Evaluating the sustainability of monitored natural attenuation in groundwater at chlorinated ethene contaminated sites

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ABSTRACT

Monitored natural attenuation (MNA) has been widely used as a remedial strategy, acknowledged by the EPA as the most appropriate technology for cost effective remediation under certain site conditions. Despite the widespread use of MNA, empirical methods are lacking to evaluate the sustainability of MNA at a site. The objective of this thesis is to investigate the natural attenuation capacity (NAC) as a quantitative metric for evaluating the sustainability of MNA for contaminants in groundwater systems.

Five DoD sites were selected for this study, where the common thread between the sites is the existence of a mature chlorinated ethene groundwater plume and the use of MNA as the long-term remediation strategy. Constituent specific NAC values were quantified and statistically examined to determine past performance of MNA at the sites. A conceptual decision model was developed to be a framework of the statistical tools demonstrated in this thesis.

Analyzing MNA sustainability at a site can be separated into two components; past performance of natural attenuation and evaluation of current MNA parameters. The former is the focus of this thesis where NAC is the screening metric and the temporal trend in the rate of natural attenuation being evaluated. Within the conceptual decision model, the use of NAC as a screening tool in combination with a specific analysis of MNA parameters allows engineers, regulators, and decision makers to clearly determine whether MNA at a site is sustainable and whether site specific remediation goals will be met.

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LIST OF ACRONYMS

AFB	Air Force Base
ARAR	Applicable or Relevant and Appropriate Requirements
BGS	below ground surface
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COC	Constituent of concern
CVOC	chlorinated volatile organic compound
DCE	Dichloroethene
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DoD	Department of Defense
FDEP	Florida Department of Environmental Protection
IR	Installation Restoration
MCL	maximum contaminant level
MCLG	maximum contaminant level goals
MNA	Monitored Natural Attenuation
NAES	Naval Air Engineering Station
NAPL	non-aqueous phase liquid
NAS	Natural Attenuation Software
NAVFAC	Naval Facilities Engineering Command
OU	Operational Unit
PCE	tetrachloroethene
PI	Prediction Interval
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
SZD	Source Zone Depletion
TCE	trichloroethene
TEAP	terminal electron acceptor processes
TOR	time of remediation
TOS	time of plume stabilization
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VC	vinyl chloride
VOC	volatile organic compound
WWTP	waste-water treatment plant
ZVI	zero valent iron

1. RESEARCH SCOPE AND BACKGROUND

Chapter 1 entails the scope, background and framework for the current analytical study. In Chapter 1.2 a succinct explanation of background topics is given regarding the foundational science of reductive dechlorination (RD) and natural attenuation capacity (NAC). Each of these topics have been thoroughly examined in multiple peer-reviewed documents. Chapter 1.3 highlights the value of the thesis question being examined within the context of remedial decision making for the regulatory and the landowner/responsible party.

1.1 Thesis Question Definition

Assimilative capacity of an aquatic system refers to the ability of that system to receive some amount of waste, nutrient, or pathogen loading without having a negative impact on the system reflected by regulatory limits on contaminants (Landis, 2008). Prior to the current era of environmental protection laws and natural conservation it was not uncommon to believe that groundwater and soil could absorb large quantities of contaminants without damaging the natural resource. Large scale dumping of hazardous wastes into streams, unlined pits, and the ocean were common practices in the early to mid 1900's (Colten, 1998). A significant number of sites where groundwater is currently contaminated with chlorinated solvents are the direct result of dumping practices in the early 20th century.

Based on the science of assimilative capacity, natural attenuation has developed as a somewhat assimilative means of contaminant remediation in groundwater systems. Natural attenuation is the naturally occurring process of biodegradation, sorption, and dispersion of contaminant mass in a groundwater system. Monitored natural attenuation (MNA) is the use of natural attenuation processes for the remediation of contaminants to an appropriate degree and within a reasonable timeframe based on site specific objectives (USEPA, 1999).

MNA is generally a slow and relatively inexpensive means of removing contaminant mass from a groundwater system. Despite the widespread use of MNA as a remediation strategy for more than two decades, there are currently no methods of predicting the sustainability of MNA at a site. Further, little information has been published using site data to compare changes in natural attenuation over time. Natural attenuation capacity (NAC) and several other collaborative tools discussed in this report could be the key to assessing the sustainability of MNA at a contaminant site. NAC is further explained in Chapter 1.2.1.

The objective of this thesis is to determine whether NAC is an appropriate quantitative screening metric for evaluating the sustainability of MNA of chlorinated solvents in a groundwater system. This thesis will also define the process by which a site can be evaluated for sustainable natural attenuation using NAC and other quantitative tools[i].

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[i] Some quantitative tools needed to assess sustainability of natural attenuation at a site are not within the scope of this thesis. See Chapters 4.7 and 5.3 for further explanation of quantitative tools that are outside the scope of this thesis

The approach of achieving the thesis objective is summarized in five steps:

(1) Quantifying NAC at a site based on five or more years of groundwater data
(2) Statistical analysis of NAC with respect to time to determine temporal trends
(3) Method for evaluating each new data measurement
(4) Determination of a critical NAC and defining the utility of this tool
(5) Demonstrate application to five sites where MNA is the current primary remedial strategy
(6) Develop a conceptual decision model for the determination of sustainability using NAC

Chapter 2 summarizes the methodology used to quantify a sites historical capacity for natural attenuation processes with respect to space and time. This chapter also explains statistical methods for determining the historical and predicted sustainability of natural attenuation processes at a site.

Chapter 3 provides descriptive and background information about the five sites used in the study. Chapter 4 presents the results of the statistical analysis as well as discussing site specific interpretations of the data. Chapter 5 discusses the success of the thesis, implications of findings and other related research. Additional data and supporting analysis is made available in the Appendices.

1.2 Background

The science of anaerobic biodegradation, reduction dechlorination of chlorinated ethenes, and the factors that contribute to the capacity of a groundwater system to support natural attenuation are vital building blocks to the argument being made. Subsequently, each topic is briefly explained in this chapter. Exhaustive explanations are withheld due to the general acceptance of these scientific concepts by the relevant academic communities.

1.2.1 Biodegradation of Chlorinated Ethenes

In order to discuss the sustainability of naturally attenuation in groundwater systems it is necessary to first define the processes that are actively driving attenuation. This study specifically looks at the natural attenuation of total chlorinated ethenes, which is defined as the quantitative total concentration of PCE, TCE, cis-DCE and Vinyl Chloride (VC) in a plume. The processes by which these chlorinated ethenes biodegrade are dependent on natural hydro-geological conditions, presence of reducing and fermenting microbial populations, and sufficient energy sources. Natural attenuation processes can be categorized by two primary aquifer characteristics: (1) aerobic conditions and (2) anaerobic conditions.

1.2.1.1 Aerobic Conditions

Chlorinated ethenes in aerobic aquifer conditions have been shown to undergo two main interactions with bacteria and micro-organisms that transform these potentially harmful substances into innocuous products, co-metabolism and direct oxidation.

Co-metabolism

Aerobic co-metabolism is the process by which metabolic enzymes (ie: methane monooxygenase, MMO) catalyze the oxidation of chlorinated solvents. In this reaction oxygen joins with the chlorinated solvent forming an unstable molecule. The unstable molecule degrades to a chloroacetic acid and now being water soluble will degrade farther to carbon dioxide, chloride and water. Studies have shown that co-metabolism requires at least one hydrogen attached to a carbon atom; therefore, the process does not occur with PCE (Byl & Williams, 2000).

[TCE + NADH (energy) + O_2 + MMO → TCE epoxide → dichloroacetic acid]

Direct Oxidation

Direct Oxidation is also an aerobic process by which lightly chlorinated solvents (DCA, DCE and VC), also referred to as daughter products, become electron donors to bacteria. In some cases iron-reducing bacteria can mineralize these chlorinated solvents as a substrate. In general, direct oxidation is a subsequent pathway that follows other degradation processes which act upon the parent chlorinated ethenes (PCE and TCE) (Byl & Williams, 2000).

1.2.1.2 Anaerobic Conditions and Reduction Dechlorination

Bacteria living in aquifers use inorganic electron acceptors in their metabolic processes. Oxygen is the most common inorganic electron acceptor in groundwater. When oxygen is depleted or absent, bacteria will use other electron acceptors based on availability and transfer efficiency. In an anaerobic system bacteria prefer the following acceptors in deceasing order: nitrate (NO_3^-), manganese (Mn^{4+}), iron (Fe^{3+}), sulfate (SO_4^{2+}), and carbon dioxide (CO_2) (**Table 1**).

Reductive dechlorination refers to the process by which chlorine atoms are replaced by electrons coupled to hydrogen atoms. The process repeats in what is termed sequential dechlorination. The sequence begins with the parent compound of PCE and reduces to TCE, DCE, VC, respectively. In some cases, TCE is considered the parent compound. The dechlorination of PCE and TCE can occur in strong to mild reducing conditions, however, the dechlorination of DCE and VC required strong reducing conditions such as sulfate or methanogensis (Byl & Williams, 2000).

TABLE 1: TERMINAL ELECTRON ACCEPTORS AND BY PRODUCTS IN ANAEROBIC CONDITIONS

Electron Acceptor	Byproduct	Description of Reducing Condition
Oxygen	Carbon Dioxide (CO_2)	Very mild
Nitrate (NO_3^-)	Ammonia (NH_3^+)	Mild
Manganese (Mn^{4+})	Manganese (Mn^{2+})	Mild
Iron (Fe^{3+})	Iron (Fe^{2+})	Strong
Sulfate (SO_4^{2-})	Sulfide (S^{2-})	Strong
Carbon Dioxide	Methane (CH_4)	Strong

source: (Byl & Williams, 2000) *('fair use' clause – see footnote in References)*

Dehalogenation research has shown that several factors which control the efficacy of reductive dechlorination and therefore, natural attenuation, are sufficient supply of organic carbon, strong reducing conditions (available electron acceptors), and microbial populations capable of active dechlorination. In addition, research has shown that hydrogen or acetate are the predominant electron donors in anaerobic aquifers. The source of hydrogen or acetate is the fermentation of complex organic carbon in the subsurface by fermenting microbial populations. The supply of electron donors is critical and limiting to long-term reductive dechlorination. These processes and the limiting ingredients of each are the basis for discussing the sustainability of reductive dechlorination, and consequently; natural attenuation (Rectanus, Widdowson, Chapelle, Kelly, & Novak, 2007). Reductive dechlorination is referenced often throughout this thesis as it is the primary mechanism for biodegradation in most of the sites reviewed in Chapters 3 and 4.

1.2.2 NAC as a measure of sustainability

Chapelle and Bradley defined the term Natural Attenuation Capacity for a groundwater system as the ability to lower contaminant concentrations along aquifer flowpaths. More precise language given by Chapelle and Bradley is to define NAC as the slope of the steady-state contaminant concentration profile along a groundwater flowpath. Therefore, NAC is a function of biodegradation, abiotic processes, aquifer dispersivity characteristics, and groundwater flow velocity (Bradley & Chapelle, 1998).

The solute-transport equation (Equation 1) for a one-dimensional system describes the four processes of dispersion, advection, sorption, and biodegradation.

$$\frac{\partial C}{\partial t} = -v\frac{\partial C}{\partial x} + D\frac{\partial^2 C}{\partial x^2} - \frac{K_d \rho_b}{n}\frac{\partial C}{\partial t} - kC \qquad \textbf{\textit{Equation (1)}}$$

Where C is concentration, t is time, D is the coefficient of hydrodynamic dispersion (m^2/d), v is velocity of groundwater flow (m/d), ρ_b is bulk density, K_d is a line sorption distribution coefficient, n is porosity, and k is a first-order biodegradation rate constant (d^{-1}). Under steady-state conditions the sorption process becomes negligible and Equation 1 simplifies to the ordinary differential equation shown as Equation 2.

$$D\frac{d^2C}{dx^2} - v\frac{dC}{dx} - kC = 0$$ ***Equation (2)***

The particular solution of this ODE given the boundary conditions of C = C_0 at x = 0 and C = 0 at x = ∞ is:

$$C(x) = C_0 e^{-\left[\frac{-v+\sqrt{v^2+4Dk}}{2D}\right]x}$$ ***Equation (3)***

Equation 3 describes the relationship between concentration and distance along the plume centerline and Equation 4 demonstrates the mathematic definition for NAC, which is based on Equation 3 (Bradley & Chapelle, 1998).

$$NAC = \left[\frac{-v+\sqrt{v^2+4Dk}}{2D}\right]$$ ***Equation (4)***

A graphical representation of this relationship (using hypothetical data) is shown in **Figure 1**, where total chlorinated ethene concentration data collected from wells along the plume centerline is plotted against the distance traveled along the plume centerline (dependent variable). Due to the nature of the solution (Equation 3), the axis of the independent variable must be log transformed to create a linear trend. The concentration in the source well (distance zero) in this example is 1000 [µg/L]. The equation of the regression line is displayed in the figure, where the slope of the line is -0.00132 [m^{-1}]. (Bradley & Chapelle, 1998).

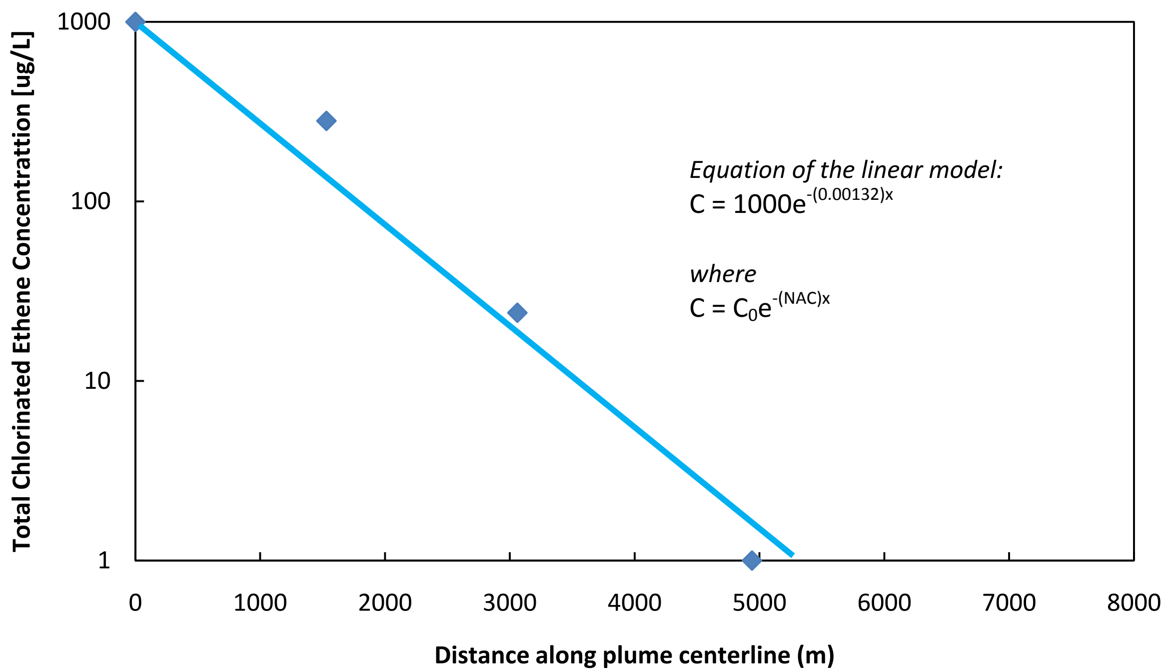

FIGURE 1: SOLUTE CONCENTRATION PROFILE (VERTICAL AXIS IS LOG SCALE), EXAMPLE OF NAC DETERMINATION

The sustainability of natural attenuation at a site is dependent on the limiting factors to the processes that make up that natural attenuation. These have been summarized as biodegradation rates, aquifer dispersivity, and groundwater flow velocity (Bradley & Chapelle, 1998). In the case of chlorinated ethenes in anaerobic groundwater system where steady-state has been achieved, the sustainability of natural attenuation is directly related to the ability of the biodegradation rate resulting from reductive dechlorination to continue.

Stating that the natural attenuation at a particular site is sustainable is, in part, inferring that the NAC capacity at the site is not decreasing with time, or that the decreasing rate of NAC at a site will not interfere with successful achievement of site specific remedial action objectives (RAO). Additionally, sustainability infers that the potentially limiting factors of reductive dechlorination (i.e. hydrogen, fermenting microbial colonies, bio-available carbon, microbial colonies feeding on the chlorinated ethenes, and anaerobic system) are found readily available in the aquifer system, so as not to be limiting. The former condition, regarding the evaluation of NAC trends at a site over time, will be examined in this report.

1.3 Value of Results

The value of this study and the tools introduced here can be summarized as providing regulating agencies or consulting engineers with a common basis for evaluating the effectiveness and sustainability of natural attenuation at chlorinated ethene contaminated sites. Clarity and statistical confidence with regard to evaluating the various components of MNA sustainability as well as formulating prediction models of a contaminant plume is worth hundreds of millions of dollars.

It is clear that across many disciplines and topics, the utility of the term "sustainability" is directly tied to level of subjectivity given to the definition. Particularly in regulated arenas such as groundwater contamination, an objective and clear definition of sustainability is vital for the widespread use of such a term. A significant achievement of this study is further clarification and framework in defining the term "sustainable MNA."

This study investigates NAC as a metric for MNA sustainability and a statistical screening tool for concluding whether the natural attenuation at the site has been performing in a sustainable manner over the period of time that data is available. Combining this analysis with an investigation into the limiting factors for reductive dechlorination at a site (see Chapter 5.4), one can make grounded statements about the likelihood for sustained natural attenuation at the site years into the future. This takes much of the guessing work out of determining long-term remedial strategies and time to reach site specific remediation goals. This ability is beneficial to regulators, responsible parties, and all those involved in the remedial decision making process at groundwater contaminated sites.

Furthermore, the process outlined in this thesis does not require additional data to be collected outside of what is generally obtained for plume observation. No additional sampling or laboratory expense is incurred to determine and observe NAC as well as this data is often available over a sufficient period of site history.

2. METHODOLOGY

Chapter 2 presents the analytical and statistical methods for addressing the central topic of this thesis; *NAC can be used as a metric for MNA sustainability of chlorinated solvent plumes in groundwater.* To determine the validity of this statement one must have criteria for selecting appropriate sites, a robust method for determining NAC, a statistically valid means of evaluating temporal changes at a site, and a site-specific critical NAC.

2.1 Criteria for Site Selection

The assessment will be performed with chlorinated solvent sites where MNA has been or can be evaluated as a remedial strategy. Sites were not necessarily limited to those where reductive dechlorination is the dominant mechanism for attenuation of a chlorinated solvent plume. Sites where physical mechanisms (e.g., dilution) are a major component to plume attenuation were considered. Each site used in this demonstration has the following characteristics:

- MNA parameters collected in accordance with EPA guidance (USEPA, 1998)
- Long-term monitoring well data sufficient to evaluate NAC over time

Following approval of the Site Selection Memo (SSM), the objective was to determine candidate sites for validating the MNA sustainability assessment as well as the SZD function (needed in a related study being completed simultaneously). Criteria for selecting these sites include the number and duration of data sets, the extent to which source concentrations decrease over time, and the extent of reductive dechlorination (ESTCP, 2008).

The five sites selected for the MNA sustainability assessment include varying levels of reductive dechlorination as well as differing forms of source remediation that has been implemented in combination with MNA:

- Chemical oxidation and emulsified vegetable oil (WWTP, NAS Pensacola)
- Emulsified zero valent iron (Areas I&J, NAES Lakehurst)
- Source extraction/recovery and containment (OU2, Hill AFB)
- Excavation and chemical oxidation (IR Site 5, NAS North Island)
- Phytoremediation (OU1, NUWC Keyport)

2.2 Determination of NAC

NAC is defined in Chapter 1.2 as the slope of the solute concentration profile (log concentration vs. distance plot). Although NAC is representative of several degradation processes, (adsorption, dilution, and biodegradation) the distinction between these factors within a dataset is not important for determining the sustainability of natural attenuation. For this reason, NAC is the most efficient means of discussing sustainability at a site.

2.2.1 Computer Applications for Determining NAC

Natural Attenuation Software (NAS) was developed through a collaboration between Naval Facilities Engineering Command (NAVFAC), United States geological Survey (USGS), and Virginia Tech. NAS is an analysis tool to estimate remediation timeframes for MNA to lower groundwater contaminant concentrations to regulatory limits. NAS is helpful in decision-making on the level of source zone treatment in conjunction with MNA using site-specific RAO.

NAS is designed for application to groundwater systems consisting of porous, relatively homogeneous, saturated media such as sands and gravels, and assumes that groundwater flow is uniform and unidirectional. NAS consists of a combination of analytical and numerical solute transport models. Natural attenuation processes that NAS models include advection, dispersion, sorption, non-aqueous phase liquid (NAPL) dissolution, and biodegradation. NAS determines redox zonation, and estimates and applies varied biodegradation rates from one redox zone to the next.

NAS models are implemented in three main interactive modules to provide estimates for:

- ***Required Source Reduction:*** target source concentration required for a plume extent to contract to regulatory limits (i.e. ***Distance of Stabilization (DOS)***),
- ***Time of Stabilization (TOS):*** time required for a plume extent to contract to regulatory limits after source reduction, and
- ***Time of Remediation (TOR):*** time required for NAPL contaminants in the source area to attenuate to a predetermined target source concentration.

Among the features offered by NAS are analysis tools for evaluating performance and sustainability over time. The feature most applicable to this work is the ability to monitor changes in natural attenuation capacities and redox conditions over time. NAS is available to the public at [http://www.nas.cee.vt.edu/index.php] (Chapelle, Widdowson, & Brauner, Methodology for Estimating Times of Remediation Associated with Monitored Natural Attenuation, 2003).

2.3 Statistical Methods

The topic of sustainability with regard to MNA of chlorinated ethene plumes has been uncharted to date. The purpose of this report is to establish a tool-kit that is statistically powerful yet functional to all parties involved in the decision making process for remediation with MNA of contaminant plumes. The determination of the sustainability of MNA at a site can be separated into two components; (1) past performance of natural attenuation and (2) evaluation of sufficient MNA parameters. The former is the focus of this report and NAC is the screening tool by which past performance of natural attenuation is evaluated. The latter, use of MNA parameters to evaluate sustainability, is beyond the scope of this thesis. A conceptual decision model is presented in Chapter 5.2 demonstrating how these two components work together to allow engineers, regulators, and decision makers to clearly determine whether MNA at a site is sustainable and whether site specific remediation goals will be met. NAC data reveal whether past years are showing sustainable or semi-sustainable trends with regard to the advection-dispersion-biodegradation processes. For more information regarding the use of MNA parameters in collaboration with NAC trends see Chapter 5.3.

2.3.1 NAC Trends

NAC is a numerical expression of the advection-dispersion-biodegradation model and can therefore be examined for trends over time. NAC is determined for every sampling event along the plume centerline and for every constituent found in the sampling events. **Figure 2** demonstrates the flow of information from independent and discrete sampling events, to the generation of a NAC values and finally a NAC vs. time trend.

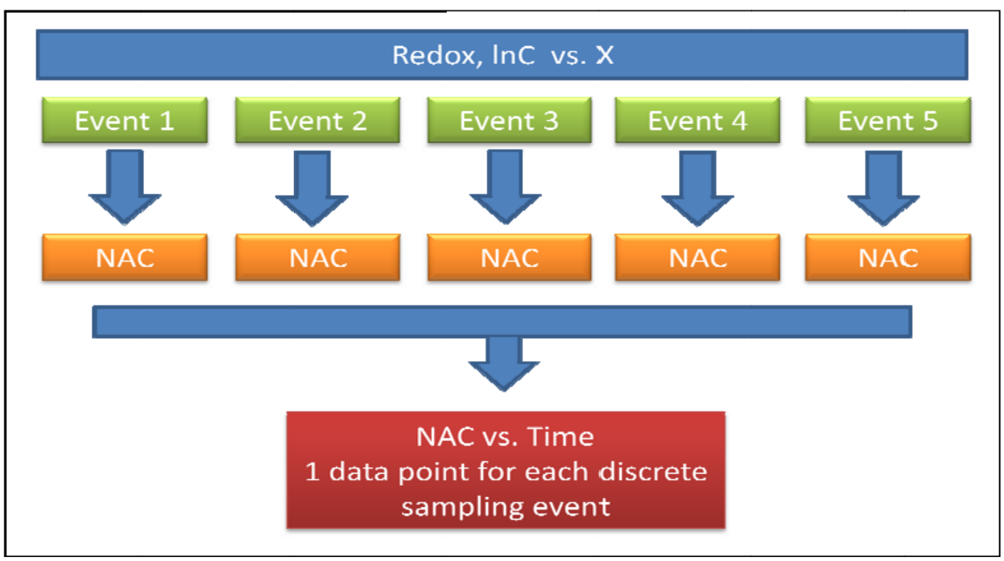

FIGURE 2: FLOW OF DATA FROM DISCRETE SAMPLING EVENTS TO PLOTTING NAC OVER TIME

2.3.1.1 **Linear Regression of NAC vs. Time**

NAC values will be determined as previously described using the NAS model and discrete sampling events. NAC is then plotted as the dependent variable with time as the independent variable. A linear regression analysis is completed to determine if slope of the *NAC v. time* trend is increasing, decreasing, or remaining statistically zero. The linear regression uses the least squares method and assumes that the data is representative of only one linear trend and assigns values for the slope (β_1) and y-intercept (β_0) with regard to the general equation (Equation 5). The variable 't' refers to time (independent variable) and the dependent variable is NAC (Milton & Arnold, 2003).

$$NAC = \beta_0 + \beta_1(t) \qquad \textbf{\textit{Equation (5)}}$$

The hypothesis question guiding the analysis of the linear regression is stated as:

Hypothesis Question: Is the slope of the linear regression equal to zero?

Null Hypothesis (H_0): *The slope of the linear regression is not different than zero.*

Alternative Hypothesis (H_A): *The slope of the linear regression is different than zero.*

The hypothesis is stated for a one sample, two sided test. The three possible outcomes of the hypothesis question are:

1) Reject the null hypothesis
2) Accept the null hypothesis
3) Fail to reject the null hypothesis

The third response infers that there was not enough data to reject the null, yet also not enough data to conclude that the null is the correct answer.

There are two types of errors associated with a hypothesis test known as Type I and Type II errors. A Type I Error, or a False Positive, occurs when the null hypothesis is rejected when it is actually true. The probability of committing a Type One error is equal to the significance level, (α) which is generally 10% in this study. A Type II Error, or a False Negative, occurs when the null hypothesis is accepted even though it is actually false.

The hypothesis is tested using the P-value generated by the linear regression. If the P-value for β_1 is greater than the significance level, α, then the answer is to accept the null hypothesis. If the P-value for

β_1 is less than the significance level, α, then the answer is to reject the null hypothesis. In cases where the slope of the regression is not zero (therefore, choose to reject the null), the sign of the slope estimate (β_1) indicates whether the trend is increasing or decreasing (Milton & Arnold, 2003).

2.3.1.2 **Statistics of Warning Signals and Risk Management**

The confidence level, α, is an important component of the statistical design that has site specific considerations. The conceptual process for predicting the sustainability of natural attenuation described in this report (Chapter 2.5) can be viewed as an alarm or warning system. The alarm is a statistical indication that the NAC at a site is decreasing, particularly if the NAC falls below the CNAC. When designing a warning system, one must chose a confidence level that is sensitive to the right inputs with regard to the site specific goals and concerns. This consideration is important to managing risks to human health, natural resources, as well as unnecessary financial expense in remedial programs.

Increasing the confidence level to 10% from the standard 5% increases the possibility of data points falling outside the prediction intervals, or stated formally, increasing the chance of false positives. A higher false positive rate means that the warning system has been made more sensitive to detecting changes in the NAC. This is favorable given the primary goal of the process is to be a warning system. The confidence interval can arguable be between 5% and 20%, with 20% being the most sensitive warning system for false positives.

In many cases, a confidence level of 10% is the most ideal compromise of sensitivity to changes in NAC as well as the increased costs associated with a more sensitive alarm. The immediate result of rejecting the null at a particular site is the need for increased sampling and monitoring to determine if the NAC is in fact changing or whether the alarm was a false positive. Therefore, one could argue that the confidence level should not be greater than 10% as it would be too sensitive to fluctuations in NAC which would create more cost through false positives. At a site where there are no pathways and/or receptors for the contaminants then one could argue that an alpha level of 5% is sensitive enough for the site and is more cost effective. The exact confidence level should be evaluated at each site. The five sites reviewed in this study use the recommended α of 10%.

There is no dogmatic rule that can be applied given the site-specific variables; rather the choice of a confidence level is a balance of protecting human health and the environment as well as protecting remedial programs from unnecessary expense.

2.3.2 Sustainability Based on Next Data Measurement

When MNA is used at a site it is highly valuable to determine whether the most recent NAC value represents a change in the previous trend. To evaluate this question two methods of using prediction intervals are available, a graphical method and tabular method. A prediction interval gives the confidence interval for the population. Prediction intervals will be used to describe the estimated range that a sample should fall within a certain percentage of the time if the trend reflects a linear regression. Prediction intervals take into account the uncertainty of the model (best fit line) as well as the uncertainty of the individual data measurement. In contrast, confidence intervals describe the uncertainty of the model only, which is why a prediction interval of equal confidence has a greater range than that of a confidence interval (Wackerly, Mendenhall III, & Scheaffer, 2002).

Use of prediction intervals in collaboration with a regression analysis is highly useful in the determination of MNA sustainability. A regression analysis is useful in determining a trend and detecting gradual changes in the trend. Prediction intervals are useful in detecting sudden changes in a trend that may be absorbed by a regression analysis. The use of both statistical tools as collaborative indicators is necessary for the accurate determination of MNA sustainability.

2.3.2.1 Graphical Method - Prediction Intervals of Single Predicted Response

A graphical representation of the prediction intervals can used to determine if the most recent NAC value falls within the predicted interval. The generation of these graphs requires a least squares linear regression of the NAC data which also includes the appropriate mathematical determination of the prediction intervals (Equation 6). In this regression analysis, the most recent NAC value is excluded. The next measurement is visually evaluated on whether it falls within the previously determined prediction limits.

Two-sided, prediction interval for individual response for a given set of values:

$$\hat{Y}\,\Big|x \pm t_{[n-k-1]}\, S \sqrt{1 + x_0'(X'X)^{-1}x_0} \qquad \textbf{Equation 6}$$

Where $\hat{\boldsymbol{Y}}\,\Big|\boldsymbol{x}$ is the predicted mean value at a given **x**, $\boldsymbol{t_{[n-k-1]}}$ refers to the Student's t distribution, **n** is the number of samples, $\boldsymbol{S}$ is the standard deviation of the sample set, and $\boldsymbol{x_0'(X'X)^{-1}x_0}$ describes a function utilizing the matrix rule of variance, (see source for further explanation) (Milton & Arnold, 2003).

The advantage of using this graphical method based on the linear regression model is that one does not have to assume the NAC trend had a slope of zero. A disadvantage of this method is that it is least accurate at the beginning and end of the data set (bowing effect, see **Figure 3**). The end of the data set is what we are interested in when evaluating the "next data point." Another disadvantage of this method is that it requires the user to visually extrapolate the prediction interval lines to the next data point (along the x-axis). These disadvantages make the traditional method of determining prediction intervals less preferred to the tabular method. For this reason, the least squares graphical method is only performed for the former WWTP site at NAS Pensacola (**Chapter 4.1**).

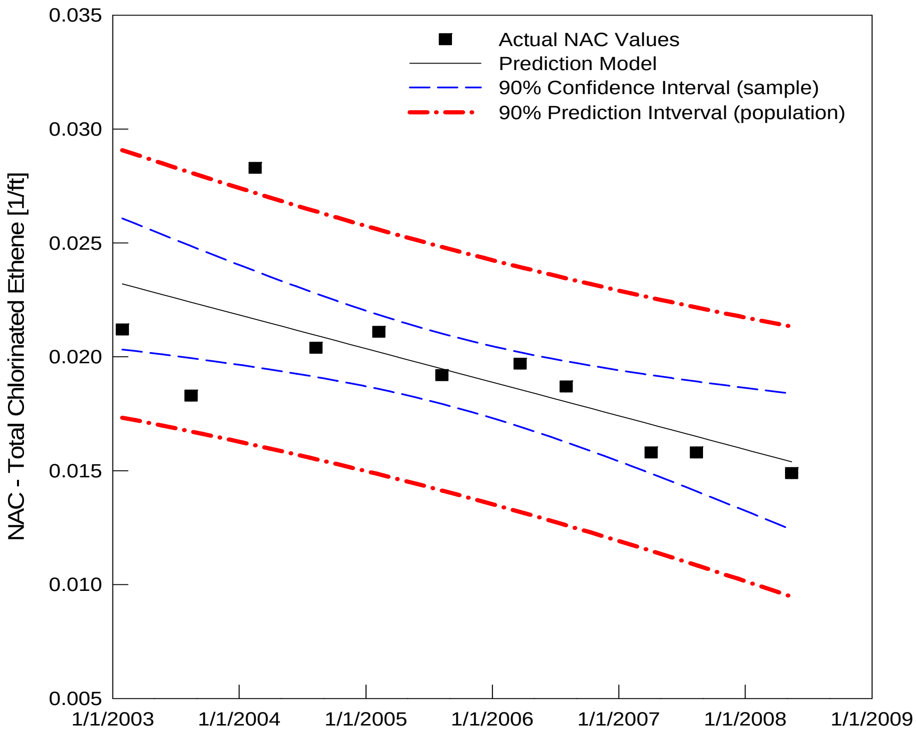

FIGURE 3: EXAMPLE GRAPHICAL REPRESENTATION OF PREDICTION INTERVALS DETERMINED FROM A LINEAR REGRESSION

2.3.2.2 **Tabular Method – Prediction Interval for the Next Single Measurement**

In *Statistical Methods for Groundwater Monitoring*, Gibbons describes the method for determining "Prediction Intervals for the next single measurement from a normal distribution." One can determine an interval that will contain some number of future measurements, k, with a given confidence level. However, in most cases involving MNA, the interest is only to see whether the next data point falls within the prediction interval (k=1). This method is known as *Prediction Intervals for the Next Single Measurement* and assumes a normal distribution of data (Gibbons, 1994). Another important assumption of this method is that the trend being analyzed has a slope of zero. Normality is tested using the Shapiro-Wilk test for data sets having 3 to 2000 measurements and the slope of trend is tested with linear regression analysis (Royston, 1982). **Equation 8** is used to determine the two-sided PI for the next single measurement. **Equation 9** is used to determine the one-sided PI for the next single measurement.

Two-sided PI:

$$\bar{x} \pm t_{[n-1,1-\alpha/2]}\, s\sqrt{1+\frac{1}{n}}$$ **Equation 8**

One-sided, PI:

$$\bar{x} \pm t_{[n-1,1-\alpha]}\, s \sqrt{1+\frac{1}{n}}$$ **Equation 9**

The symbol $\bar{\boldsymbol{x}}$ denotes the mean of the samples and $\boldsymbol{s}$ is the standard deviation of the samples. The notation $\boldsymbol{t}_{[\boldsymbol{n}-\boldsymbol{1},\boldsymbol{1}-\boldsymbol{\alpha}/\boldsymbol{2}]}$ refers to the Student's t distribution, where **n** is the number of samples and **α** is the confidence level (Gibbons, 1994).

A number of statistical software packages or tables can be used to determine the inputs for Equations 8 and 9. Open source statistical software R is utilized to determine the Student's t value as well as check that the data is normal by the Shapiro-Wilk test (R Project, 2009). Both equations are solved in a tabular format (Microsoft Excel) to determine whether a NAC value is within the prediction interval at a specified confidence level based on the history of NAC values observed at that site. The ability of this tool to produce reliable results is dependent on the number of historical sampling events from which the prediction interval is based on.

2.4 Determination of a Critical NAC

Site specific remediation goals are often determined for heavily contaminated sites and can vary from regulatory limits for groundwater based on site specific considerations, such as, cost of remediation, absence of pathways and/or receptors, containment, and land-use limitations. Site specific goals often include a distance from the contaminant source known as the point of compliance (POC) and a maximum threshold concentration that must be achieved at the POC.

When MNA is being used as the remediation strategy at a site, it is important to know what value of NAC should not be exceeded in order to achieve the site specific goals. The critical NAC (CNAC) is the greatest possible slope of the solute concentration profile that causes the plume to comply with site specific threshold concentrations at the determined POC.

To illustrate the concept of CNAC, **Figure 4** uses the fictitious total chlorinated ethene solute concentration profile used in Figure 1, where the concentration in the source well is 1000 μg/L. Suppose the site-specific goals set the maximum concentration threshold for compliance is 20 μg/L total chlorinated ethene, which is to be achieved at or before a POC location 4000 meters down-gradient from the source. The critical NAC is the slope of the line that starts at the source location with a known source concentration (1000 μg/L) and decays at an exponential rate causing it to pass directly through the intersection of the POC and threshold concentration. In this example, the CNAC is 0.00098 m^{-1}. Since the CNAC is less than the actual NAC (0.00132 m^{-1}), it can be assumed that under constant site conditions the compliance threshold will be achieved by the POC. This graphical tool is powerful in communicating how NAC relates to the achievement of site-specific remediation goals.

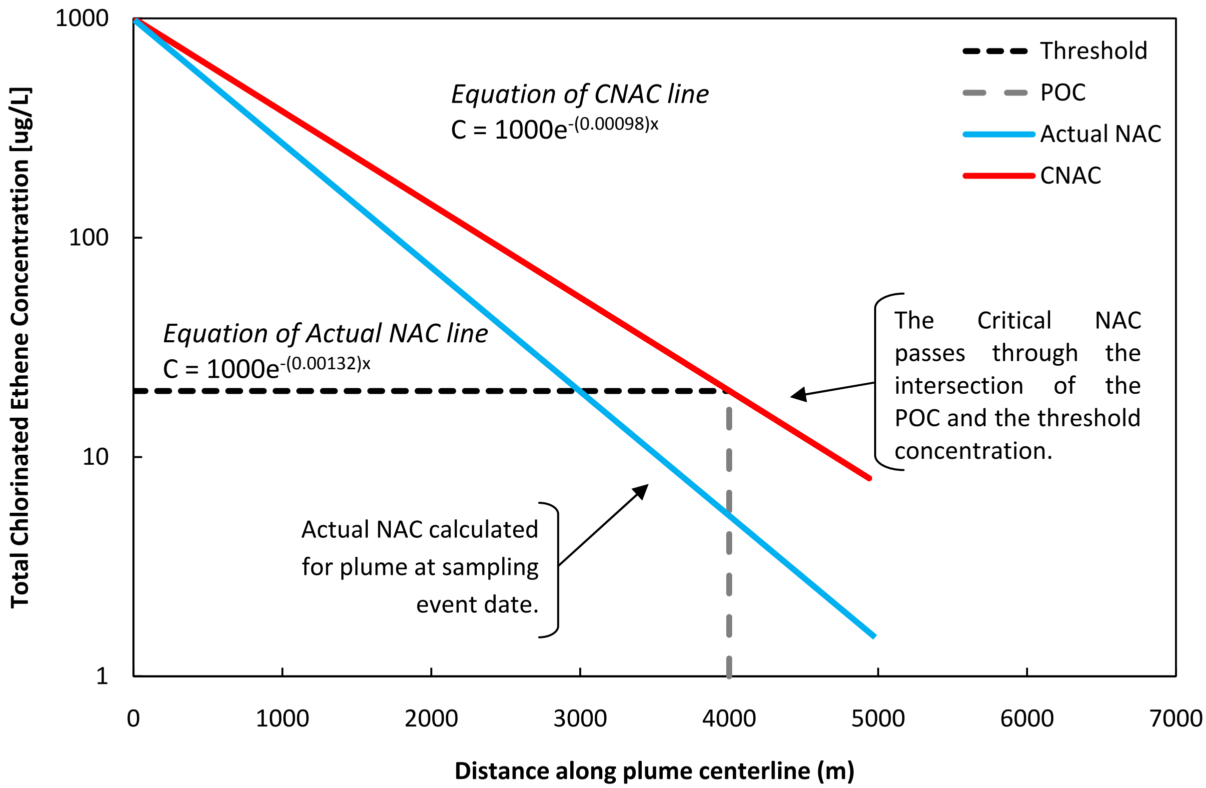

FIGURE 4: EXAMPLE OF CRITICAL NAC DETERMINATION, SOLUTE CONCENTRATION PROFILE

The solute concentration profile (above) is a single snapshot in time where a NAC value is determined from one sampling event. Quantifying a time series of NAC values allows for the determination of a representative NAC value. One objective of the CNAC analysis is to observe a prediction (best-fit) model of NAC alongside the CNAC for a site to determine a time estimate of intersection. Using the same example as Figure 4, **Figure 5a** demonstrates the CNAC as it appears on a plot of NAC with respect to time. **Figure 5b** shows a linear extrapolation of the prediction model while holding the CNAC constant. In this example, the NAC will fall below the critical value by November of 2016. Assuming a non-transient source, the capacity of the site to degrade the contaminant concentrations to meet site specific objectives will fall below the minimum requirement after November of 2016.

