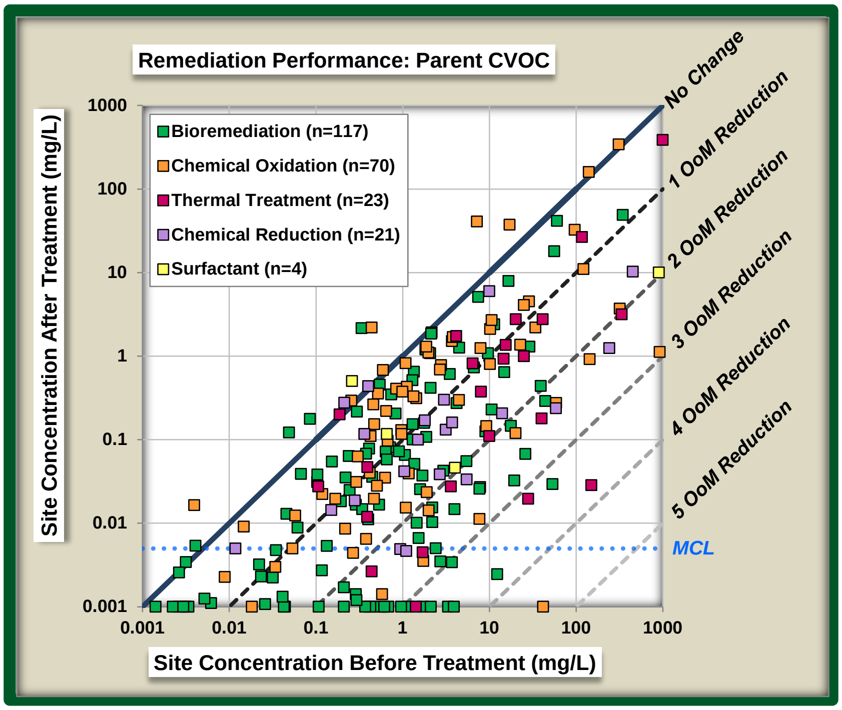
ESTCP
Cost and Performance Report

(ER-201120)



Development of an Expanded, High-Reliability Cost and Performance Database for In-Situ Remediation Technologies

March 2016

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ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 03/01/2016	**2. REPORT TYPE** Cost and Performance Report	**3. DATES COVERED** *(From - To)* October 2011 - March 2016

4. TITLE AND SUBTITLE Development of an Expanded, High-Reliability Cost and Performance Database for In-Situ Remediation Technologies	**5a. CONTRACT NUMBER** W912HQ-11-C-0040
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Travis McGuire David Adamson Charles Newell Poonam Kulkarni GSI Environmental, Inc.	**5d. PROJECT NUMBER** ER-201120
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) GSI Environmental, Inc. 2211 Norfolk Street, Suite 1000 Houston, TX 77098	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program Program Office 4800 Mark Center Drive Suite 17D03 Alexandria, VA 22350-3605	**10. SPONSOR/MONITOR'S ACRONYM(S)** ESTCP
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
N/A

14. ABSTRACT

To make this large investment in groundwater remediation technologies more effective, end-users need quantitative, accurate, and reliable performance and cost data for commonly used remediation technologies. While the data from an individual site are valuable in guiding site-specific decisions, the real value for the remediation community as a whole is in compiling and analyzing data from a range of sites to provide insight on the overall performance of technologies. The overall objective of this work was to develop a comprehensive remediation performance and cost database.

15. SUBJECT TERMS
N/A

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Travis McGuire
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	42	713-522-6300

APPENDIX

Points of Contact

ACRONYMS

AFB	Air Force Base
AMIBA	Aqueous and Mineral Intrinsic Bioremediation Assessment
CSU	Colorado State University
CVOC	Chlorinated Volatile Organic Compound
DCE	Dichloroethene
DNAPL	Dense Non-Aqueous Phase Liquid
DoD	Department of Defense
DRA	Driving Range Area
EAB	Enhanced Anaerobic Bioremediation
ESTCP	Environmental Security Technology Certification Program
FTA	Fire Training Area
GSI	GSI Environmental Inc.
GW	Groundwater
HASP	Health and Safety Plan
HPT	Hydraulic Profiling Tool
MNA	Monitored Natural Attenuation
OoM	Order of Magnitude
PBOC	Potentially-Bioavailable Organic Carbon
PCE	Tetrachloroethene
SERDP	Strategic Environmental Research and Development Program
TOC	Total Organic Carbon
TCA	1,1,1-Trichloroethane
TCE	Trichloroethene
USCS	Universal Soil Classification System
VOC	Volatile Organic Compound

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. In particular, we would like to thank Dr. Denice Nelson and Matthew McCaughey with ARCADIS for providing data for numerous sites. 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.

Dr. Hunter Anderson with the Air Force Civil Engineer Center, Scott Bowen at Tinker Air Force Base, and Mary Bitney at Altus Air Force Base are owed a special thanks for their support and assistance with the field demonstrations that were performed for this project.

Finally, we would like to thank our expert review panel, Dr. Herb Ward of Rice University, Dr. John Wilson with Scissortail Environmental Solutions, and Dr. Tom Sale of Colorado State University, for their time spent reviewing our work and their invaluable comments and suggestions.

EXECUTIVE SUMMARY

OBJECTIVES

The overall objective of this work was to develop a comprehensive remediation performance and cost database using results from numerous actual remediation projects. The project sought to expand the breadth and depth of the remediation performance and cost database compiled as part of a previous SERDP project (ER-1292) to provide a more powerful and reliable dataset. Several characteristics of remediation projects were evaluated to provide insights into factors that may affect remediation outcomes. In addition, several key focus areas were studied to provide insights on sustained treatment vs. rebound, performance of "treatment trains," and performance at "remediation done right" sites as described in the peer-reviewed literature.

The project resulted in a performance database of 235 remediation projects. The dataset suggests that concentration reductions of 0.5 to 2.0 orders of magnitude are typical when using the most common in-situ remedial technologies for groundwater treatment of chlorinated solvents.

TECHNOLOGY DESCRIPTION

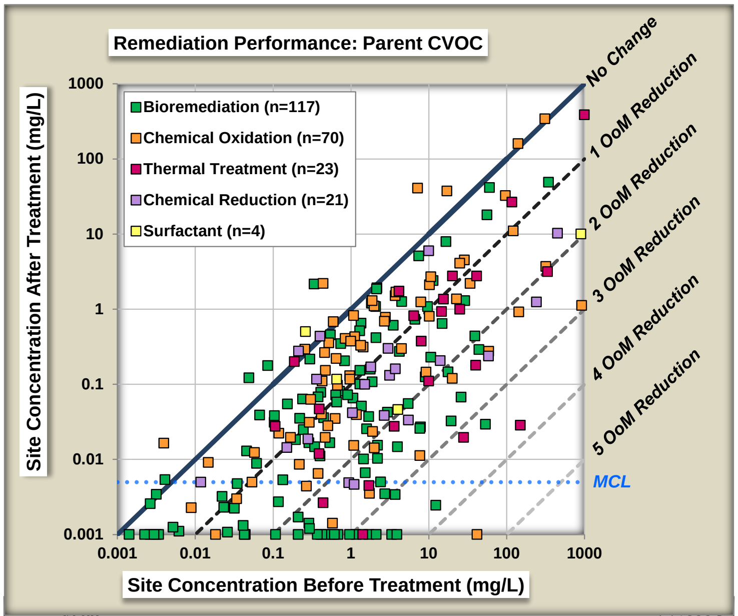
The DoD and private sector have invested billions in environmental restoration, with thousands of sites in the United States requiring some type of groundwater remediation. In the process of remediating these sites, large amounts of monitoring data are collected, including prior to the start of clean-up, during the active remediation phase, and after remediation efforts have been completed. To make this large investment in groundwater remediation technologies more effective, end-users need quantitative, accurate, and reliable performance and cost data for commonly used remediation technologies. While the data from an individual site are valuable in guiding site-specific decisions, the real value for the remediation community as a whole is in compiling and analyzing data from a range of sites to provide insight on the overall performance of technologies.

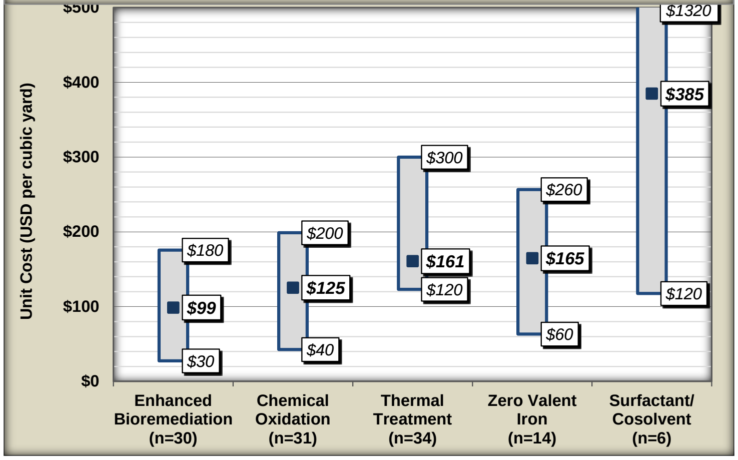
The project consisted of two primary components:

1) Data mining and analysis to extract meaningful remediation performance and cost information from a large number of sites for the following technologies: i) enhanced bioremediation; ii) chemical oxidation; iii) thermal treatment; iv) chemical reduction; v) surfactant flushing; and vi) MNA. The methodology for assessing performance involved calculating geometric mean and maximum concentrations from "before" and "after" treatment. From these before and after treatment concentrations, the *Order of Magnitude* (OoM) reduction achieved by the remedial technology was calculated, providing a single performance metric for each site.
2) Focused field studies aimed at generating detailed, long-term post-remediation performance data at a small number of sites where some of the most commonly utilized technologies were applied in various permutations, but in similar hydrogeologic settings. These studies were completed at Altus AFB and Tinker AFB at areas where enhanced bioremediation or chemical oxidation were used 5 to 10 years ago.

KEY RESULTS

- The middle 50% of 235 remediation projects achieved between 0.5 and 2 OoMs reduction in the geometric mean of the parent compound (between 71% and 99% reduction), with the median reduction at about 1.1 OoM (83% reduction).
- The middle 50% of 235 remediation projects achieved between 0.2 and 1.4 OoMs reduction in the maximum concentration of the parent compound (between 41% and 96% reduction), with the median reduction at about 0.8 OoM (84% reduction).
- The unit cost for a typical in-situ remediation project ranges between \$100 and \$300 per cubic yard, but with some projects below \$10 and some over \$1000 per cubic yard. The median thermal project (n=34) was about 50% more expensive than enhanced bioremediation and chemical oxidation projects.





IMPLEMENTATION

The final products of this project include numerous charts and graphics that are intended to help inform the remedial decision-making process at sites, as well as an electronic Decision Support System that allows the user to select various site parameters and remedial technologies to see the actual remediation performance data for sites with the selected characteristics. In no case is the dataset intended to replace a thorough technology screening, design, and/or feasibility or pilot testing. Furthermore, the dataset is not intended to predict precisely what remediation outcome might be achieved at a specific site, but rather to provide a range of expectations based on levels of performance that were achieved at other sites with similar characteristics.

We expect that the dataset contained herein will have a tiered relevance as part of the remedial decision-making process, where the data will be very useful for technology screening, supportive for the conceptual design, and less useful at the detailed design stage. For sites that are already undergoing active remediation, we envision that the dataset could be particularly useful for transition assessments at complex sites and for Five-Year Reviews at federal cleanup sites.

1.0 INTRODUCTION

1.1 Background

The DoD and private sector have invested billions in environmental restoration, with thousands of sites in the United States requiring some type of groundwater remediation. To make this large investment in groundwater remediation technologies more effective, end-users need quantitative, accurate, and reliable performance and cost data for commonly used remediation technologies. The U.S. EPA cited this as a "primary research need" in the 2003 DNAPL Expert Panel document (Kavanaugh et al., 2003).

