.1	0.05
Cellulose/Lignin Ratio	25.5	21.7	25.0	14.5	23.6	24.8	20.8	26.4	23.8	17.8	30.6	28.5	19.4	18.7	44.2	39.3	35.1	35.2	24.4	26.5	38.2
Lignin/Total Nitrogen Ratio	27.1	24.2	20.7	38.9	23.8	27.8	32.4	20.1	23.8	22.4	17.7	20.1	25.8	25.4	23.3	50.5	33.1	26.8	28.5	31.0	26.8
C:N Ratio	41.5	27.7	23.1	39.1	33.5	31.9	35.0	26.8	31.5	27.4	15.2	19.9	31.4	34.7	31.3	63.3	51.6	47.1	33.5	45.3	27.8

Notes:
Analytes analyzed by the Soil and Forage Analysis Laboratory, University of Wisconsin Madison/Extension, Marshfield, WI
ft = feet
DM = dry matter
ADF = acid detergent fiber - cellulose and lignin
NDF = neutral detergent fiber - hemicellulose, cellulose, and lignin
NH4-N - ammonium as nitrogen
s.u. = standard units

TABLE 7
SOIL CONSTITUENTS
Kelly Air Force Base, San Antonio, Texas

SITE ID:	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)
MATRIX:	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
SITE AREA SAMPLED:	Upgradient	Upgradient	Upgradient	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone
LOCATION ID:	SS037MW307	SS037MW307	SS037MW307	ST008MW157	ST008MW157	ST008MW157	ST008RW256	ST008RW256	ST008RW256
SAMPLE DEPTH (FT BGS):	23	25	27	23	25	27	23	25	27
SAMPLE DATE:	8/15/2016	8/15/2016	8/15/2016	8/15/2016	8/15/2016	8/15/2016	8/15/2016	8/15/2016	8/15/2016
UNITS:	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Volatile Organic Compounds									
Tetrachloroethene	**0.000833 J**	**0.000366 J**	**0.000336 J**	<0.000297	<0.000313	<0.00561	<0.000311	<0.000388	<0.000319
Trichloroethene	**0.000617 J**	**0.000417 J**	**0.000323 J**	<0.0003	<0.000316	<0.00567	<0.000315	<0.000392	<0.000322
cis-1,2-Dichloroethene	**0.000915 J**	**0.000485 J**	**0.000283 J**	**0.000738 J**	**0.000863 J**	**0.0233**	**0.00143**	**0.00103 J**	<0.000271
Vinyl chloride	**0.000408 J**	<0.000332	<0.000325	**0.000371 J**	**0.00143**	**0.0203 J**	**0.000874 J**	**0.000583 J**	<0.000336
Magnetic Susceptibility									
Magnetic Susceptibility, Average	6.43E-07	4.01E-07	8.14E-08	1.69E-07	2.17E-07	2.51E-07	1.05E-07	1.00E-07	3.81E-07
Organic Carbon									
Fractional Organic Carbon, g C/g soil	0.00927	0.00644	0.00334	0.00224	0.00187	0.00267	0.00416	0.00428	0.00264
Fractional Organic Carbon, mg/kg	9,270	6,440	3,340	2,240	1,870	2,670	4,160	4,280	2,640
Potentially-Bioavailable Organic Carbon, mg/kg	82.3	67.7	53.1	61.5	100.8	48.8	57.1	49.5	54.2
Fractional Organic Matter, %	1.6	1.11	0.576	0.387	0.323	0.461	0.717	0.738	0.456
Other									
Total Solids, %	77.6	87.7	89.5	93.1	88.2	86.1	88.7	71.1	86.6

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN and Microbial Insights, Knoxville, TN.
2. Detected VOC concentrations shown in bold.
3. J = estimated concentration between the method detection limit and the laboratory reporting limit.
4. < = concentration less than the specified method detection limit.

GSI ENVIRONMENTAL

TABLE 8
MICROBIAL PARAMETERS IN SOIL
Kelly Air Force Base, San Antonio, Texas

SITE ID:	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)
MATRIX:	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
SITE AREA SAMPLED:	Upgradient	Upgradient	Upgradient	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone
LOCATION ID:	SS037MW307	SS037MW307	SS037MW307	ST008MW157	ST008MW157	ST008MW157	ST008RW256	ST008RW256	ST008RW256
SAMPLE DEPTH (FT BGS):	23	25	27	23	25	27	23	25	27
SAMPLE DATE:	8/15/2016	8/15/2016	8/15/2016	8/15/2016	8/15/2016	8/15/2016	8/15/2016	8/15/2016	8/15/2016
UNITS:	cells/g	cells/g	cells/g	cells/g	cells/g	cells/g	cells/g	cells/g	cells/g
Reductive Dechlorination									
Dehalococcoides spp. (DHC)	**1,420**	<200	<200	<200	<200	<200	<200	<200	<200
tceA Reductase (TCE)	<200	<200	<200	<200	<200	<200	<200	<200	<200
BAV1 Vinyl Chloride Reductase (BVC)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Vinyl Chloride Reductase (VCR)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Dehalobacter spp. (DHBt)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Dehalobacter DCM (DCM)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Dehalogenimonas spp. (DHG)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Desulfitobacterium spp. (DSB)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Dehalobium chlorocoercia (DECO)	**31,100**	<200	<200	<200	<200	<200	<200	<200	<200
Desulfuromonas spp. (DSM)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Chloroform reductase (CFR)	<200	<200	<200	<200	<200	<200	<200	<200	<200
1,1 DCA Reductase (DCA)	<200	<200	<200	<200	<200	<200	<200	<200	<200
1,2 DCA Reductase (DCAR)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Aerobic (Co)Metabolic									
Soluble Methane Monooxygenase (SMMO)	**12,800**	<200	<200	<200	<200	<200	<200	<200	<200
Particulate Methane Monooxygenase (PMMO)	**5550 J**	**783 J**	**1230 J**	<200	<200	<200	<200	**376 J**	<200
Toluene Dioxygenase (TOD)	<200	<200	**306 J**	<200	<200	<200	<200	<200	<200
Phenol Hydroxylase (PHE)	<200	**8100 J**	**38,300**	**11,100**	**21,100**	**12,900**	**32,100**	**11,300**	**11,700**
Trichlorobenzene Dioxygenase (TCBO)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Toluene Monooxygenase 2 (RDEG)	<200	<200	<200	<200	<200	**115,000**	<200	<200	<200
Toluene Monooxygenase (RMO)	<200	<200	<200	<200	<200	<200	<200	**376**	<200
Ethene Monooxygenase (EtnC)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Epoxyalkane transferase (EtnE)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Dichloromethane dehalogenase (DCMA)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Other									
Total Eubacteria (EBAC)	**15,600,000**	**1,110,000**	**655,000**	**612,000**	**682,000**	**583,000**	**743,000**	**787,000**	**666,000**
Sulfate Reducing Bacteria (APS)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Methanogens (MGN)	**1470 J**	<200	<200	<200	<200	<200	**90.3J**	<200	**519 J**

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Detected concentrations shown in bold.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

GSI ENVIRONMENTAL

TABLE 9
GROUNDWATER CONSTITUENTS
Kelly Air Force Base, San Antonio, Texas

SITE ID:	Kelly AFB (ISB)	Kelly AFB (ISB)	Kelly AFB (ISB)
MATRIX:	Groundwater	Groundwater	Groundwater
SITE AREA SAMPLED:	Upgradient	Treatment Zone	Treatment Zone
LOCATION ID:	SS037MW307	ST008MW157	ST008RW256
SCREEN INTERVAL:			
SAMPLE DATE:	8/16/2016	8/16/2016	8/16/2016
UNITS:	mg/L	mg/L	mg/L
Volatile Organic Compounds			
Tetrachloroethene	**0.00846**	<0.000372	<0.000372
Trichloroethene	**0.0146**	<0.000398	<0.000398
cis-1,2-Dichloroethene	**0.0822**	**0.0175**	**0.00348**
Vinyl chloride	<0.000259	**0.367**	**0.0165**
Dissolved Gasses			
Ethane	<0.00407	**0.0391**	**0.0538**
Ethene	<0.00426	**0.08**	**0.0141**
Methane	**0.0083 J**	**7.78**	**3.99**
Volatile Fatty Acids			
Acetic Acid	**0.15**	**0.028**	**0.02**
Butyric Acid	**0.013**	**0.1**	**0.0069**
Formic Acid	**0.037**	**0.04**	**0.04**
Hexanoic Acid	**0.13**	**0.2**	**0.2**
i-Hexanoic Acid	**0.2**	**0.2**	**0.2**
i-Pentanoic Acid	**0.1**	**0.1**	**0.1**
Lactic Acid	**0.012**	**0.028**	**0.017**
Pentanoic Acid	**0.02**	**0.035**	**0.016**
Propionic Acid	**0.0031**	**0.0024**	**0.0025**
Pyruvic Acid	**0.1**	**0.1**	**0.1**
Oxygen Demand and Total Organic Carbon			
Biochemical Oxygen Demand (BOD)	<3.33	<3.33	<3.33
Chemical Oxygen Demand (COD)	**9.16 J**	**14.6**	**22**
Dissolved Organic Carbon (DOC)	**0.785 BJ**	**3.22 B**	**2.65 B**
Total Organic Carbon (TOC)	**0.851 BJ**	**1.65 B**	**2.65 B**
Dissolved Ions			
Alkalinity	**376 J6**	**394**	**400**
Calcium	**106**	**115**	**112**
Chloride	**29.6**	**58.5**	**48.7**
Iron	<0.0141	**0.746**	**0.374**
Magnesium	**10.3**	**15.1**	**12.3**
Nitrate	**5.46**	<0.0227	<0.0227
Potassium	**2.53**	**1.43**	**2**
Sodium	**96.4**	**102**	**105**
Sulfate	**47.7**	**65**	**63.6**
Field Parameters			
Dissolved Oxygen			
pH, s.u.			
Redox, mV			
Specific Conductivity, mS/cm			
Temperature, ^{o}F			
Turbidity, NTU			

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN. Volatile Fatty Acids analyzed by Microseeps/Pace Analytical Services LLC, Pittsburg, PA.
2. Detected concentrations shown in bold.
3. B = analyte detected in associated method blank as well as the laboratory sample.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.
6. "-" = not analyzed; NM = Not measured.

GSI ENVIRONMENTAL

TABLE 10
MICROBIOLOGICAL PARAMETERS IN GROUNDWATER
Kelly Air Force Base, San Antonio, Texas

SITE ID:	Kelly AFB	Kelly AFB	Kelly AFB
MATRIX:	Groundwater	Groundwater	Groundwater
SITE AREA SAMPLED:	Upgradient	Treatment Zone	Treatment Zone
LOCATION ID:	SS037MW307	ST008MW157	ST008RW256
SCREEN INTERVAL:			
SAMPLE DATE:	8/16/2016	8/16/2016	8/16/2016
UNITS:	cells/mL	cells/mL	cells/mL
Reductive Dechlorination			
Dehalococcoides spp. (DHC)	**5**	**11,000**	**114,000**
tceA Reductase (TCE)	<0.1	**38.9**	**1,230**
BAV1 Vinyl Chloride Reductase (BVC)	<0.1	**39.6**	**77.4**
Vinyl Chloride Reductase (VCR)	<0.1	**952**	**15,100**
Dehalobacter spp. (DHBt)	**7.5**	**507**	**758**
Dehalobacter DCM (DCM)	<0.1	**6.7**	**31.3**
Dehalogenimonas spp. (DHG)	**352**	**25,800**	**44,500**
Desulfitobacterium spp. (DSB)	**232**	**1,060**	**2,920**
Dehalobium chlorocoercia (DECO)	**384**	**244**	**3,390**
Desulfuromonas spp. (DSM)	<0.1	**75,000**	**59,100**
Chloroform reductase (CFR)	<0.1	<0.1	<0.1
1,1 DCA Reductase (DCA)	<0.1	<0.1	<0.1
1,2 DCA Reductase (DCAR)	<0.1	<0.1	<0.1
Aerobic (Co)Metabolic			
Soluble Methane Monooxygenase (SMMO)	**2,410**	**1,560**	**485**
Particulate Methane Monooxygenase (PMMO)	**2,000**	**1,860**	**3,050**
Toluene Dioxygenase (TOD)	**36.7**	**65.1**	**722**
Phenol Hydroxylase (PHE)	**210**	**64.8**	**371**
Trichlorobenzene Dioxygenase (TCBO)	<0.1	<0.1	<0.1
Toluene Monooxygenase 2 (RDEG)	**467**	**46.6**	**41.1**
Toluene Monooxygenase (RMO)	**276**	**17.6**	**73.6**
Ethene Monooxygenase (EtnC)	<0.1	<0.1	<0.1
Epoxyalkane transferase (EtnE)	**87.8**	<0.1	**89.9**
Dichloromethane dehalogenase (DCMA)	<0.1	<0.1	<0.1
Other			
Total Eubacteria (EBAC)	**190,000**	**479,000**	**1,250,000**
Sulfate Reducing Bacteria (APS)	**141,000**	**362,000**	**671,000**
Methanogens (MGN)	**15.1**	**9,290**	**17,000**

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Detected concentrations shown in bold.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

TABLE 11
ISOTOPE RESULTS IN GROUNDWATER
Kelly Air Force Base, San Antonio, Texas

Site ID	Matrix	Location ID	Site Area Sampled	Sample Date	δ13C (‰)		
					TCE	cis-1,2-DCE	Vinyl Chloride
Kelly AFB (ISB)	Groundwater	SS037MW307	Upgradient	8/6/2016	-22.98	-19.50	ND
Kelly AFB (ISB)	Groundwater	ST008MW157	Treatment Zone	8/6/2016	ND	38.70	-12.86
Kelly AFB (ISB)	Groundwater	ST008RW256	Treatment Zone	8/6/2016	ND	29.62	7.39

Notes:
1. Samples analyzed by Pace Analytical CSIA Center, Pittsburg, PA.
2. ND = not detected

