TECHNICAL REPORT

Methods for Minimization and Management of Variability in Long-Term Groundwater Monitoring Results
Task 2 & 3 Report

ESTCP Project ER-201209

DECEMBER 2015

Thomas McHugh
Poonam Kulkarni
Lila Beckley
Charles Newell
Brian Strasters
GSI Environmental, Inc.

Distribution Statement A

This document has been cleared for public release

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
20-12-2015	Task Report	Sept 2012 to Dec 2015

4. TITLE AND SUBTITLE
A New Method to Optimize Monitoring Frequency and Evaluate Long-Term Concentration Trends

5a. CONTRACT NUMBER
W912HQ-12-C-0055

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
McHugh, Thomas E ., Kulkarni, Poonam R., Beckley, Lila M., Newell, Charles J., Strasters, Brian A.

5d. PROJECT NUMBER
ER-201209

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
GSI Environmental Inc.;
2211 Norfolk, Suite 1000
Houston, Texas 77098

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Environmental Security and Technology Certification Program
4800 Mark Center Drive, Suite 17D08
Alexandria, VA 22350-3600

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
ER-201209

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Cost-effective, long-term monitoring schemes are needed in order to understand the long-term changes in contaminant concentrations. The optimization method and evaluation of concentration trends presented in this report can help project managers answer the following key questions: 1) How much monitoring data do I need to determine a site's long-term source attenuation rate with a defined level of accuracy or confidence? 2) What are the trade-offs between monitoring frequency vs. the time required for trend identification? 3) When will this site meet the groundwater clean-up goal? For instance, for a fixed number of monitoring events, doubling the time between monitoring events (e.g., changing from quarterly monitoring to semi-annual monitoring) will double the accuracy of estimated attenuation rate. For a fixed monitoring frequency (e.g., semi-annual monitoring), increasing the number of monitoring events by 60% will double the accuracy of estimated attenuation rate. Combining these two factors, doubling the time between monitoring events (e.g., quarterly monitoring to semi-annual monitoring) while decreasing the total number of monitoring events by 38% will result in no change in the accuracy of estimated attenuation rate. However, the time required to collect this dataset will increase by 25%. Understanding that the trade-off between monitoring frequency and monitoring duration is not site-specific should simplify the process of optimizing groundwater monitoring frequency at contaminated

15. SUBJECT TERMS
15. SUBJECT TERMS
Monitoring frequency optimization, Long-term concentration trends, Attenuation Rates

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE		119	Thomas McHugh
					19b. TELEPHONE NUMBER *(Include area code)* 713-522-6300

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

TABLE OF CONTENTS

E.0 EXECUTIVE SUMMARY 1
E.1 DEVELOPMENT OF THE EVALUATION METHODS 1
E.2 APPLICATION OF THE OPTIMIZATION METHOD TO TWENTY SITES 2
E.3 APPLICATION OF THE VARIABILITY ANAYSIS METHOD TO TWENTY SITES 4

1.0 INTRODUCTION 6
1.1 BACKGROUND 6
1.2 OBJECTIVE OF TASK 2 8
1.3 OBJECTIVE OF TASK 3 8

2.0 BASIS FOR THE MONITORING OPTIMIZATION AND TREND ANALYSIS METHODS 10
2.1 LONG-TERM MONITORING RECORD 10
2.2 CHARACTERISTICS OF THE LONG-TERM TREND 11
2.3 CHARACTERISTICS OF SHORT-TERM VARABILITY 11
2.3.1 Short-Term Variability is Mostly Time Independent 13
2.3.2 Short-Term Variability is Proportional to the "True" Concentration 17
2.3.3 Short-Term Variability Can Be Described by a Log-normal Distribution 18

3.0 DEVELOPMENT OF MONITORING OPTIMIZATION METHOD 21
3.1 GENERATION OF SIMULATED MONITORING DATA 21
3.2 DETERMINATION OF MONITORING REQUIRED TO IDENTIFY A TREND 22
3.2.1 Trend Confidence and Accuracy 22
3.2.2 Use of Monte Carlo Analysis to Determine Monitoring Requirements 22
3.3 CALIBRATION OF MONITORING OPTIMIZATION USING HISTORICAL SITE MONITORING DATA 24
3.3.1 Calculation of the long-term attenuation rate 24
3.3.2 Calculation of the short-term variability factor 24
3.4 DEVELOPMENT AND USE OF EXCEL-BASED MONITORING OPTIMIZATION AND TREND ANALYSIS TOOLKIT 24
3.5 EVALUATION OF SENSITIVITY TO MODEL ASSUMPTIONS 25
3.5.1 The Effect of Time Dependence in Short-Term Variability 25
3.5.2 The Effect of Proportionality to the "True" Concentration 25
3.5.3 Short-Term Variability can be Described by a Log-normal Distribution 26

4.0 DEVELOPMENT OF TREND ANALYSIS METHOD 27
4.1 EVALUATION OF OVERALL SOURCE ATTENUATION RATE 27
4.2 EVALUATION OF DIFFERENCES IN INDIVIDUAL WELL ATTENUATION RATES 27

5.0 RESULTS FROM APPLICATION OF THE MONITORING OPTIMIZATION AND TREND ANALYSIS TOOLKIT 29
5.1 APPLICATION TO TWENTY SITES 29
5.1 RESULTS OF MONITORING VARIABILITY ANALYSIS 30
5.2 RESULTS OF OPTIMIZATION ANALYSIS 34
5.3 TRADEOFF BETWEEN MONITORING TIME, MONITORING FREQUENCY 37

6.0 REFERENCES 39

LIST OF TABLES

Table 1.1 Number of Monitoring Wells and Monitoring Frequency in Large Monitoring Databases 7
Table 2.1 Sites Included in Analysis of Characteristics of Short-Term Variability 12
Table 2.2 Results Summary for Evaluation of Time Dependence of Short-Term Variability 15
Table 2.3 Results Summary for Evaluation of the Distribution of Short-Term Variability 20
Table 5.1 Sites Included in Evaluation of Monitoring Optimization and Trend Analysis Toolkit Results 30
Table 5.2 Long-Term Attenuation Rates and Short-Term Variability for Evaluation Sites 31
Table 5.3 Evaluation of Individual Well Attenuation Rates at 20 Sites 33
Table 5.4 Number of Quarterly Monitoring Events Required to Characterize the Long-Term Attenuation Rate with Medium Confidence 35
Table 5.5 Number of Quarterly Monitoring Events Required to Characterize the Long-Term Attenuation Rate with Medium Accuracy 36
Table 5.6 Trade Off Between Monitoring Frequency and Monitoring Time 37

LIST OF FIGURES

Figure 2.1 Method for Evaluation of Time Dependence of Short-Term Variability in Groundwater Monitoring Results 13
Figure 2.2 Example Results for Evaluation of Time Dependence of Short-Term Variability in Groundwater Monitoring Results. About Half the Sites Studied Resembled Example 1 and Half Example 2 14
Figure 2.3 Results for Evaluation of Time Dependence of Short-Term Variability for Task 1 Sites 16
Figure 2.4 Representative Results for Evaluation of the Relationship between Short-Term Variability and "True" Concentration 17
Figure 2.5 Example Results for Evaluation of the Distribution of Short-Term Variability: TCE, Superfund Site, Montana 19

APPENDICES

Appendix A: Statistical Properties of Short-Term Variability in Groundwater Monitoring Results at 10 Sites
Appendix B: Effect of Monitoring Frequency and Monitoring Duration on Accuracy and Confidence in the Long-Term Attenuation Rate
Appendix C: Monitoring Optimization and Trend Analysis Toolkit and User's Guide

ACRONYMS

COC	Chemical of concern
DoD	Department of Defense
ERPIMS	Environmental Restoration Program Information Management System
ESTCP	Environmental Security Technology Certification Program
ft	Foot, feet
GTS	Geostatistical Temporal-Spatial
LTM	Long term monitoring
MAROS	Monitoring and Remediation Optimization System
MNA	Monitored Natural Attenuation
NIRIS	Naval Installation Restoration Information Solution
O&M	Operation and Maintenance
PCE	Tetrachloroethylene
RPD	Relative percent difference
RV	Recreational vehicle
SERDP	Strategic Environmental Research and Development Program
TCE	Trichloroethylene
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compound

E.0 EXECUTIVE SUMMARY

The purpose of this ESTCP project is to develop methods to understand and manage variability in groundwater monitoring results. The primary goal of Tasks 2 and 3 are to develop a new method to evaluate long-term concentration trends and optimize monitoring frequency based on an understanding of the short-term variability and long-term attenuation rate at a particular site.

The optimization method (Task 2) is designed to help a project manager answer two questions:

> Question 1: How much monitoring data do I need to determine a site's long-term source attenuation rate with a defined level of accuracy or confidence?
>
> Question 2: What are the trade-offs between monitoring frequency (e.g., quarterly, semi-annually, or annually) vs. the time required for trend identification (the number of years until you get the answer to Question 1)?

The evaluation of concentration trends (Task 3) is designed to help the project manager answer two questions:

> Question 1: When will this site meet the groundwater clean-up goal (i.e., What is the long-term attenuation rate for the key contaminant at my site)?
>
> Question 2: Do any individual wells appear to be attenuating more slowly than the source as a whole?

E.1 DEVELOPMENT OF THE EVALUATION METHODS

The evaluation methods developed for Tasks 2 and 3 are based on the statistical characteristics of long-term monitoring records. The long-term monitoring record from a monitoring well is controlled by two very different factors: the *long-term concentration trend* and *short-term variability*.

1) The *long-term concentration trend* can be reasonably approximated by first-order decay, which we call a source attenuation rate.
2) The *short-term variability* signal is basically a random, log-normally distributed, and time independent process that is proportional to the signal of the "true" concentration.

Based on this understanding, the variability analysis method uses Monte Carlo analysis to evaluate whether the differences in observed long-term attenuation rates between individual monitoring wells are consistent with the random effects of short-term monitoring variability or indicative of true spatial differences in attenuation rates within different portions of the groundwater plume.

The optimization method uses a simulated dataset that matches the statistical properties of the site being evaluated. This simulated dataset is used to determine how much monitoring data is required to determine the long-term source attenuation rate for each monitoring well with a defined level of confidence or accuracy.

<u>Attenuation rate confidence</u>: Is the source attenuation rate significantly different from zero? In other words, how likely is it that the observed change in concentration over time reflects a true long-term trend rather than an artifact of the random variability? Knowing the confidence in the source attenuation rate is important when you are demonstrating that contaminant concentrations are actually decreasing.

Attenuation rate accuracy: What is the uncertainty associated with the estimated source attenuation rate? For example, what is the 95% confidence interval? Knowing the accuracy of the source attenuation rate is important when you are estimating the time required for concentrations to decrease to a numerical clean-up goal.

The variability analysis and optimization methods have been implemented in Excel spreadsheet form (see Appendix C). The variability analysis method can be used to evaluate whether individual monitoring wells with slower attenuation rates are likely to impact the overall site remediation timeframe:

1) Use the Excel spreadsheet tool to estimate the site remediation timeframe using i) historical monitoring data from 4 to 20 monitoring wells with at least two years' worth of monitoring events for each well (recommended at least 5 monitoring events), ii) a representative current source area contaminant concentration, and iii) a numerical clean-up goal.
2) Using the historical monitoring data, the Excel tool will identify whether any individual monitoring wells exhibit attenuation rates that are slower than the range expected due to the effects of short-term variability.
3) If slower attenuation rate wells are identified, evaluate whether these monitoring wells are likely to prevent attainment of the clean-up goals within the desired timeframe. For example, slower source area wells may delay attainment of the overall clean-up goal. However, slower plume wells may not delay overall clean-up because the current contaminant concentrations in these wells are typically lower than in source area wells.

This new optimization method can be used to select an appropriate monitoring frequency as follows:

1) Select the primary goal of long-term monitoring. This optimization method is appropriate when the long-term monitoring data will be used to either:
    i) demonstrate that constituent concentrations are decreasing: the method will determine the amount of monitoring needed to determine the direction of the long-term trend (i.e., increasing or decreasing) with a defined level of confidence; OR
    ii) determine how fast concentrations are decreasing or when concentrations will decrease to a clean-up goal: the method will determine the amount of data needed to estimate the long-term attenuation rate with a defined level of accuracy. The attenuation rate can be used to estimate when concentrations will decrease to a clean-up goal.
2) Identify the timeframe in which the monitoring goal should be met. In other words, how quickly does the demonstration of decreasing concentrations or time to clean-up need to be made?
3) Based on the monitoring goal and the decision timeframe, use the Excel spreadsheet tool to determine the appropriate monitoring frequency.

As discussed in Section 2.2, the evaluation methods are based on the assumption of first-order source attenuation. Therefore, the evaluation methods will be less accurate for sites where the true source attenuation deviates significantly from first-order.

E.2 APPLICATION OF THE OPTIMIZATION METHOD TO TWENTY SITES

In order to evaluate typical results, the optimization analysis method has been applied to twenty contaminated groundwater sites: nine benzene sites, eight PCE/TCE sites, and three arsenic sites. For each site, we answered the two optimization questions from above.

Question 1: How much monitoring data do I need to determine a site's long-term source attenuation rate with a defined level of accuracy or confidence?

Table E.1: Monitoring Data Required to Determine the Long-Term Attenuation Rate

Accuracy/Confidence Goal	Years of Quarterly Monitoring Required		
	Best Site	**Median Site**	**Worst Site**
Medium Confidence: Statistically-significant decreasing concentration trend ($p<0.1$) for 80% of monitoring wells	2.8 years	7.3 years	30 years
Medium Accuracy: Determine the long-term attenuation rate with an accuracy (i.e., 95% confidence interval) of +/- 50% or +/- 0.1 yr^{-1} (whichever is larger) for 80% of monitoring wells.	4 years	7.4 years	14.5 years

Our evaluation of real datasets showed that characterization of the long-term trend with either medium confidence or medium accuracy almost always requires four or more years of quarterly monitoring data.

Based on application of the Monitoring Optimization and Trend Analysis Toolkit at 20 sites, additional key findings are:

- It is important for project managers to recognize that apparent trends characterized using too little data can be misleading and may result in inappropriate management decisions.
- When evaluating natural attenuation, there are often situations where the project manager can be confident that contaminant concentrations are decreasing but highly uncertain as to when numerical clean-up goals will be attained.
- For sites with slow attenuation rates, it may be difficult to prove with statistical confidence that contaminant concentrations are decreasing.

Question 2: What are the trade-offs between monitoring frequency (e.g., quarterly, semi-annually, or annually) vs. the time required for trend identification (the number of years until you get the answer to Question 1).

For Question 2, the answer is the same for all sites. Although the time required to characterize the long-term attenuation rate depends on both the short-term variability and the attenuation rate, the trade-off between monitoring frequency and monitoring time is independent of these parameters. The relative trade off between monitoring frequency and time required to characterize the long-term trend is summarized in Table E.2.

Table E.2 Trade Off Between Monitoring Frequency and Monitoring Time

Monitoring Frequency	Relative Time Required to Characterize Long-Term Trend	Relative Cost to Characterize Long-Term Trend	Relative Value of One Monitoring Event
Weekly	0.40	5.3	0.19
Monthly	0.67	2.0	0.50
Quarterly	**1**	**1**	**1**
Semi-Annual	1.25	0.63	1.6
Annual	1.56	0.39	2.6
Every 2 Yrs	1.95	0.24	4.1
Every 5 Yrs	2.85	0.15	6.7

Note: Relative cost is the same as the relative total number of monitoring events required (i.e., based on the assumption that cost is proportional to number of monitoring events). See Appendix B for derivation of these relationships.

For example, a site that required four years of quarterly monitoring to characterize the long-term attenuation rate would require five years (= 4 x 1.25) of semiannual monitoring to characterize the long-term trend with the same level of accuracy. Four years of quarterly monitoring is 16 total monitoring events while five years of semiannual monitoring is ten total monitoring events. Therefore, the relative cost of the annual monitoring program would be 60% (10/16) of the cost of the quarterly monitoring program. **A project manager can use the trade off between monitoring frequency and monitoring time to select an optimal monitoring frequency.**

E.3 APPLICATION OF THE VARIABILITY ANAYSIS METHOD TO TWENTY SITES

In order to evaluate typical results, the trend analysis method has been applied to the same twenty contaminated groundwater sites. For each site, we answered the two variability analysis questions from above.

Question 1: When will this site meet the groundwater clean-up goal (i.e., What is the long-term attenuation rate for the key contaminant at my site)?

The remediation timeframe is estimated using the long-term attenuation rate and user-specified values for current source area concentration and remediation goal. In order to capture some of the uncertainty associated with estimating remediation timeframes, the tool uses the 25th percentile and 75th percentile attenuation rates from individual monitoring wells to calculate a time range. For the benzene and TCE/PCE sites, we used the recent concentration in the most contaminated monitoring well as the current source area concentration and 5 ug/L as the remediation goal. We did not evaluate remediation timeframes at the three arsenic sites because arsenic concentrations appeared to be increasing at two of these three sites. For the nine benzene sites, the 25th percentile remediation time ranged from 2 to 22 years, with a median of 14 years; the 75th percentile remediation time ranged from 3.3 to >1000 years, with a median of 27 years. For the eight TCE/PCE sites, the 25th percentile remediation time ranged from 3 to 76 years, with a median of 24 years; the 75th percentile remediation time ranged from 20 to >1000 years, with a median of 288 years.

Question 2: Do any individual wells appear to be attenuating more slowly than the source as a whole?

The 20 test sites included a total of 254 individual monitoring wells. Of those wells, 158 (62%) had long-term attenuation rates that were within the expected range based on the overall source attenuation rate and the expected effect of short-term variability. 50 monitoring wells showed faster than expected attenuation

rates and 46 wells showed slower than expected attenuation rates. Of the 20 test sites, all of the sites had at least one monitoring well with an attenuation rate that was either faster or slower than expected. This suggests at most sites, the variation in attenuation sites between monitoring wells is only partly explained by the effects of short-term variability on observed attenuation rates. Other effects such as matrix diffusion, multiple source areas, and/or true spatial variations in attenuation processes likely contribute to observed variations in attenuation rates across individual sites.

Although all of the sites had at least one monitoring well with an attenuation rate outside of the expected range, only 10 of the 20 sites had a "slower well" in the source area such that the "slower well" might control the overall site remediation timeframe. At the other 10 sites, the slower attenuation rate wells were monitoring wells with lower contaminant concentrations and would not be expected to affect the overall time required to attain the groundwater clean-up goals. At the 10 sites where slower attenuation rates could affect the overall remediation timeframe, the user of the Monitoring Optimization and Trend Analysis Toolkit would i) evaluate whether the remediation timeframe for the slower attenuation rate wells is consistent with the remediation objectives for the site and ii) if not, target the area of the slower wells for additional remedial actions.

1.0 INTRODUCTION

The purpose of this ESTCP project is to develop methods to understand and manage variability in groundwater monitoring results. The specific goals of the project are as follows:

1) Task 1: Validate the use of improved field sampling procedures for the collection of groundwater samples in order to minimize variability in groundwater monitoring results.
2) Task 2: Develop and validate an improved method to optimize monitoring frequency for Monitored Natural Attenuation (MNA) sites and sites with long-term active remedies based on a site-specific evaluation of the short-term variability and long-term attenuation rate.
3) Task 3: Develop and validate an improved method to identify long-term concentration trends that better accounts for the potentially confounding effects of short-term variability.

This report describes the results for Task 2 and Task 3.

1.1 BACKGROUND

Purpose of Long-Term Monitoring: Once a contaminant plume has been shown to be stable or shrinking (either from MNA alone or due to a long-term containment remedy such as groundwater pump and treat), the primary purpose of long-term monitoring is to document progress towards attainment of the long-term contaminant concentration goal. The results from SERDP project ER-1705 have shown that variation in groundwater results has two distinct components:

i) random variability that occurs over a short time scale (i.e., short-term variability) and

ii) a long-term change in concentration that continues over a period of years (i.e., the long-term concentration trend; McHugh et al., 2011). If the contaminant plume is stable or shrinking in size then the long-term concentration trend in an individual monitoring well must be decreasing (assuming no new release of contamination at the site).

The long-term change (i.e., the attenuation rate) is of primary interest for i) documenting that contaminant concentrations are decreasing over time or ii) estimating the time required to attain clean-up goals. Therefore, it is useful to establish a monitoring frequency that allows the long-term trend to be characterized with a desired level of accuracy or confidence within a desired time period.

Methods for Optimizing Long-Term Monitoring Frequency: Current schemes for optimizing monitoring frequency, however, include methods that do not adequately account the effect of monitoring frequency and monitoring duration on the accuracy and confidence in the long-term trend. For example, the current version of the Monitoring and Remediation Optimization System (MAROS) software recommends a monitoring frequency for each individual well (or the site as a whole) based on the prior observed rate of change in concentration (MAROS, 2012). The Geostatistical Temporal Spatial (GTS) software uses iterative thinning or a temporal variogram constructed from prior monitoring results to optimize monitoring frequency (AFCEC, 2010). None of these methods provide the user with an understanding of either i) the total amount of monitoring data required to characterize the long-term trend with a defined level of confidence or accuracy or ii) the trade-off between monitoring frequency and time required to characterize the long-term trend.

As a result of the evaluation methods, **none of the currently available monitoring optimization tools quantify the relationship between monitoring frequency, monitoring duration, and accuracy of the long-term concentration trend**. For Task 2 of this project, we have developed a new method to determine how much monitoring data is required to characterize the long-term trend with a defined level of accuracy or confidence.

Methods for Evaluating Progress in Remediation: Trend analysis is commonly used to evaluate progress in remediation (e.g., U.S. EPA, 2011; MAROS, 2012). Trend analysis can be used to answer two key questions related to groundwater monitoring:

1) Are contaminant concentrations decreasing over time?
2) What is the attenuation rate and when will the site remediation goals be attained?

One parametric method (linear regression) and two non-parametric methods (Mann-Kendall and Theil-Sen Slope Estimator) are commonly used to evaluate concentration trends over time. Mann-Kendall can only be used to evaluate the concentration trend (i.e., are concentrations increasing or decreasing) while linear regression and the Theil-Sen Slope Estimator can be used to evaluate both concentration trend and attenuation rate. Trend analysis may be conducted for individual monitoring wells or using for the plume as a whole (i.e., using a representation of plume mass or average plume concentration).

Current trend analysis schemes typically do not do a good job of evaluating differences in attenuation between monitoring wells. Observed differences in attenuation between monitoring wells may be due to either i) the effect of short-term variability causing random variations apparent attenuation or ii) true spatial differences contaminant attenuation. True differences in attenuation rates may be caused by spatial variations in the effects of active remediation systems (for sites with active remediation), the presences of multiple sources areas with different attenuation rates, or spatial differences in plume attenuation due to differences in matrix diffusion or other contaminant fate processes. **Accurately distinguishing between random variations in well-specific attenuation rates and true spatial differences in plume attenuation is important for evaluating the true effectiveness of site remediation.** For Task 3 of this project, we have developed a new method for evaluating the importance and practical significance of observed differences in attenuation rates between monitoring wells at a site.

Number of Monitoring Wells in the United States: Because there is no comprehensive, national database of groundwater monitoring results, it is difficult to estimate the total number of monitoring wells at contaminated sites. However, different organizations maintain large databases that can be used to estimate the overall level of effort expended in groundwater monitoring. The California Geotracker database, for instance, includes monitoring results for contaminated groundwater clean-up sites in California. Both the Air Force (ERPIMS) and Navy (NIRIS) have databases that include groundwater monitoring results for most of the groundwater clean-up sites being managed by these service branches. Table 1.1 summarizes the number of monitoring wells currently being sampled that are included in these databases.

Table 1.1 Number of Monitoring Wells and Monitoring Frequency in Large Monitoring Databases

Database (Year Evaluated)	Number of Monitoring Wells	Monitoring Frequency (Percentage of Wells)		
		Quarterly	Semi-Annually	Annually
California GeoTracker Database (2012)	56,000	25%	45%	30%
Air Force ERPIMS Database (2013)	11,800	4%	15%	81%
Navy NIRIS Database (2013)	9,200	Not Available	Not Available	Not Available
Army (estimate based on NRC Report)	20,000	Not Available	Not Available	Not Available

Although we were not able to obtain information on the number of monitoring wells sampled by the Army, the Army is responsible for approximately 50% of the contaminated sites being managed by the DoD (NRC, 2013). If these sites have, on average, the same number of monitoring wells as Navy and Air Force sites, then the available data suggest that the DoD is currently sampling over 40,000 monitoring wells per year. At $1,000 per sample per well (including labor cost for sample collection and data management), this would represent a cost of $40,000,000 to $120,000,000 per year depending on monitoring frequency. This estimated monitoring cost is similar to a recent estimate by the National Research Council of "over $100,000,000" annual monitoring costs at DoD facilities (NRC, 2013). If we assume that the number of monitoring wells in each state is proportional to the population, then the 56,000 monitoring wells in California represent 12% (U.S. Census Bureau, 2014) of the monitoring wells in the United States. This suggests that there are over 460,000 monitoring wells currently being sampled at least annually in the United States.

Given the number of monitoring wells at DoD sites and in the United States as a whole, it is important to quantify this variability, evaluate it in terms of overall monitoring objectives, and use it to develop cost effective and efficient monitoring programs.

1.2 OBJECTIVE OF TASK 2

The objective of this task is to develop and validate an improved method to optimize groundwater monitoring frequency for sites undergoing long-term monitoring (i.e., during MNA or during the operation and maintenance (O&M) phase of a long-duration active remedy). This method uses information regarding short-term monitoring variability and the long-term contaminant attenuation rate to answer these questions:

Question 1: How much monitoring data do I need to determine a site's long-term source attenuation rate with a defined level of accuracy or confidence?

Question 2: What are the trade-offs between monitoring frequency (e.g., quarterly, semi-annually, or annually) vs. the time required for trend identification (the number of years until you get the answer to Question 1)?

This project developed tools that can be used by site managers to answer these questions. In particular, the specific project objectives were to:

1) *Characterize* the statistical properties of short-term variability in several actual site groundwater monitoring datasets;
2) *Develop* a method to optimize monitoring frequency based on an understanding of the short-term variability and long-term attenuation rate at a particular site; and
3) *Create* a simple spreadsheet tool that will help site managers implement this optimization method and incorporate the method into comprehensive Long-Term Monitoring Optimization (LTMO) packages at DoD sites around the country.

1.3 OBJECTIVE OF TASK 3

The objective of this task is to develop and validate an improved method to distinguish between random variability in observed attenuation rates and true spatial differences in remedy performance. This method uses information regarding short-term monitoring variability and the long-term contaminant attenuation rate to answer these questions:

Question 1: When will this site meet the groundwater clean-up goal (i.e., What is the long-term attenuation rate for the key contaminant at my site)?

Question 2: Do any individual wells appear to be attenuating more slowly than the source as a whole?

This project developed tools that can be used by site managers to answer these questions. In particular, the specific project objectives were to:

1) *Develop* a method to distinguish between random variations in attenuation rates and true spatial differences in remedy performance; and
2) *Create* a simple spreadsheet tool that will help site managers implement this remedy performance evaluation method and incorporate the method into comprehensive Long-Term Monitoring Optimization (LTMO) packages at DoD sites around the country.

1.4 APPLICABILITY OF EVALUATION METHODS AND TOOLKIT

As discussed in Section 2.2 of this report, the data evaluation methods are based on an assumption of first order source attenuation. The evaluation methods should not be applied to monitoring records where first order attenuation is clearly not applicable. For example, the methods should not be applied to monitoring records covering an initial period of plume expansion followed by stabilization and decrease. For sites where short-duration active remediation has been applied (e.g., chemical oxidation, thermal treatment), the first order source attenuation concept is applicable to the polishing period after active remediation is complete. In other words, the method described in this manual is for long periods where the effects of active remediation or natural attenuation processes are relatively constant. Monitoring records before- and after-aggressive remediation **should not be combined.**

2.0 BASIS FOR THE MONITORING OPTIMIZATION AND TREND ANALYSIS METHODS

The purpose of Tasks 2 and 3 for this project is to demonstrate improved data analysis methods that better account for the confounding effects of short-term variability on the long-term concentration trend. This improved data analysis method is based on three fundamental observations regarding groundwater monitoring results:

1) Long-term monitoring record: The long-term monitoring record from a monitoring well is controlled by two very different factors: the *long-term concentration trend* and *short-term variability*.
2) The *long-term trend* can be reasonably approximated by first-order decay, which we call a source attenuation rate.
3) The *short-term variability* signal is basically a random, log-normally distributed, and time independent process that is proportional to the signal of the "true" concentration.

The basis for each of these observations is described below.

2.1 LONG-TERM MONITORING RECORD

The contaminant concentration measured in a water sample collected from a monitoring well is a function of two factors: i) the "true" underlying concentration and ii) variability. The "true" concentration can be thought of as the concentration that would be measured if the aquifer was homogenous with uniform groundwater flow and there was no sampling or analytical variability. However, the actual measured concentrations are distorted by several types of variability including:

- ***Signal Variability.*** Changes in constituent concentration within the bulk groundwater in the vicinity of the monitoring well. These changes may be due to source remediation or may reflect variations in groundwater flow direction, water table fluctuation, or other short-term changes in the fate and transport of volatile organic compounds (VOCs) from the source to the monitoring point that are not directly related to the long-term trend.

- ***Aquifer and Well Dynamics.*** When constituent concentrations are stratified within the aquifer, then flow dynamics within the monitoring well and the impact of the sampling method on those flow dynamics can impact the monitoring results.

- ***Sample Collection and Handling.*** VOCs, by their nature, move readily from water to air. As a result, VOC loss during sample collection and handling can contribute to variability between samples and loss of accuracy in monitoring. Such VOC losses can occur in conventional groundwater sampling, for example, when the water sample is poured into a sampling vial. Other constituents may also be affected by sample collection and handing procedures. For example, metals results can be affected by the amount of sediment entrained in the sample.

- ***Sample Analysis.*** Monitoring accuracy depends on the accuracy, precision, and reproducibility of the laboratory analysis. However, prior studies have found that analytical variability is a small component of overall monitoring variability (McHugh et al., 2011).

The primary purpose of long-term monitoring is to track the change in "true" concentration over time. The differences in how the "true" concentration and the variability change over time can be used to develop an optimized monitoring scheme.

2.2 CHARACTERISTICS OF THE LONG-TERM TREND

Following the initial release of contaminants into groundwater, contaminant concentrations may increase with time as they dissolve into water and migrate from the source area. However, at a site without on-going releases into the environment and where the groundwater plume is no longer expanding, the long-term concentration trend must be decreasing as contaminants are depleted from the source area. For many temporal monitoring records, a linear model and a first-order model provide similar statistical fits (i.e., similar R^2 values; McHugh et al., 2011; Newell et al., 2006). However, it has been widely observed that linear models under-predict remediation time frames due to tailing in contaminant concentrations (USEPA, 1989, USEPA, 1996, NRC, 2013).

At contaminated groundwater sites, the change in contaminant concentration in a monitoring well over a long time period typically reflects the long-term change in mass flux from the source area (Newell et al., 2002). The change in mass flux over time will be first order when the flux from the source is proportional to the source mass (Newell and Adamson, 2005). Matrix diffusion and other processes can cause deviations from first-order decay, however, first-order decay usually provides a reasonable fit to the observed change in concentration over time and is the most commonly used source decay model (Newell et al., 2006; McHugh et al., 2011). First order attenuation rates are almost always used to represent the attenuation reflected in historical site monitoring data. Although more sophisticated multi-parameter models exist which try to more accurately account for effects such as matrix diffusion, the estimation of input parameter values for these model using statistical regression methods is often impractical due to the high levels of short-term variability typically observed in historical monitoring records.

Caution: The evaluation methods based on first order source attenuation should not be applied to monitoring records where first order attenuation is clearly not applicable. For example, the methods should not be applied to monitoring records covering an initial period of plume expansion followed by stabilization and decrease. For sites where short-duration active remediation has been applied (e.g., chemical oxidation, thermal treatment), the first order source attenuation concept is applicable to the polishing period after active remediation is complete. In other words, the method described in this manual is for long periods where the effects of active remediation or natural attenuation processes are relatively constant. Monitoring records before- and after-aggressive remediation **should not be combined.**

2.3 CHARACTERISTICS OF SHORT-TERM VARABILITY

Short-term variability is the change in contaminant concentration in a monitoring well that is unrelated to the long-term trend. Although there has been a lot of effort to understand the characteristics of the long-term trend, there has been much less effort to understand the characteristics of short-term variability.

In order to evaluate the characteristics of short-term variability on groundwater monitoring records, we evaluated long-term monitoring records from 10 contaminated sites covering a range of contaminants and geographic settings. For each site, we selected monitoring wells with at least 8 monitoring events where the primary contaminant was detected in at least 80% of these events. The selected sites and wells are summarized in Table 2.1.

Table 2.1 Sites Included in Analysis of Characteristics of Short-Term Variability

Site	Primary Contaminant	Number of Monitoring Wells	Number of Monitoring Events per Well	Typical Monitoring Frequency
Landfill #1, Wisconsin[1]	Arsenic (dissolved)	8	18 - 19	Quarterly
Landfill #2, Wisconsin[1]	Arsenic (dissolved)	9	20 - 106	Quarterly
Landfill #3, Wisconsin[1]	Arsenic (dissolved)	20	8 - 9	Quarterly
Superfund Site, Montana[2]	TCE	35	8 - 29	Semiannually - Annually
Superfund Site, California[2]	TCE	9	10 - 11	Semiannually - Annually
Superfund Site, New Hampshire[2]	TCE	5	18 - 34	Quarterly - Semiannually
UST Site, Alaska[3]	Benzene	11	25 - 43	Quarterly – Semiannually
UST Site, Oregon[3]	Benzene	10	19 - 43	Quarterly – Semiannually
UST Site, California[3]	Benzene	12	10 – 37	Quarterly – Semiannually
UST Site, New Jersey[3]	Benzene	8	20 - 29	Quarterly

Note: Data Sources 1) Wisconsin GEMS database, 2) database of Superfund groundwater monitoring results compiled by GSI, 3) database of UST groundwater monitoring results compiled by GSI and used in SERDP Project ER-1705.

For each site, we used least squares regression with a first order decay model (i.e., $C = C_0e^{-kt}$) to identify the long-term trend. The residuals (i.e., the difference between the modeled and measured concentrations) were then used to characterize the short-term variability.

The results for each site analyzed are provided in Appendix A. As described below, we have found that short-term variability is: i) mostly time independent and ii) proportional to the "true" concentration (i.e., variability as a percent of the true concentration doesn't change much over the long-term monitoring record at a particular well). These results are consistent with the results from SERDP project ER-1705 and have been used to develop the optimization methodology for this project.

2.3.1 Short-Term Variability is Mostly Time Independent

If the semi-random short-term variability is time dependent, then the difference between the measured result and the long-term trend will be correlated for sample events close in time. In other words, if the measured concentration during one sample event is above the long-term trend, then the measured concentration during the next event will more likely be above the long-term trend than below the long-term trend.

What are "paired residuals"?

A residual is the different between the measured concentration and the long-term concentration trend. Paired residuals are the residuals from two different monitoring events from the same well.

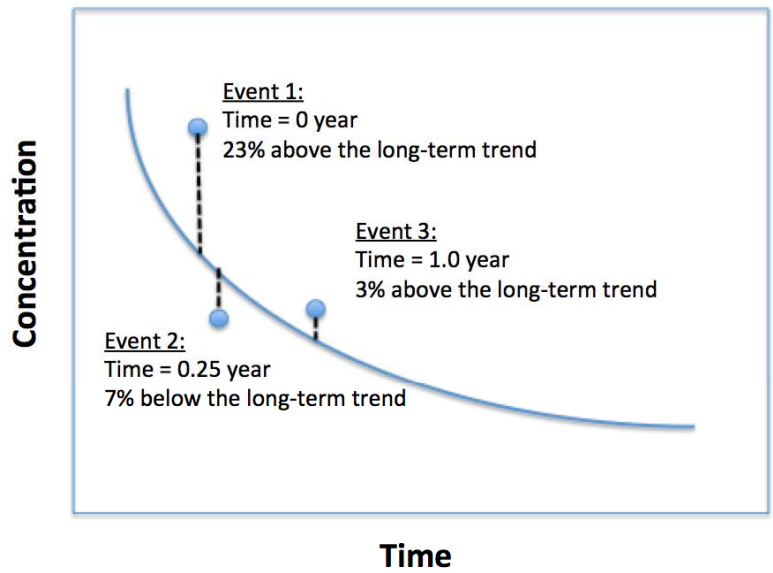
Evaluation Method: We evaluated the time dependence of short-term variability by determining the difference between paired residuals as a function of the time between measurements (Figure 2.1).

Evaluation of Short-Term Variability: Time Dependence

1) Use least squares regression to characterize the long-term attenuation rate

2) Calculate the normalized residuals (i.e., the percent difference between each measured value and the long-term trend)

3) Calculate the difference between normalized residual values as a function of time between measurement events

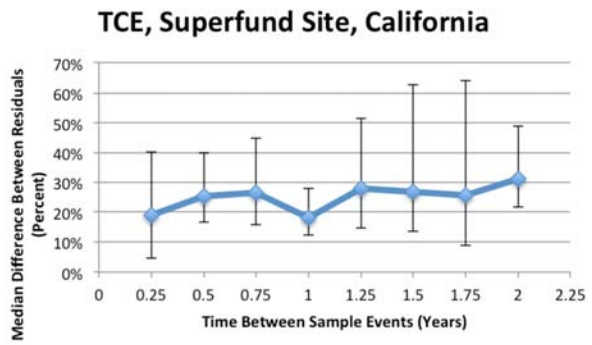
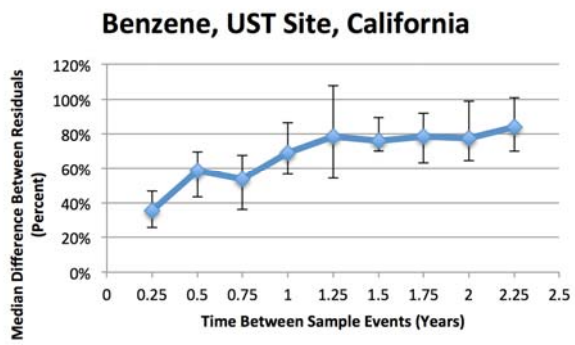


Comparison	Time	Difference
Event 1 to Event 2	0.25 years	30%
Event 2 to Event 3	0.75 years	10%
Event 1 to Event 3	1.0 years	20%

Figure 2.1 Method for Evaluation of Time Dependence of Short-Term Variability in Groundwater Monitoring Results

Results from Data Mining from 10 Sites: Our analysis indicates that, for most sites, most of the short-term variability in monitoring results (i.e., variability unrelated to the long-term trend) was independent of time, over a time scale of three months to more than one year. Example results are provided in Figure 2.2. The results for all 10 sites are summarized in Table 2.2 and full results are presented in Appendix A.

For five of the ten sites, the short-term variability was independent of the time between sample events for at least one year (i.e., Figure 2.2, Example 1). In other words, the median difference in concentration between two sample events was the same regardless of whether the samples were collected three months apart, six months apart, nine months apart or one year apart. For the other five sites, the median difference in concentration between samples increased with increasing time (i.e., Figure 2.2, Example 2). At these sites, we determined the time scale for the short-term variability by evaluating how long it took for the difference in concentration to stabilize. In addition, we calculated the proportion of the short-term variability that was time dependent by evaluating how much the concentration difference increased from the three month time separation (i.e., 0.25 years) to the time separation where the concentration difference stabilized (i.e., 1.25 years in Example 2).

Example 1. Difference in concentration between sample events does not increase with time for at least one year.	Example 2. Difference in concentration between sample events increases with time for 1.25 years and then stabilizes. Median difference in concentration at 1.25 years is approximately 2 times higher than difference at 0.25 years.
	
Finding: 100% of short-term variability is **time independent.**	Finding: Approximately 50% of short-term variability is **time dependent** after 1.25 years (Time scale is 1.25 years).

Note: Error bars show 95% confidence interval for median values.

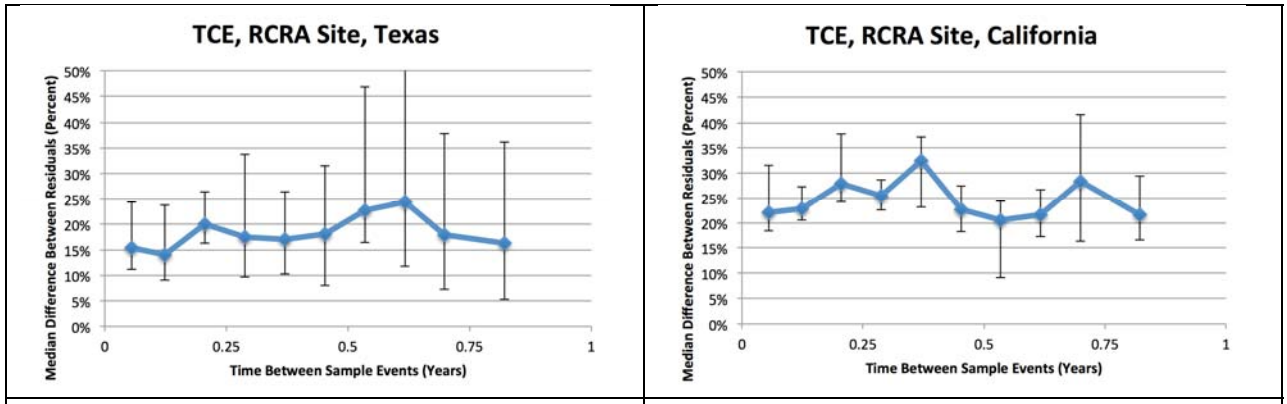
Figure 2.2 Example Results for Evaluation of Time Dependence of Short-Term Variability in Groundwater Monitoring Results. About Half the Sites Studied Resembled Example 1 and Half Example 2

Table 2.2 Results Summary for Evaluation of Time Dependence of Short-Term Variability

Constituent	Site	Percentage of Short-term Variability that is Time Dependent (Variability Changes Over Time)	Percentage of Short-term Variability that is Time Independent (Variability Doesn't Change Over Time)	Time Scale for Time Dependent Variability
Arsenic	Landfill #1, Wisconsin	30%	70%	0.75 years
Arsenic	Landfill #2, Wisconsin	40%	60%	2.0 years
Arsenic	Landfill #3, Wisconsin	0%	100%	Not Applicable
TCE	Superfund Site, Montana	0%	100%	Not Applicable
TCE	Superfund Site, California	0%	100%	Not Applicable
TCE	Superfund Site, New Hampshire	45%	55%	1.5 years
Benzene	UST Site, Alaska	40%	60%	0.5 years
Benzene	UST Site, Oregon	0%	100%	Not Applicable
Benzene	UST Site, California	50%	50%	1.25 years
Benzene	UST Site, New Jersey	0%	100%	Not Applicable

In summary, 100% of short-term variability was **time independent** for five of the ten sites evaluated. For the sites where there was some increase in the difference between measurements over time, it didn't last long: 50% or more of short-term variability was time independent for all five of these sites and the time scale for the time dependent component was two years or less. Our conclusion that short-term variability is mostly time independent is consistent with our prior evaluation of historical groundwater monitoring datasets from Hill AFB and Marine Corps Logistics Base Albany for SERDP Project ER-1705. This prior analysis found that the difference in concentration between samples collected from the same monitoring well was independent of the time between sampling events over a time scale of up to one year (McHugh et al., 2011).