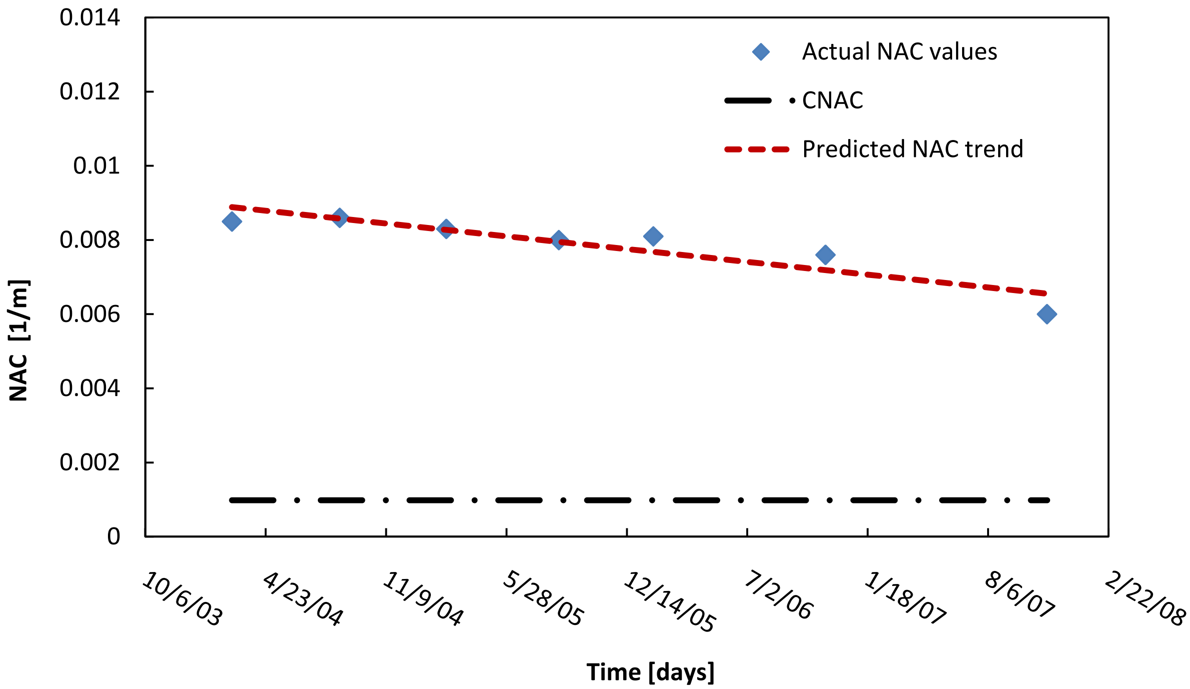

FIGURE 5A: EXAMPLE OF NAC AND CNAC WITH RESPECT TO TIME

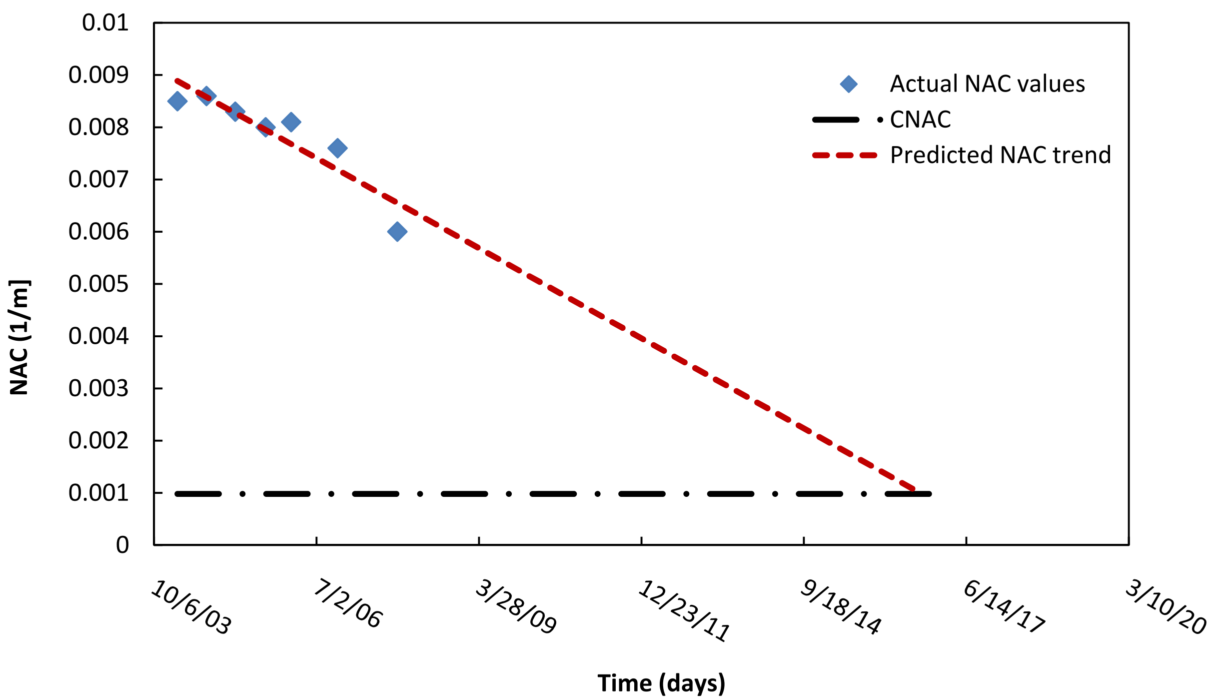

FIGURE 5B: EXAMPLE OF NAC AND CNAC WITH RESPECT TO TIME, EXTRAPOLATED TO THE POINT OF INTERSECTION

3. SITE DESCRIPTIONS

Chapter 3 provides relevant descriptions of the contaminated sites utilized in this study, including: the site location, pertinent historical uses, geology/hydrogeology characteristics, extent of contamination by chlorinated ethenes, and an overview of remedial actions. No new analysis is completed in these site descriptions, rather; it is a contextual summary for the data analysis in Chapter 4.

The goal of these brief site descriptions is to highlight site specific information regarding the chlorinated ethene pollution source, dispersion/advection/degradation pathways. Since remedial actions can have a significant impact on the statistical analysis presented in Chapter 4, a thorough analysis of the historical timeline of remediation interventions is critical.

3.1 NAS Pensacola, WWTP

The following chapter provides a general overview of the contaminant plume originating at the former Waste Water Treatment Plant (WWTP) at NAS Pensacola. The site is also known as OU-10, NAS Pensacola. As previously mentioned, no new analysis is completed in this chapter, rather; it is a contextual summary for the data analysis in Chapter 4. The primary source for Chapter 3.1 is the USGS report titled, *Natural and Enhanced Attenuation of Benzene, Chlorobenzenes, and Chlorinated Ethenes at the WWTP, NAS Pensacola* (2008).

3.1.1 Site Location and History

NAS Pensacola occupies approximately 5,800 acres on a peninsula in southern Escambia County, 5 miles south of Pensacola, FL. The on-site waste-water treatment plant (WWTP) has been used to process wastewater since 1941, when the sewage treatment facility was first installed. During the 1950's and 60's, the WWTP received industrial waste from paint and electroplating operations. Much of this waste was processed concurrently with sewage waste. In 1971, the WWTP was upgraded to separate the treatment of industrial and domestic wastes. Wastewater treated at this site contained organic solvents (including chlorinated ethenes, benzene, and chlorobenzenes), phenols, chromium electroplating wastes (including cyanide and other heavy metals), and wastes from a chemical conversion coating process for aluminum. Drying beds were used to dewater the sludge generated by the waste-treatment processes. These abandoned drying beds were the source of environmental contamination that was addressed under RCRA (Chapelle, 2008).

3.1.2 Site Geology/Hydrogeology

The WWTP is underlain by marine and fluvial terrace sediments deposits of Quaternary age. Sediments exposed at land surface and extending to a depth of about 40 feet are predominantly fine to medium sands that form a shallow water-table aquifer. This water-table aquifer is underlain by lower-permeability silts and clays of marine origin that act as a confining bed. This confining bed is underlain by permeable sands and gravel that form a confined aquifer system. This confined aquifer is known locally as the “main producing zone” and has been used for water supply. At the WWTP, the confined main producing zone has higher water levels than the overlying water-table aquifer. Thus, the site is characterized by an upward hydraulic gradient. The combination of the confining bed and the upward hydrologic gradient prevents downward movement of ground water at this site (Ensafe/Allen and Hoshall, 1995). Because of this, most of the contaminants are present in the water-table aquifer between a depth of 20 to 40 feet below land surface. Pensacola Bay, located immediately adjacent to the WWTP, serves as the regional discharge area for both the shallow water-table aquifer and the underlying main producing zone (Chapelle, 2008).

3.1.3 Contaminant Distribution

The chlorinated ethene plume present at the WWTP is delineated by section A-A′, and the chlorinated benzene plume is delineated by section B-B’ (**Figure 6**). Studies by the U.S. Geological Survey beginning in 1996 (USGS, 1999) indicated that conditions were favorable for natural attenuation processes to treat chlorinated ethene-contaminated ground water. Specifically, it was shown that chlorinated ethenes were rapidly transformed to non-toxic byproducts (carbon dioxide, chloride, and ethane) prior to discharging into Pensacola Bay. Chlorinated benzenes were more recalcitrant under the ambient anoxic conditions of ground water, but were removed at the freshwater/saltwater mixing zone of the aquifer prior to reaching Pensacola Bay. The observed chlorobenzene removal appears to reflect the combined effects of mixing at the freshwater/saltwater interface near Pensacola Bay and biodegradation processes (Chapelle, 2008).

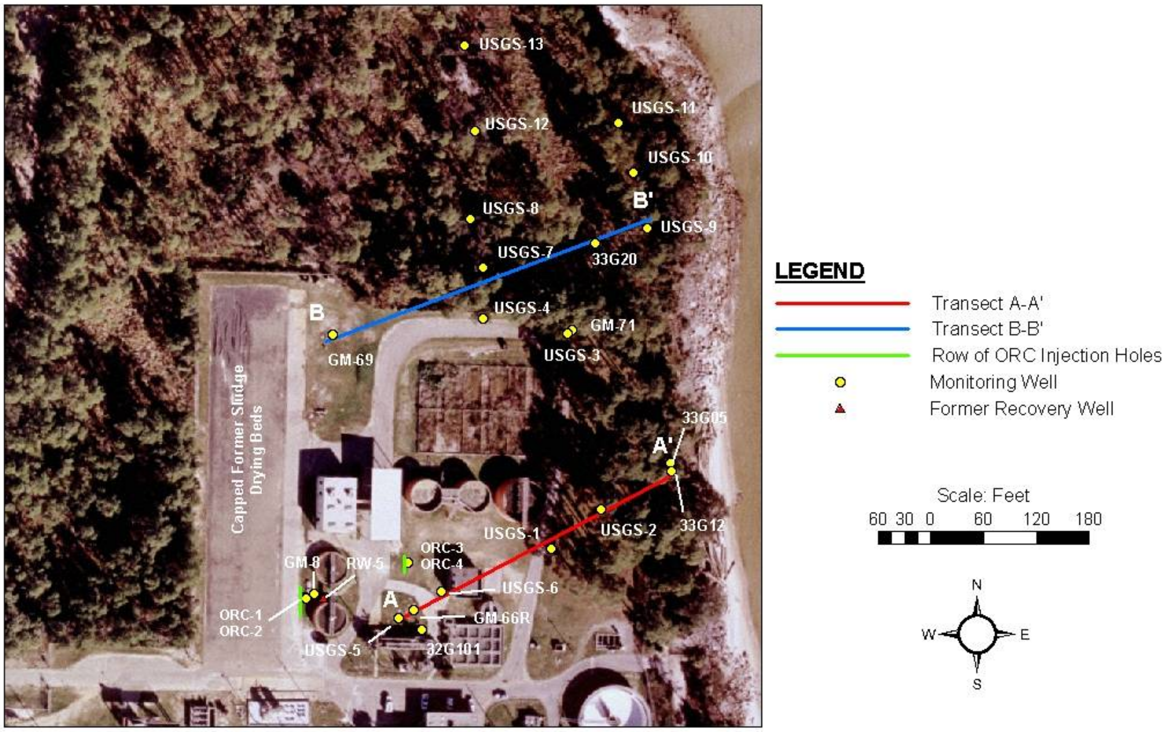

FIGURE 6: SITE MAP OF THE OU-10 AT NAS PENSACOLA SHOWING TRANSECTS A-A' AND B-B' (CHAPELLE, 2008)

3.1.4 Remedial Activity Summary

Information regarding the chlorinated benzene plume has been provided for thoroughness, but the chlorinated ethene plume (TCE, cis-DCE, and VC) is the subject of this analysis. OU-10 has undergone three stages of remedial activities to consider when evaluating the historical concentration data, include; source excavation, in-situ oxidation using Fenton's Reagent, and MNA. Additionally, several possible strategies for remediating the source area of flowpath A-A' including biostimulation and bioaugmentation of reductive dechlorination are currently being evaluated by the Navy (Chapelle, 2008).

According to Final Record of Decision (ROD) by EnSafe/Allen and Hoshall (1997) contaminated soils and sediment from the former sludge drying beds was removed to a depth of six feet. The area was backfilled with clean sand and capped with high-density asphalt. The exact date of this excavation action has not been confirmed, however, it occurred between the ROD issuance and the construction of the groundwater-recovery system in 1998-1999. A groundwater-recovery system was installed to pump and treat contaminated groundwater. The pump and treat was discontinued in 1999 when the USGS concluded that the site was favorable for natural attenuation (USGS, 1999). In December 1998 a series of in-situ oxidation injections of Fenton's Reagent near IMW-66 (well was damaged by injections and replaced with well GM-66R) were completed.

Approximately 40,560 lbs (4,089 gallons) of 50% hydrogen peroxide and an equivalent volume of ferrous iron catalyst solution were injected between December 8 and December 12, 1998. This treatment led to an initial decline in chlorinated ethene concentrations.

However, since 2001, groundwater monitoring has documented a rebound of chlorinated ethene concentrations that have returned to pre-Fenton's treatment levels in the source area of plume A-A'. Groundwater monitoring has also shown, however, that the efficiency of natural attenuation in plume A-A' has not been lowered by Fenton's treatment, and concentrations of chlorinated ethenes continue to attenuate prevent migration of contaminants to Pensacola Bay at concentrations exceeding Florida Department of Environmental Protection (FDEP) Groundwater Cleanup Target Levels (GCTLs) (Chapelle, 2008).

According to the 2008 USGS Annual Report on natural attenuation at the site, several possible strategies for remediating the source area of flowpath A-A', including biostimulation and bioaugmentation of reductive dechlorination, are being evaluated. To that end, in July of 2008, a biostimulation/bioaugmentation (bioaug) demonstration project was implemented in the source area of plume A-A'. Concentrations of trichloroethene in the contaminant source area decreased from approximately 5,000 µg/L in May 2008 (pre-bioaug) to approximately 420 µg/L in November of 2008 (Chapelle, 2008).

3.2 NAES Lakehurst, Sites I&J

The following chapter provides a general overview of NAES Lakehurst, Sites I&J. As previously mentioned, no new analysis is completed in this chapter, rather; it is a contextual summary for the data analysis in Chapter 4. The primary sources for Chapter 3.2 are the *Remedial Action Report for Nanoscale Particle Treatment of Groundwater at Areas I&J* (PARS Environmental, Inc., 2006), *Five-Year Review Report, NAES Lakehurst* (Environmental Management, NAES Lakehurst, January 2006), *Final Report – Groundwater Natural Restoration Study, and Areas I and J* (Dames and Moore, 1999).

3.2.1 Site Location and History

The Naval Air Engineering Station (NAES) Lakehurst station presents a surface of 7,412 acres and it is located within the Pinelands National Reserve in central New Jersey. Lakehurst began as a remote ammunition proving ground for the Russian Imperial Government in 1915. Currently, Lakehurst operates as the Aircraft Platform Interface Group for technical mission support. Area I, which consists of five contaminants sites, is located in the south central portion of the facility and the former catapult test facility built in 1958. Area J, which consists of four contaminants sites, is located in the central-western portion of the facility to the west of Area I. In 1960s and subsequent years, disposal of industrial waste water into holding ponds and swales were typical on-site operations at Areas I and J. The consequences of these actions appeared in the late 1980's when analyses of ground water quality conducted in this area revealed that these operations caused the contamination of the aquifer. In particular for Areas I and J, the quality analyses indicated the presence of VOCs in the ground water. **Figure 7** depicts the site map and the cis-DCE plume in ground water Areas I and J in 1999 (Dames and Moore, 1999).

3.2.2 Site Geology/Hydrogeology

NAES Lakehurst is located in the Atlantic Coastal Plain. The uppermost aquifer is the Cohansey Sand Formation which is exposed throughout most of the county surface. This formation is permeable and constitutes one of the principal aquifers in the Ocean County. In the vicinity of the NAES, this formation has reported as being a characteristically yellowish-brown, unfossiliferous, cross-stratified, pebbly, ilmenitic fine to very coarse-grained quartz sand that is locally cemented with iron oxide. Based on excavations conducted within the NAES borders, the upper 20 to 100 feet of strata underlying the center is primarily a fine to coarse grained quartz sand. Fine gravel and silt is commonly present intermixed with the sand. The depth of bedrock in the surrounding area of the NAES Site is approximately 1,800 feet. Pumping tests conducted in the main aquifer of Area I yielded values for the horizontal hydraulic conductivity between 63 and 99 ft/day. The water table is typically shallow with regional values fluctuating between 6 and 40 feet below the surface. The regional horizontal flow rate has been reported to be 4 ft/day. However, Dames and Moore (1999) reported that the flow rate at the site is significant lower (0.15 ft/day) (Widdowson, Chapelle, Casey, & Kram, 2008).

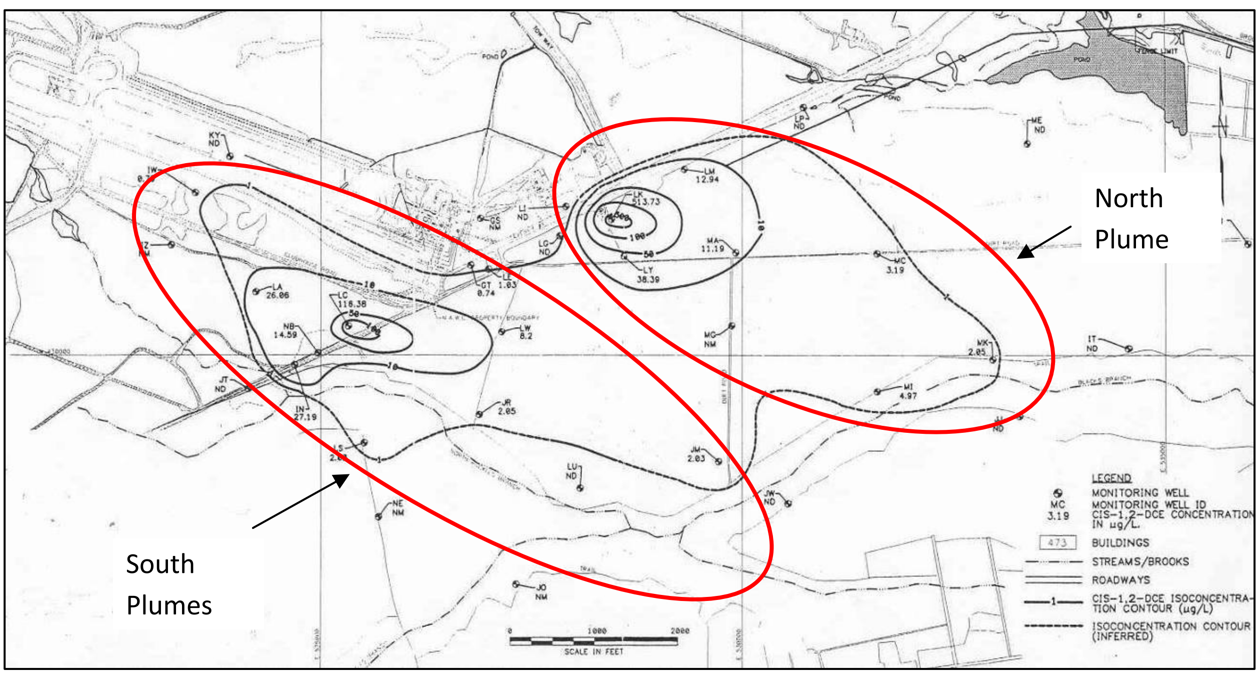

FIGURE 7: SITE MAP OF AREAS I AND J AT NAES LAKEHURST, NY (DAMES AND MOORE, 1999).

3.2.3 Contaminant Distribution

The contamination in Areas I & J at are primarily due to the discharge of water containing TCE, hydraulic fluid and ethylene glycol, along with the steam-cleaning operation of equipment. The monitoring program revealed the existence of three VOC plumes; one North plume and two South plumes (Figure 7). Only the North Plume is statistically analyzed in Chapter 4, however, since the North and South plumes have been historically referenced and remediated together this chapter includes some descriptive details regarding the southern plumes.

The highest levels of contaminants are registered in deep wells (between 50 and 70 feet depth) in all three plumes. The North plume starts in a region close to Site 25, and then, contaminants are transported by the ground water system in the east direction approximately 5,000 feet. This plume is widely spread due to changes observed in the flow direction. The South plume nearest North plume (SP1) seems to have its source in the area covered by Sites 6, 7, and 24. The contaminant released in this area has been transported 4,000 feet in the east direction. The second South plume (SP2) moves from an area close to Site 3 towards the south-east a distance of 3,000 feet. The predominant constituent in these three plumes is cis-DCE. The concentration data suggest that the plumes are in steady state and that natural attenuation is taking place (Dames and Moore, 1999).

3.2.4 Remedial Activity Summary

The first remedial alternative proposed to clean the aquifer was a groundwater recovery, treatment, and recharge system. Later, a study conducted in late 1993 and early 1994 revealed that this system was not going to be effective in removing the contaminant. Furthermore, it will cause the loss of several acres of wetland. Instead, an approach involving source remediation followed by MNA was proposed as a new remedial alternative to restore the aquifer (Widdowson, Chapelle, Casey, & Kram, 2008). The MNA remedial alternative was studied from 1996-1999 and it has proved to be efficient in degrading the CVOC plume in Areas I and J while the existing geochemical and biological conditions remained stable. Time to reach ARARs for the site with MNA was determined to be 44 years, revised in 2004 to 48 years. The ROD, issued on August 30, 1999, stated the final strategy for the site would be a combination of source treatment (not determined at that point) at the “Hotspots” and long-term MNA. The initial recommendation was a pilot study for co-metabolism as the source treatment. The study was completed between July 1999 and July 2000 and determined to be ineffective at significant source reduction. April 2001 laboratory tests indicated that bimetallic nanoscale particle technology may be effective at the site. Field testing of the injected zero valent iron (ZVI) began in February 2002. Positive results lead to a larger study in 2003, where 1200 gallons of 2.0 gram/L nanoscale particle slurry was injected at ten locations up-gradient of well LK. The result was an average reduction of 74% for total VOCs, 79% for TCE and 83% for DCE (Environmental Management, NAES Lakehurst, January 2006). A second round of ZVI treatment by Pars Environmental Inc. occurred in November 2005. In this treatment 2800 lbs of ZVI was spread between the northern and southern plumes. The primary target area in the northern plume was up-gradient of well NI, which exhibited the highest levels of chlorinated ethenes (PARS Environmental, Inc., 2006).

MNA is currently being implemented at the site, with compliance goals set for the plume. If the ARARs are not met at the point of compliance down-gradient of the plume, then the Technical Review Committee (TRC) will consider whether further remedial action is necessary (Environmental Management, NAES Lakehurst, January 2006).

3.3 Hill AFB, OU2

The following chapter provides a general overview of Hill AFB, Operable Unit 2 (OU2). As previously mentioned, no new analysis is completed in this chapter, rather; it is a contextual summary for the data analysis in Chapter 4. The primary source for Chapter 3.3 is the *Conceptual Model Update for Operable Unit 2 Source Zone: Hill Air Force Base* (URS and Intera, 2003).

3.3.1 Site Location and History

Hill Air Force Base (AFB) in Ogden, Utah has been a working Army and Air Force facility since 1920 and has supported a variety of manufacturing, storage, distribution, airplane maintenance, and missile storage operations. These operations generated and used wastes including chlorinated and non-chlorinated solvents, degreasers, and fuels. In 1987 Hill AFB was placed on the EPA's National Priority List (NPL) under CERCLA and the research and remediation processes have been ongoing since then. Operable Unit 2 (OU2) is one of the several contaminated sites existing within Hill AFB. This site, along the northeastern boundary of the base was used as a dumping site of an estimated 45 to 50-thousand gallons of chlorinated organic solvents and degreasing agents from 1967 to 1975. DNAPL sources were composed primarily of TCE with smaller amounts of tetrachloroethene (PCE) and 1,1,1- trichloroethane (1,1,1-TCA) and were dumped in unlined trenches and have contaminated the underlying aquifers. **Figure 8** depicts the site map and the TCE plume in the ground water system at OU2 in 2003 (URS and Intera, 2003).

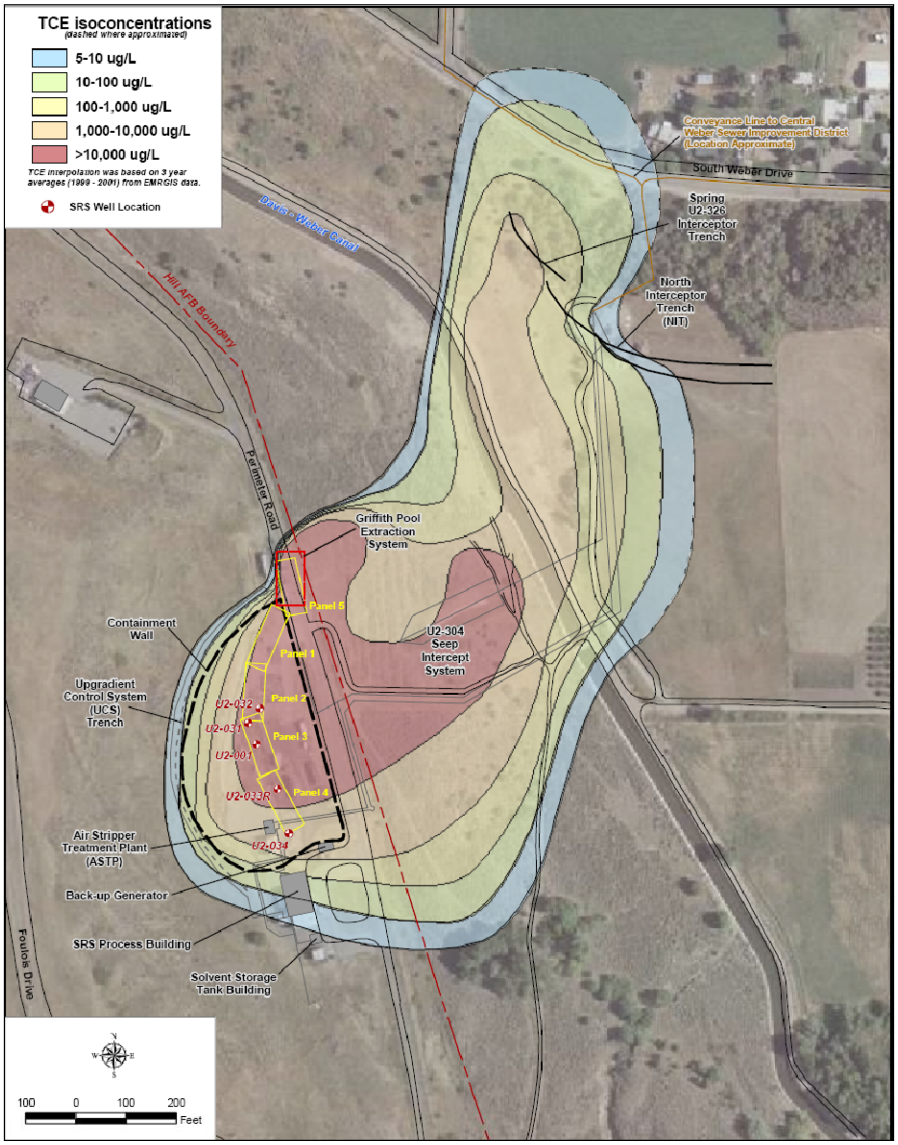

FIGURE 8: SITE MAP OF OU2 AT HILL AFB OGDEN, UT (URS AND INTERRA, 2005)

3.3.2 Site Geology/Hydrogeology

Three major geological formations dominate the geology of the OU2 site. The source area is located in the shallow region of the Provo Formation. Contaminant migrated vertically through this formation so the Alpine and Weber Formations are the main regions considered for plume simulations. The Provo Formation is composed of unconsolidated silts, sands, and gravels. This formation is located at the topographic high of the contaminated site. The underlying clay aquifer has a complicated topography with a paleochannel eroded into the surface of the clay aquitard. The Alpine Formation and Weber River Floodplain are located North/Northwest of the source area and have been contaminated through transport. Understanding the location and features of the separate formations is needed for simulating groundwater flow and contaminant transport at this site (URS and Interra, 2005).

3.3.3 Contaminant Distribution

Over the next 30 years the high density, low viscosity, and low solubility DNAPL has formed pools in low-lying areas of the underlying clay aquitard and has migrated north/northeast in the direction of ground water flow. Due to the geology of the site, the source contaminant has settled into approximately five separate relative topographic low points present in the clay paleochannel underlying the dumping site (**Figure 9**). A TCE plume derived from the source zone extends nearly 1,500 ft (URS and Intera, 2003).

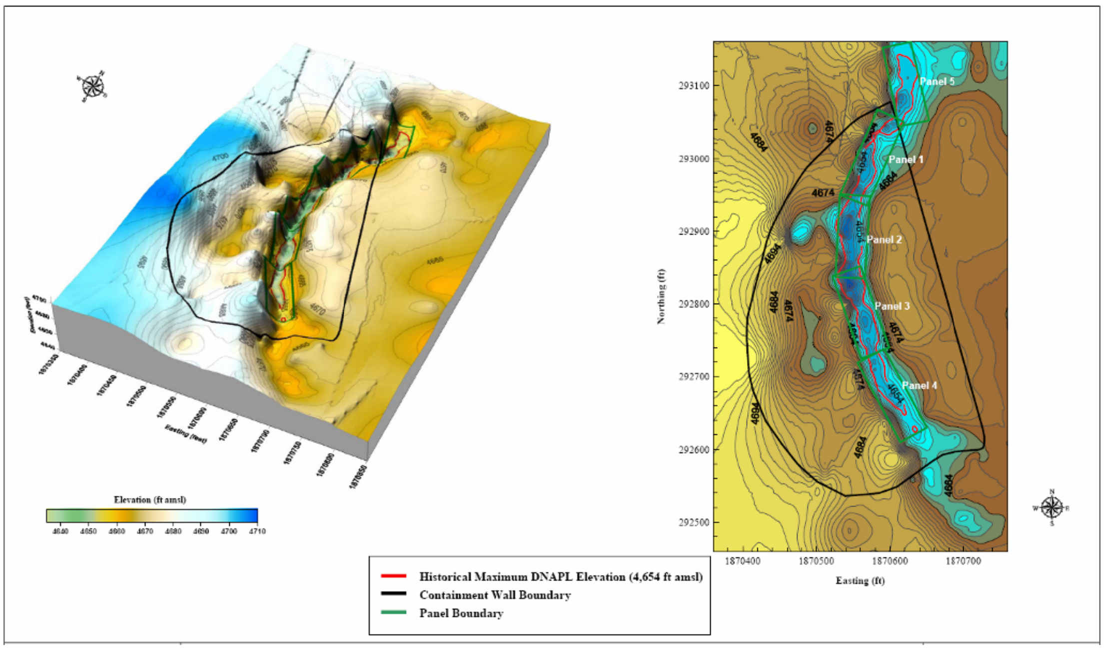

FIGURE 9: OU2 SOURCE AREA (URS AND INTERA, 2003)

3.3.4 Remedial Activity Summary

Several remedial actions focusing on the removal of DNAPL and prevention of plume expansion have taken place since this site was added to the NPL. Most resources have been expended in source recovery and remediation in the source zone. Remediation began in 1993 with the implementation of the source recovery system, which includes a groundwater recovery well field and process treatment facility. In 1996, a slurry containment wall reaching to the underlying clay aquitard was constructed to 1) encompass most of the source area and minimize the volume of clean groundwater entering the source zone and 2) provide a barrier to the movement of contaminants from the source zone to the non-source area. After the construction of the containment wall an additional DNAPL pool was discovered outside the wall; this part of the source zone located outside of the containment wall was labeled as panel 5. In 1997, the Griffith Pool DNAPL extraction system, a system of 17 extraction wells installed in and around panel 5, was installed. From 1992 to 2002 several individual experimental DNAPL recovery operations and innovative remediation techniques were implemented in the source area and have resulted in a total DNAPL recovery of approximately 43,823 gallons, or approximately 90% of the estimated initial source volume (URS and Intera, 2003).

Measures have been taken to prevent plume expansion in the non-source area as well. Interceptor trenches were constructed to collect contaminated groundwater flowing through the aquifer and pump this water to a treatment facility. The North Interceptor trench, which was constructed near the leading edge of the contaminated groundwater plume, was intended to intercept the groundwater with TCE concentrations greater than 5μg/L before it spread contamination further down-gradient. The Spring U2-326 Interceptor Trench was built two years after the construction of the North Interceptor Trench to extend the region of groundwater interception northwestwardly. The Spring U2-304 Seep Interceptor Trench was installed to collect groundwater from the center of the plume, but this trench has remained dry for most of its operational life. A total of 3 trenches have been constructed but are fairly shallow in relationship to the depth of the aquifer and their impact of groundwater flow and contaminant interception is questionable (URS and Intera, 2003).

3.4 NAS North Island, IR Site 5

The following chapter provides a general overview of Naval Air Station North Island (NASNI), Installation Restoration (IR) Site 5. As previously mentioned, no new analysis is completed in this chapter, rather; it is a contextual summary for the data analysis in Chapter 4. The primary source for Chapter 3.4 is the Evaluation Monitored Natural Attenuation, Installation Restoration Site 5, Unit 2 (Wiedemeier and Associates, 2006).

3.4.1 Site Location and History

Naval Air Station North Island is located in San Diego County, California, southwest of the City of San Diego. Situated on the Silver Strand Peninsula, the air station is surrounded by the Pacific Ocean on the south and San Diego Bay on the west and north. The approximate size of the installation is 2,520 acres.

IR Site 5 is located in the southeastern corner of NASNI in San Diego County, California. Site 5 is subdivided into Units 1 and 2 to differentiate the former municipal landfill and a former liquid waste disposal area, respectively. **Figure 10** shows the location, topography, and geographical features of IR Site 5 and the boundaries of Units 1 and 2.

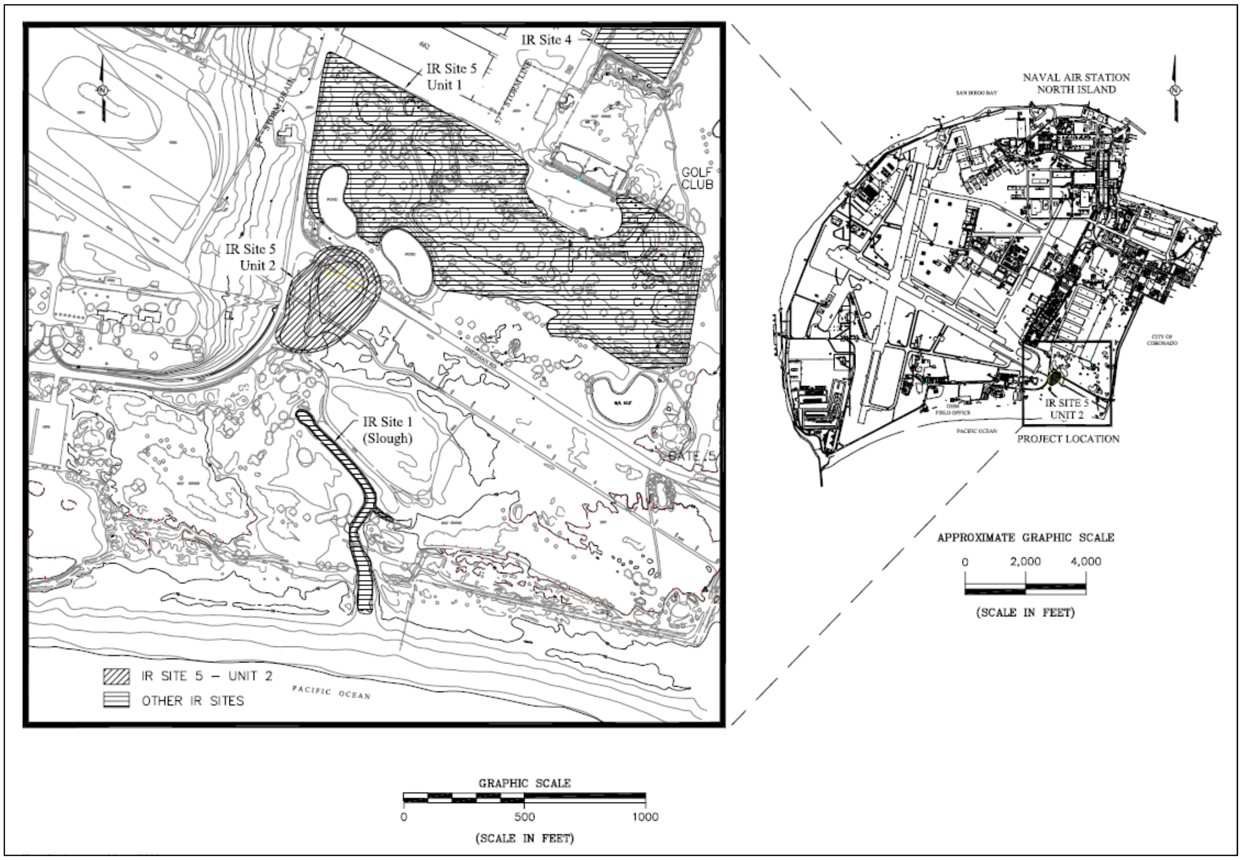

FIGURE 10: NAS NORTH ISLAND, INSTALLATION MAP (WIEDEMEIR AND ASSOCIATES, 2006)

Unit 2 of IR Site 5 is the focus of the data presented in this report. Unit 2 is located about 1,800 feet from the western limit of the city of Coronado (**Figures 10 and 11**). The site is generally flat, covered mostly with sand, extends over approximately 3.4 acres, and is located predominately within the approach for NASNI runway 29 (Wiedemeier and Associates, 2006). According to the Removal Action Closeout Report, the nearest natural (non-intrusive) pathway to potential environmental and human receptors is a stormwater drainage slough (IR Site 1 – Outfall 16) that is located approximately 550 feet south of the identified Unit 2 source area. This slough receives stormwater drainage and conveys it southward to the Pacific Ocean (Walton, 1988).