More recently, the National Research Council, in their report on *Alternatives for Managing the Nation's Complex Contaminated Groundwater Sites* (NRC, 2013), stated that:

> *"The Committee could identify only limited data upon which to base a scientifically supportable comparison of remedial technology performance,"*
>
> *"Adequate performance documentation generated throughout the remedial history at sites either is not available or does not exist for the majority of completed remediation efforts," and*
>
> *"There is a clear need for publically accessible databases that could be used to compare the performance of remedial technologies at complex sites (performance data could be concentration reduction, mass discharge reduction, cost, time to attain drinking water standards, etc.)"*

Large amounts of monitoring data are collected as part of all remediation projects, including prior to the start of clean-up (to characterize the extent of impacts and to provide a baseline for measuring performance), during the active remediation phase (to determine if process modifications are necessary), and after remediation efforts have been completed (to assess performance and progress towards compliance goals). Monitoring-related expenditures can easily exceed the actual cost of clean-up at some sites. While the data from an individual site are valuable in guiding site-specific decisions, the real value for the remediation community as a whole is in compiling and analyzing data from a range of sites to provide insight on the overall performance of technologies. In effect, data mining leverages the money already spent for monitoring during past remediation projects, thereby providing a sounder basis for future financial decisions at other sites.

As part of a SERDP-funded project (ER-1292), GSI compiled a detailed historical database on the performance and costs of source depletion technologies. This cost and performance database was the highest quality dataset assembled to date (based on the data density and publication of peer-reviewed papers). The project represented the first rigorous, independent performance evaluation of four commonly utilized remediation technologies: enhanced bioremediation, chemical oxidation, surfactant/cosolvent flushing, and thermal treatment. Key findings from the project were disseminated via publications in scientific journals and these publications, listed below, were in turn heavily cited in the literature:

- Remediation Performance at 59 Sites: McGuire et al., 2006 (108 Google Scholar citations)
- Remediation Cost at 36 Sites: McDade et al., 2005 (33 Google Scholar citations)
- Source Attenuation Rates at 23 sites: Newell et al., 2006 (33 Google Scholar citations)
- Source Decay Models: Newell and Adamson, 2005 (25 Google Scholar citations)

The extensive utilization of this dataset was evidence that the remediation community has an essential need for high-quality, reliable remediation performance and cost data.

1.2 Objective of the Demonstration

The overall objective of this work was to expand the breadth and depth of the remediation performance and cost database compiled as part of the previous SERDP project (ER-1292) to provide a more powerful and reliable dataset. Specific project objectives were as follows:

- Expand the existing performance and cost database to include more sites and longer post-remediation monitoring periods;
- Examine longer-term datasets to determine whether patterns in sustained treatment and rebound are consistent with findings from our previous work;
- Explore key factors that may contribute to, or affect, remediation performance, sustained treatment, and rebound;
- Evaluate and add performance data from existing technology-specific ESTCP performance studies;
- Explore the potential benefits of successive applications of different remediation technologies, or "treatment train" sites;
- Examine 3 to 4 remediation projects described in the peer-reviewed literature, to evaluate the performance for "remediation-done-right" sites;
- Execute a field program at 3 to 4 sites to collect additional post-remediation monitoring data to fill in gaps related to long-term performance, rebound, and secondary water quality impacts; and
- Expand the SERDP Decision Support System software with the results of the study.

The final products of this project include numerous charts and graphics that are intended to help inform the remedial decision-making process at sites, as well as an electronic Decision Support System that allows the user to select various site parameters and remedial technologies to see the actual remediation performance data for sites with the selected characteristics. In no case is the dataset intended to replace a thorough technology screening, design, and/or feasibility or pilot testing. Furthermore, the dataset is not intended to predict precisely what remediation outcome might be achieved at a specific site, but rather to provide a range of expectations based on levels of performance that were achieved at other sites with similar characteristics.

We expect that the dataset contained herein will have a tiered relevance as part of the remedial decision-making process, where the data will be very useful for technology screening, supportive for the conceptual design, and less useful at the detailed design stage. For sites that are already undergoing active remediation, we envision that the dataset could be particularly useful for transition assessments at complex sites and for Five-Year Reviews at federal cleanup sites.

1.3 Regulatory Drivers

Regulatory cleanup requirements are a primary driver for most groundwater remediation projects. At many sites, restoring groundwater to a potentially-usable source of drinking water is the ultimate goal, requiring that contaminant concentrations be remediated below the federal primary drinking water standards, or Maximum Contaminant Levels (MCLs). For chlorinated solvents, which were the focus contaminants for this project, the MCLs are typically two to five *Orders of Magnitude* lower than groundwater concentrations commonly encountered in source zones, as depicted on Figure 1.1.

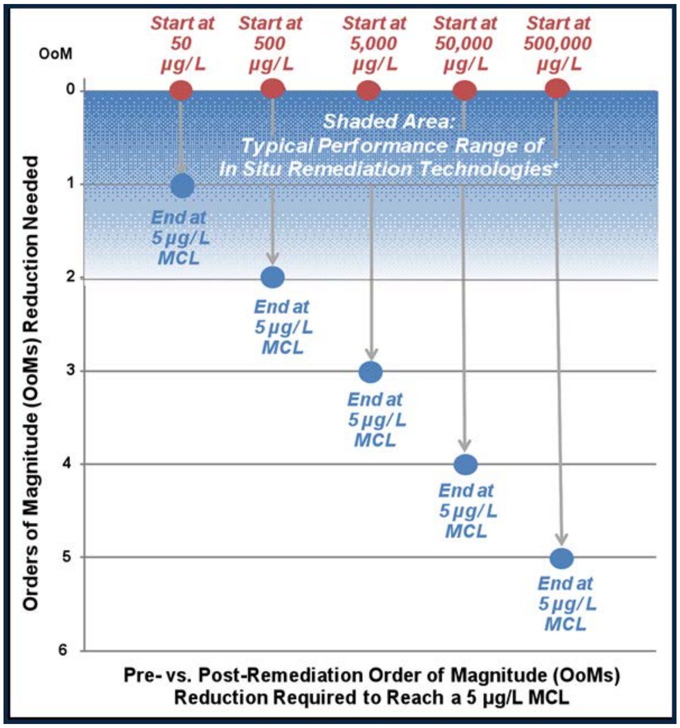


Figure 1.1: Order of Magnitude Reduction Required to Reach a 5 ug/L MCL (from ITRC, 2011; derived from Sale et al., 2008).

** Typical Performance Range of In-Situ Remediation Technologies in this graphic was based on the findings of our previous SERDP study as reported in McGuire et al., 2006.*

2.0 TECHNOLOGY

2.1 Technology Description

The project consisted of two primary components: i) data mining and analysis to extract meaningful remediation performance and cost information from a large number of sites; and ii) focused field studies aimed at generating detailed, long-term post-remediation performance data at a small number of sites where some of the most commonly utilized technologies were applied in various permutations, but in similar hydrogeologic settings. Each of these is described in more detail in the sections below.

Data Mining

Data mining works on the simple principle that the more data that are available to be compiled and analyzed (especially if the data originated from multiple sources), the more powerful are the conclusions that can be made. Data mining allows a user to test a hypothesis, or alternatively, to develop new hypotheses based on patterns that may not have been previously apparent.

The data mining project focused on in-situ groundwater remediation technologies, with a secondary emphasis on untreated (natural attenuation) sites. Ex-situ technologies and soil-focused remediation technologies were excluded, though sites where one of these technologies had been applied in the past did not necessarily result in exclusion of the site from further consideration. To the extent practicable, efforts were made to exclude sites or portions of sites where these other technologies appeared to have affected the performance of the in-situ groundwater remediation technology.

Data mining efforts focused on the following technologies: enhanced bioremediation; chemical oxidation; thermal treatment; and chemical reduction. In addition to these active remediation technologies, an emphasis was placed on adding more natural attenuation sites to the database as a basis for comparison.

The critical data that were required for a site to be included in the database consisted of the following parameters: i) application of one of the technologies listed above for the treatment of chlorinated solvents in groundwater; ii) actual groundwater concentration data from within the treatment zone for the parent compound from before and after treatment (i.e., reported "percent reduction" values were excluded); iii) treatment date(s); and iv) at natural attenuation sites, a data record spanning at least four years. Additional information, such as site location, daughter product concentrations, treatment amendments or configurations, treatment zone dimensions, lithology, and costs, were also obtained when available.

Performance Calculations

The ultimate goal of the data mining effort was to produce a single performance metric for each site based on actual concentration versus time data from one or more wells located within the treatment zone. To achieve this goal, concentration data from each well at a site was separated into before treatment and after treatment time periods. Next the geometric mean of each time period was calculated resulting in a single "before" concentration and a single "after" concentration for each well. The before and after data points from multiple wells were further reduced by calculating the median value. This produced a single before treatment concentration and a single after treatment concentration for each site.

From these before and after treatment concentration values for each site, the *Order of Magnitude* (OoM) reduction achieved by the remedial technology was calculated using the equation below to result in a single performance metric for each site.

$$OoM\ Reduction = -\log\left(\frac{C_{after}}{C_{before}}\right)$$

Calculating OoM reduction as the negative logarithm of the after-to-before concentration ratio produces a simple metric with a typical range of 0 to 5, with each integer representing an order-of-magnitude. The method is analogous to calculation of pH or pK_a values in chemistry. OoMs directly correlate to "the number of 9s in percent reduction" as shown on Table 2.1.

Table 2.1. OoM Reduction vs. Percent Reduction

OoM Reduction	Corresponding Percent Reduction
1	90%
2	99%
3	99.9%
4	99.99%
5	99.999%

For natural attenuation sites, the first year of the monitoring data and the last year of the monitoring data were used in lieu of the "before" and "after" treatment periods discussed above for active remediation sites.

Cost Calculations

Costs associated with remediation projects were extracted from the site information when available. The protocol was similar to that used for an earlier compilation under SERDP ER-1292 (McDade et al., 2005). Quality of the cost information varied from detailed cost breakdowns to lump costs reported for an entire project without details on what was included or excluded. To the extent practicable, only those costs directly associated with the remediation project were included in the cost analysis.

Costs were normalized by the treatment volume (as in-place cubic yards) to allow for more direct comparison between technologies. As such, only sites with both cost information and treatment volume data were included in the cost analysis. Costs associated with natural attenuation projects were not evaluated.

Expert Panel Meeting

An Expert Panel was convened to review the project methods and findings. The panelists were: Dr. John Wilson, Scissortail Environmental Solutions; Dr. Herb Ward, Rice University; and Dr. Tom Sale, Colorado State University. The project team presented details of the project technical approach and results to the Panel. The panel provided feedback and suggestions during the meeting, and were also given the opportunity to provide additional feedback after the meeting.

Overall, the experts concluded that the project data were useful for remedial decision-making and that the findings provided a useful "Range of Expectations." They stressed a tiered relevance, where the data will be very useful for technology screening, supportive for the conceptual design, and less useful at the detailed design stage. The Panel agreed that use of geometric mean concentrations was appropriate for determining representative groundwater conditions, but that evaluation of maximum concentrations remains important from a regulatory perspective. Additional feedback from the Expert Panel can be found in the ESTCP Final Report for this project.

Focused Field Studies

Focused field studies were performed at two sites: Tinker Air Force Base (AFB) in Oklahoma City, Oklahoma and Altus AFB in Altus, Oklahoma. The two sites are located approximately 120 miles apart and have similar hydrogeologic settings. At Tinker AFB, two areas were selected for testing: Fire Training Area 2 (FTA-2) and the Driving Range Area (DRA). At Altus AFB, the groundwater source area associated with Building 323 was selected for testing. Table 2.2 summarizes the characteristics of the focused field study testing sites. Additional details of the testing program can be found in the Final Demonstration Plan (GSI, 2013) and in the ESTCP Final Report for this project.