Results from Task 1 Dataset, Focused Monitoring of Two Actual Field Sites: The Task 1 field program evaluated the effect of different purge and no purge sample collection methods on monitoring variability (See Kulkarni et al., 2015 for details on these sites). For the evaluation of time dependence of short-term variability, we used the results from the low flow purge sample event to evaluate short-term variability. This allowed us to evaluate variability over a time scale of as little as one month, compared to a minimum of three months (i.e., quarterly sampling) for the other sites. For both of the Task 1 field sites, **short-term variability was independent of time** over a time period of one to ten months (see Figure 2.3). In other words, the median difference in concentration between two samples collected four weeks apart was the same as the median difference in concentration for samples collected 40 weeks apart. Results are shown for TCE, however, the same pattern was observed for other VOCs at both sites (see Appendix A).



Finding: 100% of short-term variability is time independent.	Finding: 100% of short-term variability is time independent.

Note: Error bars show 95% confidence interval for median values.

Figure 2.3 Results for Evaluation of Time Dependence of Short-Term Variability for Task 1 Sites

Implications for Monitoring Optimization and Trend Analysis Toolkit: The time independence of variability in groundwater monitoring results makes it easier to simulate groundwater monitoring data because the random variability component does not need to be linked to the time between sample events. This, in turn, makes it easier to evaluate the effect of changes in sampling frequency on the ability to characterize the long-term trend. As discussed in Section 3.5.1, the Monitoring Optimization and Trend Analysis Toolkit is not overly sensitive to the assumption that the short-term variability is time independent. As long as the duration of the monitoring record is at least 3 times the time scale of the short-term variability (i.e., a monitoring record of six years for the worst site evaluated), the presence of time dependence should not affect the results of the analysis.

2.3.2 Short-Term Variability is Proportional to the "True" Concentration

There are a number of reasons to expect that short-term variability would be proportional to the "true" concentration. The alternative is that the magnitude of variability is independent of the "true" concentration. It is likely that much of the variability in the subsurface (i.e., signal variability and well and aquifer dynamics) is driven by the mixing of contaminated water from the source area with clean water from other areas. The effect of these dilution processes on the measured concentration would be proportional to the original source concentration. Similarly, variability due to loss of volatiles during sample collection and analysis would be proportional to the "true" concentration. Measurement error may also be a function of analytical instrument precision and independent of the sample concentration, however, our prior analysis has shown that variability between field or laboratory duplicate samples is much smaller than short-term variability between samples collected on different days (McHugh et al., 2011).

For each dataset in the current analysis, we plotted the absolute value of the residual (the difference between a data point and the predicted concentration by the first order decay model) vs. the predicted concentration (i.e., the concentration predicted by the regression model, our best estimate of the "true" concentration). For each dataset, these plots showed a positive linear correlation between the residual and the predicted concentration. Representative results are presented in Figure 2.4 and full results are presented in Appendix A.

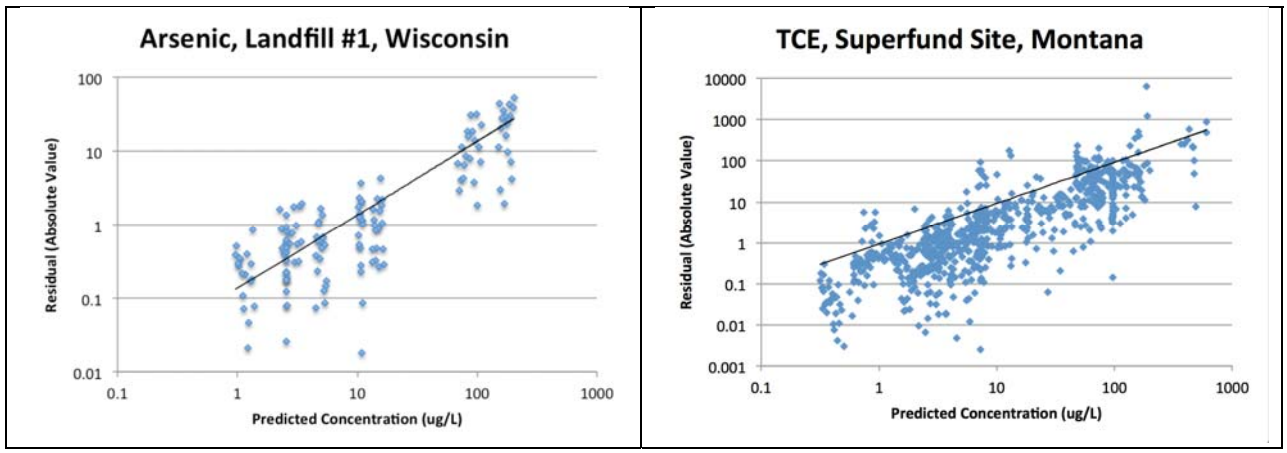


Figure 2.4 Representative Results for Evaluation of the Relationship between Short-Term Variability and "True" Concentration

Finding: The magnitude of short-term variability in groundwater monitoring results is proportional to the "true" concentration.

Implications for Monitoring Optimization and Trend Analysis Toolkit: The variability component in simulated groundwater monitoring data needs to be scaled to be proportional to the "true" concentration.

2.3.3 Short-Term Variability Can Be Described by a Log-normal Distribution

Environmental data are commonly assumed to be log-normally distributed. If groundwater monitoring results are log-normally distributed and short-term variability is proportional to the "true" concentration, then one would expect the short-term variability to also be log-normally distributed.

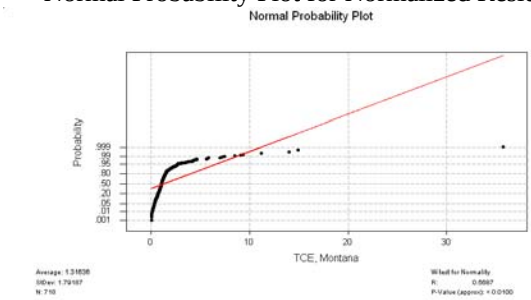
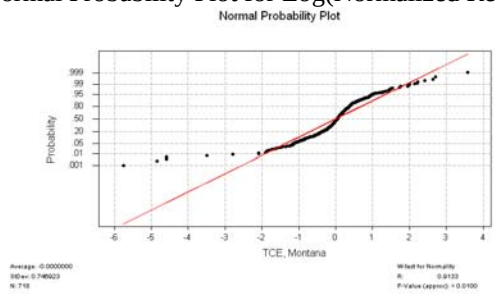
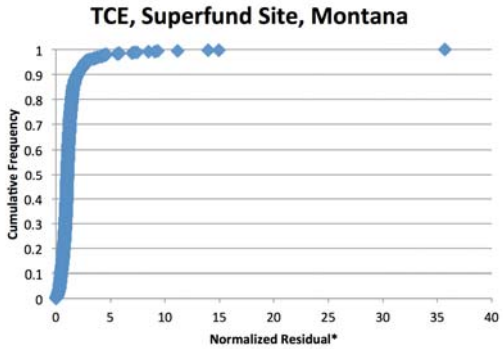
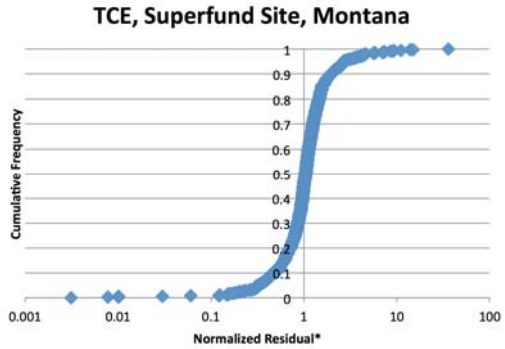
Normal vs. Log-normal Distribution:

A normal distribution describes a commonly observed distribution of measurements where the individual measurements are distributed around the mean (average) of the measurements in the shape of a bell curve. For a log-normal distribution, the logarithm of the individual measurements has a normal distribution.

For each dataset, we evaluated the distribution of residuals. Because the residuals are proportional to the "true" concentration, we normalized each residual value by the predicted concentration for that measurement:

Equation 2.1: $$\text{Normalized residual} = \frac{\text{Residual}}{\text{Predicted Concentration}} + 1$$

This normalization also controlled for i) the observation that the magnitude of the residual is proportional to the concentration and ii) differences in concentration between wells. Note that we added one to the normalized residual in Equation 2.1 so that the minimum value would be zero rather than -1. This does not change the statistical distribution of the normalized residuals, but allows us to plot the values on a log scale. Normalizing the residual also allowed us to combine results from different monitoring wells at an individual site giving us a larger dataset and higher statistical power than could be obtained from one individual well. The distribution of the residuals was evaluated visually using cumulative frequency plots and normal distribution plots. Statistical tests for normality were not used because, for large datasets, even small deviations from a normal distribution results in statistically-significant differences. The graphical analyses were conducted for both the normalized residuals and log-transformed normalized residuals in order to evaluate the fit with a normal and a log-normal distribution. An example of the graphic analysis is provided in Figure 2.5.

Evaluation of Normal Distribution	Evaluation of Log-Normal Distribution
Normal Probability Plot for Normalized Residuals 	Normal Probability Plot for Log(Normalized Residuals) 
Cumulative Frequency Plot: Normal Scale 	Cumulative Frequency Plot: Log Scale 
Finding: Data has a poor fit with a normal distribution	Finding: Data has a moderate fit with a log-normal distribution

Note: * = See Equation 2.3.1 for normalization.

Figure 2.5 Example Results for Evaluation of the Distribution of Short-Term Variability: TCE, Superfund Site, Montana

The results of this analysis for all 10 sites are summarized in Table 2.3. All of the datasets showed a moderate or good fit with a log-normal distribution. However, only four of the ten datasets showed a moderate or good fit with a normal distribution. Six of the ten datasets showed a strong rightward skew in the normal probability plots and the cumulative distribution plots, indicative of a log-normal or other non-normal distribution. For all six of these datasets, better fits were obtained for log-transformed data indicating that the datasets were better described by a log-normal distribution than a normal distribution. Although the datasets were generally more consistent with a log-normal distribution, for many of the datasets, a small number of observations deviated from the mean by a larger amount than would be expected for a log-normal distribution. The results for TCE at the Superfund Site in Montana show the presence of such outliers (see Figure 2.5).

Table 2.3 Results Summary for Evaluation of the Distribution of Short-Term Variability

Constituent	Site	Visual Fit to Normal Distribution	Visual Fit to Log-Normal Distribution
Arsenic	Landfill #1, Wisconsin	Good	Good
Arsenic	Landfill #2, Wisconsin	Poor	Good
Arsenic	Landfill #3, Wisconsin	Good	Good
TCE	Superfund Site, Montana	Poor	Moderate
TCE	Superfund Site, California	Moderate	Moderate
TCE	Superfund Site, New Hampshire	Moderate	Moderate
Benzene	UST Site, Alaska	Poor	Moderate
Benzene	UST Site, Oregon	Poor	Good
Benzene	UST Site, California	Poor	Moderate
Benzene	UST Site, New Jersey	Poor	Moderate

Finding: for all 10 sites, the distribution of the normalized residuals was as consistent or more consistent with a log-normal distribution compared to a normal distribution.

Implication for Monitoring Optimization and Trend Analysis Toolkit: The short-term variability component in simulated groundwater monitoring data should be scaled so that the distribution is log-normal.

3.0 DEVELOPMENT OF MONITORING OPTIMIZATION METHOD

The monitoring optimization method developed for Task 2 utilizes our understanding of the characteristics of the long-term trend and short-term variability to determine how much monitoring data is needed to characterize the long-term trend. Based on the key characteristics of the long-term trend (i.e., first-order decay) and the short-term variability (i.e., mostly time independent, proportional to the long-term trend, and consistent with a log-normal distribution), we developed an optimization method that utilizes simulated monitoring data and Monte Carlo analysis to evaluate how much monitoring data are needed to define the long-term trend within a specified accuracy or a specified confidence.

3.1 GENERATION OF SIMULATED MONITORING DATA

For the Monitoring Optimization and Trend Analysis Toolkit, simulated monitoring data is generated using an algorithm that accounts for both the long-term trend and the short-term variability:

Concentration = Trend x Variability Factor

Where:

Concentration = The simulated concentration that would be measured during a monitoring event
Trend = The long-term concentration trend, an exponential decay function:

$$C_t = C_0 e^{-kt}$$

C_t = "True" concentration at time of monitoring event (predicted value with first order decay model)
C_0 = Concentration at time zero
k = First order attenuation rate ($time^{-1}$)
t = Time

Variability Factor = short-term variability, a random factor that is time independent, proportional to the "true" concentration, and log-normally distributed:

$$VF = LRN(0, SF)$$

VF = The concentration adjustment factor that accounts for short-term variability
LRN = A random number, x, with a log-normal distribution such that ln(x) has a mean of zero and a standard deviation equal to the scaling factor, SF. In Excel, this random number can be generated using the function "=LOGINV(RAND(),0,SF)". The RAND function generates a number between zero and one with a uniform distribution. The LOGINV function transforms the distribution of the random number so that ln(x) has a mean of zero and a standard deviation equal to the scaling factor, SF.

This algorithm results in simulated groundwater monitoring data with a first order time dependent long-term trend and random variability that is time independent, proportional to the "true" concentration, and is log-normally distributed. Both the first order attenuation rate and the standard deviation of the random variability can be specified.

3.2 DETERMINATION OF MONITORING REQUIRED TO IDENTIFY A TREND

A common goal of long-term monitoring is to evaluate progress towards achieving a numerical clean-up standard (U.S. EPA, 2011). Monitoring records are often reviewed to determine i) whether constituent concentrations are decreasing over time and ii) when a clean-up standard will be attained. For example, at MNA sites, the U.S. EPA recommends that monitoring data be reviewed periodically (e.g., during a five-year review) in order to ensure that the attenuation rate is sufficient to achieve the clean-up standard within the specified time frame (U.S. EPA, 2011). Although there are a number of existing tools and guidance documents that cover methods to estimate attenuation rates and remediation timeframes, these tools typically do not address the uncertainty in these estimates. When too little monitoring data is used to estimate attenuation rates, the uncertainty can be very high and the estimated attenuation rate may be far different from the actual rate. These errors can result in inappropriate site management decisions.

This ESTCP variability and optimization tool allows the user to determine how much monitoring data is needed to identify the long-term source attenuation trend with a certain amount of confidence or accuracy.

3.2.1 Trend Confidence and Accuracy

A first-order attenuation rate can be estimated from a monitoring record of concentration over time using regression analysis. However, the estimated attenuation rate will have some uncertainty due to the variability in the monitoring results. Standard statistical methods can be used to determine the uncertainty in terms of confidence and accuracy:

Attenuation rate confidence: Is the attenuation rate significantly different from zero? In other words, how likely is it that the observed change in concentration over time reflects a true long-term trend rather than an artifact of the random variability? When using regression analysis, an F-test can be used to determine the p-value (i.e., the probability that the apparent trend is due to chance).

Attenuation rate accuracy: What is the uncertainty associated with the estimated attenuation rate? For example, what is the 95% confidence interval? The statistical calculations used in the F-test can also be used to calculate a confidence interval for the attenuation rate.

Having a defined level of confidence in the long-term trend is important when a primary goal of monitoring is to demonstrate that concentrations are, in fact, decreasing over time. Having a defined level of accuracy is important when the observed long-term attenuation rate will be used to estimate the time required to achieve a numerical clean-up goal. Although confidence and accuracy are determined using the same statistical calculations, the results can be used to address two types of uncertainty. The confidence tells you the likelihood that the long-term trend is truly a decreasing trend (or truly an increasing trend). The accuracy tells you the reasonable range of true attenuation rates. For example, an attenuation rate of 0.2 yr^{-1} ± 0.1 yr^{-1} tells you that the true attenuation rate is most likely between 0.1yr^{-1} and 0.3 yr^{-1}. This corresponds to a half-life of two to seven years. If the attenuation rate is being used to estimate an attenuation timeframe, then the confidence interval can be used to evaluate the uncertainty associated with this estimate.

3.2.2 Use of Monte Carlo Analysis to Determine Monitoring Requirements

Regression analysis is used to estimate the attenuation rate (and associated confidence and accuracy) for an existing monitoring record. However, it is more difficult to determine how much future monitoring would be required to determine an attenuation rate with a desired level of confidence or accuracy. The

optimization tool uses simulated data (as described in Section 3.1) generated by a Monte Carlo analysis to determine the amount of future monitoring needed to determine an attenuation rate with a specified level of confidence or accuracy.

Monte Carlo analysis uses a large number of random simulations to define the probability of observing a specific outcome. The Monitoring Optimization and Trend Analysis Toolkit uses a large number of simulated datasets to determine the probability that a specified number of sample events will yield a monitoring record with an attenuation rate of a defined level of confidence or accuracy. The Monitoring Optimization and Trend Analysis Toolkit works as follows:

1) Simulated Dataset: The tool generates a large number of monitoring records based on a defined monitoring frequency (e.g., quarterly sampling) and a defined number of sample events per monitoring record (e.g., 10 sample events per well). Based on the number of sample events per well, the tool generates monitoring records covering 5,000 individual monitoring events. For example, for 10 events per well, the tool will simulate data for 500 monitoring records (i.e., 10 x 500 = 5000); whereas 20 events per well would yield 250 monitoring records (i.e., 20 x 250 = 5000). The monitoring records are generated based on a specified long-term trend and short-term variability as described in Section 3.1.

2) Attenuation Rate: For each monitoring record, the attenuation rate, confidence, and accuracy are determined using regression analysis. The results are tabulated to determine the percentage of monitoring records that satisfy a specified target for confidence or accuracy. For example, 63% of the monitoring records may have an attenuation rate confidence of 95% or greater.

3) Iterative Analysis: Based on the results, a new simulated dataset is generated with the number of monitoring events increased or decreased in order to increase or decrease the percentage of records that satisfy the target for confidence or accuracy. This is repeated iteratively until the percentage of records that satisfy the target for confidence or accuracy is equal to a target percentage. For example, if the user asks the tool to determine how much monitoring data is required to characterize the long-term attenuation rate with "high confidence" (defined in the tool as a p-value of <0.05), then the iterative process will continue until 80% of the monitoring records have an attenuation rate confidence of greater than 95% (i.e., p-value <0.05).

4) Results: The result of the iterative analysis determines, for a given monitoring frequency, the number of monitoring events required to determine an attenuation rate with a defined level of confidence or accuracy in a specified percentage of monitoring wells. For example, the analysis could indicate that 16 quarterly monitoring events would be required to observe a decreasing concentration trend with 95% confidence in 80% of monitoring wells. The actual results will vary depending on the site-specific "true" long-term attenuation rate and the site-specific short-term variability.

   The number of monitoring events required to observe a trend depends on the time between monitoring events; the total number of events required decreases as the time between events increases. For example, if 16 quarterly events were required to observe a trend, the analysis might show that 11 semi-annual events would be sufficient. Although this would decrease the number of monitoring events from 16 to 11, it would increase the monitoring time required from 4 years to 5.5 years. Thus, the Monitoring Optimization and Trend Analysis Toolkit allows the user to quantify the tradeoff between monitoring frequency and monitoring time.

3.3 CALIBRATION OF MONITORING OPTIMIZATION USING HISTORICAL SITE MONITORING DATA

The monitoring optimization method determines the amount of monitoring data required to observe a trend based on specified long-term attenuation rate and short-term variability factors. In order to obtain a site-specific optimized monitoring frequency, the long-term attenuation rate and short-term variability factor can be determined from historical monitoring data. The resulting optimized monitoring frequency then represents the future monitoring requirements for the specific site. To obtain reliable results, we recommend monitoring records for four or more monitoring wells, at least two years' worth monitoring events, and at least five monitoring events. The larger the data set, the more robust the results will be.

For sites without historical monitoring data, a range of typical factors are included in the User's Guide which will accompany the Monitoring Optimization and Trend Analysis Toolkit (Appendix C).

3.3.1 Calculation of the long-term attenuation rate

For each monitoring well record, the long-term attenuation rate is determined using regression analysis and a first-order attenuation model:

$$C_t = C_0 e^{-kt}$$

C_t = "True" concentration at time of monitoring event
C_0 = Concentration at time zero
k = First order attenuation rate (time^{-1})
t = Time

The attenuation rate is estimated using least squares regression to determine the first order attenuation rate that provides the best fit to the historical monitoring records. The overall attenuation rate for the site is estimated by taking the median attenuation rate for the individual monitoring records.

3.3.2 Calculation of the short-term variability factor

The short-term variability factor is determined by pooling the residuals from the regression analyses for all of the monitoring records used to estimate the long-term attenuation rate. The short-term variability factor is initially estimated as the standard deviation of the natural log of the residuals. However, because outliers can skew the distribution of the residuals (see Section 2.3.3), the variability factor is adjusted iteratively in order to minimize the difference in the distribution of the observed residuals from the historical monitoring dataset and the simulated monitoring dataset generated by the tool.

3.4 DEVELOPMENT AND USE OF EXCEL-BASED MONITORING OPTIMIZATION AND TREND ANALYSIS TOOLKIT

The monitoring optimization method described in Section 3 of this report has been implemented as an Excel-based tool, the Monitoring Optimization and Trend Analysis Toolkit. The purpose of the tool is to illustrate the implementation of the optimization method and facilitate the incorporation of the method into comprehensive long-term optimization tools developed by others. This Excel-based tool is not intended to serve as a comprehensive data management and analysis tool. It does not provide data management or other functions commonly found in other comprehensive tools such as MAROS. The tool and associated User's Guide is provided as Appendix C.

3.5 EVALUATION OF SENSITIVITY TO MODEL ASSUMPTIONS

As discussed in Section 3.1, the Monitoring Optimization and Trend Analysis Toolkit generates simulated monitoring data with short-term variability that is i) time independent, ii) proportional to the "true" concentration, and iii) log-normally distributed. We used a development version of the tool to evaluate the sensitivity of the tool results to these assumptions regarding the characteristics of the short-term variability. The results are as follows:

3.5.1 The Effect of Time Dependence in Short-Term Variability

We constructed a test version of the tool where the short-term variability was time dependent by calculating a rolling average of the random variability factors across consecutive sample events. We controlled the time scale for the random variability by controlling the time period over which the random variability values were averaged. For example, for variability with a one-year time scale and quarterly sampling, the random variability would be averaged across four sample events. This averaging smoothed the variation in concentrations because two consecutive simulated data points would share three random numbers and only have one different random number (i.e., for the second sample, the oldest random variable would be dropped and one new random variable would be added).

As long as the duration of the monitoring period was at least 3 times the time scale of the short-term variability, the version of the tool with time dependent variability yielded results very similar to the baseline version with time independent variability. Both versions yielded similar results for number of sample events needed to characterize the long-term trend with a specified level of accuracy or confidence and both versions showed a similar trade-off between monitoring frequency and monitoring durations. Based on the evaluation of the time dependence of short-term variability presented in Section 2.3.1, the longest observed timescale for short-term variability was two years. As a result, monitoring records of six years or longer would not be affected.

Finding: The optimization tool results are not very sensitive to the assumption that short-term variability is time independent.

3.5.2 The Effect of Proportionality to the "True" Concentration

In development of the optimization tool, we assumed that short-term variability is proportional to long-term variability. For sites with decreasing contaminant concentrations (i.e., most long-term monitoring sites), future concentrations are expected to be less than historical monitoring results used to calibrate the optimization tool. As a result, the absolute magnitude of the short-term variability decreases as the "true" concentration decreases over time.

When the monitoring period is short relative to the long-term trend (i.e., less than one half-life), the assumption has very little effect because the "true" concentration does not change much over the monitoring period. When the monitoring period is long relative to the long-term trend (i.e., three or more half-lives), making the short-term variability independent of the "true" concentration over-estimates the variability late in the monitoring record which would overestimate the amount of monitoring required to characterize the long-term trend.

Finding: The optimization tool results are potentially sensitive to the assumption that short-term variability is proportional to the "true" concentration. However, the short-term variability was observed to be proportional to the "true" concentration at all ten of the evaluation sites. This provides high confidence that this assumption is valid.

3.5.3 Short-Term Variability can be Described by a Log-normal Distribution

We constructed a test version of the tool where the short-term variability was simulated as normally distributed rather than log-normally distributed. In evaluating the difference between normally distributed and log-normally distributed short-term variability, we observed that:

- Outlier measurements decrease the accuracy and confidence in the long-term trend.
- Normally distributed data have fewer outliers than log-normally distributed data.

As a result, the version of the tool that simulated short-term variability as normally distributed typically required fewer monitoring events to characterize a long-term trend with a defined level of confidence or accuracy. For sites where the short-term variability is log-normally distributed, simulation of this variability as normally distributed would result in an underestimation of the amount of monitoring required to characterize the long-term attenuation rate.

Finding: The optimization tool results are potentially sensitive to the assumption that short-term variability is log-normally distributed. However, nine of the ten evaluation sites were observed to contain outlier values that were more consistent with a log-normal distribution than a normal distribution. As a result, assuming normally distributed short-term variability is likely to underestimate monitoring requirements at a large proportion of sites.

4.0 DEVELOPMENT OF TREND ANALYSIS METHOD

The trend analysis method developed for Task 3 utilizes our understanding of the characteristics of the long-term trend and short-term variability to determine whether the observed differences in long-term attenuation rates between monitoring wells are an artifact of short-term variability or reflect true spatial differences in contaminant concentration reduction. This part of the tool helps the user answer two questions:

Question 1: When will this site meet the groundwater clean-up goal (i.e., What is the long-term attenuation rate for the key contaminant at my site)?

Question 2: Do any individual wells appear to be attenuating more slowly than the source as a whole?

To answer Question 2, we developed a trend evaluation method that determines the expected range of observed attenuation rates for individual monitoring wells based on the site-specific average long-term attenuation rate and short-term variability. The observed individual attenuation rates are compared to the expected range in order to identify specific monitoring wells that may be exhibiting attenuation rates that are distinct from the overall site trend. A weight of evidence approach is then used to determine whether the trends in these individual wells are truly different from the overall site attenuation rate.

4.1 EVALUATION OF OVERALL SOURCE ATTENUATION RATE

The evaluation of the overall source attenuation rate and remediation timeframe is straightforward. The tool allows the user to enter concentration vs. time monitoring records for up to 20 individual monitoring wells (and up to 25 monitoring events for each well). For each individual well, the tool uses linear regression to estimate the first-order attenuation rate (i.e., the best-fit slope for natural log concentration vs. time). **The overall source attenuation rate is estimated as the median attenuation rate for the individual monitoring wells included in the analysis.**

The remediation timeframe is calculated using the source attenuation rate and user-specified values for representative source area concentration and groundwater remediation goal:

$$t = \frac{Ln(C/C_0)}{k}$$

Where:
t = estimated remediation timeframe (years)
C_0 = current representative source area concentration (ug/L or any alternative concentration units)
C = groundwater remediation goal (ug/L or any alternative concentration units)
k = attenuation rate (yr^{-1})

In order to capture some of the uncertainty associated with estimation of remediation timeframes, **a range for the remediation timeframe is calculated using the 25th percentile and 75th percentile attenuation rates for the individual monitoring wells included in the analysis.**

4.2 EVALUATION OF DIFFERENCES IN INDIVIDUAL WELL ATTENUATION RATES

In order to determine whether the observed attenuation rate for an individual monitoring well is consistent with the overall attenuation rate for the site, the tool compares the observed attenuation rate for each

individual monitoring well to the expected range of attenuation rates based on the site-specific values for overall site attenuation rate and short-term variability.

As discussed in Section 3.1, the tool uses Monte Carlo analysis to simulate the effect of short-term variability on the observed attenuation rates for individual monitoring wells. The tool utilizes the overall site attenuation rate and the site short-term variability factor to simulate at least 200 individual monitoring records and to calculate the observed attenuation rate for each of these simulated records. The 5th percentile and 95th percentile observed attenuation rates from this simulated dataset are used to define the expected range of observed attenuation rates due to the effects of short-term variability. The effect of short-term variability on the observed attenuation rate is a function of monitoring frequency and the number of monitoring events in the monitoring record. Therefore, if the monitoring frequency and the number of monitoring events is different for the different monitoring well records entered by the user, the tool will simulate the expected range of attenuation rates for each separate combination of frequency and monitoring events.

For each site monitoring well included in the analysis, the attenuation rate calculated for that monitoring well is compared to the expected range attenuation rates. If the well attenuation rate is inside the expected range, then this evidence that the well attenuation rate is consistent with the overall site attenuation rate. If the well attenuation rate is outside the expected range, then this is evidence that the well attenuation rate is different from the overall site attenuation rate. Because the expected range of attenuation rates is defined by the 5th percentile and 95th percentile values, approximately 10% of individual well attenuation rates will fall outside of the expected range even if all of the variation in attenuation rates between wells is due to the effects of short-term variability. However, **if more than 10% of the individual monitoring well attenuation rates fall outside of the expected range, this is evidence that the true attenuation rates are different at different monitoring wells.**

For sites where more than 10% of the individual monitoring wells have attenuation rates that are inconsistent with the overall site attenuation rate, the tool identifies additional lines of evidence to be considered by the user when evaluating the significance of these differences:

<u>Increasing concentration trends</u>: The tool compares the number of observed increasing concentration trends to the number expected due to the effects of short-term variability. A greater than expected number of increasing concentration trends may be evidence of an expanding plume or new releases from a primary or secondary source.

<u>Contaminant concentrations</u>: The tool identifies the recent contaminant concentration in each monitoring well (i.e., the average of the four most recent measurements from that well). The total time required to attain the site remediation goal depends mostly on the attenuation rate for the most contaminated wells. As a result, slower than expected attenuation rates in less contaminated wells are less important when evaluating the overall effectiveness of a natural attenuation remedy (USEPA, 2011). However, if slower attenuation rates are observed in the wells with the highest contaminant concentrations, then these slower rates may control the time required to attain the overall site clean-up goals.

5.0 RESULTS FROM APPLICATION OF THE MONITORING OPTIMIZATION AND TREND ANALYSIS TOOLKIT

The Monitoring Optimization and Trend Analysis Toolkit has two components: i) the Monitoring Variability Tool that analyzes historical monitoring data to determine site-specific values for short-term variability and long-term attenuation and ii) the Monitoring Optimization Tool that uses site-specific values for short-term variability and long-term attenuation rate to determine the total amount of monitoring data needed to accurately characterize the long-term trend. In order to evaluate the range of results that may be obtained, both of these components have been applied to historical monitoring datasets from 20 contaminated groundwater sites: nine benzene sites, eight TCE or PCE sites, and three arsenic sites.

5.1 APPLICATION TO TWENTY SITES

The Monitoring Optimization and Trend Analysis Toolkit utilizes historical monitoring data from a site to 1) determine site-specific values for short-term variability and long-term attenuation rate, 2) evaluate whether individual well trends are consistent with the overall long-term attenuation rate, and 3) generate simulated data using Monte Carlo Analysis and use this simulated data to evaluate monitoring needs. To evaluate the performance of the tool at real monitoring sites, we utilized historical data from 20 contaminated groundwater sites to evaluate the range of short-term variability and long-term attenuation rates commonly obtained from sites with different types of chemicals of concern (COCs): benzene (representative of petroleum sites), TCE/PCE, and arsenic (representative of metals sites). For each site, we selected 5 to 20 monitoring wells where the primary constituent had been detected during at least 80% of the monitoring events (see Table 5.1). For each monitoring well, we used the 25 most recent monitoring events or all of the available monitoring data for wells with less than 25 events.

Table 5.1 Sites Included in Evaluation of Monitoring Optimization and Trend Analysis Toolkit Results

Site	Primary Contaminant	Number of Monitoring Wells	Number of Monitoring Events per Well
Landfill #1, Wisconsin[1]	Arsenic (dissolved)	8	18 - 19
Landfill #2, Wisconsin[1]	Arsenic (dissolved)	9	20 - 25
Landfill #3, Wisconsin[1]	Arsenic (dissolved)	20	8 - 9
Superfund Site, Montana[2]	TCE	20	8 - 25
Superfund Site, California[2]	TCE	9	10 - 11
Superfund Site, New Hampshire[2]	TCE	5	18 - 25
California	TCE	16	7 - 23
California	PCE	20	17 - 25
California	TCE	18	7 - 19
California	PCE	10	7 - 17
California	TCE	20	6 - 16
UST Site, Alaska[4]	Benzene	11	25
UST Site, Oregon[4]	Benzene	10	19 - 25
UST Site, California[4]	Benzene	12	10 – 25
UST Site, New Jersey[4]	Benzene	8	20 - 25
UST Site, Oregon[4]	Benzene	14	19-25
UST Site, California[4]	Benzene	9	25
UST Site, California[4]	Benzene	11	25
UST Site, California[4]	Benzene	10	15 - 25
UST Site, Alaska[4]	Benzene	14	22 - 25

Note: Data Sources 1) Wisconsin GEMS database, 2) database of Superfund groundwater monitoring results compiled by GSI, 4) California GeoTracker database, 3) database of UST groundwater monitoring results compiled by GSI and used in SERDP Project ER-1705.

5.1 RESULTS OF MONITORING VARIABILITY ANALYSIS

The Monitoring Variability Tool portion of the toolkit allows the user to evaluate the overall source area attenuation rate for a site and whether the observed differences in attenuation rates between wells are consistent with the effect of short-term variability on the observed attenuation rate.

Long-Term Attenuation Rates: For the twenty test sites, this section answers the first question from Section 1.3:

Question 1: When will this site meet the groundwater clean-up goal (i.e., What is the long-term attenuation rate for the key contaminant at my site)?

For each site, the estimated long-term attenuation rate for the source area is the median first-order source attenuation rate determined from the concentration vs. time data for each monitoring well (i.e., k_{point}). The long-term attenuation rate can be used to estimate the time required to achieve site clean-up standards (Newell et al., 2002). The median long-term attenuation rate for benzene from the nine petroleum sites (0.4 yr^{-1}) corresponds to a source half-life of 1.7 yrs while the median long-term attenuation rate for TCE/PCE from the eight chlorinated solvent sites (0.1 yr^{-1}) corresponds to a source half-life of 7 yrs. These values are similar to values obtained from previous source attenuation rate studies (e.g., Newell et al., 2006; McHugh et al., 2014). The three metal sites evaluated were all landfill sites from Wisconsin. Arsenic concentrations appeared to be increasing at two of these three sites. The results are summarized in Table 5.2.

Table 5.2 Long-Term Attenuation Rates and Short-Term Variability for Evaluation Sites

COC	Long-Term Source Attenuation (yr^{-1})	Short-Term Variability
Benzene (9 Sites)	0.4 (0.07 – 0.9)	1.5 (1.0 – 1.6)
TCE/PCE (8 Sites)	0.1 (0.02 – 1.2)	0.7 (0.5 – 1.3)
Arsenic (3 Sites)	-0.1 (-0.2 – 0.03)	0.2 (0.2 – 0.5)

Note: Values shown are Median (Minimum – Maximum) for the set of sites evaluated.

As discussed in Section 3.3, the value for the short-term variability factor is estimated as the standard deviation of the natural log of the normalized residuals from regression using a first-order decay model. While it is difficult to conceptualize the meaning of the numerical values for the short-term variability factor, the differences in the value of the short-term variability factor between sites provides information on the difference in the magnitude of short-term variability between these sites. Constituent concentrations were least variable at the three metals sites and most variable at the nine petroleum sites. The characterization of short-term variability at the nine petroleum sites and the eight chlorinated solvent sites was used to develop recommended default values for the Monitoring Optimization and Trend Analysis Toolkit for use at sites without historical monitoring data (see Appendix C, Users Guide). Section 4.2 of this report provides an analysis of the relationship between numerical values for the short-term variability factor and the amount of monitoring data required to accurately characterize the long-term concentration trend.

The remediation timeframe is estimated using the long-term attenuation rate and user-specified values for current source area concentration and remediation goal. In order to capture some of the uncertainty associated with estimating remediation timeframes, the tool uses the 25th percentile and 75th percentile attenuation rates from individual monitoring wells to calculate a time range. For the benzene and TCE/PCE sites, we used the recent concentration in the most contaminated monitoring well as the current source area concentration and 5 ug/L as the remediation goal. We did not evaluate remediation timeframes at the three arsenic sites because arsenic concentrations appeared to be increasing at two of these three sites. For the nine benzene sites, the 25th percentile remediation time ranged from 2 to 22 years, with a median of 14 years; the 75th percentile remediation time ranged from 3.3 to >1000 years, with a median of 27 years. For the eight TCE/PCE sites, the 25th percentile remediation time ranged from 3 to 76 years, with a median of 24 years; the 75th percentile remediation time ranged from 20 to >1000 years, with a median of 288 years.

<u>Differences in Attenuation Rates</u>: For the twenty test sites, this section answers the second question from Section 1.3:

Question 2: Do any individual wells appear to be attenuating more slowly than the source as a whole?

For each site, Monte Carlo simulations based on the site-specific short-term variability are used to determine the expected range of observed attenuation rates in individual monitoring wells due to the effect of short-term variability on these observed rates. The same analysis is used to determine the expected number of wells with apparently increasing concentration trends due to the effect of short-term variability. Wells with attenuation rates outside the expected range or more than the expected number of wells with increasing concentrations trends provides evidence of true differences in attenuation rates between monitoring wells. Individual monitoring wells with slower than expected attenuation rates and wells with unexpected increasing concentration trends can be further evaluated to determine whether these wells are likely to affect attainment of overall site remediation goals. For example, a slow attenuation rate well that has low contaminant concentrations relative to the source is unlikely to prevent attainment of the site remediation goal within the expected timeframe based on the overall source attenuation rate. However, a slow attenuation rate well that has high contaminant concentrations to take longer than expected to attain the clean-up goal.

The 20 test sites included a total of 254 individual monitoring wells. Of those wells, 158 (62%) had long-term attenuation rates that were within the expected range based on the overall source attenuation rate and the expected effect of short-term variability. 50 monitoring wells showed faster than expected attenuation rates and 46 wells showed slower than expected attenuation rates. Of the 20 test sites, all of the sites had at least one monitoring well with an attenuation rate that was either faster or slower than expected (Table 5.3). This suggests at most sites, the variation in attenuation sites between monitoring wells is only partly explained by the effects of short-term variability on observed attenuation rates. Other effects such as matrix diffusion, multiple source areas, and/or true spatial variations in attenuation processes likely contribute to observed variations in attenuation rates across individual sites.

Even though not all of the variation in long-term attenuation rates between monitoring wells is attributable to random variability, the ability to identify individual monitoring wells with slower than expected attenuation rates will allow for more accurate evaluation of remedy effectiveness at contaminated groundwater sites. Although all of the sites had at least one monitoring well with an attenuation rate outside of the expected range, only 10 of the 20 sites had a “slower well” in the source area such that the “slower well” might control the overall site remediation timeframe. At the other 10 sites, the slower attenuation rate wells were monitoring wells with lower contaminant concentrations and would not be expected to affect the overall time required to attain the groundwater clean-up goals. At the 10 sites where slower attenuation rates could affect the overall remediation timeframe, the user of the Monitoring Optimization and Trend Analysis Toolkit would i) evaluate whether the remediation timeframe for the slower attenuation rate wells is consistent with the remediation objectives for the site and ii) if not, target the area of the slower wells for additional remedial actions.

Table 5.3 Evaluation of Individual Well Attenuation Rates at 20 Sites

Site	Primary Contaminant	Number of Monitoring Wells	Number of Monitoring Wells with Attenuation Rates Slower than Expected[1]	Slower Wells in Source Area?[2]
Landfill #1, Wisconsin	Arsenic	8	2	Yes
Landfill #2, Wisconsin	Arsenic	9	3	No
Landfill #3, Wisconsin	Arsenic	20	0	No
Superfund Site, Montana	TCE	20	4	No
Superfund Site, California	TCE	9	1	No
Superfund Site, NH	TCE	5	0	No
California	TCE	16	5	Yes
California	PCE	20	7	Yes
California	TCE	18	0	No
California	PCE	10	2	No
California	TCE	20	0	No
UST Site, Alaska	Benzene	11	4	Yes
UST Site, Oregon	Benzene	10	0	No
UST Site, California	Benzene	12	3	Yes
UST Site, New Jersey	Benzene	8	1	Yes
UST Site, Oregon	Benzene	14	2	No
UST Site, California	Benzene	9	2	Yes
UST Site, California	Benzene	11	1	Yes
UST Site, California	Benzene	10	3	Yes
UST Site, Alaska	Benzene	14	6	Yes

Note: 1) Number of monitoring wells with attenuation rates slower than expected based on the effect of short-term variability on observed attenuation rates. 2) For this analysis, the source area wells were defined as the top 20% most contaminated wells at the site based on the more most recent sample events.

Evaluation of Apparently Increasing Concentration Trends: In addition to identifying individual monitoring wells with slower than expected attenuation rates, the Monitoring Optimization and Trend Analysis Toolkit evaluates whether the number of apparently increasing concentration trends is greater than the number expected due to the random effects of short-term variability. For our analysis of increasing concentration trends, we excluded two of the three arsenic sites because the overall concentration trend for these two sites was increasing. For the remaining 18 test sites, 37 of 225 wells (16%) showed an apparently increasing concentration trend. However, based on the overall source area attenuation rates and magnitude of short-term variability at the sites, a total of 28 apparently increasing concentrations trends were expected due to random chance. This analysis indicates that most (76%) of the apparently increasing concentration trends were due to the random effects of short-term variability on the observed attenuation rate. Apparently increasing concentration trends were observed in one or more monitoring wells at 12 of the 18 test sites. However, at 6 of these 12 sites, the number of apparently

increasing concentration trends was consistent with the number expected due to the random effects of short-term variability.