TABLE 12
SOIL CONSTITUENTS
Orlando Naval Training Center, Orlando, Florida

SITE ID:	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC
MATRIX:	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
SITE AREA SAMPLED:	Upgradient	Upgradient	Upgradient	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone
LOCATION ID:	OLD-17-10C-SB	OLD-17-10C-SB	OLD-17-10C-SB	OLD-17-53C2-SB	OLD-17-53C2-SB	OLD-17-53C2-SB	OLD-17-55C-SB	OLD-17-55C-SB	OLD-17-55C-SB
SAMPLE DEPTH (FT BGS):	42	44	46	35	37	39	35	37	39
SAMPLE DATE:	3/29/2016	3/29/2016	3/29/2016	3/29/2016	3/29/2016	3/29/2016	3/29/2016	3/29/2016	3/29/2016
UNITS:	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Volatile Organic Compounds									
Tetrachloroethene	<0.000335	<0.00034	<0.000343	<0.000339	<0.000339	<0.00034	<0.000341	<0.000336	<0.000337
Trichloroethene	<0.000338	<0.000344	<0.000346	**0.00368**	**0.00115 J**	**0.00197**	**0.00213**	**0.000948 J**	<0.000341
cis-1,2-Dichloroethene	<0.000285	<0.00029	<0.000292	**0.0079**	**0.000589 J**	**0.00204**	**0.0438**	**0.0847**	**0.107**
Vinyl chloride	<0.000353	<0.000359	<0.000361	<0.000357	<0.000358	<0.000358	**0.0138**	**0.013**	**0.000969 J**
Magnetic Susceptibility									
Magnetic Susceptibility, Average	4.80E-09	4.47E-09	1.66E-08	7.6E-09	2.90E-09	3.1E-09	5.97E-09	2.07E-09	2.47E-09
Organic Carbon									
Fractional Organic Carbon, g C/g soil	0.00136	0.00166	0.0024	0.00127	0.00212	0.00238	0.00236	0.00233	0.00143
Fractional Organic Carbon, mg/kg	1,360	1,660	2,400	1,270	2,120	2,380	2,360	2,330	1,430
Potentially-Bioavailable Organic Carbon, mg/kg	315	299	697	318	492	770	475	789	341
Fractional Organic Matter, %	0.235	0.285	0.413	0.219	0.366	0.411	0.406	0.402	0.246
Other									
Total Solids, %	82.5	81.1	80.5	81.4	81.4	81.3	81	82.2	81.8

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN and Microbial Insights, Knoxville, TN.
2. Detected VOC concentrations shown in bold.
3. J = estimated concentration between the method detection limit and the laboratory reporting limit.
4. < = concentration less than the specified method detection limit.
5. "-" = not analyzed.

GSI ENVIRONMENTAL

TABLE 13
MICROBIAL PARAMETERS IN SOIL
Orlando Naval Training Center, Orlando, Florida

SITE ID:	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC	Orlando NTC
MATRIX:	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
SITE AREA SAMPLED:	Upgradient	Upgradient	Upgradient	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone	Treatment Zone
LOCATION ID:	OLD-17-10C-SB	OLD-17-10C-SB	OLD-17-10C-SB	OLD-17-53C2-SB	OLD-17-53C2-SB	OLD-17-53C2-SB	OLD-17-55C-SB	OLD-17-55C-SB	OLD-17-55C-SB
SAMPLE DEPTH (FT BGS):	42	44	46	35	37	39	35	37	39
SAMPLE DATE:	3/29/2016	3/29/2016	3/29/2016	3/29/2016	3/29/2016	3/29/2016	3/29/2016	3/29/2016	3/29/2016
UNITS:	cells/g	cells/g	cells/g	cells/g	cells/g	cells/g	cells/g	cells/g	cells/g
Reductive Dechlorination									
Dehalococcoides spp. (DHC)	**2,960**	**901 J**	**4,190**	<200	**1,480**	**1,130**	**9,280**	**1,800**	**1,540**
tceA Reductase (TCE)	<200	<200	<200	<200	<200	<200	<200	<200	<200
BAV1 Vinyl Chloride Reductase (BVC)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Vinyl Chloride Reductase (VCR)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Dehalobacter spp. (DHBt)	<200	<200	<200	<200	**45,200**	**677,000**	**12,000**	**32,100**	**52,900**
Dehalobacter DCM (DCM)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Dehalogenimonas spp. (DHG)	**3,040 J**	**1,750 J**	**1,840 J**	**2,370 J**	<200	<200	**17,000**	<200	**14,400**
Desulfitobacterium spp. (DSB)	<200	<200	<200	<200	<200	**30,600**	**3,080 J**	<200	<200
Dehalobium chlorocoercia (DECO)	<200	<200	<200	<200	<200	<200	<200	**2,460 J**	<200
Desulfuromonas spp. (DSM)	**13,900**	**5,630 J**	**3,600 J**	**1,460 J**	**39,700**	**55,800**	**42,800**	**111,000**	**48,200**
Chloroform reductase (CFR)	<200	<200	<200	<200	<200	<200	<200	<200	<200
1,1 DCA Reductase (DCA)	<200	<200	<200	<200	<200	<200	<200	<200	<200
1,2 DCA Reductase (DCAR)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Aerobic (Co)Metabolic									
Soluble Methane Monooxygenase (SMMO)	**24,500**	**55,200**	**12,300**	<200	**867,000**	**885,000**	**2,940,000**	**37,800**	**1,600,000**
Particulate Methane Monooxygenase (PMMO)	**9,030 J**	**23,000**	**13,800**	**287,000**	**2,380 J**	**56,300**	**164,000**	**10,900**	**9,980 J**
Toluene Dioxygenase (TOD)	**133,000**	**8,560,000**	**986 J**	<200	**1,020 J**	**212 J**	**2,270 J**	**27,100**	**1,740 J**
Phenol Hydroxylase (PHE)	<200	**24,800**	<200	<200	<200	<200	<200	**6,700 J**	**38,500**
Trichlorobenzene Dioxygenase (TCBO)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Toluene Monooxygenase 2 (RDEG)	<200	<200	**9,810 J**	**13,800**	<200	<200	<200	<200	<200
Toluene Monooxygenase (RMO)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Ethene Monooxygenase (EtnC)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Epoxyalkane transferase (EtnE)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Dichloromethane dehalogenase (DCMA)	<200	<200	<200	<200	<200	<200	<200	<200	<200
Other									
Total Eubacteria (EBAC)	**1,940,000**	**1,220,000**	**1,900,000**	**2,620,000**	**24,400,000**	**24,400,000**	**12,000,000**	**11,100,000**	**7,390,000**
Sulfate Reducing Bacteria (APS)	**454,000**	**128,000**	**162,000**	**221 J**	**20,600,000**	**16,100,000**	**2,450,000**	**1,940 J**	**1,170,000**
Methanogens (MGN)	<200	<200	<200	**915 J**	<200	**1,860 J**	**1,790 J**	**3,070 J**	**4,350 J**

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Detected concentrations shown in bold.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

GSI ENVIRONMENTAL

TABLE 14
GROUNDWATER CONSTITUENTS
Orlando Naval Training Center, Orlando, Florida

SITE ID:	Orlando NTC	Orlando NTC	Orlando NTC
MATRIX:	Groundwater	Groundwater	Groundwater
SITE AREA SAMPLED:	Upgradient	Treatment Zone	Treatment Zone
LOCATION ID:	OLD-17-10C	OLD-17-53C2	OLD-17-55C
SCREEN INTERVAL:	42-47 ft bgs	35.5-40 ft bgs	35-40 ft bgs
SAMPLE DATE:	3/30/2016	3/30/2016	3/29/2016
UNITS:	mg/L	mg/L	mg/L
Volatile Organic Compounds			
Tetrachloroethene	<0.000372	<0.000372	<0.000372
Trichloroethene	<0.000398	**0.0122**	**0.00242**
cis-1,2-Dichloroethene	**0.000467 J**	**0.102**	**0.603**
Vinyl chloride	**0.000583 J**	**0.0153**	**0.0336**
Dissolved Gasses			
Ethane	<0.00407	<0.00407	<0.00407
Ethene	<0.00426	<0.00426	**0.0109 J**
Methane	**0.593**	**10.7**	**14.8**
Volatile Fatty Acids			
Acetic Acid	**0.12 B**	**0.2 B**	<0.006 B
Butyric Acid	<0.005 B	<0.005 B	<0.005 B
Formic Acid	<0.004	**0.27**	<0.004
Hexanoic Acid	<0.01	<0.01	<0.01
i-Hexanoic Acid	<0.01	<0.01	<0.01
i-Pentanoic Acid	<0.012	<0.012	<0.012
Lactic Acid	<0.003 B	<0.003 B	<0.003 B
Pentanoic Acid	<0.006	<0.006	<0.006
Propionic Acid	**1.2**	<0.001	<0.001
Pyruvic Acid	<0.012	<0.012	<0.012
Oxygen Demand and Total Organic Carbon			
Biochemical Oxygen Demand (BOD)	**7.8**	**9.3**	**16.5**
Chemical Oxygen Demand (COD)	**134**	**27**	**43.4**
Dissolved Organic Carbon (DOC)	**12**	**6.58 B**	**8.69**
Total Organic Carbon (TOC)	**12.6**	**6.12 B**	**8.41**
Dissolved Ions			
Alkalinity	**25**	**31.2**	**39.6**
Calcium	**5.61**	**6.87**	**5.83**
Chloride	**7.3**	**5.46**	**7.43**
Iron	**4.68**	**2.74**	**3.5**
Magnesium	**2.69**	**3.17**	**1.93**
Nitrate	**0.0276 J**	<0.0227	<0.0227
Potassium	**1.83**	**1.45**	**1.94**
Sodium	**9.65**	**7.5**	**9.06**
Sulfate	**0.417 J**	**14.9**	**7.48**
Field Parameters			
Dissolved Oxygen	0.73	0.68	1.12
pH, s.u.	4.28	4.84	4.71
Redox, mV	30.4	44.7	38.8
Specific Conductivity, mS/cm	0.079	0.125	0.124
Temperature, ^{o}F	72.42	74.16	74.82
Turbidity, NTU	NM	50.4	59.7

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN. Volatile Fatty Acids analyzed by Microseeps/Pace Analytical Services LLC, Pittsburg, PA.
2. Bold cells are detected concentrations.
3. B = analyte detected in associated method blank as well as the laboratory sample.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.
6. "-" = not analyzed; NM = Not measured.

GSI ENVIRONMENTAL

TABLE 15
MICROBIOLOGICAL PARAMETERS IN GROUNDWATER
Orlando Naval Training Center, Orlando, Florida

SITE ID:	Orlando NTC	Orlando NTC	Orlando NTC
MATRIX:	Groundwater	Groundwater	Groundwater
SITE AREA SAMPLED:	Upgradient	Treatment Zone	Treatment Zone
LOCATION ID:	OLD-17-10C	OLD-17-53C2	OLD-17-55C
SCREEN INTERVAL:	42-47 ft bgs	35.5-40 ft bgs	35-40 ft bgs
SAMPLE DATE:	3/30/2016	3/30/2016	3/29/2016
UNITS:	cells/mL	cells/mL	cells/mL
Reductive Dechlorination			
Dehalococcoides spp. (DHC)	<25	**95**	**116**
tceA Reductase (TCE)	<25	<0.1	<0.1
BAV1 Vinyl Chloride Reductase (BVC)	<25	**8.3**	**0.6 J**
Vinyl Chloride Reductase (VCR)	<25	<0.1	<0.1
Dehalobacter spp. (DHBt)	<25	**226**	**380**
Dehalobacter DCM (DCM)	<25	<0.1	<0.1
Dehalogenimonas spp. (DHG)	**117 J**	**105**	**1,620**
Desulfitobacterium spp. (DSB)	<25	**10**	<0.1
Dehalobium chlorocoercia (DECO)	<25	**1.3 J**	**150**
Desulfuromonas spp. (DSM)	**263 J**	**519**	**3,390**
Chloroform reductase (CFR)	<25	<0.1	<0.1
1,1 DCA Reductase (DCA)	<25	<0.1	<0.1
1,2 DCA Reductase (DCAR)	<25	<0.1	<0.1
Aerobic (Co)Metabolic			
Soluble Methane Monooxygenase (SMMO)	<25	**317**	**906**
Particulate Methane Monooxygenase (PMMO)	**470 J**	**632**	**3,090**
Toluene Dioxygenase (TOD)	**10,500**	**21.2**	**250**
Phenol Hydroxylase (PHE)	<25	<0.1	<0.1
Trichlorobenzene Dioxygenase (TCBO)	<25	<0.1	<0.1
Toluene Monooxygenase 2 (RDEG)	<25	**3.5 J**	<0.1
Toluene Monooxygenase (RMO)	<25	<0.1	<0.1
Ethene Monooxygenase (EtnC)	<25	<0.1	<0.1
Epoxyalkane transferase (EtnE)	<25	<0.1	<0.1
Dichloromethane dehalogenase (DCMA)	<25	<0.1	<0.1
Other			
Total Eubacteria (EBAC)	**534,000**	**48,800**	**226,000**
Sulfate Reducing Bacteria (APS)	**126,000**	**23,900**	**62,000**
Methanogens (MGN)	<25	**704**	**724**

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Detected concentrations shown in bold.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

GSI ENVIRONMENTAL

TABLE 16
ISOTOPE RESULTS IN GROUNDWATER
Orlando Naval Training Center, Orlando, Florida

Site ID	Matrix	Location ID	Site Area Sampled	Sample Date	δ13C (‰)		
					TCE	cis-1,2-DCE	Vinyl Chloride
Orlando NTC	Groundwater	OLD-17-10C	Upgradient	3/30/2016	ND	ND	ND
Orlando NTC	Groundwater	OLD-17-55C	Treatment Zone	3/29/2016	-12.12	-18.72	-19.6
Orlando NTC	Groundwater	OLD-17-53C2	Treatment Zone	3/30/2016	-8.13	-20.23	-22.59

Notes:
1. Samples analyzed by Pace Analytical CSIA Center, Pittsburg, PA.
2. ND = not detected