Table 2.2. Characteristics of Focused Field Study Sites

Site ID	Technology	Amendment	Time Since Treatment of GSI Sampling, yrs.
Altus Bldg. 323	Enh. Bio.	Emulsified oil	5
Tinker FTA-2	Enh. Bio.	Emulsified oil	10
Tinker DRA-1	Enh. Bio.	Lactate	10
Tinker DRA-2	Chem. Ox.	Fenton's reagent	10
Tinker DRA-3	Chem. Ox.	Potassium permanganate	10

2.2 Advantages and Limitations

Potential advantages and disadvantages of our dataset, and multi-site studies in general, are listed in Table 2.3 below. Some of these topics are further addressed in Section 4 of this report.

Table 2.3. Advantages and Potential Limitations of Multi-Site Studies

Advantages	Limitations
Researchers are independent of the technologies	Findings are not site-specific
Data analysis methods are repeatable and consistent	Pilot scale projects are mixed with full scale projects
Results cover a broad spectrum of sites	Results may not account for "intentional" shutdowns
Results are based on actual concentration data, not anecdotal information	Results may not account for different levels of design / experience
Numerous multi-site studies have been published in peer-reviewed literature	Results may not account for knowledge gained and better application over time

Use of Groundwater Concentration Data from Monitoring Wells

Groundwater concentration data from monitoring wells within the treatment zone represents the primary performance metric used in this evaluation. The strengths of using concentration data from monitoring wells include:

- Concentration data from monitoring wells is relied upon by regulatory agencies to evaluate the need for cleanup, monitor cleanup progress, and to determine if cleanup goals are met; and
- The groundwater industry is well versed in the collection and interpretation of monitoring well data.

However, there are issues with groundwater monitoring data that can complicate the analysis of remediation performance data, such as:

- Groundwater monitoring data has significant short-term variability (SERDP Project ER-1705; ESTCP Project ER-201209) that can complicate trend analysis and comparisons between data sets;
- There are different methods for well construction (e.g., short screen vs. long screen) and different groundwater sampling methods (e.g., high-volume purge vs. low-volume purge vs. no-purge) that have the potential to introduce bias in different data sets; and
- Groundwater monitoring data alone may not fully capture some site characteristics that can also influence remediation performance, such as: source zone size and architecture, groundwater flow velocity, mass distribution in different phases, and the potential for exposure via other exposure pathways.

This ESTCP project addresses these issues as follows:

Variability is addressed by "averaging" concentrations both temporally (by calculating geomean concentrations of all available monitoring events vs. any single event or narrow window in time) and spatially (by calculating the median geomean concentration for all wells in the treatment zone vs. using only concentration data from a single well) to derive "site concentration" metrics before treatment and after treatment for evaluating remediation performance.

Different methods for well construction and groundwater sampling are largely managed by relying on permanent monitoring wells with long term temporal records, which largely excludes one-time direct push sampling with short well screens. At most of these sites, if there were any changes in sampling methods over time, our experience indicates that such changes were likely approved by site stakeholders with the intention that the quality and consistency of the monitoring record would not be compromised. In addition, ESTCP Project ER-201209 concluded that the sampling method "has only a modest impact on monitoring variability and concentration" in the context of long-term monitoring programs.

3.0 PERFORMANCE OBJECTIVES

Performance objectives for the data mining component and focused field study component are provided in Tables 3.1 and 3.2.

Table 3.1. Performance Objectives for Data Mining

Performance Objective	Data Requirements	Success Criteria	Success Criteria Achieved?
Quantitative Performance Objectives			
Expand number of temporal records in database	Temporal records (concentration vs. time) at wells from new sites that were not part of the SERDP ER-1292 database	Add 30 sites to original database, representing an increase of 50% from original database	***YES: Added 176 new sites***
Expand length of temporal records in database	Updated temporal records (concentration vs. time) at wells that were included the SERDP ER-1292 database	Add 3 to 5 years of data for temporal records from 15 sites in original database, representing an increase of ~50% in the overall average temporal record length	***YES: 2 to 10 years (avg. of 6.1 years) of additional data added for 15 sites***
Qualitative Performance Objectives			
Ease of Data Collection Efforts	Feedback from site managers/agencies	Response from sufficient number of site managers	***YES: 134 new sites added electronically from online data sources***

Table 3.2. Performance Objectives for Focused Field Studies

Performance Objective	Data Requirements	Success Criteria	Success Criteria Achieved?
Quantitative Performance Objectives			
Collect data to evaluate long-term impacts following in-situ groundwater remediation	• CVOC concentrations in saturated soil and groundwater • Geochemical concentrations in groundwater • Microbial and mineralogical parameters in saturated soil groundwater	Sample collection at 100% of targeted areas	***YES: Samples collected at all proposed locations***
Qualitative Performance Objectives			
Evaluate long-term remediation impacts	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 as follows: ▪ Determine average post-treatment concentrations including new monitoring data relative to average post-treatment concentrations without the new monitoring data ▪ Determine temporal trends including the new monitoring data relative to trends without the new monitoring data • Data are sufficient to evaluate long-term geochemical changes • Data are sufficient to evaluate microbial and mineralogical conditions	***YES: Data sufficient to evaluate long-term concentration trends***

4.0 DATA MINING RESULTS

4.1 Overview of the Database

The project team reviewed thousands of pages of reports from hundreds of sites to develop a high-quality, reliable dataset of remediation projects that targeted chlorinated solvents in groundwater. The efforts resulted in the accumulation of data from 235 remediation projects and 45 natural attenuation projects. Note that the terms "site" and "project" are used somewhat interchangeably to describe the results in this section; however, some sites (i.e., the geographical location) had multiple remediation efforts (i.e., projects) that targeted different areas within the site or different groundwater-bearing units. Such instances have been categorized as unique projects in the database even though they were conducted at the same site.

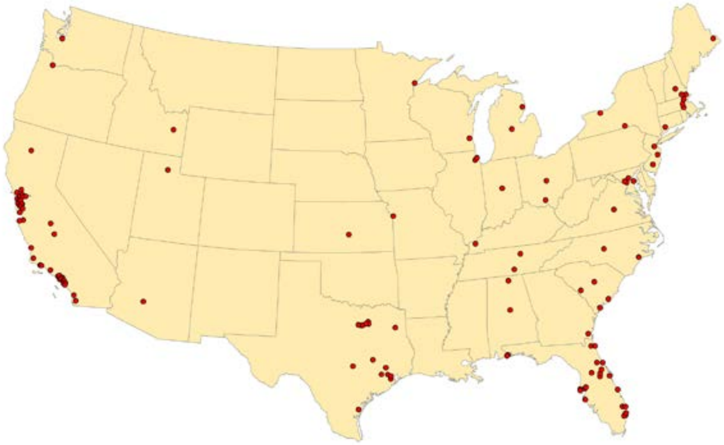
The following is a breakdown of some "database by the numbers" stats:

- 280 chlorinated solvent groundwater sites
  - ↳ ***235 in-situ remediation sites***
    - ⇨ 117 bioremediation sites
    - ⇨ 70 chemical oxidation sites
    - ⇨ 23 thermal treatment sites
    - ⇨ 21 chemical reduction sites
    - ⇨ 4 surfactant flushing sites
      - ⇔ 14 technology combination or "treatment train" sites
  - ↳ 45 natural attenuation sites
- 795 groundwater monitoring wells
  - ↳ ***710 wells at in-situ remediation sites***
  - ↳ 85 wells at natural attenuation sites
- 48,594 CVOC concentration data points
- An estimated 11,965 times that a well was sampled to collect the data in the database
  - ↳ Assuming that a well costs about $1,000 to sample (including labor, equipment, lab analyses, etc.), the approximate cost expended simply to collect the concentration data in our database was about $12 million. Of course the cost expended to implement the remediation projects was a significant multiple of this number.

Most of the projects in the database were located in the United States (see map below), with 1 site located in each of the following countries: Belgium, Canada, Czech Republic, Germany, and the United Kingdom.

4.2 Why Order of Magnitude?

An **Order of Magnitude (OoM)** is a factor of 10 change in a variable. For example, if a remediation technology reduces the dissolved phase concentration of TCE by one OoM, then the concentration is 10 times lower, equivalent to a 90% reduction. Two OoMs thus represents a reduction in concentration of 99%. The concept of OoMs is an important short hand for evaluating remediation performance because chlorinated solvent concentrations in groundwater typically span several orders of magnitude (Sale and Newell 2011), and are generally represented best by a log-normal statistical distribution.:



Location Map of In-Situ Remediation Projects in the United States

- 0 OoM: no change in concentration
- 1 OoM: 90% reduction in concentration
- 2 OoM: 99% reduction in concentration
- 3 OoM: 99.9% reduction in concentration

The superiority of OoMs over a linear model for remediation performance can be seen in the following conceptual model about remediation. If a remediation project reduces the key groundwater metric (typically the maximum concentration at a site) from 5 mg/L to 0.5 mg/L, a linear model would suggest that this project has achieved a 90% reduction and that remediation goals could be achieved for only an additional 10% of the effort. The OoM approach would say that 1 OoM has been achieved, but two more OoMs are required to reach the cleanup standard, and that 100% of the effort required to achieve the 1 OoM must be expended 2 more times in order to achieve the remediation goal (assuming the goal was to reach a 0.005 mg/L MCL).

Newell et al., 2011 used Order of Magnitudes to develop a plume classification system based on mass discharge. In their inventory of 40 sites, a nine order of magnitude difference between the largest mass discharge site (56,000 grams per day) and the smallest mass discharge site (0.00078 grams per day). Interestingly, the smallest site (0.00078 grams per day) was remediated using a thermal technology. But the key point is that removing 90% of the mass or reducing groundwater concentrations by 90% does not mean that 90% of the work has been done; because of the log-normal nature of contaminant transport and remediation processes, an Order of Magnitude model is much more appropriate for estimating remediation level of effort.

In the following sections of this ESTCP report, OoMs are used in a specific way: *to describe the reduction in groundwater concentrations from before to after an in-situ remediation project at an actual site. Different types of groundwater concentrations and calculation approaches are used, but all are reported as OoMs of reduction.*

4.3 Key Questions and Explanation of Graphics

The results of our project are presented in the following sections in the form of key questions that we believe are central to advancing the understanding of how well in-situ remediation technologies have performed (and how much they cost), and how these results might be useful for framing expectations of future or on-going remediation projects.

Much of the remediation performance results presented in the following sections are presented on graphs that we have termed "triangle charts." Data points plotted on the X-axis of the chart represent concentrations before treatment began (or the first year monitoring concentration for MNA sites). Data points plotted on the Y-axis of the chart represent concentrations after treatment ended (or the last year monitoring concentration for MNA sites). Thus each data point on the chart represents actual before and after concentrations for an individual project.

From the location where the data point falls on the chart, the diagonal lines can be used to determine the OoM reduction achieved by the project based on the before and after treatment concentrations. The blue line toward the bottom of the chart represents the typical MCL of 0.005 mg/L for TCE and PCE, and can be used to determine whether a project achieved the MCL after treatment.

As discussed in Section 2 of this report, most of the concentrations presented in the following sections are geometric means, but occasionally maximum concentrations are presented for comparison. Beneath most charts we have included discussion of the "Data Shown" and an "Explanation" to reiterate what types of concentration data are being presented and help clarify the presentation of the data. Key Points are then provided to summarize the findings and answer the Key Question that was being asked.