5.2 RESULTS OF OPTIMIZATION ANALYSIS

The Monitoring Optimization Tool portion of the toolkit allows the user to evaluate the amount of monitoring data needed to characterize the long-term attenuation rate.

Amount of Data Needed: For the twenty test sites, this section answers the first question from Section 1.2:

Question 1: How much monitoring data do I need to determine a site's long-term source attenuation rate with a defined level of accuracy or confidence?

The Monitoring Optimization and Trend Analysis Toolkit utilizes site-specific values for short-term variability and the long-term attenuation rate to determine the number of additional monitoring events required to characterize the long-term attenuation rate with a defined level of accuracy or confidence. The tool also allows the user to evaluate the trade-off between monitoring frequency and time required to characterize the long-term trend. For our 20 evaluation sites, we utilized the results from the Monitoring Optimization and Trend Analysis Toolkit to evaluate monitoring frequency options.

In order to determine the amount of monitoring data required to characterize the long-term concentration trend, we looked at i) how much monitoring is required to characterize the long-term trend with medium confidence and ii) how much monitoring data is required to characterize the long-term trend with medium accuracy. As discussed in Section 3.2.1, confidence and accuracy are determined as follows:

Attenuation rate confidence: Is the attenuation rate significantly different from zero? In other words, how likely is it that the observed change in concentration over time is not an artifact of the random variability? An F-test can be used to determine the p-value (i.e., the probability that the apparent trend is due to chance). We use these built-in definitions for attenuation rate confidence:

- High Confidence: 80% of monitoring well records at the site will exhibit a first-order source attenuation rate that is significantly different from zero with a p-value of <0.05.
- Medium Confidence: 80% of monitoring well records at the site will exhibit a first-order source attenuation rate that is significantly different from zero with a p-value of <0.1.

In other words, when the Optimization Tool is used to determine the amount of monitoring data required to characterize the long-term trend with medium confidence, the user can expect that, using that amount of monitoring data, 80% of monitoring well records would exhibit a first-order attenuation rate that is significantly different from zero with a p-value of <0.1. For example, the tool might determine that 15 quarterly monitoring events are required in order to have the power to identify statistically-significant trends (p<0.1) in 80% of wells.

Attenuation rate accuracy: What is the uncertainty associated with the estimated attenuation rate? For example, what is the 95% confidence interval? The statistical calculations used in the F-test can also be used to calculate a confidence interval for the attenuation rate. We use these built-in definitions for attenuation rate accuracy:

- High Accuracy: For 80% of monitoring well records at the site, the 95% confidence interval for the first order source attenuation will be less than +/-25% or less than +/-0.05 yr^{-1} (whichever is larger).

- Medium Accuracy: For 80% of monitoring well records at the site, the 95% confidence interval for the first order source attenuation will be less than +/-50% or less than +/-0.1 yr^{-1} (whichever is larger).

In other words, when the Optimization Tool is used to determine the amount of monitoring data required to characterize the long-term trend with medium accuracy, the user can expect that, for 80% of monitoring wells, the 95% confidence interval for the first order attenuation would be less than +/-50% or less than +/-0.1 yr^{-1} (whichever is larger). For example, the tool might determine that 12 quarterly monitoring events are required satisfy the confidence interval accuracy requirement for 80% of wells.

For the 20 evaluation sites, the number of quarterly monitoring events required to characterize the long-term attenuation rate is summarized in Tables 5.4 and 5.5.

Table 5.4 Number of Quarterly Monitoring Events Required to Characterize the Long-Term Attenuation Rate with Medium Confidence (i.e., 80% of monitoring well records at the site exhibit a first-order attenuation rate that is significantly different from zero with a p-value of <0.1)

Site	Short-Term Variability	Long-Term Attenuation Rate (yr^{-1})	Number of Quarterly Monitoring Events Required	Total Monitoring Time (Yrs)
Best Benzene Site (Site 03)	1.45	0.90	15	3.8 yrs
Typical Benzene Site (Site 11)	1.08	0.42	21	5.3 yrs
Worst Benzene Site (Site 04)	1.50	0.07	82	21 yrs
Best TCE/PCE Site (GSI 1)	1.32	1.24	11	2.8 yrs
Typical TCE/PCE Site (GSI-35)	0.55	0.08	40	10 yrs
Worst TCE/PCE Site (California)	0.65	0.02	119	30 yrs
Best Arsenic Site (3135)	0.19	-0.12	15	3.8 yrs
Typical Arsenic Site (2342)	0.20	0.03	36	9.0 yrs
Worst Arsenic Site (307)	0.50	-0.02	100	25 yrs

Note: Medium Confidence means that 80% of monitoring wells will exhibit a first-order attenuation rate that is statistically different from zero is a p-value of <0.1.

Table 5.5 Number of Quarterly Monitoring Events Required to Characterize the Long-Term Attenuation Rate with Medium Accuracy (i.e., for 80% of monitoring well records at the site, the 95% confidence interval for the first order source attenuation will be less than +/-50% or less than +/-0.1 yr^{-1}, whichever is larger).

Site	Short-Term Variability	Long-Term Attenuation Rate (yr^{-1})	Number of Quarterly Monitoring Events Required	Total Monitoring Time (Yrs)
Best Benzene Site (Site 03)	1.45	0.90	22	5.5 yrs
Typical Benzene Site (Site 11)	1.08	0.42	30	8.5 yrs
Worst Benzene Site (Site 04)	1.50	0.07	58	14.5 yrs
Best TCE/PCE Site (GSI 1)	1.32	1.24	17	4.25 yrs
Typical TCE/PCE Site (GSI-35)	0.55	0.08	30	7.75 yrs
Worst TCE/PCE Site (GSI-15)	1.17	0.15	50	12.5 yrs
Best Arsenic Site (3135)	0.19	-0.12	16	4 yrs
Typical Arsenic Site (2342)	0.20	0.03	16	4 yrs
Worst Arsenic Site (307)	0.50	-0.02	29	7.25 yrs

Note: Medium Accuracy means that 80% of monitoring wells have a 95% confidence interval for the first-order attenuation rate that is <50% of the first-order attenuation rate or <0.1 yr^{-1} (whichever is larger).

This evaluation of 20 sites supports a number of findings with respect to the amount of monitoring data required characterize the long-term concentration trend with a reasonable level of confidence or accuracy. Key findings are:

Characterizing the long-term concentration trend always takes more than two years of quarterly data: Historically, two years of quarterly monitoring data has been considered the minimum amount of monitoring data needed to characterize the long-term concentration trend. However, for the 20 sites evaluated, at least three years of quarterly data and up to 28 years of quarterly data was required to identify a statistically-significant concentration trend ($p<0.1$) in 80% of wells. At least four years and as many as 18.25 years of quarterly data were required to characterize the long-term trend with an accuracy of +/-50% or +/-0.1 yr^{-1}. For these sites, the characterization of long-term trends using less data would result in high uncertainty and potentially incorrect conclusions. For example, two years of quarterly monitoring data could show an apparent increasing concentration trend when the true long-term trend is decreasing. **It is important for project managers to recognize that apparent trends characterized using too little data can be misleading and may result in inappropriate management decisions.**

For sites with faster attenuation, it is easier to demonstrate that concentrations are decreasing than to accurately determine the attenuation rate: For sites with a long-term attenuation rate of greater than 0.1 yr^{-1} (i.e., half-life less than 7 years), the number of monitoring events required to identify a statistically-significant concentration trend ($p<0.1$) was less than the number of monitoring events required to characterize the long-term trend with an accuracy of +/-50% or +/-0.1 yr^{-1}. In other words, for these sites it takes less monitoring data to prove that concentrations are decreasing than it does to accurately characterize how quickly the concentrations are decreasing. As a result, **when evaluating natural attenuation, there are often situations where the project manager can be confident that**

contaminant concentrations are decreasing but highly uncertain as to when numerical clean-up goals will be attained.

For sites with slower attenuation, it is easier to estimate the attenuation rate than to prove statistically that concentrations are decreasing: For sites with a long-term attenuation rate of less than 0.1 yr^{-1} (i.e., half-life more than 7 years), the number of monitoring events required to identify a statistically-significant concentration trend ($p<0.1$) was greater than the number of monitoring events required to characterize the long-term trend with an accuracy of +/-50% or +/-0.1 yr^{-1}. In other words, for these sites it takes less data to figure out that concentrations are changing very slowly than it does to determine with reasonable confidence the direction of change (i.e., increasing or decreasing concentration). **For sites with slow attenuation rates, it may be difficult to prove with statistical confidence that contaminant concentrations are decreasing.** For the eight sites we evaluated with attenuation rates of less than 0.1 yr^{-1}, between 9.25 and 28 yrs of quarterly monitoring data were required to demonstrate decreasing concentration trends ($p<0.1$) in 80% of monitoring wells.

5.3 TRADEOFF BETWEEN MONITORING TIME, MONITORING FREQUENCY

This section answers the second question from Section 1.2:

Question 2: What are the trade-offs between monitoring frequency (e.g., quarterly, semi-annually, or annually) vs. the time required for trend identification (the number of years until you get the answer to Question 1).

One objective for the Monitoring Optimization and Trend Analysis Toolkit is to allow the user to evaluate the tradeoff between monitoring time and monitoring frequency. Although the time required to characterize the long-term attenuation rate depends on both the short-term variability and the long-term attenuation rate, the trade-off between monitoring frequency and monitoring time is independent of these parameters (see Appendix C). In other words, monitoring monthly rather than quarterly will always decrease the amount of time required to characterize the long-term trend by 30% (however, at the cost of having to collect twice as many samples, total). In other words, monitoring monthly for 2.8 years provides the same characterization of the long-term trend as monitoring quarterly for 4 years. Similarly, monitoring annually for seven years provides the same characterization of the long-term trend as monitoring quarterly for four years. The relative tradeoff between monitoring frequency and time required to characterize the long-term trend is summarized in Table 5.6.

Table 5.6 Trade Off Between Monitoring Frequency and Monitoring Time

Monitoring Frequency	Relative Time Required to Characterize Long-Term Trend	Relative Cost to Characterize Long-Term Trend	Relative Value of One Monitoring Event
Weekly	0.40	5.3	0.19
Monthly	0.67	2.0	0.50
Quarterly	**1**	**1**	**1**
Semi-Annual	1.25	0.63	1.6
Annual	1.56	0.39	2.6
Every 2 Yrs	1.95	0.24	4.1
Every 5 Yrs	2.85	0.15	6.7

Note: Relative cost is the same as the relative total number of monitoring events required (i.e., based on the assumption that cost is proportional to number of monitoring events).

For example, a site that required four years of quarterly monitoring to characterize the long-term attenuation rate would require five years (= 4 x 1.25) of semiannual monitoring to characterize the long-

term trend with the same level of accuracy. Four years of quarterly monitoring is 16 total monitoring events while five years of semiannual monitoring is 10 total monitoring events. Therefore, the relative cost of the semiannual monitoring program would be 63% (10/16) of the cost of the quarterly monitoring program. **A project manager can use the tradeoff between monitoring frequency and monitoring time to select an optimal monitoring frequency.** A site with limited historical data and a near-term need to know the long-term attenuation rate should be monitoring more frequently. A site with extensive historical monitoring data or where quickly understanding the long-term attenuation rate is less important can be monitored less frequently. The mathematical basis for the trade-off between monitoring frequency and monitoring time is provided in Appendix B.

6.0 REFERENCES

Air Force Civil Engineer Center (AFCEC). 2010. Geostatistical Temporal/Spatial (GTS) Software for Optimization of Long-Term Monitoring Networks Version 1.0 User's Guide. Available from Philip Hunter (philip.hunter@us.af.mil)

Kulkarni, P.R., Newell, C.J., Krebs, C.J., McHugh, T.E., Britt, S., 2015. Final Report, Methods for Minimization and Management of Variability in Long-Term Groundwater Monitoring Results, ESTCP Project ER-201209.

MAROS, 2012. Monitoring and Remediation Optimization System Software 3.0. http://www.gsi-net.com/software/free-software/maros-30.html.

McHugh, T.E., Beckley, L.M., Liu, C.Y., Newell, C.J., 2011. Factors Influencing Variability in Groundwater Monitoring Data Sets. Ground Water Monitoring & Remediation, Vol. 31, No. 2, pp. 92-101.

McHugh, T. E., Kulkarni, P. R., Newell, C. J., Connor, J. A. and Garg, S., 2014. Progress in Remediation of Groundwater at Petroleum Sites in California. Groundwater, 52: 898–907. doi:10.1111/gwat.12136

National Research Council (NRC), 2013. Alternatives for Managing the Nation's Complex Contaminated Groundwater Sites. http://www.nap.edu/catalog.php?record_id=14668.

Newell, C.J., Rifai, H.S., Wilson, J.T., Connor, J.A., Aziz, J.A., Suarez, M.P. 2002. Calculation and Use of First-Order Rate Constants for Monitored Natural Attenuation Studies. U.S. EPA Ground Water Issue. http://nepis.epa.gov/Adobe/PDF/10004674.pdf

Newell C.J., and Adamson, D.T, 2005 Planning-level Source Decay Models to Evaluate Impact of Source Depletion on Remediation Time Frame. Remediation Journal. Vol. 15, No. 4., pp. 27-47.

Newell C.J., Cowie, I., McGuire, T.M., McNab, W.W, 2006. Multiyear Temporal Changes in Chlorinated Solvent Concentrations at 23 Monitored Natural Attenuation Sites. Journal of Environmental Engineering. Vol. 123, No. 6, pp. 653-663.

U.S. Census Bureau, 2014. State and County QuickFacts, http://quickfacts.census.gov/qfd/states/06000.html, accessed 26 June 2014

U.S. EPA, 1989. Evaluation of Groundwater Extraction Remedies. EPA/540 2-89/054.

U.E. EPA, 1996. Pump-and-Treat Ground-Water Remediation. EPA/625/R-95/005.

U.S. EPA, 2011. An Approach for Evaluating the Progress of Natural Attenuation in Groundwater. EPA 600/R-11/204, December 2011.

Appendix A

Statistical Properties of Short-Term Variability in Groundwater Monitoring Results at 10 Sites

Table of Contents

A.1 List of Sites Evaluated 1
A.2 Median Difference between Residuals v. Time between Sample Events 2
A.3 Residual v. Predicted Concentration 8
A.4 Normal Probability Plots 13
A.5 Log Transformed Probability Plots 19

A.1 List of Sites Evaluated

Constituent	Site
Arsenic	Landfill #1, Wisconsin
Arsenic	Landfill #2, Wisconsin
Arsenic	Landfill #3, Wisconsin
TCE	Superfund Site, Montana
TCE	Superfund Site, California
TCE	Superfund Site, New Hampshire
Benzene	UST Site, Alaska
Benzene	UST Site, Oregon
Benzene	UST Site, California
Benzene	UST Site, New Jersey

A.2 Median Difference between Residuals v. Time between Sample Events

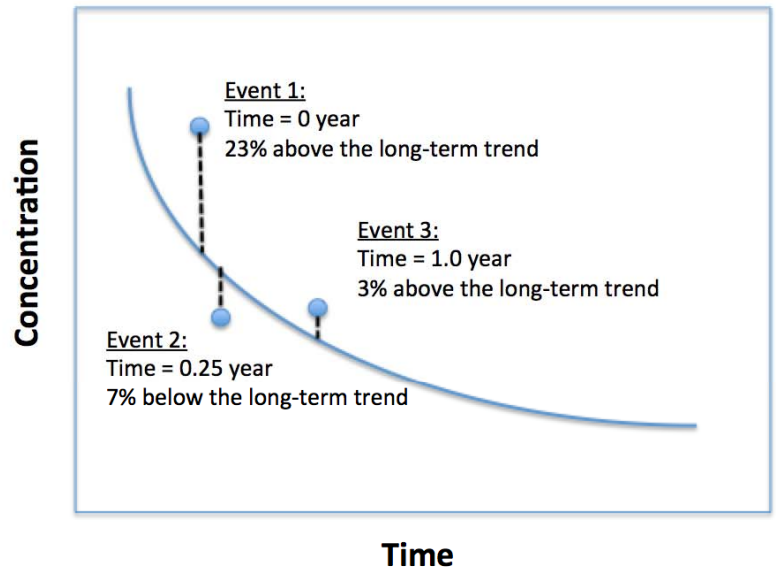
A.1.1 Calculation Method

Evaluation of Short-Term Variability: Time Dependence

1) Use least squares regression to characterize the long-term attenuation rate

2) Calculate the normalized residuals (i.e., the percent difference between each measured value and the long-term trend)

3) Calculate the difference between normalized residual values as a function of time between measurement events



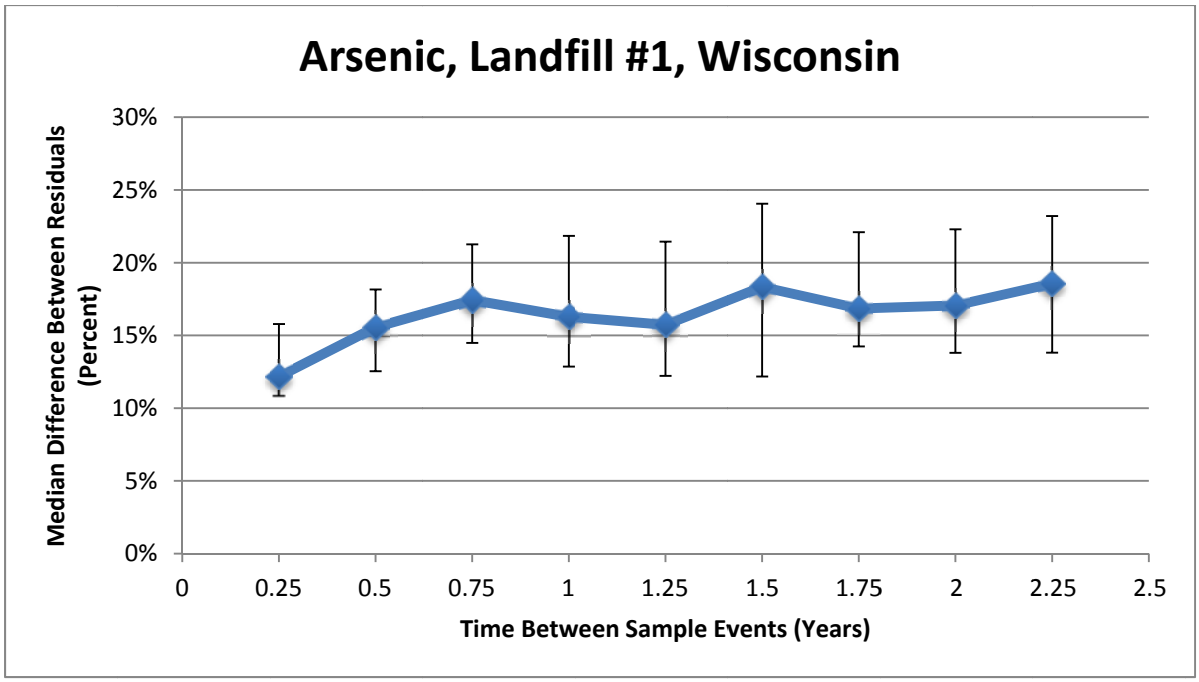
Comparison	Time	Difference
Event 1 to Event 2	0.25 years	30%
Event 2 to Event 3	0.75 years	10%
Event 1 to Event 3	1.0 years	20%

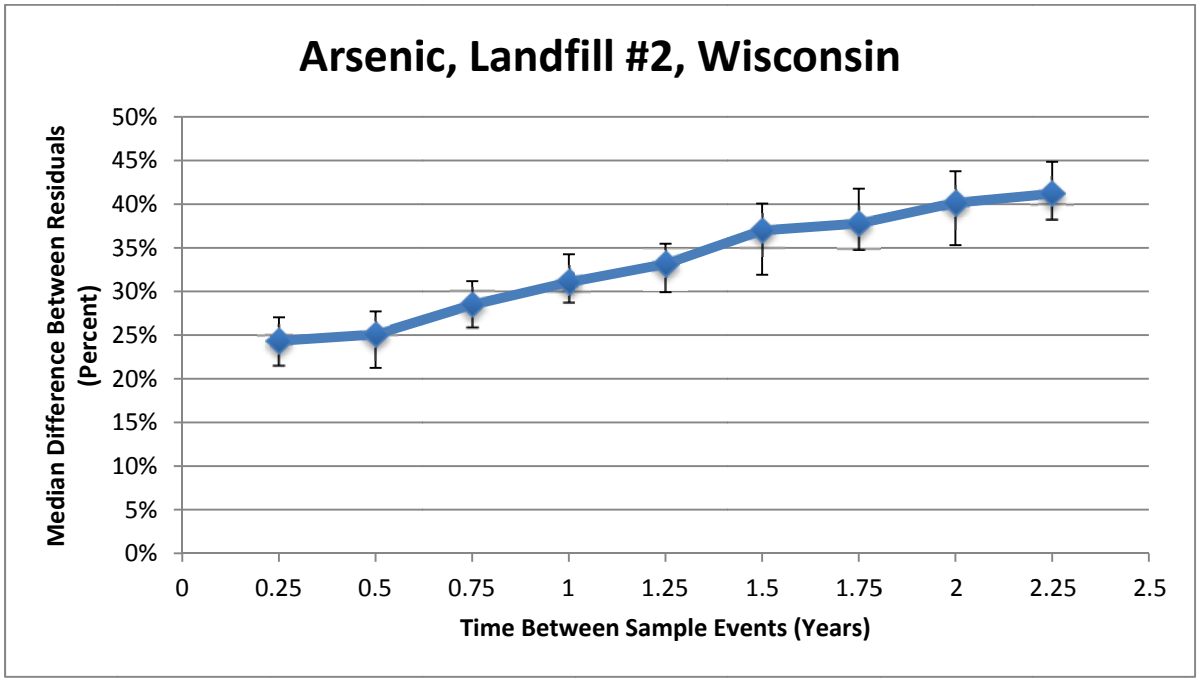
Figure A.1 Method for Evaluation of Time Dependence of Short-Term Variability in Groundwater Monitoring Results

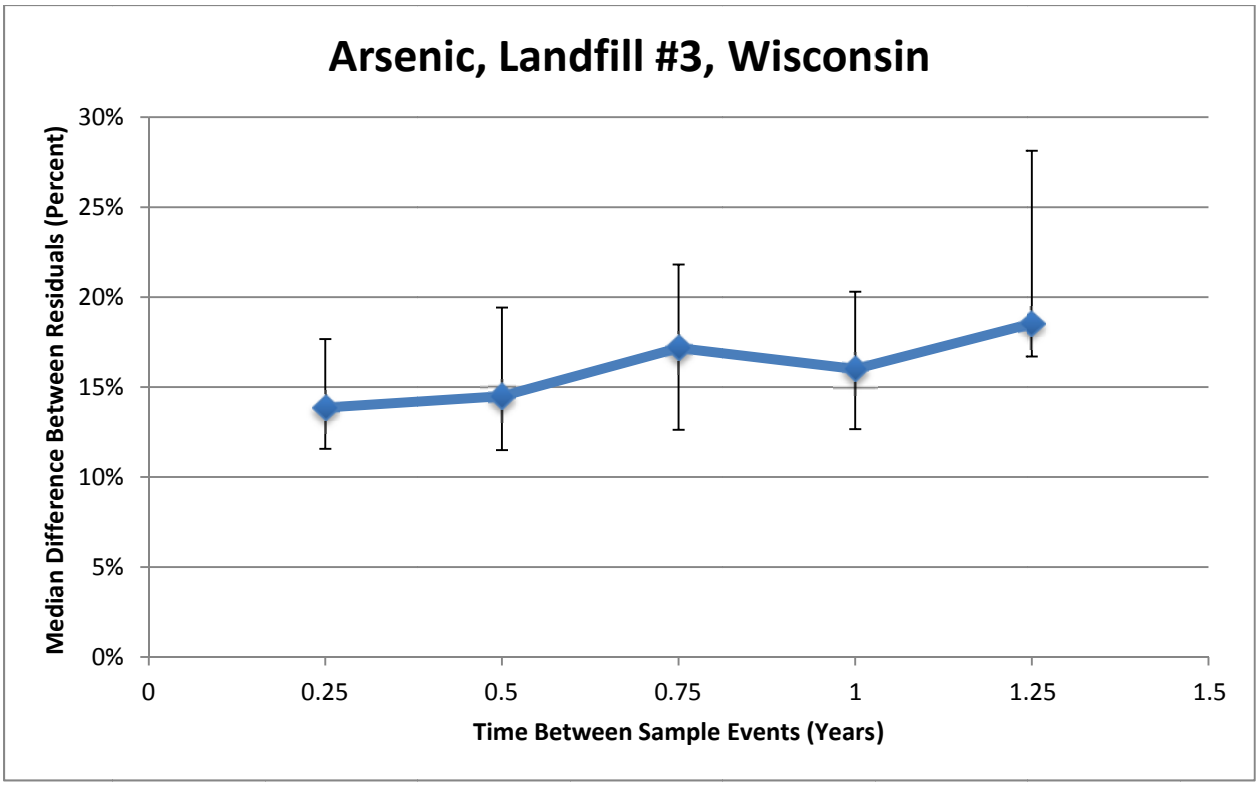
Normalized residuals were calculated for each sample event as the difference between measured and model-predicted concentration, divided by the model-predicted concentration (See Figure A.1).

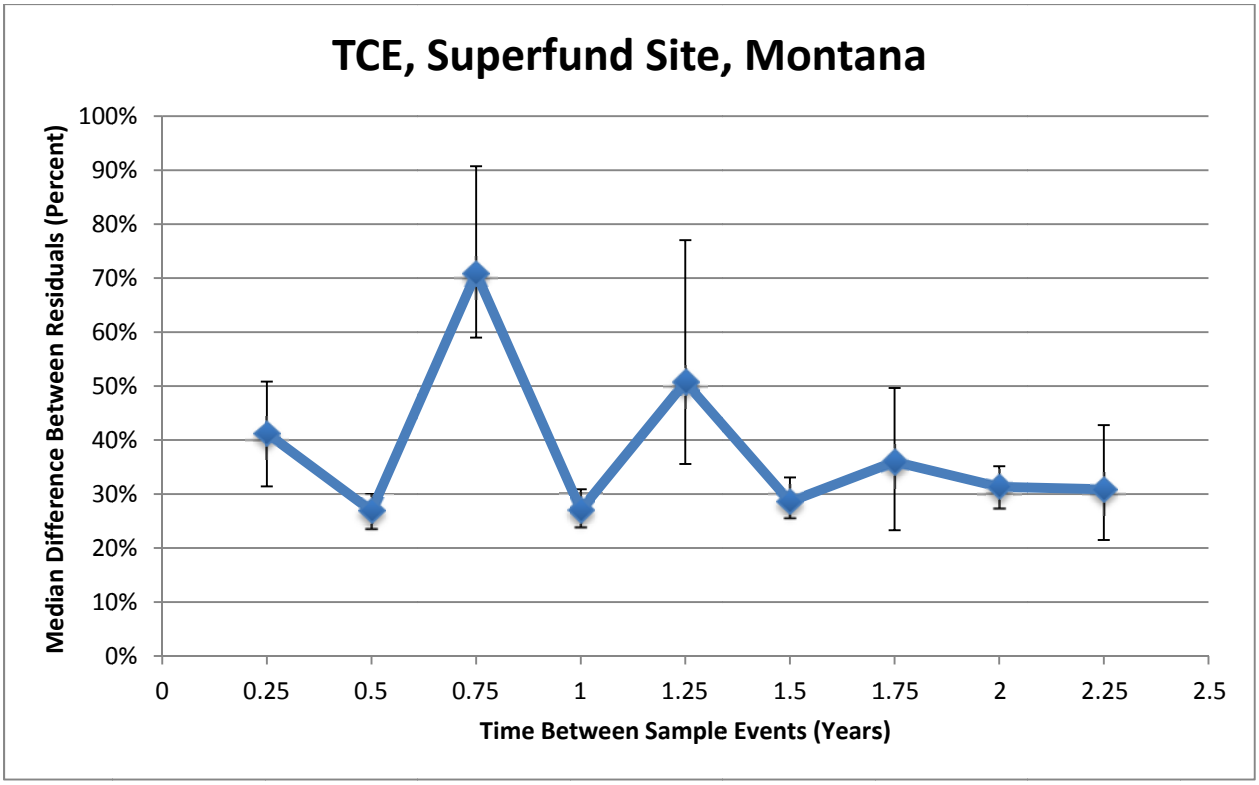
A.1.2 Time Dependence of Short Term Variability for 10 Evaluation Sites

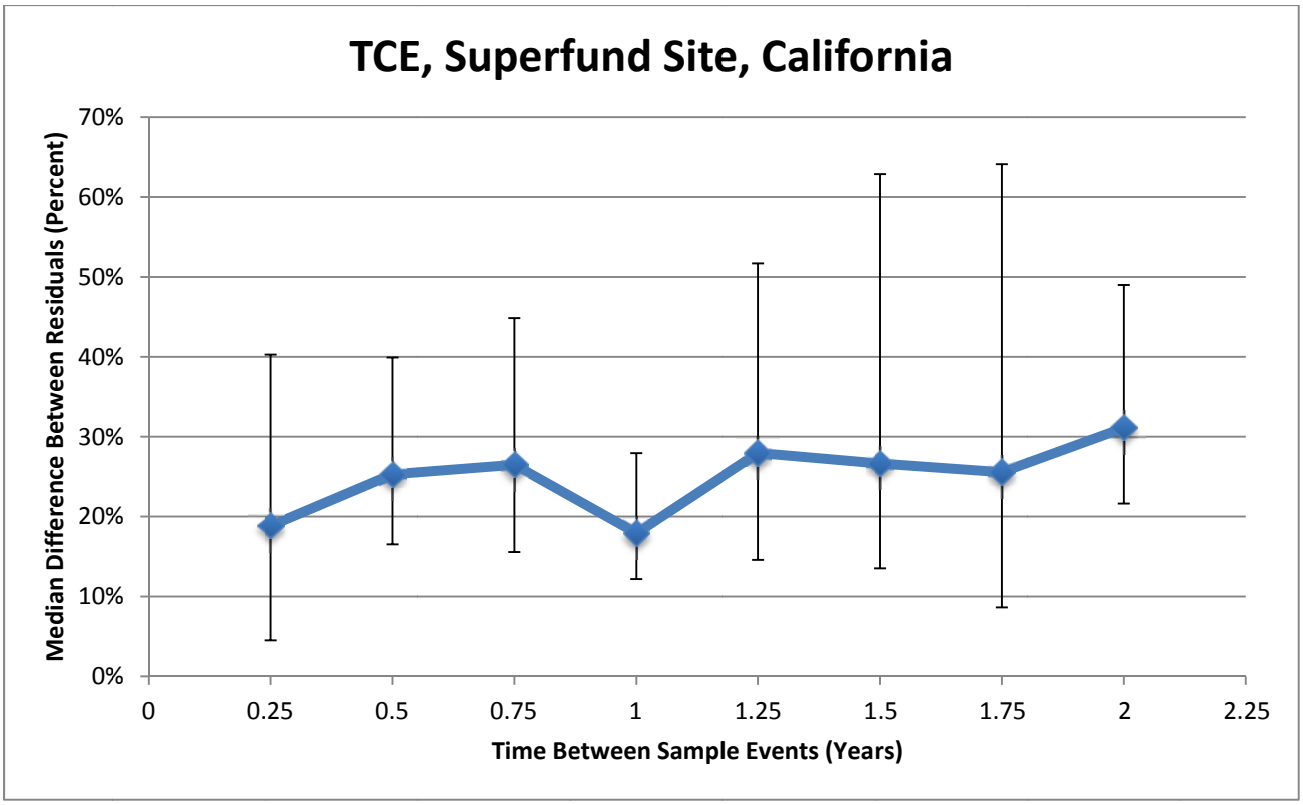
Each graph shows the median difference between normalized residuals for all pairs of monitoring events separated in time by the amount shown on the x-axis (e.g., all monitoring events separated by 0.25 years; all monitoring events separated by 0.5 yrs, etc.). The error bars show the 95% confidence interval for the median.

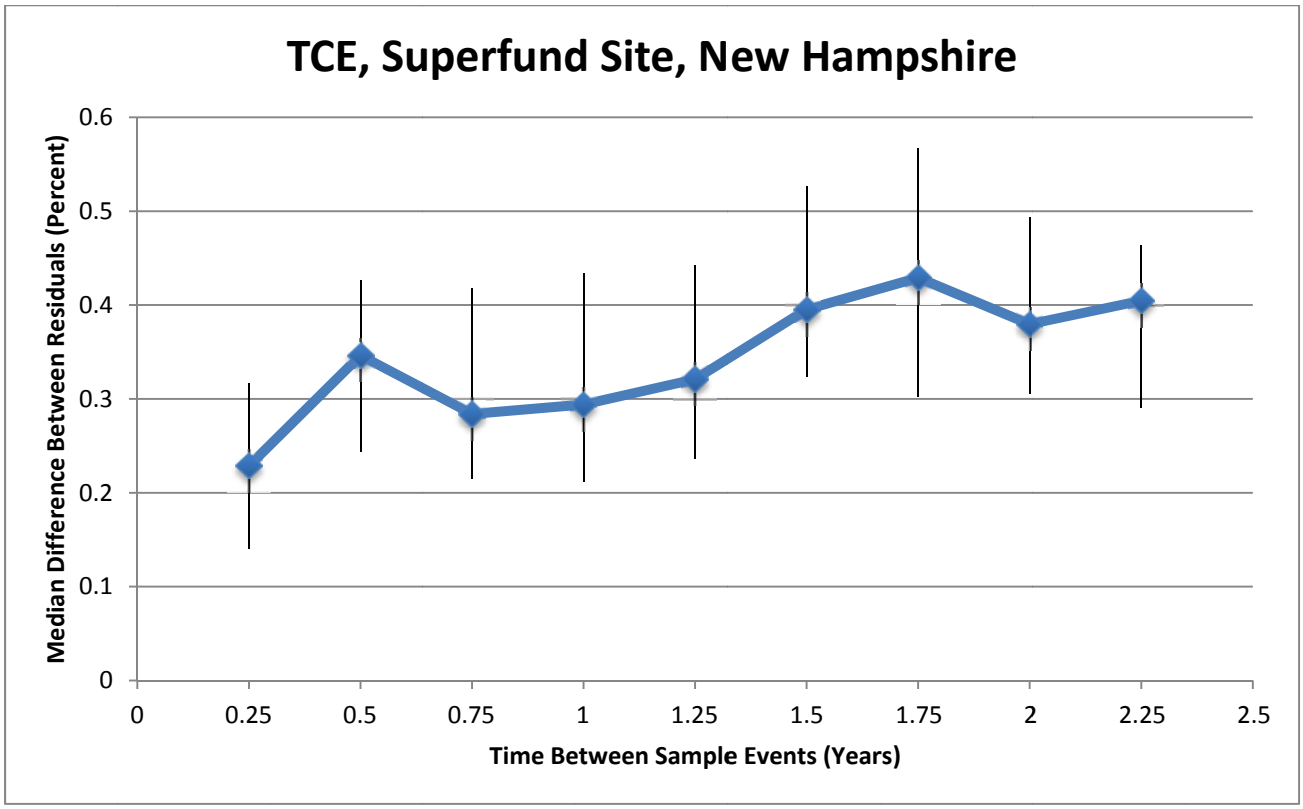

Arsenic, Landfill #1, Wisconsin
Median Difference Between Residuals (Percent)
30%
25%
20%
15%
10%
5%
0%
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
Time Between Sample Events (Years)

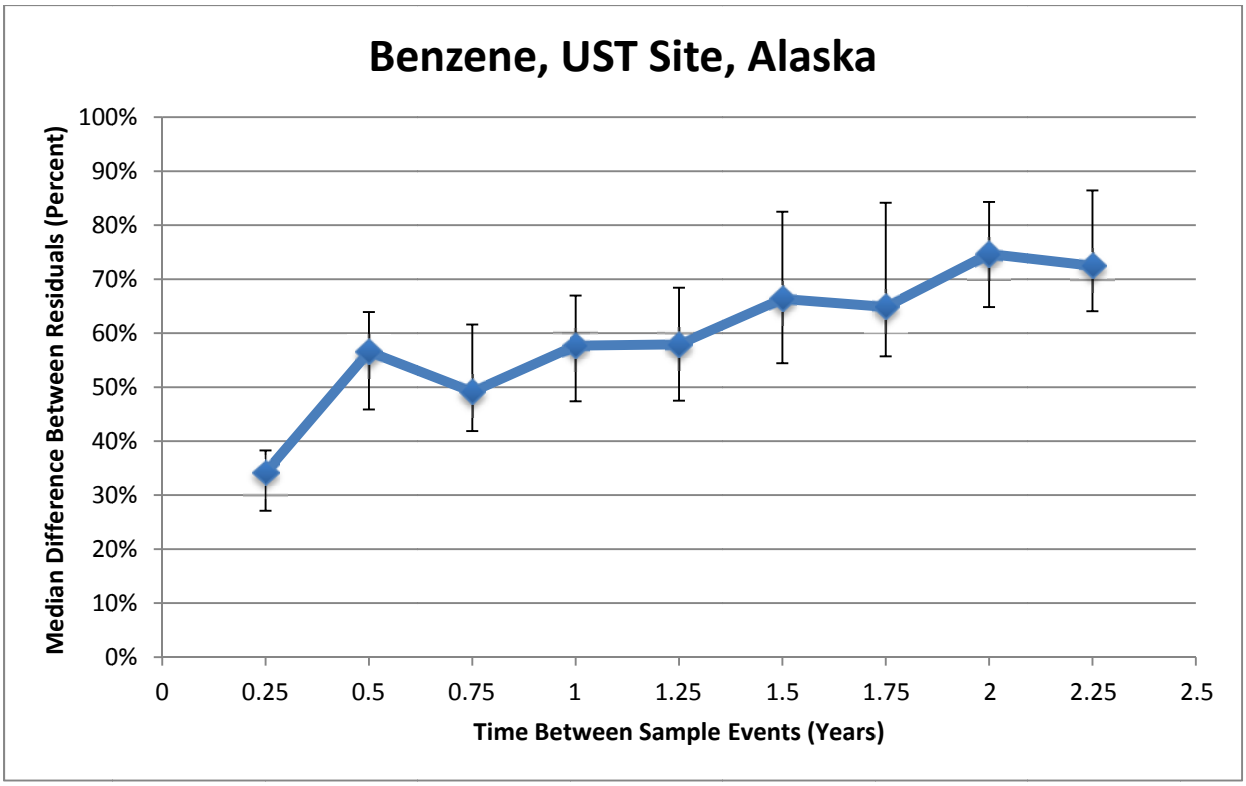

Arsenic, Landfill #2, Wisconsin
Median Difference Between Residuals (Percent)
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
Time Between Sample Events (Years)

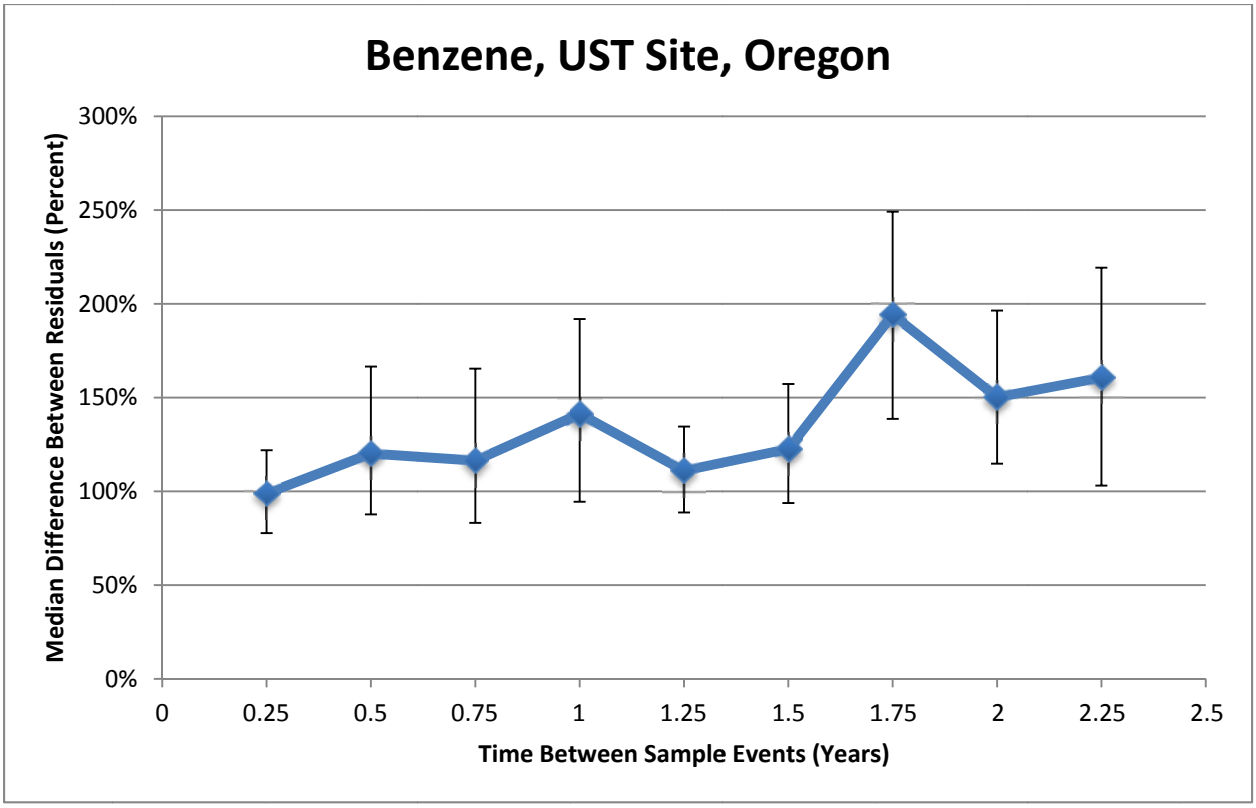

Arsenic, Landfill #3, Wisconsin
Median Difference Between Residuals (Percent)
30%
25%
20%
15%
10%
5%
0%
0
0.25
0.5
0.75
1
1.25
1.5
Time Between Sample Events (Years)