APPENDIX F   SAMPLING AND TESTING RESULTS FOR MNA SITES

England AFB Sampling and Testing Results

Hill AFB Sampling and Testing Results

Kelly AFB (Building 348) Sampling and Testing Results

TABLE 17
SOIL CONSTITUENTS
England Air Force Base, LA

SITE ID:	England AFB	England AFB	England AFB	England AFB	England AFB	England AFB	England AFB	England AFB	England AFB	England AFB
MATRIX:	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED:	Aquifer	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A
SAMPLE DEPTH (FT BGS):	79.2	79.6	80	80.4	80.8	81.2	81.6	82	82.4	82.8
SAMPLE DATE:	9/28/2016	9/28/2016	9/28/2016	9/28/2016	9/28/2016	9/28/2016	9/28/2016	9/28/2016	9/28/2016	9/28/2016
Analyte	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Volatile Organic Compounds										
Tetrachloroethene	<0.000341	<0.000333	<0.000375	<0.000351	<0.000346	<0.000343	<0.000349	<0.000336	<0.000343	<0.000341
Trichloroethene	<0.000345	<0.000337	<0.000379	<0.000355	<0.00035	<0.000347	<0.000353	<0.00034	<0.000347	<0.000345
cis-1,2-Dichloroethene	**0.00344**	**0.00356**	**0.00105 J**	**0.000744 J**	**0.00083 J**	**0.000687 J**	**0.000417 J**	<0.000286	<0.000292	<0.00029
Vinyl chloride	**0.000601 J**	**0.000498 J**	<0.000396	<0.00037	<0.000365	<0.000362	<0.000368	<0.000354	<0.000362	<0.00036
Magnetic Susceptibility										
Magnetic Susceptibility Average	6.35E-08	-	1.18E-07	-	1.19E-07	-	1.33E-07	-	1.47E-07	-
Magnetic Susceptibility StDev	4.74E-09	-	1.83E-08	-	2.66E-09	-	3.98E-09	-	4.88E-09	-
Organic Carbon										
Fractional Organic Carbon, g C/g soil	0.00593	0.00141	0.012	0.0177	0.0128	0.0133	0.0119	0.0163	0.0145	0.0126
Fractional Organic Carbon, mg/kg	5,930	1,410	12,000	17,700	12,800	13,300	11,900	16,300	14,500	12,600
Potentially-Bioavailable Organic Carbon, mg/kg	86.2	-	417.0	-	504.7	-	307.5	-	455.8	-
Fractional Organic Matter, %	1.02	0.243	2.07	3.05	2.21	2.3	2.05	2.82	2.5	2.17
Other										
Total Solids, %	80.8	82.8	73.6	78.6	79.8	80.5	79.1	82.2	80.5	80.9

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN and Microbial Insights, Knoxville, TN.
2. Detected VOC concentrations shown in bold.
3. J = estimated concentration between the method detection limit and the laboratory reporting limit.
4. < = concentration less than the specified method detection limit.
5. "-" = not analyzed.

TABLE 17
SOIL CONSTITUENTS
England Air Force Base, LA

SITE ID:	England AFB	England AFB	England AFB	England AFB	England AFB	England AFB	England AFB	England AFB	England AFB	England AFB
MATRIX:	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED:	Aquifer	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B
SAMPLE DEPTH (FT BGS):	76.7	77.1	77.5	77.9	78.3	78.7	79.1	79.5	79.9	80.3
SAMPLE DATE:	9/28/2016	9/28/2016	9/28/2016	9/28/2016	9/28-29/2016	9/28/2016	9/28/2016	9/28/2016	9/28/2016	9/28/2016
Analyte	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Volatile Organic Compounds										
Tetrachloroethene	<0.000335	<0.000299	<0.000357	<0.000346	<0.000344	<0.00035	<0.000352	<0.000343	<0.000354	<0.000351
Trichloroethene	<0.000339	<0.000302	<0.000361	<0.000349	<0.000347	<0.000353	<0.000356	<0.000347	<0.000358	<0.000354
cis-1,2-Dichloroethene	<0.000286	<0.000255	**0.000898 J**	**0.000939 J**	**0.000947 J**	**0.000776 J**	**0.000689 J**	**0.000523 J**	**0.000491 J**	**0.000427 J**
Vinyl chloride	<0.000354	<0.000315	<0.000376	<0.000364	<0.000362	<0.000369	<0.000372	<0.000362	<0.000373	<0.00037
Magnetic Susceptibility										
Magnetic Susceptibility Average	5.44E-08	-	1.06E-07	-	1.31E-07	-	1.14E-07	-	1.38E-07	-
Magnetic Susceptibility StDev	2.62E-09	-	2.8E-09	-	8.03E-09	-	1.99E-09	-	4.05E-09	-
Other										
Fractional Organic Carbon, g C/g soil	0.00642	0.00775	0.00967	0.0128	0.0113	0.0101	0.00926	0.0096	0.0104	0.0107
Fractional Organic Carbon, mg/kg	6,420	7,750	9,670	12,800	11,300	10,100	9,260	9,600	10,400	10,700
Potentially-Bioavailable Organic Carbon, mg/kg	80.4	-	322.7	-	496.6	-	459.0	-	457.8	-
Fractional Organic Matter, %	1.11	1.34	1.67	2.21	1.95	1.75	1.6	1.66	1.79	1.85
Other										
Total Solids, %	82.3	92.3	77.3	79.9	80.3	78.9	78.3	80.4	78	78.7

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN and Microbial Insights, Knoxville, TN.
2. Detected VOC concentrations shown in bold.
3. J = estimated concentration between the method detection limit and the laboratory reporting limit.
4. < = concentration less than the specified method detection limit.
5. "-" = not analyzed.

GSI ENVIRONMENTAL

TABLE 18
MICROBIOLOGICAL PARAMETERS IN SOIL
England Air Force Base, LA

SITE ID:	England AFB	England AFB	England AFB	England AFB	England AFB
MATRIX:	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED:	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A	A39L009PZ-SB-A
SAMPLE DEPTH (FT BGS):	79.2	80	80.8	81.6	82.4
SAMPLE DATE:	9/29/2016	9/29/2016	9/29/2016	9/29/2016	9/29/2016
Analyte	cells/g	cells/g	cells/g	cells/g	cells/g
Reductive Dechlorination					
Dehalococcoides spp. (DHC)	**8,680**	**6,300**	<500	**6,240**	**2,230 J**
tceA Reductase (TCE)	<500	<500	<500	<500	<500
BAV1 Vinyl Chloride Reductase (BVC)	<500	<500	<500	<500	<500
Vinyl Chloride Reductase (VCR)	<500	<500	<500	<500	<500
Dehalobacter spp. (DHBt)	<500	<500	<500	<500	<500
Dehalobacter DCM (DCM)	<500	<500	<500	<500	<500
Dehalogenimonas spp. (DHG)	<500	<500	<500	<500	<500
Desulfitobacterium spp. (DSB)	<500	<500	<500	<500	<500
Dehalobium chlorocoercia (DECO)	<500	<500	<500	<500	<500
Desulfuromonas spp. (DSM)	<500	<500	<500	<500	<500
Chloroform reductase (CFR)	<500	<500	<500	<500	<500
1,1 DCA Reductase (DCA)	<500	<500	<500	<500	<500
1,2 DCA Reductase (DCAR)	<500	<500	<500	<500	<500
Aerobic (Co)Metabolic					
Soluble Methane Monooxygenase (SMMO)	<500	<500	<500	**31,700**	<500
Particulate Methane Monooxygenase (PMMO)	<500	**5,400 J**	<500	<500	**266 J**
Toluene Dioxygenase (TOD)	**7,830 J**	<500	<500	<500	<500
Phenol Hydroxylase (PHE)	**47,700**	**53,800**	**1,270 J**	<500	**30200**
Trichlorobenzene Dioxygenase (TCBO)	<500	<500	<500	<500	<500
Toluene Monooxygenase 2 (RDEG)	<500	**9,330 J**	**19,300 J**	<500	<500
Toluene Monooxygenase (RMO)	<500	<500	<500	<500	<500
Ethene Monooxygenase (EtnC)	<500	<500	<500	<500	<500
Epoxyalkane transferase (EtnE)	<500	<500	<500	<500	<500
Dichloromethane dehalogenase (DCMA)	<500	<500	<500	<500	<500
Other					
Total Eubacteria (EBAC)	**5,320,000**	**3,900,000**	**1,580,000**	**1,430,000**	**1,580,000**
Sulfate Reducing Bacteria (APS)	<500	<500	<500	<500	**9,480 J**
Methanogens (MGN)	<500	<500	<500	<500	<500

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Bold cells are detected concentrations.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

GSI ENVIRONMENTAL

TABLE 18
MICROBIOLOGICAL PARAMETERS IN SOIL
England Air Force Base, LA

SITE ID:	England AFB	England AFB	England AFB	England AFB	England AFB
MATRIX:	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED:	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B	A39L009PZ-SB-B
SAMPLE DEPTH (FT BGS):	76.7	77.5	78.3	79.1	79.9
SAMPLE DATE:	9/29/2016	9/29/2016	9/29/2016	9/29/2016	9/29/2016
Analyte	cells/g	cells/g	cells/g	cells/g	cells/g
Reductive Dechlorination					
Dehalococcoides spp. (DHC)	**9,720**	**6,790**	**1,190 J**	**2,150 J**	<500
tceA Reductase (TCE)	<500	<500	<500	<500	<500
BAV1 Vinyl Chloride Reductase (BVC)	<500	<500	<500	<500	<500
Vinyl Chloride Reductase (VCR)	<500	<500	<500	<500	<500
Dehalobacter spp. (DHBt)	<500	<500	<500	<500	<500
Dehalobacter DCM (DCM)	<500	<500	<500	<500	<500
Dehalogenimonas spp. (DHG)	**24,600 J**	<500	<500	<500	<500
Desulfitobacterium spp. (DSB)	<500	<500	<500	<500	<500
Dehalobium chlorocoercia (DECO)	<500	<500	<500	<500	<500
Desulfuromonas spp. (DSM)	<500	<500	<500	<500	<500
Chloroform reductase (CFR)	<500	<500	<500	<500	<500
1,1 DCA Reductase (DCA)	<500	<500	<500	<500	<500
1,2 DCA Reductase (DCAR)	<500	<500	<500	<500	<500
Aerobic (Co)Metabolic					
Soluble Methane Monooxygenase (SMMO)	<500	<500	<500	<500	<500
Particulate Methane Monooxygenase (PMMO)	**790 J**	<500	<500	**3,150 J**	<500
Toluene Dioxygenase (TOD)	**709 J**	**1,380 J**	<500	**716 J**	<500
Phenol Hydroxylase (PHE)	**16,800 J**	<500	<500	<500	<500
Trichlorobenzene Dioxygenase (TCBO)	<500	<500	<500	<500	<500
Toluene Monooxygenase 2 (RDEG)	<500	<500	<500	<500	<500
Toluene Monooxygenase (RMO)	<500	<500	<500	<500	<500
Ethene Monooxygenase (EtnC)	<500	<500	<500	<500	<500
Epoxyalkane transferase (EtnE)	<500	<500	<500	<500	<500
Dichloromethane dehalogenase (DCMA)	<500	<500	<500	<500	<500
Other					
Total Eubacteria (EBAC)	**1,660,000**	**10,100,000**	**2,470,000**	**5,150,000**	**1,560,000**
Sulfate Reducing Bacteria (APS)	<500	<500	<500	<500	<500
Methanogens (MGN)	<500	**2,360 J**	<500	<500	**2,650 J**

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Bold cells are detected concentrations.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

TABLE 19
GROUNDWATER CONSTITUENTS
England Air Force Base, LA

SITE ID:	England AFB	England AFB
MATRIX:	Groundwater	Groundwater
STRATA SAMPLED:	Aquifer	Aquitard
LOCATION ID:	A39L009PZ	A39L009PZ-SB-A
SCREEN INTERVAL:		80-82 ft
SAMPLE DATE:	9/29/2016	9/28/2016
Analyte	**mg/L**	**mg/L**
Volatile Organic Compounds		
Tetrachloroethene	<0.000372	<0.000372
Trichloroethene	<0.000398	<0.000398
cis-1,2-Dichloroethene	**0.0318**	**0.0109**
Vinyl chloride	**0.0313**	**0.00534**
Dissolved Gasses		
Ethane	<0.00407	<0.00407
Ethene	**0.0125 J**	<0.00426
Methane	**2.29**	**3.16**
Volatile Fatty Acids		
Acetic Acid	<0.1	<0.1
Butyric Acid	<0.1	<0.1
Formic Acid	<0.1	<0.1
Hexanoic Acid	<0.2	<0.2
i-Hexanoic Acid	<0.2	<0.2
i-Pentanoic Acid	<0.1	<0.1
Lactic Acid	<0.2	<0.2
Pentanoic Acid	<0.1	<0.1
Propionic Acid	<0.1	<0.1
Pyruvic Acid	<0.1	<0.1
Oxygen Demand and Total Organic Carbon		
Biochemical Oxygen Demand (BOD)	<3.33	<3.33
Chemical Oxygen Demand (COD)	**7.44 J**	**32.9**
Dissolved Organic Carbon (DOC)	**1.96**	**2.79**
Total Organic Carbon (TOC)	**2.29**	**2.95**
Dissolved Ions		
Alkalinity	**459**	**467**
Calcium	**95.6**	**120**
Chloride	**12.7**	**16.9**
Iron	<0.0141	**0.0324 J**
Magnesium	**53.3**	**47**
Nitrate	<0.0227	<0.0227
Potassium	**1.18 B**	**1.7**
Sodium	**45.3**	**36.1**
Sulfate	**7.36**	**2.72 J**

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN. Volatile Fatty Acids analyzed by Microseeps/Pace Analytical Services LLC, Pittsburg, PA.
2. Bold cells are detected concentrations.
3. B = analyte detected in associated method blank as well as the laboratory sample.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.
6. "-" = not analyzed.