4.4 What Performance Has Been Achieved at In-Situ Remediation Projects?

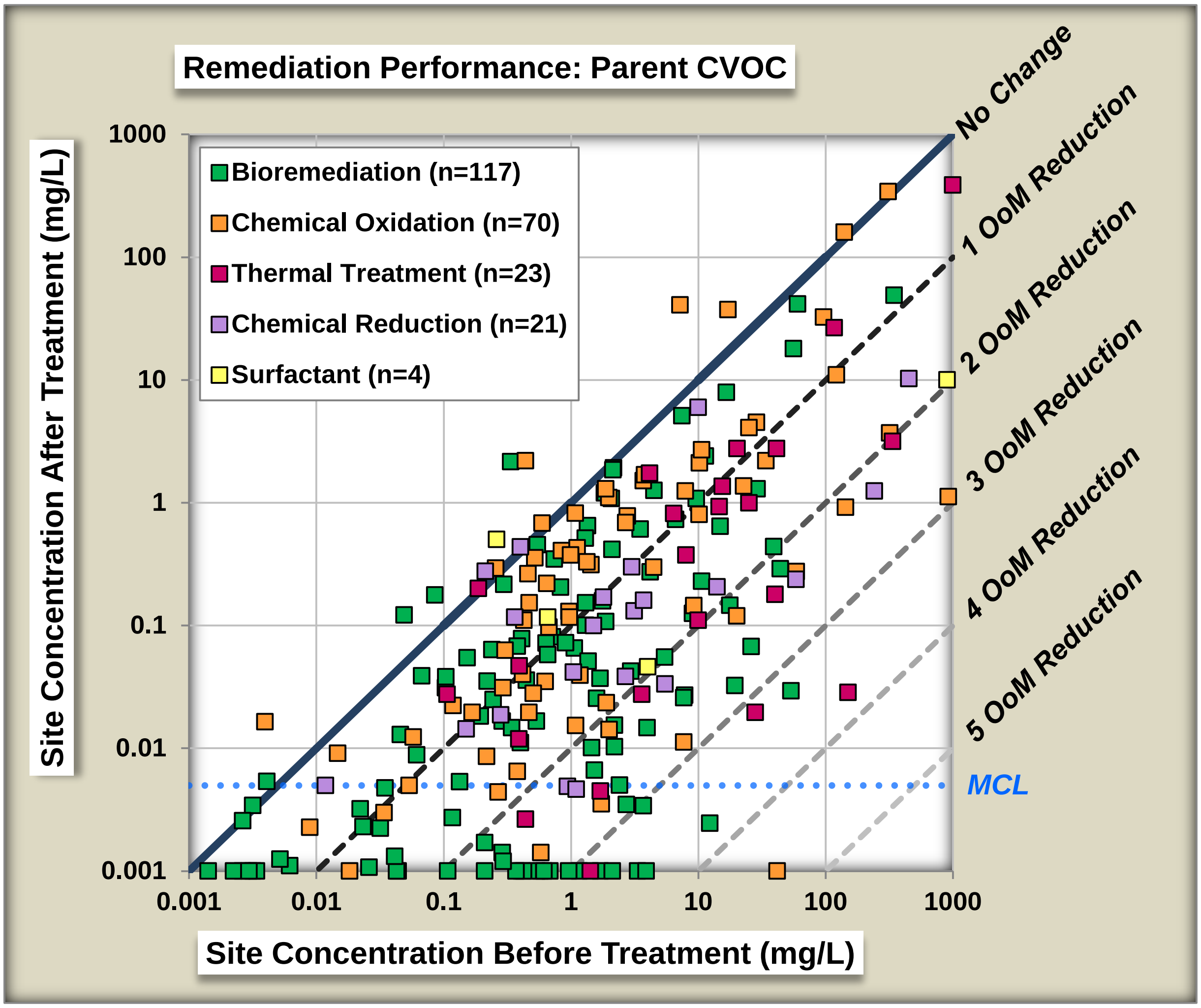


Figure 4.1. **Remediation Performance of 235 In-Situ CVOC Remediation Projects.**

Data Shown: *Geometric means of parent compound (for sites with multiple wells, the plotted value is the median of the geometric means from individual wells).*

Explanation: *Each symbol is an individual in-situ remediation project. The geometric mean treatment concentration from before treatment is shown on the X-axis, and the geometric mean treatment concentration from after treatment is shown on the Y-axis*

Key Points:

- Geometric means are shown, representing the typical before- and after-treatment concentrations from within the treatment zone.
- Parent concentrations are shown, representing mostly PCE sites, TCE sites with little or no PCE; and 1,1,1-TCA sites.

- Five remediation technologies are represented: 117 bioremediation projects; 70 chemical oxidation projects; 23 thermal remediation projects; 21 chemical reduction projects, and 4 surfactant projects.
- The performance of in-situ CVOC remediation performance technologies vary widely, from increasing by about 1 OoM to more than 4 OoM reduction in concentration.
- The middle 50% of the remediation projects achieved between 0.5 and 2 OoMs reduction in the geometric mean of the parent compound (between 70% and 99% reduction), with the median reduction at about **1.1 OoM (91% reduction).** Additional percentile results are summarized on Table 4.1 below.

Table 4.1. Order of Magnitude Reductions from 235 Active In-Situ Remediation Projects

Percentile of 235 Active In-Situ Remediation Projects	**% Reduction in Geomean of Parent Compound in Treatment Zone**	**OoM Reduction in Geomean of Parent Compound in Treatment Zone**
90%	99.8%	2.7
75%	98.9%	2.0
50%	91.2%	**1.1**
25%	71.4%	0.5
10%	30.8%	0.1

4.5 Does the Concentration Metric Matter? Geomeans vs. Maximums?

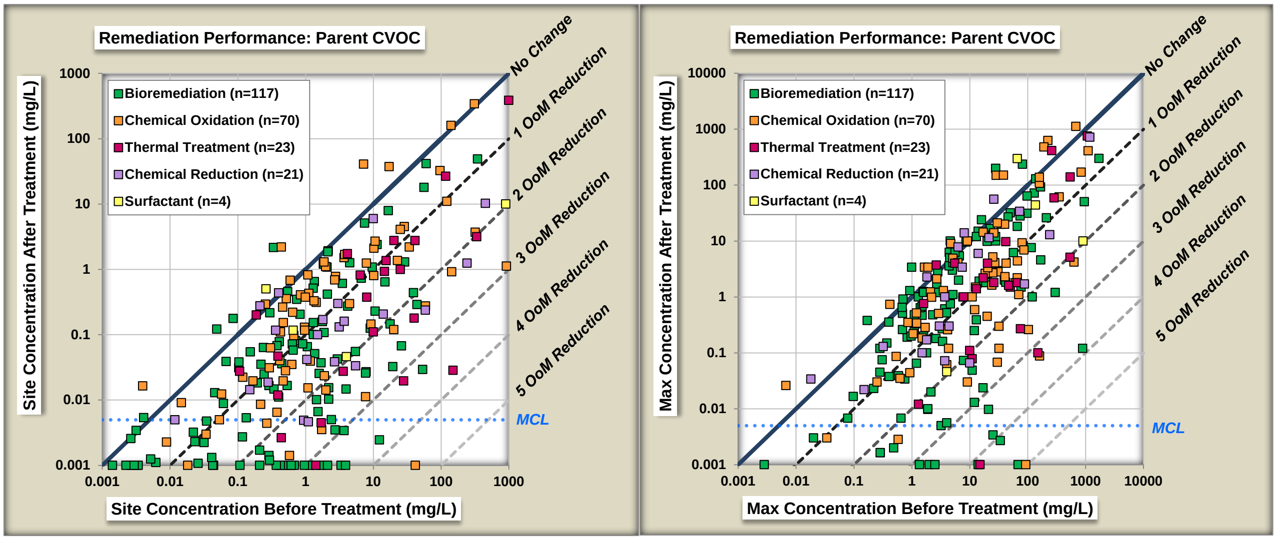


Figure 4.2. Remediation Performance Based on Geometric Mean and Site Maximum Concentrations

Data Shown: *<u>Geomean</u> before and after concentrations of parent compound in treatment zone groundwater (left panel) and <u>Maximum</u> before and after concentrations of parent compound in treatment zone groundwater (right panel).*

Table 4.2. Order of Magnitude (OoM) Reduction in Parent Compound at 235 Remediation Sites Using Change in Geometric Means vs. Change in Maximum Concentrations

Percentile of 235 Sites	OoM Reduction (% Reduction) in Parent Geomean Concentration	OoM Reduction (% Reduction) in Parent Maximum Concentration
75th	2.0 (99%)	1.4 (96%)
50th	**1.1 (91%)**	**0.8 (84%)**
25th	0.5 (71%)	0.2 (41%)

Key Points:

- Remediation performance is generally poorer when site maximums are used as the performance metric (right panels) compared to geomeans (left panels). The exception was chemical oxidation, which showed better performance when using maximums (median OoM reduction of 1.0 using maximums vs. 0.63 using geomeans).
- When using site maximums, the middle 50% of all remediation projects achieved between **0.2 and 1.4 OoMs** reduction in the site maximum concentration of the parent compound (between 41% and 96% reduction), with the median reduction at about 0.8 OoM (84% reduction). By comparison, when using geomeans for evaluating performance, the middle 50% range of all projects was **0.5 to 2 OoMs** (between 71% and 99% reduction), with a median of 1.1 OoMs (91% reduction) (see Table 4.2).
- Using site maximums as the remediation performance metric appeared to reduce the performance of both enhanced bioremediation and thermal projects by about 0.6 OoMs, while chemical reduction was reduced by about 0.5 OoMs.
- One of the members of the Expert Review Panel, Dr. John Wilson, said that the **designers of a remediation project** would be more interested in geomeans, as this metric better represents performance throughout the treatment zone (see Appendix A).
- Dr. Wilson went on to say that **environmental regulators** are likely to be more interested in site maximum concentrations as a more relevant performance metric to determine whether regulatory cleanup standards can be achieved.
- Regulatory programs do not typically allow averaging or lumping of data from individual wells, making the site maximum concentration after treatment a key regulatory metric.