From 1912 to 1935, the Army and Navy conducted flight training exercises at NASNI. The Air Station has been occupied exclusively by the Navy since 1935. Although most of the industrial operations began at NASNI in the 1920s, the generation of significant quantities of waste did not begin until the 1940s, during World War II. Between 1943 and 1945, the area of Site 5 was constructed on fill materials placed in a former bay, known as the Spanish Bight. Waste disposal activities commenced immediately after the construction of the Site 5 area, which served as a solid-waste disposal facility. The site functioned as the oily solid-waste disposal facility after the closure of the Old Spanish Bight Landfill (Site 2) in the early 1940s. Site 5 is subdivided into Units 1 and 2 to differentiate the former municipal landfill and a former liquid waste disposal area, respectively (Wiedemeier and Associates, 2006).

The site area was operated as a cut-and-cover sanitary landfill until approximately 1965. The Initial Assessment Study estimated that 1,000 to 2,000 tons of hazardous wastes were disposed of at the landfill (Brown and Caldwell, 1983).The Remedial Investigation Report states that an aerial photograph from 1948 indicated that landfill activity extended approximately 100 to 200 feet west of Rogers Road along "J" Road East. The photograph showed two rectangular hazardous waste disposal pits east of Rogers Road that are believed to be the source of the groundwater contamination (Bechtel National Inc., 1996). Waste disposal activities ceased between 1965 and 1968, and the site was operated as a transfer station to dispose of Navy wastes off-base. The operation of the transfer station was terminated in 1983. The site was redeveloped as a golf course between 1984 and remains a golf course today (Wiedemeier and Associates, 2006).

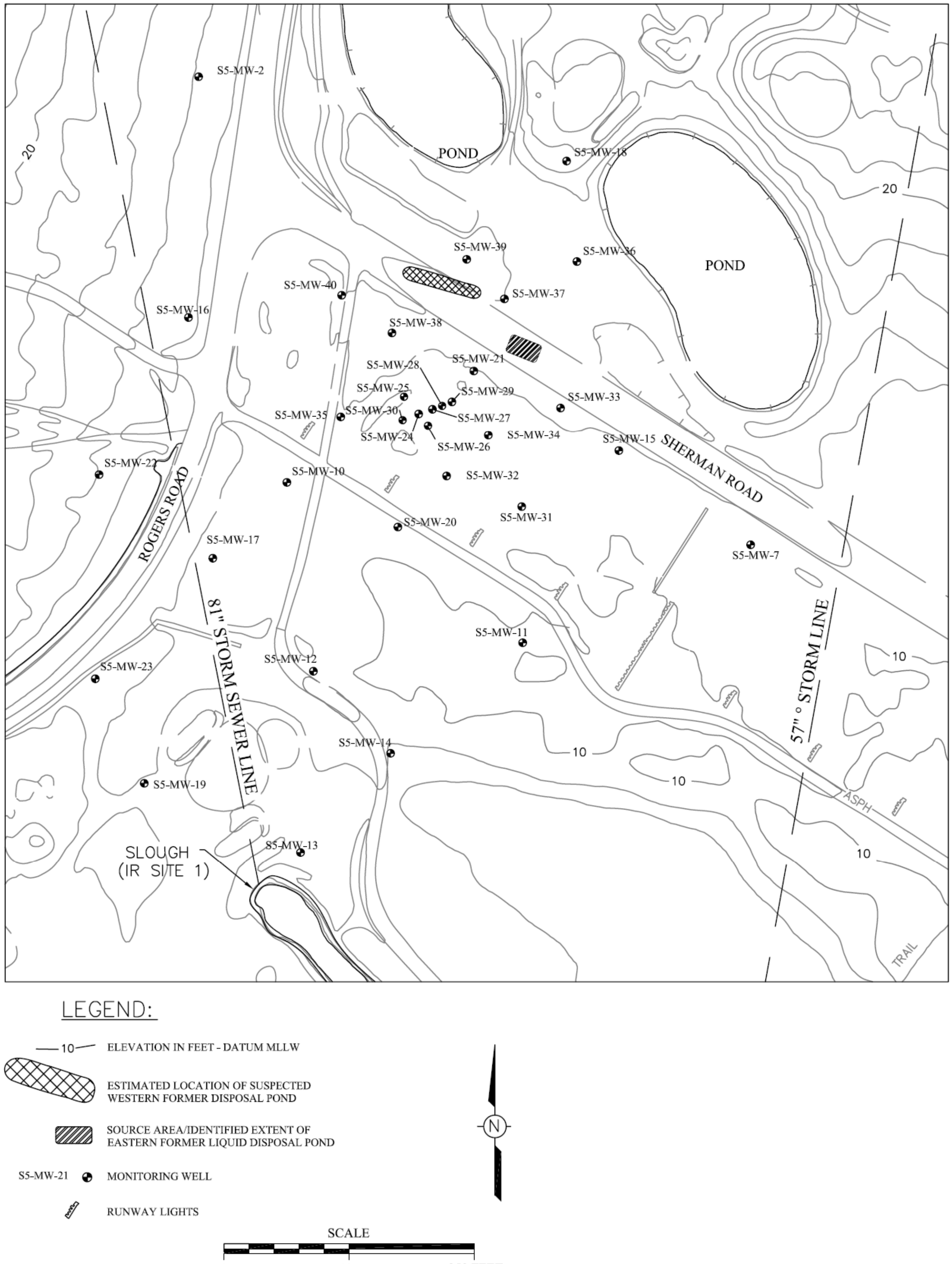

FIGURE 11: NAS NORTH ISLAND, IR SITE 5, OU2 (WIEDEMEIR AND ASSOCIATES, 2006)

3.4.2 Site Geology/Hydrogeology

The following chapter describes the geology and groundwater characteristics of NASNI as determined from historical data. Data mentioned in this chapter is taken from *Evaluation of Monitored Natural Attenuation*, by Wiedemeier and Associates (2006). Sources used in the Wiedemeier summary include: RI/FS Reports by Bechetel National Inc. (1996 and 1998), Water Quality Control Plan for the San Diego Basin by Barker et al. (1994), Site Investigation by Jacobs Engineering Group (1993), Evaluation of Monitored Natural Attenuation by Parsons (1999), Geology of the San Diego Metropolitan Area by Kenney (1975), Physical and Chemical Hydrogeology by Domenico et al. (1990), and Practical Aspects of Groundwater Modeling by Walton (1988).

Surface deposits at NASNI consist of Holocene beach sand deposits, hydraulic fill, and the Pleistocene Bay Point Formation (Kennedy, 1975). The hydraulic fill consists of very fine- to medium-grained, poorly graded, silty sands. The fill was placed above a 3- to 5-foot-thick layer of bay floor mud, consisting of organic silts and clays. These sediments are referred to as the Spanish Bight sediments. The Bay Point Formation consists of thick layers of sand, silt, and clay. Several north/south-trending faults have been observed in the vicinity of NASNI and the City of Coronado. The closest fault, identified in the 1996 RI/RFI is the north/south-trending Spanish Bight Fault that passes approximately 2,000 feet east of the site (Bechtel National Inc., 1996).

Groundwater under NASNI is part of the Coronado Hydrologic Area of the Otay Hydrologic Unit (Barker, Schwall, & Pardy, 1994). Groundwater beneath NASNI occurs in an unconfined aquifer at depths between 4 and 25 feet bgs. The base of the unconfined aquifer ranges from 85 to 120 feet bgs (Jacobs Engineering Group, 1995). Irrigation of the golf course creates a large groundwater recharge zone and produces a radial flow of groundwater from the golf course to the shorelines of San Diego Bay and the Pacific Ocean (Parsons, 1999).

Four major stratigraphic layers have been observed at the NASNI Site 5 Unit 2; hydraulic fill, beach sand, Spanish Bight sediments, and Bay Point Formation sediments. Hydraulic fill material, placed above the Spanish Bight sediment layer during 1944 to fill a former embayment, comprises the top 5 to 10 feet of soils at the site. The hydraulic fill consists primarily of fine silty sand, as observed from soil samples collected during drilling activities. Beach sand detected south of S5-MW-20 extends toward the stormwater discharge slough. Beach sands are believed to extend from the southern portion of the site to the Pacific Ocean. The hydraulic fill materials and beach sand in the upper 10 to 15 feet of soil at the site are underlain by a zone of low- permeability silt and clay comprising the Spanish Bight sediments (Bechtel National Inc., 1996). The Spanish Bight sediments are approximately 3 to 5 feet thick and act as a low permeability layer between the overlying hydraulic fill and beach sands and the underlying Bay Point Formation. The Bay Point Formation is composed of silt, sand, and clay extending more than 40 feet below the bottom of the Spanish Bight sediment layer. **Figure 12** shows the potentiometric surface in October 2005. Based on several potentiometric delineations, the groundwater flows generally to the southwest.

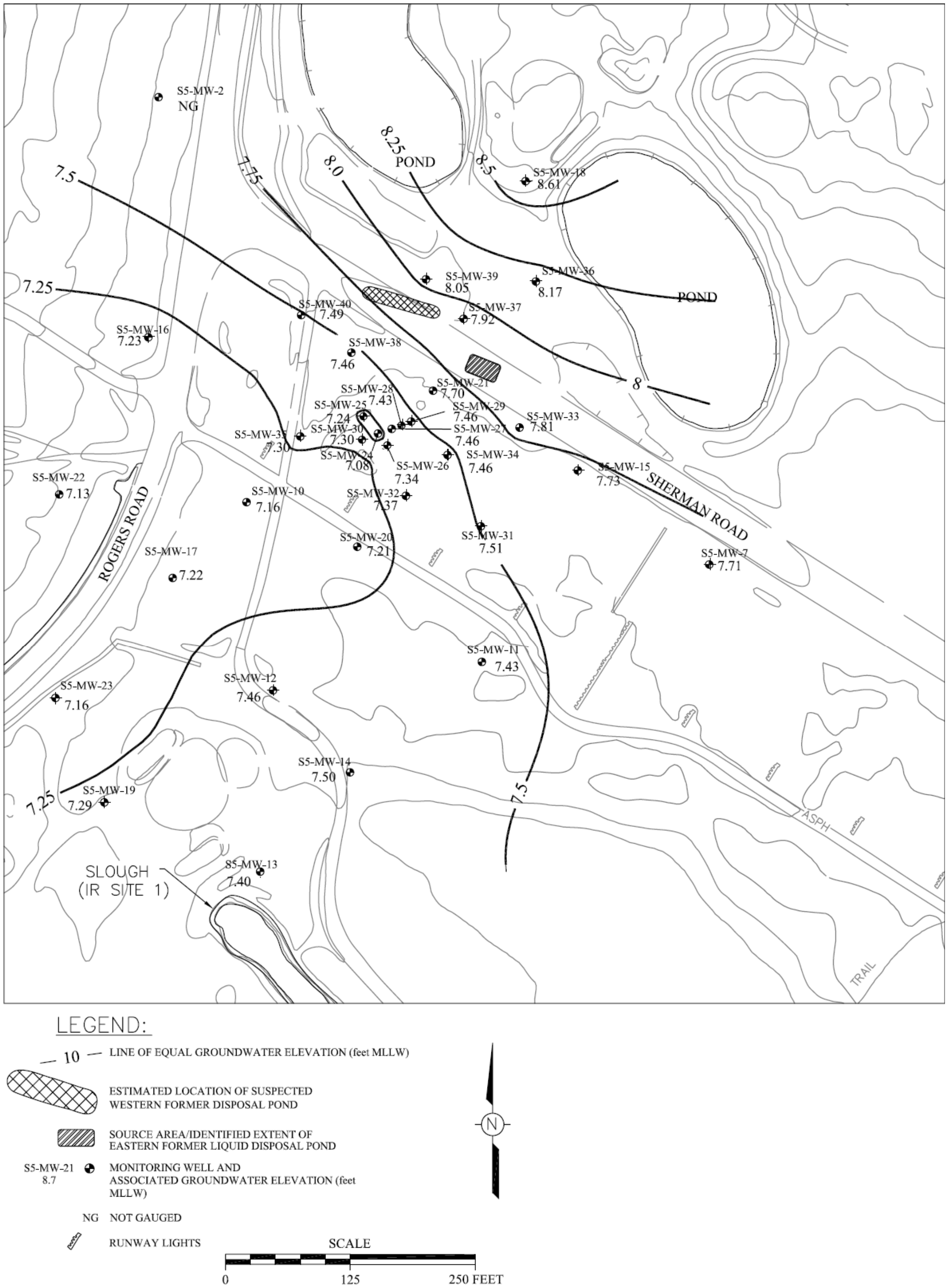

FIGURE 12: POTENTIOMETRIC SURFACE AT NASNI, IR SITE 5, UNIT 2 (WIEDEMEIR AND ASSOCIATES, 2006)

Hydraulic gradients calculated between 2003-2005 range from 0.0052 foot per foot (ft/ft) for to 0.0026 ft/ft with an average gradient of 0.004 ft/ft. The highest hydraulic conductivity value measured within the hydraulic fill material at well S5-MW-20 was 49 feet per day (ft/day), and the highest value measured within the beach sand material in the southern vicinity of the site (S5-MW-13) was 89 ft/day. The geometric mean of hydraulic conductivity values estimated for S5-MW-20 and S5-MW-13 were 37 ft/day and 49 ft/day, respectively (Wiedemeier and Associates, 2006).

Due to the difficulty involved in accurately determining effective porosity, accepted literature values for the type of soil comprising the shallow saturated zone were used. Wiedemeier and Associates (2006) referenced the published estimates by Walton (1988) and Domenico et al. (1990), which give a range of effective porosity for fine to coarse sand of 10 to 35 percent. The aquifer matrix, as determined from this and previous investigations, consists of very fine, silty sand to coarse sand. As a representative value, Wiedemeier and Associates assumed an effective porosity of 25 percent for the site. Using this relationship in conjunction with site-specific average hydraulic conductivity (37 ft/day) and average hydraulic gradient (0.004 ft/ft), and an assumed effective porosity of 25 percent, the average groundwater seepage velocity for the site is calculated as 0.59 ft/day, or approximately 216 feet per year (ft/yr) (Wiedemeier and Associates, 2006).

3.4.3 Contaminant Distribution

This chapter describes the magnitude and extent of contamination at NASNI, although the nature and extent of contamination presented herein is limited to chlorinated ethenes. Other contaminants found at the site include petroleum hydrocarbons such as BTEX, TMB, naphthalene, as well as other constituents.

As previously mentioned, an estimated 1,000 to 2,000 tons (0.5 percent of the total quantity of the landfill debris) of hazardous waste was disposed of at the landfill. These wastes were not separated or segregated from nonhazardous refuse. The exact nature and quantity of the liquid wastes that were disposed of in the pits are unknown. Chlorinated ethenes are the most prevalent contaminant found in the groundwater at the site.

Data used in this report was collected between 1997 and 2005. **Figures 13 and 14** are isopleth maps representing the distribution of the sum of chlorinated ethenes in groundwater for the first and last sampling periods. The highest chlorinated ethene concentrations have historically been detected in samples collected from monitoring wells S5-MW-20, S5-MW-21, and S5-MW-26. In addition, monitoring wells S5-MW-25, S5-MW-28, and S5-MW-30 also have exhibited elevated (i.e., greater that 10,000 µg/L) concentrations of chlorinated ethenes. Concentrations observed in S5-MW-20 have decreased significantly over the period of observation. These observations show that the mass of chlorinated ethenes in groundwater has decreased significantly since 1997.

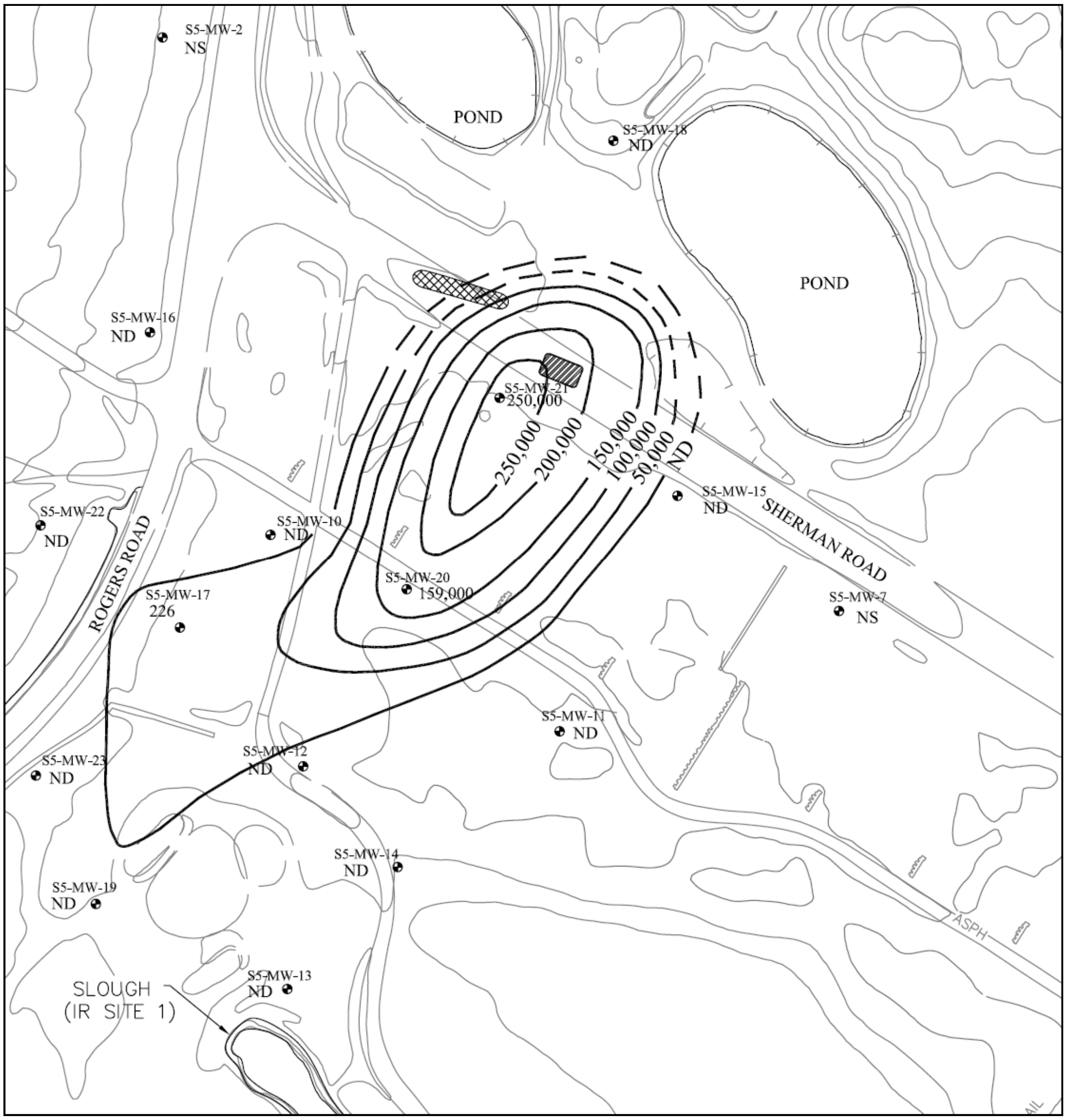

FIGURE 13: ISOPLETH MAP FOR CHLORINATED ETHENES AT NASNI, OCTOBER 1997 (WIEDEMEIER AND ASSOCIATES, 2006)

FIGURE 14: ISOPLETH MAP FOR CHLORINATED ETHENES AT NASNI, OCTOBER 2005 (WIEDEMEIER AND ASSOCIATES, 2006)

3.4.4 Remedial Activity Summary

Numerous investigations beginning in 1983 have been conducted to trace the history of waste disposal activities at the site and to delineate areas of soil and groundwater contamination. In addition, actions have been taken to remove the source of the groundwater contamination.

A natural attenuation evaluation was performed by Parsons in 1997-1998, where evidence was shown that the VOC plume was stable or receding as a result of natural attenuation. Remedial actions were conducted at the source areas between 2000 and 2003 by Shaw Environmental. Remedial activities included excavation and in-situ chemical oxidation (Wiedemeier and Associates, 2006). For more details regarding the remedial activities see the Removal Action Closeout Report (Shaw Environmental, Inc., 2003).

3.5 Naval Base Kitsap, OU 1

The following chapter provides a general overview of Operable Unit 1 (OU 1) at Naval Base Kitsap (NBK), Keyport, Washington. As previously mentioned, no new analysis is completed in this chapter, rather; it is a contextual summary for the data analysis in Chapter 4. The primary sources for Chapter 3.5 are *Selected Natural attenuation monitoring data, OU 1, June 2006*, by Dinicola and Huffman (2007) and 2007 Annual Report OU1, Naval Base Kitsap (NAVFAC, 2008).

3.5.1 Site Location and History

NBK at Keyport occupies 340 acres (including tidelands) adjacent to the town of Keyport in Kitsap County, Washington, on a small peninsula in the central portion of Puget Sound. The peninsula is bordered by Liberty Bay to the east and north and Port Orchard Inlet to the southeast (**Figure 15**). The topography of the base rises gently from the shoreline to an average elevation of 25 to 30 feet above mean sea level (msl).

It then rises steeply at the southeast corner of the site to approximately 130 feet above msl. Marine or brackish surface water bodies on and near the base include Liberty Bay, Dogfish Bay, the tide flats, a marsh, and a shallow lagoon. Fresh water bodies include two creeks that drain into the marsh and two creeks that discharge into the lagoon.

The OU 1 portion of NBK at Keyport consists of the former base landfill, approximately 9 acres in size, and the surrounding potentially contaminated environment (Figure 15). The landfill area was formerly marshland; a portion of the marsh remains on the western and southern sides of the landfill. The landfill, which is unlined at the bottom and covered with areas of grass, trees and asphalt, was the primary disposal area for both domestic and industrial wastes generated by the base from the 1930s until 1973. A burn pile for trash and demolition debris was located at the northern portion of the landfill from the 1930s to the 1960s. Unburned or partially burned materials from this burn pile were buried in the landfill or pushed into the marsh. A trash incinerator was operated at the north end of the landfill from the 1930s to the 1960s, and incinerator ash was disposed of in the landfill (NAVFAC, 2008).

Preliminary environmental site investigations and assessments conducted between 1984 and 1988 concluded that Area 1 was suspected to have contamination with the potential for impacting the environment of the site and surrounding areas. A remedial investigation (RI) and feasibility study (FS) was conducted at Area 1 between 1988 and 1993 followed by human health and ecological risk assessments (URS and SAIC, 1993). Public comments were not favorable to the proposed remedial actions and resulted in Area 1 being separated as "OU 1." Further site investigations of OU 1 took place to supplement the RI with additional data, including, five quarterly sampling events from 1995 through September of 1996 (NAVFAC, 2008).

A supplemental feasibility study was then conducted to evaluate additional remedial options, from which the current remedial alternative was selected. The OU 1 ROD was completed in September 1998 (Dinicola & Huffman, 2007).

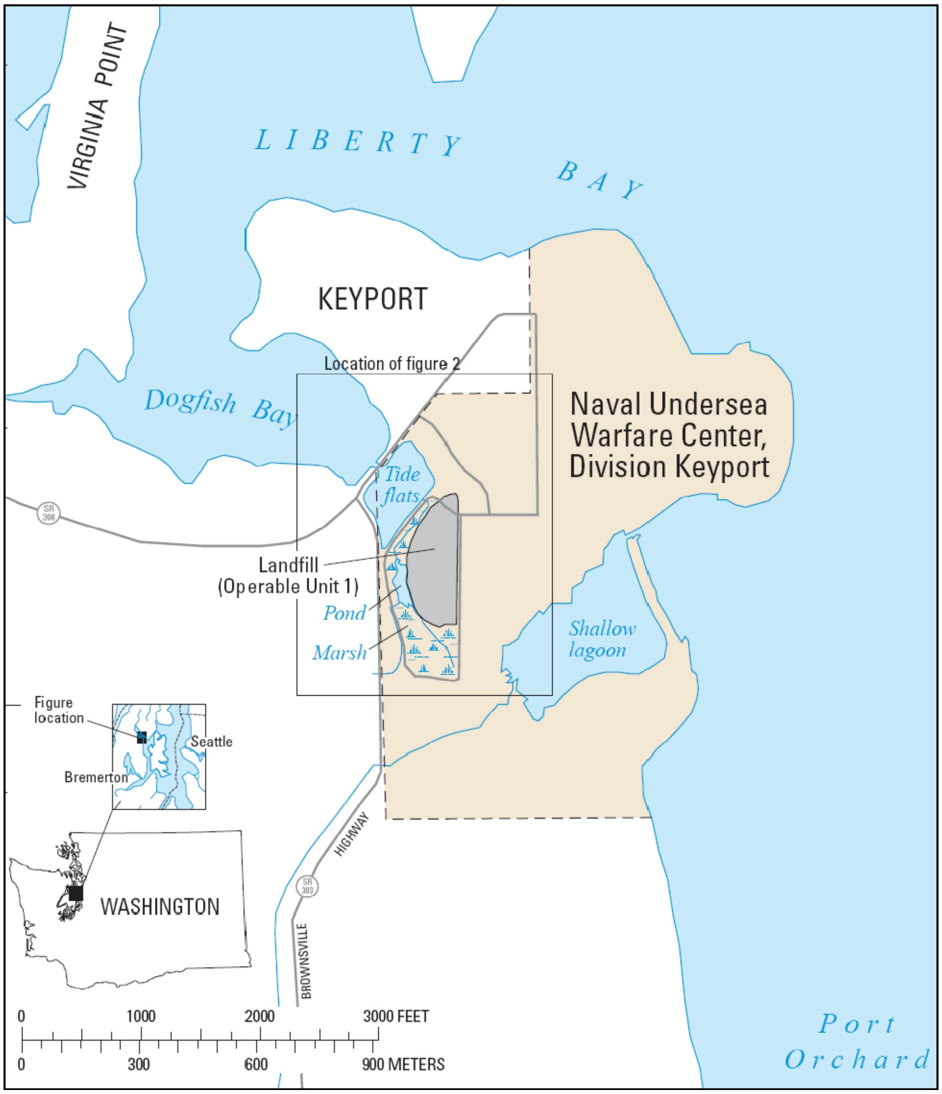

FIGURE 15: LOCATION OF OU-1, NBK, KEYPORT (USGS, 2006)

3.5.2 Site Geology/Hydrogeology

Ground water beneath OU 1 occurs within a series of aquifers that are composed of permeable sand, gravel, or fill materials separated by finer grained silt or clay layers. Contamination at OU 1 is known to occur only in about the top 60 ft of the unconsolidated deposits in the four hydrogeologic units referred to as the unsaturated zone, the upper aquifer, the middle aquitard, and the intermediate aquifer. Ground water in the unconfined upper aquifer generally flows from the east to the west toward Dogfish

Bay. Ground water in the predominately confined intermediate aquifer flows toward the landfill from the south and from the west, and then flows northwest beneath the landfill toward Dogfish Bay. Two perennial freshwater creeks drain the marsh adjacent to the landfill and discharge into the tidal flats of Dogfish Bay (Dinicola & Huffman, 2007).

3.5.3 Contaminant Distribution

The 1998 ROD lists two general classes of constituents of concern (COC) for the three potential exposure pathways at OU 1, with the source being the 9-acre former landfill: chlorinated volatile organic compounds (VOCs) and polychlorinated biphenyls (PCBs). VOCs were identified as COCs as a result of drinking water and seafood ingestion pathways, and PCBs were identified as COCs because of their potential to bio-accumulate and possibly impact the seafood ingestion pathway. VOCs are present in the groundwater of the upper and intermediate aquifers beneath the former landfill, with contaminant concentrations in the shallow aquifer exceeding those in the intermediate aquifer by an order of magnitude or more. Dense non-aqueous phase liquid (DNAPL) was not found in upper and intermediate aquifers. Groundwater from the southern portion of the landfill has historically contained the greatest concentrations of VOCs, and some VOCs have been detected in adjacent surface water in the marsh down-gradient of the landfill. The detections of VOCs in marsh water appear to be the result of ongoing groundwater discharge from the upper aquifer into the marsh. Data also suggest that VOC contaminants in the intermediate aquifer may eventually be discharged to surface water in the tide flats of Dogfish Bay.

PCBs were detected in upper aquifer groundwater, seeps, aquatic sediment, and clam tissue samples. PCBs were not detected in the intermediate aquifer groundwater. Because seep water with PCBs discharges directly into the marsh, it appears that much (if not all) of the PCBs currently migrating from the landfill into the marsh are emanating from the seep, and not from the groundwater where polychlorinated biphenyl (PCB) concentrations are low (NAVFAC, 2008).

3.5.4 Remedial Activity Summary

The 1998 ROD specified the following remedial actions at OU 1:

- Phytoremediation in landfill VOC “hot spots” – using poplar trees
- Removal of PCB-contaminated sediments from the seep area, (area containing the highest detected PCB concentrations) occurred in 1999
- Upgrade the tide gate to protect landfill from flooding and erosion during extreme tide events
- Upgrade and maintain the landfill cover
- LTM including phytoremediation monitoring, intrinsic bioremediation monitoring, and compliance monitoring
- Conduct contingent actions for off-site domestic wells, if necessary

- Implement institutional controls (NAVFAC, 2008)

The LTM program at OU 1 was started in 1999 with the sampling of groundwater from two deep water supply wells and groundwater sampling at and adjacent to the two phytoremediation plantations. During the first 4 years following phytoremediation implementation, the OU 1 LTM program consisted of three concurrent programs performed by the Navy and the U.S. Geological Survey (USGS). The Navy conducted the phytoremediation monitoring and the risk and compliance monitoring, and the USGS performed intrinsic bioremediation monitoring. Starting in 2003, risk and compliance monitoring and phytoremediation monitoring were consolidated into a single program. The USGS continues to perform the intrinsic bioremediation monitoring annually, with the most recent available report addressing results through 2006 (NAVFAC, 2008).

4. RESULTS OF NAC AND STATISTICAL ANALYSIS

Chapter 4 contains the site data analysis and statistical evaluation of NAC trends with respect to time. For each of the five sites the original data is discussed in the context of site specific considerations which affected the usability of the data and interpretation of statistical results. After the exact data intervals are determined, several statistical methods are implored, including; a linear regression analysis and the use of prediction intervals for the next measurement analysis. At all five sites the constituents TCE, cis-DCE, VC and in some cases PCE are individually measured, however; the statistical analysis pertains to total chlorinated ethenes only. Total chlorinated ethenes are being defined as the sum concentration of the individually measured constituents listed above. The term 'sampling event' in context refers to a period of one to as many as twenty-one consecutive days where wells along the plume center line were sampled and those samples were analyzed for chlorinated ethene constituent concentrations.

4.1 Statistical Analysis of NAS Pensacola, WWTP

The plume originating at the former WWTP site at NAS Pensacola is approximately 450 ft long containing the parent constituent of TCE as well as reduced forms of chlorinated ethenes (cis-DCE and VC). The plume has been observed in semi-regular intervals by various agencies (see Chapter 3.1 for site history) between March 1997 to September 2008, according to available data sources. The source area of the plume is monitored by well USGS 5 (Chapelle, 2008). **Table 2** contains the well IDs, distance the well is from the source well, and the earliest date of data available for the analysis. **Figure 16** shows a topographic plan view as well as an aerial photograph of the plume, including the well locations.

TABLE 2: WELL DESCRIPTIONS, OU-10, NAS PENSACOLA

Well ID	Distance from source along plume line (ft)	First Available Sampling Event
USGS5	0	September 8, 1998
IMW-66	30	March 24, 1997
USGS6	73	September 8, 1998
USGS1	140	March 24, 1997
USGS2	225	March 24, 1997
33G12	330	March 24, 1997

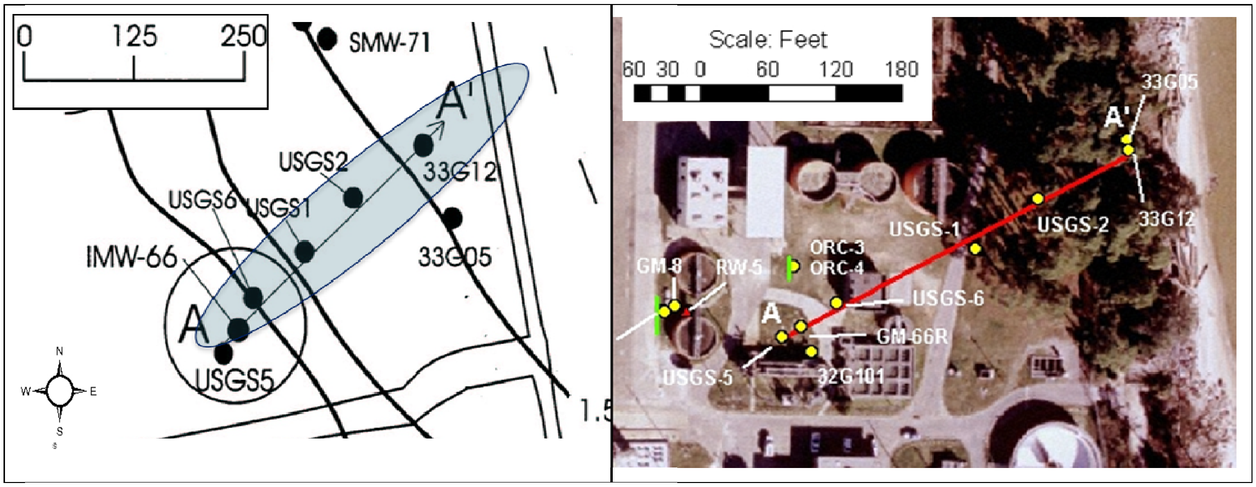

FIGURE 16: PLAN VIEW OF FORMER INDUSTRIAL WWTP, NAS PENSACOLA (CHAPELLE, 2008)

Twenty-seven sampling events occurred between March 1997 and September 2008. Not all six wells along the plume line were sampled during each of the twenty-seven sampling events. Twenty-one of the twenty-seven sampling events included five or more wells and nineteen of the sampling events included all six of the plume centerline wells. The sampling data is presented in **Appendix A**.

Figure 17 is a graphical representation of total chlorinated ethene concentrations at the source well, USGS-5. The data trend presented does not suggest that the plume is stable for the entire period shown (1997-2008). This observation is based on the variable fluctuations in concentrations from 1997 to 2008.

Previously stated in Chapter 3.1, site conditions have been favorable for natural attenuation processes to reduce chlorinated ethene-contaminated ground water at the site. More specifically, a USGS report showed that chlorinated ethenes were being rapidly transformed to non-toxic byproducts (carbon dioxide, chloride, and ethane) prior to discharging into Pensacola Bay (USGS, 1999). Remediation at the site began in 1998 with excavating and a pump and treat system. Following that an in-situ program was initiated for chemical oxidation using Fenton's Reagent. Prior to this remedial activity the plume was relatively stable, having been undisturbed for more than 20 years. The remedial action caused a decrease in the source well concentrations, which was then followed by a rebound in 2001. Remedial activity restarted in July 2008 with a biostimulation/bioaugmentation (bioaug) demonstration project which was implemented in the source area (USGS, 2008).

These factors have been considered in the process of determining the most appropriate data to use for the analysis. In particular, it has been determined that data from 2003 to 2008 reflect stable plume conditions where natural attenuation is taking place and rapid changes in constituent concentration caused by remedial activity are not seen (see Figure 17).

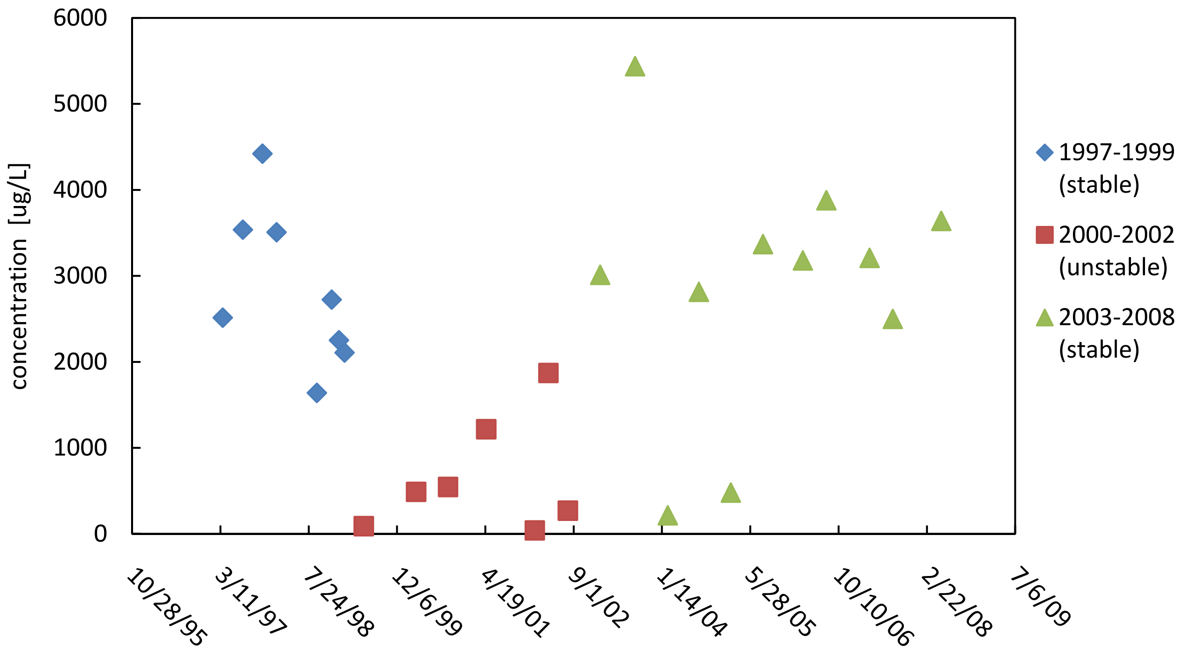

FIGURE 17: TOTAL CHLORINATED ETHENE CONCENTRATIONS AT THE SOURCE, WELL USGS-5, OU-10, NAS PENSACOLA

Figure 18 suggests that plume stability is regained and an absence of influences from remedial actions on the sampling data for 2003-2008. Each well along the plume centerline is shown here with the total chlorinated ethene concentration trend with respect to time. No irregularities exist in this time period. Eleven sampling events occurred between Jan 2003 and June 2008. **Table 3** displays the resulting total chlorinated ethene concentrations for the target time period.