GSI ENVIRONMENTAL

TABLE 20
MICROBIOLOGICAL PARAMETERS IN GROUNDWATER
England Air Force Base, LA

SITE ID:	England AFB	England AFB
MATRIX:	Groundwater	Groundwater
STRATA SAMPLED:	Aquifer	Aquitard
LOCATION ID:	A39L009PZ	A39L009PZ-SB-A
SCREEN INTERVAL:		80-82 ft
SAMPLE DATE:	9/29/2016	9/28/2016
Parameter	cells/mL	cells/mL
Reductive Dechlorination		
Dehalococcoides spp. (DHC)	**224**	**34.9**
tceA Reductase (TCE)	<0.1	<0.1
BAV1 Vinyl Chloride Reductase (BVC)	**13.5**	**10.7**
Vinyl Chloride Reductase (VCR)	<0.1	<0.1
Dehalobacter spp. (DHBt)	**100**	<0.1
Dehalobacter DCM (DCM)	<0.1	<0.1
Dehalogenimonas spp. (DHG)	**7,510**	<0.1
Desulfitobacterium spp. (DSB)	**293**	<0.1
Dehalobium chlorocoercia (DECO)	**432**	<0.1
Desulfuromonas spp. (DSM)	**8.2**	<0.1
Chloroform reductase (CFR)	<0.1	<0.1
1,1 DCA Reductase (DCA)	<0.1	<0.1
1,2 DCA Reductase (DCAR)	<0.1	<0.1
Aerobic (Co)Metabolic		
Soluble Methane Monooxygenase (SMMO)	**520**	**3.9 J**
Particulate Methane Monooxygenase (PMMO)	**258**	**2.1 J**
Toluene Dioxygenase (TOD)	**46.6**	**0.6 J**
Phenol Hydroxylase (PHE)	**662**	**10.2**
Trichlorobenzene Dioxygenase (TCBO)	<0.1	<0.1
Toluene Monooxygenase 2 (RDEG)	**1,720**	<0.1
Toluene Monooxygenase (RMO)	<0.1	<0.1
Ethene Monooxygenase (EtnC)	<0.1	<0.1
Epoxyalkane transferase (EtnE)	<0.1	<0.1
Dichloromethane dehalogenase (DCMA)	<0.1	<0.1
Other		
Total Eubacteria (EBAC)	**662,000**	**4,510**
Sulfate Reducing Bacteria (APS)	**62,500**	<0.1
Methanogens (MGN)	**1,420**	**0.7 J**

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Bold cells are detected concentrations.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

TABLE 21
ISOTOPE RESULTS IN GROUNDWATER
England Air Force Base, LA

Site ID	Matrix	Location ID	Strata Sampled	Sample Date	δ13C (‰)		
					TCE	cis-1,2-DCE	Vinyl Chloride
England AFB	Groundwater	A39L009PZ	Aquifer	9/29/2016	ND	-15.9	-19.91
England AFB	Groundwater	A39L009PZ-SB-A	Aquitard	9/28/2016	ND	-15.14	-26.02

Notes:
1. Samples analyzed by Pace Analytical CSIA Center, Pittsburg, PA.
2. ND = not detected

GSI ENVIRONMENTAL

TABLE 22
SOIL CONSTITUENTS
Hill Air Force Base, UT

SITE ID:	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB
MATRIX:	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED:	Aquifer	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A
SAMPLE DEPTH (FT BGS):	72.7	73.1	73.5	73.9	74.3	74.7	75.1	75.5	75.9	76.3
SAMPLE DATE:	12/7/2015	12/7/2015	12/7/2015	12/7/2015	12/7/2015	12/7/2015	12/7/2015	12/7/2015	12/7/2015	12/7/2015
Analyte	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Volatile Organic Compounds										
Tetrachloroethene	**0.000552 J**	**0.000395 J**	**0.00146**	**0.0129 J**	**0.0255 J**	**0.0194 J**	<0.00524	<0.00614	<0.00518	<0.000326
Trichloroethene	**0.0311**	**0.0218**	**0.0847**	**0.616**	**2.07**	**2.96**	<0.0053	<0.00621	<0.00523	<0.000329
cis-1,2-Dichloroethene	**0.000539 J**	**0.000539 J**	**0.00147**	**0.00715 J**	**0.0152 J**	**0.0211 J**	<0.00446	<0.00523	<0.00441	<0.000277
Vinyl chloride	<0.000291	<0.000291	<0.000291	<0.00567	<0.00626	<0.0064	<0.00553	<0.00647	<0.00546	<0.000343
Magnetic Susceptibility										
Magnetic Susceptibility Average	2.03E-07	-	8.63E-08	-	8.3265E-08	-	1.79E-07	-	2.03E-07	-
Magnetic Susceptibility Standard Deviation	1.28E-08	-	4.72E-09	-	3.78E-09	-	2.49E-09	-	6.21E-09	-
Organic Carbon	-	-	-	-	-	-	-	-	-	-
Fractional Organic Carbon, g C/g soil	0.00135	0.00137	0.00734	0.00735	0.00787	0.00739	0.00927	0.0083	0.00849	0.0086
Fractional Organic Carbon, mg/kg	1,350	1,370	7,340	7,350	7,870	7,390	9,270	8,300	8,490	8,600
Potentially-Bioavailable Organic Carbon, mg/kg	55.3	-	160.3	-	290.9	-	446.6	-	378.75	-
Fractional Organic Matter, %	0.233	0.237	1.27	1.27	1.36	1.27	1.6	1.43	1.46	1.48
Other	-	-	-	-	-	-	-	-	-	-
Total Solids, %	89	89.7	76.7	81.7	81.9	76.5	77.3	81.6	82.1	80

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN and Microbial Insights, Knoxville, TN.
2. Detected VOC concentrations shown in bold.
3. J = estimated concentration between the method detection limit and the laboratory reporting limit.
4. < = concentration less than the specified method detection limit.
5. "-" = not analyzed.

TABLE 22
SOIL CONSTITUENTS
Hill Air Force Base, UT

SITE ID:	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB
MATRIX:	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED:	Aquifer	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B
SAMPLE DEPTH (FT BGS):	76.2	76.6	77	77.4	77.8	78.2	78.6	79	79.4	79.8
SAMPLE DATE:	12/8/2015	12/8/2015	12/8/2015	12/8/2015	12/8/2015	12/8/2015	12/8/2015	12/8/2015	12/8/2015	12/8/2015
Analyte	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Volatile Organic Compounds										
Tetrachloroethene	<0.00566	**0.000645 J**	**0.00871 J**	**0.0134 J**	**0.0142 J**	**0.0278**	**0.0364 J**	**0.0149 J**	<0.00545	<0.0069
Trichloroethene	**0.0808**	**0.0514**	**0.283**	**0.467**	**0.496**	**1.02**	**1.18**	**0.595**	**0.468**	**0.41**
cis-1,2-Dichloroethene	<0.00482	**0.00083 J**	<0.00435	<0.00464	<0.00964	**0.00724 J**	<0.00893	<0.00476	**0.0115 J**	<0.00588
Vinyl chloride	<0.00596	<0.000291	<0.00538	<0.00575	<0.0119	<0.00538	<0.011	<0.00589	<0.00575	<0.00728
Magnetic Susceptibility										
Magnetic Susceptibility Average	2.58E-07	-	9.9443E-08	-	9.90E-08	-	9.7699E-08	-	9.5811E-08	-
Magnetic Susceptibility Standard Deviation	1.47E-08	-	5.93E-09	-	6.38E-09	-	1.78E-09	-	2.79E-09	-
Other	-	-	-	-	-	-	-	-	-	-
Fractional Organic Carbon, g C/g soil	0.0359	0.00176	0.00672	0.0074	0.00714	0.00752	0.00629	0.00464	0.00235	0.00815
Fractional Organic Carbon, mg/kg	35,900	1,760	6,720	7,400	7,140	7,520	6,290	4,640	2,350	8,150
Potentially-Bioavailable Organic Carbon, mg/kg	64.1	-	224.4	-	270.15	-	210.7	-	127.2	-
Fractional Organic Matter, %	6.19	0.303	1.16	1.28	1.23	1.3	1.08	0.799	0.405	1.4
Other	-	-	-	-	-	-	-	-	-	-
Total Solids, %	94.6	90	74.4	74.9	79.8	78.4	82.7	84.2	83.2	80.4

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN and Microbial Insights, Knoxville, TN.
2. Detected VOC concentrations shown in bold.
3. J = estimated concentration between the method detection limit and the laboratory reporting limit.
4. < = concentration less than the specified method detection limit.
5. "-" = not analyzed.

GSI ENVIRONMENTAL

TABLE 23
MICROBIOLOGICAL PARAMETERS IN SOIL
Hill Air Force Base, UT

SITE ID:	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB
MATRIX:	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED:	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A	U2-043-SB-A
SAMPLE DEPTH (FT BGS):	72.7	73.5	74.3	75.1	75.9
SAMPLE DATE:	12/7/2015	12/7/2015	12/7/2015	12/7/2015	12/7/2015
SAMPLE TYPE:	N	N	N	N	N
Parameter	**cells/g**	**cells/g**	**cells/g**	**cells/g**	**cells/g**
Reductive Dechlorination					
Dehalococcoides spp. (DHC)	<200	<200	<200	**1,170**	<200
tceA Reductase (TCE)	<200	<200	<200	<200	<200
BAV1 Vinyl Chloride Reductase (BVC)	<200	<200	<200	<200	<200
Vinyl Chloride Reductase (VCR)	<200	<200	<200	<200	<200
Dehalobacter spp. (DHBt)	<200	<200	<200	<200	<200
Dehalobacter DCM (DCM)	<200	<200	<200	<200	<200
Dehalogenimonas spp. (DHG)	<200	<200	<200	**1,180 J**	<200
Desulfitobacterium spp. (DSB)	<200	<200	<200	<200	<200
Dehalobium chlorocoercia (DECO)	<200	<200	<200	<200	<200
Desulfuromonas spp. (DSM)	<200	<200	<200	<200	<200
Chloroform reductase (CFR)	<200	<200	<200	<200	<200
1,1 DCA Reductase (DCA)	<200	<200	<200	<200	<200
1,2 DCA Reductase (DCAR)	<200	<200	<200	<200	<200
Aerobic (Co)Metabolic					
Soluble Methane Monooxygenase (SMMO)	**29,000**	<200	<200	**43,800**	**8,990 J**
Particulate Methane Monooxygenase (PMMO)	**367 J**	**3,460 J**	<200	<200	**3,130 J**
Toluene Dioxygenase (TOD)	**250 J**	<200	<200	<200	<200
Phenol Hydroxylase (PHE)	<200	**4,060 J**	<200	<200	<200
Trichlorobenzene Dioxygenase (TCBO)	<200	<200	<200	<200	<200
Toluene Monooxygenase 2 (RDEG)	<200	<200	<200	<200	<200
Toluene Monooxygenase (RMO)	<200	<200	<200	<200	<200
Ethene Monooxygenase (EtnC)	<200	<200	<200	<200	<200
Epoxyalkane transferase (EtnE)	<200	<200	<200	<200	<200
Dichloromethane dehalogenase (DCMA)	<200	<200	<200	<200	<200
Other					
Total Eubacteria (EBAC)	**4,900,000**	**1,690,000**	**1,990,000**	**7,690,000**	**3,640,000**
Sulfate Reducing Bacteria (APS)	<200	<200	**6,490 J**	<200	<200
Methanogens (MGN)	**129 J**	<200	<200	<200	<200

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Detected concentrations shown in bold.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

GSI ENVIRONMENTAL

TABLE 23
MICROBIOLOGICAL PARAMETERS IN SOIL
Hill Air Force Base, UT

SITE ID:	Hill AFB	Hill AFB	Hill AFB	Hill AFB	Hill AFB
MATRIX:	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED:	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B	U2-043-SB-B
SAMPLE DEPTH (FT BGS):	76.2	77	77.8	78.6	79.4
SAMPLE DATE:	12/8/2015	12/8/2015	12/8/2015	12/8/2015	12/8/2015
SAMPLE TYPE:	N	N	N	N	N
Parameter	**cells/g**	**cells/g**	**cells/g**	**cells/g**	**cells/g**
Reductive Dechlorination					
Dehalococcoides spp. (DHC)	<200	<200	<200	<200	**35,200**
tceA Reductase (TCE)	<200	<200	<200	<200	<200
BAV1 Vinyl Chloride Reductase (BVC)	<200	<200	<200	<200	<200
Vinyl Chloride Reductase (VCR)	<200	<200	<200	<200	<200
Dehalobacter spp. (DHBt)	<200	<200	<200	<200	<200
Dehalobacter DCM (DCM)	<200	<200	<200	<200	<200
Dehalogenimonas spp. (DHG)	<200	<200	<200	<200	<200
Desulfitobacterium spp. (DSB)	<200	<200	<200	<200	**1,620 J**
Dehalobium chlorocoercia (DECO)	**2,230 J**	**3,760 J**	**5,870 J**	**2,860 J**	**2,110 J**
Desulfuromonas spp. (DSM)	<200	<200	<200	<200	<200
Chloroform reductase (CFR)	<200	<200	<200	<200	<200
1,1 DCA Reductase (DCA)	<200	<200	<200	<200	<200
1,2 DCA Reductase (DCAR)	<200	<200	<200	<200	<200
Aerobic (Co)Metabolic					
Soluble Methane Monooxygenase (SMMO)	**17,900**	**38,000**	**49,500**	<200	**16,700**
Particulate Methane Monooxygenase (PMMO)	<200	<200	<200	<200	**230 J**
Toluene Dioxygenase (TOD)	<200	**431 J**	<200	<200	<200
Phenol Hydroxylase (PHE)	**1,790 J**	<200	<200	**62,600**	**32,300**
Trichlorobenzene Dioxygenase (TCBO)	<200	<200	<200	<200	<200
Toluene Monooxygenase 2 (RDEG)	<200	<200	**33,100**	**2,910 J**	<200
Toluene Monooxygenase (RMO)	<200	<200	<200	<200	<200
Ethene Monooxygenase (EtnC)	<200	<200	<200	<200	<200
Epoxyalkane transferase (EtnE)	<200	<200	<200	<200	<200
Dichloromethane dehalogenase (DCMA)	<200	<200	<200	<200	<200
Other					
Total Eubacteria (EBAC)	**3,320,000**	**6,110,000**	**12,100,000**	**3,720,000**	**1,590,000**
Sulfate Reducing Bacteria (APS)	<200	<200	<200	<200	<200
Methanogens (MGN)	<200	<200	<200	<200	<200

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Detected concentrations shown in bold.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

TABLE 24
ISOTOPE RESULTS IN SOIL
Hill Air Force Base, UT

Site ID	Matrix	Lab ID	Location ID	Strata Sampled	Sample Date	δ13C (‰)		
						PCE	TCE	cis-1,2-DCE
Hill AFB	Soil	18003-1	U2-043-SB-A	Aquitard	12/7/2015	ND	ND	ND
Hill AFB	Soil	18003-2	U2-043-SB-A	Aquitard	12/7/2015	ND	-24.21	ND
Hill AFB	Soil	18003-3	U2-043-SB-B	Aquitard	12/8/2015	ND	ND	ND
Hill AFB	Soil	18003-4	U2-043-SB-B	Aquitard	12/8/2015	ND	ND	ND
Hill AFB	Soil	18003-5	U2-043-SB-B	Aquitard	12/8/2015	ND	-25.14	ND
Hill AFB	Soil	18003-6	U2-043-SB-B	Aquitard	12/8/2015	ND	ND	ND