4.6 Does Performance Vary Significantly Between Technologies?

4.6.1 Is There a Difference in the Performance Data for the Four Major Technologies?

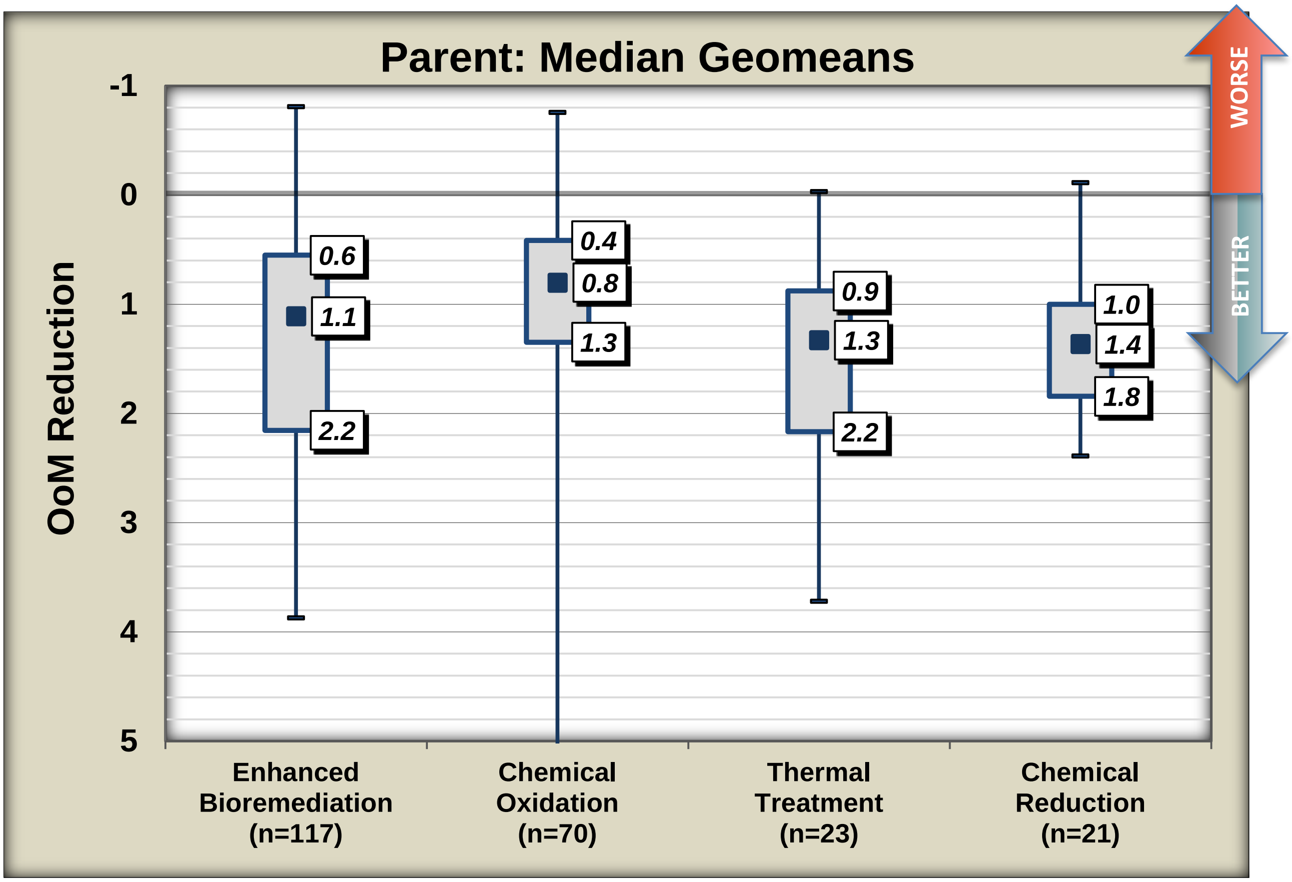


Figure 4.3. Groundwater Remediation Performance by Technology Based on Geomeans

Data Shown: *Change in geomean of parent compound concentrations in treatment zone groundwater by four different in-situ technologies.*

Explanation: *The grey boxes and upper and lower numbers show the 75th percentile and 25th percentile range (the middle 50%) of OoM Reduction for each technology. The black box and middle number are the median value. The upper and lower "whiskers" represent the maximum and minimum values.*

Key Points:

- When considering *geomean* concentrations for the *parent* compound, there does not appear to be significant differences in the performance of the four main technologies.
- Chemical oxidation appeared to have the worst performance (lowest OoM reduction) and thermal the best, but this is not statistically significant at 0.05 confidence level.
- But these conclusions change if a different metric is applied, such as the reduction in Total CVOCs (parents + daughter compounds + other CVOCs).

- Thermal treatment has been considered by some to have much better performance than other in-situ remediation technologies. However, practitioners often cite high performing *unsaturated soil* treatment projects to support this claim. This ESTCP project has focused exclusively on the change in **saturated zone groundwater concentrations** as measured in treatment zone monitoring points, and with the metric of *OoM reduction of parent compound concentrations in groundwater* thermal remediation performance is similar to the other technologies.
- Thermal remediation projects did appear to be applied at higher concentration sites (median before treatment concentration of 10 mg/L for the parent compound) and bioremediation has been applied at lower concentration sites (median before treatment concentration of 0.74 mg/L) (see Figure 4.4 and Table 4.3).

Table 4.3. Before- and After-Treatment Groundwater Concentrations based on Geometric Means by Technology.

	Parent Median Geomean Before (mg/L)	**Parent Median Geomean After (mg/L)**	**% Reduction in Parent Concentration**	**OoM Reduction in Parent Concentration***
Bioremediation (n=117)	0.74	0.027	96%	**1.4**
Chemical Oxidation (n=70)	1.1	0.27	77%	**0.6**
Thermal Treatment (n=23)	10	0.20	98%	**1.7**
Chemical Reduction (n=21)	1.8	0.13	93%	**1.1**

* Note the slight differences in median OoM Reduction values on this table and Figure 4.3 result from the order in which the negative log is applied to the before and after concentration data. For Figure 4.3, the negative log of individual projects was calculated first, then the median value was calculated for presentation on the chart. In this table the median concentrations of individual projects was first calculated, then the negative log of the medians was calculated.

4.7 Does Performance Change when using Total CVOCs vs. Parent Compounds?

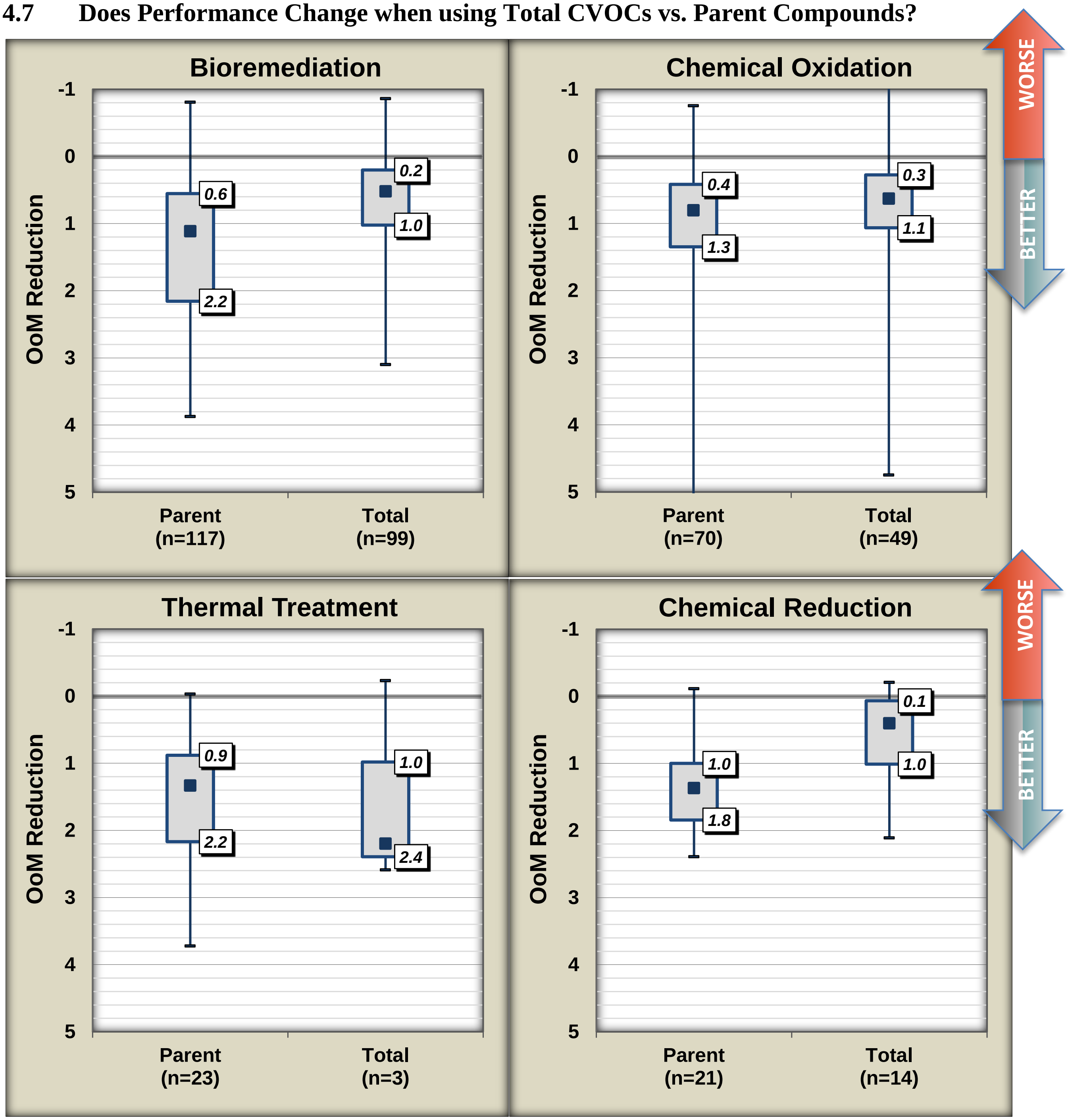


Figure 4.4. **Comparison of Remediation Performance Based on Parent Compound (left whisker plot in each panel) and Total CVOC Concentration (right whisker plot in each panel).**

Data Shown: *OoM reduction distribution based on geomean concentrations of Parent vs. Total CVOC concentration for bioremediation, chemical oxidation, thermal treatment, and chemical oxidation projects.*

Explanation: *The grey boxes and numbers show the 75th percentile and 25th percentile range (the middle 50%) of OoM reductions. The black box shows the median value. The "whiskers" show the maximum and minimum values.*

Key Points:

- The contaminant metric, in this case the Parent compound vs. Total CVOCs (i.e., parent plus daughter products), affects the performance of each remediation technology. Poorer performance was generally observed when the Total CVOC was the contaminant metric.
- Chemical oxidation projects were least impacted when *Total CVOC concentrations* were used compared to the *parent compound concentration. The median OoM reduction was only slightly smaller for Total CVOCs than parent compound concentrations, though this results is statistically significant (p=0.0003 based on Mann-Whitney test).* This pattern is expected as chemical oxidation does not result in the production of daughter products.
- Bioremediation and chemical reduction projects had worse performance when Total CVOCs is used as a metric compared to parent compound reductions ($p<0.05$ for both technologies based on Mann-Whitney test). This is also expected because these technologies convert parent compounds to daughter products, and both are generally less efficient at removing the lower chlorinated CVOCs.
- Thermal remediation projects also had worse performance for Total CVOCs; however, only 6 thermal projects reported Total CVOC data. No statistical difference could be established.
- The question of which metric is more appropriate to use is a complicated one, as one commonly found non-parent compound (cis-1,2-DCE) has significantly lower risk than its parent compound, while 1,1-DCE, a degradation product of 1,1,1-TCA has higher risk. The natural attenuation potential for lower chlorinated compounds is generally higher than the parent compounds as aerobic biodegradation reactions can degrade several of the key daughter products (such as vinyl chloride). For this project most of the analysis focused on the reduction in the parent compounds, but the data in Figure 4.7 are shown for comparison purposes.
- Analysis of Total CVOCs was problematic due to inconsistent availability of daughter product concentrations among the data sources (and even within individual sites) and the high variability in detection limits and concentrations of the daughter products. For example, sites often had elevated detection limits for daughter products with sporadic detections at concentrations sometimes higher and sometimes lower than the detection limits reported in other samples collected from the same monitoring well. Therefore, only detected concentrations of daughter products were quantified in the database, which further reduced the data population available for evaluation of Total CVOCs. Another option would have been to quantify non-detects as the detection limit, or one-half the detection limit, but doing so would have likely resulted in an over-estimate of actual concentrations due to the often elevated detection limits. As such, the analysis of Total CVOC performance data and associated outcomes carry greater uncertainty than the results based on parent CVOC concentrations.