TABLE 3: TOTAL CHLORINATED ETHENE CONCENTRATION, JAN 2003 - JUNE 2008, OU-10, NAS PENSACOLA

Sampling Event	Concentration Total Chlorinated Ethene (µg/L)					
	USGS-5	IMW66	USGS-6	USGS-1	USGS-2	33G12
1/29/2003	3013	184	1329	616	26	1
8/15/2003	5440	571	2939	1037	42	9
2/16/2004	215	318	1351	676	28	3
8/10/2004	2815	1081	315	567	61	11
2/7/2005	480	1841	1615	920	54	7
8/8/2005	3370	4434	884	567	61	11
3/22/2006	3180	4890	1147	576	70	11
8/2/2006	3880	4630	1277	635	77	15
4/4/2007	3210	479	986	588	74	8

Sampling Event	Concentration Total Chlorinated Ethene (µg/L)					
	USGS-5	**IMW66**	**USGS-6**	**USGS-1**	**USGS-2**	**33G12**
8/13/2007	2500	5350	978	556	63	42
5/14/2008	3640	950	1548	521	78	-

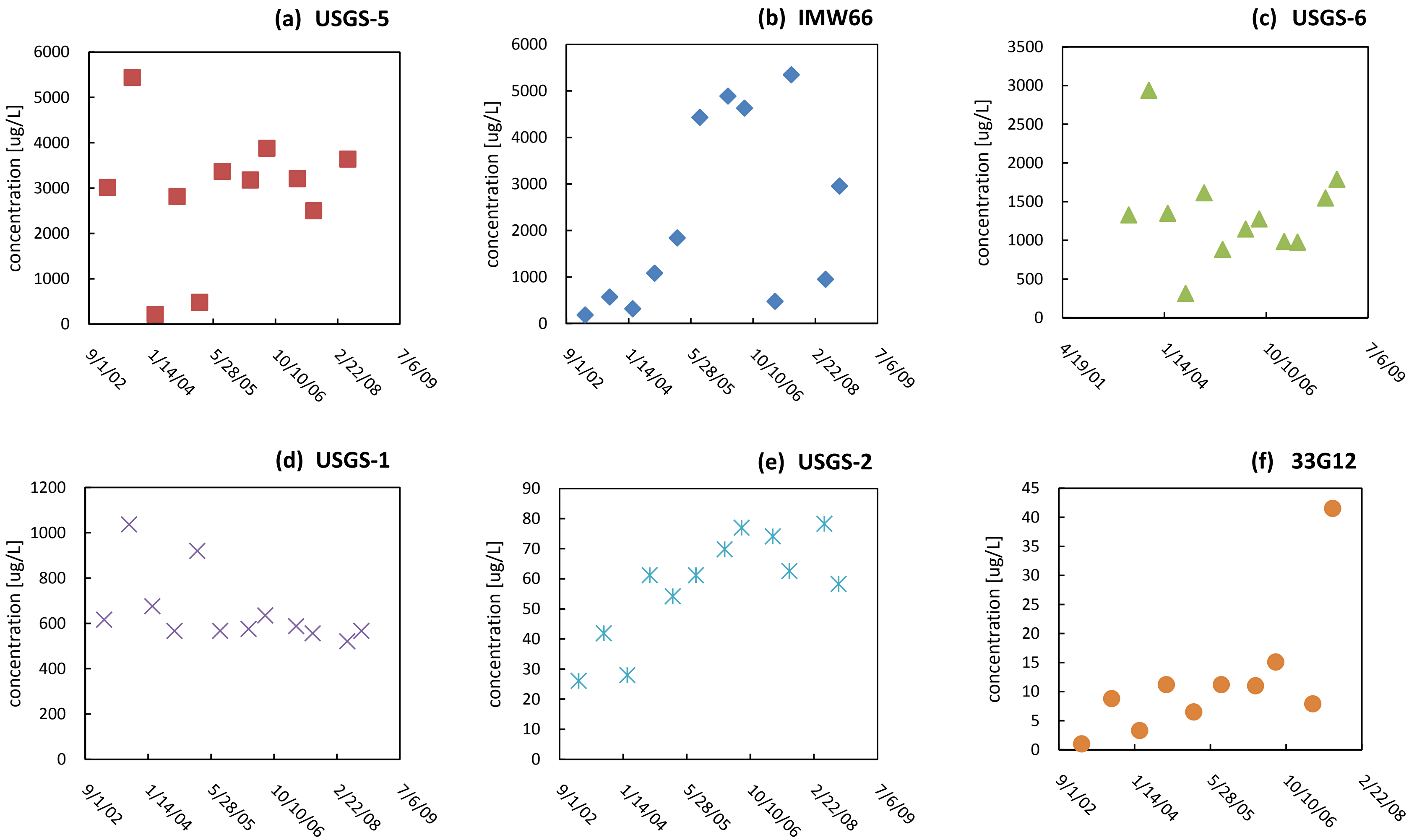

FIGURE 18: TOTAL CHLORINATED ETHENE CONCENTRATIONS IN VARIOUS WELLS ALONG THE PLUME CENTERLINE, OU-10, NAS PENSACOLA

4.1.1 Utilizing NAC as a statistical screening tool

NAC is determined by finding the slope of the solute concentration profile. **Figure 19** is a solute profile from OU10 of the sampling event on May 14, 2008. The independent variable in the figure is distance along the plume centerline, and the NAC value is highlighted as the slope of the trend. This analysis is completed for each sampling event to find the NAC for total chlorinated ethenes and other dominant chlorinate ethene constituents. The slope of the total chlorinated ethene concentration profile in Figure 19 is -0.0149 [µg/L-ft], corresponding to the NAC value of 0.0149 (1/ft).

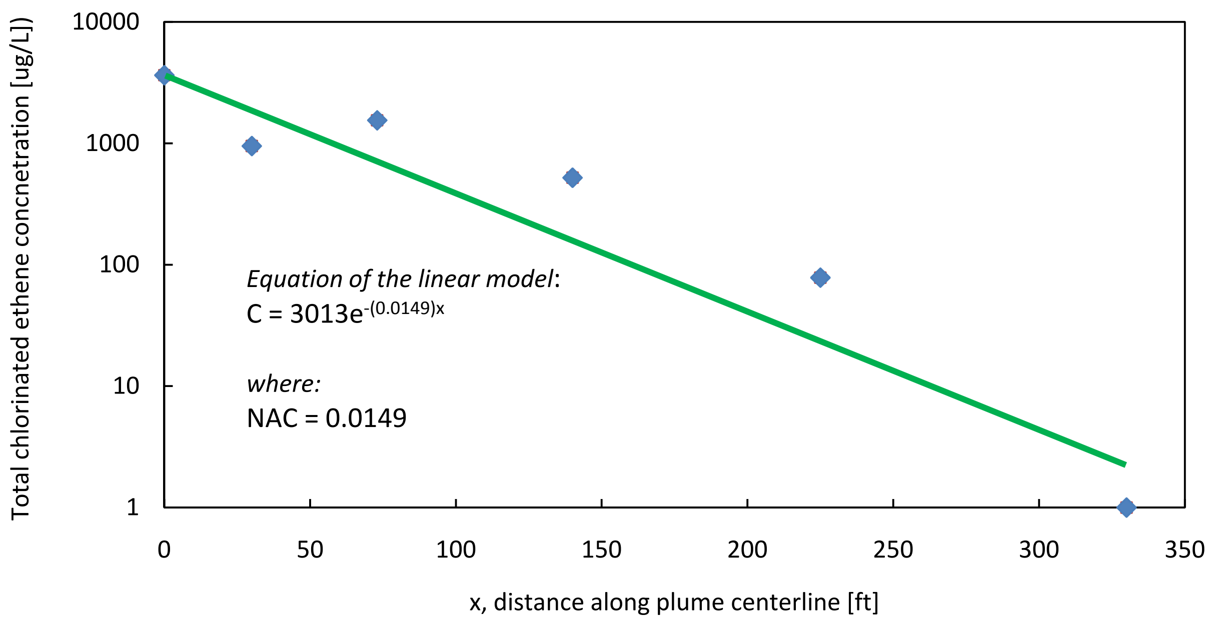

FIGURE 19: SOLUTE CONCENTRATION PROFILE, TOTAL CHLORINATED ETHENE, 5/14/08, OU-10, NAS PENSACOLA

A summary of NAC values for the source compound (TCE) and total chlorinated ethenes at each sampling event are displayed in **Table 4**. The time trends for NAC of both TCE and total chlorinated ethenes are displayed in **Figure 20 and 21**. Figure 20 displays NAC as a function of time for all available data for the site (1998-2008). The variability is notable and is likely caused by various remedial actions at the site. Figure 21 shows NAC as a function of time for the period that has been determined as stable and the source is not transient. For the entire period observed, TCE has remained the dominant chlorinated ethene species in the plume. The close similarity between the NAC values for TCE and the NAC for total chlorinated ethene (Figure 21) demonstrates the significant influence that the most concentrated chlorinated ethene (TCE in this case) has on the total chlorinated ethane concentration. The NAC trend appears to be decreasing, an observation that must be statistically tested.

TABLE 4: NAC VALUES, OU-10, NAS PENSACOLA

Sampling Event	Total Clor. Ethenes	TCE
1/29/2003	0.0212	0.0201
8/15/2003	0.0183	0.0226
2/16/2004	0.0283	0.031
8/10/2004	0.0204	0.0241
2/7/2005	0.0211	0.0217
8/8/2005	0.0192	0.0202
3/22/2006	0.0197	0.0205
8/2/2006	0.0187	0.0196
4/4/2007	0.0158	0.0164
8/13/2007	0.0158	0.0165
5/14/2008	0.0149	0.0191

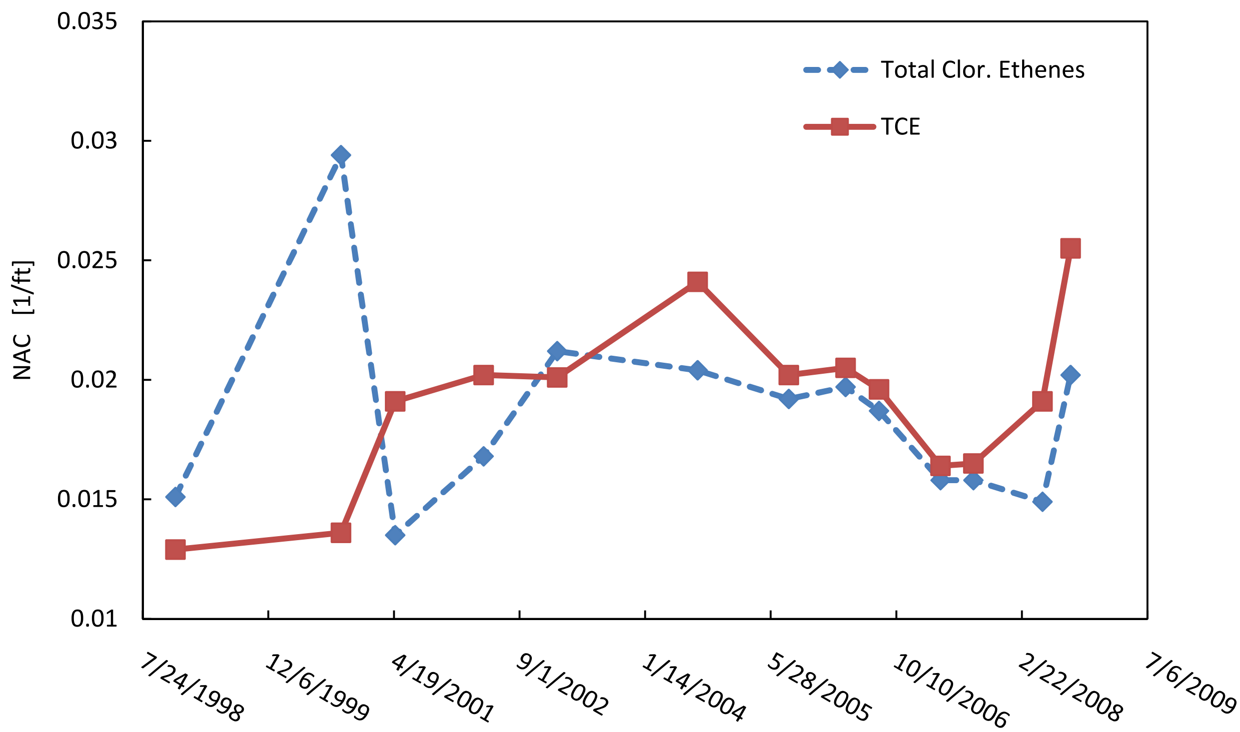

FIGURE 20: NAC AS A FUNCTION OF TIME, ALL DATA (1998-2008), OU-10, NAS PENSACOLA

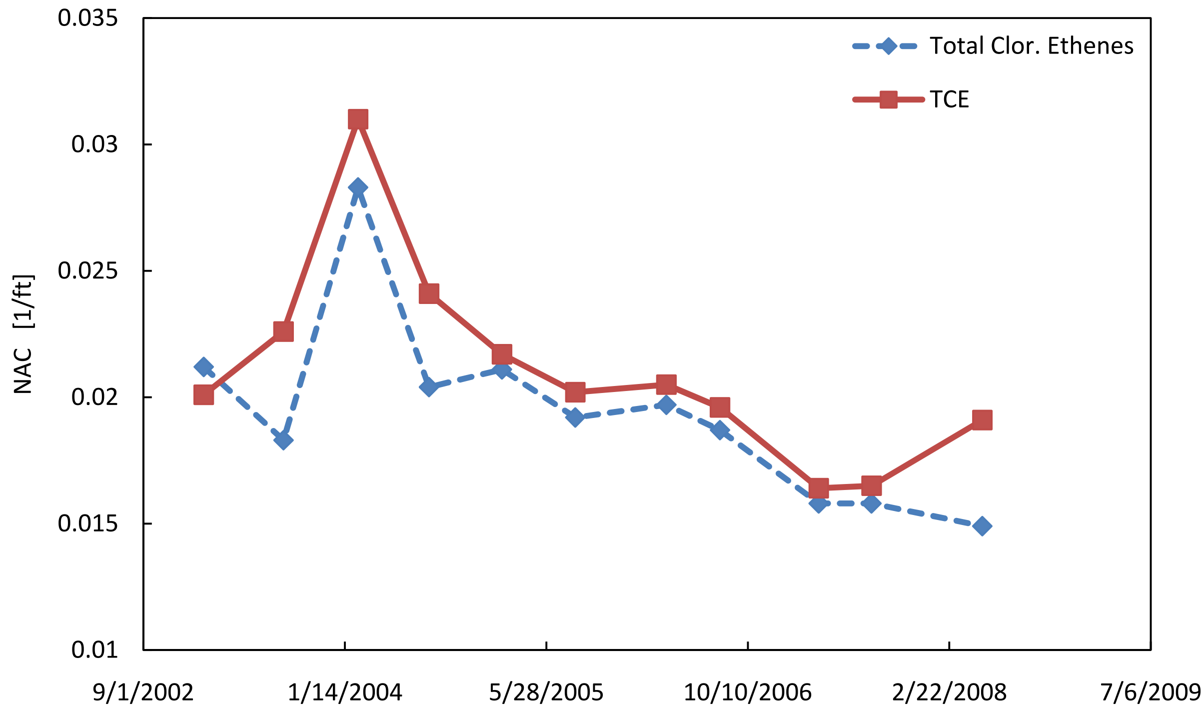

FIGURE 21: NAC AS A FUNCTION OF TIME, 2002-2008, OU-10, NAS PENSACOLA

4.1.1.1 Linear Regression

A linear regression is performed on the time trend series of total chlorinated ethene NAC values. Explanation of the purpose and description of the linear regression has been provided in Chapter 2.3. The hypothesis question is stated, "*Is the slope of the linear regression equal to zero?*" The complete results of the linear regression analysis, which is the statistical tool used to evaluate the hypothesis are contained in **Appendix A**. **Table 5** is a summary of the linear regression results which includes a 90% prediction interval around the predicted model. The mathematic description of the prediction model is shown in **Equation 10**.

TABLE 5: SUMMARY OF SLOPE ESTIMATE FROM LINEAR REGRESSION ANALYSIS OF NAC AS A FUNCTION OF TIME, NAC OF TOTAL CHLORINATED ETHENES, OU-10, NAS PENSACOLA

Parameter	Value
*Slope estimate, (β_1)	-4.040 E-06
Alpha. (α)	0.10
Standard Error (β_1)	1.408 E-06
t Stat (β_1)	-2.87
P-value	0.02
Lower Confidence Interval, 90%	-6.622 E-06

Parameter	Value
Upper Confidence Interval, 90%	-1.458 E-06

**slope of NAC decreasing with respect to time*

$$NAC = -4.04x10^{-6}\left(t^{\text{ii}}\right) + 0.1753$$ **Equation 10**

Using the assumption that the data is representative of a single linear trend, the linear regression analysis fits the most appropriate linear model to the data set. In doing so, a valid prediction of future trends is possible as long as the residual values are reasonably small. It is apparent from **Figure 22** that the largest residuals are found in the first three data points, suggesting that most of the uncertainty about the linearity of the data comes from the first 13 months. A residual plot is provided in **Appendix A**. However, the primary purpose of the linear regression is to test the hypothesis. The estimated slope of the line is [$-4.04x10^{-6}$] negative, indicating a decreasing NAC at the site. The P-value, a more robust test of the slope sign, corroborates this fact since a value of 0.0185 is less than the alpha (0.10) value. The last check is to verify that zero does not fall within the 90% confidence intervals. It does not, therefore, the conclusion is to reject the null hypothesis. The slope of the NAC with respect to time trend is not zero and is negative in sign. If the confidence interval was raised to 99% then the conclusion would be to fail to reject the null, thus, the slope of NAC with respect to time would be statistically zero. This fact highlights the importance of purposeful determination of the confidence level at a site.

[ii] Time (t) is in days, where day 1 corresponds to January 1, 1900.

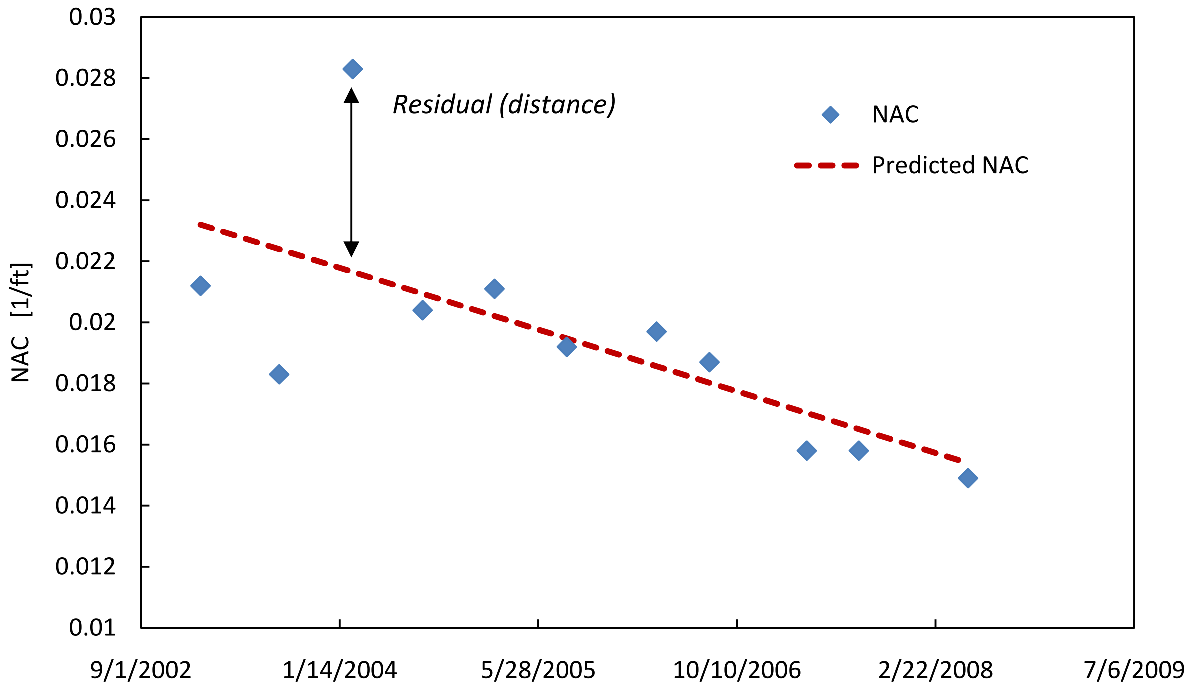

FIGURE 22: PREDICTED MODEL AND ACTUAL NAC VALUES, TOTAL CHLORINATED ETHENES, OU-10, NAS PENSACOLA

4.1.1.2 Graphical Method of Determining Upper/Lower Prediction Intervals

Prediction intervals can be used to determine whether the next measurement falls within the range of values that represent the previously established trend. The first prediction interval method being shown for NAS Pensacola requires a linear regression analysis whereby the 90% prediction interval is calculated with all available data except the latest NAC value. Of the two prediction interval methods considered, this method is preferred at sites where the data is statistically increasing or decreasing. The data calculated for Site is shown in **Table 6**. Note that the most recent NAC value for total chlorinated ethenes (5/14/2008) has not been included in the determination of the predicted trend and prediction intervals.

TABLE 6: DETERMINATION OF PREDICTION VALUES AND PREDICTION INTERVALS FOR NAC OF TOTAL CHLORINATED ETHENES, OU-10, NAS PENSACOLA

Date	NAC	Predicted Values*	90% LCL*	90% UCL*	90% LPL*	90% UPL*
1/29/2003	0.0212	0.0231	0.0198	0.0263	0.0167	0.0295
8/15/2003	0.0183	0.0223	0.0196	0.025	0.0162	0.0285
2/16/2004	0.0283	0.0216	0.0193	0.0239	0.0157	0.0276

Date	NAC	Predicted Values*	90% LCL*	90% UCL*	90% LPL*	90% UPL*
8/10/2004	0.0204	0.0209	0.019	0.0229	0.0151	0.0268
2/7/2005	0.0211	0.0202	0.0185	0.022	0.0145	0.026
8/8/2005	0.0192	0.0195	0.0178	0.0213	0.0138	0.0253
3/22/2006	0.0197	0.0187	0.0167	0.0207	0.0128	0.0245
8/2/2006	0.0187	0.0182	0.0159	0.0204	0.0122	0.0241
4/4/2007	0.0158	0.0172	0.0144	0.02	0.011	0.0234
8/13/2007	0.0158	0.0167	0.0135	0.0199	0.0104	0.0231
5/14/2008	0.0149					

**Calculations completed using Sigma Plot 11*

The data presented in Table 6 is transformed to a graphical representation (**Figure 23**) and the last NAC measurement (5/14/2008) is added to the graph. This last data point is evaluated for whether it falls with the prediction interval. The visual evaluation is significantly easier in cases where the slope of the predicted values (linear model fit) is zero. However, the value of this method is that one can evaluate linear prediction models where the slope is not statistically zero. This method is based off the least squares regression and only makes the assumption that the data is normally distributed. As can be seen in Figure 23, when the data trend has a slope not equal to zero, the prediction intervals can be extrapolated in order to evaluate whether the next data point falls within the previous models predicted limits.

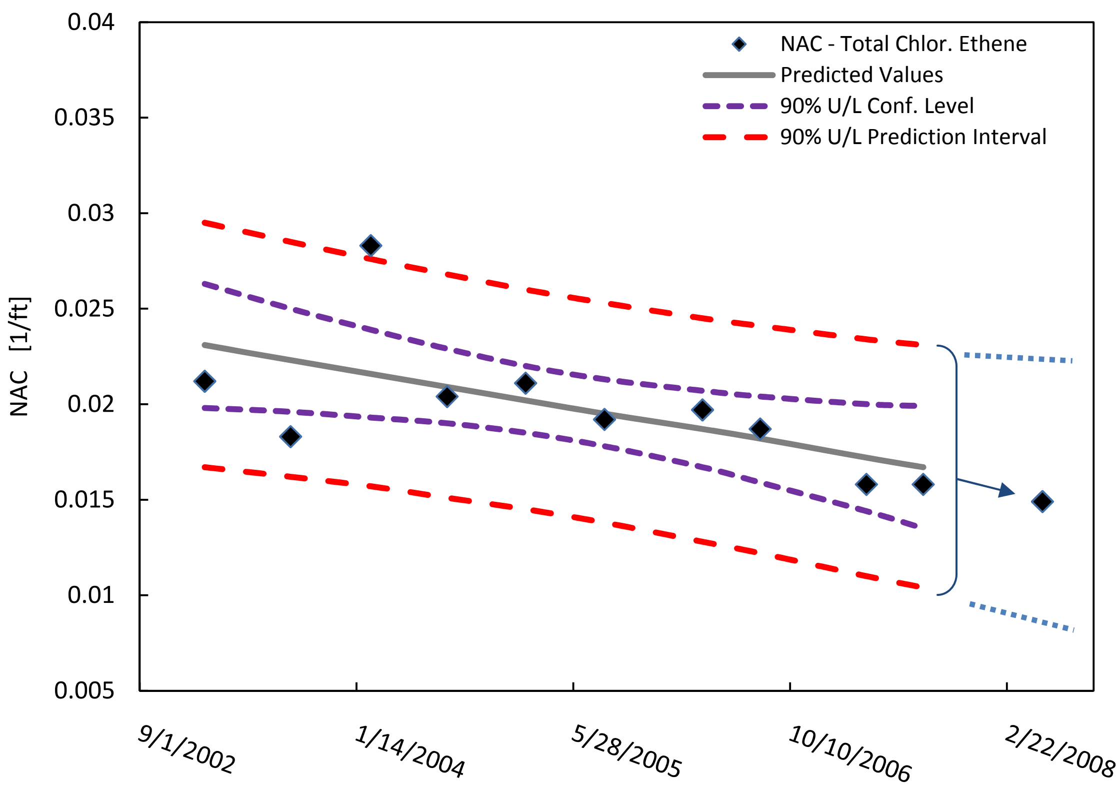

FIGURE 23: PREDICTION INTERVAL DETERMINED FOR THE EVALUATION OF THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENES, OU-10, NAS PENSACOLA

The next data point, representing the sampling event May 14, 2008, does fall within the prediction interval represented in Figure 23 by a red dashed line and then extrapolated by a blue dashed line. The resulting conclusion is that the data point is a continuation of the same trend previously observed at the site. This process is repeatable for each new sampling event. The result of adding the May 14, 2008 sampling event data to the model is that the predicted values and prediction interval slightly change, **Figure 24**. These changes are relatively insignificant and do not change any results. In theory, additional values that follow the predicted model should tighten the confidence and prediction intervals. A sudden shift or expansion of the prediction interval caused by one data point can be an indicator that the NAC trend has changed.

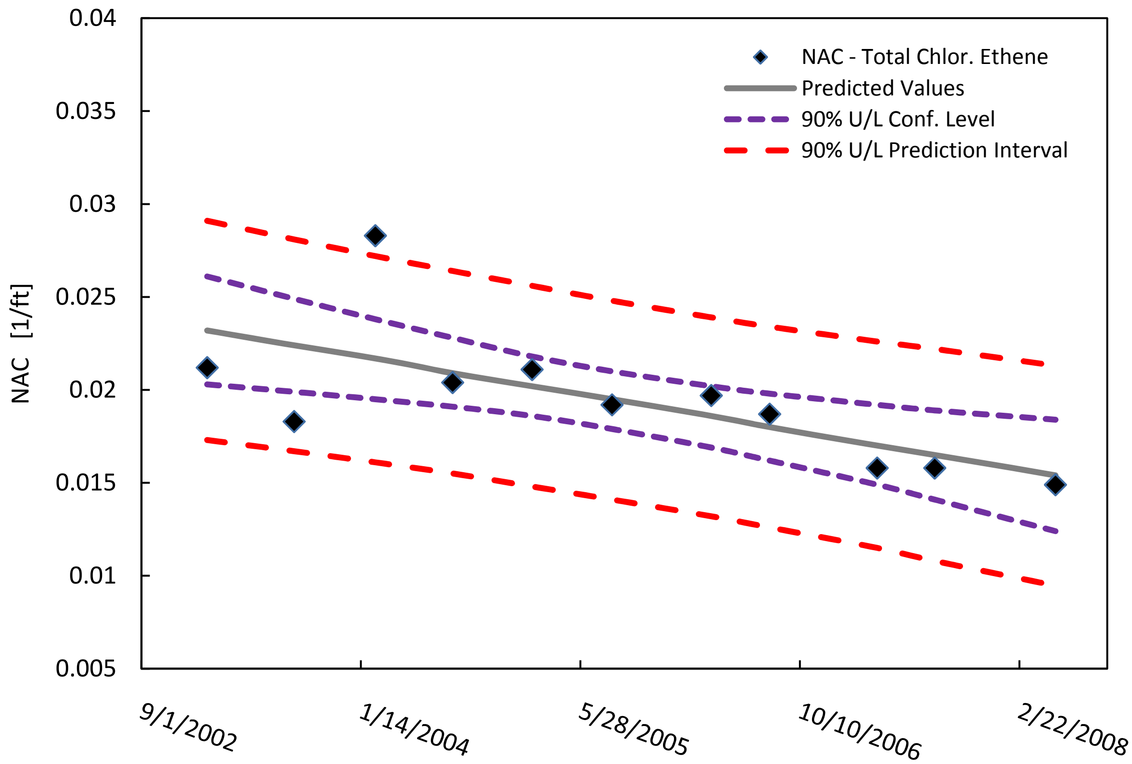

FIGURE 24: PREDICTION INTERVAL AFTER INCLUSION OF MOST RECENT MEASUREMENT, TOTAL CHLORINATED ETHENES, OU-10, NAS PENSACOLA

4.1.1.3 Tabular method of determining prediction intervals for the next single measurement

The tabular method of determining prediction intervals for the next single measurement is in some cases a more robust statistical method than the visual determination method previously described. Its primary limitation is that it is not designed to be used on trends where the slope is not zero. It involves a simple process of calculations followed by interpreting the statistical output. The data for OU-10 was processed through a spreadsheet with some calculations completed in R, an open source statistical program. R is used to determine the Student's t value and to conduct the Shapiro Wilk test of normality on with each new measurement. The results for OU-10 are displayed in **Tables 7** and **8**. Table 7 shows the two-sided prediction interval, which is displayed graphically in **Figure 25**. Table 8 shows the one-sided prediction interval, which is displayed graphically in **Figure 26**. Of the eight NAC values that are statistically tested (in Tables 7 and 8) for whether they comply with the two prediction interval sets, only one measurement falls outside the intervals. The NAC value representing the sampling event on April 4, 2007 is slightly lower than the one-sided lower prediction interval (see Figure 26). The NAC data in Figures 25 and 26 appears to be approaching the lower prediction interval in both the one-sided and two-sided cases. The reason for this is that the tabular method of determining prediction intervals makes the assumption that the data has a slope of zero (horizontal). With a decreasing slope, the data will approach and in some cases cross the lower prediction interval. For this reason, the former method of determining a prediction interval is preferred for OU-10 at NAS Pensacola. Notable, but not influential, the normal distribution assumption fails for three of nine Shapiro-Wilk tests. This is not influential on the interpretation because the failures occurred early in the data set and the normal distribution probability increases with each new measurement.

TABLE 7: DETERMINATION OF TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT AND QUALITATIVE INTERPRETATION, OU-10, NAS PENSACOLA

DATE	NAC	Mean	Std. Dev.	Sample No.	Student's t	Shapiro-Wilk p-value*	Two-sided, Upper PI**	Two-sided, Lower PI**	Qualitative Evaluation
1/29/2003	0.0212								
8/15/2003	0.0183								
2/16/2004	0.0283	0.02260	0.00514	3	2.91999	0.5457			
8/10/2004	0.0204	0.02205	0.00434	4	2.35336	0.2884	0.040	0.005	
2/7/2005	0.0211	0.02186	0.00378	5	2.13185	0.1097	0.033	0.011	
8/8/2005	0.0192	0.02142	0.00355	6	2.01505	0.0450	0.031	0.013	
3/22/2006	0.0197	0.02117	0.00331	7	1.94318	0.0137	0.029	0.014	
8/2/2006	0.0187	0.02086	0.00319	8	1.89458	0.0052	0.028	0.014	The NAC value (0.0187) is within the PI (0.028,0.014), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
4/4/2007	0.0158	0.02030	0.00342	9	1.85955	0.0606	0.027	0.014	The NAC value (0.0158) is within the PI (0.027,0.014), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
8/13/2007	0.0158	0.01985	0.00353	10	1.83311	0.0630	0.027	0.014	The NAC value (0.0158) is within the PI (0.027,0.014), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
5/14/2008	0.0149	0.01940	0.00367	11	1.81246	0.0993	0.027	0.013	The NAC value (0.0149) is within the PI (0.027,0.013), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
Next Value	TBD						0.026	0.012	TBD with next sampling event

**alpha value for Shapiro-Wilk test is 0.05*

**alpha value for Prediction Interval is 0.10

TABLE 8: DETERMINATION OF ONE-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT AND QUALITATIVE INTERPRETATION, OU-10, NAS PENSACOLA

DATE	NAC	Mean	Std. Dev.	Sample No.	Student's t	Shapiro-Wilk p-value*	One-sided, Lower PI*	Qualitative Evaluation
1/29/2003	0.0212							
8/15/2003	0.0183							
2/16/2004	0.0283	0.02260	0.00514	3	1.88562	0.5457		
8/10/2004	0.0204	0.02205	0.00434	4	1.63774	0.2884	0.0114	
2/7/2005	0.0211	0.02186	0.00378	5	1.53321	0.1097	0.0141	
8/8/2005	0.0192	0.02142	0.00355	6	1.47588	0.0450	0.0155	
3/22/2006	0.0197	0.02117	0.00331	7	1.43976	0.0137	0.0157	
8/2/2006	0.0187	0.02086	0.00319	8	1.41492	0.0052	0.0161	The NAC value (0.0187) is GREATER than the lower, one-sided PI (0.0161), this newest NAC value does NOT reflect a change in the previously established site degradation rate.
4/4/2007	0.0158	0.02030	0.00342	9	1.39682	0.0606	0.0161	The NAC value (0.0158) is LESS than the lower, one-sided PI (0.0161), this newest NAC value MAY INDICATE a change from the previous site degradation rate.
8/13/2007	0.0158	0.01985	0.00353	10	1.38303	0.0630	0.0153	The NAC value (0.0158) is GREATER than the lower, one-sided PI (0.0153), this newest NAC value does NOT reflect a change in the previously established site degradation rate.
5/14/2008	0.0149	0.01940	0.00367	11	1.37218	0.0993	0.0147	The NAC value (0.0149) is GREATER than the lower, one-sided PI (0.0147), this newest NAC value does NOT reflect a change in the previously established site degradation rate.
Next Value	TBD						0.0141	TBD with next sampling event

**alpha value for Shapiro-Wilk test is 0.05*

**alpha value for Prediction Interval is 0.10

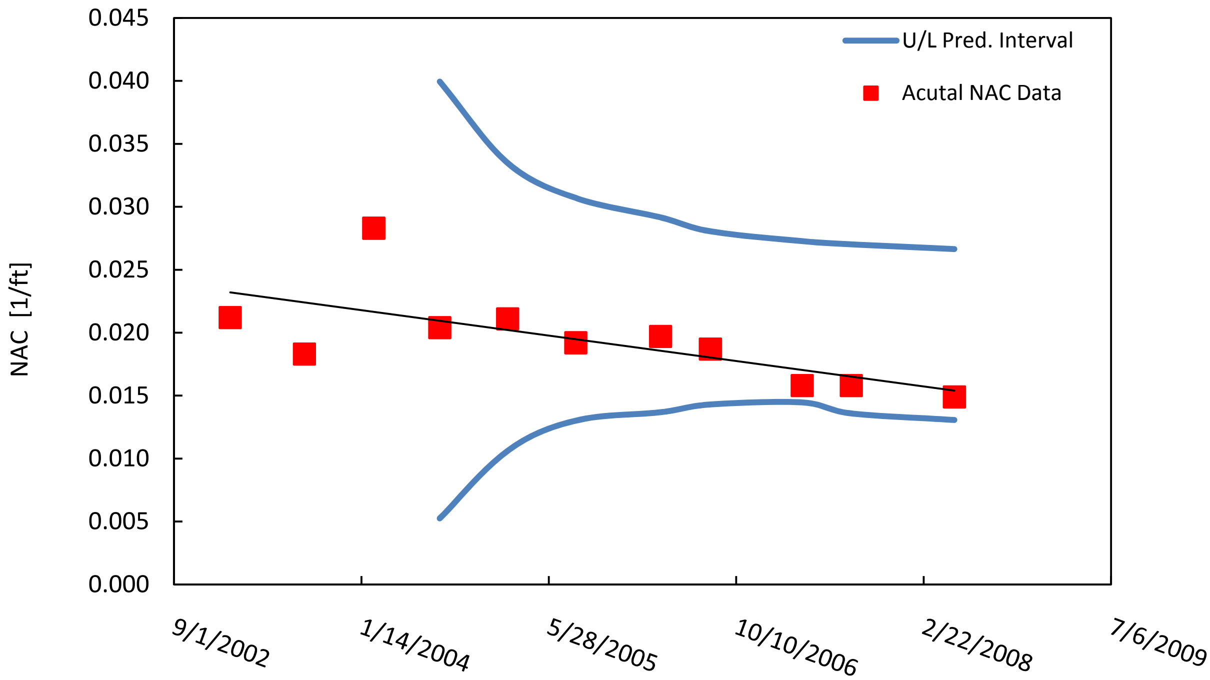

FIGURE 25: TWO-SIDED PREDICTION INTERVAL CALCULATED FOR THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENES, OU-10, NAS PENSACOLA

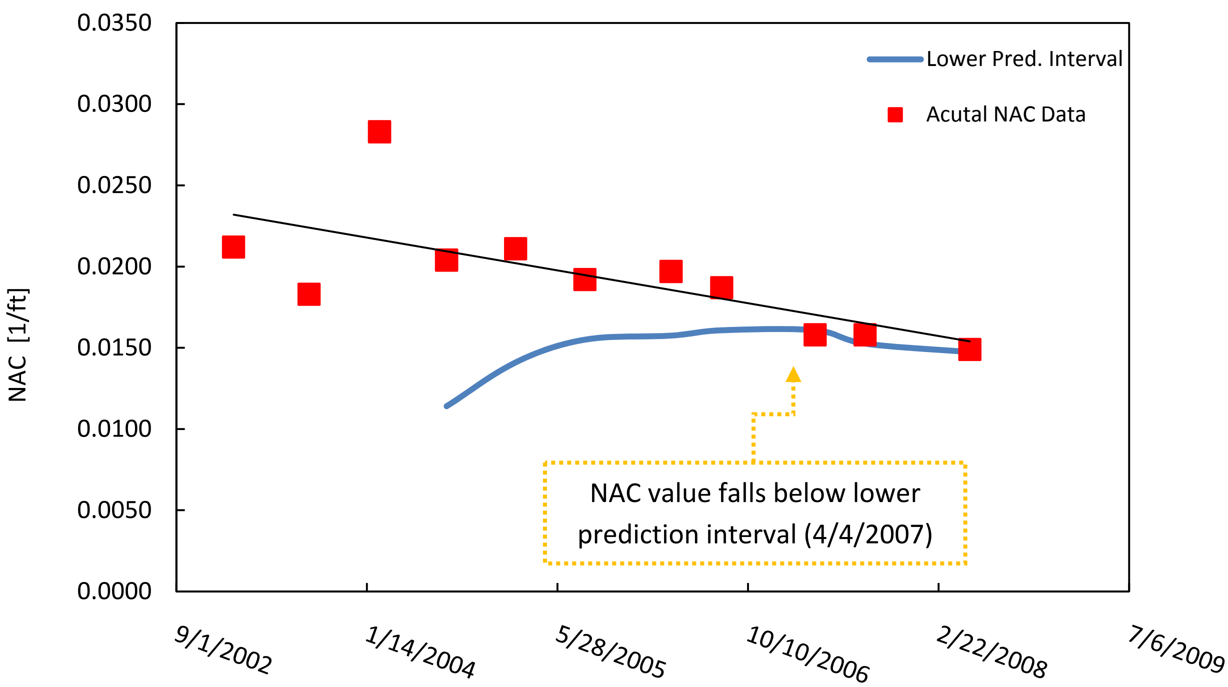

FIGURE 26: ONE-SIDED PREDICTION INTERVAL CALCULATED FOR THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENES, OU-10, NAS PENSACOLA

4.1.1.4 **Evaluation of Critical NAC**

Critical NAC must be evaluated with data from a single sampling event, for best results April 4, 2007 was selected. **Figure 27** shows the decision parameters for establishing and evaluating the critical NAC at the Site. The POC is not explicitly stated in the ROD, however it is being assumed that the most downgradient well is also the POC (well 33G12) (Ensafe/Allen & Hoshall, 1997). Well 33G12 is located 330 ft downgradient from the source and is close in proximity to the Pensacola Bay (Chapelle, 2008). The threshold concentration that must be achieved by the POC is based on the ARAR. The 1997 ROD states that without justification, the ARARs will default to the accepted drinking water standards for the EPA or State of Florida, whichever is the lowest (Ensafe/Allen & Hoshall, 1997). There are no maximum contaminant levels (MCLs) for total chlorinated ethene; rather each constituent is regulated independently. The federal MCLs for TCE, cis-DCE, and VC are 5-μ/L, 70-μ/L, and 2-μ/L, respectively (USEPA, 2009). Florida Department of Environmental Protection (FDEP) has established even lower state regulatory limits on these constituents than the EPA requirements. The state MCLs for TCE, cis-DCE, and VC are 3-μ/L, 70-μ/L, and 1-μ/L (Florida Department of Environmental Protection, 2008).