Notes:
1. Samples analyzed by Pace Analytical CSIA Center, Pittsburg, PA.
2. ND = not detected

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TABLE 25
GROUNDWATER CONSTITUENTS
Hill Air Force Base, UT

SITE ID:	Hill AFB	Hill AFB
MATRIX:	Groundwater	Groundwater
STRATA SAMPLED:	Aquifer	Aquitard
LOCATION ID:	U2-043	U2-043-SB-A
SCREEN INTERVAL:		
SAMPLE DATE:	12/9/2015	12/7/2015
Analyte	**mg/L**	**mg/L**
Volatile Organic Compounds		
Tetrachloroethene	**0.0017**	**0.00164**
Trichloroethene	**0.332**	**0.281**
cis-1,2-Dichloroethene	**0.00817**	**0.00691**
Vinyl chloride	<0.000259	<0.000259
Dissolved Gasses		
Ethane	<0.00407	**0.00826 J**
Ethene	<0.00426	<0.00426
Methane	<0.00291	**0.0474**
Volatile Fatty Acids		
Acetic Acid	**0.031 J**	-
Butyric Acid	**0.011 J**	-
Formic Acid	**0.072 J**	-
Hexanoic Acid	<0.014	-
i-Hexanoic Acid	<0.014	-
i-Pentanoic Acid	<0.015	-
Lactic Acid	<0.014	-
Pentanoic Acid	<0.015	-
Propionic Acid	<0.015	-
Pyruvic Acid	<0.015	-
Oxygen Demand and Total Organic Carbon		
Biochemical Oxygen Demand (BOD)	<3.33	-
Chemical Oxygen Demand (COD)	<3	-
Dissolved Organic Carbon (DOC)	**1.71**	-
Total Organic Carbon (TOC)	**1.24**	**10.4**
Dissolved Ions		
Alkalinity	**197**	-
Calcium	**33.1**	-
Chloride	**66.2 B**	-
Iron	**0.0362 J**	-
Magnesium	**21**	-
Nitrate	**0.71**	-
Potassium	**8.5**	-
Sodium	**63.1**	-
Sulfate	**38.1**	-

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN. Volatile Fatty Acids analyzed by Microseeps/Pace Analytical Services LLC, Pittsburg, PA.
2. Detected concentrations shown in bold.
3. B = analyte detected in associated method blank as well as the laboratory sample.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.
6. "-" = insufficient water production volume for sample collection

GSI ENVIRONMENTAL

TABLE 26
MICROBIOLOGICAL PARAMETERS IN GROUNDWATER
Hill Air Force Base, UT

SITE ID:	Hill AFB	Hill AFB
MATRIX:	Groundwater	Groundwater
STRATA SAMPLED:	Aquifer	Aquitard
LOCATION ID:	U2-043	U2-043-SB-A
SCREEN INTERVAL:		
SAMPLE DATE:	12/9/2015	12/7/2015
Parameter	cells/mL	cells/mL
Reductive Dechlorination		
Dehalococcoides spp. (DHC)	<0.1	<4
tceA Reductase (TCE)	<0.1	<4
BAV1 Vinyl Chloride Reductase (BVC)	<0.1	<4
Vinyl Chloride Reductase (VCR)	<0.1	<4
Dehalobacter spp. (DHBt)	<0.1	<4
Dehalobacter DCM (DCM)	<0.1	<4
Dehalogenimonas spp. (DHG)	**7.7**	<4
Desulfitobacterium spp. (DSB)	<0.1	<4
Dehalobium chlorocoercia (DECO)	**2.7 J**	<4
Desulfuromonas spp. (DSM)	<0.1	<4
Chloroform reductase (CFR)	<0.1	<4
1,1 DCA Reductase (DCA)	<0.1	<4
1,2 DCA Reductase (DCAR)	<0.1	<4
Aerobic (Co)Metabolic		
Soluble Methane Monooxygenase (SMMO)	**41.6**	**46.8 J**
Particulate Methane Monooxygenase (PMMO)	**4.7**	**13.7 J**
Toluene Dioxygenase (TOD)	**1.5 J**	<4
Phenol Hydroxylase (PHE)	**42.7**	<4
Trichlorobenzene Dioxygenase (TCBO)	<0.1	<4
Toluene Monooxygenase 2 (RDEG)	**143**	**41.8 J**
Toluene Monooxygenase (RMO)	<0.1	<4
Ethene Monooxygenase (EtnC)	**2 J**	<4
Epoxyalkane transferase (EtnE)	<0.1	<4
Dichloromethane dehalogenase (DCMA)	<0.1	<4
Other		
Total Eubacteria (EBAC)	**16,700**	**61,700**
Sulfate Reducing Bacteria (APS)	<0.1	<4
Methanogens (MGN)	**0.9 J**	**3 J**

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Detected concentrations shown in bold.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

TABLE 27
ISOTOPE RESULTS IN GROUNDWATER
Hill Air Force Base, UT

Site ID	Matrix	Location ID	Strata Sampled	Sample Date	δ13C (‰)		
					TCE	cis-1,2-DCE	Vinyl Chloride
Hill AFB	Groundwater	U2-043	Aquifer	12/9/2015	-23.58	-28.02	ND
Hill AFB	Groundwater	U2-043-SB-A	Aquitard	12/7/2015	-22.58	-30.04	ND

Notes:
1. Samples analyzed by Pace Analytical CSIA Center, Pittsburg, PA.
2. ND = not detected

TABLE 28
SOIL CONSTITUENTS
Kelly Air Force Base, San Antonio, Texas

SITE ID:	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)
MATRIX:	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED	Aquifer	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A
SAMPLE DEPTH (FT BGS):	23.2	23.6	24.6	25	25.4	25.8	26.2	26.6	27	27.4
SAMPLE DATE:	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016
UNITS:	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg
Volatile Organic Compounds										
Tetrachloroethene	<0.000276	<0.000276	**0.000404 J**	**0.00045 J**	<0.000276	<0.000276	<0.000276	<0.000276	<0.000276	<0.000276
Trichloroethene	**0.00301**	**0.0109**	**0.016**	**0.0265**	**0.0313**	**0.0266**	**0.0234**	**0.00972**	**0.0219**	**0.0098**
cis-1,2-Dichloroethene	**0.00356**	**0.0116**	**0.00646**	**0.00534**	**0.00529**	**0.00506**	**0.00327**	**0.00122 J**	**0.00232**	**0.00107 J**
Vinyl chloride	<0.000291	<0.000291	<0.000308	**0.000391 J**	<0.000291	<0.000291	<0.000291	<0.000291	<0.000291	<0.000291
Magnetic Susceptibility										
Magnetic Susceptibility Average	-	1.24E-07	-	6.75E-08	-	7.62E-08	-	6.40E-08	-	7.77E-08
Organic Carbon										
Fractional Organic Carbon, g C/g soil	0.00466	0.00817	0.00991	0.011	0.0111	0.0125	0.0121	0.0106	0.0137	0.0133
Fractional Organic Carbon, mg/kg	4,660	8,170	9,910	11,000	11,100	12,500	12,100	10,600	13,700	13,300
Potentially-Bioavailable Organic Carbon, mg/kg	-	47.8	-	29.8	-	46.3	-	31.3	-	49.2
Fractional Organic Matter, %	0.804	1.41	1.71	1.9	1.91	2.15	2.08	1.83	2.36	2.29
Other										
Total Solids, %	86.2	84.8	81.3	79.4	80	80.8	80.9	81.1	80.8	81.3

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN and Microbial Insights, Knoxville, TN.
2. Detected VOC concentrations shown in bold.
3. J = estimated concentration between the method detection limit and the laboratory reporting limit.
4. < = concentration less than the specified method detection limit.
5. "-" = not analyzed.

TABLE 28
SOIL CONSTITUENTS
Kelly Air Force Base, San Antonio, Texas

SITE ID:	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)
MATRIX:	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
	Aquifer	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B
SAMPLE DEPTH (FT BGS):	22.8	23.2	23.6	24	24.4	24.8	25.2	25.6	26	26.4
SAMPLE DATE:	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016
UNITS:	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg
Volatile Organic Compounds										
Tetrachloroethene	<0.000276	<0.000276	**0.00267**	**0.00267**	**0.00166**	**0.00236**	**0.000537 J**	**0.000408 J**	**0.000561 J**	<0.000276
Trichloroethene	**0.00736**	**0.0216**	**0.0909**	**0.0852**	**0.0595**	**0.114**	**0.0625**	**0.081**	**0.111**	**0.0559**
cis-1,2-Dichloroethene	**0.000774 J**	**0.00251**	**0.00858**	**0.00674**	**0.00467**	**0.00791**	**0.00329**	**0.00472**	**0.00425**	**0.00254**
Vinyl chloride	<0.000291	<0.000291	**0.000378 J**	<0.000291	<0.000291	**0.000488 J**	<0.000291	<0.000291	**0.000507 J**	<0.000291
Magnetic Susceptibility										
Magnetic Susceptibility Average	1.12E-07	-	6.02E-08	-	7.55E-08	-	8.83E-08	-	7.29E-08	-
Other										
Fractional Organic Carbon, g C/g soil	0.00371	0.00437	0.0119	0.0115	0.0116	0.0113	0.0101	0.0113	0.0115	0.0118
Fractional Organic Carbon, mg/kg	3,710	4,370	11,900	11,500	11,600	11,300	10,100	11,300	11,500	11,800
Potentially-Bioavailable Organic Carbon, mg/kg	37.9	-	20.6	-	41.2	-	50.9	-	44.1	-
Fractional Organic Matter, %	0.64	0.754	2.05	1.99	1.99	1.95	1.75	1.94	1.99	2.04
Other										
Total Solids, %	92.8	90.7	79.3	72.2	81.6	80.8	78.2	80.3	73.2	76.4

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN and Microbial Insights, Knoxville, TN.
2. Detected VOC concentrations shown in bold.
3. J = estimated concentration between the method detection limit and the laboratory reporting limit.
4. < = concentration less than the specified method detection limit.
5. "-" = not analyzed.

GSI ENVIRONMENTAL

TABLE 29
MICROBIAL PARAMETERS IN SOIL
Kelly Air Force Base, San Antonio, Texas

SITE ID:	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)
MATRIX:	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED:	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A	KY036MW026-SB-A
SAMPLE DEPTH (FT BGS):	23.6	25	25.8	26.6	27.4
SAMPLE DATE:	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016
SAMPLE TYPE:	N	N	N	N	N
UNITS:	cells/g	cells/g	cells/g	cells/g	cells/g
Reductive Dechlorination					
Dehalococcoides spp. (DHC)	<200	<200	<200	<200	<200
tceA Reductase (TCE)	<200	<200	<200	<200	<200
BAV1 Vinyl Chloride Reductase (BVC)	<200	<200	<200	<200	<200
Vinyl Chloride Reductase (VCR)	<200	<200	<200	<200	<200
Dehalobacter spp. (DHBt)	<200	<200	<200	<200	<200
Dehalobacter DCM (DCM)	<200	<200	<200	<200	<200
Dehalogenimonas spp. (DHG)	<200	<200	<200	<200	<200
Desulfitobacterium spp. (DSB)	<200	<200	<200	<200	<200
Dehalobium chlorocoercia (DECO)	<200	<200	<200	<200	<200
Desulfuromonas spp. (DSM)	<200	<200	<200	<200	**3,610 J**
Chloroform reductase (CFR)	<200	<200	<200	<200	<200
1,1 DCA Reductase (DCA)	<200	<200	<200	<200	<200
1,2 DCA Reductase (DCAR)	<200	<200	<200	<200	<200
Aerobic (Co)Metabolic					
Soluble Methane Monooxygenase (SMMO)	<200	<200	<200	**1,870 J**	<200
Particulate Methane Monooxygenase (PMMO)	**49,000**	**441 J**	**1,670,000**	**876 J**	**2,200 J**
Toluene Dioxygenase (TOD)	<200	<200	**519 J**	<200	<200
Phenol Hydroxylase (PHE)	<200	<200	<200	<200	<200
Trichlorobenzene Dioxygenase (TCBO)	<200	<200	<200	<200	<200
Toluene Monooxygenase 2 (RDEG)	<200	<200	<200	<200	<200
Toluene Monooxygenase (RMO)	<200	<200	<200	<200	<200
Ethene Monooxygenase (EtnC)	<200	<200	<200	<200	<200
Epoxyalkane transferase (EtnE)	<200	<200	<200	<200	<200
Dichloromethane dehalogenase (DCMA)	<200	<200	<200	<200	<200
Other					
Total Eubacteria (EBAC)	**1,700,000**	**3,230,000**	**1,740,000**	**2,020,000**	**2,970,000**
Sulfate Reducing Bacteria (APS)	<200	<200	<200	<200	<200
Methanogens (MGN)	<200	<200	<200	**2,960 J**	**1,200 J**

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Detected concentrations shown in bold.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