4.8 How Frequently Did In-Situ Remediation Projects Achieve MCLs?

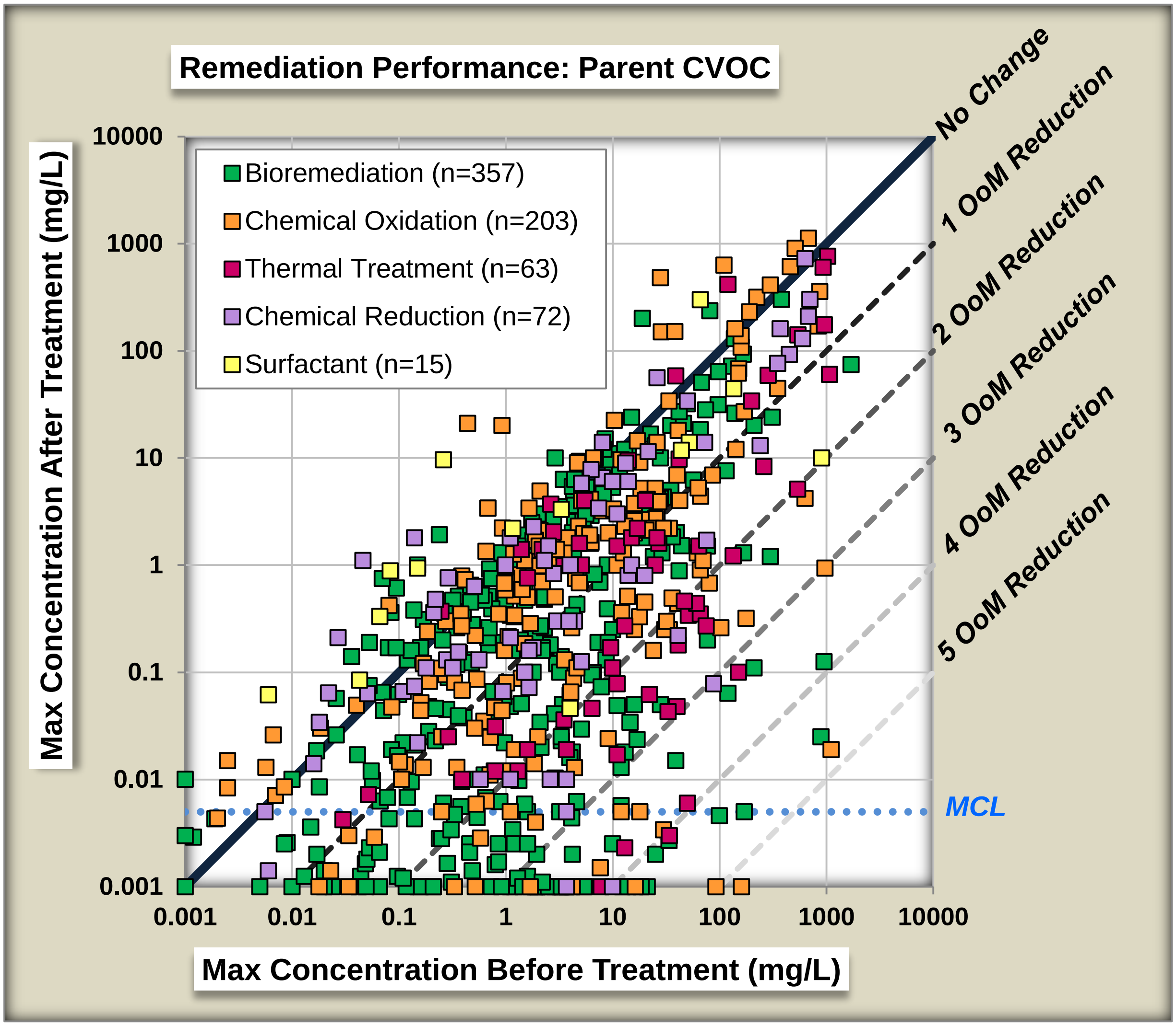


Figure 4.5. Change in Maximum Parent Compound Concentration for All 711 Wells Analyzed for this Project.

Data Shown: *Change in maximum concentration of parent compound.*

Explanation: *Each dot represents an individual well, showing the maximum before treatment concentration (X-axis) and after-treatment concentration (Y-axis). The dashed blue line shows the most common Maximum Concentration Limits (MCL) for chlorinated parent compounds, 0.005 mg/L.*

Table 4.4. Wells and Sites That Reached MCLs for Parent CVOC

	Total Number Of Monitoring Wells/Sites	Number of Wells/Sites That Reached MCLs for Parent CVOC based on Max. Concentration After Treatment	Number of Wells/Sites That Reached MCLs for Parent CVOC based on Max. Concentration After Treatment
Wells	710	146	21%
Sites	235	17	7%

Key Points

- Only 21% of 710 monitoring wells at 235 sites achieved a typical MCL of 0.005 mg/L for the parent CVOC based on maximum concentrations after treatment (Table 4.4).
- Only 7% of 235 sites achieved MCLs at every monitoring well for the parent CVOC based on maximum concentrations after treatment (Table 4.4). Of these 17 sites, 8 of them achieved a post-treatment maximum concentration of 0.001 mg/L (essentially non-detect).
- The 17 sites that did achieve MCLs at “all” wells for the parent CVOC were relatively special cases in that 10 of the 17 sites had only 1 monitoring well.
- Interestingly, 15 of the 17 sites had PCE as the parent compound, which may be more of a function that many of the smaller dry cleaner sites only were represented by one well that was sampled before and after treatment.
- The 17 sites that reached MCLs for the parent CVOC at all wells were treated using these technologies:
    - 13 Bioremediation sites,
    - 3 Chemical Oxidation sites, and
    - 1 Thermal Treatment site.

4.9 What is the Cost of In-Situ Treatment?

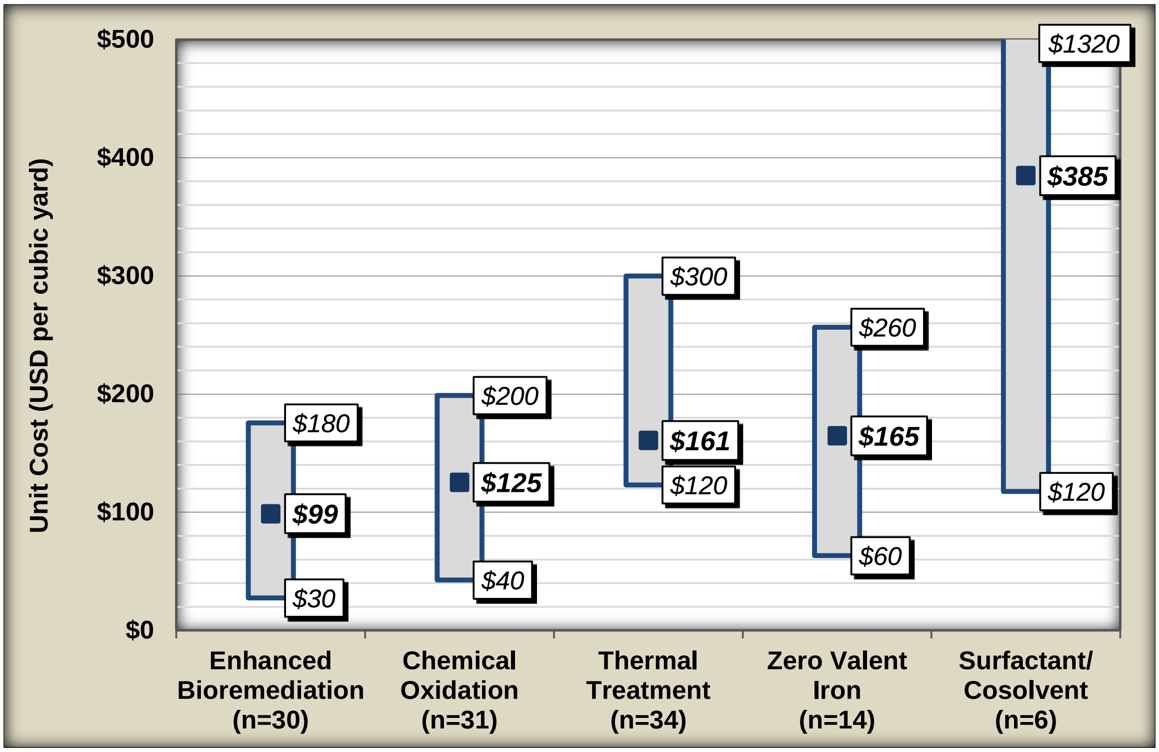


Figure 4.6. Middle 50% Unit Costs for 115 In-Situ Remediation Projects (Normal Scale).

Data Shown: *Unit cost of in-situ treatment in US dollars per cubic yard.*

Explanation: *The grey boxes and numbers show the 75th percentile and 25th percentile range (the middle 50%) of OoM results for each category. The black box and bold number shows the median value.*

Key Points

- Developing comparable unit costs for remediation projects is challenging as not all projects account for the same items. The costs reported in this section are the project team's best attempt to provide comparable, relative costs. In most cases the costs include design, permitting, construction, and operating. Typical groundwater monitoring and site characterization costs are not included.
- The unit costs for a typical in-situ remediation project ranges between $100 and $300 per cubic yard, but with some projects below $10 and some over $1000 per cubic yard.
- The median thermal project (n=34) was about 50% more expensive than enhanced bioremediation and chemical oxidation projects (Figure 4.6). The limited number of surfactant projects were much more expensive than other technologies.
- The performance of a remediation project did not seem to be correlated to unit costs. This is surprising, as more resources suggest more intense treatment that should translate to higher performance. But the remediation projects in this database may reflect costs that deal with

external factors, such as access, high concentrations, difficult hydrogeologic conditions, and therefore unit cost for treatment may not correlate to outcome at many sites.

- Remediation costs for bioremediation, chemical oxidation, and thermal treatment had about 40% to 50% positive correlation with treatment volume.
- Thermal projects had the highest total costs compared to bioremediation, chemical oxidation, and chemical reduction, with most of the thermal projects exceeding $1 million. Only a few bioremediation and chemical oxidation projects exceeded $1 million in total costs.

4.10 Are the Benefits of In-Situ Remediation Sustained for Years, or Do Concentrations Eventually Rebound?

4.10.1 What is the Prevalence of Rebound for Different Technologies?

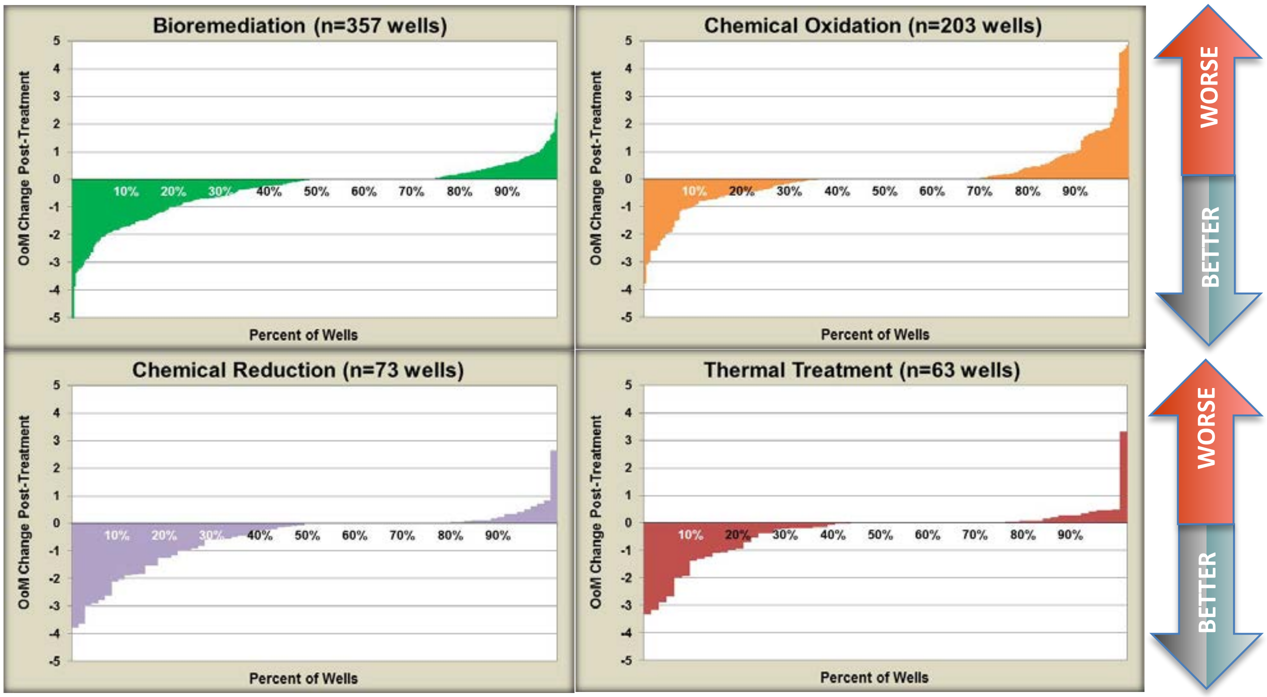


Figure 4.7. Rebound Frequency by Monitoring Well for Four In-Situ Remediation Technologies

Data Shown: *Frequency of rebound in monitoring wells, showing change in geomean parent concentrations from first monitoring period after actual remediation activities are terminated to last monitoring period (from 1 to 12 years).*

Explanation: *More colored bars above the "0" line in each panel shows rebound.*

Key Points

- Rebound can be defined in many ways. For this project it was defined as an increase in concentration (expressed as a change in OoMs) from first monitoring period after actual remediation activities are terminated to last monitoring period**.** This ranged from as little as one year for some sites to up to around 12 years at a few sites.