In July of 2008 the Navy and USGS began a biostimulation and bioaugmentation demonstration project at the source area to determine if the technology could reduce the source concentrations further. Natural attenuation is measurably occurring at the site but not at rate capable of achieving state MCLs by the final well in the plume line being analyzed. The CNAC determination is based on the assumption that the POC of located 330 feet from the source. This assumption is necessary for CNAC determination but not supported by other documentation.

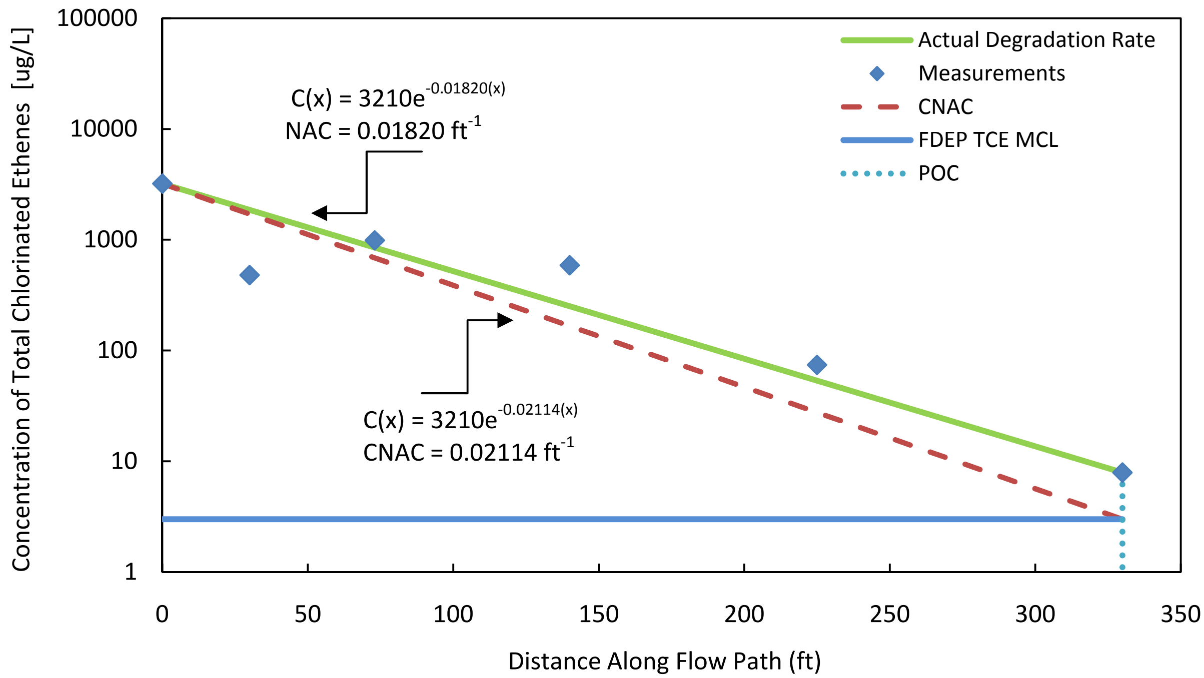

FIGURE 27: SEMI-LOG PLOT OF CONCENTRATION VS. DISTANCE FOR THE DETERMINATION OF CRITICAL NAC, BASED ON 4/4/2007 SAMPLING EVENT, OU-10, NAS PENSACOLA

4.1.2 Summary and Discussion of Key Findings

OU-10 at NAS Pensacola is a site where reductive dechlorination has been shown to be ongoing for more than a decade. Although source removal and remediation has occurred, the primary remediation mechanism for containing the plume between 2003–2008 is MNA. In fact, MNA is expected to degrade a large portion of the chlorinated ethene mass over the coming decades. The responsible parties must determine if MNA will continue to sufficiently degrade the contaminants at the site.

Of the twenty-seven sampling events, eleven sampling events were taken during the most recent period of stability. Stability reflects a mature plume where the affects of in-situ remediation have been exhausted. Site data was manipulated into the form of NAC, the screen tool for evaluating sustainability. A linear regression analysis of NAC with respect to time shows that NAC at OU-10 is decreasing with time (at 90% confidence). Through the linear regression analysis a linear predictive model of the decreasing NAC rate was estimated to be -4.04×10^{-6} ft^{-1}. The linear model is written as:

$$NAC = -4.04x10^{-6}\,(t) + 0.1753$$

A prediction interval around the predicted linear model was developed and evaluated in graphical form. Extrapolating the prediction interval indicates that the newest measurement (sampling event on 5/14/2008) falls within the predicted limits. This test supports the argument that the NAC data reflect a continuous linear regression with a negative slope. A more robust statistical method, whereby the prediction interval for the next measurement is determined, corroborates this conclusion. In this later method, it was shown that the newest measurement does not reflect a change in the previously established rate of natural attenuation at the Site (NAC). The one exception to this is the NAC value from April 4, 2007 when evaluated with a one-sided prediction interval at a confidence level of 90%. This exception is highlighted in Figure 26, but is not a convincing "alarm" given that the following two measurements are above the lower prediction interval. The one-sided lower prediction interval is the most sensitive warning signal to decreases in the degradation rate. The data available supports the conclusion that NAC can be represented by a single linear trend.

The hypothetical CNAC was determined to be greater than the actual NAC on April 4, 2007, an indication that the rate of natural attenuation in the plume is slower than what is needed to comply with state MCLs by the POC. The CNAC is hypothetical because the POC is assumed and not supported by other documentation. In addition, the CNAC tool should be used cautiously when evaluating a site because it is based on a single sampling event. Completing multiple site CNAC evaluations is recommended for any site.

In summary of OU-10 at NAS Pensacola:

- Efficient reductive dechlorination within contaminant plume
- Complete transformation of TCE to ethene before Pensacola Bay
- Assumption of NAC v. Time trend being a single linear regression is reasonable (based on residuals and prediction intervals)
- NAC is decreasing at this Site
- Prediction interval based on least squares method is more reliable for Site (due to decreasing NAC)
- CNAC is greater than NAC on 4/4/07, signaling that NAC at site may be too slow to achieve FDEP regulatory limits for TCE by monitoring well 33G12. Efforts to remediate the plume are ongoing.

4.2 Statistical Analysis of NAES Lakehurst, North Plume

The nomenclature "north" and "south" plumes are more readily used for distinction in historical documents regarding the two distinct plumes at Sites I&J, therefore the term north plume will be used from this point forward to describe the area of interest. The north plume originating at former liquid disposal pits at NAES Lakehurst is approximately 5000 ft long containing the chlorinated ethene parent constituent of PCE as well as reduced forms of chlorinated ethenes (TCE, cis-DCE, and VC). The constituent cis-DCE is the most concentrated chlorinated ethene at the site (Widdowson, Chapelle, Casey, & Kram, 2008). The plume has been observed in semi-regular intervals by various agencies (see Chapter 3.2 for site history) starting in February 1996 to present day, however, the most recent data available for analysis is November 2007 (Environmental Management, NAES Lakehurst, January 2006).

Remediation of the plume source has primarily involved in-situ injection of ZVI between February 2002 and November 2005 (Environmental Management, NAES Lakehurst, January 2006) and (PARS Environmental, Inc., 2006). Since that remedial action took place a long-term MNA approach has been implemented with an estimated time to clean up being 48 years (PARS Environmental, Inc., 2006). Prior to the remediation efforts, the plume was determined to be at steady-state with natural attenuation occurring (Dames and Moore, 1999). No formal methods of steady-state determination have been used in this analysis; however, reasonable qualification for the assumption is given in this chapter.

The source area is monitored by well Wells NI and LK. Well LK was treated as the source well until NI was established in 2004, only 14 feet away from LK (Dames and Moore, 1999) and (Environmental Management, NAES Lakehurst, January 2006). **Table 9** contains the well IDs, distance the well is from the source well, and the earliest date of data available for the analysis. **Figure 28** shows a plan view of the north plume, including the well locations.

TABLE 9: WELL DESCRIPTIONS, NORTH PLUME, NAES LAKEHURST

Well ID	Distance from source along plume line [ft]*	First Available Sampling Event
NI	0 (-14)	Feb. 27, 2004
LK	14 (0)	Feb. 16, 1996
MA	1544 (1530)	Feb. 16, 1996
MC	3074 (3060)	Feb. 16, 1996
MK	4954 (4940)	Feb. 16, 1996

*parentheses in column indicate distance from well LK, prior to establishing well NI, Feb. 27, 2004

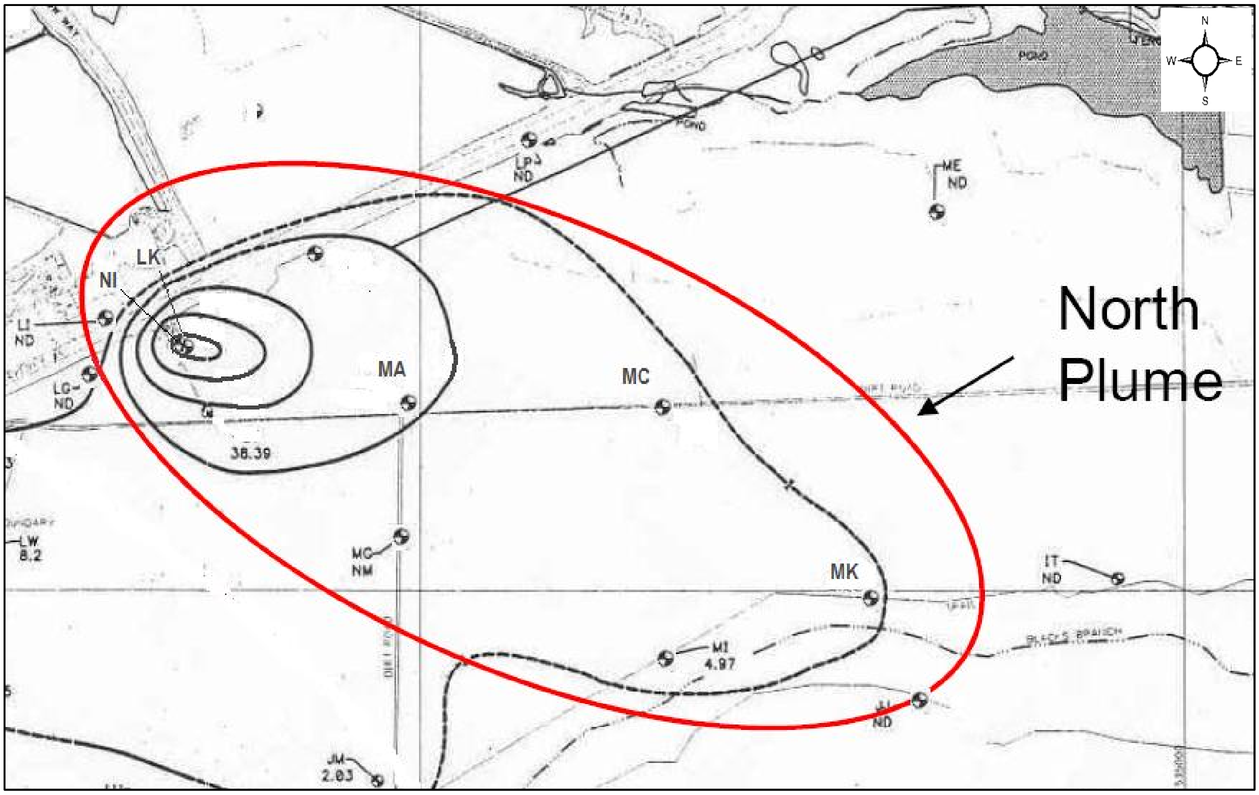

FIGURE 28: PLAN VIEW OF NORTH PLUME, NAES LAKEHURST (DAMES AND MOORE 1999).

Twenty-four sampling events occurred between February 1996 and November 2007. Not all five wells along the plume line were sampled during each of the twenty-four sampling events. Twenty-three of the twenty-four sampling events included four or more wells. The eight most recent sampling events included all five of the plume centerline wells. The sampling data is presented in **Appendix B**.

Figures 29-31 are graphical representations of total chlorinated ethene concentrations at the source wells. Figure 29 shows the widest range of source observation available at the site, starting in February 1996 to November 2007. It is clear that remediation has caused instability in the plume, where the concentration drop prior to September 2000 does not reflect natural attenuation. Figure 30 highlights the concentration data at well LK from September 2000 to November 2007. The affects of two separate ZVI injections at the source can be seen, as well as a rebound following the first injection.

To avoid the influence of the ZVI injections completely would reduce the data to the three most recent sampling events. Three sampling events are insufficient for the statistical analysis being performed. These facts have been considered in the process of determining the most appropriate data set to use for the analysis. Data collected between 2004 and 2007 reflect a nearly steady-state plume trend as well as sufficient data sets for the statistical analysis. The data at wells LK and NI, both arguably representing the source of the plume, are displayed in Figure 31.

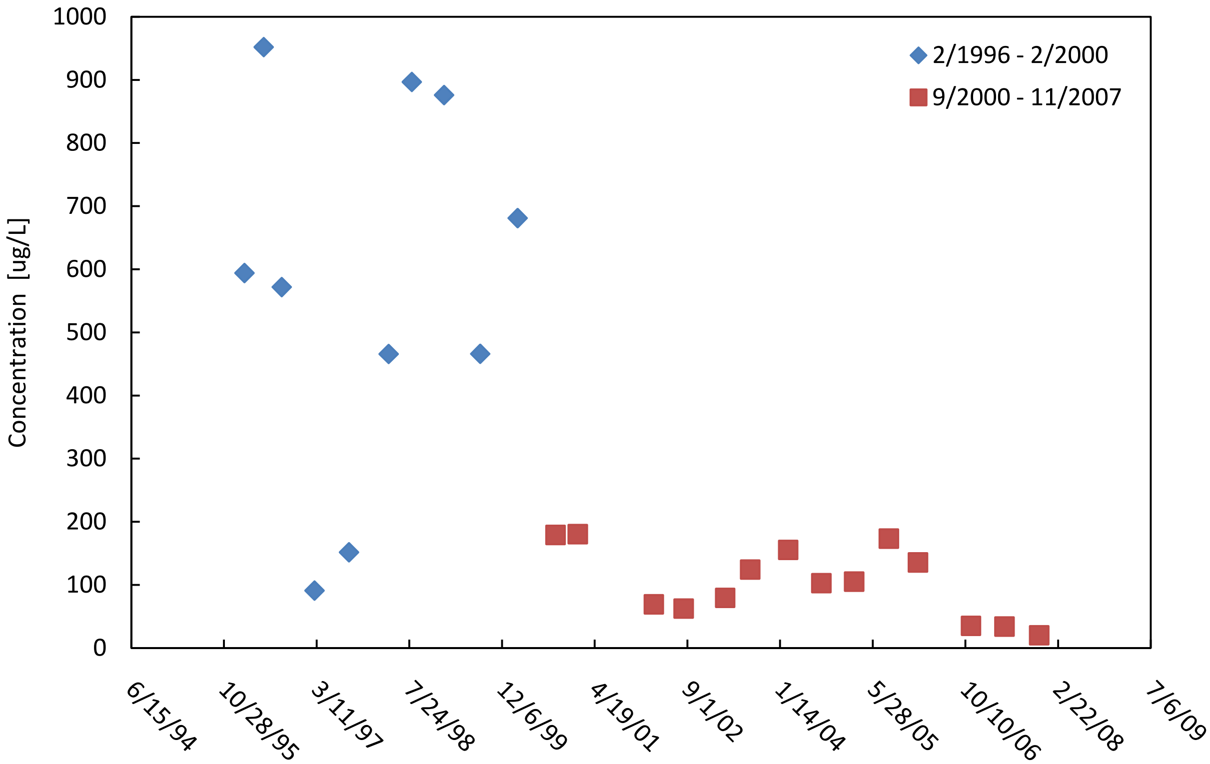

FIGURE 29: TOTAL CHLORINATED ETHENE CONCENTRATIONS AT THE SOURCE WELL LK, NORTH PLUME, NAES LAKEHURST

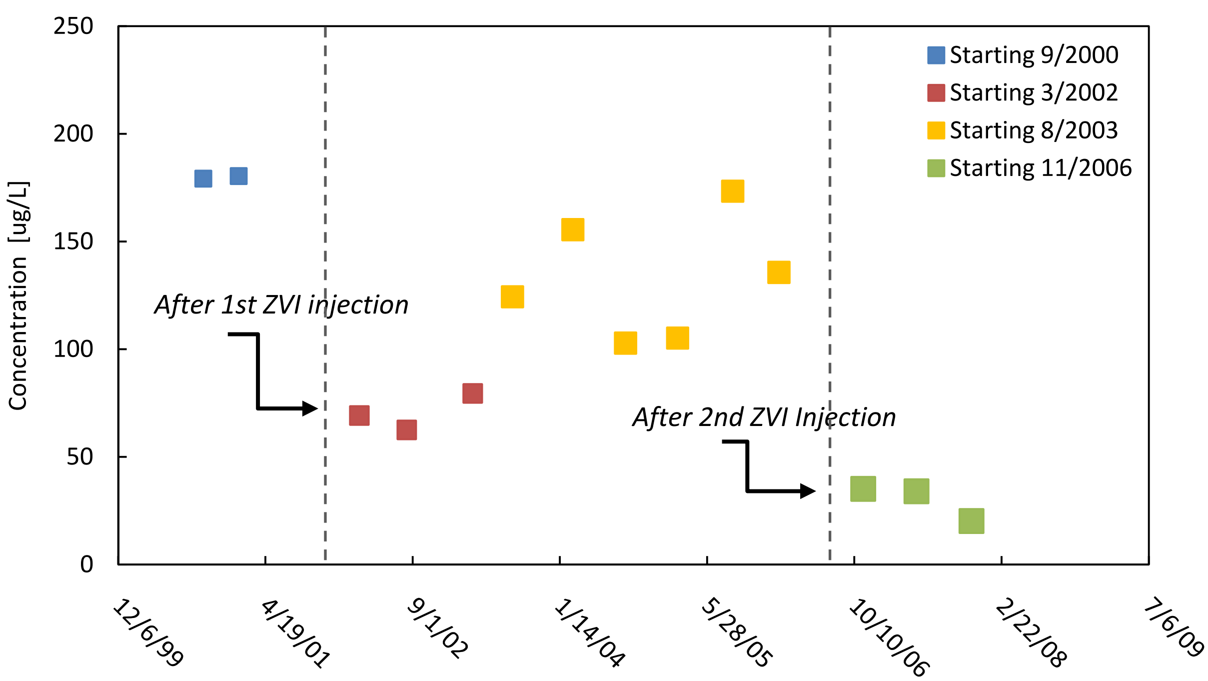

FIGURE 30: TOTAL CHLORINATED ETHENE CONCENTRATIONS AT THE SOURCE WELL LK, NORTH PLUME, NAES LAKEHURST

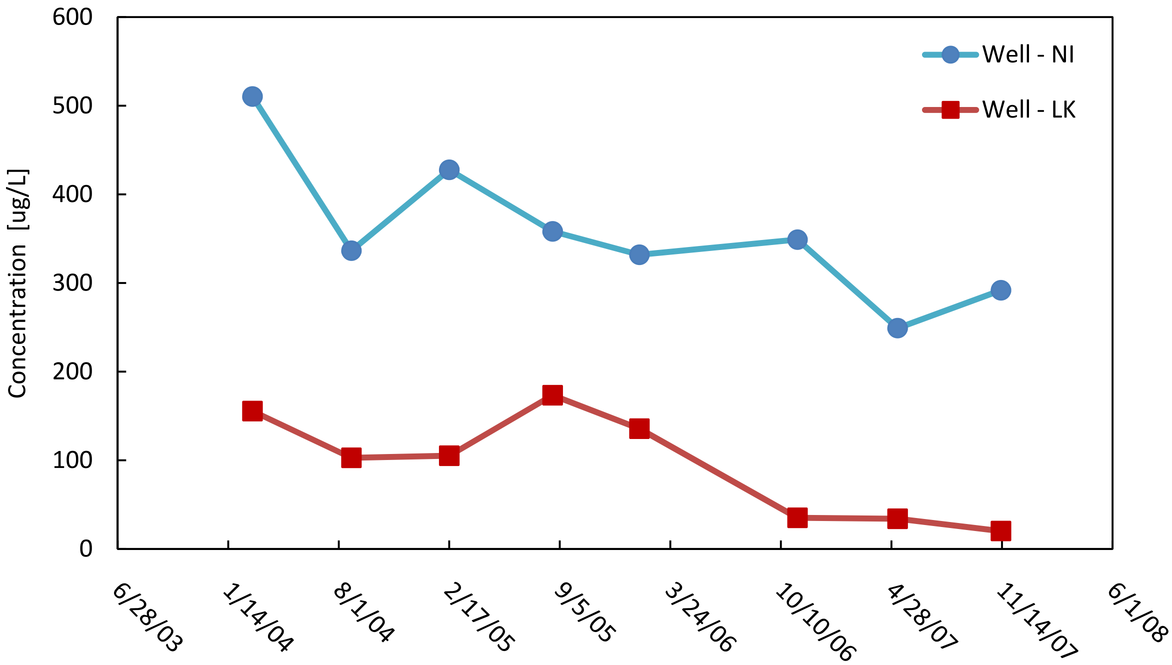

FIGURE 31: TOTAL CHLORINATED ETHENE CONCENTRATIONS AT THE SOURCE WELL LK, NORTH PLUME, NAES LAKEHURST

Eight sampling events occurred between February 2004 and November 2007 at the north plume. **Table 10** displays the resulting total chlorinated ethene concentrations for the target time period. In addition, the original data is displayed in **Figure 32**, where the total chlorinated ethene as a function of time is displayed for each of the five wells. Review of Figure 32 supports the assumption of semi-stability, given the acknowledgement of remedial affects within the data set.

TABLE 10: TOTAL CHLORINATED ETHENE CONCENTRATION, NORTH PLUME, NAES LAKEHURST

Sampling Event	Concentration Total Chlorinated Ethene (µg/L)				
	NI	LK	MA	MC	MK
2/27/2004	510.3	155.47	61.17	11.67	2.63
8/24/2004	336.4	102.81	30.29	9.606	2.113
2/17/2005	427.71	105.16	51.4	9.743	2.025
8/23/2005	358.21	173.35	138.66	8.662	2.073
1/27/2006	331.8	135.65	46.76	8.891	1.964
11/9/2006	348.9	35.12	58.462	0.754	1.744
5/9/2007	249.03	34.01	45.7	0	1.45
11/12/2007	291.7	20.18	73.12	9.57	1.52

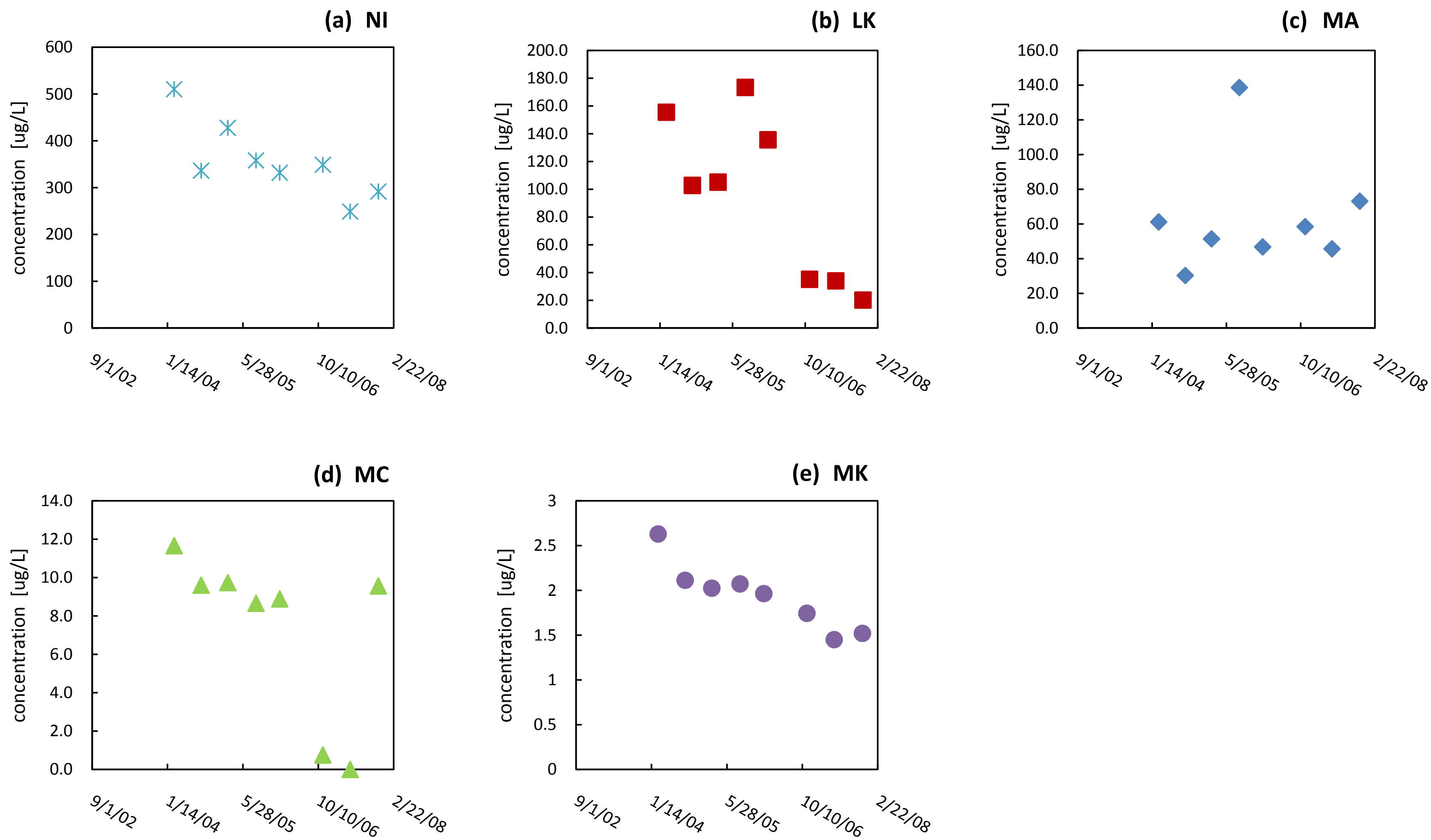

FIGURE 32: TOTAL CHLORINATED ETHENE CONCENTRATIONS IN VARIOUS WELLS ALONG THE PLUME CENTERLINE, NORTH PLUME, NAES LAKEHURST

4.2.1 *Utilizing NAC as a statistical screening tool*

NAC is determined by finding the slope of the solute concentration profile. **Figure 33** is a solute profile from the north plume of the sampling event on August 24, 2004. The independent variable in the figure is distance along the plume centerline, and the NAC value is highlighted as the slope of the trend. This analysis is completed for each sampling event to find the NAC for total chlorinated ethenes and other dominant chlorinate ethene constituents. The slope of the total chlorinated ethene concentration profile in Figure 33 is -0.0008 [µg/L-ft], corresponding to the NAC value of 0.0008 [1/ft].

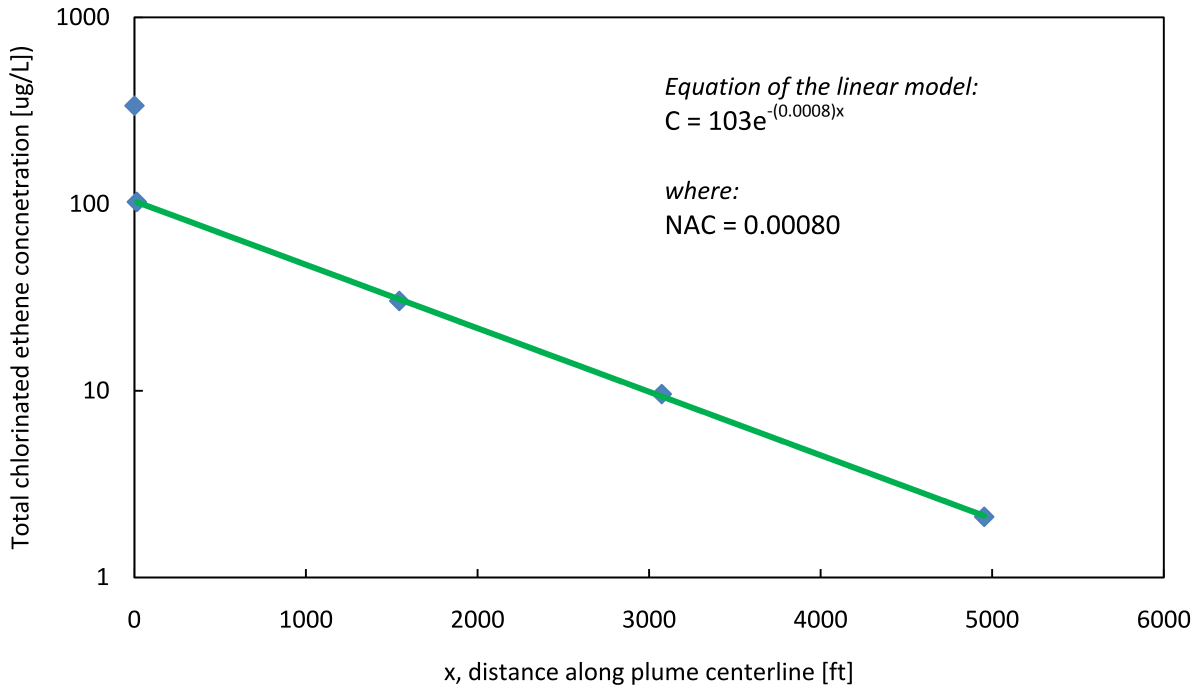

FIGURE 33: SOLUTE CONCENTRATION PROFILE, TOTAL CHLORINATED ETHENE, 8/24/04, NORTH PLUME, NAES LAKEHURST

Figure 34 shows NAC for total chlorinated ethene as a function time over the entire span of available data (1996-2007). Variability prior to the 2002 ZVI injections is assumed to be related to several pilot scale remedial approaches that were not established at full scale. As previously mentioned, data prior to 2004 is not used in the analysis in order to work with a non-transient, stable plume that is relatively free of non-natural remedial effects. **Figure 35** displays NAC as a function of time after 2003.

The parent compounds TCE was the actual constituent disposed of at Sites I&J. However, due to reductive dechlorination, concentrations of cis-DCE and VC are approximately an order of magnitude greater than TCE in the time period being evaluated. The total chlorinated ethene concentration is most significantly impacted by cis-DCE. NAC values for cis-DCE, TCE, and total chlorinated ethene were determined at every sampling event (**Table 11**) and the time trends of NAC for these constituents are displayed in Figure 35.

TABLE 11: NAC VALUES, NORTH PLUME, NAES LAKEHURST

Sampling Event	Total Clor. Ethenes	TCE	cis-DCE
2/27/2004	0.0008	0.0006	0.0009
8/24/2004	0.0008	0.0004	0.0009
2/17/2005	0.0008	0.0005	0.0010
8/23/2005	0.0009	0.0010	0.0010
1/27/2006	0.0008	0.0005	0.0010
11/9/2006	0.0009	0.0005	0.0006
5/9/2007	0.0003	N/A	0.0006
11/12/2007	0.0006	0.0004	0.0008

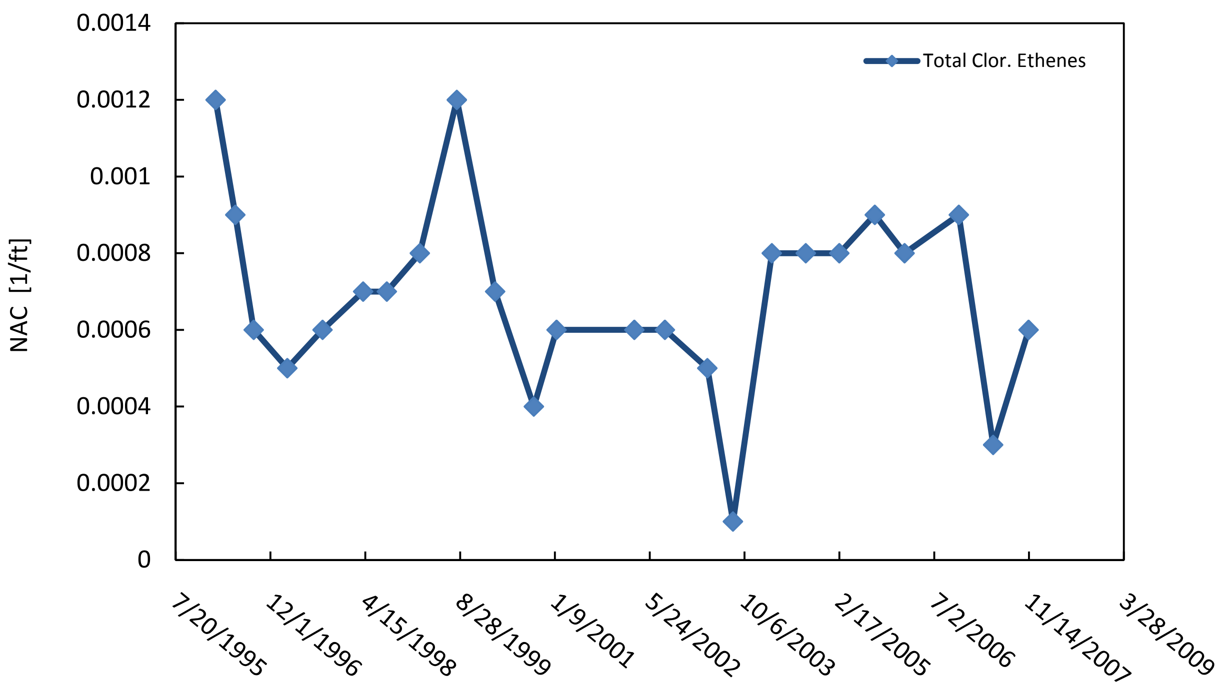

FIGURE 34: NAC AS A FUNCTION OF TIME, ALL DATA (1996-2007), NORTH PLUME, NAES LAKEHURST

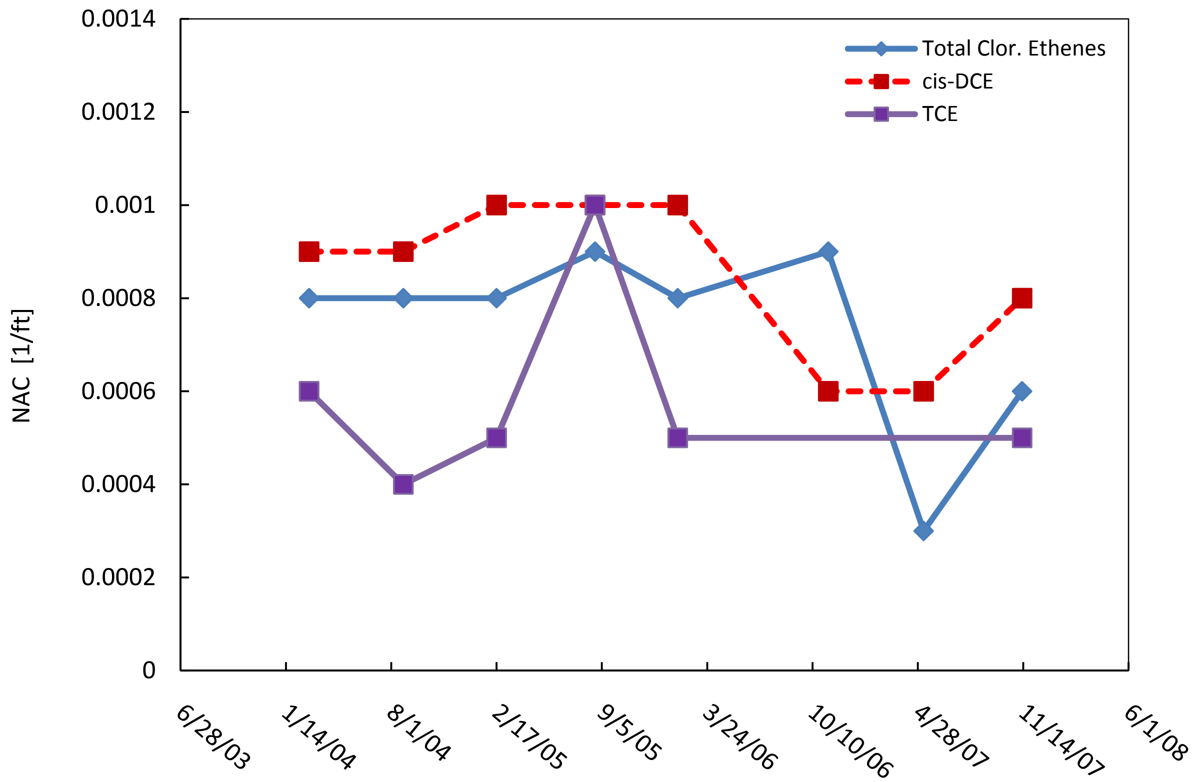

FIGURE 35: NAC AS A FUNCTION OF TIME, 2004-2007, NORTH PLUME, NAES LAKEHURST

4.2.1.1 Linear Regression

A linear regression is performed on the time trend series of total chlorinated ethene NAC values. A thorough explanation of the purpose and description of the linear regression has been provided in Chapter 2.3. The hypothesis question is stated, *"Is the slope of the linear regression equal to zero?"* The complete results of the linear regression analysis, which is the statistical tool used to evaluate the hypothesis are contained in **Appendix B**. **Table 12** is a summary of the linear regression results which includes a 90% prediction interval around the predicted model. The mathematic description of the predicted model is **Equation 11**.