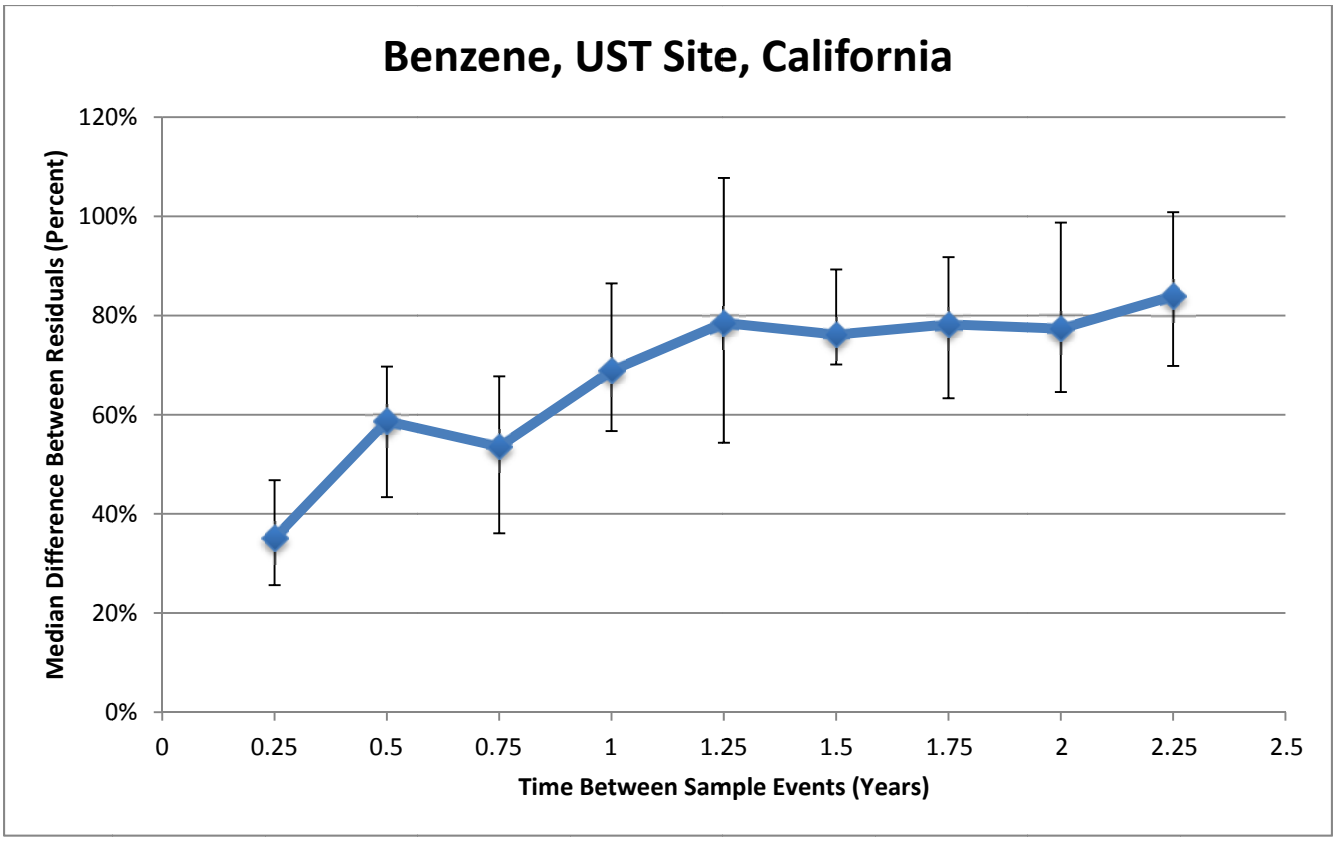

TCE, Superfund Site, Montana
Median Difference Between Residuals (Percent)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
Time Between Sample Events (Years)

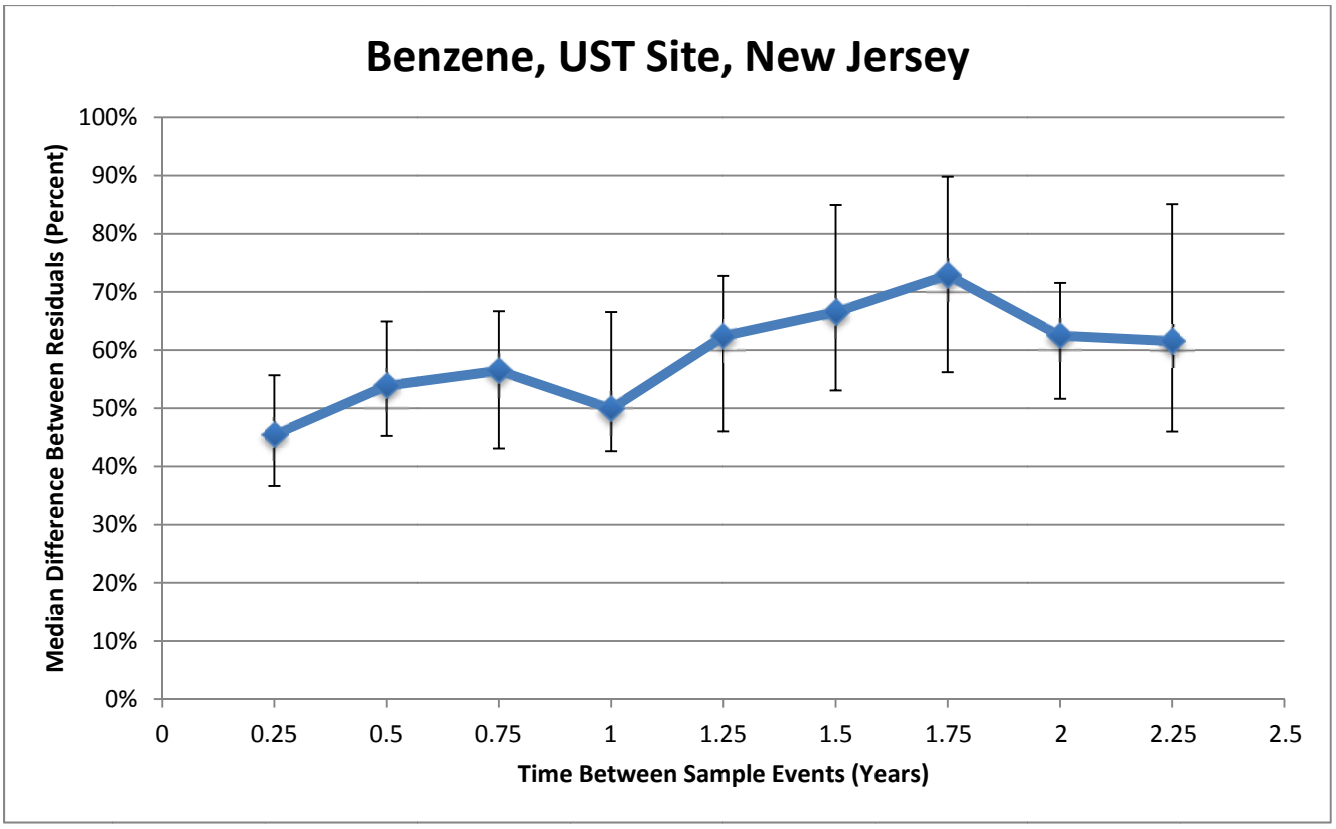

TCE, Superfund Site, California
Median Difference Between Residuals (Percent)
70%
60%
50%
40%
30%
20%
10%
0%
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
Time Between Sample Events (Years)


TCE, Superfund Site, New Hampshire
Median Difference Between Residuals (Percent)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
Time Between Sample Events (Years)

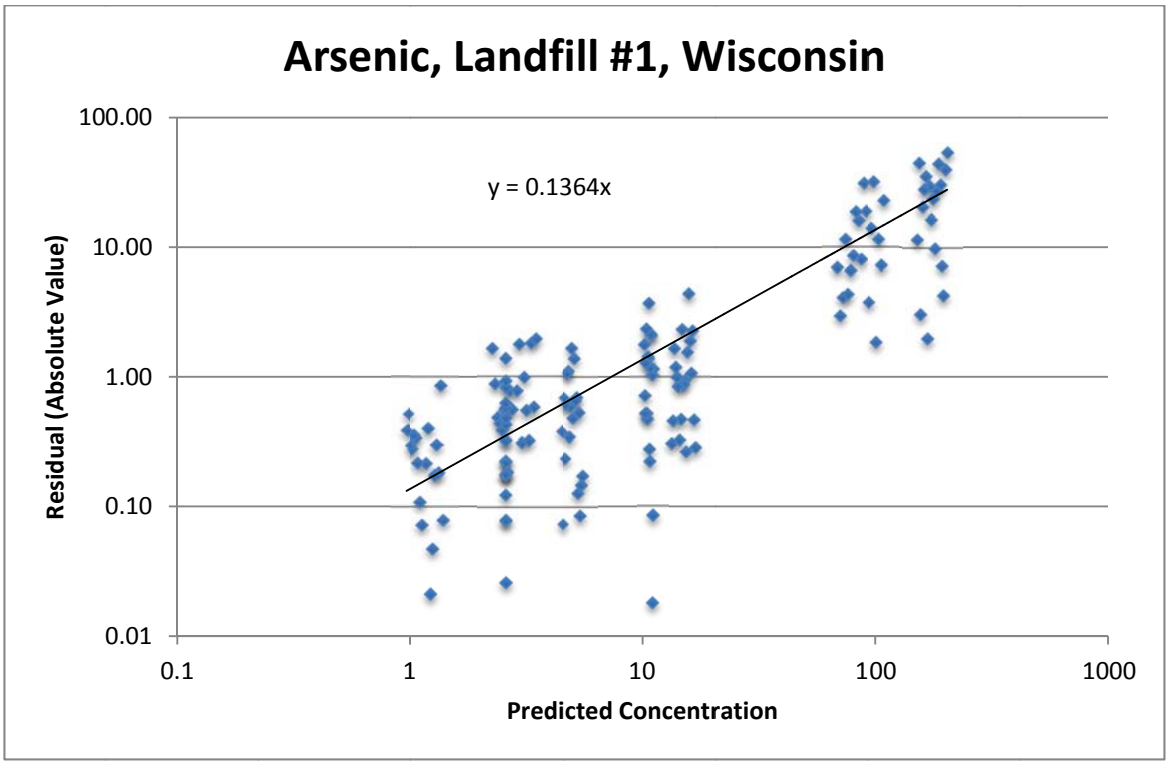

Benzene, UST Site, Alaska
Median Difference Between Residuals (Percent)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
Time Between Sample Events (Years)

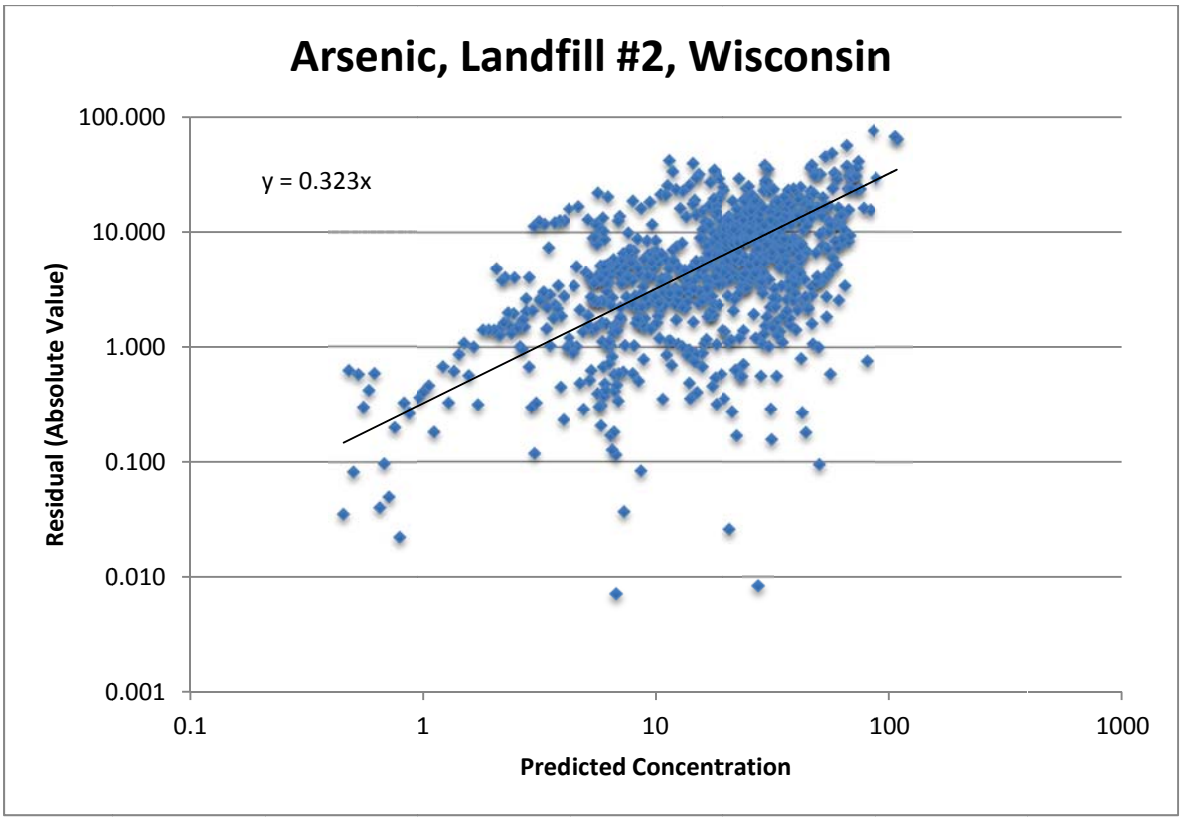

Benzene, UST Site, Oregon
Median Difference Between Residuals (Percent)
300%
250%
200%
150%
100%
50%
0%
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
Time Between Sample Events (Years)

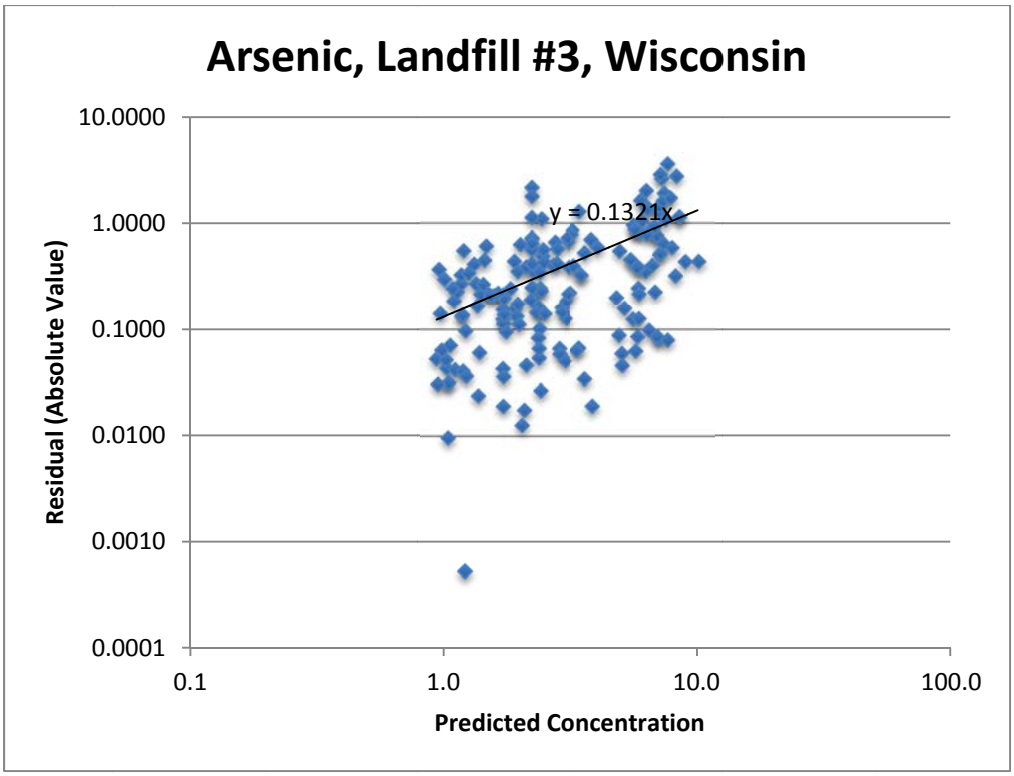

Benzene, UST Site, California
Median Difference Between Residuals (Percent)
120%
100%
80%
60%
40%
20%
0%
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
Time Between Sample Events (Years)

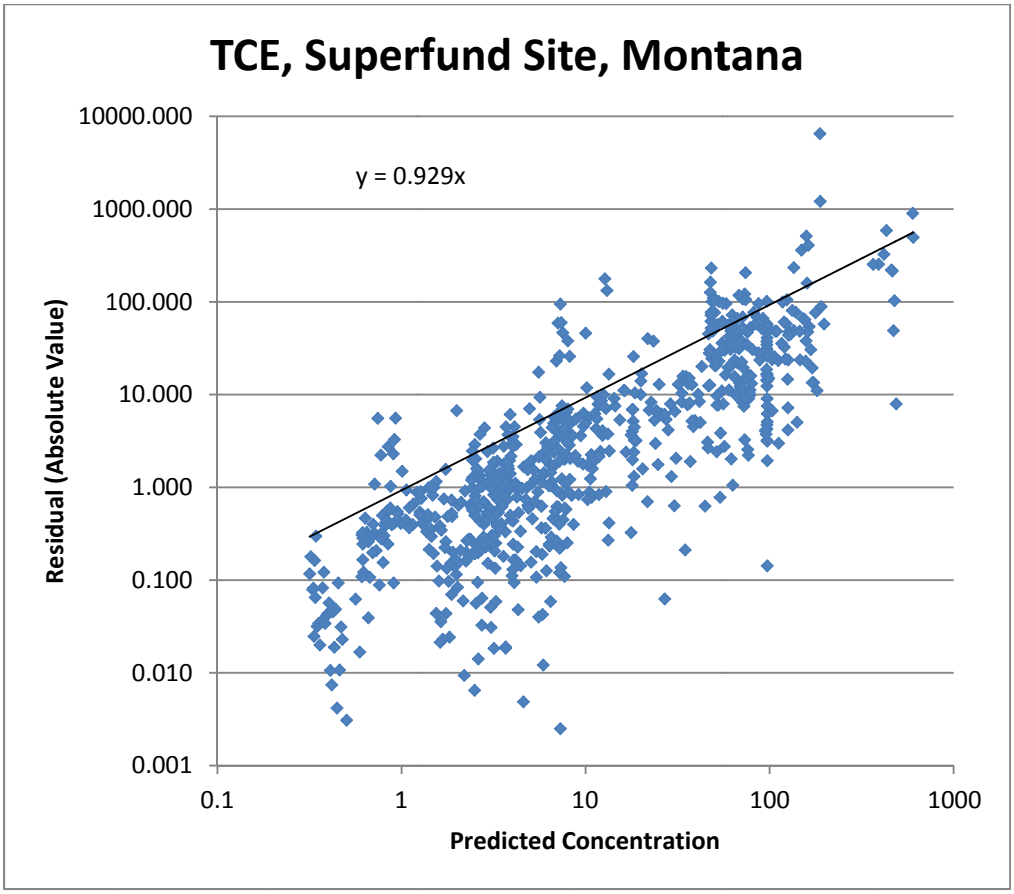

Benzene, UST Site, New Jersey
Median Difference Between Residuals (Percent)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
Time Between Sample Events (Years)

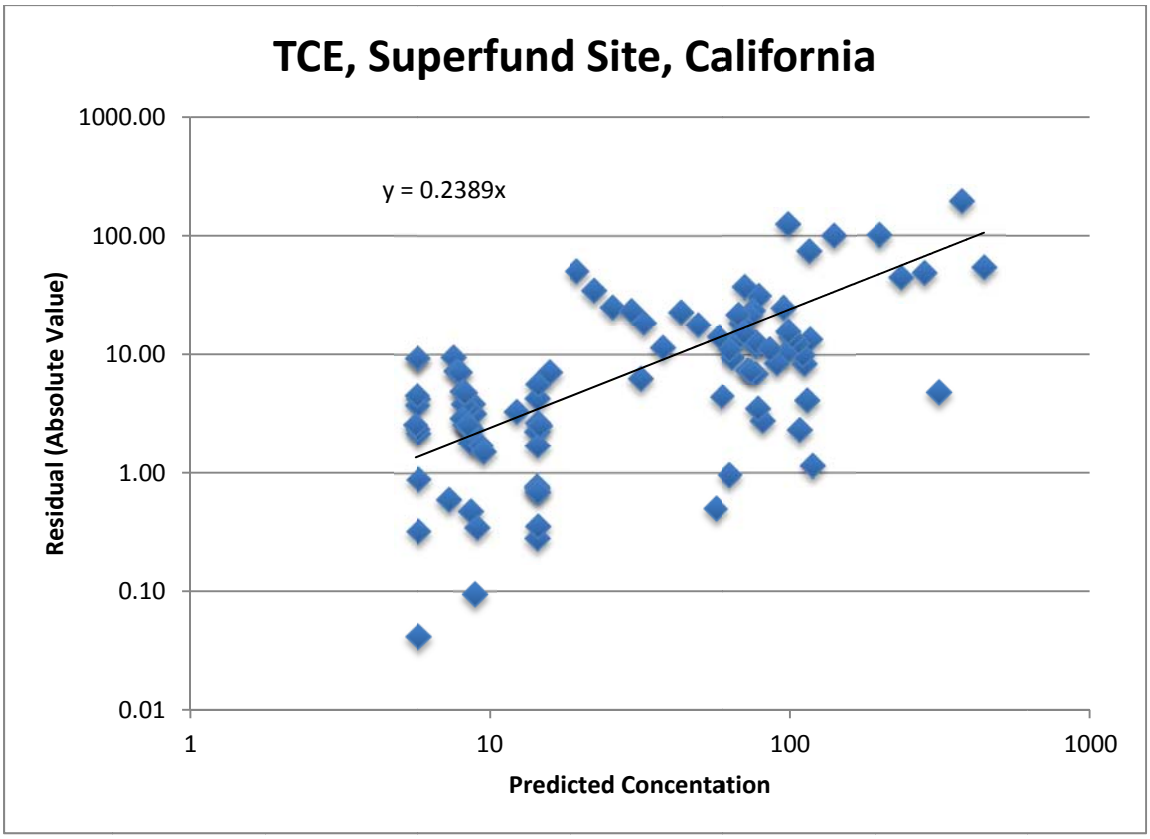
A.3 Residual v. Predicted Concentration

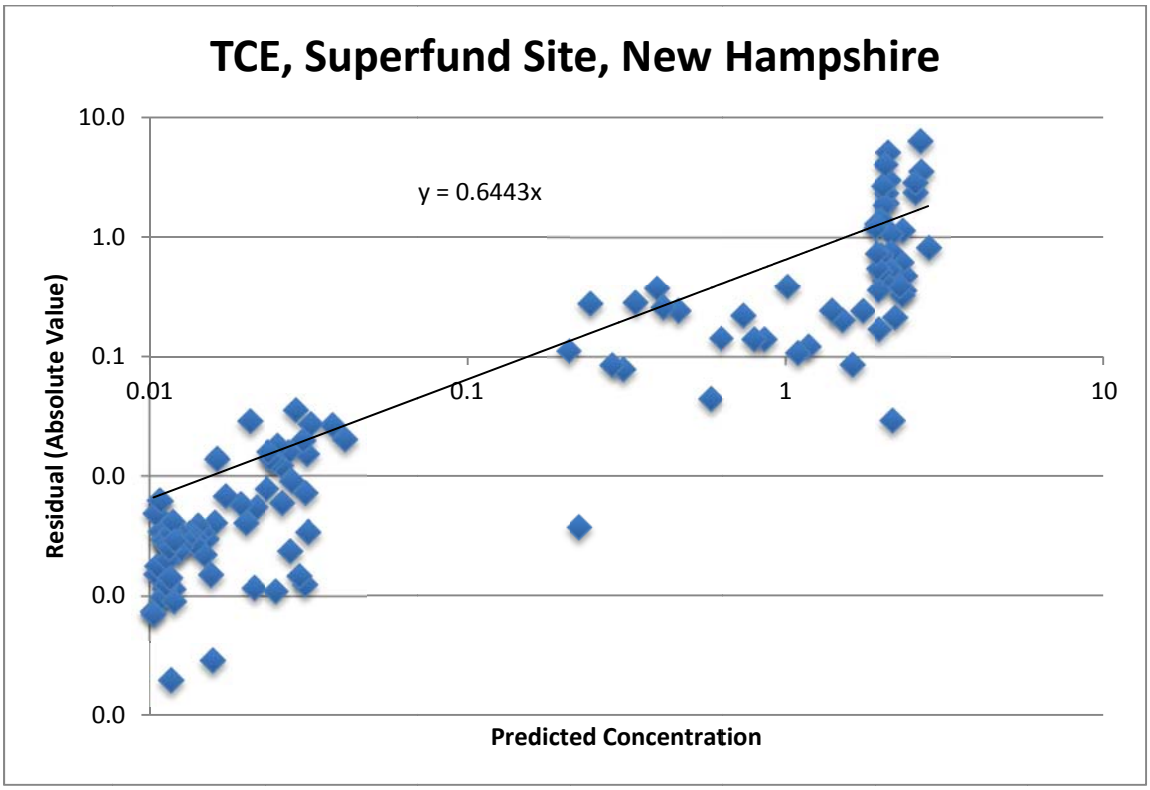


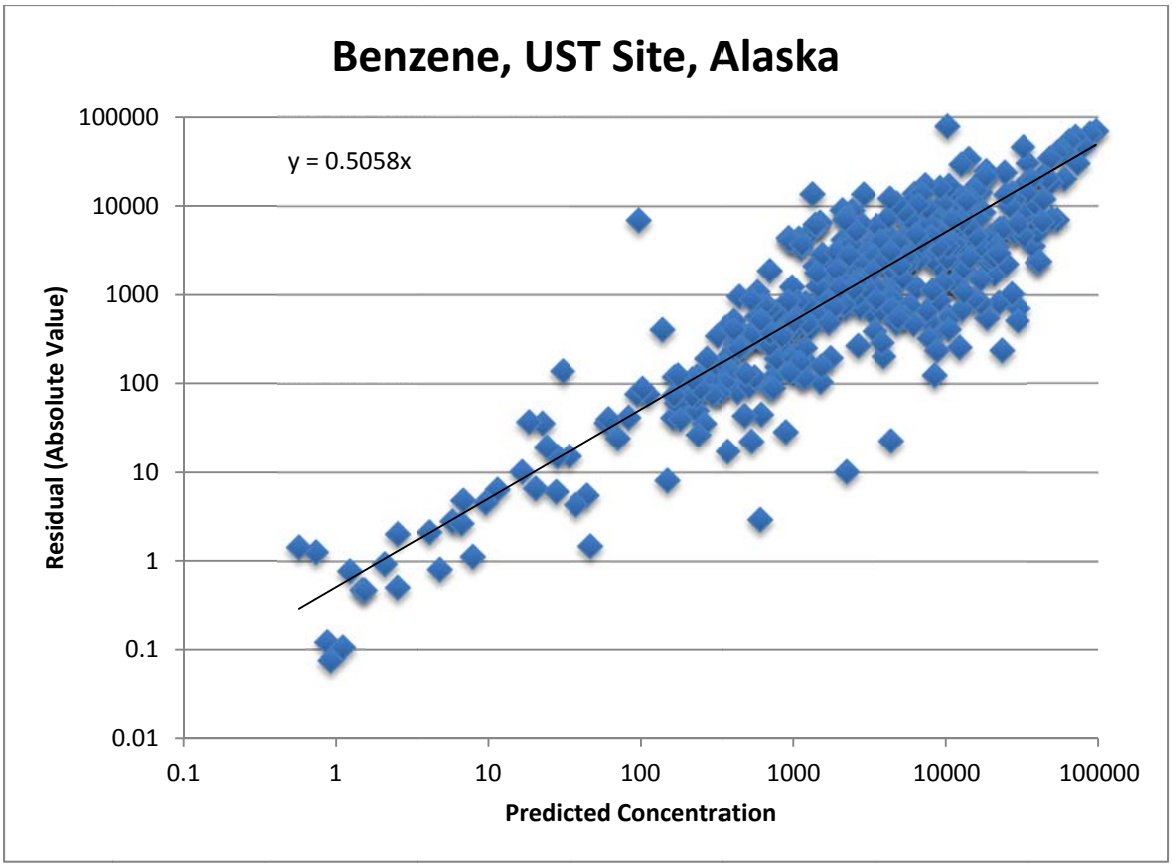


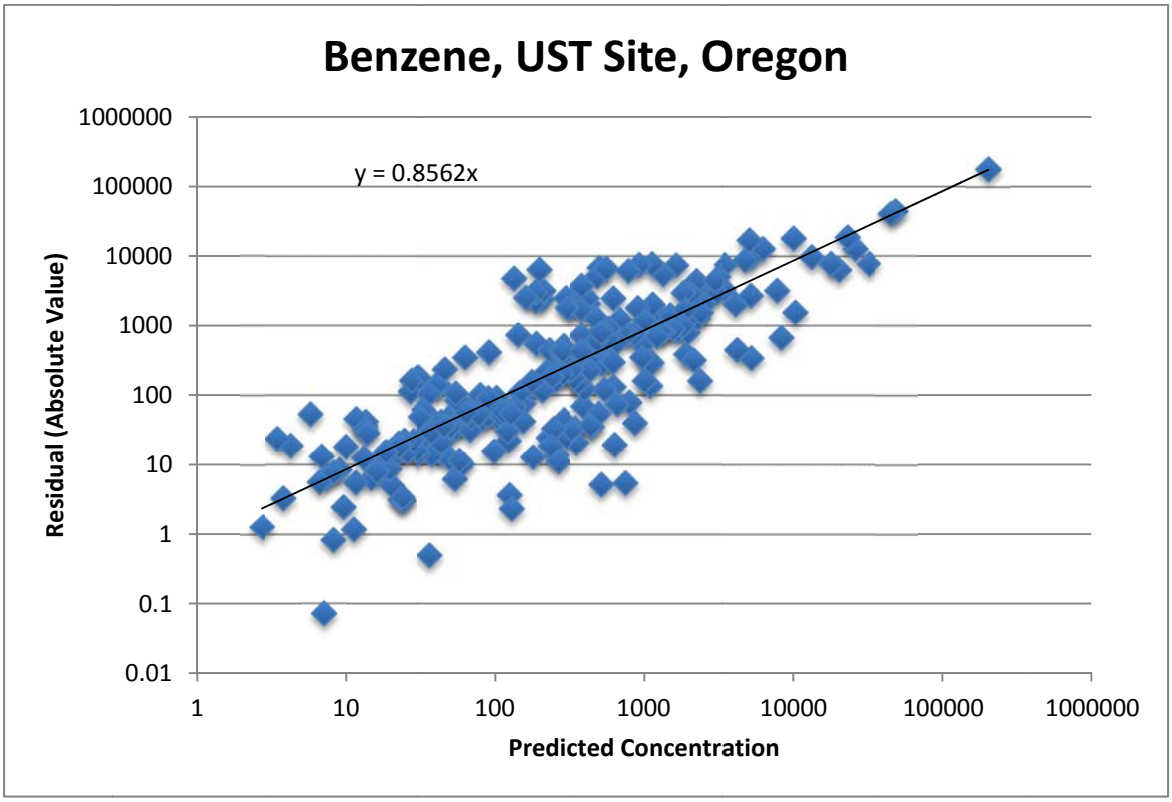

Arsenic, Landfill #3, Wisconsin
10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
Residual (Absolute Value)
y = 0.1321x
0.1
1.0
10.0
100.0
Predicted Concentration

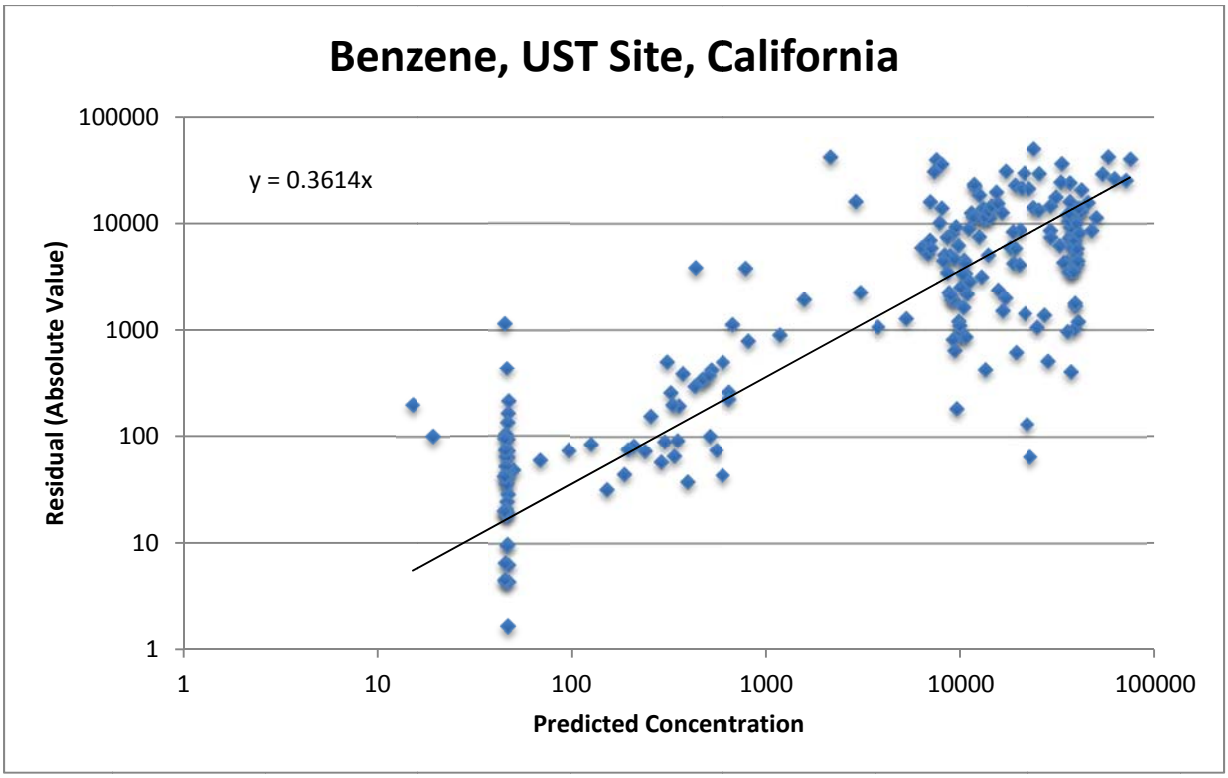

TCE, Superfund Site, Montana
10000.000
1000.000
100.000
10.000
1.000
0.100
0.010
0.001
Residual (Absolute Value)
y = 0.929x
0.1
1
10
100
1000
Predicted Concentration

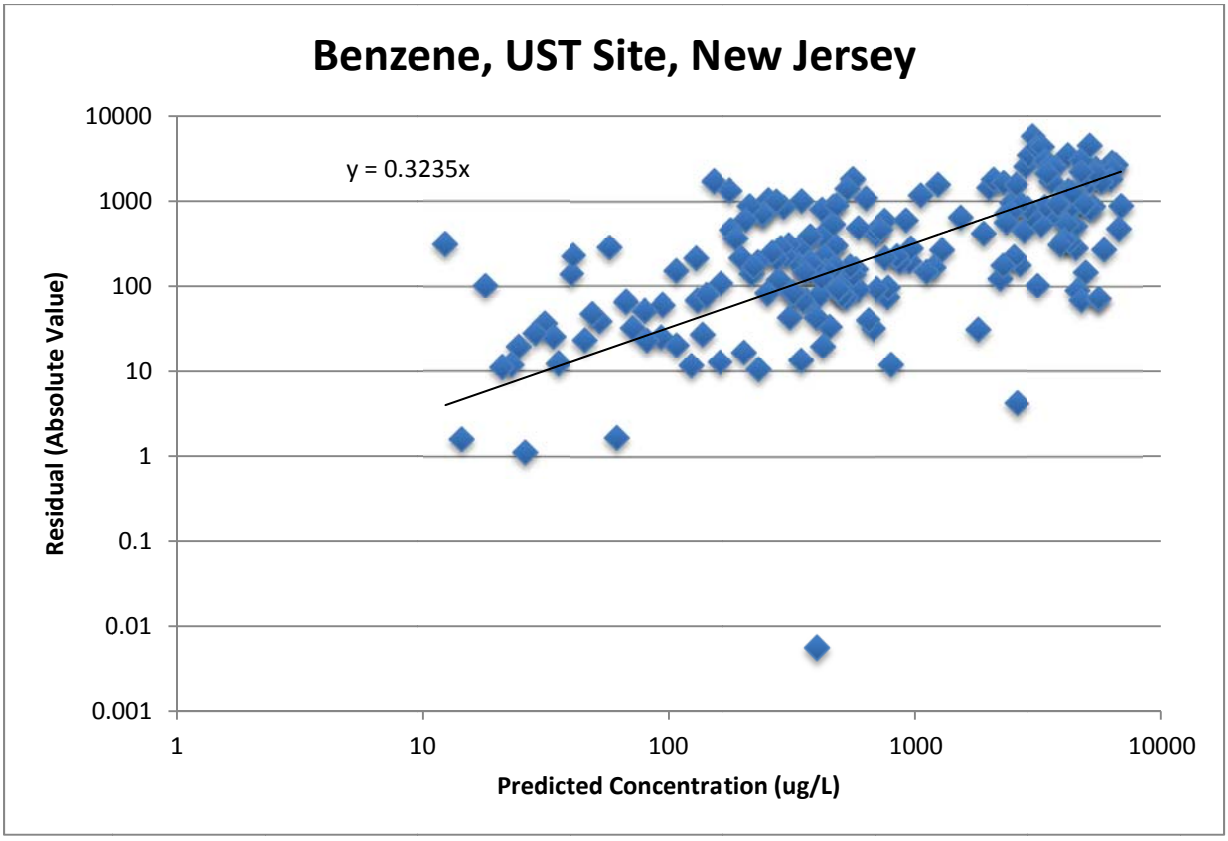

TCE, Superfund Site, California
y = 0.2389x
1000.00
100.00
10.00
1.00
0.10
0.01
Residual (Absolute Value)
1
10
100
1000
Predicted Concentation


TCE, Superfund Site, New Hampshire
y = 0.6443x
10.0
1.0
0.1
0.0
0.0
0.0
Residual (Absolute Value)
0.01
0.1
1
10
Predicted Concentration


Benzene, UST Site, Alaska
y = 0.5058x
Residual (Absolute Value)
100000
10000
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10000
100000
Predicted Concentration


Benzene, UST Site, Oregon
y = 0.8562x
Residual (Absolute Value)
1000000
100000
10000
1000
100
10
1
0.1
0.01
1
10
100
1000
10000
100000
1000000
Predicted Concentration

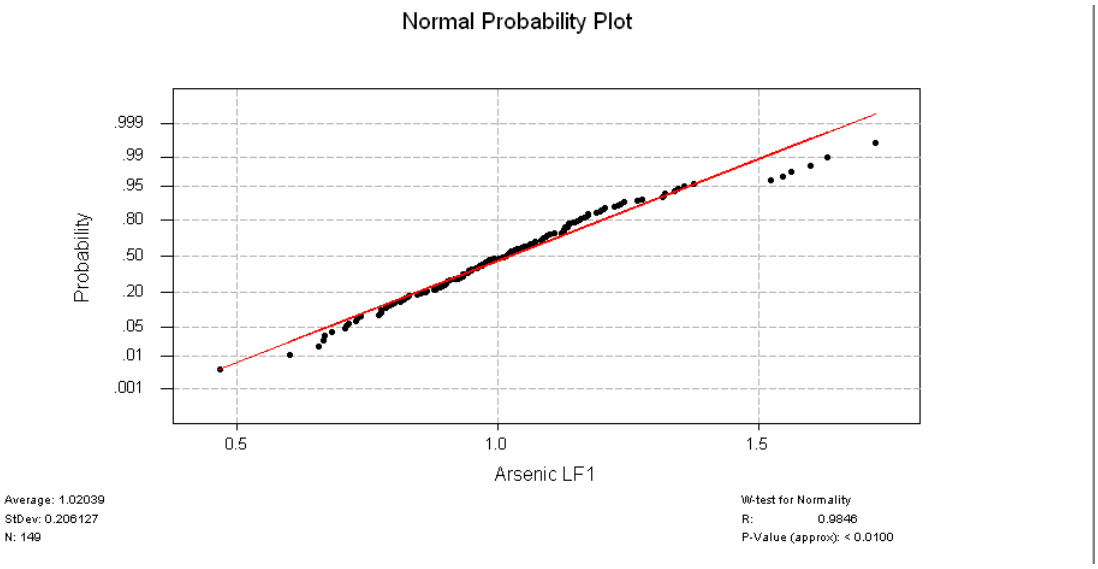

Benzene, UST Site, California
y = 0.3614x
Residual (Absolute Value)
100000
10000
1000
100
10
1
1
10
100
1000
10000
100000
Predicted Concentration


Benzene, UST Site, New Jersey
y = 0.3235x
Residual (Absolute Value)
10000
1000
100
10
1
0.1
0.01
0.001
1
10
100
1000
10000
Predicted Concentration (ug/L)

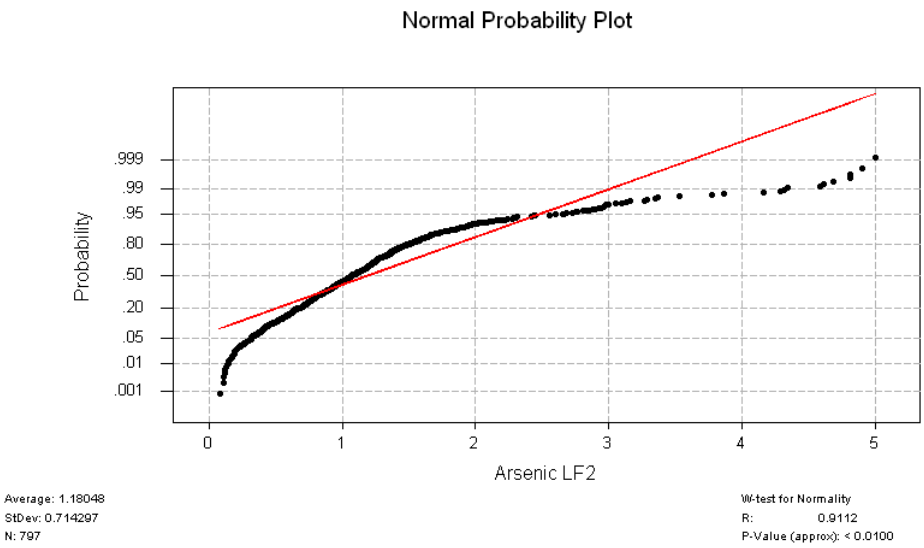
A.4 Probability Plots for Short-Term Variability (Normalized Residuals)

Each graph shows the normal probability plot for the normalized residuals calculated as shown in Figure A.1.