- With this definition, rebound was observed in a few monitoring wells for all technologies.
- Chemical oxidation projects appeared to have the most rebound, with about 30% of the monitoring wells showing rebound. About 10% of the chemical oxidation monitoring wells had rebound of 2 orders of magnitude compared to the post-treatment concentrations.
- Bioremediation had the next highest rebound, with about 25% of wells showing rebound. The severity of rebound was not as high as chemical oxidation, however.
- Thermal and chemical reduction project appeared to have the least rebound.
- The performance at bioremediation sites with shorter post-treatment monitoring records (<3 years) was similar to that observed at sites with longer post-treatment monitoring records (3 to 12 years). The median OoM reduction for sites with less than 3 years of post-treatment monitoring data (median = 1.1) is not significantly different than the median OoM reduction for sites with longer monitoring periods (median = 1.0) (p=0.80 based on Mann Whitney test).
- There were a significant number of sites where the post-treatment concentration fell below the MCL for PCE/TCE, including 26 (31%) of the sites with shorter monitoring periods and 13 (38%) of the sites with longer monitoring period. There were only 4 sites (5%) with less than 3 years of monitoring data where the post-treatment concentration was greater than the pre-treatment concentration.
- This evaluation also shows that there is little reason to expect additional rebound if longer-term monitoring (i.e., more than 3 years) is implemented. This pattern should help alleviate stakeholder or regulatory concerns that a shorter-duration monitoring program (i.e., less than 3 years) would "miss" rebound, and it suggests that remediation performance can be adequately assessed within 3 years.

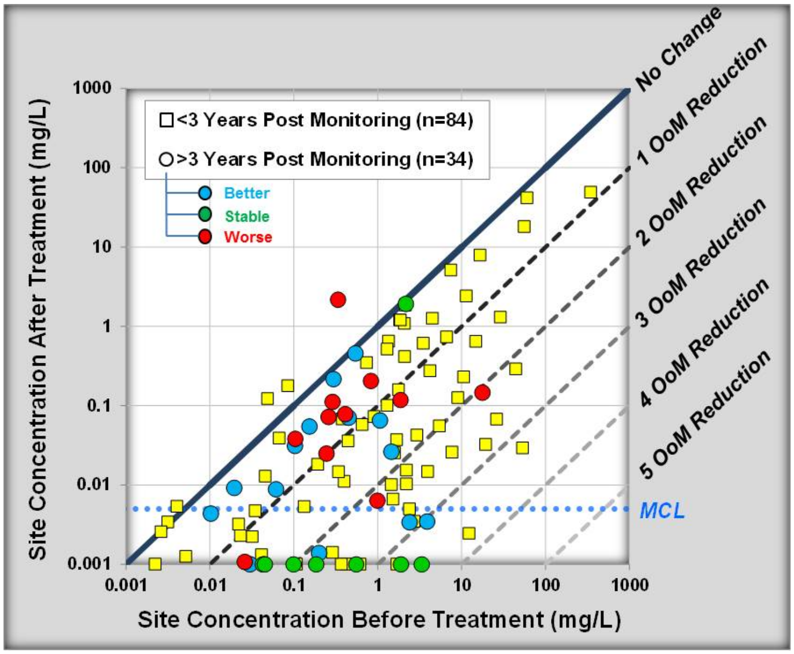


Figure 4.8. Before-Treatment and After-Treatment Concentrations at Bioremediation Sites with Short Post-Treatment Monitoring Records vs. Long Post-Treatment Monitoring Records.

Data Shown: *Change in maximum concentration of parent compound at enhanced bioremediation sites.*

Explanation: *Each dot represents an individual site, showing the maximum before-treatment concentration (X-axis) and after-treatment concentration at the end of the sampling record (Y-axis). Square symbols represent sites with less than 3 years of after-treatment monitoring; round symbols show sites that enjoyed continued reductions in concentration (blue circles); green* *showed relatively stable concentrations (green circles); and red show sites where concentrations increased over a 3+ year after-remediation monitoring period.*

4.10.2 *What is Bioremediation Sustained Treatment and How Often is It Observed?*

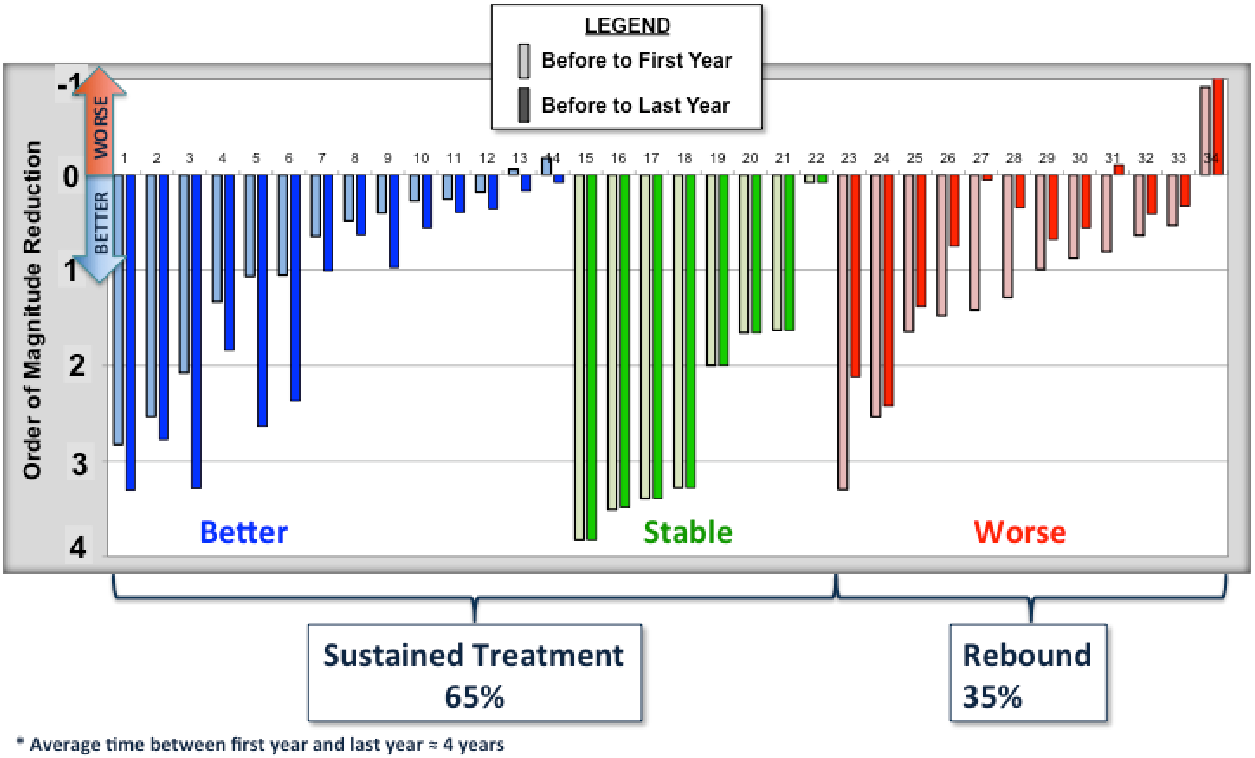


Figure 4.9. **Analysis of Sustained Treatment at 34 Bioremediation Sites with Long-Term After-Treatment Data**

Data Shown: *Order of Magnitude (OoM) reduction in geomeans of parent compound.*

Explanation: *Two bars are shown for each site with enough after-treatment data to be analyzed for sustained treatment. The Left Bar (light colored) shows observed OoM reductions from before-treatment parent concentrations to first year after treatment ends; the Right Bar shows before-treatment parent concentrations to last year of monitoring (typically 6 years after treatment ends).*

Key Points

- Sustained treatment is the continuation of attenuation processes at sites after active treatment ends due to the effects of: 1) endogenous decay; 2) activation of reactive minerals; and 3) electron donor diffusion. Since most of these support and/or result from microbial activity, sustained treatment is of particular interest at bioremediation sites.
- A total of 34 bioremediation sites had enough post-remediation concentration data (at least 3 years, median of 5 years, maximum of 12 years) to analyze sustained treatment.

- A total of 14 of these sites improved over the long after remediation-period, and 8 were about the same. A total of 12 of these bioremediation sites had increasing concentrations (rebound) during the after-remediation period. This suggests that 65% of the sites may have exhibited sustained treatment, while the remaining 35% of the bioremediation sites exhibited rebound.
- For the entire set of sites where rebound was observed, the median concentration reduction over the post-treatment monitoring period changed from 90% (after the first year) to 67% (after the last year). This suggests that the degree of concentration rebound is generally modest at sites where it occurs.
- The results suggest that sustained treatment processes are providing some benefit by preventing concentration rebound at the majority of these sites, but that these processes do not necessarily contribute to further concentration reductions except at a subset of sites.

4.11 How Does Active Remediation Compare to Monitored Natural Attenuation (MNA)?

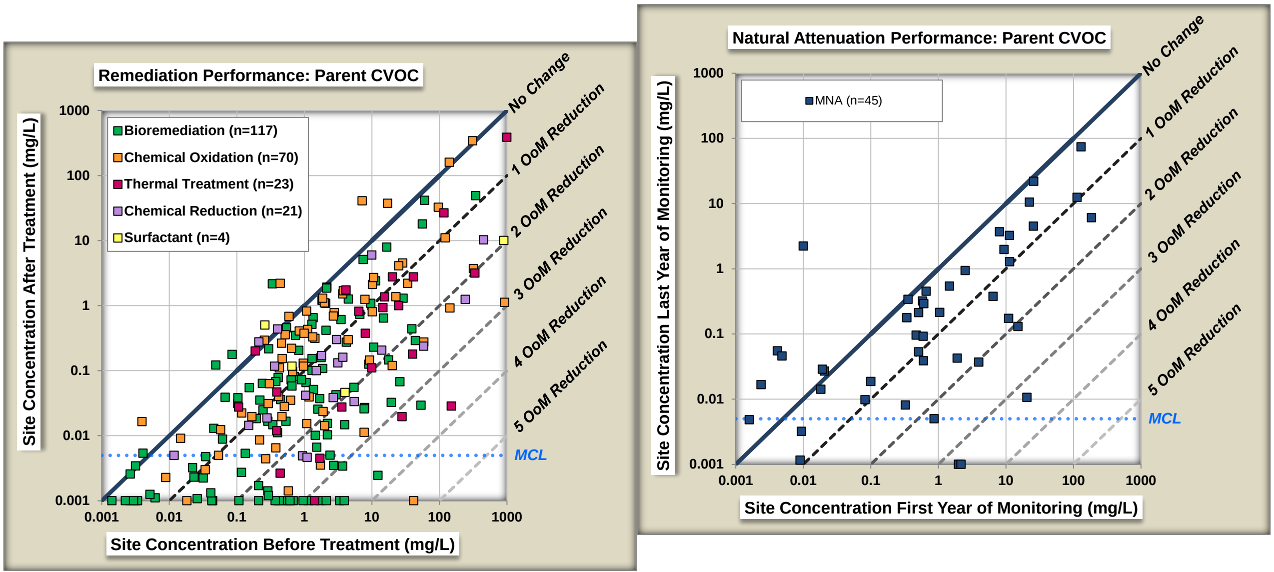


Figure 4.10. Performance of 235 Active Remediation Projects vs. 45 Monitored Natural Attenuation Projects

Data Shown: *Parent compound geomean concentration before and after treatment for remediation sites (left panel) and geomean of first year and last year concentrations for MNA sites (right panel).*

Explanation: *Each dot represents an individual project, showing the geomean before treatment concentration (X-axis) and after-treatment concentration at the end of the sampling record (Y-axis). The left panel is the same one shown in Figure 4.1. The right panel shows the results from 45 MNA sites.*

Key Points

- The performance of MNA projects can be compared to active remediation projects using similar analysis and metrics as was used for evaluating performance at active remediation projects. The change in the geometric mean of the parent compound concentration for the first year to the last year of the MNA monitoring record was about 0.7 OoMs (Table 4.5). This is only slightly lower than the median OoM reduction of 1.1 observed for all 235 of the remediation projects (see Table 4.1).