TABLE 12: SUMMARY OF SLOPE ESTIMATE FROM LINEAR REGRESSION ANALYSIS OF NAC AS A FUNCTION OF TIME, NAC OF TOTAL CHLORINATED ETHENES, NORTH PLUME, NAES LAKEHURST

Statistic	Value
*Slope estimate, (β_1)	-2.291E-07
Alpha. (α)	0.10
Standard Error (β_1)	1.412E-07
t Stat (β_1)	-1.6227

Statistic	Value
P-value	0.1558
Lower Confidence Interval, 90%	-5.035E-07
Upper Confidence Interval, 90%	4.524E-08

**slope of NAC decreasing with respect to time*

$$NAC = -2.291x10^{-7}\left(t^{\text{iii}}\right) + 0.009606$$ **Equation 11**

The linear regression analysis fits the most appropriate linear model to the data set. In doing so, a valid prediction of future trends is possible as long as the residual values are reasonably small. It is apparent from **Figure 36** that the largest residuals are found in the last three sampling events, suggesting that most of the uncertainty about the linearity and/or slope of the data comes from approximately the last 12 months. A residual plot is provided in **Appendix B**. While speculative, one could suggest that the increasing residual distance with respect to time from the prediction model (Figure 36) has one of two explanations. Either the second to last sampling event (May 9, 2007) represents an outlier caused by non-representative factors or the data represents more than one trend of NAC at the site. Either are possible, and the fact that in-situ remediation with ZVI occurred in 2005 should be considered. **Figure 37** is the same linear prediction model presented in Figure 36, however; the sampling event on May 9, 2007 was omitted from the analysis. It is clear that the measurement made May 9, 2007 has a significant impact on the prediction model. Since the potential outlier occurred near the end of the data set, additional measurements are required to determine the whether it is an outlier or representative of a change in NAC.

However, the primary purpose of the linear regression is to test the hypothesis. The estimated slope of the line is [$-2.291x10^{-7}$] negative, indicating a decreasing NAC at the site. The P-value, a more robust test of the hypothesis, is greater than the alpha (0.10) value. The interpretation of this test is that one cannot conclude with 90% confidence that the slope of the regression is different than zero. This is validated by the fact that zero falls between the 90% (and 95%) confidence interval. The conclusion is to fail to reject the null hypothesis, and therefore the slope of the NAC with respect to time trend is not statistically different than zero. If the confidence interval was lowered to 80% then the conclusion would be to reject the null. As previously stated, determining the appropriate confidence level at a site has significant impact on the conclusions.

[iii] Time (t) is in days, where day 1 corresponds to January 1, 1900.

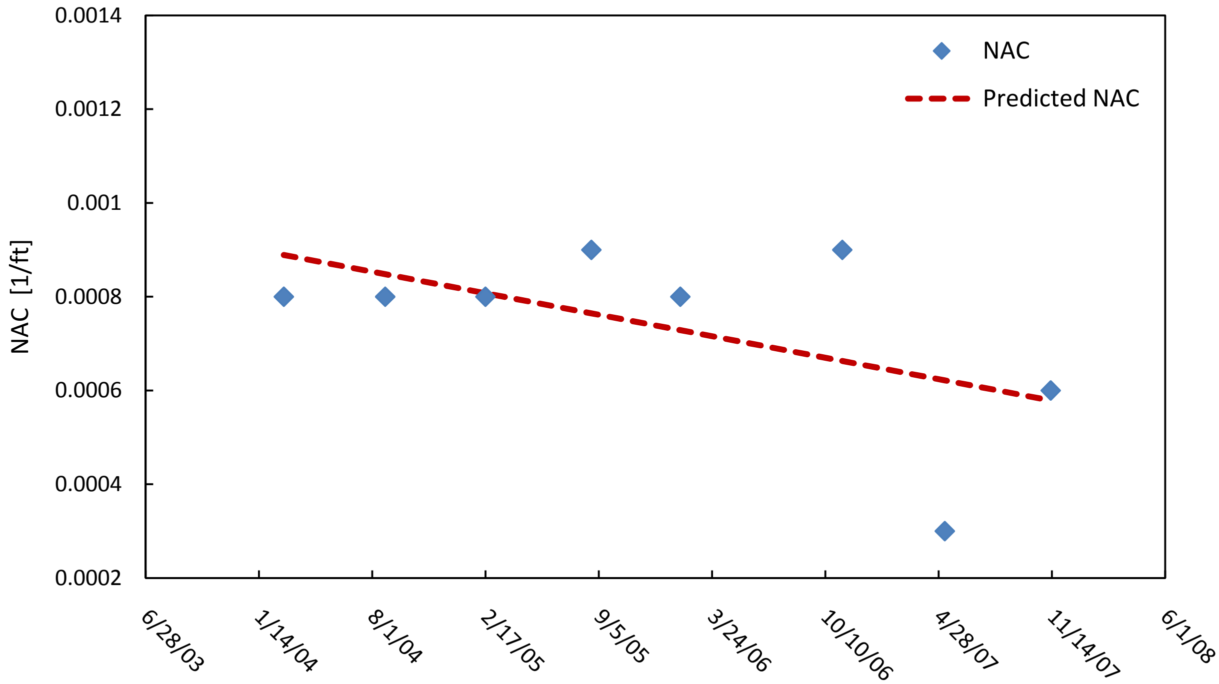

FIGURE 36: PREDICTED MODEL AND ACTUAL NAC VALUES, TOTAL CHLORINATED ETHENES, NORTH PLUME, NAES LAKEHURST

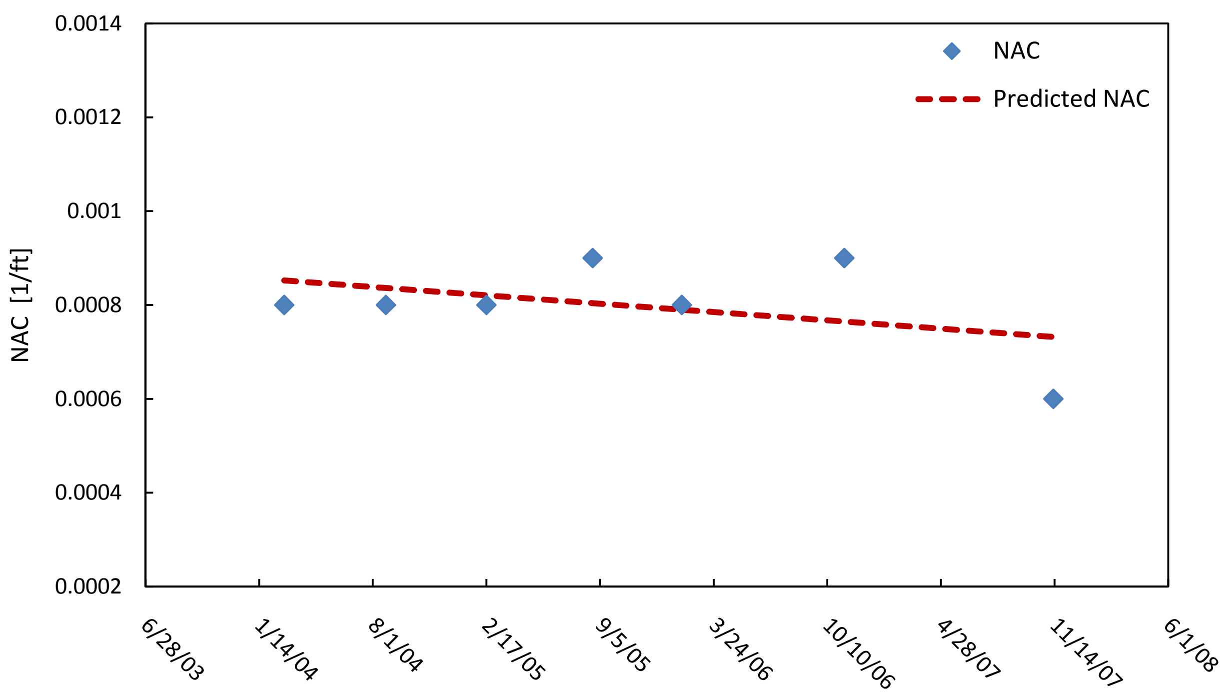

FIGURE 37: PREDICTED MODEL AND ACTUAL NAC VALUES, TOTAL CHLORINATED ETHENES, DATA FROM 5/9/2007 OMITTED, NORTH PLUME, NAES LAKEHURST

4.2.1.2 **Tabular method of determining prediction intervals for the next single measurement**

The tabular method of determining prediction intervals for the next single measurement is most appropriate for the Site given that the linear regression slope has been determined to be no different than zero. This method involves a step-wise calculation process followed by interpreting the statistical output. The data for the north plume has been processed through a series of calculations in a custom spreadsheet (**Tables 13-14**) with the help of a statistical program, R. R is used to determine the Student's t value and to conduct the Shapiro Wilk test of normality on with each new measurement. The results are displayed in Tables 13 and 14. Table 13 displays the two-sided prediction interval, which is displayed graphically in **Figure 38**. Table 14 displays the one-sided prediction interval, which is displayed graphically in **Figure 39**. Due to the limited variability of the data a prediction interval is not calculated until the fifth measurement. The fifth and sixth measurement fall within the prediction limits, however, the seventh measurement falls well below the lower prediction interval for both the one-sided and two-sided calculations. The prediction interval is significantly widened by the seventh measurement, thus the eighth easily falls within the prediction interval.

As mentioned in **Chapter 4.2.1.1**, more data is needed to determine what has happened at the site in the last 6-12 months, but two suppositions can be made in order to explain how the data is interpreted. Sudden expansions or shifts in the prediction interval are a sign that the NAC trend has changed or that an outlier is affecting the data trend. If the data change is only reflected by one data point, then an outlier maybe the correct interpretation. However, the remediation timeline for the north plume corroborates with the timeline of the expansion seen in the prediction interval; the last remediation event was the injection of ZVI near well NI in November 2005 (22 months prior). While there is not enough data after the interval expansion to completely validate a multi-linear model, it is possible that the measurements prior to 5/9/07 reflect advanced reductive dechlorination as a result of ZVI in the aquifer. Conversely, measurements on or after 5/9/07 reflect a slowing or critical biological consumption of the ZVI, thus decreasing the rate of reductive dechlorination. **Figure 40** demonstrates a hypothetical multi-trend, linear model for the data presented. To determine the validity of this supposition as well as the degree of change in the NAC trend would require additional data.

The "warning signal" has been shown to be a major success with this Site. Abnormalities are apparent in Figures 38 and 39, which caused warning signals in the analytical process. Using the historical remediation timeline in conjunction with the NAC temporal data leads to a logical explanation and quantitative determination of an NAC change.

TABLE 13: DETERMINATION OF TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT AND QUALITATIVE INTERPRETATION, NORTH PLUME, NAES LAKEHURST

DATE	NAC	Mean	Std. Dev.	No. Samples	Student's t	Shapiro Wilk, p-value*	Two-sided, Upper PI**	Two-sided, Lower PI**	Qualitative Evaluation
2/27/2004	0.00080								
8/24/2004	0.00080								
2/17/2005	0.00080	0.00080	0.00	3	2.91999	NA***			
8/23/2005	0.00090	0.00083	5.00E-05	4	2.35336	0.001241	8.000E-04	8.000E-04	
1/27/2006	0.00080	0.00082	4.47E-05	5	2.13185	0.000131	9.566E-04	6.934E-04	The NAC value (0.0008) is within the PI (0.0009566,0.0006934), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
11/9/2006	0.00090	0.00083	5.16E-05	6	2.01505	0.00135	9.244E-04	7.156E-04	The NAC value (0.0009) is within the PI (0.0009244,0.0007156), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
5/9/2007	0.00030	0.00076	2.07E-04	7	1.94318	0.000699	9.457E-04	7.209E-04	The NAC value (0.0003) is NOT within the PI (0.0009457,0.0007209), the newest NAC value does reflect a change from the previously established site degradation rate.
11/12/2007	0.00060	0.00074	2.00E-04	8	1.89458	0.00866	1.187E-03	3.271E-04	The NAC value (0.0006) is within the PI (0.001187,0.000327), the newest NAC value does NOT reflect a change from the previously established site degradation rate. However, the NAC value does not fit within the prediction interval presented for 5/9/2007. This change may reflect a change in NAC.
Next Value	TBD						1.139E-03	3.365E-04	TBD with next sampling event

**alpha value for Shapiro-Wilk test is [0.05]*

***alpha value for Prediction Interval is [0.10]*

****Notable, but not significant to the interpretation is the fact that the Shapiro Wilk normality test was failed for each measurement.*

TABLE 14: DETERMINATION OF ONE-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT AND QUALITATIVE INTERPRETATION, NORTH PLUME, NAES LAKEHURST

DATE	NAC	Mean	Std. Dev.	No. Samples	Student's t	Shapiro Wilk, p-value*	One-sided, Lower PI**	Qualitative Evaluation
2/27/2004	0.0008							
8/24/2004	0.0008							
2/17/2005	0.0008	0.00080	0.00000	3	1.88562	NA***		
8/23/2005	0.0009	0.00083	0.00005	4	1.63774	0.001241	8.00E-04	
1/27/2006	0.0008	0.00082	0.00004	5	1.53321	0.000131	7.33E-04	The NAC value (0.0008) is GREATER than the lower, one-sided PI (0.000733), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
11/9/2006	0.0009	0.00083	0.00005	6	1.47588	0.00135	7.45E-04	The NAC value (0.0009) is GREATER than the lower, one-sided PI (0.000745), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
5/9/2007	0.0003	0.00076	0.00021	7	1.43976	0.000699	7.51E-04	The NAC value (0.0003) is LESS than the lower, one-sided PI (0.000751), this newest NAC value MAY INDICATE a change from the previous site degradation trend.
11/12/2007	0.0006	0.00074	0.00020	8	1.41492	0.00866	4.39E-04	The NAC value (0.0006) is GREATER than the lower, one-sided PI (0.000439), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
Next Value	TBD						4.38E-04	TBD with next sampling event

**alpha value for Shapiro-Wilk test is 0.05*

**alpha value for Prediction Interval is 0.10

***Shapiro Wilk normality test was failed for each measurement.

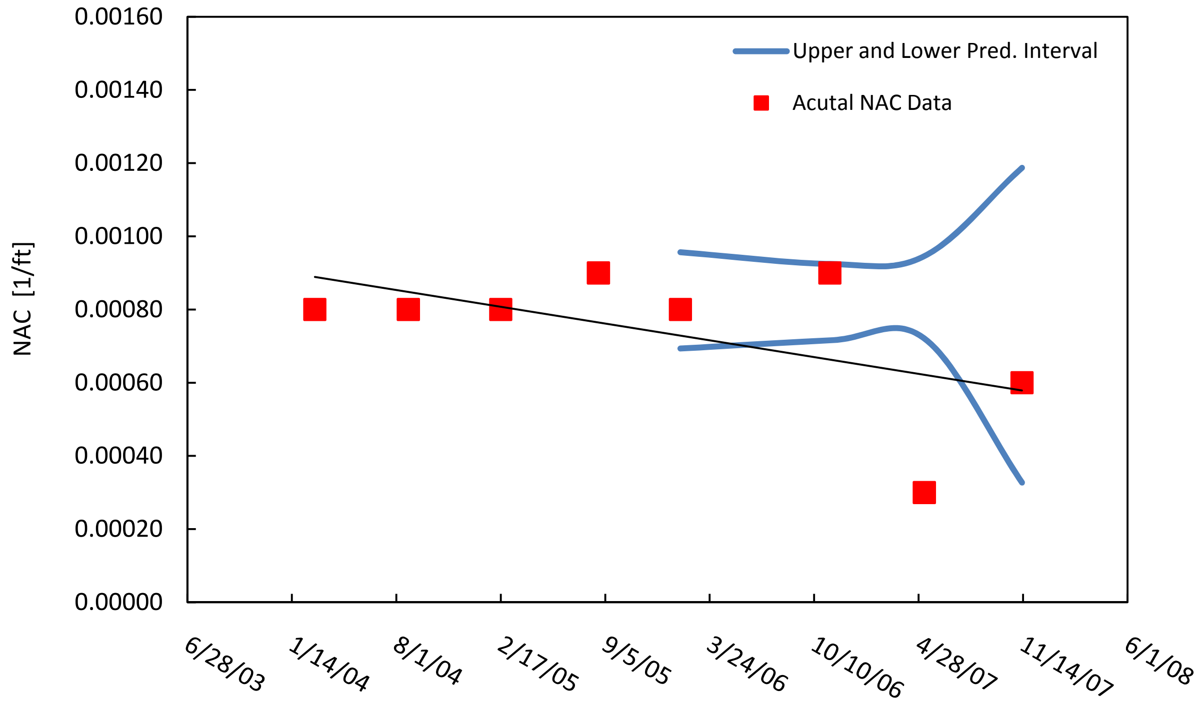

FIGURE 38: TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENES, NORTH PLUME, NAES LAKEHURST

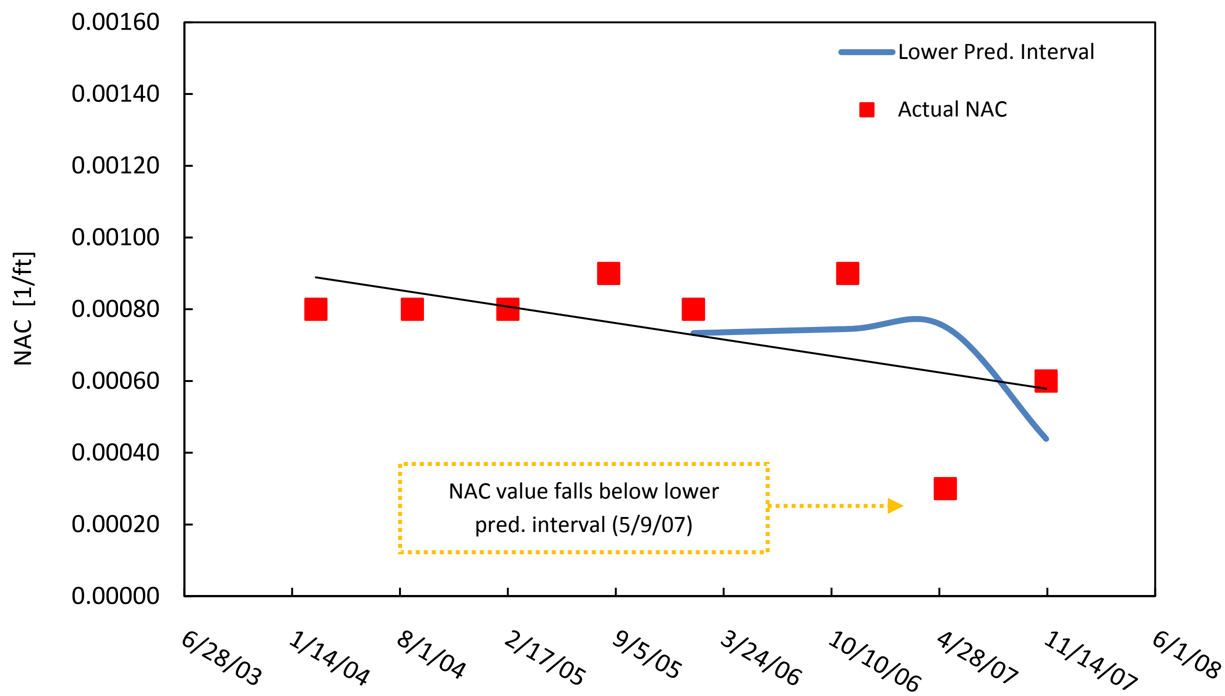

FIGURE 39: ONE-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENES, NORTH PLUME, NAES LAKEHURST

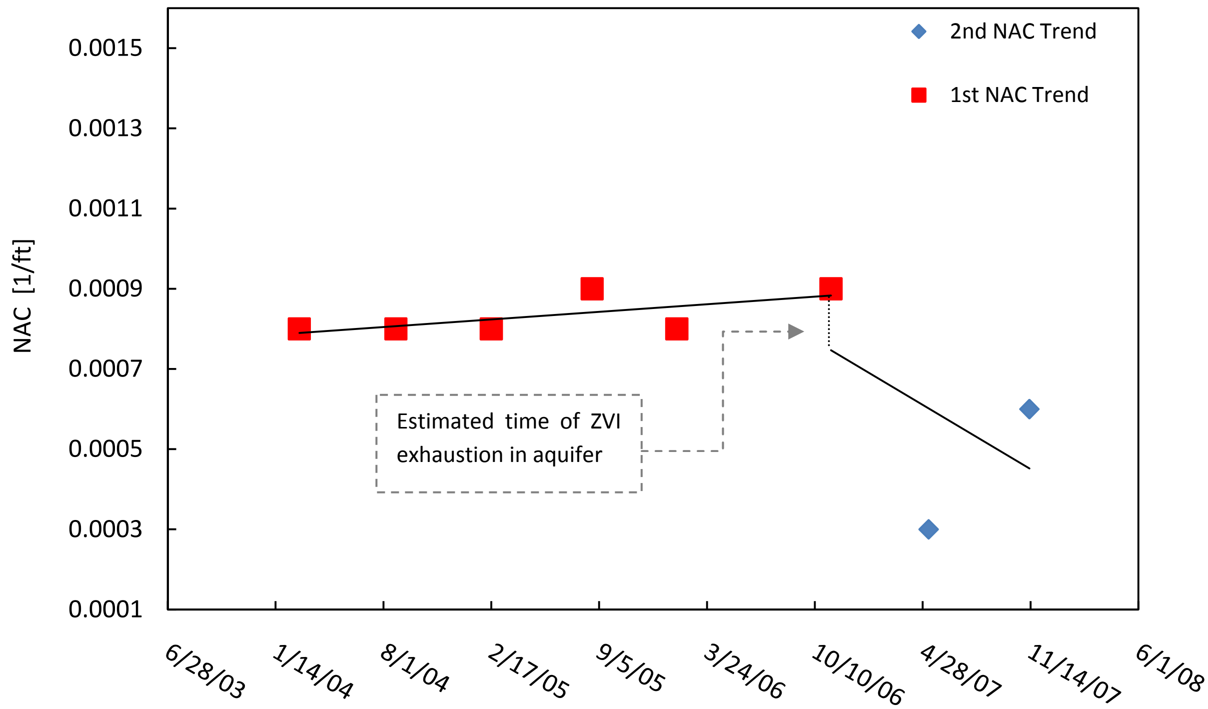

FIGURE 40: MULTI-LINEAR INTERPRETATION OF NAC TREND, NORTH PLUME, NAES LAKEHURST

4.2.2 Summary and Discussion of Key Findings

The north plume of sites I&J at NAES Lakehurst has demonstrated a slow reductive dechlorination for the duration of the time the plume has been studied. This is supported by the length of the plume through the aquifer system. The rate of the reductive dechlorination was determined to be slower than desired for achieving ARARs and so ZVI has been used as a catalyst in the attenuation processes. Although remediation has occurred as recent as November 2005, the current primary remedial mechanism being implored in recent years is MNA. MNA has been predicted to degrade contaminants to compliance levels within 48 years. Despite this projection, biannual monitoring will continue to determine if MNA is still degrading contaminants and if that process is slowing. The question remains: are the natural attenuation processes at the site sustainable and sufficient to achieve all ARARs?

Of the twenty-four sampling events, the most recent eight were selected for analysis. It is preferable to use data representing a non-transient and stable plume, but the most reliable data set available is characteristic of semi-steady state conditions where the impact of the most recent remedial action may still be affecting some of the measurements. Site data was manipulated into the form of NAC, the screening tool for evaluating sustainability. A linear regression analysis of NAC with respect to time shows that NAC at the north plume is not statistically changing (90% confidence), even though an initial observation of the data could lead to the conclusion that it is decreasing. Through the linear regression analysis a linear predictive model of the potentially decreasing NAC rate was estimated to be -2.29×10^{-7} ft^{-1}. A prediction interval for the next measurement was determined and revealed that the data may reflect one of two conditions: either (1) the second to last measurement is an outlier or (2) the monitoring of natural attenuation at the site in the last 12 months demonstrates a new NAC trend. Based on site remedial history, the latter is considered more likely, yet neither can be confirmed without more data. If the rate of attenuation is decreasing rapidly at the site, a new NAC value must be determined. This will require a sufficient number of sampling events after November 2005.

This site analysis demonstrates the value of the statistical process described and the effectiveness of a warning system approach. In this case, the two large residuals, rapidly changing prediction intervals and historical site remedial activity have all been used to highlight a potential shift in the capacity of the site for natural attenuation.

In summary of the north plume of sites I&J at NAES Lakehurst:

- In-efficient reductive dechlorination within contaminant plume (long plume)
- Tabular prediction interval for next measurement is best approach for Site
- ZVI ('02 & '05) caused plume to contract
- Assuming a single linear regression for NAC temporal trend;
    - Slope of is not different than zero, estimated as slightly decreasing
    - may be missing the real trend(s)
- Assuming a multiple linear regression for NAC temporal trend(s);
    - rapid expansion of PI is a warning of potential trend change
    - last 2 measurements may reflect a new trend (possibly due to exhaustion of ZVI)
    - future data may show a new NAC
- Successful "warning signal" effect from data

4.3 Statistical Analysis of Hill AFB, OU2

The plume at OU2 originated from the former practice of dumping used solvents, fuels and wastes into unlined trenches at Hill AFB. The geographic extent of the TCE contaminant plume is approximately 1500 ft long. TCE and PCE are found at the site, including forms of reduced chlorinated ethenes (cis-DCE and VC) (URS and Intera, 2003). The plume has been observed in semi-regular intervals by various agencies (see Chapter 3.3 for site history) from March 1987 to present day, although sufficient data for the plume line is available between February 1998 and April 2008 (most recent data not yet published). The plume source DNAPL settled at the bottom of the aquifer in topographic low points in the clay paleochannel. The stationary nature of the source led to the primary means of remediation at the site being source recovery through extraction wells and interceptor trenches. Other measures have included containment barriers. It has been estimated that 90% of the contaminant source has been removed by containment and extraction systems between 1993 and 2002 (URS and Intera, 2003).

No in-situ, chemical, or biological remediation has been done at OU2, thereby leaving no reason to expect the data to be affected biologically or chemically by factors outside the natural aquifer system. However, flow changes caused by containment structures could affect data results. The data being observed is from wells located downgradient of the extraction systems and containment barriers. The interceptor trenches are expected to have little impact on the measurements recorded (URS and Intera, 2003). The plume is stable and the source well, OU2-085, is located to the north east of the containment area. Water flow is generally to the north and north-east (URS and Interra, 2005).

Six wells were chosen for characterizing the plume over time. **Table 15** contains the well IDs, distance the well is from the source well, and the earliest date of available data. **Figure 41** is a plan view of the plume, including the well locations.

TABLE 15: WELL DESCRIPTIONS, OU2, HILL AFB

Well ID	Distance from source along plume line (ft)	First Available Sampling Event
OU2-085	0	2/6/1998
OU2-021R	407	5/26/1994
OU2-039	616	9/23/1998
OU2-043	717	9/28/1995
OU2-082	945	1/15/1998
OU2-086	1209	1/7/1998

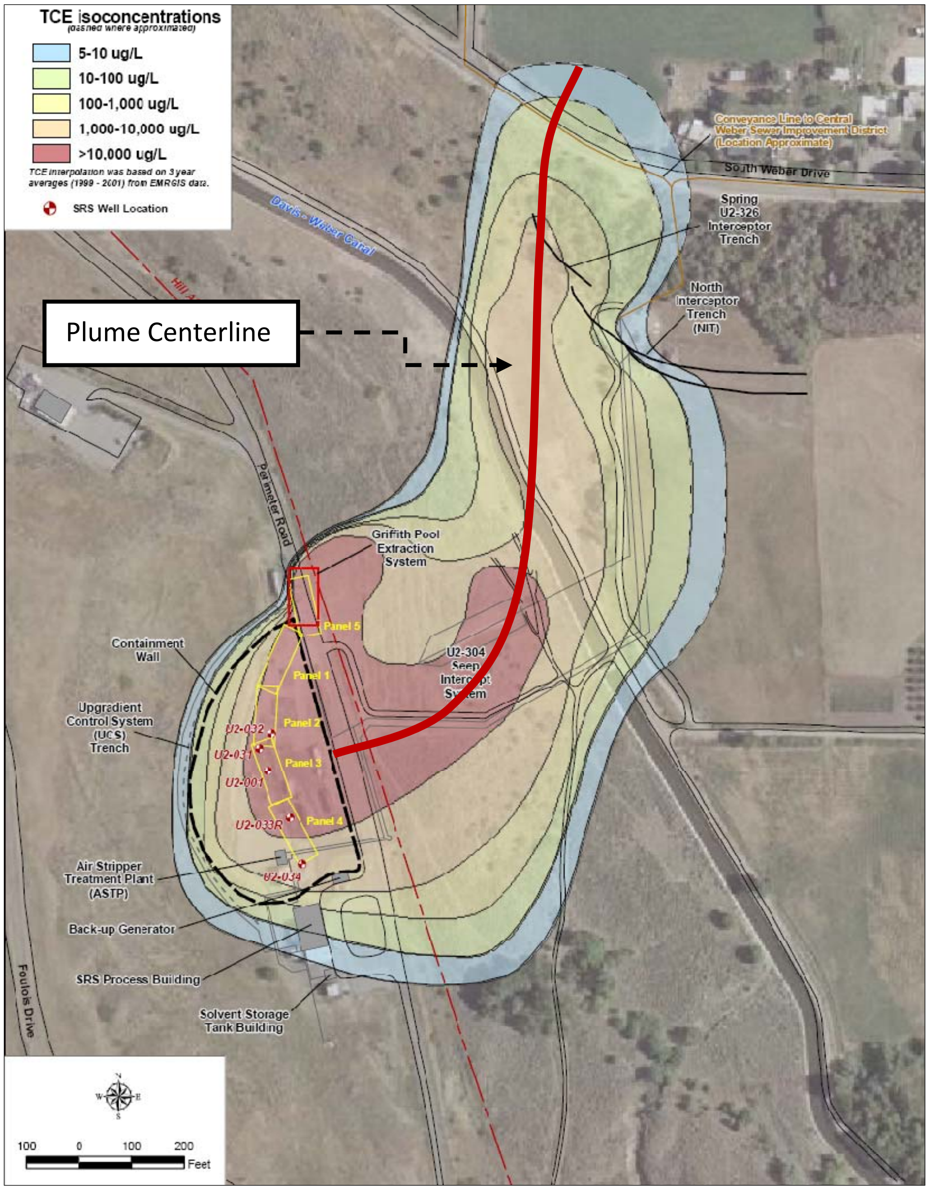

FIGURE 41: SITE MAP OF OU2 AND TCE PLUME EXTENTS, HILL AFB, OGDEN, UT (URS AND INTERRA, 2005)

Twenty-nine sampling events occurred between May 1994 and May 2008. From these sampling events, a smaller group of sampling events was formed based on the following criteria: a valid source well measurement, matching dates for sampling of 4 or more target wells, and the earliest measurements in the group to exhibit consistent trends with the bulk data set[iv]. These factors have been considered in

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[iv] "At the monitoring well immediately downgradient of the source (Well U2-085), the TCE concentration did not increase following construction of the wall, but instead tended to fluctuate with an increasing trend over time" (Widdowson et al., 2008, pp.D11). The sampling event on 2/6/1998 was not used because it exhibited the fluctuation described above and attributed to the affect of the containment wall on the groundwater flow.

the process of determining the most appropriate data to use for the analysis. In particular, it has been determined that data from 1999 to 2008 reflect stable plume conditions where rapid changes in constituent concentrations caused by remedial activity are not seen. Fifteen sampling events matched these criteria and will be used in the data analysis of the OU2 (**Table 16**). The full set of data is presented in **Appendix C**. **Figure 42** is a graphical representation of total chlorinated ethene concentrations at the source well, OU2-085, for these fifteen sampling events. The boundary conditions applied to the definition of NAC may be violated by the concentration data displayed in Figure 42. The boundary condition assumption is that the source well is non-transient. In this case the last 4 data measurement in Figure 42 may show a decreasing trend at the source well. This is noted in the conclusions, but four data points is too few to determine whether this trend will hold over time. **Figure 43** depicts the concentration of total chlorinated ethene in all six wells with respect to time. A decreasing trend without significant variation that is seen in the source well is also apparent in the other five wells. The redox conditions at the site can be described as oxic. Historic monitoring in the six wells show that a significant amount of oxygen is available in the plume and therefore, reductive dechlorination is not occurring (**Table 17**) (Widdowson et al, 2008). Although anaerobic biological degradation is not an active process at OU2, natural attenuation is being observed at the Site and can be attributed to sorption, dilution, advection, and potentially other aerobic degradation processes.

TABLE 16: TOTAL CHLORINATED ETHENE CONCENTRATION, OU2, HILL AFB

Sampling	Concentration Total Chlorinated Ethene (µg/L)					
Event	**USGS-5**	**IMW66**	**USGS-6**	**USGS-1**	**USGS-2**	**33G12**
3/24/1999	40774.3	7012.7	2017.6	2834.4	2400.8	69.48
6/24/1999	24062	3666	-	2362	1858	64
7/17/2000	35200	4362.2	-	2186	1414.3	71.4
1/11/2002	35176.4	4710.4	1079.8	1315.9	1477.7	-
6/27/2002	32458.4	4604.9	1625.5	1570.6	1554.7	74.2
10/2/2002	24046	5004	1374.35	1582.06	2037.5	62.2
11/3/2003	20754.7	3176.2	976.7	1383.1	1685.8	56.9
5/3/2004	35160.7	4322.3	666.6	1424.3	2291.6	67.9
10/14/2004	27048	2589.6	1401.6	1408.4	2184.4	46.3
5/6/2005	35654.6	2319.7	406.2	1429.6	2171.3	48.9
10/21/2005	24442.2	1656.1	829.7	1057.5	1663.7	65.9
5/16/2006	22156.3	1735.9	677.6	1084.4	1792.9	51.1
10/13/2006	19846.9	2227	961.6	1236.3	2025.5	48.4
4/26/2007	15643.4	1812.4	727.6	1225.8	1628.1	40.8
10/5/2007	13745.1	1902.2	477.8	860.8	1222.4	34.8

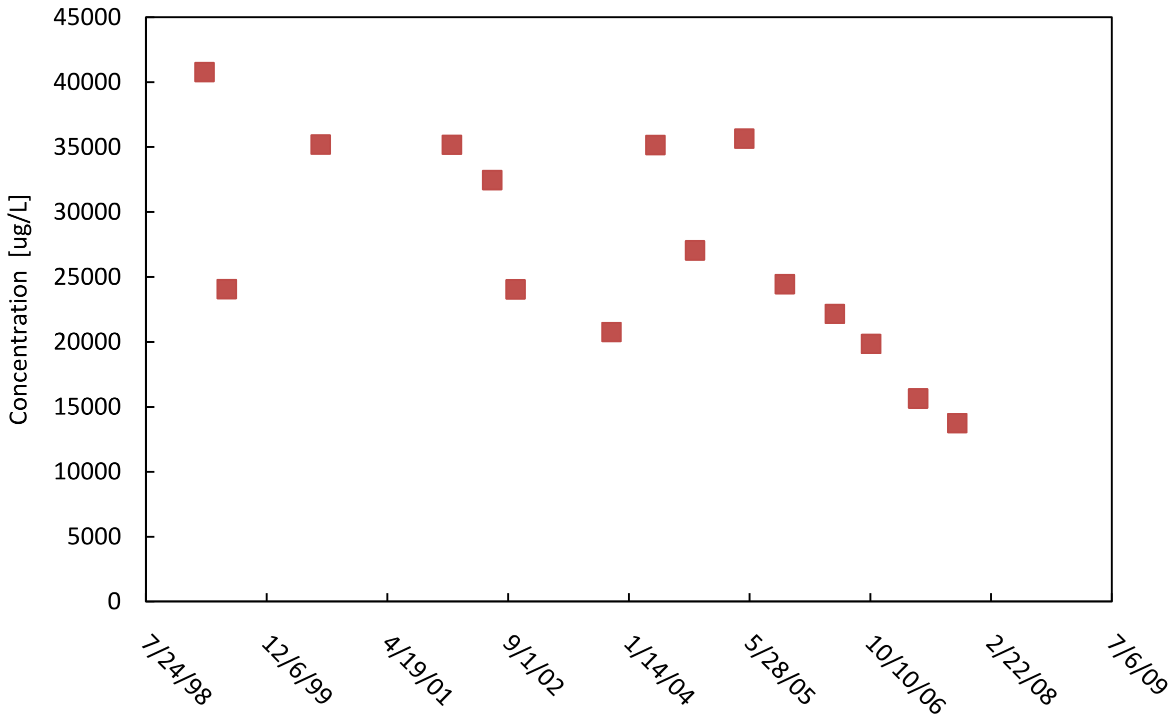

FIGURE 42: TOTAL CHLORINATED ETHENE CONCENTRATIONS AT THE SOURCE, WELL OU2-085, HILL AFB

TABLE 17: TOTAL CHLORINATED ETHENE CONCENTRATION, OU2, HILL AFB

Well Name	Oxygen [mg/L]	Nitrate [mg/L]	Iron(II) [mg/L]	Sulfate [mg/L]	Redox Condition
U2-085	3.3	4.578	0.04	41	Oxic
U2-021R	3.4	0.007	NS	80	Oxic
U2-039	2.7	BD	NS	30	Oxic
U2-043	13.48	2.9	0.056	NS	Oxic
U2-082	243.34	3.6	4861	BD	Oxic

BD – Below Detection
NS – Not Sampled

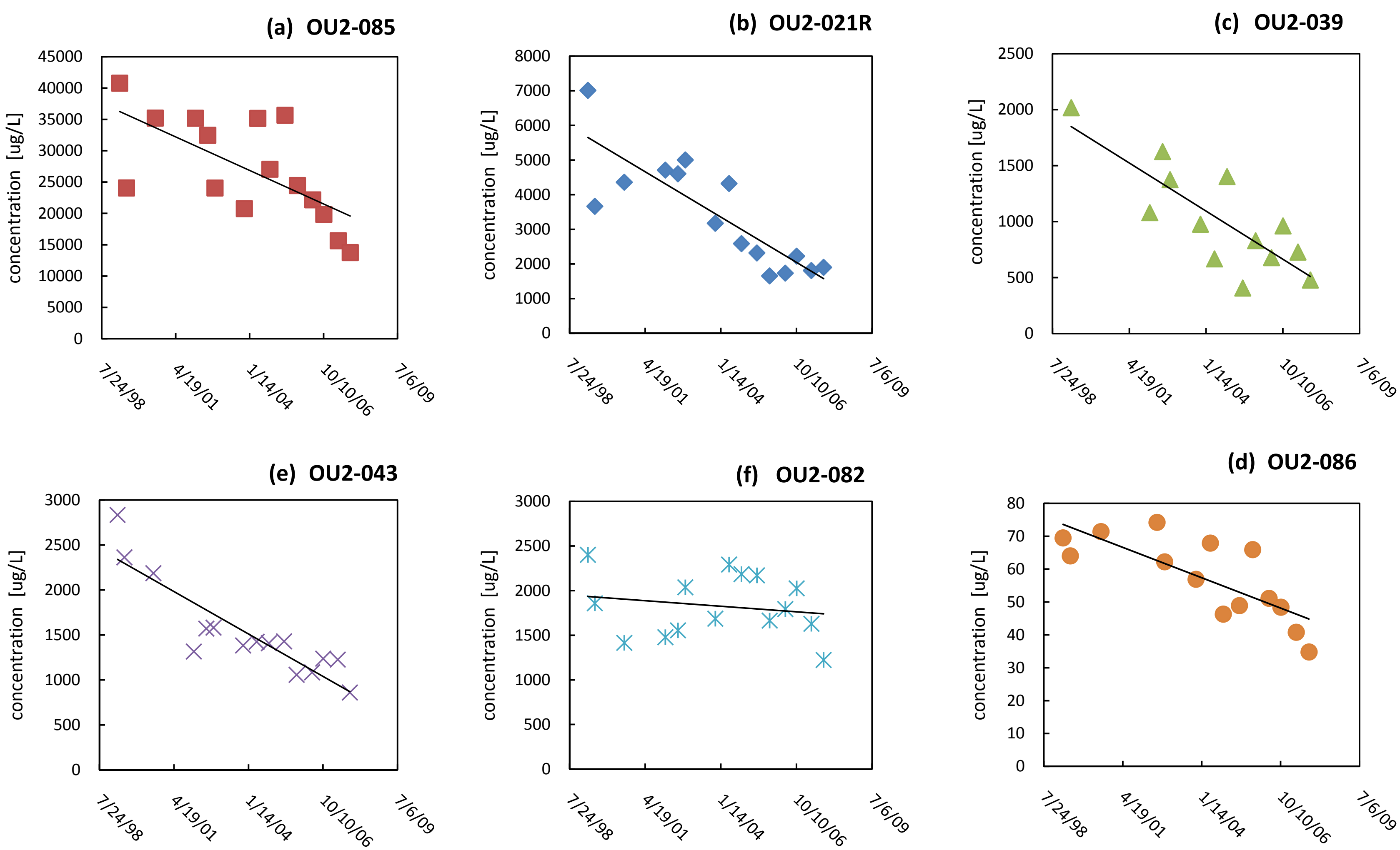

FIGURE 43: TOTAL CHLORINATED ETHENE CONCENTRATIONS IN VARIOUS WELLS ALONG THE PLUME CENTERLINE, OU2, HILL AFB

4.3.1 Utilizing NAC as a statistical screening tool

NAC is determined by finding the slope of the solute concentration profile. **Figure 44** is a solute profile from OU2 of the sampling event on June 27, 2002. The independent variable in the figure is distance along the plume centerline, and the NAC value is highlighted as the slope of the trend. This analysis is completed for each sampling event to find the NAC for total chlorinated ethenes and other dominant chlorinate ethene constituents. The slope of the total chlorinated ethene concentration profile in Figure 44 is -0.0044 (μg/L-ft), corresponding to the NAC value of 0.0044 (1/ft).