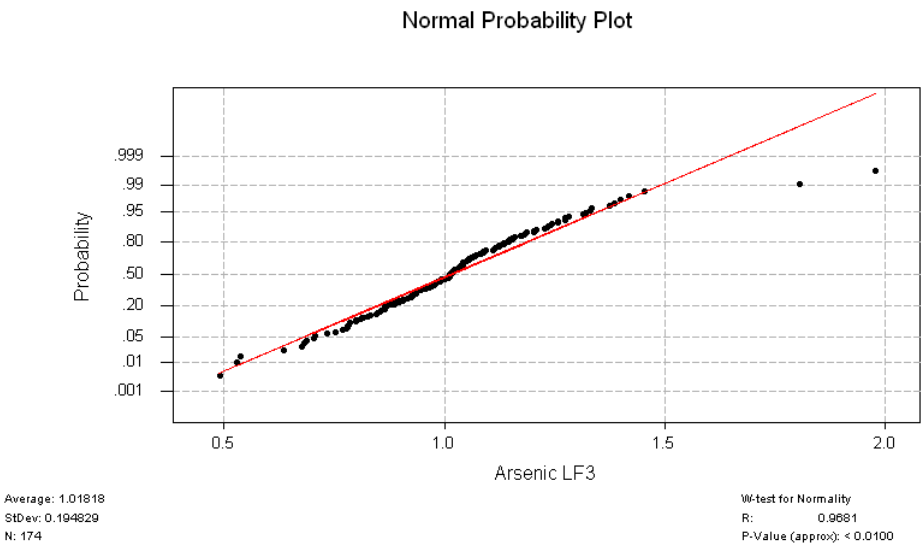
Arsenic, Landfill #1, Wisconsin



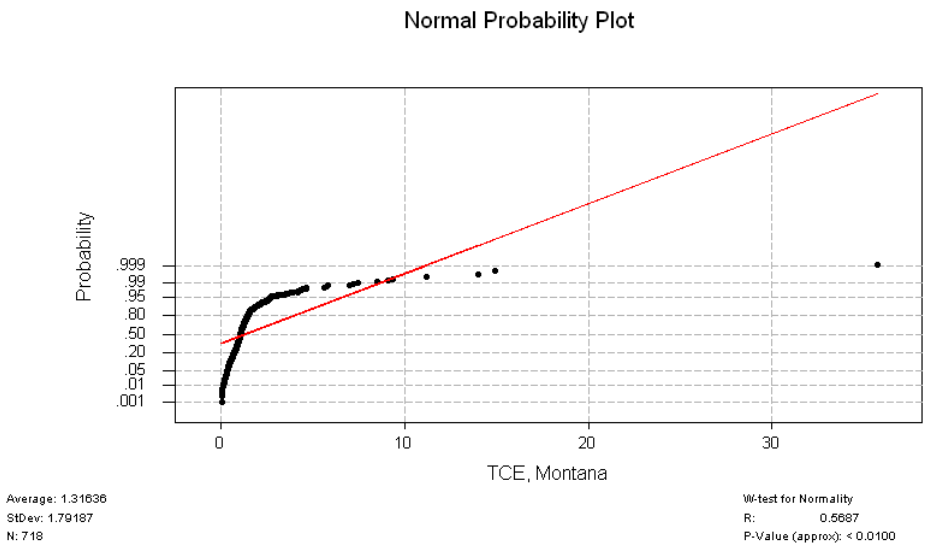
Arsenic, Landfill #2, Wisconsin



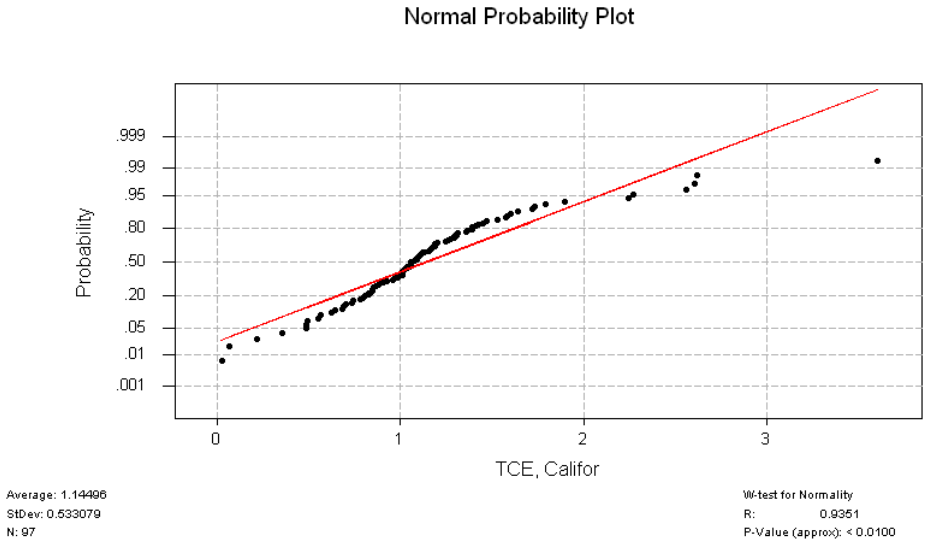
Arsenic, Landfill #3, Wisconsin



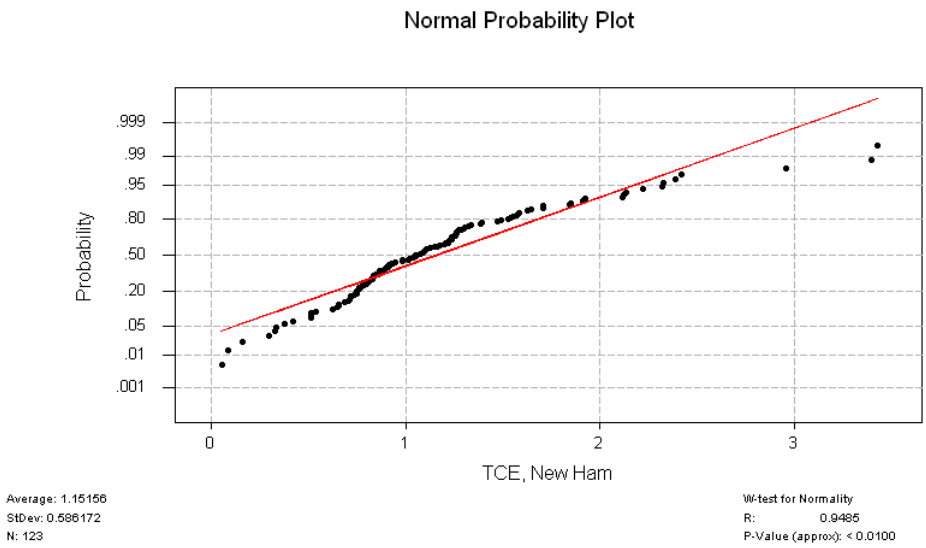
TCE, Superfund Site, Montana



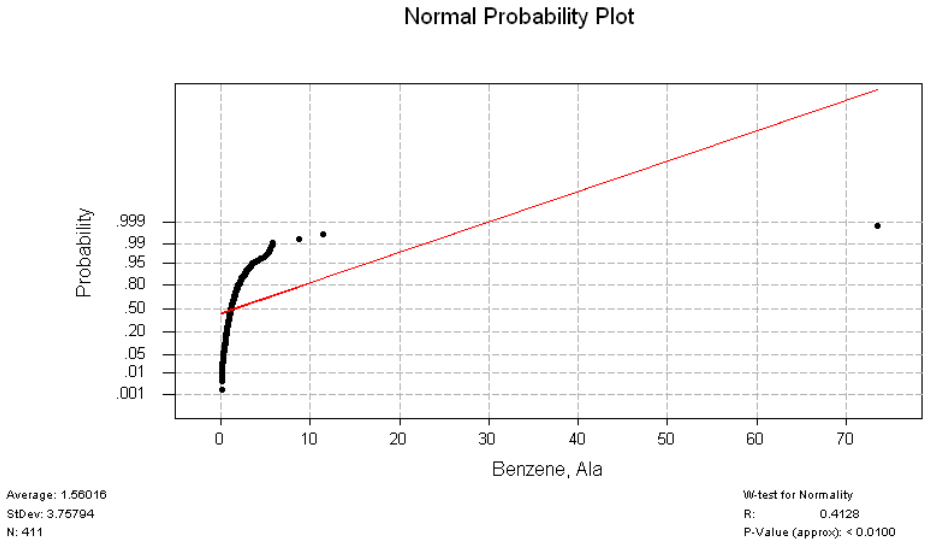
TCE, Superfund Site, California



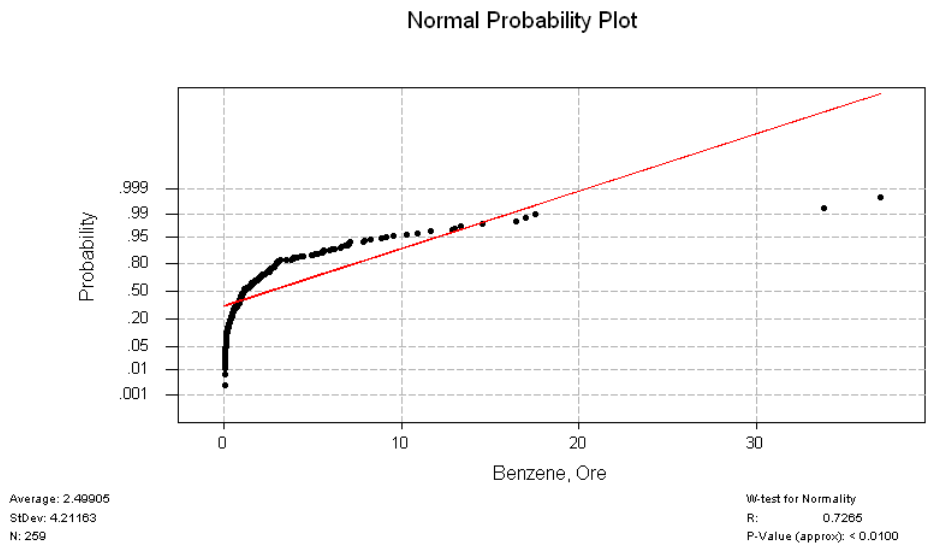
TCE, Superfund Site, New Hampshire



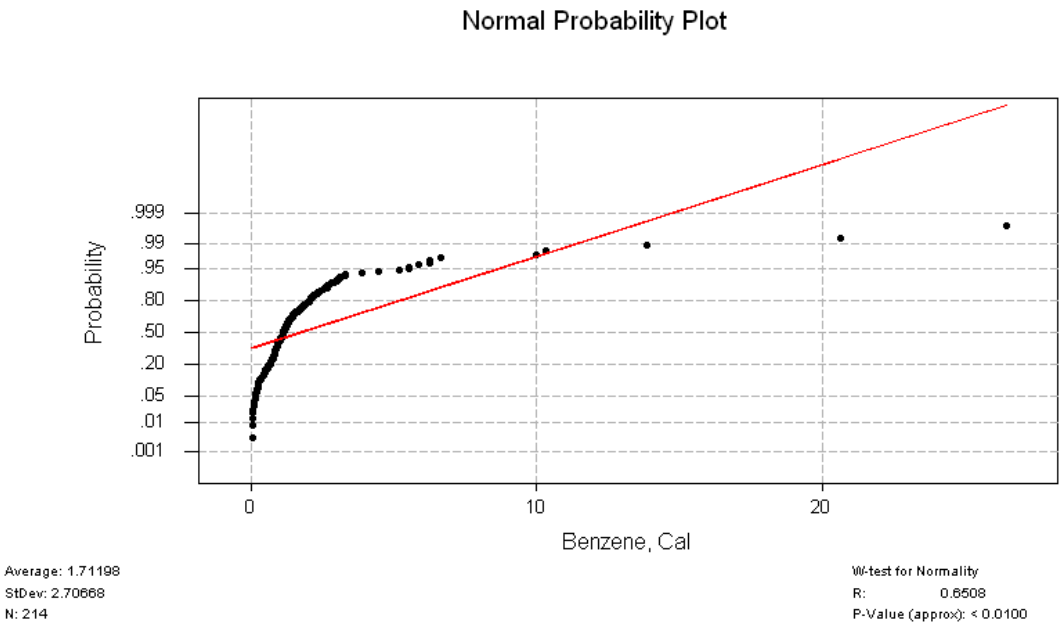
Benzene, UST Site, Alaska



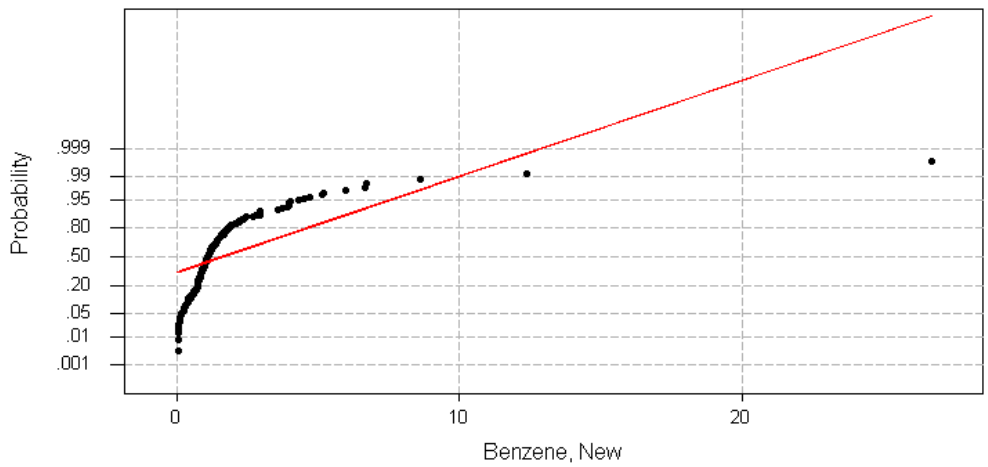
Benzene, UST Site, Oregon



Benzene, UST Site, California



Benzene, UST Site, New Jersey



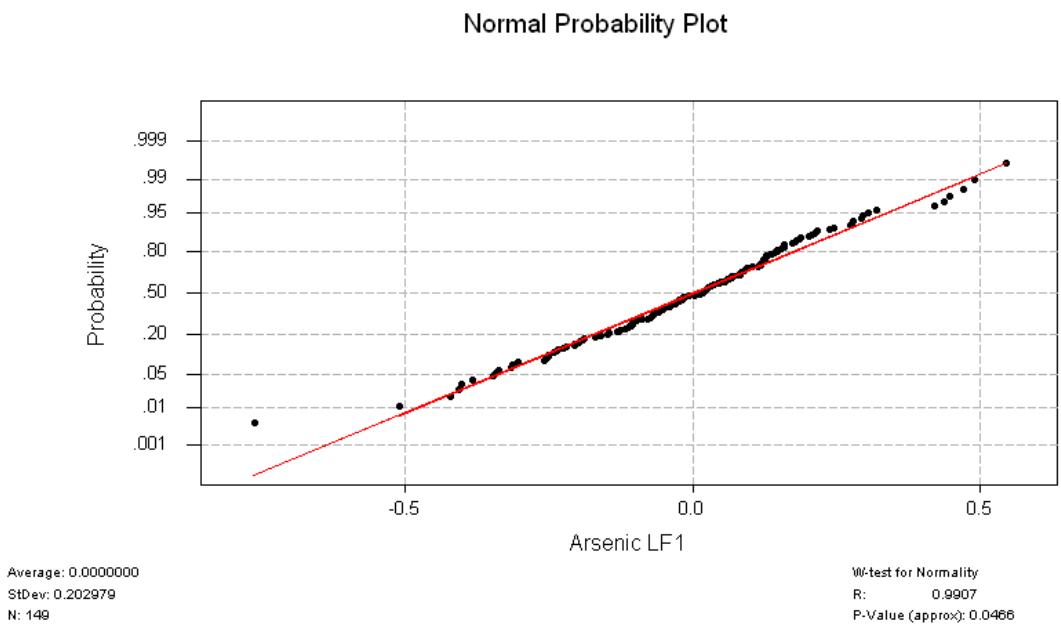
Average: 1.60382
StDev: 2.33912
N: 196

W-test for Normality
R: 0.6490
P-Value (approx): < 0.0100

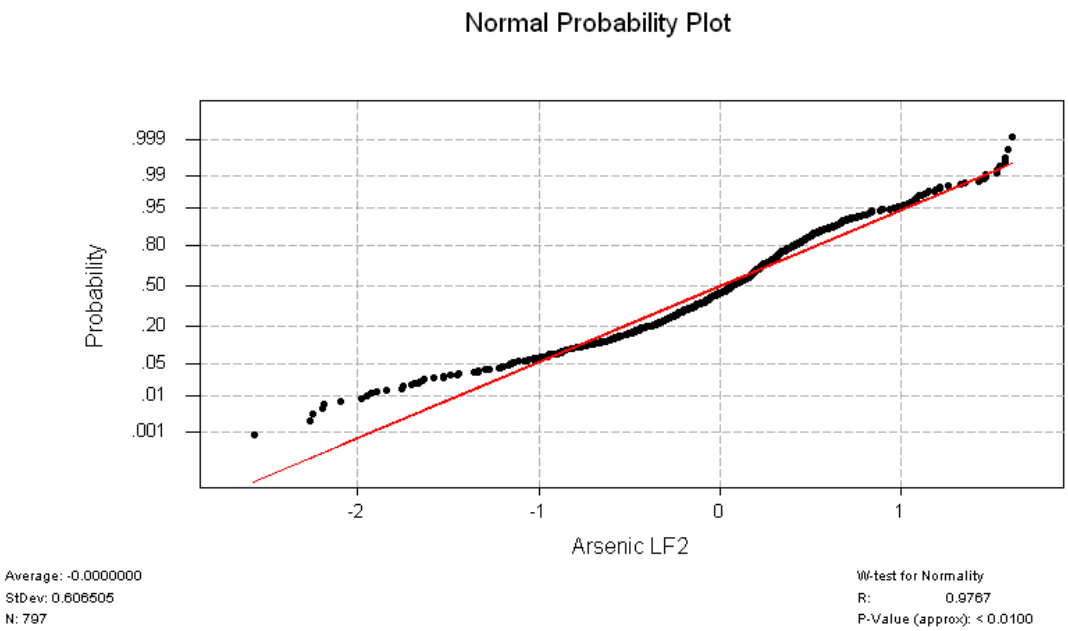
A.5 Probability Plots for Short-Term Variability (Log Transformed Normalized Residuals)

Each graph shows the normal probability plot for the log transformed normalized residuals. Normalized residuals calculated as shown in Figure A.1.

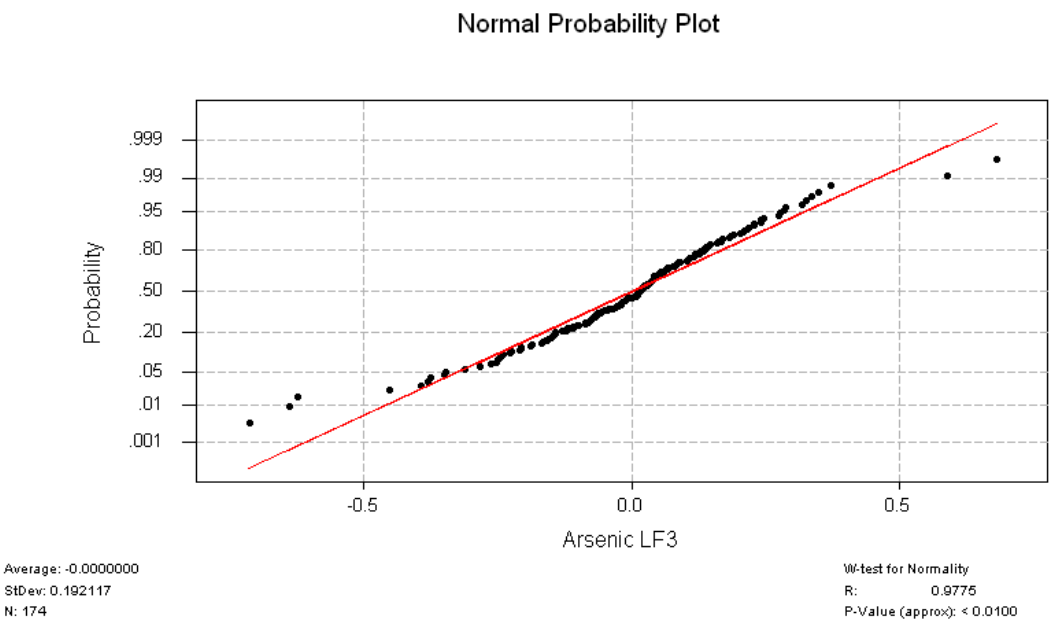
Log Transformed Normalized Residuals, Arsenic. Landfill #1, Wisconsin



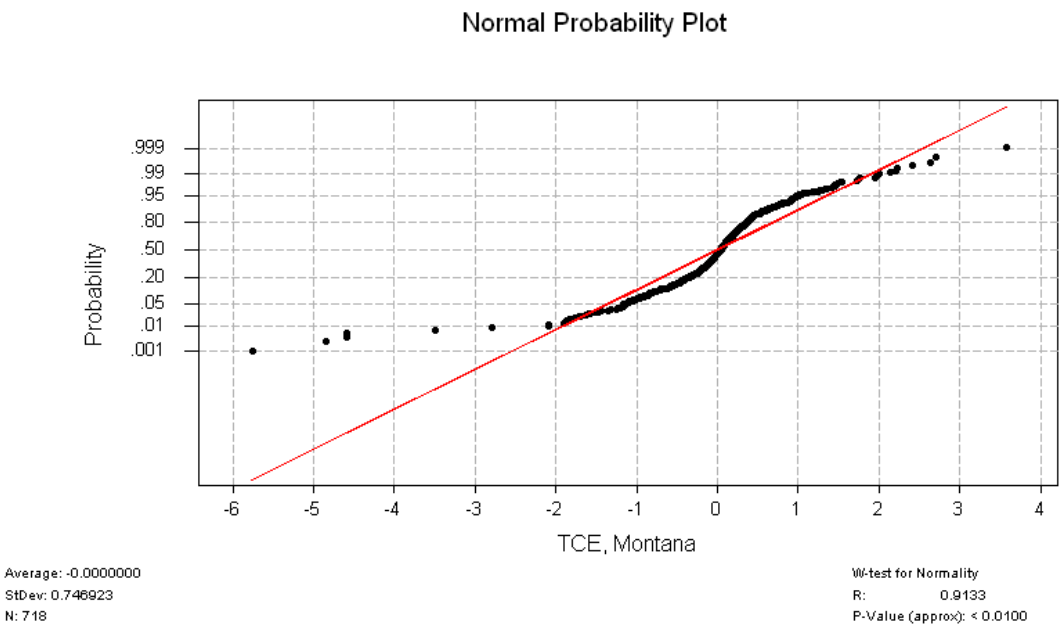
Log Transformed Normalized Residuals, Arsenic, Landfill #2, Wisconsin



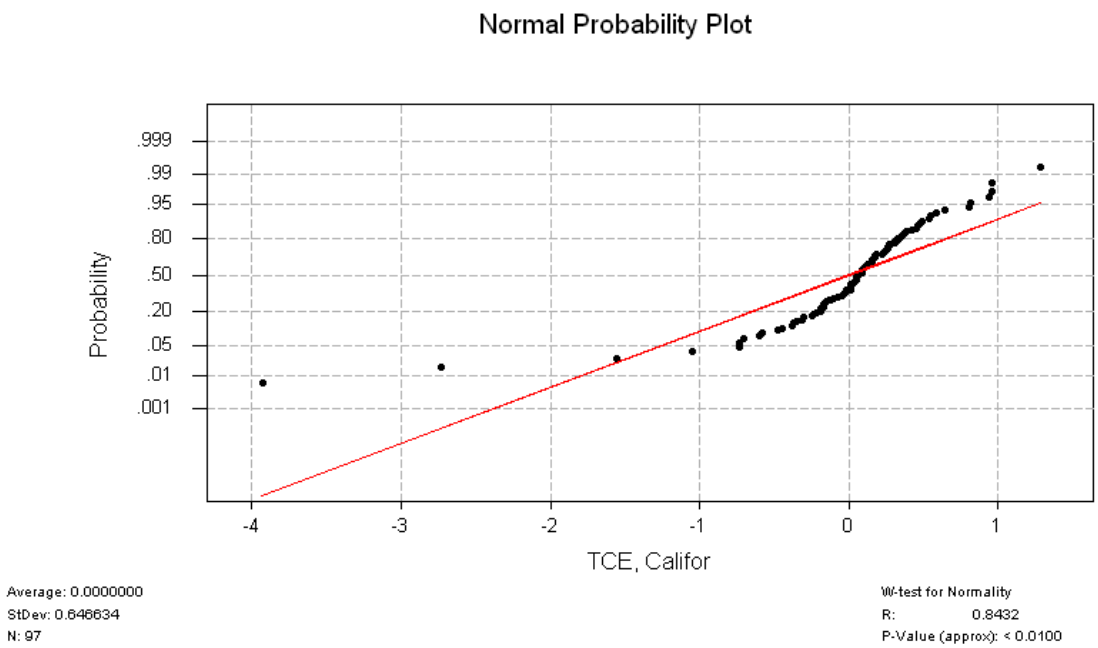
Log Transformed Normalized Residuals, Arsenic, Landfill #3, Wisconsin



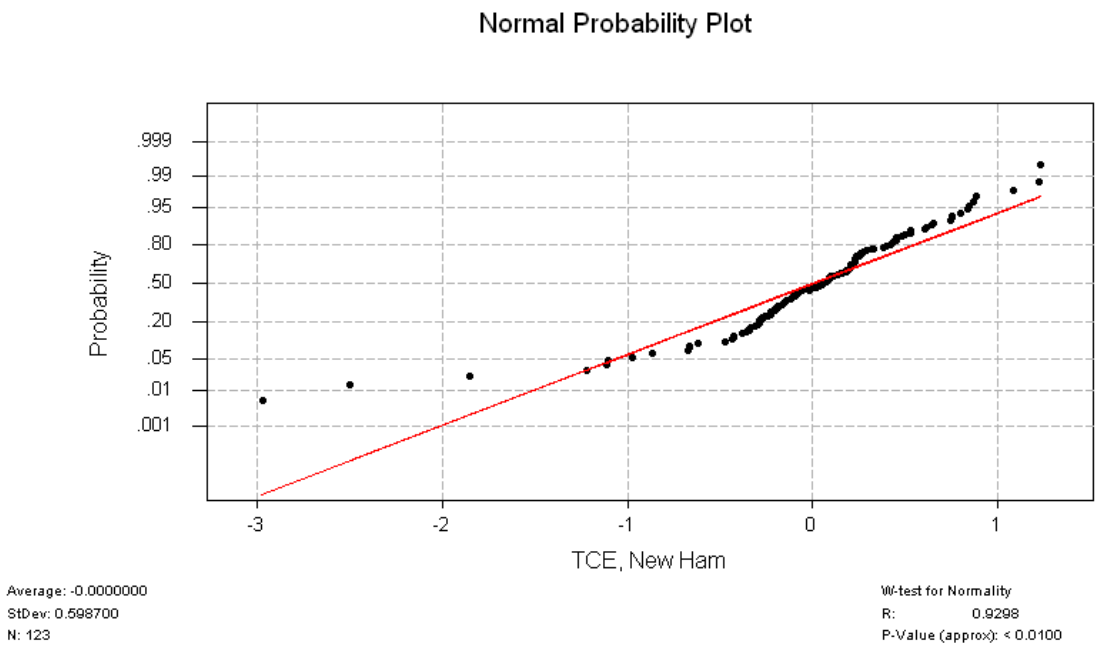
Log Transformed Normalized Residuals, TCE, Superfund Site, Montana



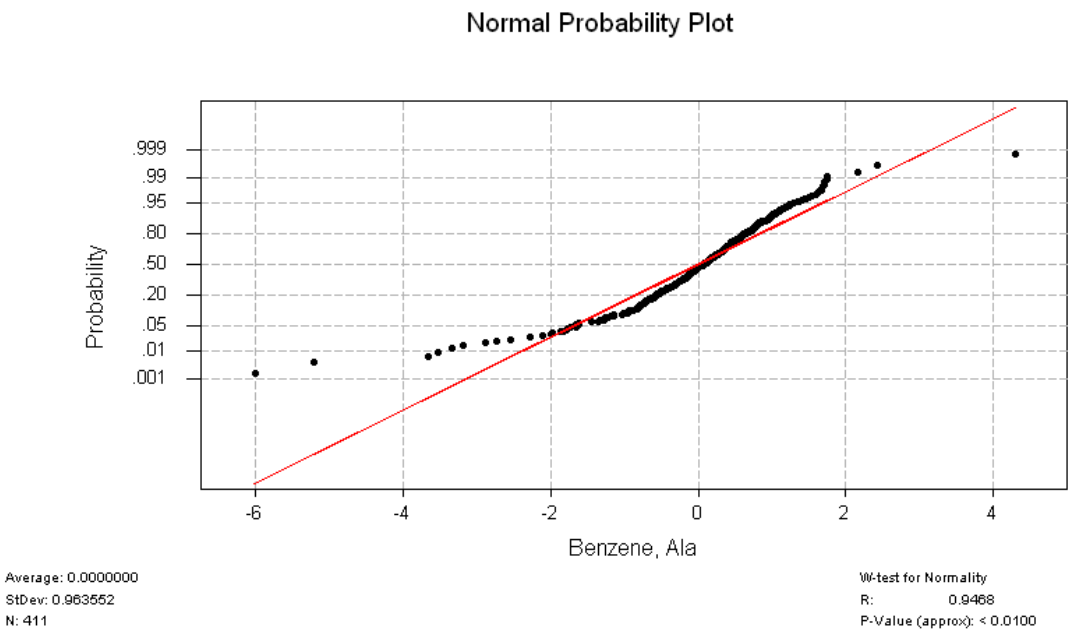
Log Transformed Data, TCE, Superfund Site, California



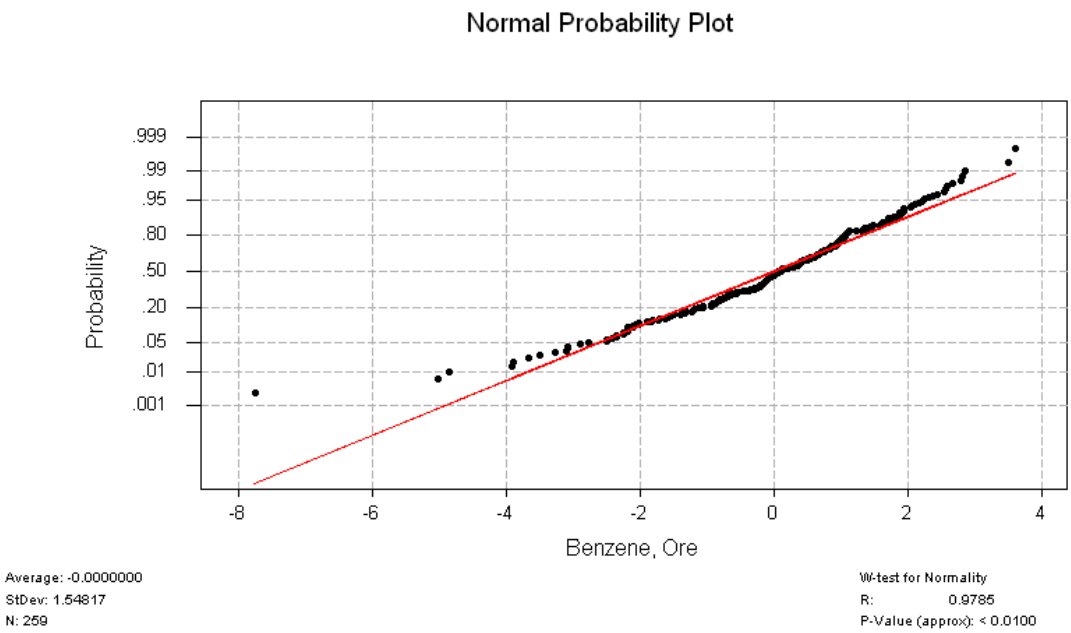
Log Transformed Normalized Residuals, TCE, Superfund Site, New Hampshire



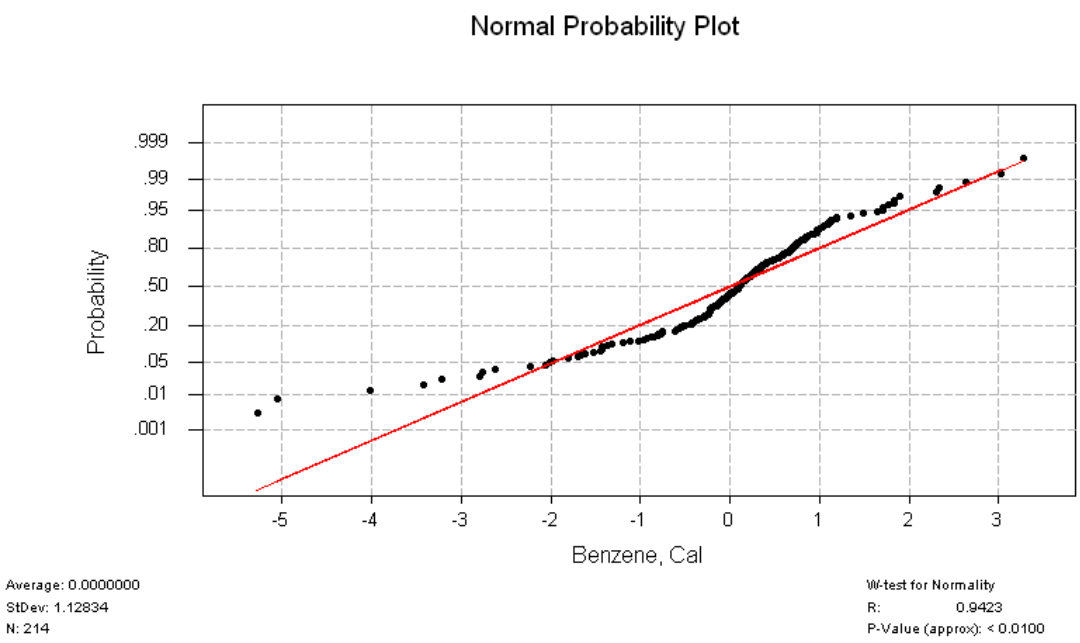
Log Transformed Normalized Residuals, Benzene, UST Site, Alaska



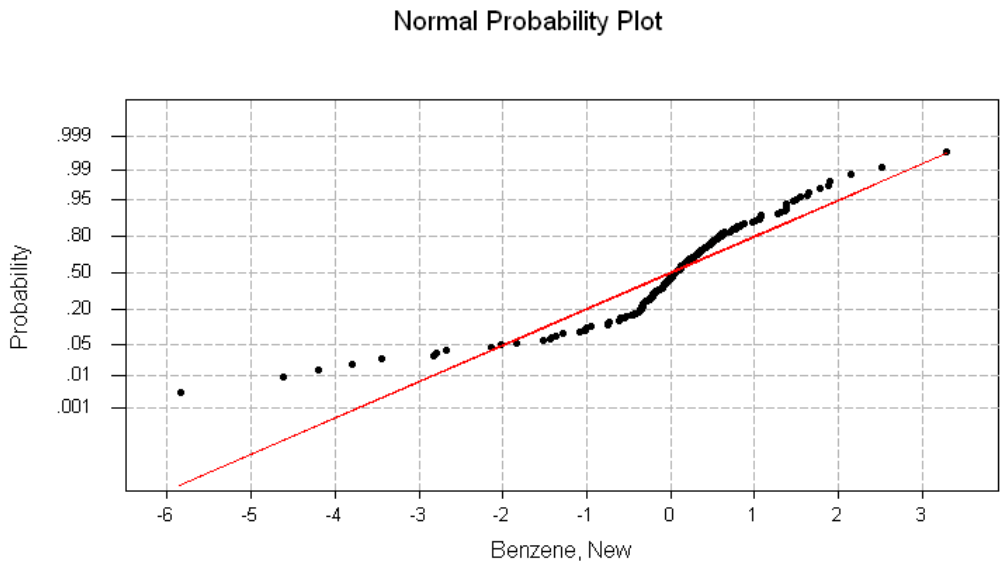
Log Transformed Normalized Residuals, Benzene, UST Site, Oregon



Log Transformed Normalized Residuals, Benzene, UST Site, California



Log Transformed Normalized Residuals, Benzene, UST Site, New Jersey



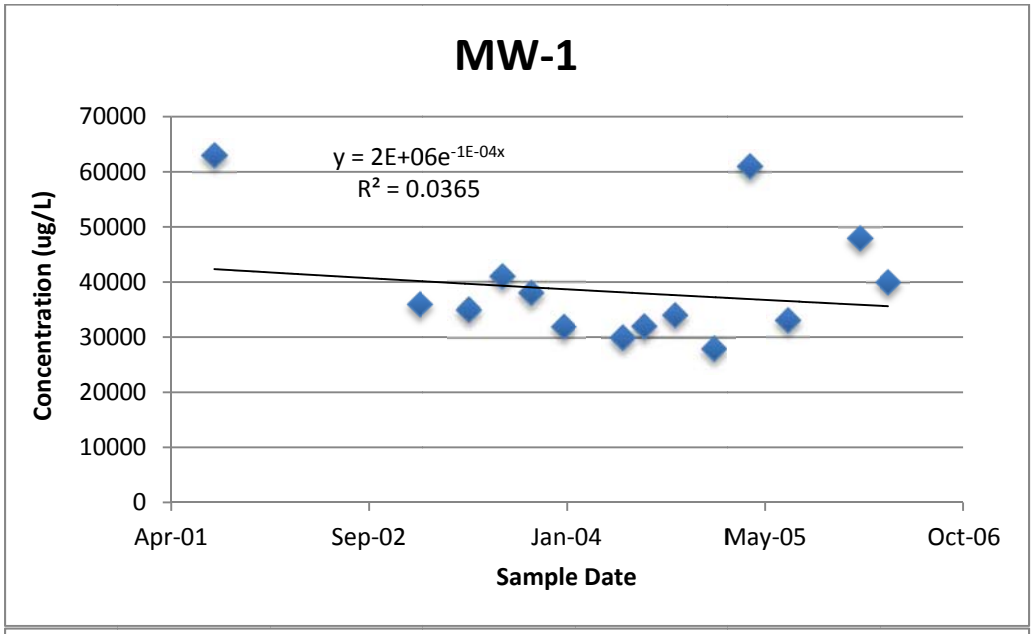
Average: 0.0000000
StDev: 1.10357
N: 196

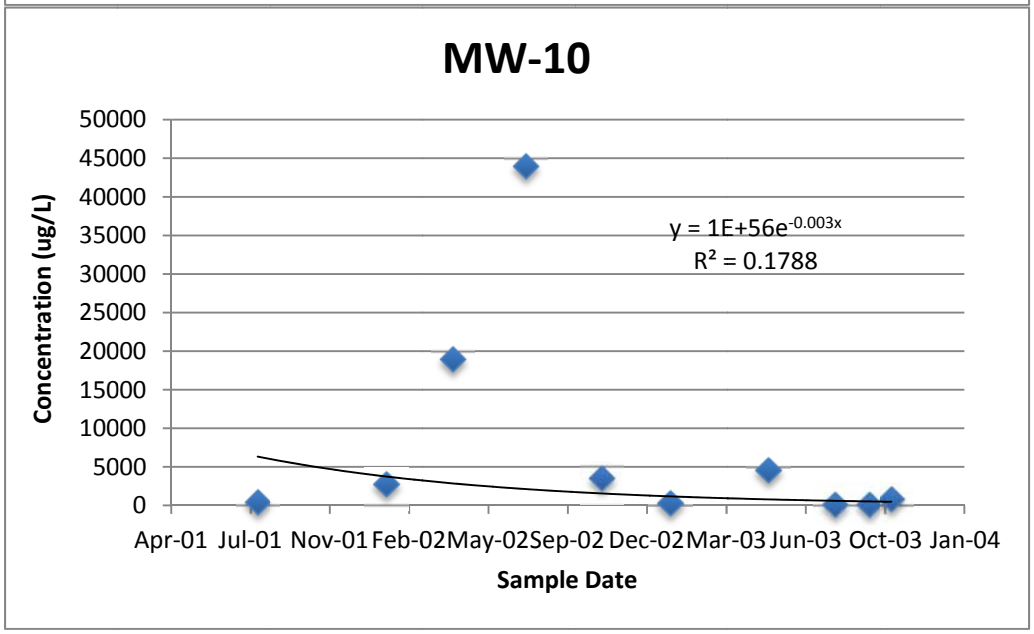
W-test for Normality
R: 0.9154
P-Value (approx): < 0.0100

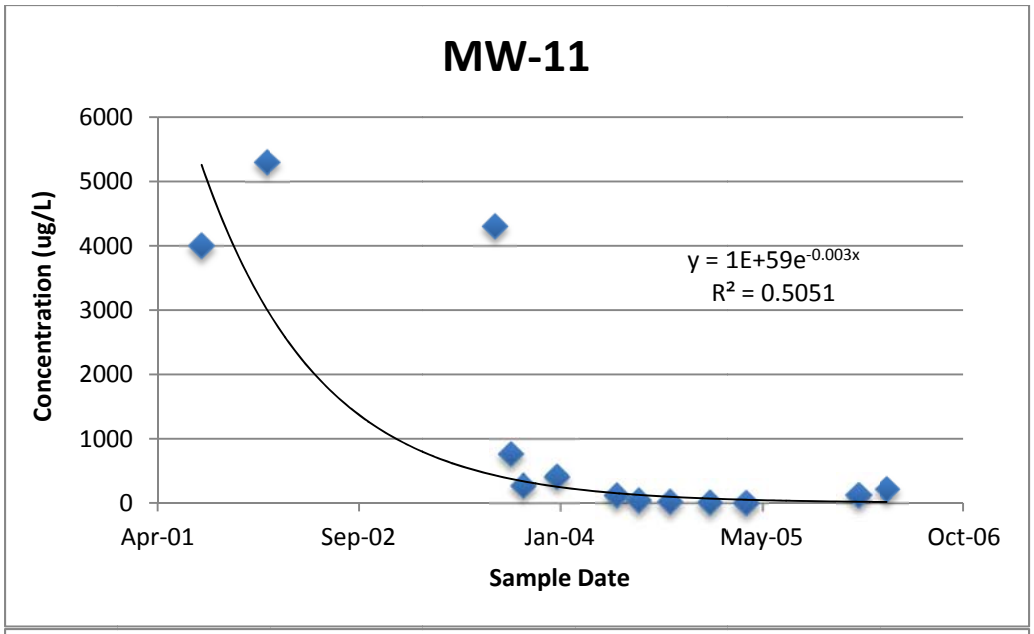
A.6 Best Fit Curves (exponential decay model) for Individual Monitoring Wells From Four of the Test Sites.