TABLE 29
MICROBIAL PARAMETERS IN SOIL
Kelly Air Force Base, San Antonio, Texas

SITE ID:	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)	Kelly AFB (MNA)
MATRIX:	Soil	Soil	Soil	Soil	Soil
STRATA SAMPLED:	Aquifer	Aquitard	Aquitard	Aquitard	Aquitard
LOCATION ID:	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B	KY036MW026-SB-B
SAMPLE DEPTH (FT BGS):	22.8	23.6	24.4	25.2	26
SAMPLE DATE:	2/17/2016	2/17/2016	2/17/2016	2/17/2016	2/17/2016
SAMPLE TYPE:	N	N	N	N	N
UNITS:	cells/g	cells/g	cells/g	cells/g	cells/g
Reductive Dechlorination					
Dehalococcoides spp. (DHC)	<200	<200	<200	<200	<200
tceA Reductase (TCE)	<200	<200	<200	<200	<200
BAV1 Vinyl Chloride Reductase (BVC)	<200	<200	<200	<200	<200
Vinyl Chloride Reductase (VCR)	<200	<200	<200	<200	<200
Dehalobacter spp. (DHBt)	<200	<200	<200	<200	<200
Dehalobacter DCM (DCM)	<200	<200	<200	<200	<200
Dehalogenimonas spp. (DHG)	<200	<200	<200	<200	<200
Desulfitobacterium spp. (DSB)	<200	<200	<200	<200	<200
Dehalobium chlorocoercia (DECO)	<200	<200	<200	<200	<200
Desulfuromonas spp. (DSM)	<200	<200	<200	<200	<200
Chloroform reductase (CFR)	<200	<200	<200	<200	<200
1,1 DCA Reductase (DCA)	<200	<200	<200	<200	<200
1,2 DCA Reductase (DCAR)	<200	<200	<200	<200	<200
Aerobic (Co)Metabolic					
Soluble Methane Monooxygenase (SMMO)	**28,700**	**19,800**	**1,270 J**	<200	<200
Particulate Methane Monooxygenase (PMMO)	**2,890 J**	**134,000**	**980,000**	**29,100**	**579,000**
Toluene Dioxygenase (TOD)	<200	<200	<200	<200	**3,550 J**
Phenol Hydroxylase (PHE)	<200	<200	<200	<200	<200
Trichlorobenzene Dioxygenase (TCBO)	<200	<200	<200	<200	<200
Toluene Monooxygenase 2 (RDEG)	<200	**14,200**	<200	**2,090 J**	<200
Toluene Monooxygenase (RMO)	<200	<200	<200	<200	<200
Ethene Monooxygenase (EtnC)	<200	<200	<200	<200	<200
Epoxyalkane transferase (EtnE)	<200	<200	<200	<200	<200
Dichloromethane dehalogenase (DCMA)	<200	<200	<200	<200	<200
Other					
Total Eubacteria (EBAC)	**1,920,000**	**1,680,000**	**2,400,000**	**1,600,000**	**7,910,000**
Sulfate Reducing Bacteria (APS)	<200	<200	<200	<200	<200
Methanogens (MGN)	<200	<200	<200	<200	<200

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Detected concentrations shown in bold.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

GSI ENVIRONMENTAL

TABLE 30
GROUNDWATER CONSTITUENTS
Kelly Air Force Base, San Antonio, Texas

SITE ID:	Kelly AFB (MNA)	Kelly AFB (MNA)
MATRIX:	Groundwater	Groundwater
STRATA SAMPLED:	Aquifer	Aquitard
LOCATION ID:	KY036MW026	KY036MW026-SB-B
SCREEN INTERVAL:		25-26 ft
SAMPLE DATE:	2/16/2016	2/17/2016
UNITS:	mg/L	mg/L
Volatile Organic Compounds		
Tetrachloroethene	**0.00439**	<0.00186
Trichloroethene	**0.227**	**0.146**
cis-1,2-Dichloroethene	**0.113**	**0.0673**
Vinyl chloride	**0.00643**	**0.00392 J**
Dissolved Gasses		
Ethane	<0.00407	**0.00458 J**
Ethene	<0.00426	<0.00426
Methane	**0.294**	**0.154**
Volatile Fatty Acids		
Acetic Acid	<0.1 B	**0.11 B**
Butyric Acid	<0.1 B	<0.1 B
Formic Acid	<0.1 B	**0.18 B**
Hexanoic Acid	<0.2	<0.2
i-Hexanoic Acid	<0.2	<0.2
i-Pentanoic Acid	<0.1	<0.1
Lactic Acid	<0.2	<0.2
Pentanoic Acid	<0.1	<0.1
Propionic Acid	<0.1	<0.1
Pyruvic Acid	<0.1	<0.1
Oxygen Demand and Total Organic Carbon		
Biochemical Oxygen Demand (BOD)	<3.33	<3.33
Chemical Oxygen Demand (COD)	**3.15 J**	**16.3**
Dissolved Organic Carbon (DOC)	**0.91 J**	**1.04**
Total Organic Carbon (TOC)	**0.61 J**	**1.27**
Dissolved Ions		
Alkalinity	**270**	**279**
Calcium	**92.3**	**86.2**
Chloride	**23.5**	**25.1**
Iron	<0.0141	<0.0141
Magnesium	**9.73**	**9.33**
Nitrate	**0.179**	**0.478**
Potassium	**2.18**	**2.92**
Sodium	**51.1**	**47.9**
Sulfate	**18.6**	**17.1**

Notes:
1. Samples analyzed by ESC Lab Sciences, Mount Joliet, TN. Volatile Fatty Acids analyzed by Microseeps/Pace Analytical Services LLC, Pittsburg, PA.
2. Detected concentrations shown in bold.
3. B = analyte detected in associated method blank.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

GSI ENVIRONMENTAL

TABLE 31
MICROBIOLOGICAL PARAMETERS IN GROUNDWATER
Kelly Air Force Base, San Antonio, Texas

SITE ID:	Kelly AFB (MNA)	Kelly AFB (MNA)
MATRIX:	Groundwater	Groundwater
STRATA SAMPLED:	Aquifer	Aquitard
LOCATION ID:	KY036MW026	KY036MW026-SB-B
SCREEN INTERVAL:		25-26 ft
SAMPLE DATE:	2/16/2016	2/17/2016
UNITS:	cells/mL	cells/mL
Reductive Dechlorination		
Dehalococcoides spp. (DHC)	**3,500**	**2.4**
tceA Reductase (TCE)	**78**	<0.2
BAV1 Vinyl Chloride Reductase (BVC)	**392**	<0.2
Vinyl Chloride Reductase (VCR)	**126**	<0.2
Dehalobacter spp. (DHBt)	**370**	**56.9**
Dehalobacter DCM (DCM)	<0.1	<0.2
Dehalogenimonas spp. (DHG)	**2670**	**0.3 J**
Desulfitobacterium spp. (DSB)	<0.1	<0.2
Dehalobium chlorocoercia (DECO)	**1,070**	<0.2
Desulfuromonas spp. (DSM)	**24,100**	**34.2**
Chloroform reductase (CFR)	<0.1	<0.2
1,1 DCA Reductase (DCA)	<0.1	<0.2
1,2 DCA Reductase (DCAR)	<0.1	<0.2
Aerobic (Co)Metabolic		
Soluble Methane Monooxygenase (SMMO)	**1,920**	**363**
Particulate Methane Monooxygenase (PMMO)	**2,500**	**105**
Toluene Dioxygenase (TOD)	**10.3**	**1.2 J**
Phenol Hydroxylase (PHE)	**575**	<0.2
Trichlorobenzene Dioxygenase (TCBO)	<0.1	<0.2
Toluene Monooxygenase 2 (RDEG)	**875**	**10.1 J**
Toluene Monooxygenase (RMO)	**0.1 J**	<0.2
Ethene Monooxygenase (EtnC)	**1.6 J**	<0.2
Epoxyalkane transferase (EtnE)	**23.7**	<0.2
Dichloromethane dehalogenase (DCMA)	<0.1	<0.2
Other		
Total Eubacteria (EBAC)	**1,120,000**	**10,100**
Sulfate Reducing Bacteria (APS)	**385,000**	**46.1**
Methanogens (MGN)	**785**	**37.2**

Notes:
1. Samples analyzed by Microbial Insights, Knoxville, TN.
2. cells/mL = cells per milliliter
3. Detected concentrations shown in bold.
4. J = estimated concentration between the method detection limit and the laboratory reporting limit.
5. < = concentration less than the specified method detection limit.

TABLE 32
ISOTOPE RESULTS IN GROUNDWATER
Kelly Air Force Base, San Antonio, Texas

Site ID	Matrix	Location ID	Strata Sampled	Sample Date	δ13C (‰)		
					PCE	TCE	cis-1,2-DCE
Kelly AFB (MNA)	Groundwater	KY036MW026	Aquifer	2/16/2016	-24.82	-25.79	-24.51
Kelly AFB (MNA)	Groundwater	KY036MW026-SB-B	Aquitard	2/17/2016	ND	-25.94	-24.46

Notes:
1. Samples analyzed by Pace Analytical CSIA Center, Pittsburg, PA.
2. ND = not detected

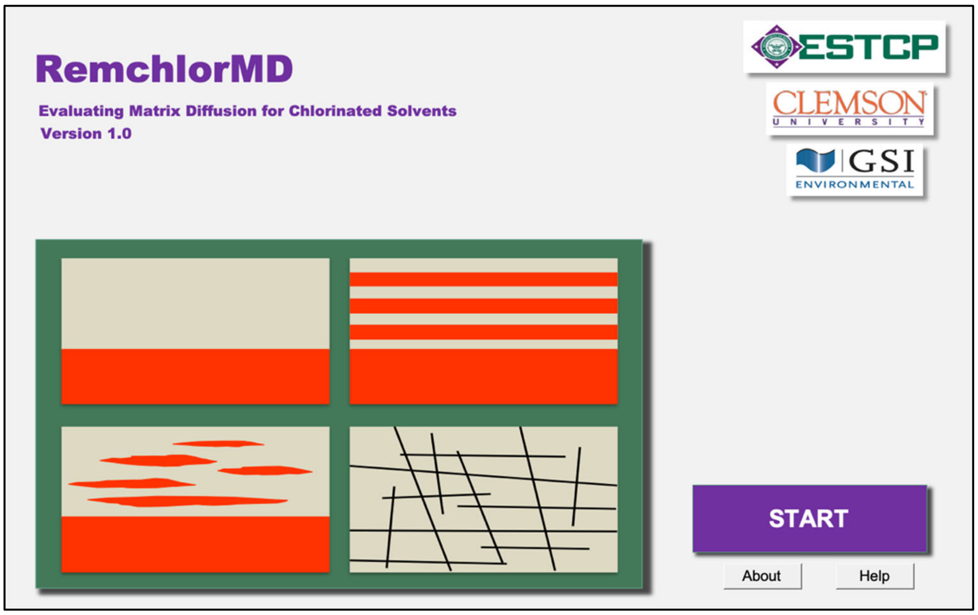
APPENDIX G FACT SHEET ON USE OF LOW-K MNA DATA IN MATRIX DIFFUSION MODELING

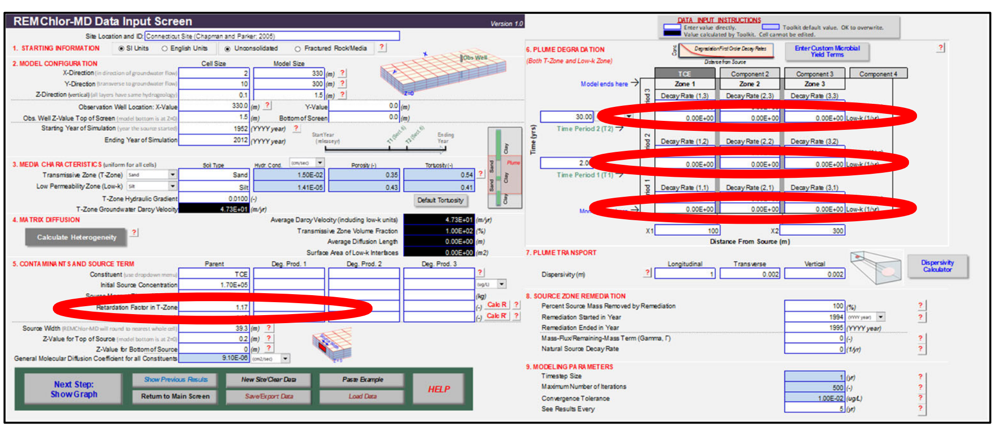
FACT SHEET ON USE OF LOW-K MNA DATA IN MATRIX DIFFUSION MODELING

The REMChlor-MD computer model (ESTCP Project ER-201426) provides a practical and efficient mathematical method to account for the effects of matrix diffusion in groundwater transport and remediation. By accounting for contaminant diffusion in and out of heterogeneous settings, including fractured porous media and sites with extensive low permeability layers and lenses, site decisions regarding plume migration and the effectiveness of in-situ remediation can now be evaluated. However, some of the input data required to model matrix diffusion is relatively unusual. The data generated as part of the ER-201420 ESTCP Project described in this report do provide insights on how to build and simulate matrix diffusion at your site.

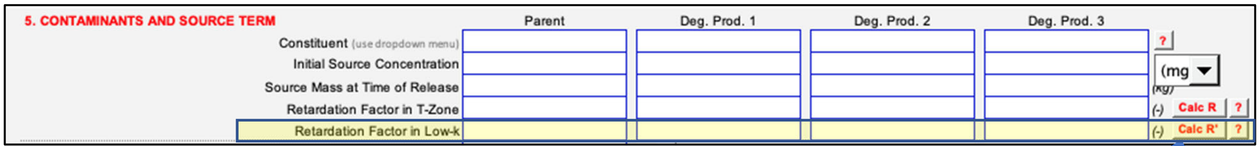
REMChlor-MD Model

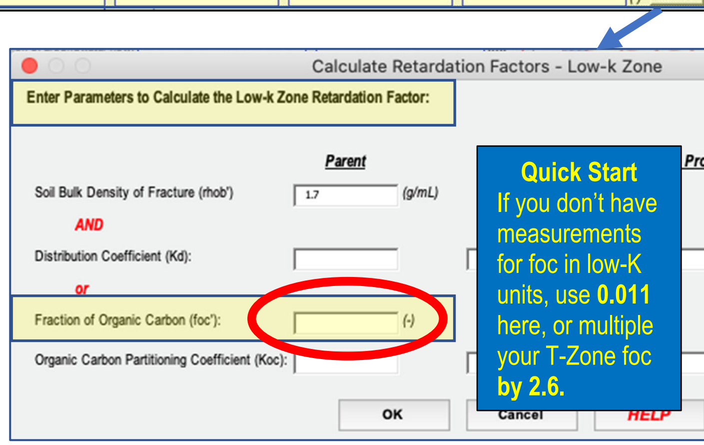
The REMChlor-MD (Falta et al., 2013; Farhat et al., 2018) model introduction screen is shown below (search “ESTCP Project ER-201426” to download model and the User’s Manual). The input screen is also shown below, with red circles showing matrix diffusion input data that are required, but generally new to many groundwater modelers. These key data are presented in more detail on the following pages.