- MNA Sites had lower before treatment concentrations (median of 0.67 mg/L) compared to the active remediation sites (median of 1.3 mg/L), indicating that MNA is generally applied at lower concentration sites.
- A key differentiator is the time required to achieve the observed OoM reductions. For the active projects, the median treatment duration was 0.5 years. For the MNA projects, the median monitoring duration (analogous to "treatment" duration) was 8.7 years and ranged from 4.1 to 15 years.
- Using a very crude extrapolation of the medians, about 14 years would be required for the median OoM reduction at MNA sites to reach a value of 1.1 OoM reduction, the median performance achieved by active remediation. Therefore, active remediation speeds up the remediation process by about 13.5 years assuming no rebound or sustained treatment for the active projects, continued treatment by MNA, and holds only for this particular metric (geometric means of the parent compound).
- This type of analysis comparing the "time gained" toward achieving groundwater restoration by active remediation was discussed in Newell et al., 2006.

Table 4.5. Change in Parent Compound Geometric Mean Concentrations for Four Active In-Situ Remediation Technologies vs. MNA.

	Parent Median Geomean Concentration Before Treatment (mg/L)	Parent Median Concentration After Treatment (mg/L)	Median % Reduction in Geomean of Parent Compound in Treatment Zone	Median OoM Reduction Geomean of Parent Compound in Treatment Zone
Enhanced Bioremediation	0.74	0.03	96%	1.4
Chemical Oxidation	1.1	0.27	77%	0.6
Thermal Treatment	10	0.20	98%	1.7
Chemical Reduction	1.8	0.13	93%	1.1
MNA*	0.67	0.13	81%	0.7

* *Geomean concentrations for MNA sites based on First Year and Last Year of monitoring record.*
Median treatment time for 45 MNA Projects: 8.7 years.
Median treatment time for 235 Active Remediation Projects: 0.5 years.

4.12 What "Percent Complete to Restoration" Does a Typical Active In-Situ Remediation Project Achieve?

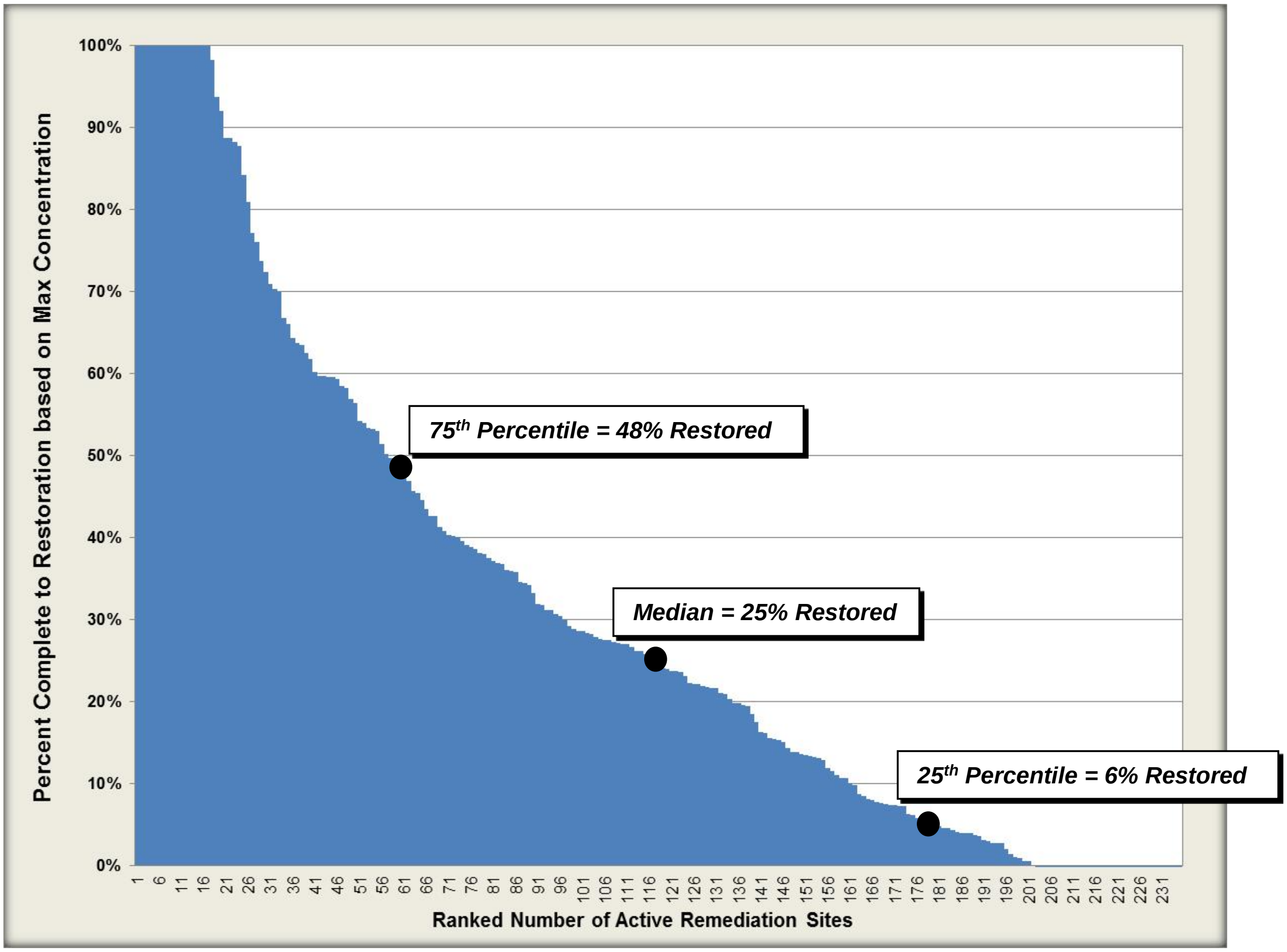


Figure 4.11. Approximate Percent Complete to Groundwater Restoration Achieved for 235 Active Remediation Sites Using Order of Magnitude Metric

Data Shown: *Percent complete to restoration based on maximum concentrations after treatment of parent compound in the treatment zone, where the percent to restoration is calculated relative to a 0.005 mg/L target concentration (values greater than 100% and less than 0% not shown)*

Explanation: *Each bar is an individual remediation project and assumes the OoM reduction in the maximum concentration of the parent compound can be used to calculate an approximate "Percent Complete to Restoration" metric. The sites that are at 100% achieved an after-remediation project maximum concentration less than the MCL; sites at 0% showed an increase in the after-remediation project maximum concentration compared to before treatment.*

Key Points

- The OoM metric assumes that remediation is a log-normal type activity, where progress can be measured by the number of OoMs a project achieves.

- If one extends the OoM metric all the way to a typical low part per billion cleanup standard (in this case we assume a 0.005 mg/L MCL), then two numbers can be compared: 1) the number of OoMs a remediation project actually achieved; and 2) the number of OoMs that are still required to reach a cleanup goal. Then the percent complete can be estimated using #1 divided by the sum of #1 and #2. For example, if the before treatment parent compound concentration was 5.000 mg/L; and if the project reduced concentrations to 0.05 mg/L, then 2 OoMs were achieved. However, to reach the metric used in this calculation (an MCL at 0.005 mg/L), an additional 1 OoM is required. Therefore this project achieved a 67% (1 ÷ 3) "percent complete to restoration."
- This calculation is sensitive to the choice of the metric (we used before and after treatment maximum concentrations as maximums are more relevant for a regulatory performance metric (see Section 4.7.1). The calculation is also sensitive to the cleanup target concentration (we used 0.005 mg/L, even though some sites are controlled by compounds that may have different MCLs).
- The "percent complete to restoration" metric is an indication of how far the site has to go achieve MCLs at the site. This number has been used in litigation cases to estimate what percentage of the required total remediation cost has been expended with the existing project, assuming that active remediation will be pursued until MCLs are reached. However, if more passive treatment approaches are used (e.g., MNA or containment) to manage the residual contamination, two implications are: 1) remediation timeframes will be longer; and 2) future costs are likely to be lower.
- The calculation does not account for any sustained treatment, source attenuation, or treatment train type projects after the original remediation project is complete.
- If one accepts these assumptions and limitations, it suggests that current practice as reflected in the 235-site database typically gets between 6% and 48% (this is the middle 50% of the sites shown in Figure 4.32), with a median of 25% of "Percent Complete to Restoration".

5.0 RESULTS OF SPECIAL TOPIC STUDIES

This section describes the results of special studies that were conducted to further assess in-situ remediation performance at CVOC groundwater sites. For more complete information on these topics see the ESTCP Final Report for this project.

Results of Focused Field Studies

Long-term follow-up sampling was performed for 5 remediation projects that were previously conducted at Tinker AFB and Altus AFB. The objective was to further evaluate long-term concentration trends following in-situ remediation. Results demonstrated that sustained treatment was still occurring 5 to 10 years after treatment at 2 bioremediation sites where a slow-release substrate was used. Concentrations had rebounded to pre-treatment levels at 1 bioremediation site where a soluble substrate was used. For the 2 chemical oxidation sites tested, 1 site rebounded to near pre-treatment levels, while concentrations remained depressed at the other site.

Analysis of "Remediation Done Right" Sites

To get an independent perspective on in-situ remediation performance, a review of three well-implemented, well-reported, peer-reviewed remediation projects was performed (Heron et al., 2005; Hood et al., 2008; and Thomson et al., 2007). These projects represent "remediation done right" for individual one-phase treatment projects (i.e., treatment trains are excluded from this analysis). The objective was to evaluate the performance for well-designed, well executed, and well-documented in-situ remediation projects in the scientific literature. The results reported for these three projects indicated that two of three sites outperformed many of the sites in the 235 site database (achieving parent CVOC reductions of 2.7 and 3.5 OoMs), while the third site had a result more comparable to the median of the 235 site dataset with a 0.8 OoM reduction.

Table 5.1. OoM Reduction in Parent Compound at 235 Databases Sites vs. 3 "Remediation Done Right" Sites

Median OoM (%) Reduction for 235 Database Sites	Median OoM (%) Reduction for 3 "Remediation Done Right" Sites
1.1 (91%)	**2.7 (99.8%)**

Analysis of Treatment Train Sites

14 sites in the database implemented multiple technologies in successive treatments or "treatment trains." Overall the treatment train sites achieved about a 2.3 OoM reduction based on the median of all 14 sites. This is significantly higher than the median OoM reduction of 1.1, as well as the 75th percentile of 2.0 OoM, observed for all 235 of the remediation projects. Based on the poorer OoM reduction typically achieved by the first technology at these sites, it is likely that a key factor in the success of the second technology was the benefit of lessons learned from the first technology implementation.

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