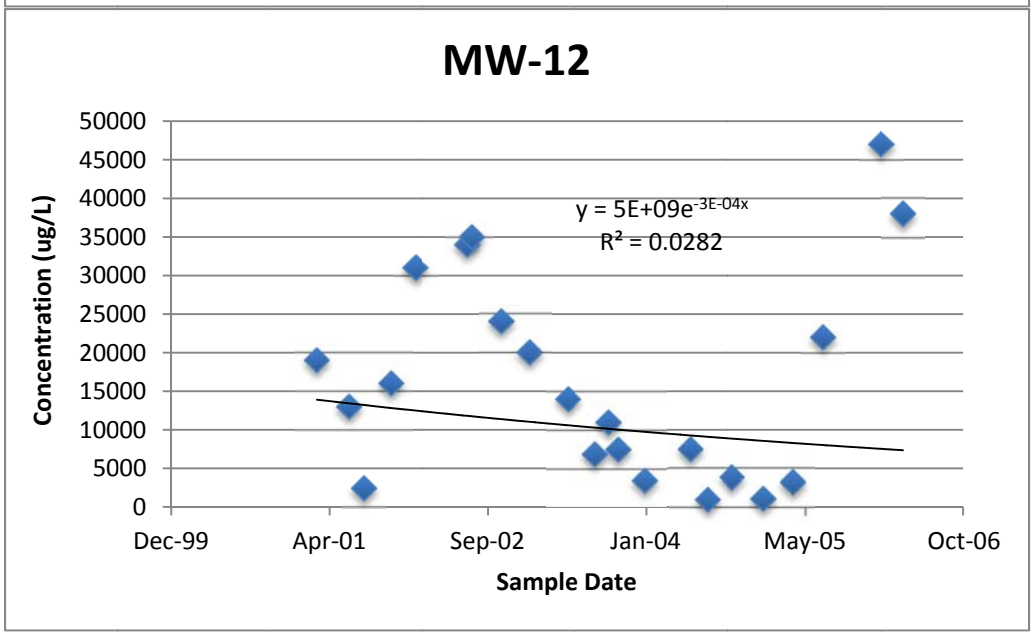
Each graph shows concentration vs. time monitoring record for an individual monitoring well and the best fit exponential decay curve for the monitoring data.

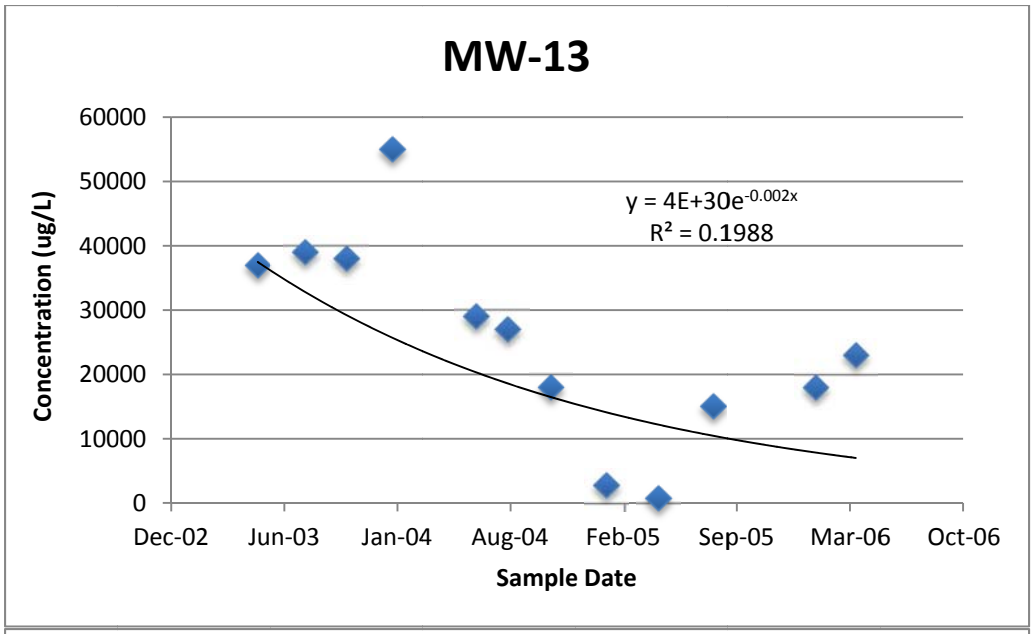
Benzene, UST Site, California

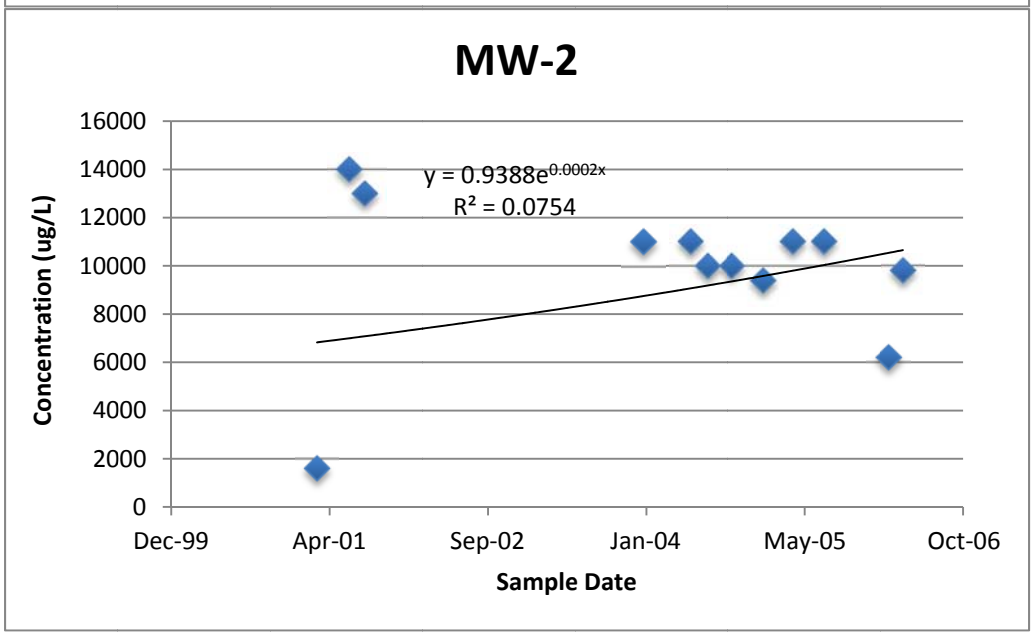


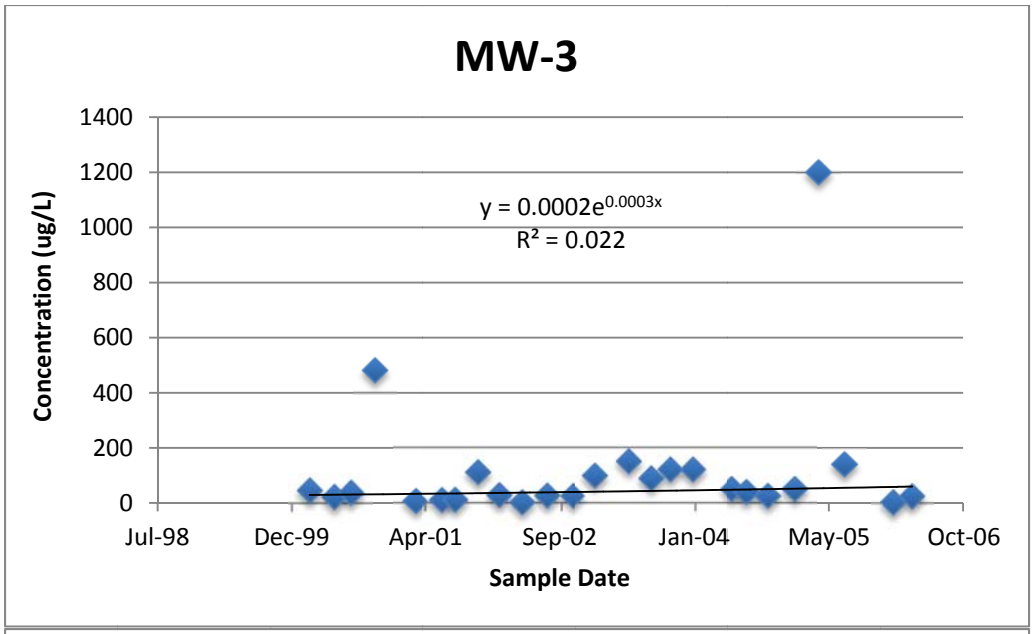


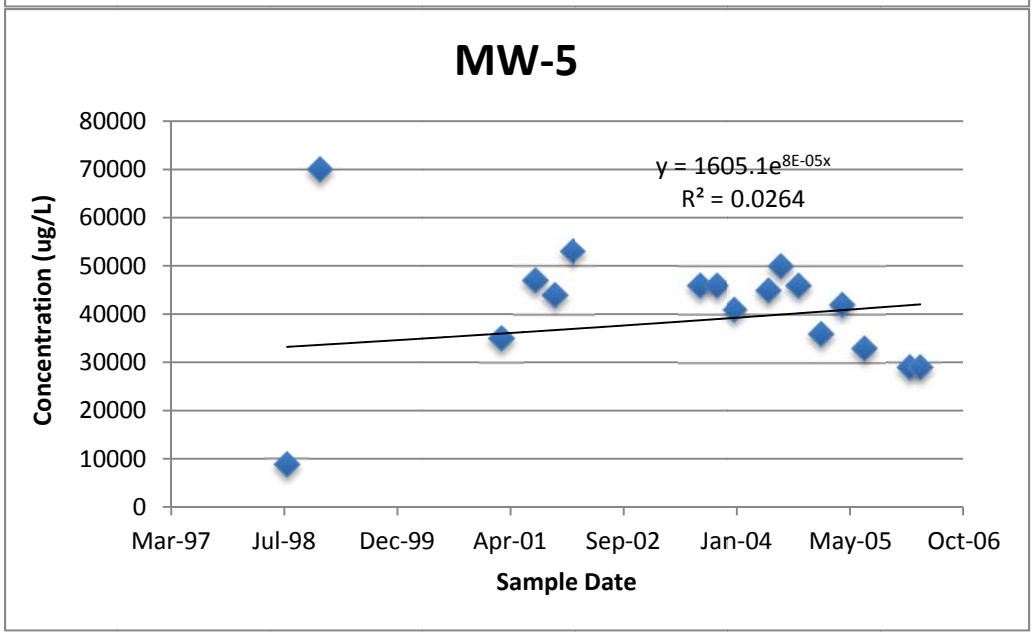

MW-11
6000
5000
4000
3000
2000
1000
0
Concentration (ug/L)
y = 1E+59e-0.003x
R² = 0.5051
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Sample Date

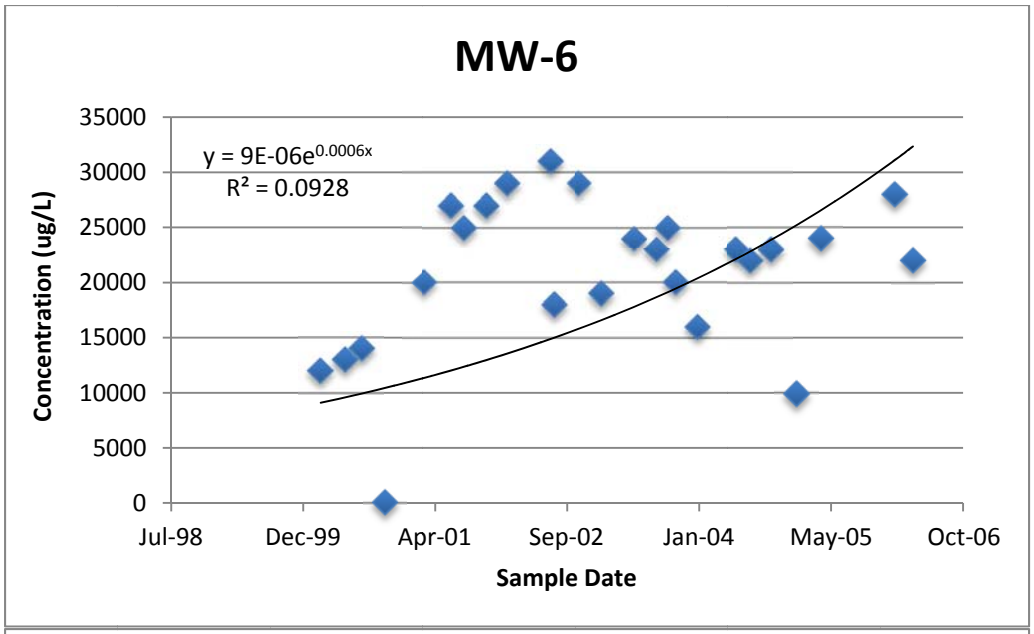

MW-12
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Concentration (ug/L)
y = 5E+09e-3E-04x
R² = 0.0282
Dec-99
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Sample Date

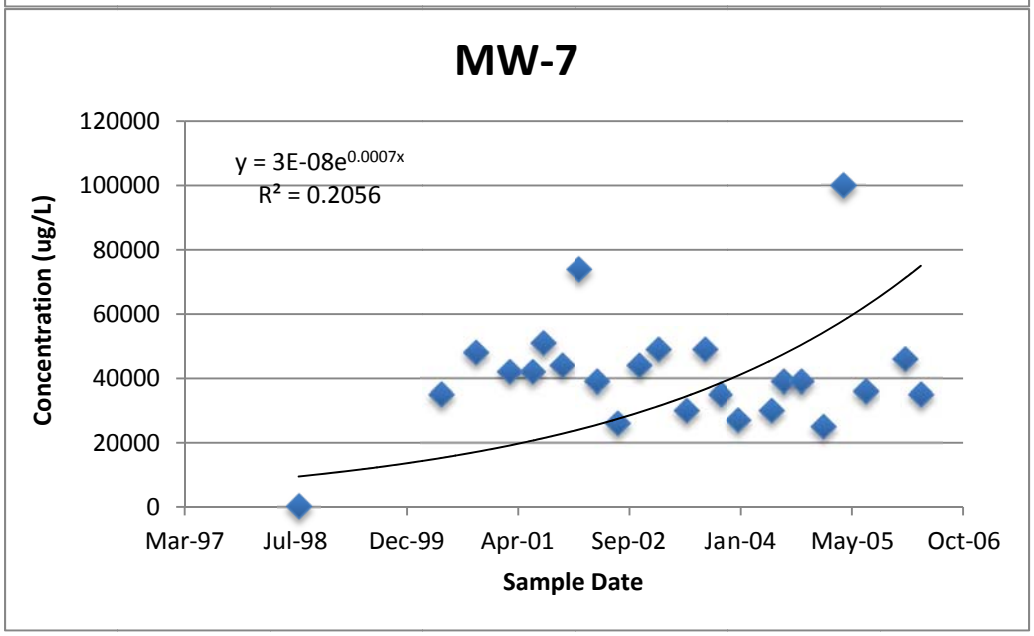

MW-13
60000
50000
40000
30000
20000
10000
0
Concentration (ug/L)
y = 4E+30e-0.002x
R² = 0.1988
Dec-02
Jun-03
Jan-04
Aug-04
Feb-05
Sep-05
Mar-06
Oct-06
Sample Date

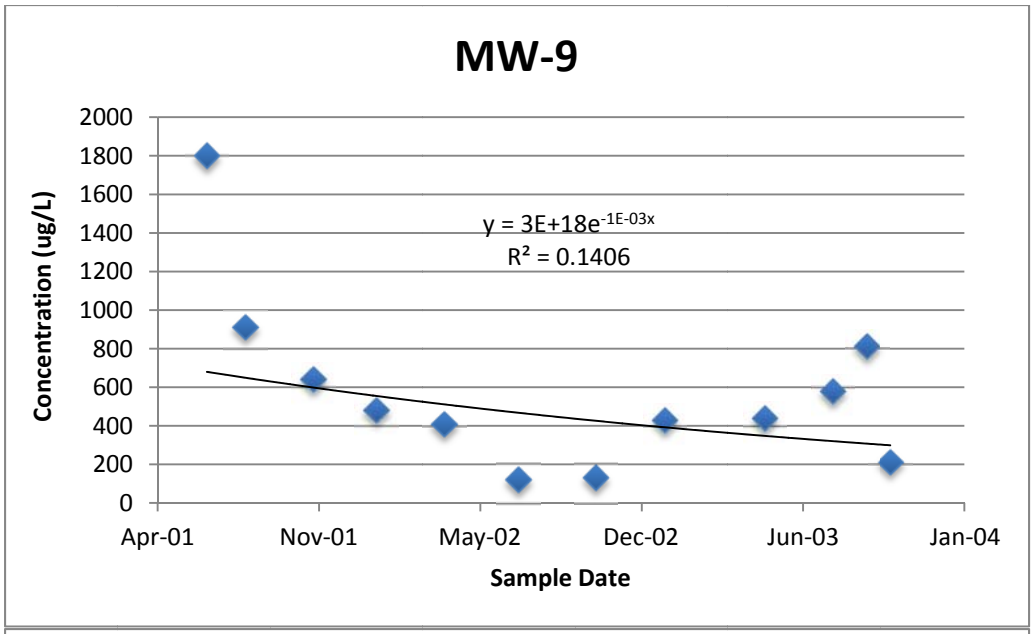

MW-2
16000
14000
12000
10000
8000
6000
4000
2000
0
Concentration (ug/L)
y = 0.9388e0.0002x
R² = 0.0754
Dec-99
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Sample Date

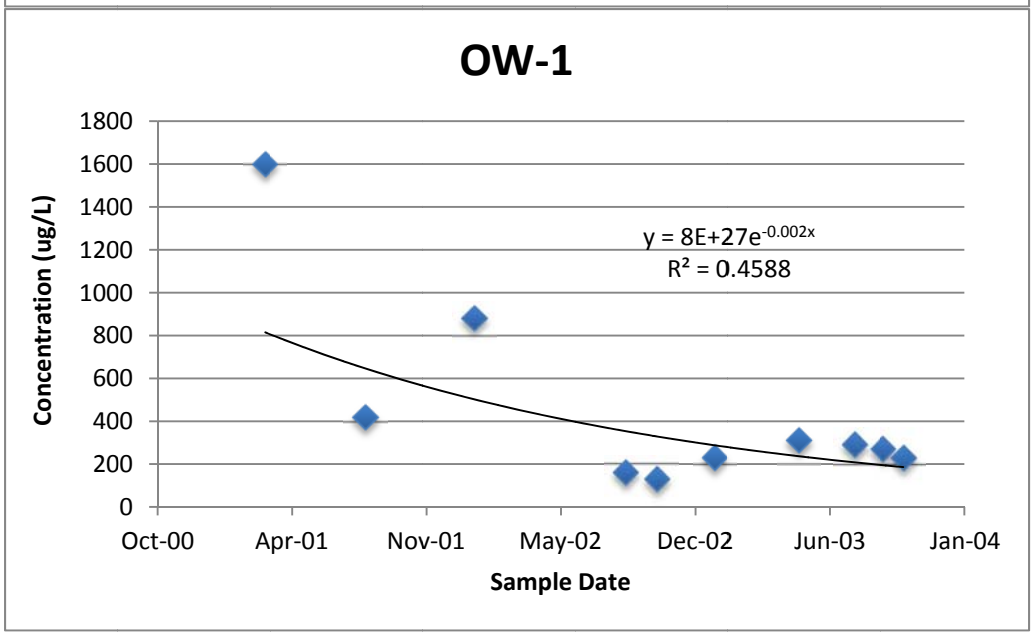

MW-3
1400
1200
1000
800
600
400
200
0
Concentration (ug/L)
y = 0.0002e^0.0003x
R² = 0.022
Jul-98
Dec-99
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Sample Date


MW-5
80000
70000
60000
50000
40000
30000
20000
10000
0
Concentration (ug/L)
y = 1605.1e^8E-05x
R² = 0.0264
Mar-97
Jul-98
Dec-99
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Sample Date

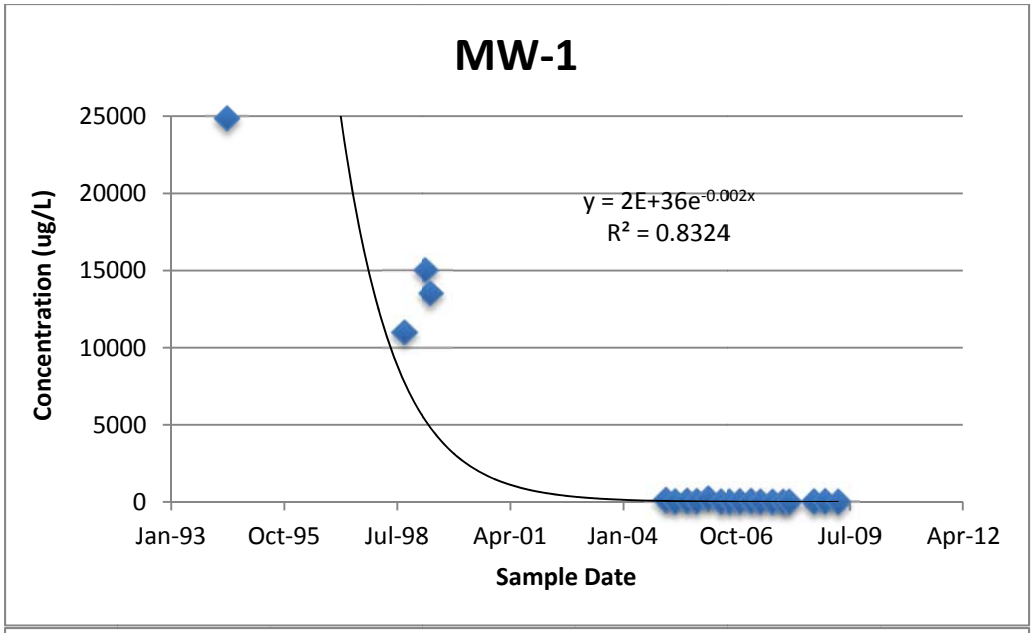

MW-6
y = 9E-06e^0.0006x
R² = 0.0928
Concentration (ug/L)
35000
30000
25000
20000
15000
10000
5000
0
Jul-98
Dec-99
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Sample Date

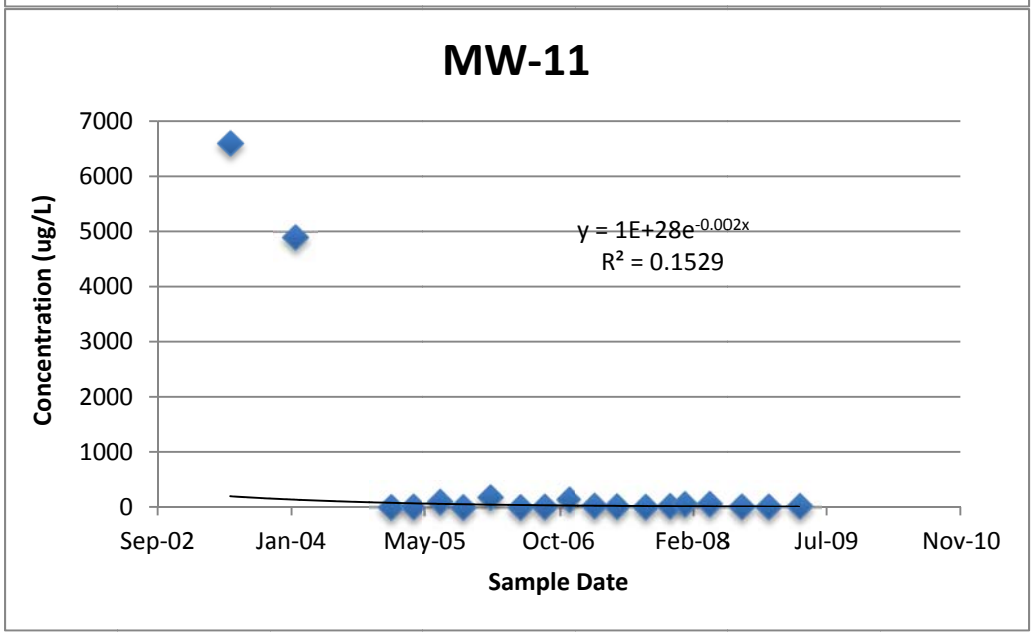

MW-7
y = 3E-08e^0.0007x
R² = 0.2056
Concentration (ug/L)
120000
100000
80000
60000
40000
20000
0
Mar-97
Jul-98
Dec-99
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Sample Date

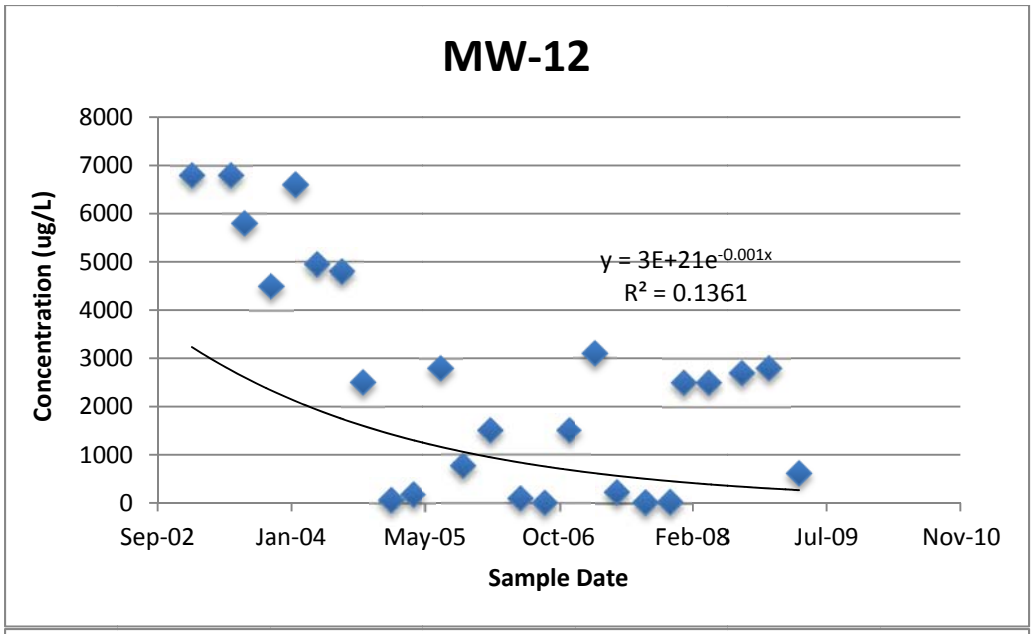

MW-9
Concentration (ug/L)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
y = 3E+18e-1E-03x
R² = 0.1406
Apr-01
Nov-01
May-02
Dec-02
Jun-03
Jan-04
Sample Date

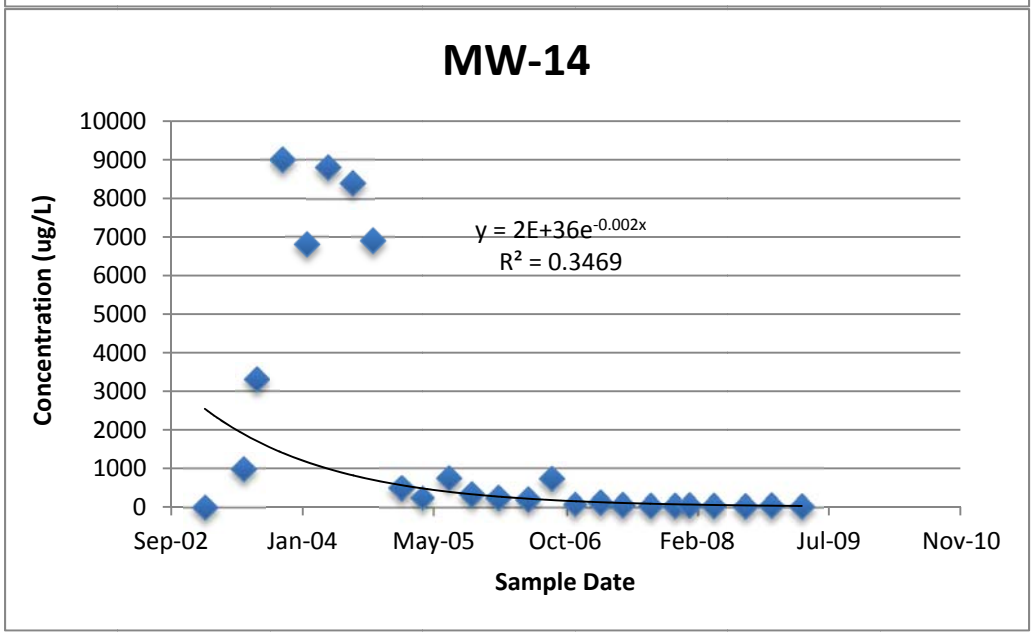

OW-1
Concentration (ug/L)
1800
1600
1400
1200
1000
800
600
400
200
0
y = 8E+27e-0.002x
R² = 0.4588
Oct-00
Apr-01
Nov-01
May-02
Dec-02
Jun-03
Jan-04
Sample Date

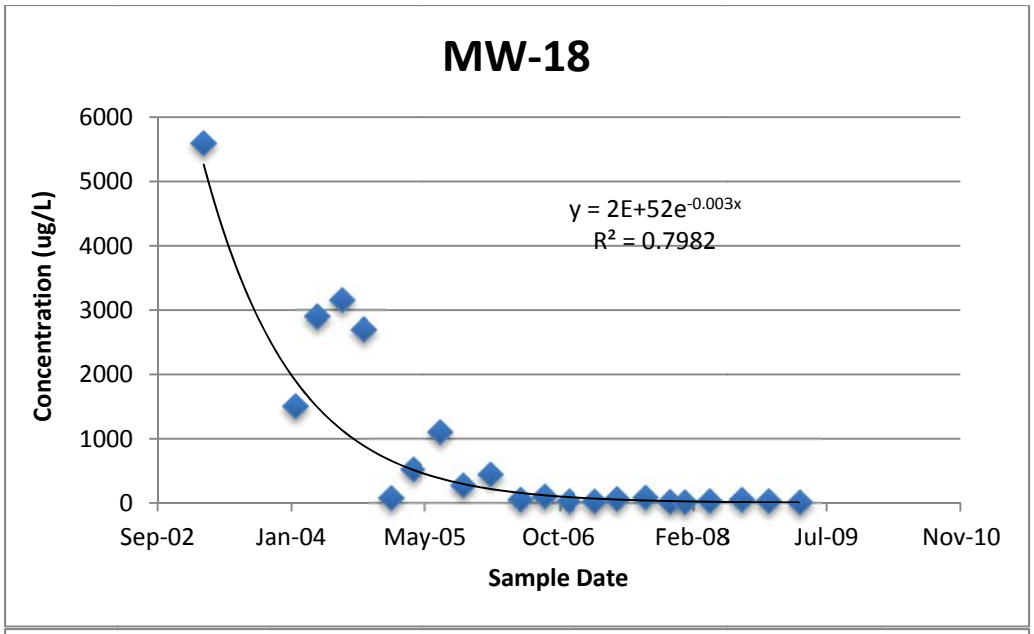
Benzene, UST Site, Oregon

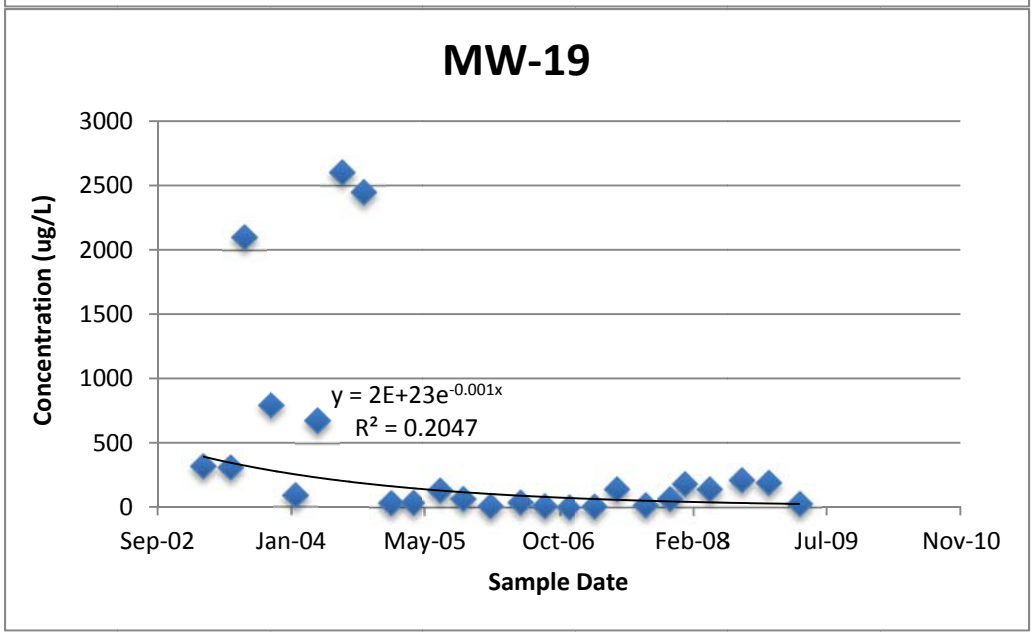


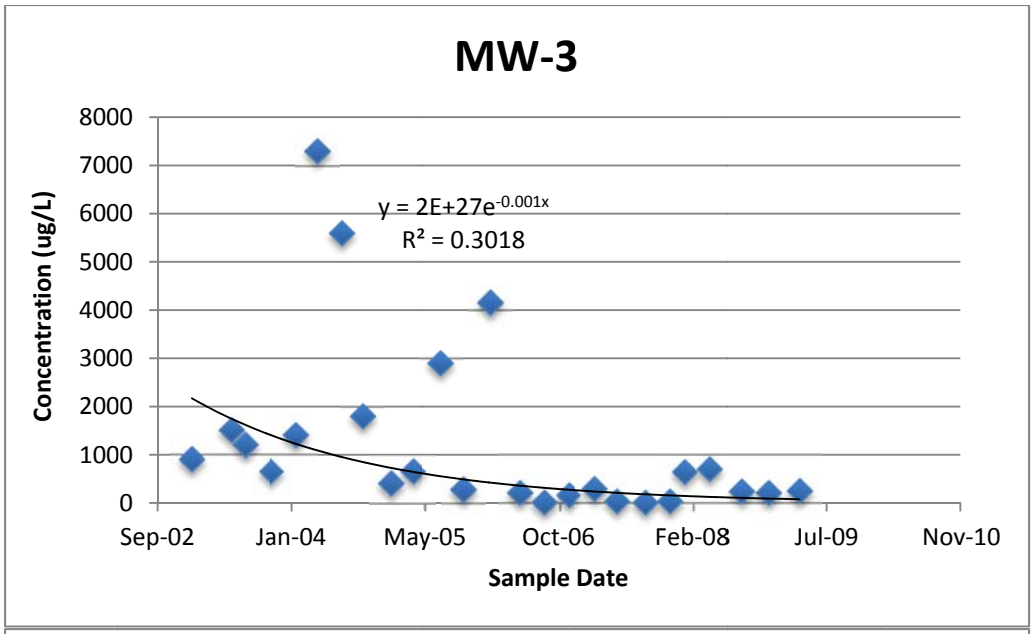


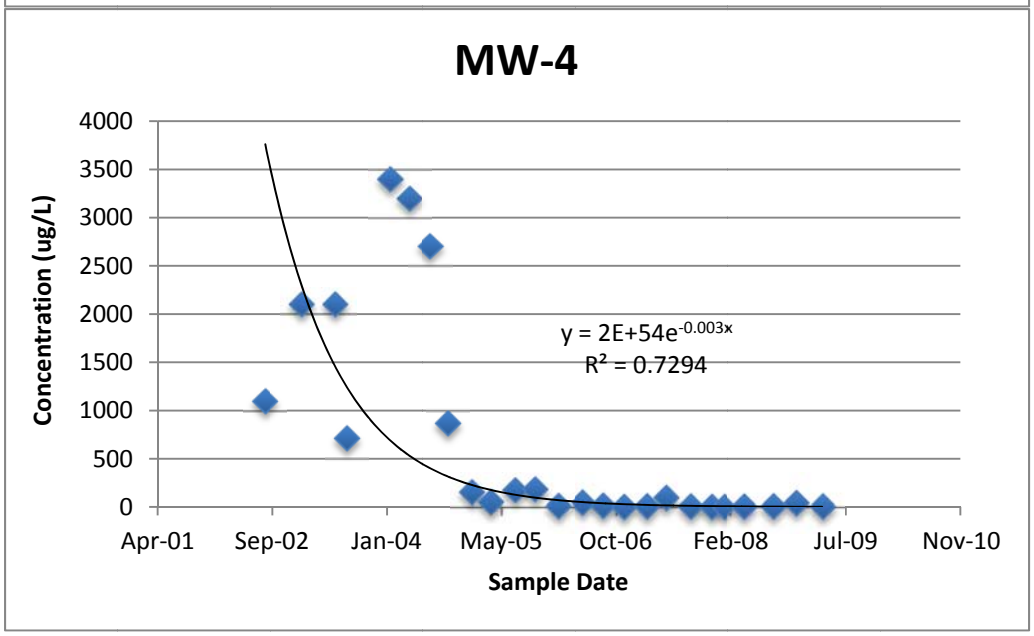

MW-12
Concentration (ug/L)
8000
7000
6000
5000
4000
3000
2000
1000
0
y = 3E+21e-0.001x
R² = 0.1361
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Sample Date

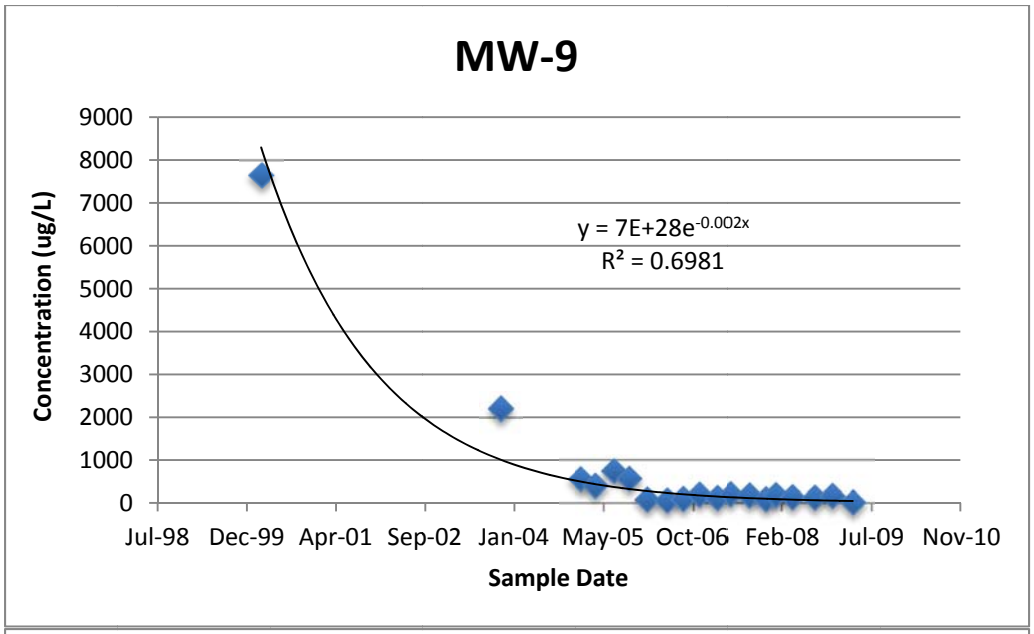

MW-14
Concentration (ug/L)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
y = 2E+36e-0.002x
R² = 0.3469
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Sample Date

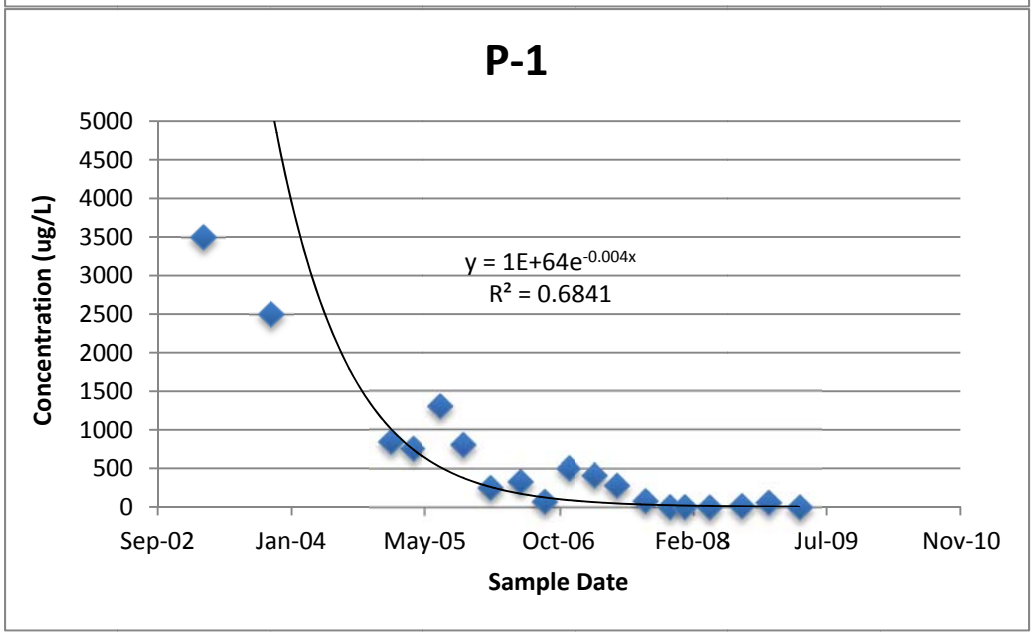

MW-18
6000
5000
4000
3000
2000
1000
0
Concentration (ug/L)
y = 2E+52e-0.003x
R² = 0.7982
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Sample Date