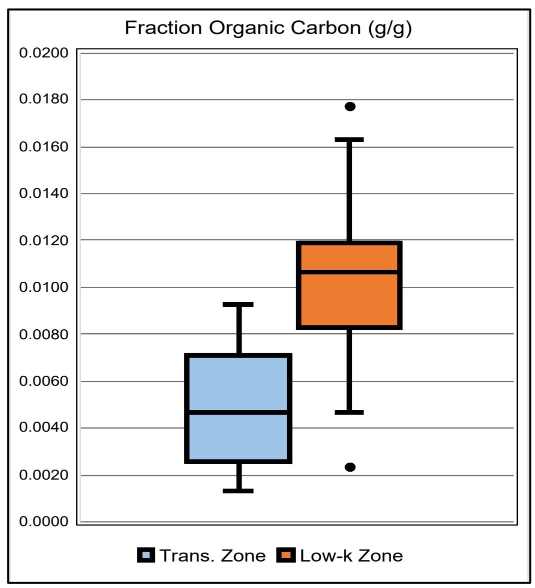
Key Input #1: What is the Retardation Factor of the Low Permeability ("Low-K") Zone?





We often measure the transmissive zone ("T-Zone") geologic media (e.g., sands/gravels) to determine the fraction organic carbon (foc) to get the retardation factor for a groundwater transport model. In situations where foc data are not available for the transmissive zone, often a value of 0.001 is used as a conservative rule of thumb to run the model (see REMChlor-MD manual). The typical range is reported as 0.0002 - 0.02 for transmissive zones. But measurement of foc in the low-K geologic media (such as silty or clayey media) is not a typical practice. **If these data are not available, what values for foc are appropriate for the low-K units?**

This project collected a total of 18 and 48 samples from transmissive zone and low-K units, respectively (typically 4 transmissive and 16 low-K samples each from England AFB, Hill AFB, and Kelly AFB. As shown in the box plots to the right, the median foc for the aquifer transmissive zone (blue box, right) is 0.0047 grams foc per gram of soil. (The box defines the 75th and 25th percentiles of the samples, the whiskers are the extremes, the median is the horizontal line, and the dots are statistical outliers). The median foc for the 48 low-K samples was **0.011 g/g** (1.1%). The low-K unit foc was about 2.6 times higher than the transmissive zone foc, so if only transmissive zone foc data are available one could **multiply those values by 2.6** to get an estimate for the foc in the low-K zone.



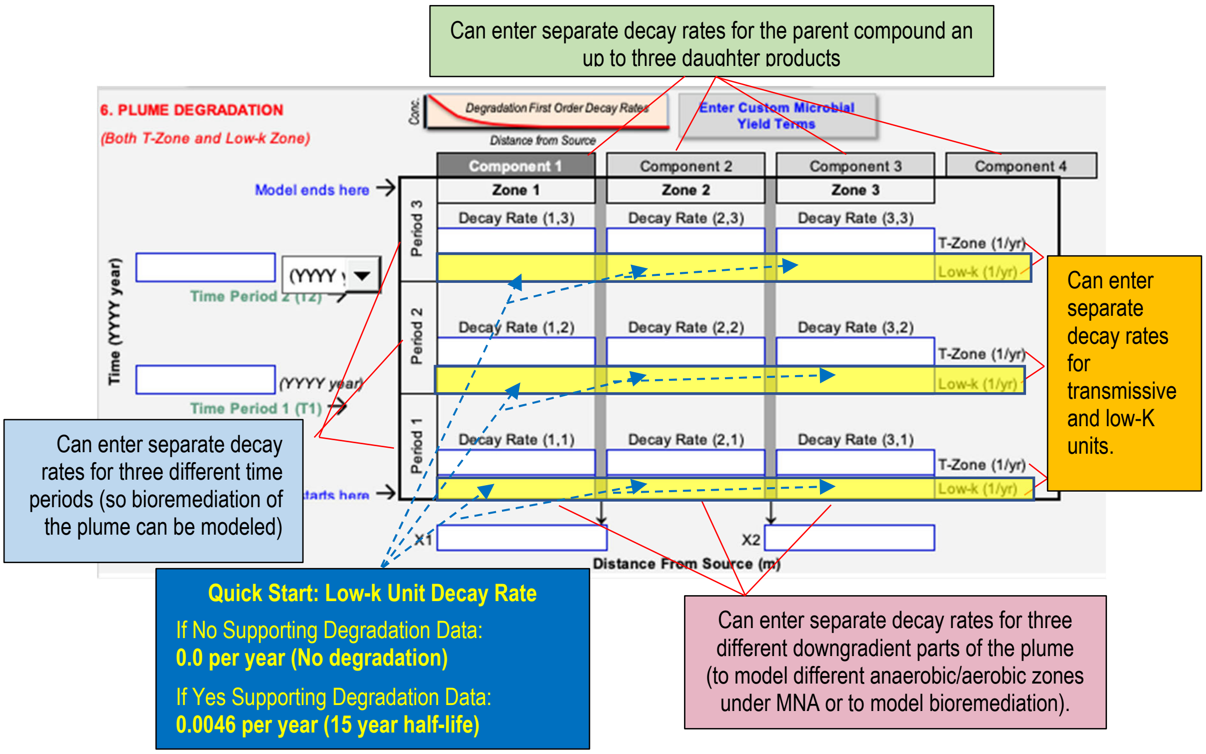
KEY POINT: REMChlor-MD Fraction Organic Carbon (foc) in Low-k Zones

If you don't know foc values to enter in REMChlor-MD, consider using:

- A value of **0.011** grams foc per gram soil (-) for the low-K zones in the model, **or**
- Multiply your transmissive zone foc **by 2.6** to get a low-K zone foc value.

Key Input #2: What Decay Rates for the Low-K Unit to use in REMCHLOR-MD?

The ability to put in different decay rates for chlorinated solvents is one of the most powerful but one of the most challenging parts of using REMChlor-MD. One can put in a decay rate (in units of per year) for:



At this stage of the matrix diffusion/chlorinated solvent conceptual model, the decay rate over time is assumed to stay relatively constant so the same values will be used for Period 1, 2, and 3. Similarly, any type of remediation will have relatively little effect on the low-K zones, so the same values will be used for Zones 1, 2, and 3. But what values should be entered into the model? Due to the nascent nature of this topic, the REMChlor-MD manual does not discuss low-K decay rates in any detail, but three case studies assumed no degradation in low-K zones.

SERDP Project ER-1740 (Sale et al., 2013) provides the state of knowledge about biodegradation of chlorinated solvents in low-K units as of the year 2014. They reported:

> *In all of the above studies, microorganisms, such as Dehalococcoides, were observed not only within the most porous sections of the subsurface, but well inside geological materials with low permeabilities – i.e., 10's of centimeters or more from an interface with a high permeability zone (Lima et al. 2012a; Lima et al. 2012b; Scheutz et al. 2010; Takeuchi et al. 2011). Microbial numbers were admittedly relatively low, as were the growth rates. Nevertheless, the impact these microbial communities exerted on the distribution of contaminants may have been considerable. Therefore, these populations are likely to play an important role in contaminant natural attenuation, to control rates of back diffusion, and to influence the longevity of plumes sustained by back-diffusion.*

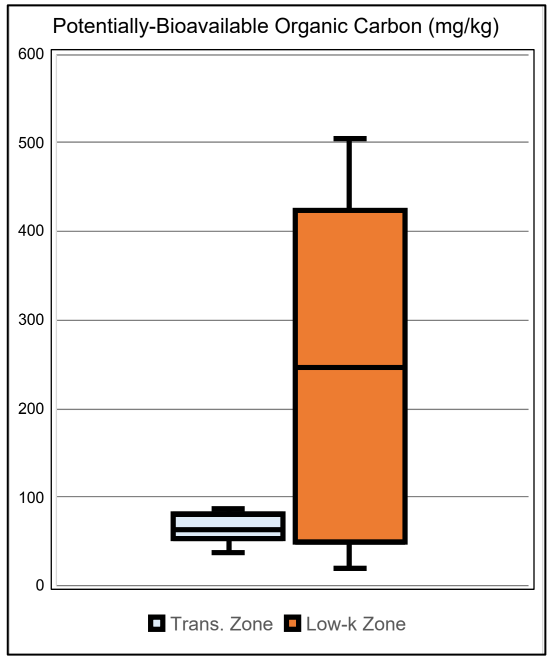
Three detailed field studies where low-K zones were evaluated for degradation were discussed:

- Florence, South Carolina: .... **Strong** Evidence of degradation in low-K zones
- Jacksonville, Florida:.................. **Limited** Evidence of degradation in low-K zones
- CS-10 Plume, Massachusetts:... **No** Evidence of degradation in low-K zones

Key Input #2: What Decay Rates for the Low-K Unit to use in REMCHLOR-MD? (cont'd)

The data generated as part of the ER-201420 ESTCP Project described in this report do provide additional data and interpretations about if and how to model degradation in low-K units via these lines of evidence.

Qualitative Information PBOC: The low-K sample analysis showed that low-K units did have a substantial amount of potentially-available bioavailable organic carbon (PBOC) that could sustain reductive dichlorination reactions in low permeability media such as silts and clays. The median PBOC concentration was **247 mg/kg**, about four times higher than the median value of 64 mg/kg in the transmissive zone geologic media.



Semi-Quantitative Information Source History Modeling: High-resolution low-K zone soil data comprised of closely spaced samples collected vertically within the low-K units were used to compile TCE *soil concentration* vs *penetration depth* data in low-K units collected at four different sites to determine if using biodegradation rates within these low-K zones, in the form of first order decay coefficients, made a 1-D diffusion model more accurate. The Source History Tool (Farhat et al., 2013) was used to compare the actual data vs. diffusion model output for low-K clay stratum at two sites at Hill Air Force Base (AFB) and two sites at Kelly AFB (Appendix D).

A reconstruction of the source history based on trichloroethene (TCE) soil concentrations in the low-K zone, indicated:

- Unclear if degradation was occurring at Location A of Hill AFB.
- Potentially slow degradation **with a half-life of >10 years** was occurring within the low-K unit at Location B of Hill AFB.
- Unclear if degradation was occurring at Location A of Kelly AFB.
- Unclear if degradation was occurring at Location B of Kelly AFB.

Semi-Quantitative Information Data Mining: Multi-year chlorinated ethene concentration vs. time data were compiled from over 500 sites and a total of over 1,500 monitoring wells in the California Geotracker database. Key criteria for inclusion were minimum concentrations of any chlorinated ethene greater than 50 ug/L, at least five years of monitoring data, and at least four monitoring points. Sites were divided into two categories, likely dry cleaner sites and Department of Defense sites (see ER-201429 Final Report, Appendix C).

One relevant analysis was to evaluate the k_{point} (first-order decay rate for concentration vs. time rates at any well; Newell et al., 2002) for low concentration wells that were likely dominated by matrix diffusion processes and not high strength source zones. These data show how quickly these likely matrix diffusion sources are decaying when a first-order decay model is applied. The resulting half-lives (and their corresponding first order decay rates) are presented below.

Dataset	PCE	TCE	cis-1,2-DCE
	First order degradation rate, per year *(First order degradation half-life, years)*		
Presumed Mostly PCE Sites (Dry Cleaners) Site Maximum Concentration < 50 μg/L	**0.096** *(7.2)*	**0.052** *(13)*	**0.034** *(21)*
Presumed Mostly TCE Sites (DOD Facilities) Site Maximum Concentration < 50 μg/L	**0.054** *(13)*	**0.046** *(15)*	**0.050** *(14)*

This analysis shows that these sources decay very slowly, with concentrations falling by 50% every 7 to 20 years. If one assumes that these concentrations are primarily sustained by matrix diffusion sources and no DNAPL sources, then the decay within these units is unlikely to be faster than the rates presented in the table above. Therefore, if no site-specific data are available, one could assume that an upper bound degradation half-life is about 15 years (first order decay rate of **0.046 per year**). If there is qualitative evidence that some type of decaying is occurring in the low-K zones (via molecular biological tools, isotope analysis, detailed analysis of daughter product generation, abiotic degradation indicators, etc.) then this type of rate could be used in REMChlor-MD.

KEY POINT: REMChlor-MD First Order Decay Rates in Low-K Zones

Absent site-specific first order decay rates to enter into REMChlor-MD, weigh these lines of evidence to come up with values to use in your model:

- Of three sites evaluated as part of SERDP Project ER-1740, one site had **Strong Evidence** of degradation in low-K units; one **Limited Evidence**, and one **No Evidence**.
- All three sites analyzed by this project had Potentially Bioavailable Organic Carbon (PBOC), indicating that many sites may have some type of naturally occurring electron donor that could sustain biodegradation. The presence of PBOC **is not confirmatory** but is just a “potential” driver of biodegradation in low-K zones.
- When the high resolution concentration vs. vertical penetration depth from four locations at two sites was analyzed with the ESTCP Source History Tool (Farhat et al., 2013), only one site had a strong enough signal to discern a first order decay half-life in the low-K unit. **This half-life was greater than 10 years (> 0.0693 per year decay rate).**
- When over 1500 monitoring wells with low concentration chlorinated ethene concentration vs. time data were evaluated, it suggested that an appropriate general decay rate to use is about 15 years **(0.046 per year decay rate).**
- Overall, if you do not have any supporting information that degradation is occurring in low-K zones, assume the degradation rate is zero **(enter 0.0 per year in decay rates for low-K media in REMChlor-MD).**
- If you have some qualitative evidence that degradation is occurring in low-K zones (molecular biological tools, isotope analysis, detailed analysis of daughter product generation, abiotic degradation indicator) then use a **30 year half-life (enter 0.023 per year in decay rates for low-K media in REMChlor-MD).**
- If you have some **quantitative rate data** on what low-K degradation rates are, use those values directly in REMChlor-MD in units of per year.

REFERENCES

Falta, R. W., Farhat, S. K., Newell, C. J., & Lynch, K. (2018). REMChlor-MD Software Tool. In. Environmental Security Technology Certification Program (ESTCP).

Farhat, S. K., Newell, C. J., Falta, R., & Lynch, K. (2018). REMChlor-MD User's Manual In. Environmental Security Technology Certification Program (ESTCP).

Farhat, S., de Blanc, P., Newell, C., & Adamson, D. (2013). Source History Tool. In (Vol. ER-201032): Environmental Security Technology Certification Program.

Newell, C. J., H.S. Rifai, J.T. Wilson, J.A. Connor, J.J. Aziz, and M.P. Suarez. (2002). Calculation and Use of First-Order Rate Constants For Monitored Natural Attenuation Studies. In *U.S. Environmental Protection Agency. EPA/540/S-02/500. November 2002*.