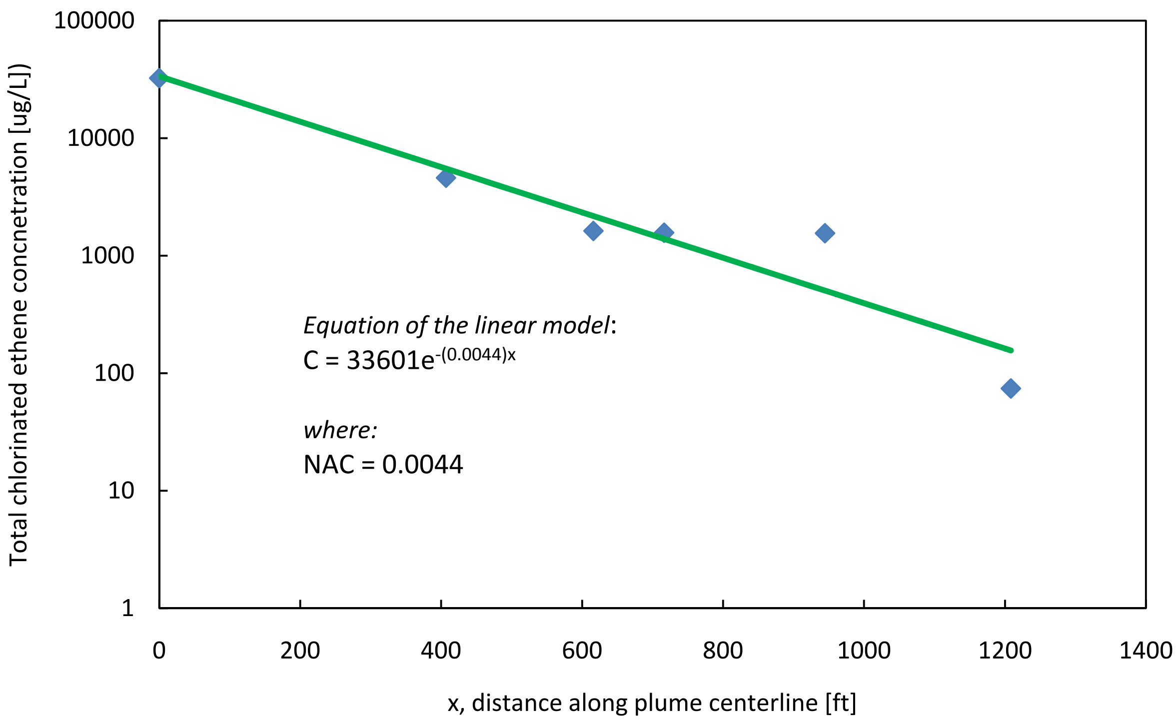

FIGURE 44: SOLUTE CONCENTRATION PROFILE, TOTAL CHLORINATED ETHENE, 6/27/02, OU2, HILL AFB

The NAS software package is used to determine NAC values the parent constituent (TCE) and total chlorinated ethene for every sampling event, shown for OU2 in **Table 18**. The time trend of NAC for TCE and total chlorinated ethenes are displayed in **Figure 45**. TCE is displayed in the figure with total chlorinated ethene because it is the parent chlorinated ethene and the plume is estimated to be more than 70% TCE, with the next most concentrated chlorinated ethene being 9% PCE (Widdowson, Chapelle, Casey, & Kram, 2008). Therefore, TCE has a significant impact on the total chlorinated ethene NAC values and trend.

TABLE 18: NAC VALUES, OU2, HILL AFB

Sampling Event	Total Clor. Ethenes	TCE
3/24/1999	0.0046	0.0046
6/24/1999	0.0038	0.0038
7/17/2000	0.0045	0.0046
1/11/2002	0.0046	0.0047
6/27/2002	0.0044	0.0045
10/2/2002	0.0043	0.0043
11/3/2003	0.0041	0.0041
5/3/2004	0.0044	0.0044
10/14/2004	0.0043	0.0044
5/6/2005	0.0044	0.0043
10/21/2005	0.004	0.004
5/16/2006	0.0041	0.0039
10/13/2006	0.0041	0.004
4/26/2007	0.004	0.0039
10/5/2007	0.0041	0.004

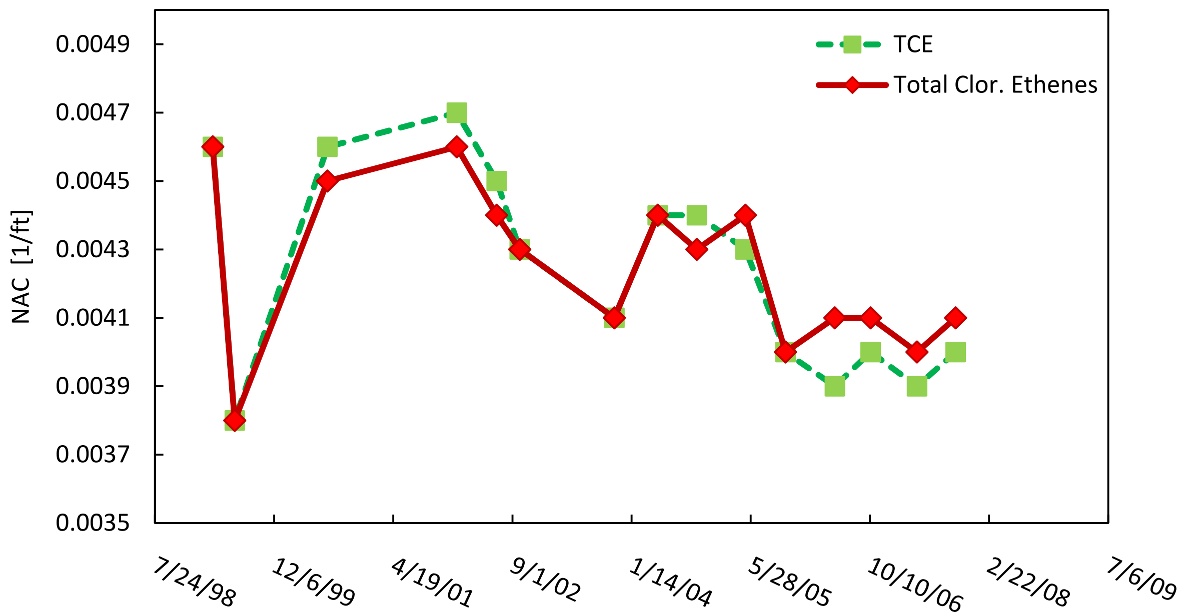

FIGURE 45: NAC AS A FUNCTION OF TIME, OU2, HILL AFB

4.3.1.1 Linear Regression

A linear regression is performed on the time trend series of NAC values. A thorough explanation of the purpose and description of the linear regression has been provided in Chapter 2.3. The hypothesis question is stated, *"Is the slope of the linear regression equal to zero?"* The complete results of the linear regression analysis, which is the statistical tool used to evaluate the hypothesis are contained in **Appendix C**. **Table 19** is a summary of the linear regression results which includes a 90% prediction interval around the predicted model. The mathematic description of the predicted model is **Equation 12**.

TABLE 19: SUMMARY OF SLOPE ESTIMATE FROM LINEAR REGRESSION ANALYSIS OF NAC AS A FUNCTION OF TIME, NAC OF TOTAL CHLORINATED ETHENES, OU2, HILL AFB

Statistic	Value
*Slope estimate, (β_1)	-9.669E-08
Alpha. (α)	0.10
Standard Error (β_1)	5.976E-08
t Stat (β_1)	-1.6181
P-value	0.1296
Lower Confidence Interval, 90%	-2.025E-07
Upper Confidence Interval, 90%	9.134E-09

**slope of NAC changing with respect to time*

$$NAC = -9.669x10^{-8}\left(t^{v}\right) + 0.007917 \qquad \textbf{Equation 12}$$

The linear regression analysis fits the most appropriate linear model to the data set. In doing so, a valid prediction of future trends is possible as long as the residual values are reasonably small. It is apparent from **Figure 46** that the largest and only significant residual is the second measurement (6/24/1999), which gives evidence that a single linear regression is a suitable model for predicting natural attenuation at the site. A residual plot is provided in **Appendix C**. However, the primary purpose of the linear regression is to test the hypothesis. The estimated slope of the predicted model is $[-9.669x10^{-8}]$ slightly negative, but at such a small degree that there may not be any slope to the actual data. The p-value (0.1296), a more robust test of the slope sign, is greater than the alpha (0.10) value leading to the conclusion that the slope of the line is not statistically different than zero. The last check prescribed in this method is to determine if zero is within the 90% confidence intervals. It does, therefore, the conclusion is to fail to reject the null hypothesis. The slope of the data is not statistically different than

[v] Time (t) is in days, where day 1 corresponds to January 1, 1900.

zero. If the confidence interval was lowered to 80% then the conclusion would be to reject the null hypothesis. This fact emphasizes the importance of thoughtful determination of the most appropriate confidence level for a particular site.

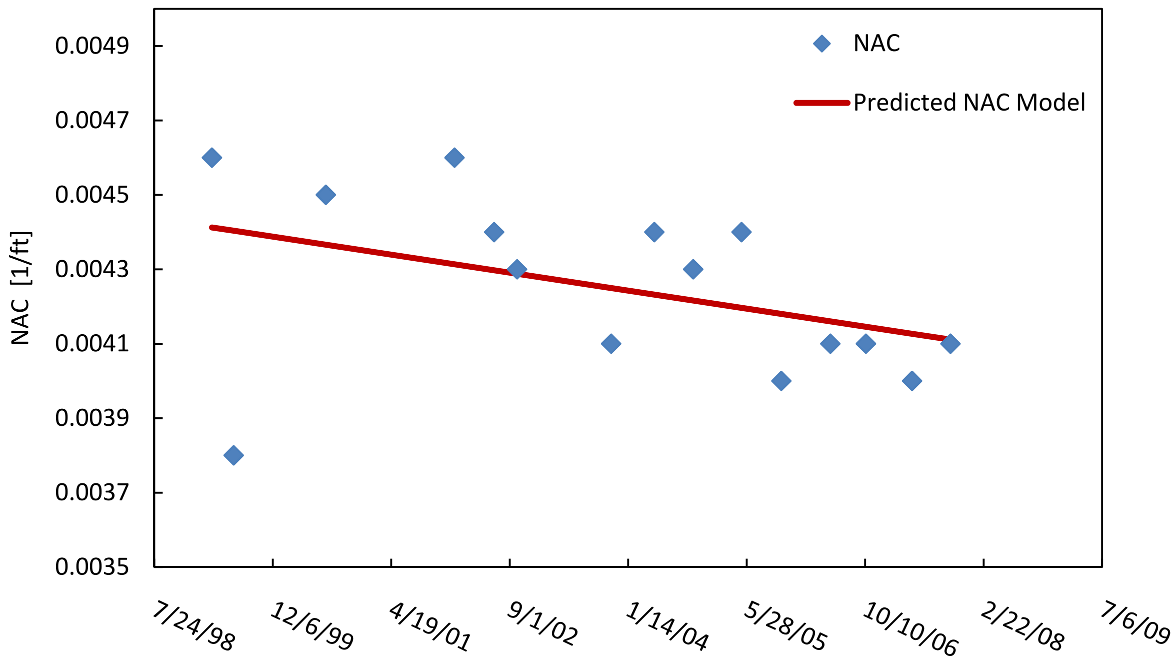

FIGURE 46: PREDICTED LINEAR MODEL AND ACTUAL NAC VALUES, TOTAL CHLORINATED ETHENES, OU2, HILL AFB

4.3.1.2 Tabular method of determining prediction intervals for the next single measurement

The tabular method of determining prediction intervals for the next single measurement is most appropriate for the Site given that the linear regression slope has been determined to be not different than zero. It involves a step-wise process followed by interpreting the statistical output. The data for OU2 is processed through a series of calculations with the help of a statistical program, R. R is used to determine the Student's t value and to conduct the Shapiro Wilk test of normality on with each new measurement. The results for OU2 are displayed in **Tables 20** and **21**. Table 20 displays the two-sided prediction interval, which is displayed graphically in **Figure 47**. Table 21 displays the one-sided prediction interval, which is displayed graphically in **Figure 48**. Of the fifteen NAC values that are statistically tested for whether they comply with the two prediction interval sets, no measurement falls outside the limits.

Calculating prediction intervals in this way assumes that the trend has a slope of zero, allowing the prediction interval to be made without the use of the independent variable, time. This assumption is not completely met and may account for the inclination of the data to fall closer to the lower prediction interval. The second assumption required for this method is that the data is normally distributed. The data is normally distributed as evidenced by the Shapiro-Wilk tests displayed in Tables 19 and 20.

TABLE 20: DETERMINATION OF TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT AND QUALITATIVE INTERPRETATION, OU2, HILL AFB

DATE	NAC	Mean	Std. Dev.	Sample No.	Student's t	Shapiro Wilk, p-value*	Two-sided, Upper PI**	Two-sided, Lower PI**	Qualitative Evaluation
3/24/99	0.00460								
6/24/99	0.00380								
7/17/00	0.00450								
1/11/02	0.00460								
6/27/02	0.00440	0.00438	0.00	5	2.13185	0.0303			
10/2/02	0.00430	0.00437	3.01E-04	6	2.01505	0.0781	5.162E-03	3.598E-03	
11/3/03	0.00410	0.00433	2.93E-04	7	1.94318	0.2985	5.022E-03	3.711E-03	The NAC value (0.00410) is within the PI (0.005162, 0.003598), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
5/3/04	0.00440	0.00434	2.72E-04	8	1.89458	0.2060	4.937E-03	3.720E-03	The NAC value (0.00440) is within the PI (0.004937, 0.003720), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
10/14/04	0.00430	0.00433	2.55E-04	9	1.859548	0.2246	4.885E-03	3.790E-03	The NAC value (0.00430) is within the PI (0.004885, 0.003790), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
5/6/05	0.00440	0.00434	2.41E-04	10	1.833113	0.1265	4.833E-03	3.834E-03	The NAC value (0.00440) is within the PI (0.004833, 0.003834), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
10/21/05	0.00400	0.00428	2.44E-04	11	1.81246	0.2780	4.804E-03	3.876E-03	The NAC value (0.00400) is within the PI (0.004804, 0.003876), the newest NAC value does NOT reflect a change from the previously established site degradation rate.

DATE	NAC	Mean	Std. Dev.	Sample No.	Student's t	Shapiro Wilk, p-value*	Two-sided, Upper PI**	Two-sided, Lower PI**	Qualitative Evaluation
5/16/06	0.00410	0.00431	1.91E-04	12	1.79589	0.4432	4.742E-03	3.818E-03	The NAC value (0.00410) is within the PI (0.004742, 0.003818), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
10/13/06	0.00410	0.00427	1.89E-04	13	1.78229	0.4979	4.667E-03	3.953E-03	The NAC value (0.00410) is within the PI (0.004667, 0.003953), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
4/26/07	0.00400	0.00421	1.66E-04	14	1.77093	0.4803	4.619E-03	3.921E-03	The NAC value (0.00400) is within the PI (0.004619, 0.003921), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
10/5/07	0.00410	0.00418	1.55E-04	15	1.76131	0.4230	4.515E-03	3.905E-03	The NAC value (0.00410) is within the PI (0.004515, 0.003905), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
Next Value	TBD						4.462E-03	3.898E-03	TBD with next sampling event

**alpha value for Shapiro-Wilk test is 0.05*

**alpha value for Prediction Interval is 0.10

TABLE 21: DETERMINATION OF ONE-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT AND QUALITATIVE INTERPRETATION, OU2, HILL AFB

DATE	NAC	Mean	Std. Dev.	Sample No.	Student's t	Shapiro Wilk, p-value*	One-sided, Lower PI**	Qualitative Evaluation
3/24/99	0.00460							
6/24/99	0.00380							
7/17/00	0.00450							
1/11/02	0.00460							
6/27/02	0.00440	0.00438	0.00033	5	1.53321	0.0303		
10/2/02	0.00430	0.00437	0.00030	6	1.47588	0.0781	3.82E-03	
11/3/03	0.00410	0.00433	0.00029	7	1.43976	0.2985	3.89E-03	The NAC value (0.00410) is GREATER than the lower, one-sided PI (0.00389), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
5/3/04	0.00440	0.00434	0.00027	8	1.41492	0.2060	3.88E-03	The NAC value (0.00440) is GREATER than the lower, one-sided PI (0.00388), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
10/14/04	0.00430	0.00433	0.00025	9	1.396815	0.2246	3.93E-03	The NAC value (0.00430) is GREATER than the lower, one-sided PI (0.00393), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
5/6/05	0.00440	0.00434	0.00024	10	1.383029	0.1265	3.96E-03	The NAC value (0.00440) is GREATER than the lower, one-sided PI (0.00396), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
10/21/05	0.00400	0.00431	0.00025	11	1.37218	0.2780	3.99E-03	The NAC value (0.00400) is GREATER than the lower, one-sided PI (0.00399), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
5/16/06	0.00410	0.00429	0.00025	12	1.36343	0.4432	3.95E-03	The NAC value (0.00410) is GREATER than the lower, one-sided PI (0.00395), this newest NAC value does NOT reflect a change in the previously established site degradation trend.

DATE	NAC	Mean	Std. Dev.	Sample No.	Student's t	Shapiro Wilk, p-value*	One-sided, Lower PI**	Qualitative Evaluation
10/13/06	0.00410	0.00428	0.00024	13	1.35622	0.4979	3.94E-03	The NAC value (0.00410) is GREATER than the lower, one-sided PI (0.00394), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
4/26/07	0.00400	0.00426	0.00024	14	1.35017	0.4803	3.94E-03	The NAC value (0.00410) is GREATER than the lower, one-sided PI (0.00394), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
10/5/07	0.00410	0.00425	0.00024	15	1.34503	0.4230	3.92E-03	The NAC value (0.00410) is GREATER than the lower, one-sided PI (0.00392), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
Next Value	TBD						3.92E-03	TBD with next sampling event

**alpha value for Shapiro-Wilk test is 0.05*

**alpha value for Prediction Interval is 0.10

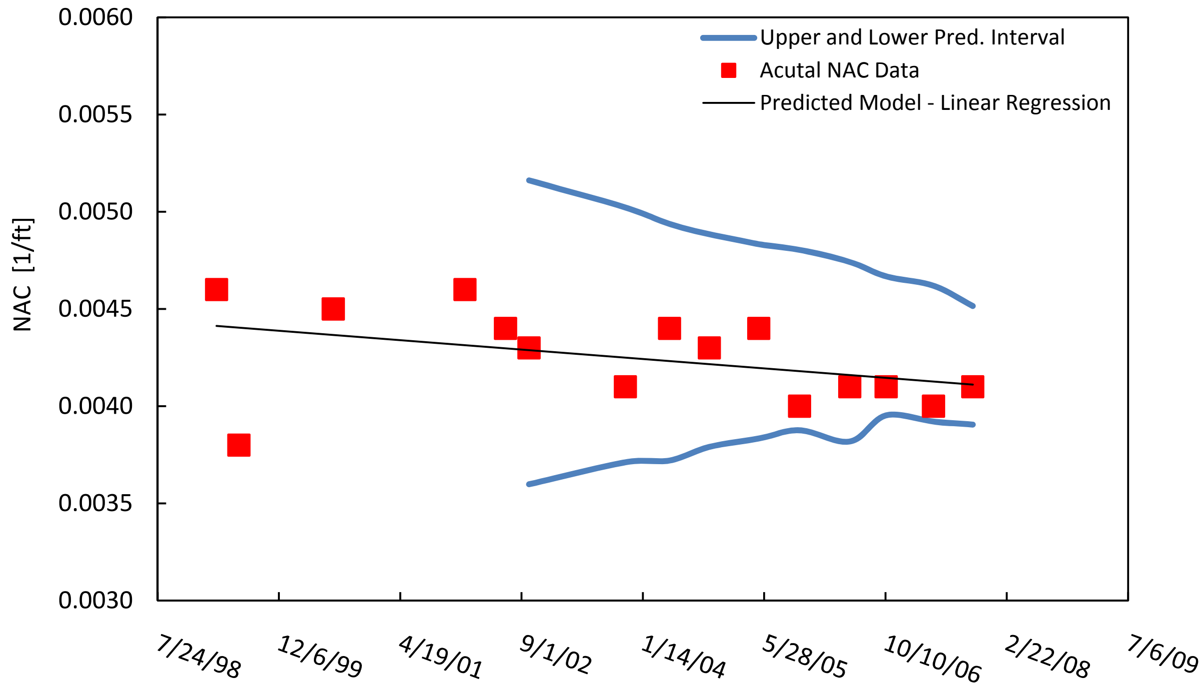

FIGURE 47: TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENES, OU2, HILL AFB

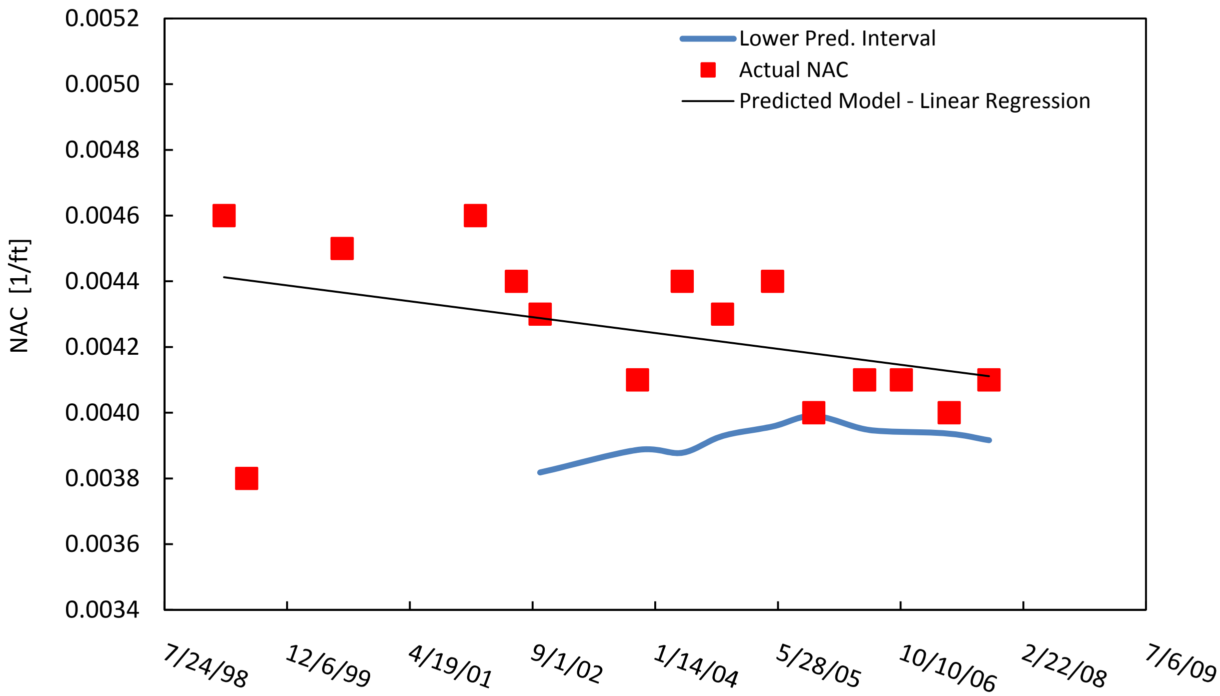

FIGURE 48: TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENES, OU2, HILL AFB

4.3.2 *Summary and Discussion of Key Findings*

OU2 at Hill AFB, Utah is a site where reductive dechlorination is not believed to be taking place do to the high levels of oxygen in the aquifer. It has been estimated that 90% of the contaminant mass (approximately 70% TCE) has been removed through pump and treat systems. Almost all of the source areas have containment barriers to prevent groundwater migration and transport of the solvents (URS and Intera, 2003). The plume down-gradient of the source area is considered to be stable, yet attenuating very slowly by means of dilution, sorption, and potentially other aerobic biological or chemical processes. This is shown by the very long plume (1500 feet), which stretches off of the installation boundary, and eventually drops below regulatory limits (Widdowson, Chapelle, Casey, & Kram, 2008). The appearance of a decreasing trend (last 4 years) in the source concentration data is of some concern given the assumption of a non-transient source. If the source continues to show a transient trend, then the mathematical basis for this determination of the NAC value is no longer valid because the boundary conditions have been altered.

Of the twenty-seven sampling events, fifteen events meet the criteria necessary for this analysis, including: a valid source well measurement, matching dates for sampling of 4 or more target wells, and the earliest measurements to be exhibiting consistent trends with the bulk data set. The remediation activities did not involve in-situ injections and therefore had limited affect on the stability of the plume down-gradient of the source. Site data was manipulated into the form of NAC, the screen tool for evaluating sustainability. A linear regression analysis of NAC with respect to time shows that the slope of the trend in not statistically different than zero at a confidence of 90%. The linear regression also estimates that the trend is slightly decreasing according to the following equation:

$$NAC = -9.669x10^{-8}\,(Date) + 0.007917$$

Further, the prediction interval for the next measurement concludes that each new measurement from the sixth through the fifteenth is within the 90% prediction interval. The prediction interval developed by this method does not show any sudden changes, rather consistently becomes more narrow with additional data points.

In summary of OU2 at Hill AFB:

- Slow natural attenuation, no significant reductive dechlorination observed
- Tabular prediction interval for next measurement is best approach for Site
  - Although data appears to be approaching the lower prediction interval (indication of slope actually being negative)
- Assuming a single linear regression of NAC v. time trend (90% conf level)
  - slope not different than zero
  - estimate of slope is slightly decreasing
  - Prediction interval narrows, indicates the linear prediction model is a good fit
- Boundary conditions may be violated by a transient source

4.4 Statistical Analysis of NASNI, IR Site 5

The Unit 2 plume at IR site 5 originated from liquid disposal pits where waste solvents were regularly dumped over an extended period of time. The plume is approximately 500 ft long and contains the parent constituents of PCE and TCE as well as daughter forms of chlorinated ethenes, cis-DCE and VC. The source area is monitored by well S5-MW-21. **Table 22** contains the well IDs, distance the well is from the source, and the earliest sampling event date of the available data. **Figure 49** is a plan view of the plume area with isopleth lines of total chlorinated ethenes (Wiedemeier and Associates, 2006).

TABLE 22: WELL DESCRIPTIONS, IR SITE 5, NASNI

Well ID	Distance from source along plume line (ft)	First Available Sampling Event
S5-MW-21	0	September 8, 1998
S5-MW-26	71	March 24, 1997
S5-MW-20	187	September 8, 1998
S5-MW-12	372	March 24, 1997
S5-MW-19	609	March 24, 1997

Numerous investigations beginning in 1983 have been conducted to trace the history of waste disposal activities at the site and to delineate areas of groundwater contamination. In addition, partial excavation of the source occurred in 1999. In-situ chemical oxidation was implemented in several stages between 1999 and 2003 in order to reduce the source mass into nonhazardous compounds. Since that time MNA has remained the primary remedial mechanism at the site. A natural attenuation evaluation was performed by Parsons in 1997-1998, where evidence was shown that the VOC plume was stable or receding as a result of natural attenuation. The 2006 Evaluation of MNA concluded that the natural attenuation at the site was efficiently reducing the contaminant mass through reductive dechlorination (Wiedemeier and Associates, 2006). The timeline of remedial activity is important in determining what data is best for use in the statistical analysis. The goal is to measure natural attenuation changes and to do so one must limit nonrelated noise in the data from remedial activity.

North Island is a unique site in comparison to the other four sites considered in this report. The contaminants were originally TCE and PCE based on historical knowledge of operations at the facility. However, TCE and PCE made up less than 0.1% of the contaminant mass in the source well in 1998. Through rapid reductive dechlorination at this mature site the parent contaminants have been almost completely reduced to the daughter compounds of cis-DCE and VC, both of which are very concentrated within the plume. These daughter constituents are further reduced to nonhazardous compounds within several hundred feet of the source. Ethene and chloride have been measured at elevated concentrations along the plume line giving “further evidence that extremely efficient reductive dechlorination of chlorinated compounds is occurring at the site” (Wiedemeier and Associates, 2006). The sampling data is presented in **Appendix D**.

Reliable data regarding PCE and TCE is very limited due to the high detection limits required to detect cis-DCE and VC in the groundwater samples. As a result, most of the TCE and PCE measurements are recorded as “less than” values. TCE and PCE measurements have been excluded from the total chlorinated ethene concentration because they are inexact and negligible in comparison to cis-DCE and VC concentrations at the Site.

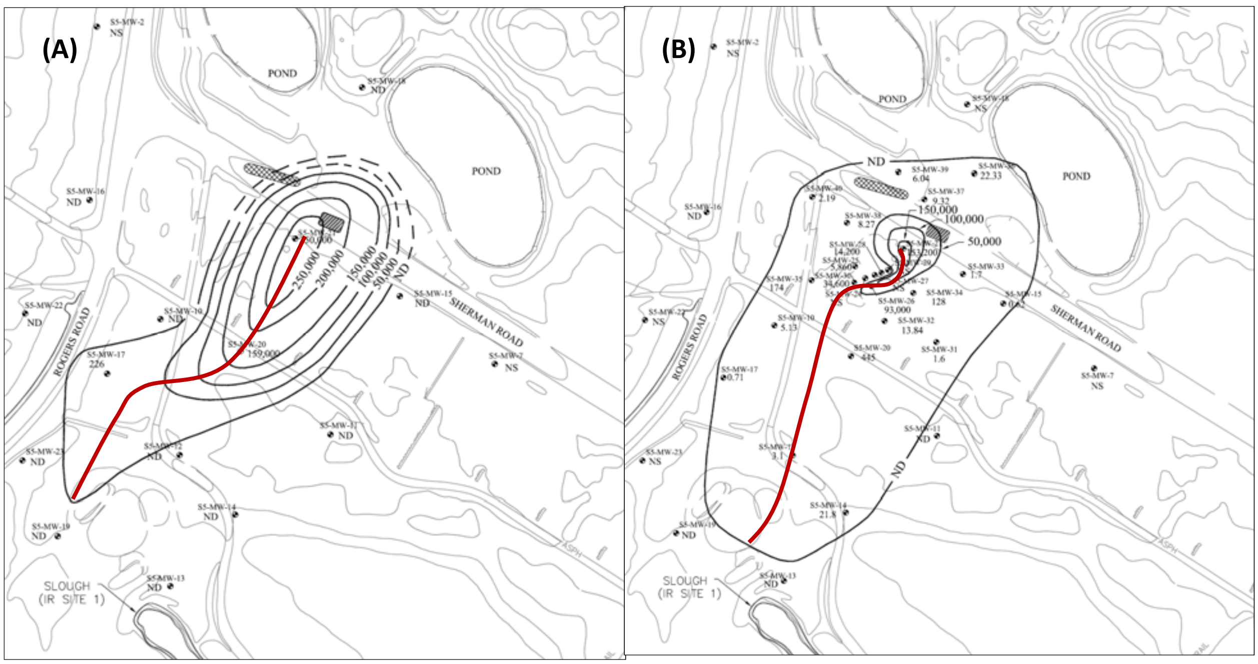

FIGURE 49A AND 49B: PLAN VIEW ISOPLETH MAPS FOR CHLROINATED ETHENES AT NASNI WITH PLUME CENTERLINE, (A) OCT 1997, (B) OCT 2005 (WIEDEMEIER AND ASSOCIATES, 2006)

Twelve sampling events occurring between 1997 and 2005 were chosen based on a sufficient number of measurements from the five centerline wells needed to determine a NAC value. **Figure 50** is a graphical representation of total chlorinated ethene concentrations at the source well, S5-MW-21. No trend is immediately obvious from the data at the source well. Stability of the plume was formally determined prior to the in-situ chemical oxidation at the Site in 1999. **Figure 51a-e** demonstrates the rapid transformation of chlorinated ethenes to reduced daughter products in the reductive dechlorination process. Particularly notable is the severe drop in concentration between wells S5-MW-20 and S5-MW-12 (Figure 51c-d). Plume stability is not expected between 2000 and 2003 because of the chemical oxidation injections, and this is corroborated by the variability of trends in Figure 51. **Table 23** displays the resulting total chlorinated ethene concentrations for the target time period (Wiedemeier and Associates, 2006).

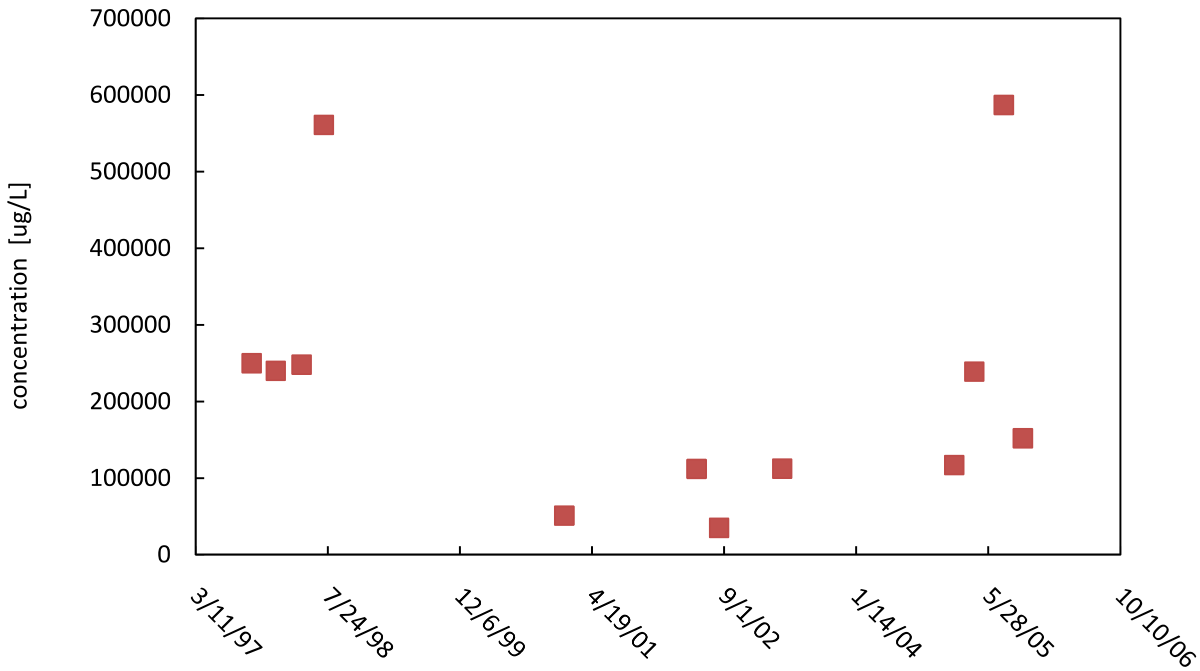

FIGURE 50: TOTAL CHLORINATED ETHENE CONCENTRATIONS AT THE SOURCE, WELL S5-MW-21, IR SITE 5, NASNI

TABLE 23: TOTAL CHLORINATED ETHENE CONCENTRATION, IR SITE 5, NASNI

Sampling	Concentration Total Chlorinated Ethene (µg/L)				
Event	**S5-MW-21**	**S5-MW-26**	**S5-MW-20**	**S5-MW-12**	**S5-MW-19**
10/9/1997	250000	NS	157000	BD	BD
1/8/1998	240000	NS	220000	BD	BD
4/16/1998	248000	NS	184000	44	BD
7/9/1998	561000	NS	101000	BD	BD
1/4/2001	51000	NS	1490	BD	BD
5/20/2002	112000	13400	24	NS	NS
8/13/2002	35000	13980	14	NS	NS
4/9/2003	112300	NS	7	BD	BD
1/19/2005	117000	91,000	25	2	NS
4/5/2005	239000	89,000	47	23	3
7/26/2005	587000	87,000	801	45	BD
10/6/2005	152000	93,000	445	3	BD

NS – not sampled
BD – below detection limits

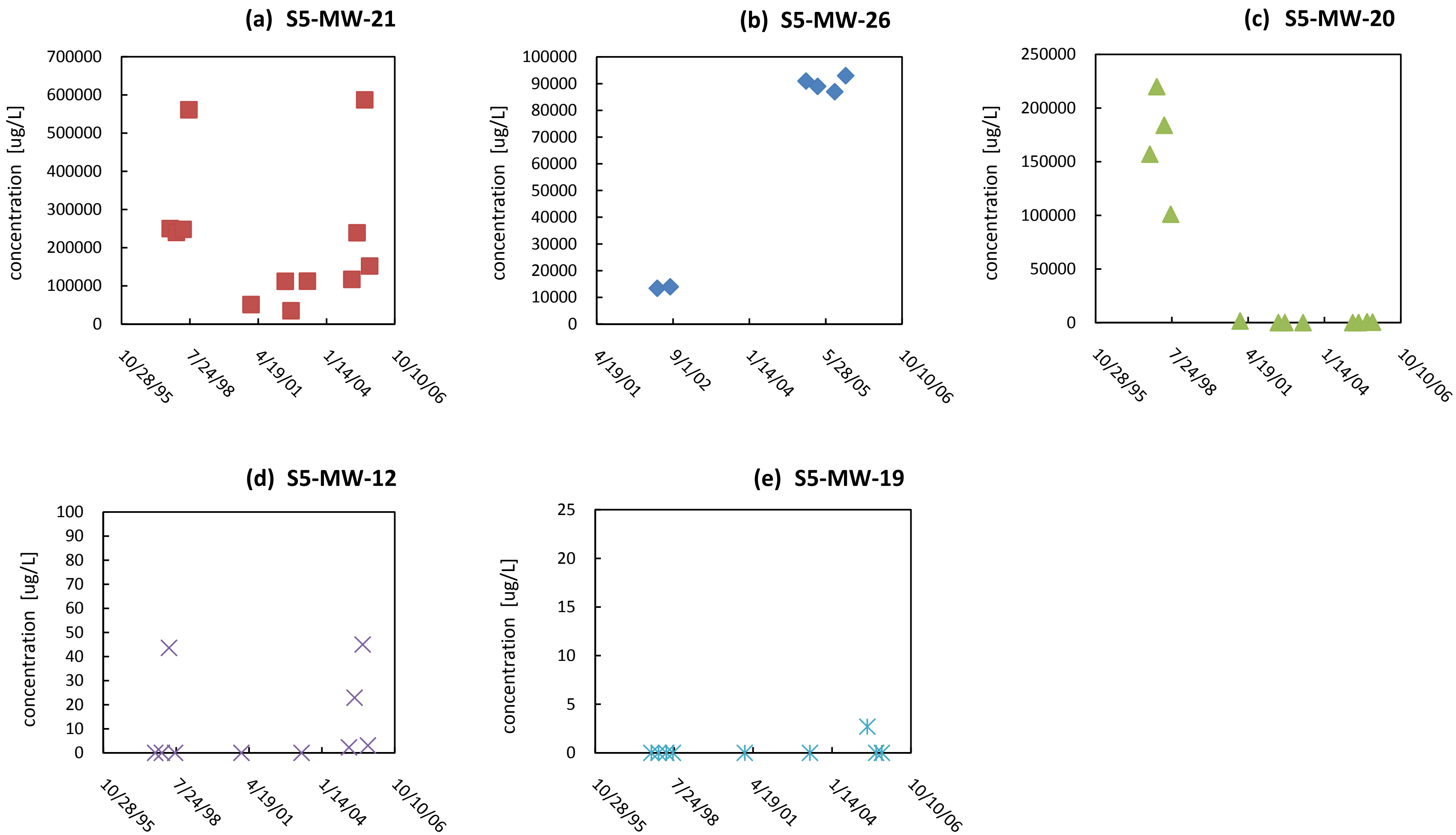

FIGURE 51: TOTAL CHLORINATED ETHENE CONCENTRATIONS IN VARIOUS WELLS ALONG PLUME CENTERLINE, IR SITE 5, NASNI

4.4.1 Utilizing NAC as a statistical screening tool at IR Site 5, NASNI

NAC is determined by finding the slope of the solute concentration profile. **Figure 52** is a solute profile from IR Site 5 of the sampling event on July 26, 2005. The independent variable in the figure is distance along the plume centerline, and the NAC value is highlighted as the slope of the trend. This analysis is completed for each sampling event to find the NAC for total chlorinated ethenes and other dominant chlorinate ethene constituents. The slope of the total chlorinated ethene concentration profile in Figure 52 is -0.026 [µg/L-ft], corresponding to the NAC value of 0.026 [ft^{-1}].