MW-19
3000
2500
2000
1500
1000
500
0
Concentration (ug/L)
y = 2E+23e-0.001x
R² = 0.2047
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Sample Date

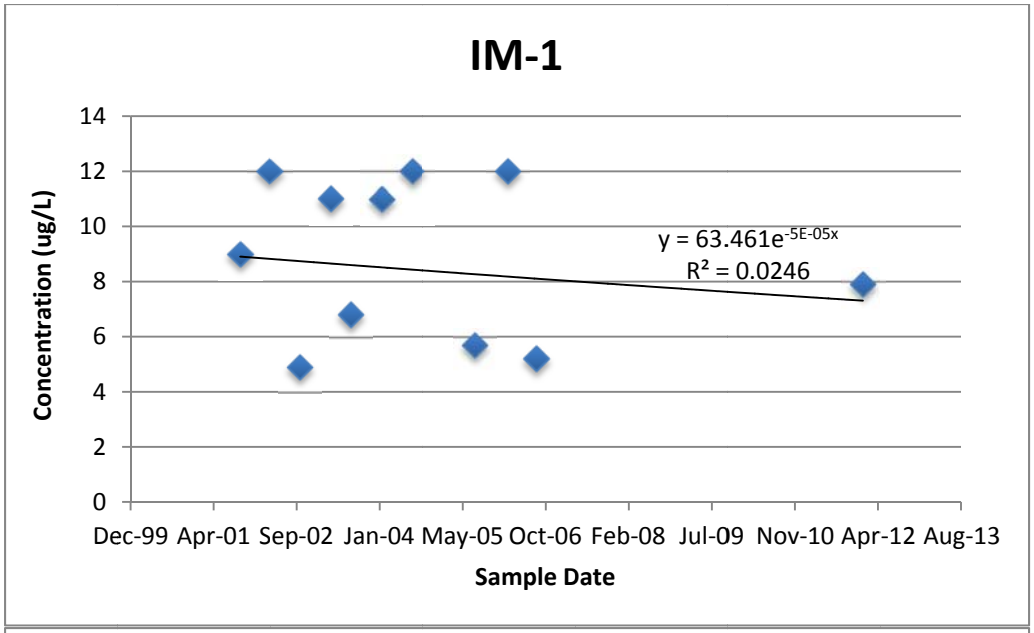

MW-3
8000
7000
6000
5000
4000
3000
2000
1000
0
Concentration (ug/L)
y = 2E+27e-0.001x
R² = 0.3018
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Sample Date

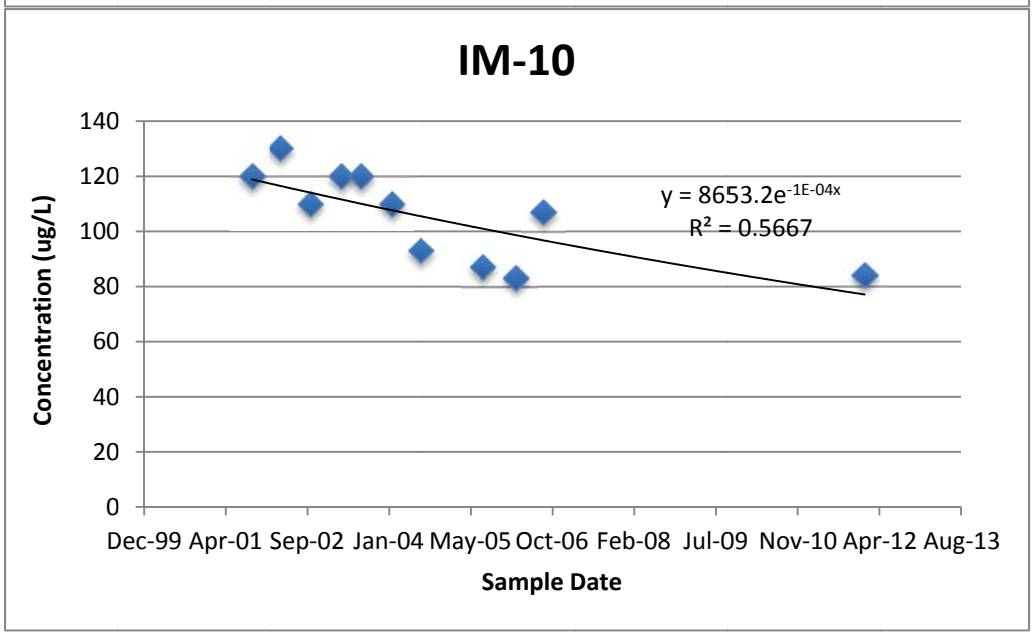

MW-4
4000
3500
3000
2500
2000
1500
1000
500
0
Concentration (ug/L)
y = 2E+54e-0.003x
R² = 0.7294
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Sample Date

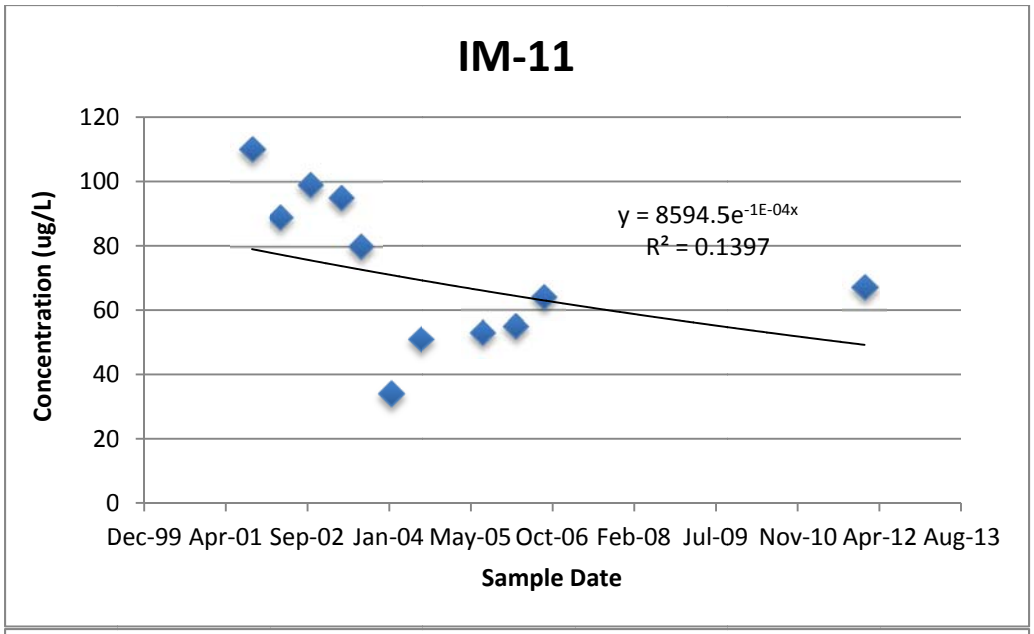

MW-9
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Concentration (ug/L)
y = 7E+28e-0.002x
R² = 0.6981
Jul-98
Dec-99
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Sample Date

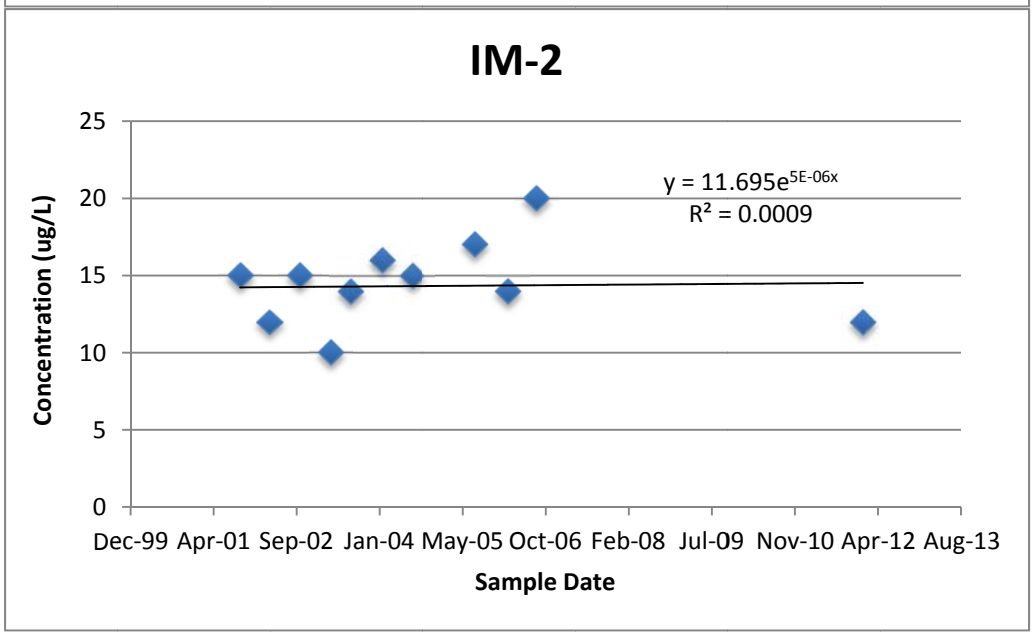

P-1
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Concentration (ug/L)
y = 1E+64e-0.004x
R² = 0.6841
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Sample Date

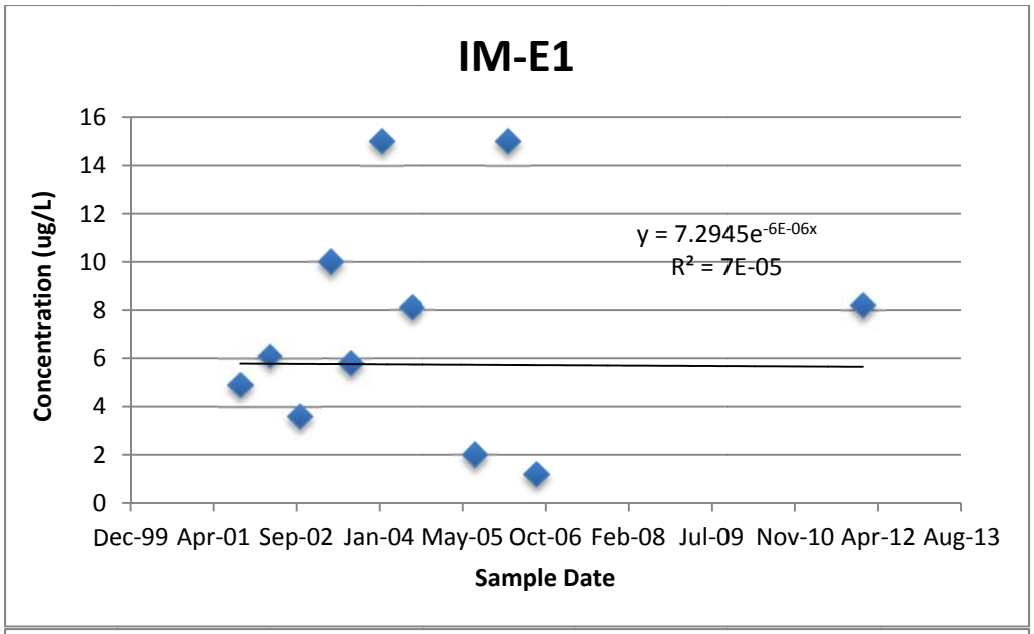
TCE, Superfund Site, California

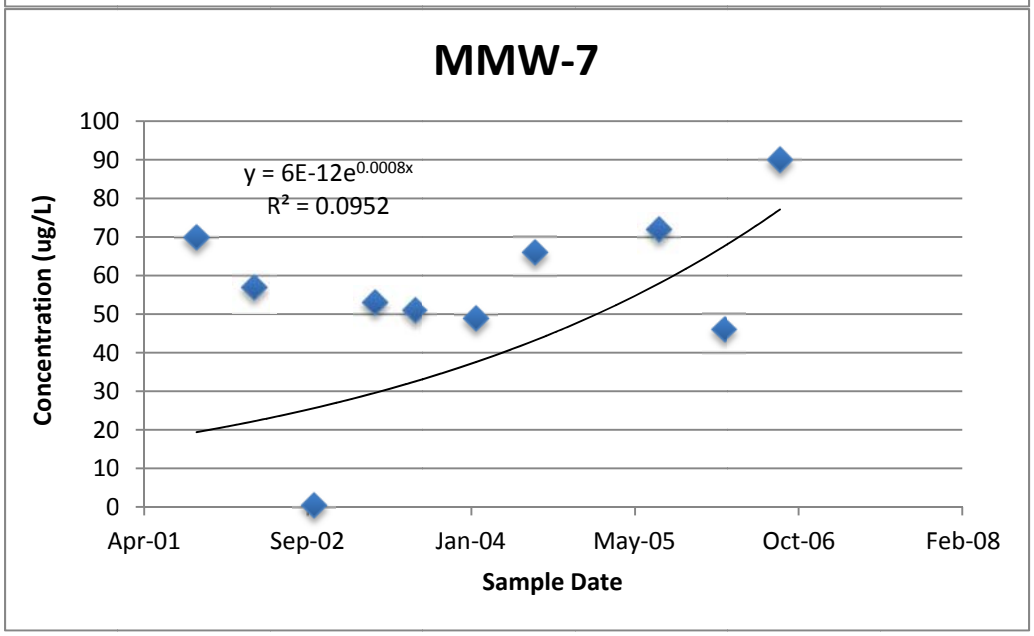


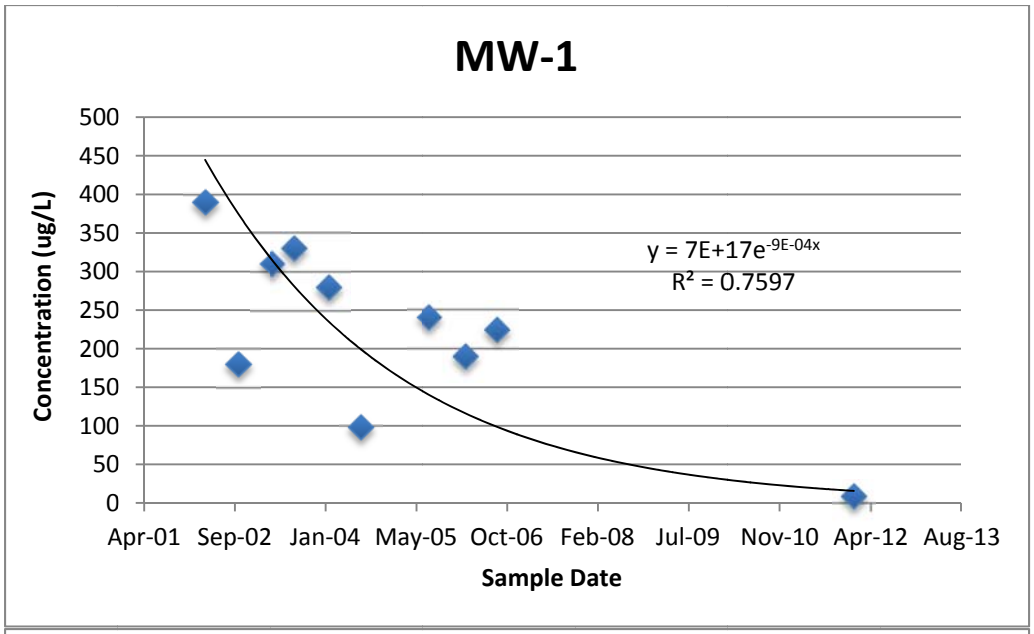


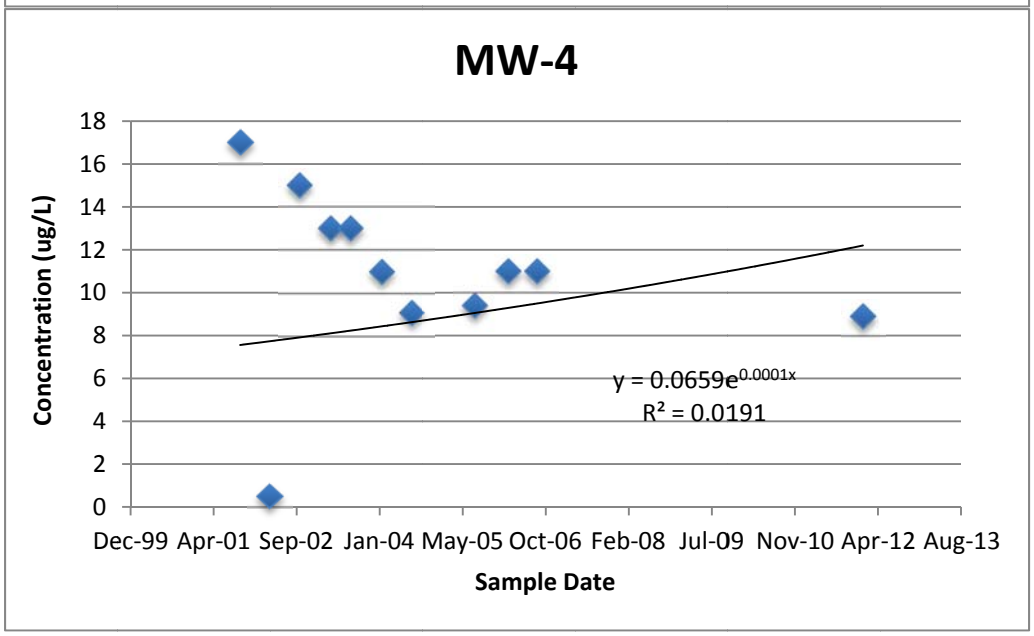

IM-11
120
100
80
60
40
20
0
Concentration (ug/L)
y = 8594.5e-1E-04x
R² = 0.1397
Dec-99 Apr-01 Sep-02 Jan-04 May-05 Oct-06 Feb-08 Jul-09 Nov-10 Apr-12 Aug-13
Sample Date

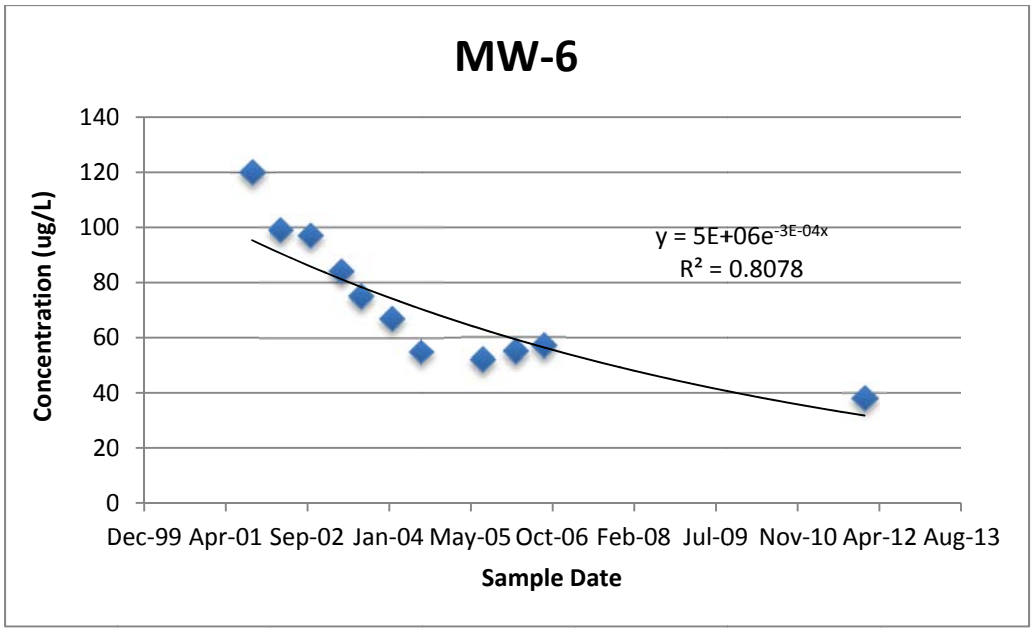

IM-2
25
20
15
10
5
0
Concentration (ug/L)
y = 11.695e5E-06x
R² = 0.0009
Dec-99 Apr-01 Sep-02 Jan-04 May-05 Oct-06 Feb-08 Jul-09 Nov-10 Apr-12 Aug-13
Sample Date


IM-E1
Concentration (ug/L)
16
14
12
10
8
6
4
2
0
y = 7.2945e-6E-06x
R² = 7E-05
Dec-99 Apr-01 Sep-02 Jan-04 May-05 Oct-06 Feb-08 Jul-09 Nov-10 Apr-12 Aug-13
Sample Date

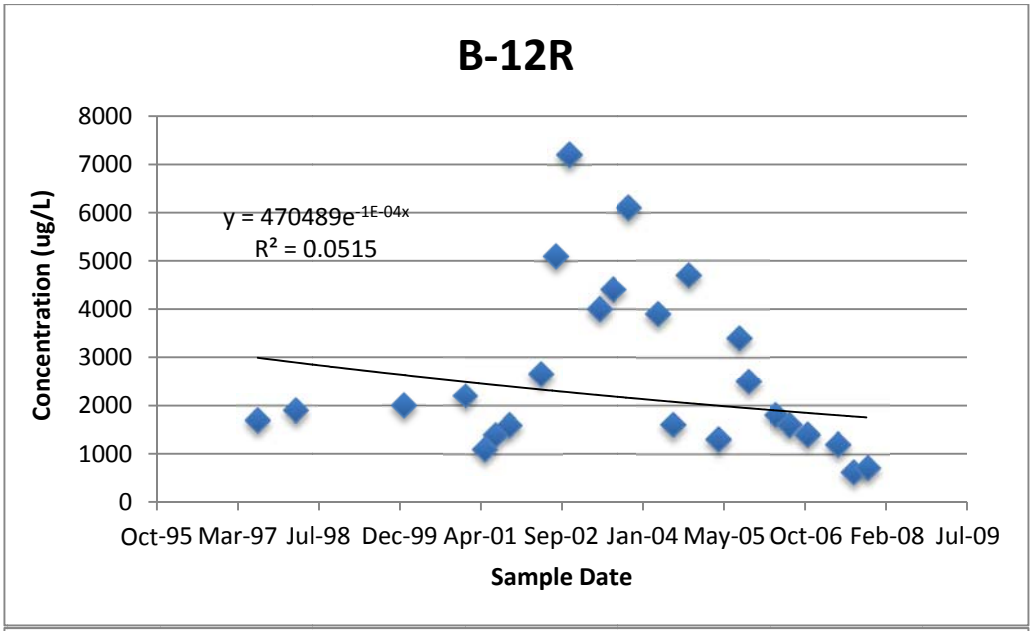

MMW-7
Concentration (ug/L)
100
90
80
70
60
50
40
30
20
10
0
y = 6E-12e0.0008x
R² = 0.0952
Apr-01 Sep-02 Jan-04 May-05 Oct-06 Feb-08
Sample Date

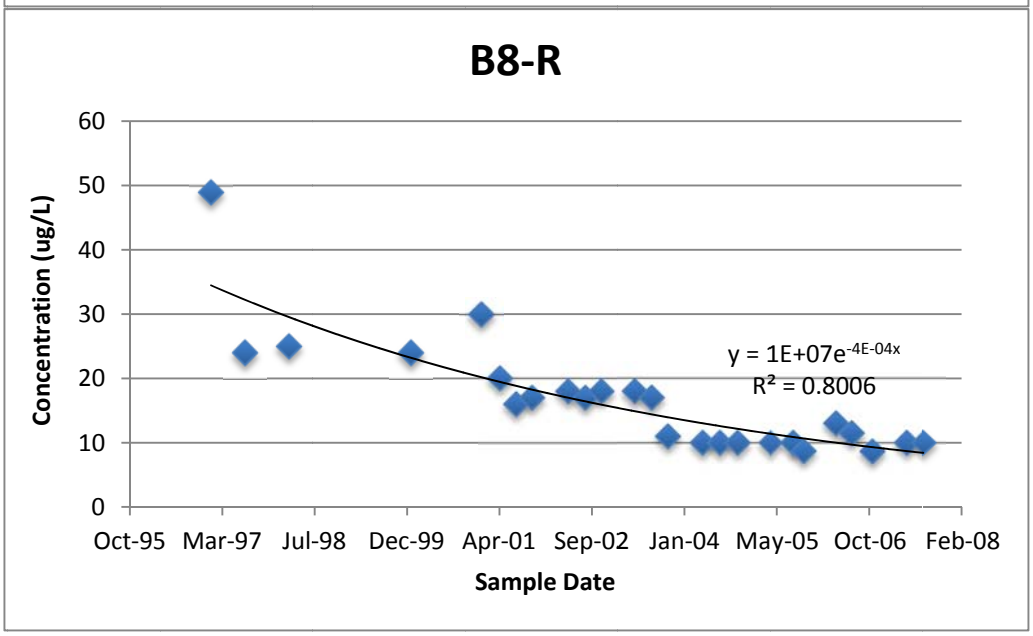

MW-1
Concentration (ug/L)
500
450
400
350
300
250
200
150
100
50
0
y = 7E+17e-9E-04x
R² = 0.7597
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Apr-12
Aug-13
Sample Date

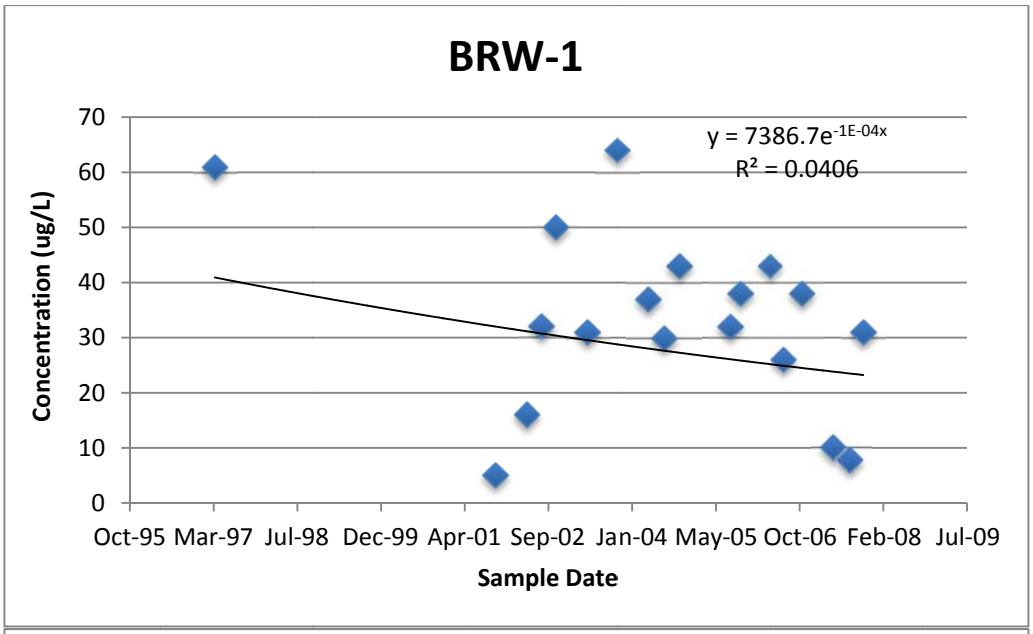

MW-4
Concentration (ug/L)
18
16
14
12
10
8
6
4
2
0
y = 0.0659e0.0001x
R² = 0.0191
Dec-99
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Apr-12
Aug-13
Sample Date

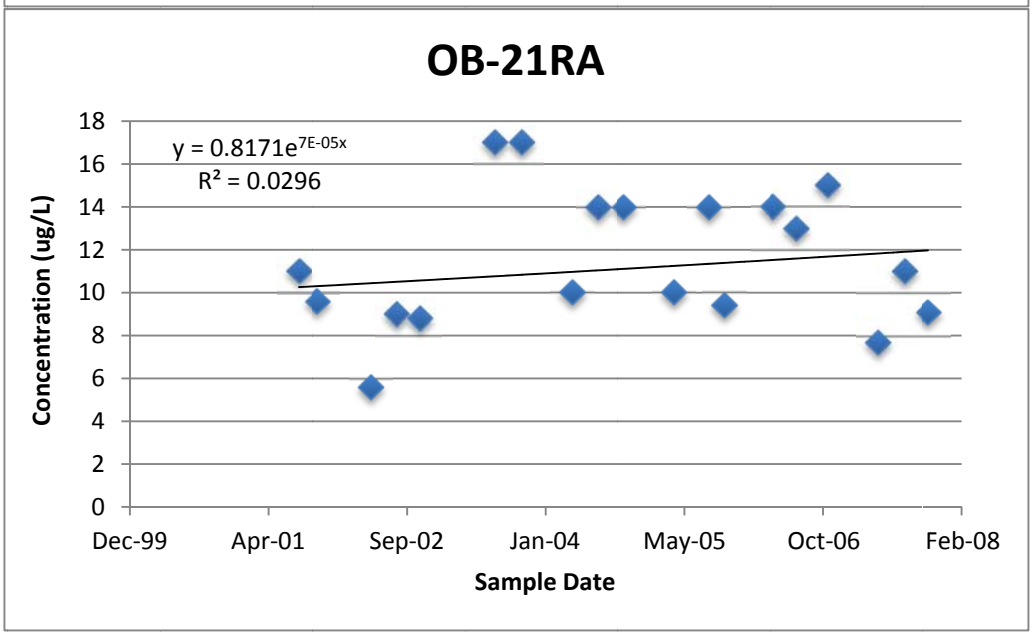

MW-6
140
120
100
80
60
40
20
0
Concentration (ug/L)
y = 5E+06e-3E-04x
R² = 0.8078
Dec-99
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Jul-09
Nov-10
Apr-12
Aug-13
Sample Date

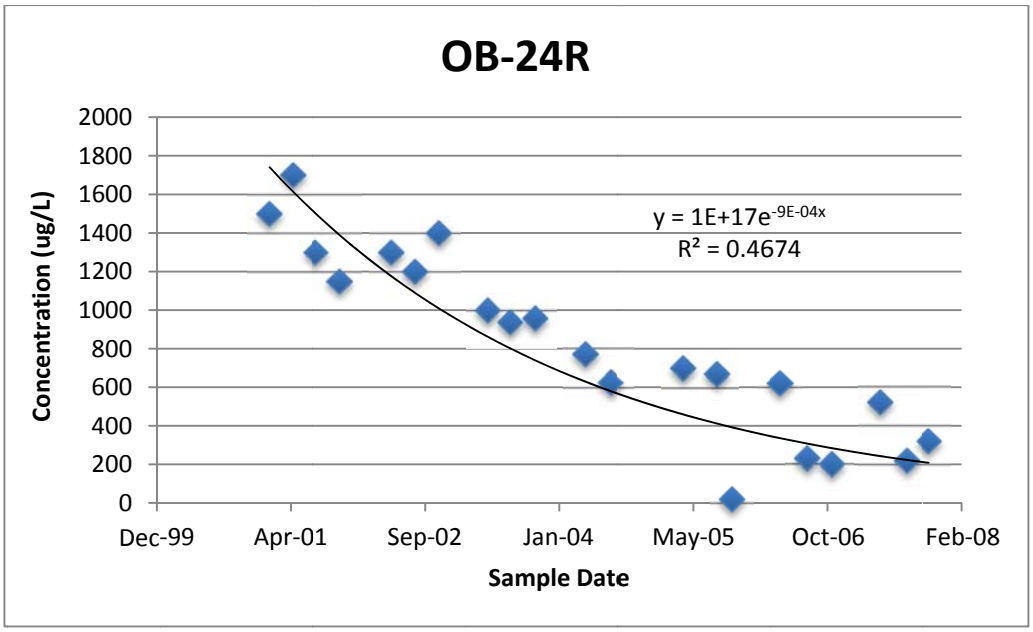
TCE, Superfund Site, New Hampshire






BRW-1
y = 7386.7e-1E-04x
R² = 0.0406
Concentration (ug/L)
70
60
50
40
30
20
10
0
Oct-95 Mar-97 Jul-98 Dec-99 Apr-01 Sep-02 Jan-04 May-05 Oct-06 Feb-08 Jul-09
Sample Date


OB-21RA
y = 0.8171e7E-05x
R² = 0.0296
Concentration (ug/L)
18
16
14
12
10
8
6
4
2
0
Dec-99 Apr-01 Sep-02 Jan-04 May-05 Oct-06 Feb-08
Sample Date


OB-24R
Concentration (ug/L)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
y = 1E+17e-9E-04x
R² = 0.4674
Dec-99
Apr-01
Sep-02
Jan-04
May-05
Oct-06
Feb-08
Sample Date

Appendix B

Effect of Monitoring Frequency and Monitoring Duration on Accuracy and Confidence in the Long-Term Attenuation Rate

Table of Contents

B.1 Purpose 1

B.2 Calculation of Accuracy and Confidence for Attenuation Rates 1

B.3 The Effect of Monitoring Frequency and Monitoring Duration on Attenuation Rate Accuracy and Confidence 2

Figures

Figure 1. Effect of Monitoring Frequency and Number of Sample Events on Accuracy of the Long-Term Trend.

Figure 2. Trade-off Between Monitoring Frequency and Monitoring Duration for Determination of the Long-Term Attenuation Rate.

B.1 Purpose

The purpose of this ESTCP project is to develop methods to understand and manage variability in groundwater monitoring results. The primary goal of Task 2 is to develop a new method to optimize monitoring frequency based on an understanding of the short-term variability and long-term attenuation rate at a particular site. The optimization method is designed to help a project manager answer two questions:

Question 1: How much monitoring data do I need to determine a site's long-term source attenuation rate with a defined level of accuracy or confidence?

Question 2: What are the trade-offs between monitoring frequency (e.g., quarterly, semi-annually, or annually) vs. the time required for trend identification (the number of years until you get the answer to Question 1)?

This appendix presents the mathematical basis for the trade-off between monitoring frequency and time (i.e., Question 2) that is presented in Section 4.3 of the main report. The goals are to:

- Show the mathematical calculation of accuracy and confidence when using regression to estimate the long-term attenuation rate.
- Show how changes in monitoring frequency and monitoring duration affect the accuracy and confidence in the attenuation rate.
- Use these relationships to show the trade-off between monitoring frequency (i.e., money) and monitoring duration (i.e., time) for estimation of the long-term attenuation rate with a defined level of accuracy or confidence.

B.2 Calculation of Accuracy and Confidence for Attenuation Rates

Ordinary linear regression (or the non-parametric equivalent) is commonly used to estimate the long-term attenuation rate from concentration vs. time monitoring records. In linear regression, both confidence and accuracy of the long-term attenuation rate (i.e., the regression slope) are a function of standard error of the regression (SE):

$$SE = \frac{Var\ (Residuals)}{Var\ (X)} \quad (1)$$

$$Var\ (Residuals) = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{(n-2)}} \quad (2)$$

$$Var(X) = \sqrt{\sum(x_i - \bar{x})^2} \quad (3)$$

Where x is the independent variable (i.e., time for groundwater monitoring data) and y is the dependent variable (i.e., contaminant concentration for a linear model or Ln(Conc.) for a first-order decay model). $\bar{x}$ is the average value of x and $\hat{y}$ is the value of y predicted by the regression model.

The **accuracy of the long-term attenuation** rate can be expressed in terms of the confidence interval (CI):

$$CI = SE\ x\ t_{statistic} \quad (4)$$

The value of the $t_{statistic}$ is commonly determined using a look-up table and is function of the degrees of freedom, which for regression is two less than the number of data points (i.e., n-2) and the desired level of confidence (e.g., 95% confidence).

The **confidence for the long-term attenuation rate** is determined by calculating a t_{score}:

$$t_{score} = \frac{attenuation\ rate}{SE} \quad (5)$$

The level of confidence that the attenuation rate is not equal to zero is the value for the level of confidence for which the $t_{statistic}$ from the look-up table is equal to the calculated t_{score} for the regression.

B.3 The Effect of Monitoring Frequency and Monitoring Duration on Attenuation Rate Accuracy and Confidence

As shown in Equations 1 to 5, both the accuracy and the confidence in the long-term trend are inversely proportional to the standard error of the regression (and are therefore directly proportional to the variability of the independent variable; Equation 3). In other words, as the standard error of the regression increases, the 95% confidence interval for the trend increases (accuracy decreases) and as the standard error of the regression increases, the t_{score} decreases (confidence decreases). Therefore, an evaluation of how monitoring frequency and monitoring duration affect the standard error of the regression will explain how these two factors affect the accuracy and confidence for the long-term attenuation rate.

For a fixed number of monitoring events, when the time between the monitoring events is doubled (e.g., a change from quarterly to semiannual monitoring), the variability of the independent variable is doubled (Equation 3).

Example 1: Effect of monitoring frequency on variability of the independent variable.

1) For eight quarterly monitoring events, t = 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, and 2

   $Var(T) = \sqrt{\sum(t_i - \bar{t})^2}$ = 1.6

2) For eight semi-annual monitoring events, t = 0.5, 1, 1.5, 2, 2.5, 3, 3.5, and 4

   $Var(T) = \sqrt{\sum(t_i - \bar{t})^2}$ = 3.2

<u>Finding</u>: Doubling the time between monitoring events doubles the variability (Equation 3).

Because the variability of the residuals is independent of the monitoring frequency, when the time between monitoring events is doubled, the standard error is decreased by 50% (Equation 1). This, in turn, decreases the confidence interval for the long-term trend by 50% (Equation 4); in other words, the accuracy is doubled (see Figure 1A). The standard error is also a function of the number of data points used to characterize the trend. For uniformly spaced measurements, standard error will decrease by 50% (i.e., the accuracy is doubled) when the number of data points is increased by 60% (Equations 1 and 3; Figure 1B).

Example 2: Effect of monitoring number of monitoring events on variability of the independent variable.

3) For ten quarterly monitoring events, t = 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, and 2.5

   $Var(T) = \sqrt{\sum(t_i - \bar{t})^2}$ = 2.3

4) For 16 quarterly monitoring events (a 60% increase), t = 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 2.75, 3, 3.25, 3.5, 3.75, and 4.

   $Var(T) = \sqrt{\sum(t_i - \bar{t})^2}$ = 4.6

<u>Finding</u>: Increasing the number of monitoring events by 60% doubles the variability (Equation 3).

The relationships between monitoring frequency and accuracy and monitoring duration and accuracy are constant regardless of the magnitude of either the attenuation rate (i.e., the slope of the regression line) or the short-term variability (i.e., the residuals).

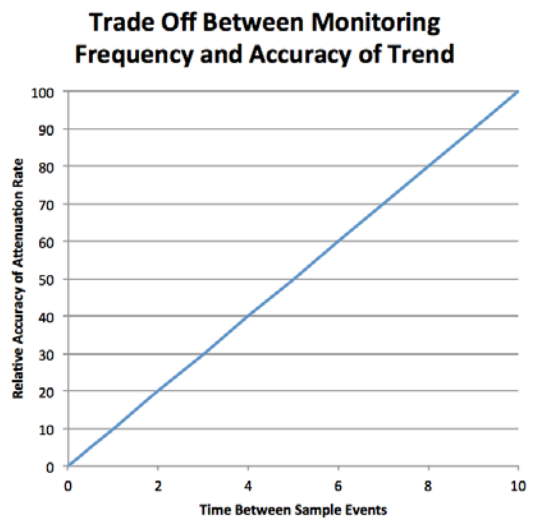
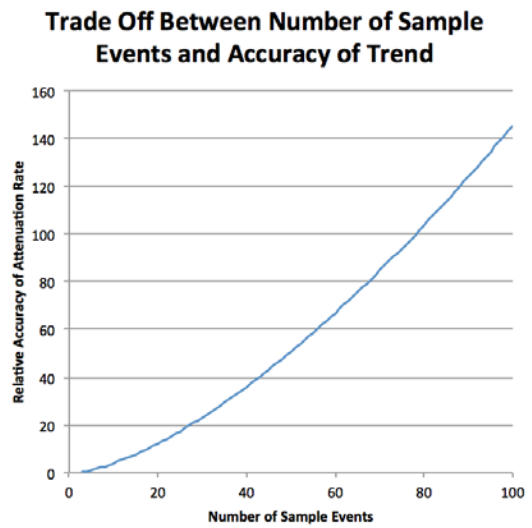
A	B
	
Key Point: Doubling the time between sample events doubles the accuracy of the attenuation rate (assuming that the number of monitoring events does not change)	**Key Point: Increasing the number of sample events by 60% doubles the accuracy of the attenuation rate (assuming that the time between monitoring events does not change)**

Figure 1. Effect of Monitoring Frequency and Number of Sample Events on Accuracy of the Long-Term Trend.

These two mathematical relationships (i.e., the effect of monitoring frequency on accuracy and the effect of the number of measurements on accuracy) together define the relationship between monitoring frequency and time required to define a trend with a specified level of confidence or accuracy. If you double the time between monitoring events (e.g., quarterly to semiannual monitoring), you can decrease the total number of measurements by 38% (Figure 2A) and obtain the same level of confidence or accuracy in the results. However, the time required to complete the required number of measurement will increase by 25% (Figure 2B). In other words, 4 years of quarterly monitoring (16 sample events) will characterize a long-term trend with the same level of accuracy as 5 years of semiannual monitoring (10 sample events). This relationship is the same when using either a linear model or a first-order model for the long-term trend (because the first-order model simply uses linear regression for log concentration vs. time).