Sale, T., Parker, B., Newell, C. J., Devlin, J. F., Adamson, D. T., Chapman, S., & Saller, K. (2013). Management of Contaminants Stored in Low Permeability Zones, A State-of-the-Science Review. . In (Vol. ER-1740). https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-1740: Strategic Environmental Research and Development Program (SERDP).

APPENDIX H FACT SHEET ON ASSESSING POST-BIOREMEDIATION SUSTAINED TREATMENT

FACT SHEET ON ASSESSING POST-BIOREMEDIATION SUSTAINED TREATMENT

Sustained treatment is a term used to describe the enhanced attenuation capacity within an in-situ bioremediation (ISB) treatment zone that can prolong the benefits of ISB treatment after the depletion of the primary organic substrate. Results of the field demonstrations conducted for ESTCP Project ER-201429, along with the accompanying data mining study of 34 projects with long-term monitoring data, indicate that sustained treatment of chlorinated volatile organic compound (CVOC) concentrations is observed at approximately three-quarters of sites where ISB was used to treat chlorinated solvents in groundwater. While site-specific hydrogeologic conditions, design considerations, and implementation effectiveness undoubtedly factor into the remedial outcome for any ISB application, these results suggest that a generally well designed and implemented ISB project more often than not will benefit from sustained treatment, at a minimum in terms of rebound suppression for the parent CVOC, for a period of at least 3 to more than 15 years after the end of treatment.

This fact sheet summarizes findings and methodologies developed under ESTCP Project ER-201429 into simple worksheets that can be used to evaluate sustained treatment at other ISB sites using a lines-of-evidence approach. Worksheets are provided for sites where ISB was applied via an injected organic substrate (e.g., emulsified vegetable oil, molasses, etc.) and via a mulch permeable reactive barrier (i.e., a "Biowall"). It is intended that use of these worksheets will target sites where at least two years of monitoring data are available following the last injection event or following installation of the Biowall.

The box below summarizes the key parameters and lines of evidence used in the assessment, an explanation of how these parameters are assessed along with any associated critical values for assessment, and how to determine whether your site-specific data reflects sustained treatment occurrence. Professional judgement and consideration of the overall site conceptual model should be applied to make an overall determination of the impact of sustained treatment on the efficacy of the technology to meet remedial objectives of the project.

KEY PARAMETERS / LINES OF EVIDENCE FOR ASSESSING SUSTAINED TREATMENT

The following CVOC concentration metrics should be considered as primary lines of evidence in the sustained treatment assessment:

- **Parent CVOC Concentration Change over Post-Treatment Monitoring Period:** Calculate the concentration reduction for the parent CVOC (typically PCE or TCE) over the post-treatment monitoring period to evaluate the occurrence of sustained treatment vs. rebound. If two or more years of post-treatment data are available, use the average concentration from the first year of the post-treatment monitoring record and the average concentration from the most recent year. Use only monitoring wells within the ISB treatment footprint. A decrease in parent CVOC concentrations over the post-treatment monitoring period is a strong indicator of sustained treatment, as is maintenance of non-detect concentrations. Relatively small concentration increases that still result in overall "stable" concentrations also suggests sustained treatment, but additional monitoring may be necessary to confirm lack of rebound. McGuire et al. (2006) defined rebound as a 25% increase in parent CVOC concentrations over the post-treatment monitoring period.
- **CVOC Concentration Trend of Parent and Daughter Products:** Calculate the Mann-Kendall statistical trend for the first 4 to 8 monitoring events immediately following the end of ISB treatment (i.e., the last injection) and the most recent 4 to 8 monitoring events. Note that a minimum of 4 sampling events are required for trend calculation; however, up to an additional 4 events may be needed to establish a trend due to natural variability of groundwater monitoring data. Calculate the trend for parent and daughter products. If insufficient data are available for daughter products, consider using the molar concentration of the sum of the parent and daughter products (i.e., Total CVOCs). An improved trend result (e.g., increasing to stable, stable to decreasing, etc.) is a strong indicator of sustained treatment, as is maintaining a decreasing trend. A degradation in the trend from decreasing to stable, or maintaining a stable trend, also indicates sustained treatment occurrence, but additional monitoring or stronger consideration of the other lines of evidence may be needed to support the findings.

Continued on next page…

KEY PARAMETERS / LINES OF EVIDENCE FOR ASSESSING SUSTAINED TREATMENT

The following parameters should be considered as supporting lines of evidence in the sustained treatment assessment:

- **Total Organic Carbon (TOC) in Groundwater:** TOC in groundwater is greatly increased as a result of ISB and is evaluated two ways in the sustained treatment assessment. First, the site-specific concentration is compared to a critical value of 20 mg/L, which is the value established by US EPA (1998) as necessary to support natural attenuation of chlorinated solvents in groundwater. Values exceeding 20 mg/L are indicative of conditions amenable to sustained treatment. Second, TOC is evaluated within the ISB treatment footprint relative to upgradient (naturally-occurring or “background”) concentrations. Increased TOC within the treatment zone indicates that geochemistry within the ISB treatment zones continues to be influenced by ISB and may continue to support sustained treatment.
- **Ethene and Methane in Groundwater:** Ethene and methane are dissolved gasses that are generally elevated in groundwater as a result of ISB. For the sustained treatment assessment, these gasses are evaluated within the ISB treatment footprint relative to upgradient (naturally-occurring or “background”) concentrations. Increased ethene and methane within the treatment zone indicates that geochemistry within the ISB treatment zone continues to be influenced by ISB and may continue to support sustained treatment. Similar to TOC, concentration magnitudes of ethene and methane can also be compared to values from US EPA (1998), which are 0.1 mg/L ethene and 0.5 mg/L methane, for supporting evidence.
- ***Dehalococcoides sp.* (Dhc) in Groundwater:** Concentrations of Dhc, the microorganisms most commonly associated with complete reductive dechlorination of chlorinated ethenes in groundwater, are generally stimulated as a result of ISB, particularly at sites where bioaugmentation is part of the remedial strategy. Dhc concentrations are evaluated two ways in the sustained treatment assessment. First, the site-specific concentration is compared to 10,000 cells/mL, which is the screening criterion proposed by Lu et al. (2006) to identify sites where biological reductive dechlorination is predicted to proceed at “generally useful” rates. A concentration exceeding 10,000 cells/mL is a strong indicator of sustained treatment potential. Second, Dhc concentrations are evaluated within the ISB treatment footprint relative to upgradient (naturally-occurring or “background”) concentrations. Increased Dhc levels within the treatment zone indicates that the treatment zone continues to be influenced by ISB and may continue to support sustained treatment.
- **Sum of Reductive Dechlorinators in Groundwater:** Several microbial species are capable of reductive dechlorination and may be stimulated by ISB, including *Dehalococcoides*, *Dehalobacter*, *Desulfitobacterium*, and *Desulfuromonas* spp. The sum concentration of these species, as measured by the QuantArray-Chlor lab method, can be used as an additional line of evidence for sustained treatment by comparison to the screening criterion discussed above (i.e., 10,000 cells/mL), as well as comparison of concentrations within the treatment zone vs. upgradient. Increased concentrations within the treatment zone indicates that the treatment zone continues to be influenced by ISB and may continue to support sustained treatment.
- **Compound Specific Isotopes (^{13}C) in Groundwater:** Carbon isotope enrichment of the individual CVOCs can be measured and evaluated as part of a sustained treatment assessment. Enrichment of compound-specific isotopes within the treatment zone compared to upgradient concentrations indicate the occurrence of sustained treatment; however, concentrations in upgradient may often be below detection limits limiting the effectiveness of this parameter. When considered with the higher cost of isotope sampling, this parameter is not expected to be used at most sites for sustained treatment assessment.
- **Potentially-Bioavailable Organic Carbon (PBOC) in Aquifer Sediments:** PBOC represents the fraction of organic carbon associated with aquifer sediments that may be available to support ongoing biodegradation of contaminants and may be enhanced following an ISB remedy through application of the organic substrate, as well as through microbial carbon cycling. Chapelle et al. (2012) proposed a threshold screening criterion of 200 mg/kg needed to support reductive dechlorination in aquifers. PBOC levels exceeding this threshold are a strong indicator of sustained treatment potential. For the sustained treatment assessment, PBOC can be evaluated within the ISB treatment footprint relative to upgradient (naturally-occurring or “background”) concentrations. Increased PBOC within the treatment zone indicates that conditions within the ISB treatment zone continues to be influenced by ISB and may continue to support sustained treatment. A disadvantage of using PBOC as a line of evidence in the sustained treatment assessment is the requirement for collection of soil samples for analysis. An attempt to use BOD of groundwater samples as a cost-effective surrogate for PBOC proved unsuccessful due elevated detection limits for BOD.
- **Forage Analysis of Mulch Biowall Sediments:** This parameter, applicable to mulch biowall sites only, provides a measure of the bioavailable fraction of mulch remaining. A cellulose plus hemi-cellulose to lignin ratio greater than 1 is indicative of sustained treatment potential (Ahmad et al., 2007).

Worksheet for Sustained Treatment Assessment for Post-ISB Sites

Parameter / Line of Evidence	Critical Value / Relationship	Site-Specific Results	Data Support Evidence of Sustained Treatment?
Parent CVOC Concentration Change over Post-Treatment Monitoring Period	Decrease in parent CVOC conc. from first year of post-treatment monitoring vs. last year of post-treatment monitoring		
CVOC Concentration Trend of Parent and Daughter Products	Mann-Kendall trend from the most recent 4-8 monitoring events is same as (or better than) trend from first 4-8 post-treatment monitoring events		
TOC in Groundwater	TOC > 20 mg/L (USEPA, 1998)		
TOC in Groundwater	Treatment Zone (TZ) > Upgradient (UG)		
Ethene in Groundwater	Ethene > 0.1 mg/L (USEPA, 1998)		
Ethene in Groundwater	Treatment Zone (TZ) > Upgradient (UG)		
Methane in Groundwater	Methane > 0.5 mg/L (USEPA, 1998)		
Methane in Groundwater	Treatment Zone (TZ) > Upgradient (UG)		
Dehalococcoides in Groundwater	Treatment Zone (TZ) > Upgradient (UG)		
Dehalococcoides in Groundwater	> 10^4 cells/mL (Lu et al., 2006)		
Sum of Reductive Dechlorinators in GW	> 10^4 cells/mL		
^{13}C of CVOCs in Groundwater	Enrichment of ^{13}C signature relative to upgradient monitoring locations		
PBOC in Aquifer Sediment	PBOC > 200 mg/kg (Chapelle et al., 2012)		

Worksheet for Sustained Treatment Assessment within a Biowall

Parameter / Line of Evidence	Critical Value / Relationship	Site-Specific Results	Data Support Evidence of Sustained Treatment?
Parent CVOC Concentration Change over Post-Treatment Monitoring Period	Decrease in parent CVOC conc. from first year of post-treatment monitoring vs. last year of post-treatment monitoring		
CVOC Concentration Trend of Parent and Daughter Products	Mann-Kendall trend from the most recent 4-8 monitoring events is same as (or better than) trend from first 4-8 post-treatment monitoring events		
TOC in Groundwater	TOC > 20 mg/L (USEPA, 2008)		
TOC in Groundwater	Within Biowall (WB) > Upgradient (UG)		
Ethene in Groundwater	Ethene > 0.1 mg/L (USEPA, 1998)		
Ethene in Groundwater	Within Biowall (WB) > Upgradient (UG)		
Methane in Groundwater	Methane > 0.5 mg/L (USEPA, 1998)		
Methane in Groundwater	Within Biowall (WB) > Upgradient (UG)		
Dehalococcoides in Groundwater	> 10^4 cells/mL (Lu et al., 2006)		
Sum of Reductive Dechlorinators in GW	> 10^4 cells/mL		
^{13}C of CVOCs in Groundwater	Enrichment of ^{13}C signature relative to upgradient monitoring locations		
PBOC Analysis of Mulch	PBOC > 200 mg/kg (Chapelle et al., 2012)		
Forage Analysis of Mulch	Cellulose + Hemi-cellulose to Lignin Ratio > 1 (Ahmad et al., 2007)		

Worksheet for Sustained Treatment Assessment Downgradient of a Mulch Biowall

Parameter / Line of Evidence	Critical Value / Relationship	Site-Specific Results	Data Support Evidence of Sustained Treatment?
Parent CVOC Concentration Change over Post-Treatment Monitoring Period	Decrease in parent CVOC conc. from first year of post-treatment monitoring vs. last year of post-treatment monitoring		
CVOC Concentration Trend of Parent and Daughter Products	Mann-Kendall trend from the most recent 4-8 monitoring events is same as (or better than) trend from first 4-8 post-treatment monitoring events		
TOC in Groundwater	TOC > 20 mg/L (USEPA, 2008)		
TOC in Groundwater	Downgradient (DG) > Upgradient (UG)		
Ethene in Groundwater	Ethene > 0.1 mg/L (USEPA, 1998)		
Ethene in Groundwater	Downgradient (DG) > Upgradient (UG)		
Methane in Groundwater	Methane > 0.5 mg/L (USEPA, 1998)		
Methane in Groundwater	Downgradient (DG) > Upgradient (UG)		
Dehalococcoides in Groundwater	Downgradient (DG) > Upgradient (UG)		
Dehalococcoides in Groundwater	> 10^4 cells/mL (Lu et al., 2006)		
Sum of Reductive Dechlorinators in GW	> 10^4 cells/mL		
^{13}C of CVOCs in Groundwater	Enrichment of ^{13}C relative to upgradient location		
PBOC in Aquifer Sediment	PBOC > 200 mg/kg (Chapelle et al., 2012)		

REFERENCES

Ahmad, F., T.M. McGuire, R.S. Lee, and E. Becvar, 2007. Considerations for the Design of Organic Mulch Permeable Reactive Barriers, *Remediation,* 18(1), 59-72.

Chapelle, F.H., L.K. Thomas, P.M. Bradley, H.V. Rectanus, and M.A. Widdowson. 2012. Threshold amounts of organic carbon needed to initiate reductive dechlorination in ground-water systems. *Remediation Journal*. 22(3): 19-28.

Lu, X., J.T. Wilson, and D.H. Kampbell, 2006. Relationship between Dehalococcoides DNA in groundwater and rates of reductive dechlorination at field scale. *Water Research*, 40, no. 16: 3131-3140. https://doi.org/10.1016.j.watres.2006.05.030.

USEPA, 2009. *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater*. US Environmental Protection Agency, EPA/600/R-98/128 September 1998.