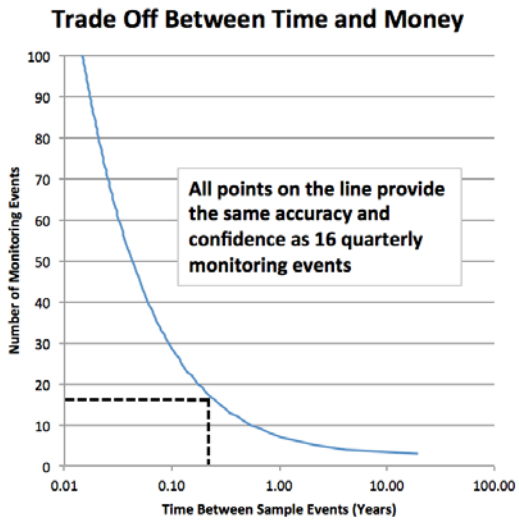
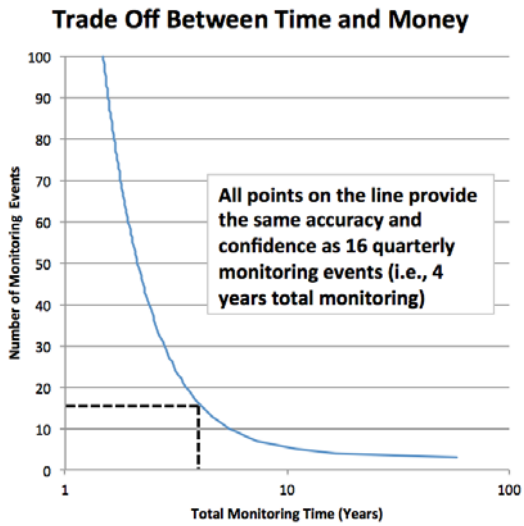
A	B
	
Key Point: If you double the time between sample events and decrease the number of data points by 38%, you have no change in the accuracy of your attenuation rate.	**Key Point: If you double the time between sample events and increase the total monitoring time by 25%, you have no change in the accuracy of your attenuation rate.**

Figure 2. Trade-off Between Monitoring Frequency and Monitoring Duration for Determination of the Long-Term Attenuation Rate.

B.4 Non-Parametric Methods to Estimate the Attenuation Rate

The use of linear regression to estimate the attenuation rate from a groundwater monitoring dataset is based on a number of assumptions regarding the characteristics of the dataset, most important homoscedasticity (i.e., the residual errors should be independent of time, the independent variable). Deviations from the required assumptions will cause errors in the calculated accuracy and confidence for the attenuation rate.

The Thiel-Sen slope estimator is sometimes used as a non-parametric alternative to linear regression for estimation of attenuation rates from groundwater monitoring datasets. Using this approach, a slope is calculated for each pair-wise combination of monitoring data points and the attenuation rate is estimated as the median value for all of the calculated slopes. The confidence for the attenuation rate can be determined using the Wilcoxon Signed Rank test and the accuracy of the attenuation rate can be expressed using a confidence interval around the median slope value.

When using non-parametric Thiel-Sen method to estimate the attenuation rate, the effect of monitoring frequency and the number of sample events on the accuracy and confidence of the attenuation rate is more difficult to quantify. However, these trade-offs should be similar to those observed when using linear regression. If the magnitude of the short-term variability is independent of time, then for a fixed number of monitoring events, doubling the time between monitoring events (i.e., quarterly monitoring to semi-

annual monitoring) should decrease the standard deviation of the population of calculated slope values by approximately 50%, resulting in a corresponding increase accuracy and confidence for the median value. Increasing the number of monitoring events by 60% results in an approximately 160% increase in the number of pair-wise combinations of monitoring data points that can be used to calculate individual slope values. This 1.6x increase in the size of the slope dataset will result in a corresponding increase in the accuracy and confidence in the estimated attenuation rate (i.e., the median value for the population of slope values). Although the effect of monitoring frequency and the number of sample events on the accuracy and confidence of the attenuation rate may not be exactly the same for the Theil-Sen method as for linear regression, this trade-off is still and function of the attenuation rate estimation method and is not site-specific.

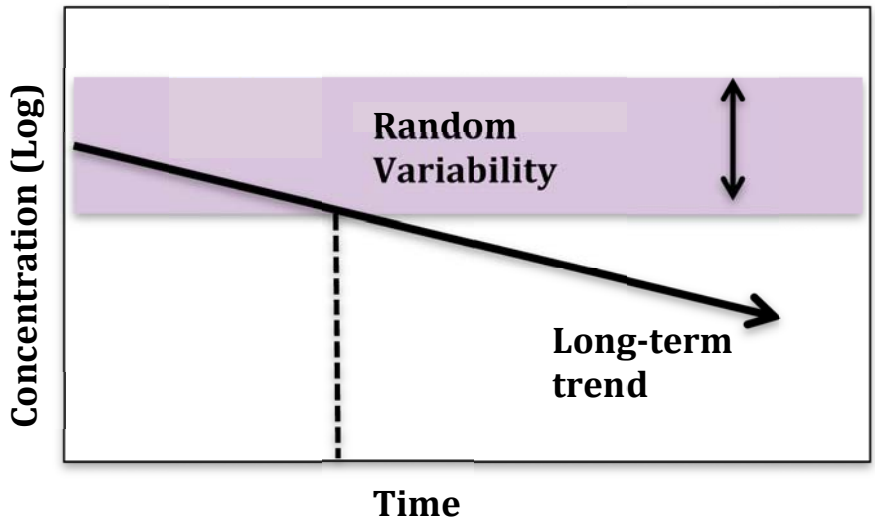
Appendix C

Monitoring Optimization and Trend Analysis Toolkit and User's Guide

Monitoring Optimization and Trend Analysis Toolkit

USER'S GUIDE

ESTCP Project ER-201209
Methods for Minimization and Management of Variability in Long-Term Groundwater Monitoring Results



GSI Environmental, Inc.
2211 Norfolk, Suite 1000, Houston, Texas 77098-4054 713.522.6300

TABLE OF CONTENTS

1.0 FREQUENTLY ASKED QUESTIONS 3

2.0 EXECUTIVE SUMMARY 5

3.0 BACKGROUND 7

4.0 MONITORING FREQUENCY OPTIMIZATION TOOLKIT: OVERVIEW 8
- 4.1 Platform and Architecture 8
- 4.2 Basic Structure 8
- 4.3 General Instructions and Navigation 8
  - 4.3.1 Instructions 8
  - 4.3.2 Navigation Panel 9
  - 4.3.3 Cell Legend 9
  - 4.3.4 Help Buttons 9

5.0 MAIN MENU 10

6.0 MONITORING VARIABILITY TOOL 12
- 6.1 Questions 12
- 6.2 Input 12
  - 6.2.1 Data Entry 12
  - 6.2.2 Data Analysis and Results 12
  - 6.2.3 Navigation 12
- 6.3 Results 13
  - 6.3.1 Data Entry 13
  - 6.3.2 Data Analysis and Results 13
  - 6.3.3 Navigation 14
- 6.3 Well Trends 13
  - 6.3.1 Data Entry 13
  - 6.3.2 Data Analysis and Results 13
  - 6.3.3 Navigation 14

7.0 MONITORING OPTIMIZATION TOOL 16
- 7.1 Questions 16
- 7.2 Inputs 16
  - 7.2.1 Accuracy 17
  - 7.2.2 Confidence 17
- 7.3 Advanced Controls 17
- 7.4 Calculate 17
- 7.5 Results 18
- 7.6 How Do I Decide between Sampling Options? ..... 18\
- 7.7 Navigation 18

8.0 MISCELLANEOUS 20
- 8.1 Unprotecting Individual Sheets and Viewing Hidden Interface 20
- 8.2 Calculations for Advanced Users 20

9.0 LIMITATIONS 21

10.0 REFERENCES 22

1.0 FREQUENTLY ASKED QUESTIONS

a) Who should use this toolkit?

The primary purposes of this toolkit are i) to evaluate the overall source attenuation rate while accounting for the effect of random variability in apparent attenuation rates in individual monitoring wells and ii) to determine the amount of groundwater monitoring data required to characterize the long-term source attenuation rate for sites undergoing long-term monitoring (i.e., during an MNA process, either when MNA is a stand-alone remedy or when MNA is applied as a polishing step after active remediation). This tool should be applied at sites where one purpose of long-term monitoring is to characterize the rate of contaminant concentration over time.

The toolkit will help the user select an optimal monitoring frequency and evaluate the relationship between monitoring frequency and time required to characterize the long-term trend.

The user can select the optimal monitoring frequency through this process:

1) Select the primary goal of long-term monitoring: This optimization method is appropriate when the long-term monitoring data will be used to either
   i) demonstrate that constituent concentrations are decreasing OR
   ii) estimate when concentrations will decrease to a clean-up goal
2) Identify the timeframe in which the monitoring goal should be met. In other words, how quickly does the demonstration of decreasing concentrations or estimation of time to clean-up need to be made?
3) Based on the monitoring goal and the decision timeframe, use the Excel spreadsheet toolkit to determine the appropriate monitoring frequency.

b) What questions are addressed by the toolkit?

Monitoring Variability

Question 1: When will this site meet the groundwater clean-up goal?

Question 2: Do any wells appear to be attenuation more slowly than the source as a whole?

Monitoring Optimization

Question 1: How much monitoring data do I need to determine a site's long-term source attenuation rate with a defined level of accuracy or confidence?

Question 2: What are the trade-offs between monitoring frequency and time required for trend identification?

c) What data is required for the implementation of this toolkit?

For a site-specific evaluation of the source attenuation rate and short-term variability, the tool requires historical monitoring data for at least four monitoring wells and at least two years' worth of monitoring events (recommended at least five monitoring events) for each well. Using

more historical data will result in more accurate results. For sites with time dependence in short-term variability, monitoring records of six years or longer will yield the most accurate results.

If historical monitoring data is not available, for Monitoring Optimization, the user can enter estimated values for short-term variability and long-term attenuation rate (see Section 7.1 of this Guide).

The data evaluation methods used in this tool are based on an assumption of first order source attenuation. The tool should not be applied to monitoring records where first order attenuation is clearly not applicable. For example, the tool should not be applied to monitoring records covering an initial period of plume expansion followed by stabilization and decrease. For sites where short-duration active remediation has been applied (e.g., chemical oxidation, thermal treatment), the first order source attenuation concept is applicable to the polishing period after active remediation is complete. In other words, the method described in this manual is for long periods where the effects of active remediation or natural attenuation processes are relatively constant. Monitoring records before- and after-aggressive remediation ***should not be combined.***

d) How do I choose between accuracy and confidence?

*The user should choose "**Confidence**" if a primary objective is collecting enough data to demonstrate (with a defined level of confidence)* ***that constituent concentrations in the monitoring well are actually decreasing over time****.*

*The user should choose "**Accuracy**" if a primary objective is collecting enough data to* ***estimate the time required to for constituent concentrations in the monitoring well to decline to a defined numerical standard*** *based on the observed source attenuation rate*

e) What are the key results?

Monitoring Variability:

For Question 1: The tool tells you the overall attenuation rate and short-term variability of the source area, as well as a range of when you can expect the site to obtain the clean-up goal.

For Question 2: The tools tells you if the number of wells with observed "slower" attenuation rates or with observed "increasing" concentration trends are within the amount expected due to short-term variability or if they actually represent slower attenuation or increasing trends. These results allow the user to evaluate whether there are true differences in attenuation rates between monitoring wells at a site.

Monitoring Optimization:

For Question 1: The tool tells you your options for sampling in the future to determine the source attenuation rate for a defined level of accuracy or confidence.

For Question 2: The tool tells you the total number of future monitoring events (and estimated cost) to characterize the long-term attenuation rate. Different results are provided for different monitoring frequencies (e.g., quarterly, semi-annual, annual).

2.0 EXECUTIVE SUMMARY

The Monitoring Optimization and Trend Analysis Toolkit optimizes groundwater monitoring frequency for your site based on site-specific values for the long-term source attenuation rate and the magnitude of short-term variability. The Toolkit includes the following:

Main Menu:

1) Choose Monitoring Variability Tool if you have historical data for at least four wells and at least two years' worth of monitoring events (recommended at least five monitoring events).
2) Choose Monitoring Optimization Tool if you don't have historical monitoring data from your site.

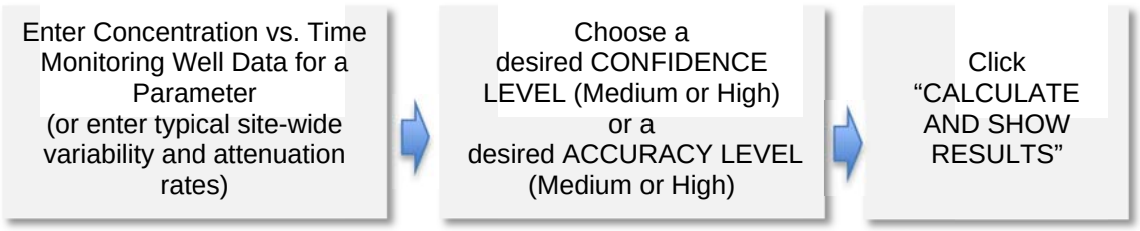
Monitoring Variability Tool:

1) Enter at least two years' worth of most recent monitoring results (recommended at least five monitoring events) for 4 to 20 monitoring wells. Use of more monitoring results will increase the accuracy of the results.
2) After entering data, click "Calculate Results" (may take a while) and then "Review Results". The Results page presents a number of pieces of information to answer the questions for the Monitoring Variability Tool.
    a. To answer the first part of Question 1, the page shows the Long-Term Attenuation Rate and Short-Term Variability for the source area overall.
    b. To answer the second part, enter the Representative Source Area Concentration (default is the maximum Recent Concentration) and Groundwater Clean-Up Goal you wish to be used to calculate when the goal will be met. The tool then calculates the clean-up time using the 25th and 75th percentile attenuation rates from the wells.
    c. To answer Question 2, the page shows two summary tables detailing the Glide Paths and Concentration Trends at the site. Review these tables to determine if the observed "slower" Glide Paths and "increasing" Concentration Trends are actually indicative of "slow" Glide Paths or "increasing" Trends or not.
    d. Next, review the table that presents, for each well, the Recent Concentration (average of 5 most recent values), the Long-Term Attenuation Rate, and the Concentration Trend direction. This will help you decide if the wells with slower attenuation rates or increasing trends will delay clean-up attainment.
    e. After reviewing all of this, choose click "Show Well Trends".
3) The Well Trends page shows the two summary tables from the Results page, with graphs below for each well giving a more in depth view of the trends for each well. Review these tables for more detailed information on the each well's effect on clean-up attainment. Then, click on "Go To Optimization".

Monitoring Optimization Tool:

1) Use the Short-Term Variability value and Long-Term Attenuation Rate calculated from your site data or enter typical values (See Section 6).
2) Set the Historical Monitoring Frequency as the most common type of sampling frequency for the data already collected, and enter the number of Years of Historical Monitoring Data Collected.

3) Choose "Confidence" if the primary monitoring goal is to demonstrate decreasing concentrations. Choose "Accuracy" if the primary monitoring goal is to estimate remediation timeframes.
4) Choose your desired level of confidence or accuracy for the long-term trend that will be measured by future monitoring. "Medium" confidence or accuracy represents a reasonable minimum amount of data required to support decision making.
5) If you would like more exact control over the confidence or accuracy, check "Advanced Controls" and enter the specific level of confidence or accuracy and the Percent of Wells that will meet that parameter.
6) Click "Calculate and Show Results". The tool will calculate a set of seven options that provide different combinations of monitoring frequency and time required to characterize the long-term attenuation rate with the specified level of accuracy or confidence.



Option	Sample Frequency	Total Sampling Events	Cost Per Well ($K)
Option 1:	Sample weekly for 1.1 years	59	89
Option 2:	Sample monthly for 2.0 years	24	35
Option 3:	Sample quarterly for 3.0 years	12	18
Option 4:	Sample semiannually for 3.8 years	8	11
Option 5:	Sample annually for 5.2 years	5	8
Option 6:	Sample every 2 years for 7.7 years	4	6
Option 7:	Sample every 5 years for 12.8 years	3	4

Figure E1: Sample Monitoring Optimization Tool Results table

3.0 BACKGROUND

The Monitoring Optimization and Trend Analysis Toolkit provides a method to distinguish between random variations in attenuation rates and true spatial differences in remedy performance and provides recommendations for optimized groundwater monitoring frequency based on a site-specific evaluation of the magnitude of short-term variability and the long-term attenuation rate. The Toolkit uses site-specific data to determine clean-up horizons and possible problem wells and simulated monitoring datasets that match the short-term variability and long-term source attenuation rate characteristics of your site in order to determine the number of monitoring events required to characterize the long-term trend with a defined level of accuracy or statistical confidence.

This User's Guide focuses on the practical aspects of using the Toolkit. The development of the Toolkit is documented in the report "Task 2 Report: Methods for Minimization and Management of Variability in Long-Term Groundwater Monitoring Results, ESTCP Project ER-201209" (McHugh et al., 2015).

4.0 MONITORING OPTIMIZATION AND TREND ANALYSIS TOOLKIT: OVERVIEW

4.1 Platform and Architecture

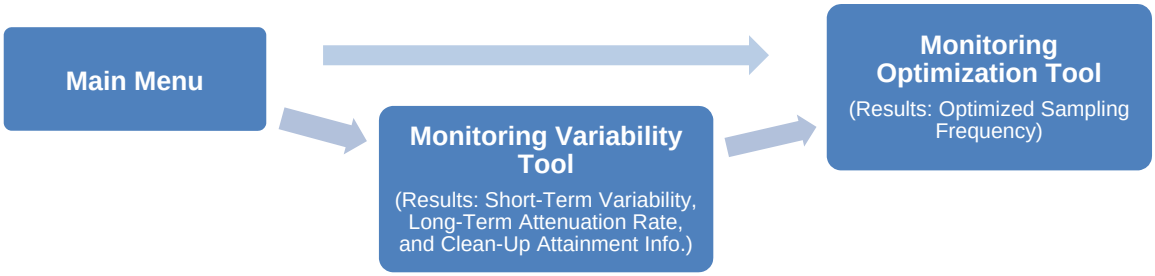
The toolkit is built on the Microsoft Excel platform with a user-friendly interface. The tool opens on the Main Menu page, which contains a flow chart that directs the user to either the *Monitoring Variability Tool* or the *Monitoring Optimization Tool.*

The Monitoring Variability Tool uses historical groundwater monitoring data from individual wells in order to calculate the site's overall short-term variability and long-term attenuation rate. Subsequently, the user is directed to the Monitoring Optimization Tool.

The Monitoring Optimization Tool uses the short-term variability and long-term attenuation rate to determine options for sampling frequencies needed to capture the true attenuation rates of the groundwater constituents at the site.

4.2 Basic Structure

The basic structure of the Toolkit is as follows. Each square indicates what the user will find at each step, as well as the name of the page it is found on in parenthesis.



4.3 General Instructions and Navigation

Each screen has four main components that help in using the tool and navigating between screens:

i) Instructions
ii) Navigation Panel
iii) Cell Legend
iv) Help Buttons

4.3.1 Instructions

Instruction boxes are located in the top left corner of all screens and contain specific steps or instructions the user should follow in order to operate the page effectively. Each section of the page also has the particular Instruction number (i.e., 1,2,3,4) next to the section title.

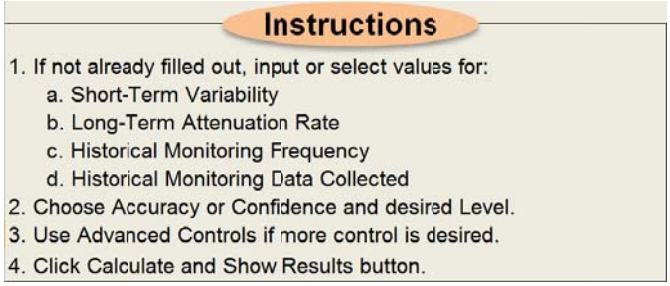


Figure 1: Example Instruction Box

4.3.2 Navigation Panel

Navigation panels are located in the top right corner of each page and contain buttons that will advance the user to different screens (Figure 2). They also contain buttons to go to previous pages, as well as to review or edit inputs.

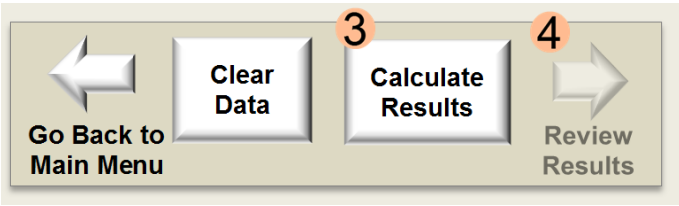


Figure 2: Input page Navigation Panel

4.3.3 Cell Legend

Cells of interest are categorized as either an Input or Calculated cell (Figure 3). Users are able to enter project or site-specific information into the Input cells (colored white). Some of these Input cells will have drop-down lists, while others will require manual entry of data. Calculated cells (tan colored) contain calculated values that the user is unable to change.

	= Input cell.
	= Calculated cell.

Figure 3: Cell Legend

4.3.4 Help Buttons

Help buttons are available to the right of many of the Toolkit's cells, titles, and buttons (as shown below). The user can click these to get more information about the closest topic.

Figure 4: Help Button

5.0 MAIN MENU

The Main Menu page contains a flowchart (Figure 5) that leads the user through several questions, and directs them to the appropriate Tool.

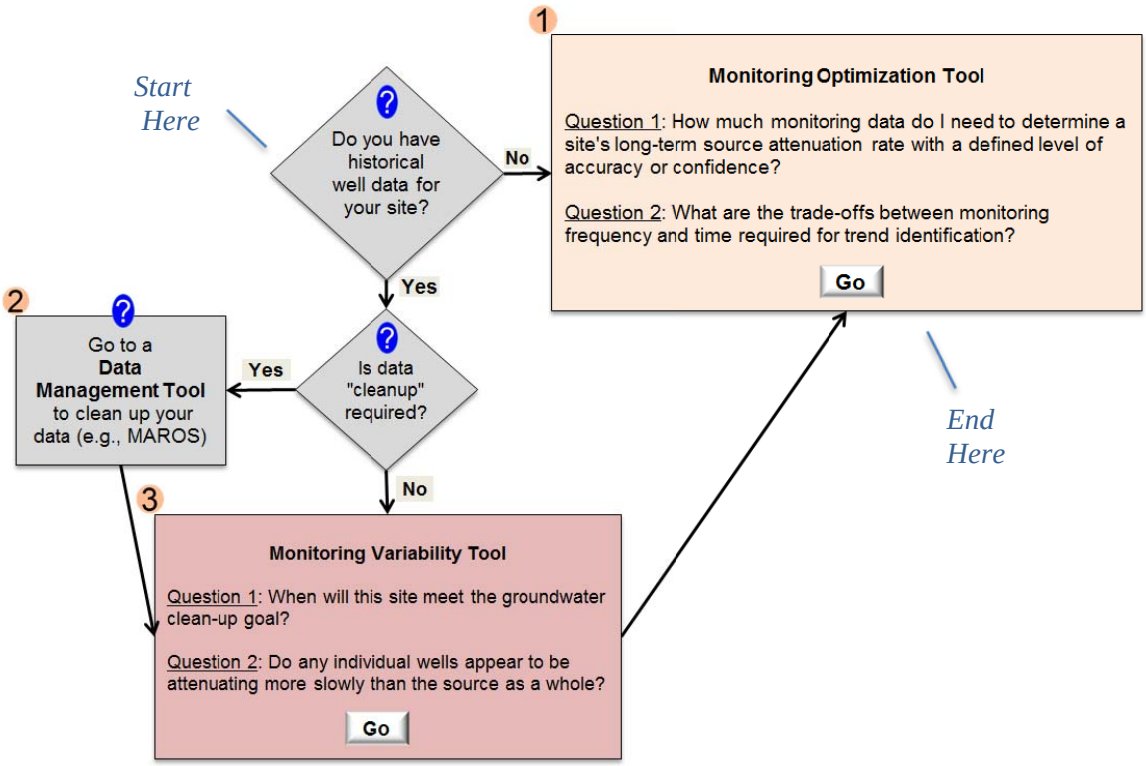


Figure 5: Toolkit Outline Flowchart

The flowchart questions are as follows:

(1) Do you have historical well data for your site?

Historical site data can be used in the Monitoring Variability Tool to derive site-specific estimates of short-term variability and long-term attenuation rates. Data for at least 4 wells and up to a maximum of 20 wells with at least two years of recent sampling events (recommended at least five sampling events) for each well are required to run this tool. Choose wells where the primary contaminant of concern is detected for at least 80% of monitoring events.

If Yes: Proceed to Question 2 below.

If No: Go to Monitoring Optimization Tool

(2) Is data "cleanup" required?

The Monitoring Variability Tool requires data in the following format:

- Dates in chronological order

- Dates in MM/DD/YYYY format
- Concentrations as numerical values (i.e., no flags)
- Non-detects replaced with the appropriate numerical values
- All concentration data must be in the same units (either mg/L or ug/L)

As seen in the table below, typical historical groundwater monitoring data can be available in many formats and styles, and may require "clean-up" before being entered into the toolkit. Various scenarios of original data, and the final required format are presented below.

Table 1: Examples of Clean-Up Scenarios for Historical Monitoring Data

Scenario	**Original Monitoring Data**		**"Cleaned-Up" Format Required for Tool**		**Notes**
	Sample Date	*TCE Conc.*	*Sample Date*	*TCE Conc.*	
1	June 10, 2001	250	06/10/2001	250	Dates in MM/DD/YYYY format
2	3/15/1995	ND	3/15/1995	1	Non-detects replaced with numerical values
3	8/12/2004	<5	8/12/2004	5 (or 2.5)	Non-detects replaced with numerical values
4	14/1/2003	125	1/14/2003	125	Dates in MM/DD/YYYY format
5	3/14/1989	45 J	3/14/1989	45	Concentrations as numerical values

If Yes: Go to a Data Management Tool to clean-up your data (e.g., MAROS).

A tool such as MAROS can help the user manage data and meet the requirements listed above. After completion of this step, navigate back to the Monitoring Variability Tool.

If No: Go to Monitoring Variability Tool

6.0 MONITORING VARIABILITY TOOL

6.1 Questions

The Monitoring Variability Tool answers two questions:

Question 1: When will this site meet the groundwater clean-up goal?

Question 2: Do any individual wells appear to be attenuating more slowly than the source as a whole?

Going through the Tool will provide the answers to these questions.

6.2 Input

6.2.1 Data Entry

On the Input page the user should enter the following information:

- Site Info
- Site Name
- Contaminant of Concern
- Concentration Units (Note: This is a dropdown menu of either mg/L or ug/L)

Historical groundwater monitoring data should be entered next as follows:

- Well Name: This is text (i.e., MW-2)
- Date: Arranged chronologically in MM/DD/YYYY format.
- Concentration: Numerical values (e.g., no text strings) in consistent units (mg/L or µg/L).

The Toolkit allows for the data entry and analysis of between 4 and 20 wells, with data from at least two years of sampling events (and a recommended minimum of five events). If more than 25 sampling events exist at a site, it is recommended to select the 25 most recent sampling events.

6.2.2 Data Analysis and Results

No results are displayed on the Input page.

6.2.3 Navigation

The navigation options are as follows:

- *Go Back to Main Menu* - Takes the user back to the Main Menu page
- *Clear Data* - Clears all data input thus far
- *Calculate Results* - Calculates both individual well results and overall (i.e., for the entire site) results, which can be seen on the Results page. Results must be re-calculated any time the data Input page is edited.
- *Review Results* - Takes the user to the Results page

6.3 Results

6.3.1 Data Entry

On the Results page, the user should enter the following information:

- Representative Source Area Concentration: Numerical value that defaults to the maximum well Recent Concentration
- Groundwater Clean-Up Goal: Numerical value

6.3.2 Data Analysis and Results

The first data are answers to the first part of Question 1:

Question 1a: What is the overall attenuation rate for the key contaminant at my site?

These answers are:

- *Long-Term Attenuation Rate*: The overall attenuation rate is the median of the individual well attenuation rates. A positive value indicates a decreasing concentration trend.
- *Short-Term Variability*: For the overall dataset, the short-term variability is estimated as the standard deviation of the natural log of the normalized residual from the attenuation rate regression analysis. However, this standard deviation value is optimized to reduce the influence of outlier values in the dataset.

The Tool then uses the previously entered information to answer the second part of Question 1:

Question 1b: When will this site meet the groundwater clean-up goal?

The Tool gives a range of years that the user can expect the groundwater clean-up goal to be achieved, based on the 25th and 75th percentile attenuation rates from the wells.

From here, the Tool shows two summary tables that answer Question 2. The first – Attenuation Rate Summary – shows how many wells can be expected to have Faster, Within Range, or Slower Glide Paths (based of Short-Term Variability) and how many wells actually do fall into those categories. The second – Concentration Trend Summary – shows the same information for Increasing and Decreasing Concentration Trends. Based on these results, the Tool provides two "Yes" or "No" answers to Question 2.

Below these tables, data for individual wells is presented, which gives a more detailed look at these wells. The Tool gives the user these instructions:

What to do next: If the answer to Question 2 is "Yes", evaluate the individual wells with slower attenuation rates or increasing concentrations. Consider whether these wells will delay attainment of the overall site clean-up goals.

In order to do this, the Tool presents these data for each well:

- *Recent Concentration*: The average of the most recent five concentration values.
- *Long-Term Attenuation Rate*

- *Rate:* For individual wells, the long-term attenuation rate is estimated using least squares regression and a first-order (exponential) decay model. A positive value indicates a decreasing concentration trend (Newell et al., 2002).
- *Glide Path:* Identifies whether the attenuation rate glide path for each individual well is slower or faster than the overall rate for the site. If the glide path is "Within Range", then the difference between the attenuation rate for the well and the overall attenuation rate for the site is consistent with the effects of short-term monitoring variability.
- *Accuracy:* The attenuation rate accuracy is based on the 95% confidence interval for the attenuation rate as follows.
    - High Accuracy: confidence interval <±0.05 or <±25% of attenuation rate;
    - Medium Accuracy: confidence interval <±0.1 or <±50% of attenuation rate;
    - Low Accuracy: confidence interval >0.1 and >50% of attenuation rate

  When the accuracy for a well is "Low", the user should be cautious in using the observed attenuation rate for predicting future contaminant concentrations.

- *Concentration Trend*
    - *Direction*: Whether or not the long-term trend shows increasing or decreasing constituent concentrations
    - *Confidence:* The statistical confidence that the true attenuation rate is not zero. This is based on the p-value of the attenuation rate at this well.
        - High Confidence: $p<0.05$;
        - Medium Confidence: $0.05<p<0.1$;
        - Low Confidence: $p>0.1$

What is p-value?

The p-value is the probability that the apparent pattern in the data (e.g., a decreasing concentration trend) is due to random chance. In other words, when the p-value is less than 0.1, there is a greater than 90% chance that the observed decreasing concentration trend is real.

6.3.3 Navigation

The navigation options are as follows:

- *Edit Well Data* - Takes the user back to the Input page
- *Show Well Trends* - Takes the user to the Well Trends page

6.4 Well Trends

6.4.1 Data Entry

No inputs are entered on the Well Trends page.

6.4.2 Data Analysis and Results

On this page, the Tool shows the same two summary tables as on the Results page that answer Question 2. The first – Attenuation Rate Summary – shows how many wells can be expected to have Faster, Within Range, or Slower Glide Paths (based of Short-Term Variability) and how many wells actually do fall into those categories. The second – Concentration Trend Summary – shows the same information for Increasing and Decreasing Concentration Trends. Based on these results, the Tool provides two "Yes" or "No" answers to Question 2.

Also as in the Results page, below these tables data for individual wells is presented, which gives a more detailed look at these wells. The Tool gives the user these instructions:

What to do next: If the answer to Question 2 is "Yes", evaluate the individual wells with slower attenuation rates or increasing concentrations. Consider whether these wells will delay attainment of the overall site clean-up goals.

On this page, these data are presented as graphs that show, for each well, the Well Trend in red and the Site (Median), Upper 95%, and Lower 95% Trends in black. This shows the user how the individual well related to the rest of the site, to determine if it will delay attainment.

Below each graph, the Tool shows whether the well has an Increasing or Decreasing Trend and whether the Attenuation Rate is Slower, Faster, or Within Range of the Site 95% Confidence Trends.

A key is shown at the top of this page to explain this to the user.

6.4.3 Navigation

The navigation options are as follows:

- *View Results* - Takes the user back to the Results page
- *Go To Optimization* - Takes the user to the Optimization page

7.0 MONITORING OPTIMIZATION TOOL

7.1 Questions

The Monitoring Optimization Tool answers two questions:

Question 1: How much monitoring data do I need to determine a site's long-term source attenuation rate with a defined level of accuracy or confidence?

Question 2: What are the trade-off between monitoring frequency and time required for trend identification?

Going through the Tool will provide the answers to these questions.

7.2 Inputs

The Monitoring Optimization Tool page requires values for: i) Short-Term Variability and ii) Long-Term Attenuation Rate. As such, if the user provided historical monitoring data and ran the Monitoring Variability Tool, the two parameters will have been calculated and will appear on this page. If no historical monitoring data is available, the user should input typical values for short-term variability and long-term attenuation rates. Typical values for these parameters are as follows:

Table 2: Typical Values for Short-Term Variability and Long-Term Attenuation Rate

Constituent	Short-Term Variability	Long-Term Attenuation Rate
Petroleum Hydrocarbons	1.0 to 2.0	0.35 yr^{-1}
Chlorinated Solvents	0.5 to 1.0	0.12 yr^{-1}

For characterization of short-term variability and long-term attenuation rates at 20 sites, see Section 4.1 of Task 2 Report, Methods for Minimization and Management of Variability in Long-Term Groundwater Monitoring Results, ESTCP Project ER-201209.

Information on the historical groundwater monitoring data should be entered next, if applicable:

- *Historical Monitoring Frequency*: The sampling frequency for monitoring data already collected at the site. The user can select from pre-defined options, including: quarterly, semiannually, etc. If different wells had various monitoring frequencies, please select the most common type.

- *Years of Historical Monitoring Data Collected*: The number of years of monitoring data already collected. If different wells have been monitoring for different time intervals, choose a value representative of a typical well.

The user must then calibrate the Tool so the results will be calculated to the desired detail. As such, the user must choose between "Accuracy" and "Confidence", at a "Medium" or "High" level.

Choose "Confidence" if a primary goal of monitoring is to demonstrate that contaminant concentrations are actually decreasing.

Choose "Accuracy" if a primary goal of monitoring is to estimate the time required for contaminant concentrations to decrease to a numerical clean-up goal.

These variables are described below.

7.2.1 Accuracy

The Optimization Tool will determine how many monitoring events are required to determine the long-term attenuation rate with a level of accuracy or a confidence specified by the user. The number of monitoring events is calculated so that 80% of the resulting monitoring records will meet the level of accuracy or confidence specified by the user. The accuracy is based on the 95% confidence interval for the attenuation rate.

Two options are available for selection: i) "High" (i.e., the value must be below either 0.05 or 0.25 times the Long-Term Attenuation Rate, whichever is larger); and ii) "Medium" (i.e., it must be below 0.1 or 0.5 times the Long-Term Attenuation Rate, whichever is larger). Selecting "Medium" will result a reasonable minimum amount of monitoring data needed to support decision-making. The user should recognize that, after this minimum is obtained, accuracy will continue to increase over time if monitoring is continued.

7.2.2 Confidence

The confidence is the statistical confidence that the attenuation rate is not zero, based on the p-value for the first-order attenuation rate using least square regression.

Two options are available for selection: i) "High" (i.e., the value must be below 0.05); and ii) "Medium" (i.e., value must be below 0.1). Selecting "Medium" will result a reasonable minimum amount of monitoring data needed to support decision-making. The user should recognize that, after this minimum is obtained, confidence will continue to increase over time if monitoring is continued.

7.3 Advanced Controls

The advanced controls give the user the ability to input a specific value for the level of accuracy or level of confidence, rather than "High" or "Medium". The user can also specify the percentage of monitoring records that will meet the specified level of accuracy or confidence.

- *Accuracy:* The confidence interval for the attenuation rate. If the user enters 0.1, then the maximum acceptable confidence interval will be ±0.1. For advanced controls, the user also specifies the percentage of well monitoring records that must achieve this maximum confidence interval.

- *Confidence:* The required maximum p-value for the attenuation rate. For example, a p-value of 0.1 corresponds to a 90% confidence that the attenuation rate is not equal to zero. For advanced controls, the user also specifies the percentage of well monitoring records than must achieve this maximum p-value.

- *Percent of Wells*: The percentage of monitoring well records that will meet requirements for Accuracy or Confidence. For regular controls, this value is 80%. For advanced controls, the user specifies the value.

7.4 Calculate

Once the inputs are set, the user should click the "Calculate and Show Results" button to calculate and populate the "Results" table as described in Section 7.4 below.

7.5 Results

As previously described, the Tool helps answers two main questions as follows:

Question 1: How much monitoring data do I need to determine a site's long-term source attenuation rate with a defined level of accuracy or confidence?

As the Answer indicates, different sampling options, from weekly to every 5 years, are presented in order to understand "how much additional monitoring data you need to accurately characterize your long term trend". A sample table is shown below.

Option	Sample Frequency	Total Sampling Events	Cost Per Well ($K)
Option 1:	Sample weekly for 1.6 years	82	123
Option 2:	Sample monthly for 2.7 years	33	49
Option 3:	Sample quarterly for 4.1 years	16	25
Option 4:	Sample semiannually for 5.0 years	10	15
Option 5:	Sample annually for 6.5 years	7	10
Option 6:	Sample every 2 years for 9.0 years	5	7
Option 7:	Sample every 5 years for 18.4 years	4	6

Figure 6: Example Sampling Requirements to Characterize the Long-Term Attenuation Rate with High Confidence

This table presents the following values:

- *Sample Frequency* - The length of time required to sample at different frequencies, from weekly (Option 1) to every 5 years (Option 7).

- *Total Sampling Events* - Number of sampling events that will occur at the specific sampling frequency for the total time period.

- *Cost Per Well* - The approximate cost of this sampling program per well, in thousands of dollars. This value per well is based on a sample cost of $1,500 per event. This assumed cost includes labor and materials cost for sample collection, laboratory analysis, data management, and reporting.

Question 2: What are the trade-off between monitoring frequency and time required for trend identification?

As the Answer indicates, the table also responds to Question 2, where "[all] options presented are equivalent". These trade-offs are explained below.

As shown in the "Sample Frequency" column in Figure 6, there are trade-offs between the future sampling frequency and the total time of monitoring required. For instance, if the user decides to sample once a month, it would take 2.7 years to know a site's long term source attenuation rate

with a defined confidence or accuracy. Comparatively, if the user were to sample once a year, the total monitoring time period would be 6.5 years to attain the same information.

7.6 How Do I Decide between Sampling Options?

Each of the different sampling options yields a monitoring dataset that can be used to characterize the long-term attenuation rate with the same level of confidence and accuracy. The final choice of monitoring frequency should be based on considerations of time and cost, answering the question:

What is the most cost effective monitoring option that will allow me to make decisions within the required timeframe?

Take, for example, a site where MNA has been selected as the remedy with the performance requirement that contaminant concentrations are demonstrated to be, in fact, decreasing at the time of the first five-year review. For this site, if the Monitoring Optimization Tool provided the monitoring shown in Figure 6, then the user would choose to monitor semi-annually because this five years of monitoring at this frequency would serve to document the long-term attenuation rate with high confidence. In contrast, 6.5 years of annual monitoring would be required to determine the long-term trend with high confidence, a time period that exceeds the requirement for demonstrating decreasing concentrations within five years.

7.7 Navigation

The navigation options on this page are as follows:

- *View Well Trends* - Takes the user back to the Well Trends page, if the user went through the Monitoring Variability Tool
- *Calculate and Show Results* - Calculates the monitoring frequency results and fills out the results table
- *Start New Project* - Asks the user for confirmation, then clears all current data and brings the user to the Main Menu page
- *Save & Exit* - Allows the user to name and save the file, then exits the Toolkit

8.0 MISCELLANEOUS

8.1 Unprotecting Individual Sheets and Viewing Hidden Interface

Individual spreadsheets and cells within the tool have been protected, except for any input cells. In order to generally unprotect the sheet, go to *Review* on the toolbar, and click *Unprotect Sheet*.

In order to view any of the hidden interface, go to *File>Options>Advanced* or go to View on the toolbar and select what you would like to view (e.g., sheet tabs, formula bar, or headings). In order to view hidden cells, select cells near the hidden cells and go to *Home* on the toolbar and click *Format>Hide & Unhide* and select what you would like to unhide.

8.2 Calculations for Advanced Users

Several tabs with background calculations have been hidden for simplicity. These can be seen by going to *Home* on the toolbar and clicking *Format>Hide & Unhide>Unhide Sheet…* and selecting which sheet you would like to unhide.. The hidden sheets and a brief description of their contents are as follows:

1. *Well Calculations* - Calculates the Individual Well Results shown on the Results page.

2. *Residuals Calculations* - Used to correct the Short-Term Variability to match a log-normal distribution.

3. *Random Data Calculations* - Calculates the simulated well data that are checked against the accuracy or confidence parameters.

4. Trend Calculations – Calculates the trend information for the Well Trends page.

5. *Referenced Values* - Contains values that are referenced in the Toolkit (e.g. in dropdowns).

9.0 LIMITATIONS

This Excel-based tool has been developed by GSI Environmental under Department of Defense contract W912HQ-12-C-0055. Neither GSI nor any of GSI's employees, subcontractors, consultants, or other assigns make any warranty or representation, either express or implied, with respect to the accuracy, completeness, or utility of the information contained herein, or assume any liability or responsibility for any use, or the results of such use, of any information or process disclosed in this publication, or represent that its use would not infringe upon privately owned rights.

Users of this tool should not rely exclusively on the information contained in this document. Sound business, scientific, engineering, and safety judgment should be used in employing the information contained herein.

Where applicable, authorities having jurisdiction should be consulted.

GSI is not undertaking to meet the duties of employers, manufacturers, or suppliers to warn and properly train and equip their employees, and others exposed, concerning health and safety risks and precautions, nor undertaking their obligations to comply with authorities having jurisdiction.

10.0 REFERENCES

Newell, C.J., Rifai, H.S., Wilson, J.T., Connor, J.A., Aziz, J.A., Suarez, M.P. 2002. Calculation and Use of First-Order Rate Constants for Monitored Natural Attenuation Studies. USEPA Ground Water Issue. http://nepis.epa.gov/Adobe/PDF/10004674.pdf

McHugh, T.E., Kulkarni, P.R., Beckley, L.M., Newell, C.J., Strasters, B., 2015. A New Method to Optimize Monitoring Frequency and Evaluate Long-Term Concentration Trends, Task 2 & 3 Report, Methods for Minimization and Management of Variability in Long-Term Groundwater Monitoring Results, ESTCP Project ER-201209.