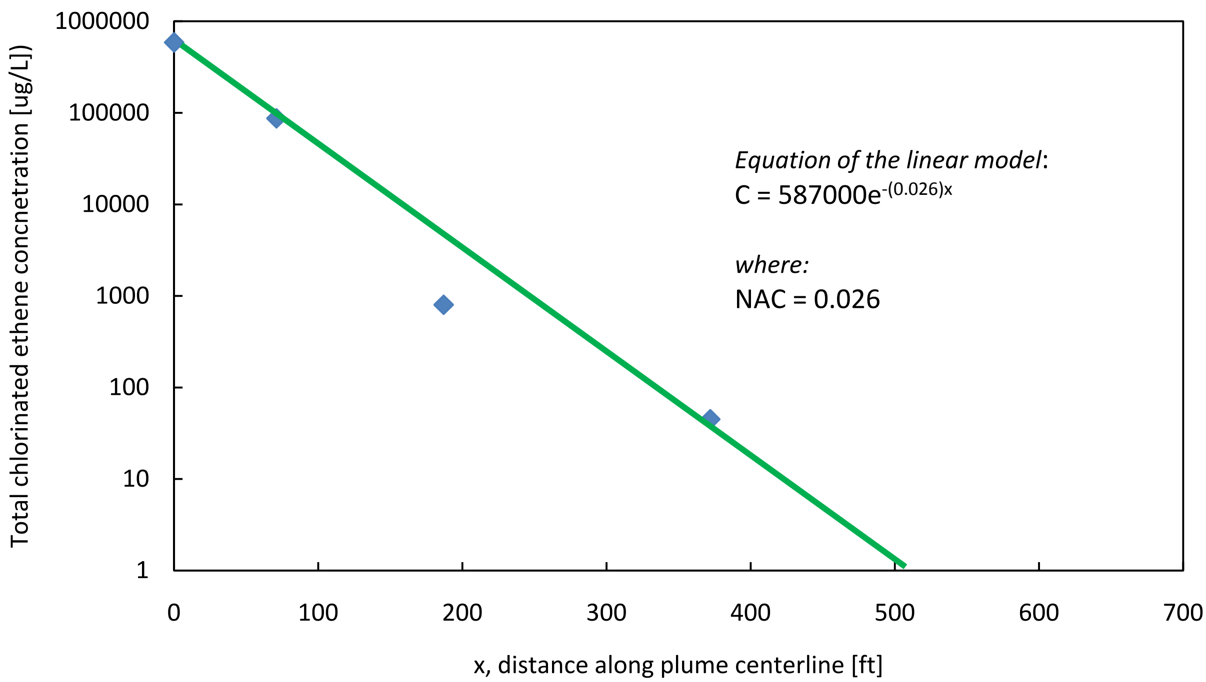

FIGURE 52: SOLUTE CONCENTRATION PROFILE, TOTAL CHLORINATED ETHENE, 7/26/05, IR SITE 5, NASNI

The parent compounds TCE and PCE were the actual constituents disposed of at IR Site 5, however; concentrations of cis-DCE and VC are as much as three orders of magnitude greater than TCE and PCE in the time period being evaluated. The total chlorinated ethene concentration is mostly composed of these two daughter compounds. NAC values for cis-DCE and total chlorinated ethene were determined at every sampling event (**Table 24**) and the time trends of NAC for these two constituents are displayed in **Figure 53**. TCE was not included in this analysis because most of the measurements were below detection limits. The general trend of NAC for total chlorinated ethenes appears to be increasing with time. The following statistical analysis will evaluate the total chlorinated ethene measurements as a linear trend.

TABLE 24: NAC VALUES, IR SITE 5, NASNI

Sampling Event	Total Clor. Ethenes	cis-DCE
10/9/1997	0.0025	0.0013
1/8/1998	0.0005	N/A
4/16/1998	0.0232	0.0226
7/9/1998	0.0092	0.0111
1/4/2001	0.0189	0.0237
5/20/2002	0.0461	0.0532
8/13/2002	0.0436	0.0437
4/9/2003	0.0265	N/A
1/19/2005	0.0322	0.0294
4/5/2005	0.0187	0.0174
7/26/2005	0.026	0.0275
10/6/2005	0.031	0.0302

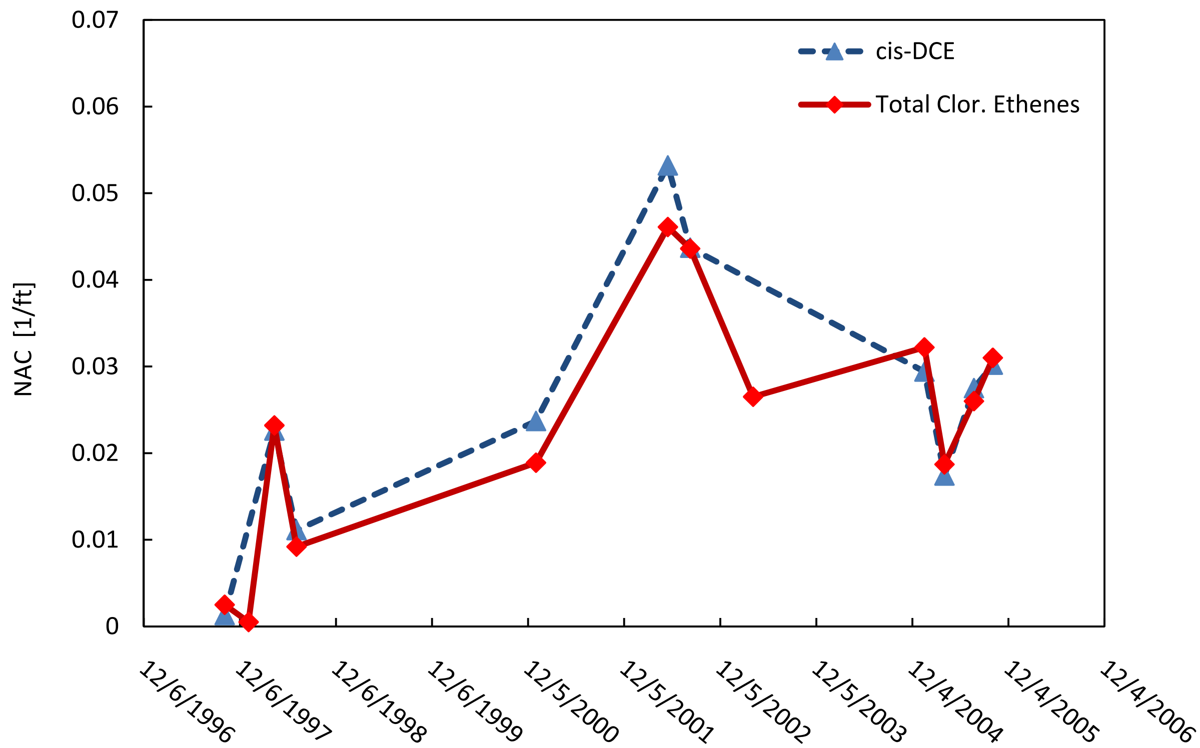

FIGURE 53: NAC AS A FUNCTION OF TIME, IR SITE 5, NASNI

4.4.1.1 Linear Regression

A linear regression was then performed on the time trend series of NAC values. A thorough explanation of the purpose and description of the linear regression has been provided in Chapter 2.3. The complete results of the linear regression analysis, which is the statistical tool used to evaluate the hypothesis are contained in **Appendix D**. **Table 25** is a summary of the linear regression results which includes a 90% prediction interval around the predicted model. The mathematic description of the predicted model is **Equation 13**.

TABLE 25: SUMMARY OF SLOPE ESTIMATE FROM LINEAR REGRESSION ANALYSIS OF NAC AS A FUNCTION OF TIME, NAC OF TOTAL CHLORINATED ETHENES, IR SITE 5, NASNI

Statistic	Value
*Slope estimate, (β_1)	7.712E-06
Alpha. (α)	0.10
Standard Error (β_1)	3.107E-06
t Stat (β_1)	2.4816
P-value	0.0325
Lower Confidence Interval, 90%	2.079E-06
Upper Confidence Interval, 90%	1.334E-05

**slope of NAC decreasing with respect to time*

$$NAC = 7.712x10^{-6}\left(t^{\mathrm{vi}}\right) + 0.264$$ **Equation 13**

The linear regression analysis does the work of fitting the most appropriate linear model to the data set. Assuming that the data can be modeled as a single linear trend, a valid prediction of future measurements is possible. One indicator of a good fit model is relatively similar and small residual values. **Figure 54** shows a relatively linear and stable upward trend in NAC, with the exception of the measurements from May and August of 2002. These two measurements occur in the remedial action period of 2000-2003, and are potentially causing an unnatural increase to the overall slope of the NAC model. By eliminating these two measurements from the linear regression (**Figure 55**) the residuals are lowered and made relatively similar in magnitude. Lower residual values infer that the predicted model fits the data better.

[vi] Time (t) is in days, where day 1 corresponds to January 1, 1900.

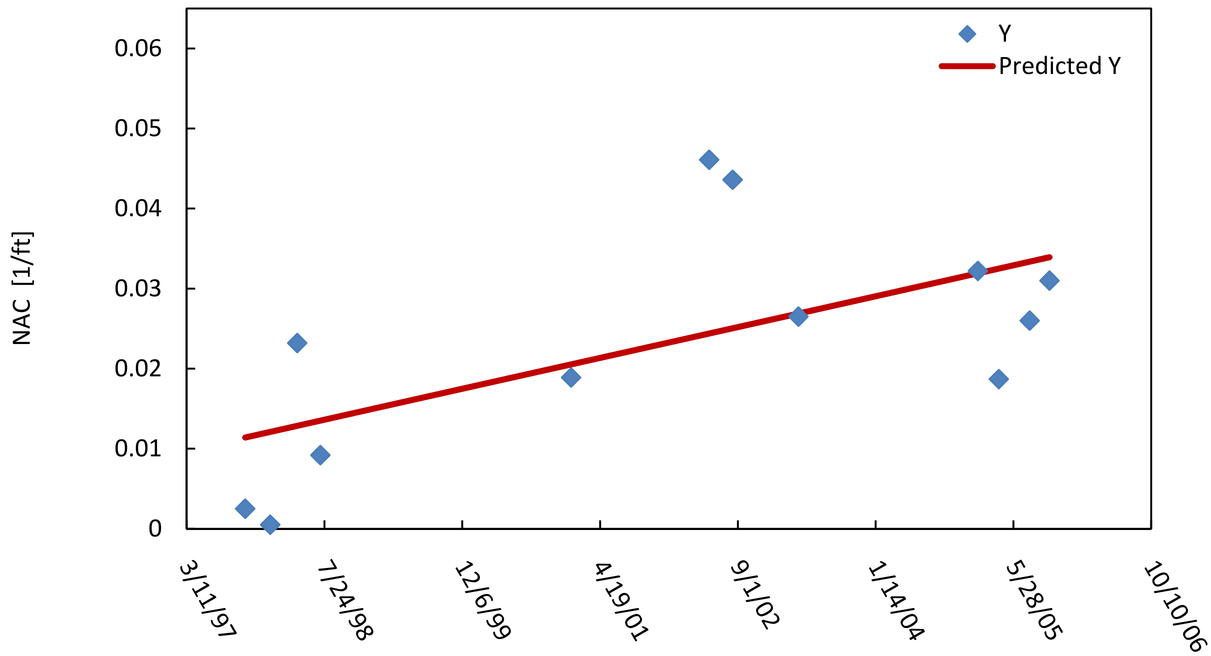

FIGURE 54: PREDICTED LINEAR MODEL AND ACTUAL NAC VALUES, TOTAL CHLORINATED ETHENES, IR SITE 5, NASNI

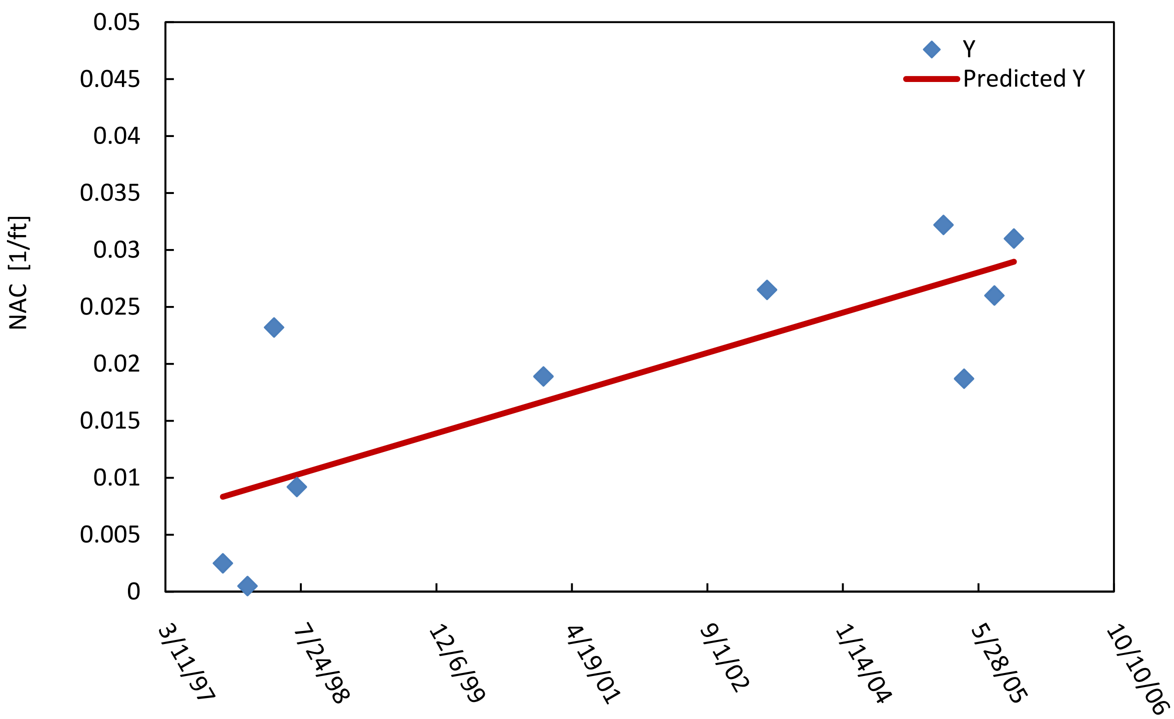

FIGURE 55: PREDICTED LINEAR MODEL AND ACTUAL NAC VALUES, TOTAL CHLORINATED ETHENES, MAY AND AUGUST 2002 OMITTED, IR SITE 5, NASNI

One should never eliminate measurements simply because it would allow a model to fit a dataset better. However, in this case, the unusually high measurements coincide with a known in-situ treatment giving reason to believe that factors outside of natural attenuation are influencing the results. A new linear regression summary is provided in **Table 26**, where the two measurements in question have been omitted. This new prediction model is defined by **Equation 14**. Excluding the two data points caused a mild change to the slope of the NAC regression model, from $7.712x10^{-6}$ to $7.066x10^{-6}$ yet still both regressions reflect the same conclusion about the direction of the sloping trend. It is reasonable and arguably more accurate to exclude the doubtful data and therefore to use the new predicted model to describe the plume trend.

TABLE 26: LINEAR REGRESSION ANALYSIS RESULTS, 2002 DATA OMITTED, IR SITE 5, NASNI

Statistic	Value
*Slope, (β_1)	7.066E-06
Alpha. (α)	0.10
Standard Error (β_1)	1.918E-06
t Stat (β_1)	3.6844
P-value	**0.0062**
Lower 95%	2.643E-06
Upper 95%	1.149E-05
Lower 90%	**3.500E-06**
Upper 90%	**1.063E-05**

**slope of NAC increasing with respect to time*

$$NAC = 7.066x10^{-6}(t) + 0.2440$$ **Equation 14**

However, the primary purpose of the linear regression is to test the hypothesis stated early. The estimated slope of the line is [$7.066x10^{-6}$] positive, indicating an increasing NAC at the site. The P-value, a more robust test of the slope sign, corroborates this fact since a p-value of [0.0062] is less than the alpha (0.10) value. The last check is to verify that zero does not fall within the 90% confidence intervals, which it does not. The conclusion is to reject the null hypothesis. The slope of the NAC with respect to time trend is not statistically zero and is positive in sign.

4.4.1.2 Tabular method of determining prediction intervals for the next single measurement

The tabular method of determining prediction intervals is not designed for use with increasing trends such as IR Site 5. However, in some cases the tabular method still proves to be a powerful visual tool in communicating the continuity of a historical trend and the effects of outliers. For a longer time period it would be more appropriate to use the graphical method of determining the prediction interval. For this site, the tabular method allows the user to visually isolate the outlier by the effect on the prediction interval.

The data for IR Site 5 is processed through a spreadsheet with the help of a statistical program, R. R is used to determine the Student's t value and to conduct the Shapiro Wilk test of normality on with each new measurement. The results of the calculations for the entire dataset (including the two questionable measurements from 2002) are displayed in **Figure 56** and **Table 27**. Similar to the discussion of the linear regression, the data in 2002 appears to be influenced by outside factors in Figure 56. The sampling event for May 2002 is outside the prediction interval and therefore causes the next prediction interval to expand significantly.

The prediction interval calculation was repeated for the dataset, omitting May and August of 2002. This new analysis is displayed in **Table 28** and **Figure 57**. Excluding the two non-stable measurements from the dataset resulted in a tighter prediction interval where all the measurements are within the prediction intervals limits. The analysis corroborates with the linear regression, that the exclusion of data from year 2002 generates a more accurate linear regression model of NAC at the Site. It is notable that the data is representative of a normal distribution, verified by nine Wilk-Shapiro tests. One-sided interval calculations and graphs provide no new insight and are provided in **Appendix D**.

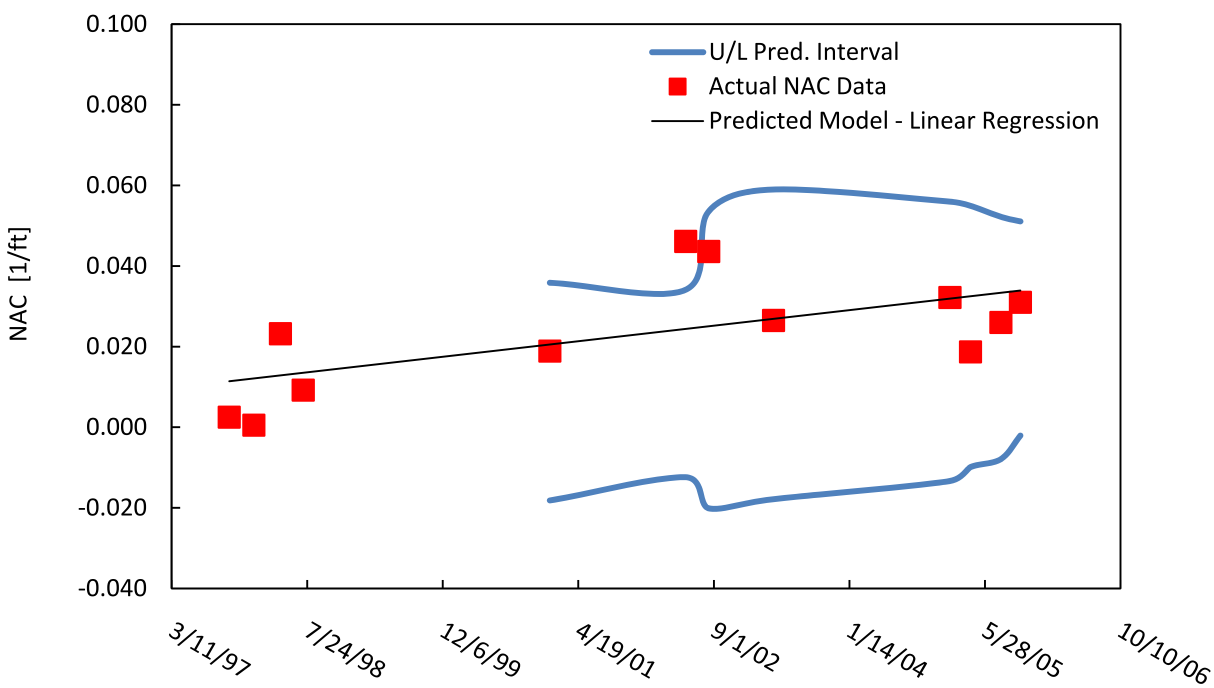

FIGURE 56: TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENES, FULL DATASET, IR SITE 5, NASNI

TABLE 27: DETERMINATION OF TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT AND QUALITATIVE INTERPRETATION, FULL DATASET, IR SITE 5, NASNI

DATE	NAC	Mean	Std. Dev.	Sample No.	Student's t	Shapiro Wilk, p-value*	Two-sided, Upper PI**	Two-sided, Lower PI**	Qualitative Evaluation
10/9/97	0.00250								
1/8/98	0.00050								
4/16/98	0.02320								
7/9/98	0.00920	0.00885	0.01	4	2.35336	0.3557			
1/4/01	0.01890	0.01086	0.01	5	2.13185	0.4916	3.586E-02	-1.816E-02	
5/20/02	0.04610	0.01673	1.69E-02	6	2.01505	0.4011	3.412E-02	-1.240E-02	
8/13/02	0.04360	0.02057	1.85E-02	7	1.94318	0.3029	5.356E-02	-2.010E-02	The NAC value (0.0436) is within the PI (0.05356, 0.0201), ***
4/9/03	0.02650	0.02131	1.72E-02	8	1.89458	0.4669	5.897E-02	-1.783E-02	The NAC value (0.0265) is within the PI (0.05897, 0.01783), ***
1/19/05	0.03220	0.02252	1.65E-02	9	1.859548	0.6330	5.596E-02	-1.334E-02	The NAC value (0.0322) is within the PI (0.05596, 0.01334), ***
4/5/05	0.01870	0.02214	1.56E-02	10	1.833113	0.6825	5.493E-02	-9.884E-03	The NAC value (0.0187) is within the PI (0.05493, 0.009884), ***
7/26/05	0.02600	0.02449	1.40E-02	11	1.81246	0.7072	5.220E-02	-7.917E-03	The NAC value (0.026) is within the PI (0.0522, 0.007917), ***
10/6/05	0.03100	0.02754	1.13E-02	12	1.79589	0.7760	5.107E-02	-2.085E-03	The NAC value (0.031) is within the PI (0.05107, 0.002085), ***
	TBD						4.865E-02	6.433E-03	TBD with next sampling event

**alpha value for Shapiro-Wilk test is 0.05*

**alpha value for Prediction Interval is 0.10

***the newest NAC value does NOT reflect a change from the previously established site degradation rate.

TABLE 28: DETERMINATION OF TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT AND QUALITATIVE INTERPRETATION, 2002 DATA OMITTED, IR SITE 5, NASNI

DATE	NAC	Mean	Std. Dev.	Sample No.	Student's t	Shapiro Wilk, p-value*	Two-sided, Upper PI**	Two-sided, Lower PI**	Qualitative Evaluation
10/9/97	0.00250								
1/8/98	0.00050								
4/16/98	0.02320								
7/9/98	0.00920	0.00885	0.01	4	2.35336	0.3557			
1/4/01	0.01890	0.01086	0.01	5	2.13185	0.4916	**3.586E-02**	**-1.816E-02**	
4/9/03	0.02650	0.01347	1.10E-02	6	1.89458	0.4669	**3.412E-02**	**-1.240E-02**	The NAC value (0.0265) is within the PI (0.03412, 0.0124), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
1/19/05	0.03220	0.01614	1.23E-02	7	1.859548	0.6330	**3.590E-02**	**-8.964E-03**	The NAC value (0.0322) is within the PI (0.0359, 0.008964), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
4/5/05	0.01870	0.01646	1.14E-02	8	1.833113	0.6825	**4.051E-02**	**-8.225E-03**	The NAC value (0.0187) is within the PI (0.04051, 0.008225), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
7/26/05	0.02600	0.01940	1.02E-02	9	1.81246	0.7072	**3.860E-02**	**-5.673E-03**	The NAC value (0.026) is within the PI (0.03897, 0.001667), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
10/6/05	0.03100	0.02321	7.51E-03	10	1.79589	0.7760	**3.897E-02**	**-1.667E-04**	The NAC value (0.031) is within the PI (0.03897, 0.0001667), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
Next Value	TBD						**3.737E-02**	**9.058E-03**	TBD with next sampling event

**alpha value for Shapiro-Wilk test is 0.05*

**alpha value for Prediction Interval is 0.10

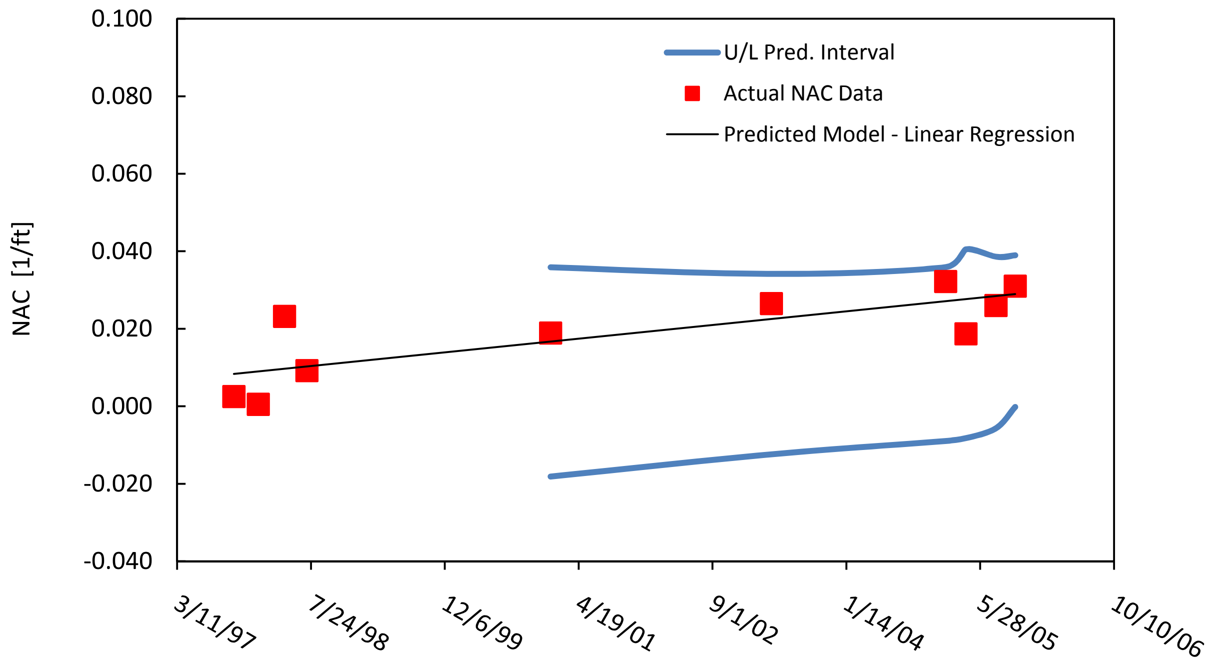

FIGURE 57: TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENES, 2002 DATA OMITTED, IR SITE 5, NASNI

4.4.2 Summary and Discussion of Key Findings

Rapid and efficient reductive dechlorination has been shown at NASNI, IR Site 5. The original groundwater contaminants were PCE and TCE, almost all of which has been transformed, both naturally and through chemical oxidation, into the daughter compounds of cis-DCE and VC. The contaminants meet regulatory limits at an approximate distance of 500 feet from the liquid waste disposal pits (Wiedemeier and Associates, 2006).

At first the maximum amount of available data was used, which included twelve sampling events between 1997 and 2005. After completing a linear regression and prediction interval analysis the two sampling events from 2002 were closely examined for outside interference. Between 1999 and 2002 chemical oxidation was completed at the plume source and is a plausible cause for the unexplained and concurrent jump in NAC at the Site. The linear regression and prediction interval analysis was then completed without the 2002 data, resulting in a better prediction model with smaller residuals (lower variability) and a tighter prediction interval. The equation of the predicted model is:

$$NAC = 7.066x10^{-6}(t) + 0.2440$$

The linear regression confirmed that NAC at the site is statistically increasing and the 90% prediction interval confirmed that the data represented a single linear trend with each new measurement. While the NAC is historically increasing, in order to determine whether the natural attenuation at the Site is sustainable for future years would require a larger analysis described in **Chapter 5.2**.

In summary of IR Site 5, NAS North Island:

- Very rapid and efficient reductive dechlorination (short plume) observed at the site
- 2002 in-situ chemical oxidation matches time of increase in NAC
- Assumption of single linear trend is supported (residuals and prediction interval)
- Omitting 2002 data allows for a better linear fit, while not changing any conclusions
    - Residual analysis
    - Improved "smoothing" of prediction interval
- Future data is needed to determine if this omission is supported

4.5 Statistical Analysis of Naval Base Kitsap, OU1

The plume at OU-1 originated from a former landfill constructed with fill in a tidal marsh on Naval Base Kitsap in Washington State. The 9-acre landfill on OU-1 has two distinct plumes, referred to as the north and south plumes. The north plume will be the focus of this report, given that the south plume is under a greater influence from tidal fluctuations. The north plume at OU-1 is present in the upper aquifer and extends approximately 200 ft before interacting with surface water in marsh/stream. While less documented than NASNI IR Site 5, OU-1 appears to resemble many similarities to IR Site 5 (NASNI), including; transformation of almost all parent chlorinated ethenes into daughter compounds through natural attenuation. The chlorinated ethene plume is primarily comprised of cis-DCE and VC within the period that data is available (1999-2006). The parent compounds of TCE and PCE are present in some of the wells at low concentrations. Due to the great difference in concentration levels of the daughter compounds and the parent compounds, laboratory analysis were limited to focusing on the upper limits (NAVFAC, 2008). Consequently, many of the TCE and PCE measurements are stated as "less than" values. Since PCE and TCE values are orders of magnitude lower than cis-DCE and VC, they are being considered negligible to the determination of total chlorinated ethenes at the Site. After partial excavation of contaminated soil in 1999, phytoremediation has remained the only additional mechanisms for remediation to natural biodegradation processes. Also important to the interpretation of data trends is that redox conditions at the site vary between aerobic to mildly reducing (sulfate reducing) (NAVFAC, 2008).

Annual monitoring data is available for three wells located along the plume centerline from 1999-2006. The source area is monitored by well P1-4. **Table 29** contains the well IDs, distance the well is from the source well, and the earliest date of data available for the analysis. **Figure 58** shows a plan view of OU-1 with an estimated plume extent and well locations.

TABLE 29: WELL DESCRIPTIONS, OU1 – NORTH PLUME, NBK

Well ID	Distance from source along plume line (ft)	First Available Sampling Event
P1-4	0	6/9/1999
P1-3	80	6/9/1999
MW1-2	160	6/9/1999

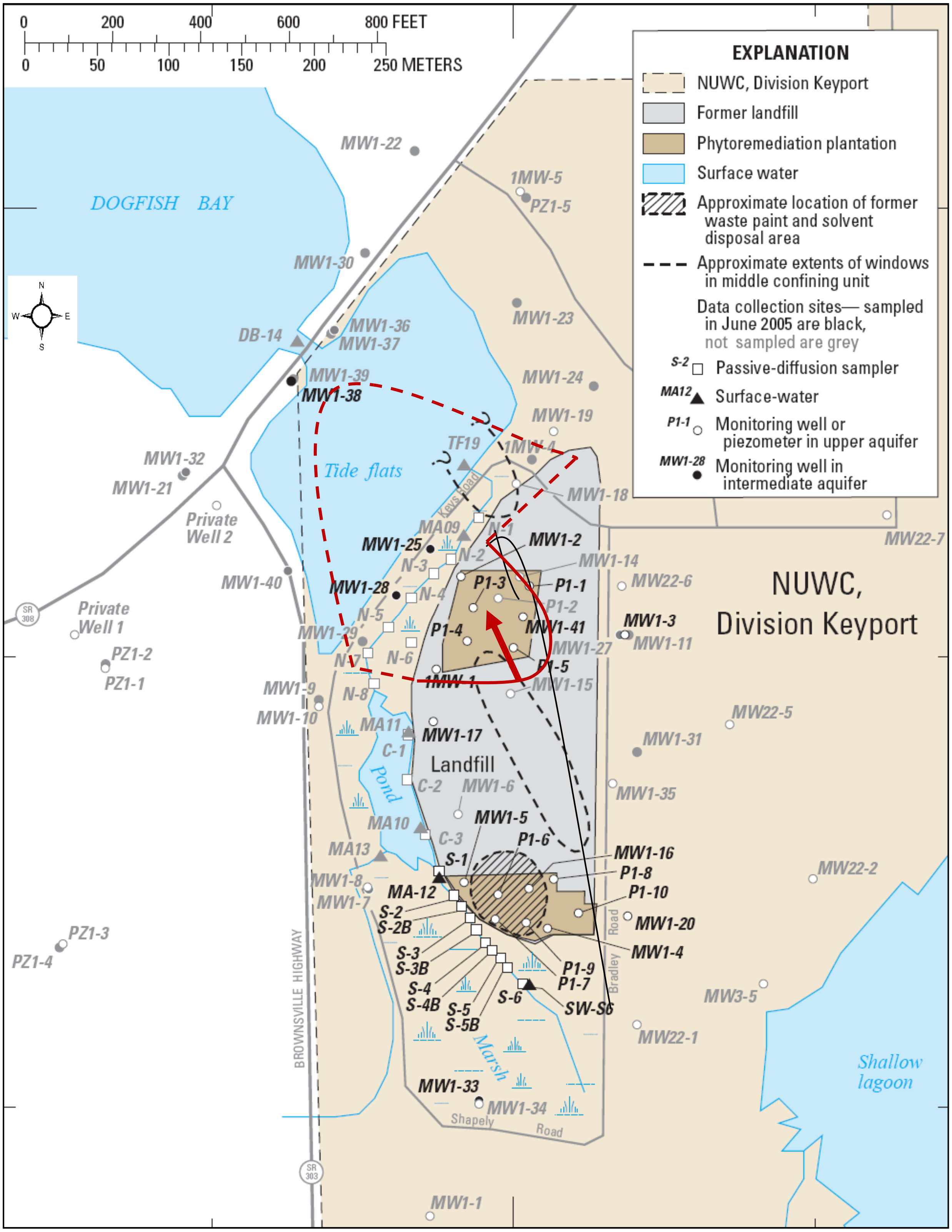

FIGURE 58: PLAN VIEW OF FORMER LANDFILL, OU1, NBK (DINICOLA & HUFFMAN, 2007)

There have been seven sampling events between 1999 and 2006, but only five of these events involved all three wells. The sampling data is presented in **Appendix A**.

Figure 59 shows the concentration of total chlorinated ethene at the source well with respect to time. The concentration at the source appears to be decreasing at a steady rate, which is indicative of stable plume conditions. The absence of in-situ remediation as well as the age of the plume is also a good indication that the source is stable.

Redox conditions at the site are mildly favorable for reductive dechlorination, and attenuation through a number of processes is represented in the overall trend of the data. OU-1 is utilizing phytoremediation to draw contaminated water out of the upper aquifer before they are transported into the tidal marsh leading to Dogfish Bay. The planted trees have shown progress at up-taking contaminants and slowing down the migration of groundwater through the former landfill (NAVFAC, 2008). Plant uptake of contaminants is another attenuation factor that is factored into the dispersion-advection-degradation model by means of the biodegradation rate, k (explained in Chapter 1.2.2).

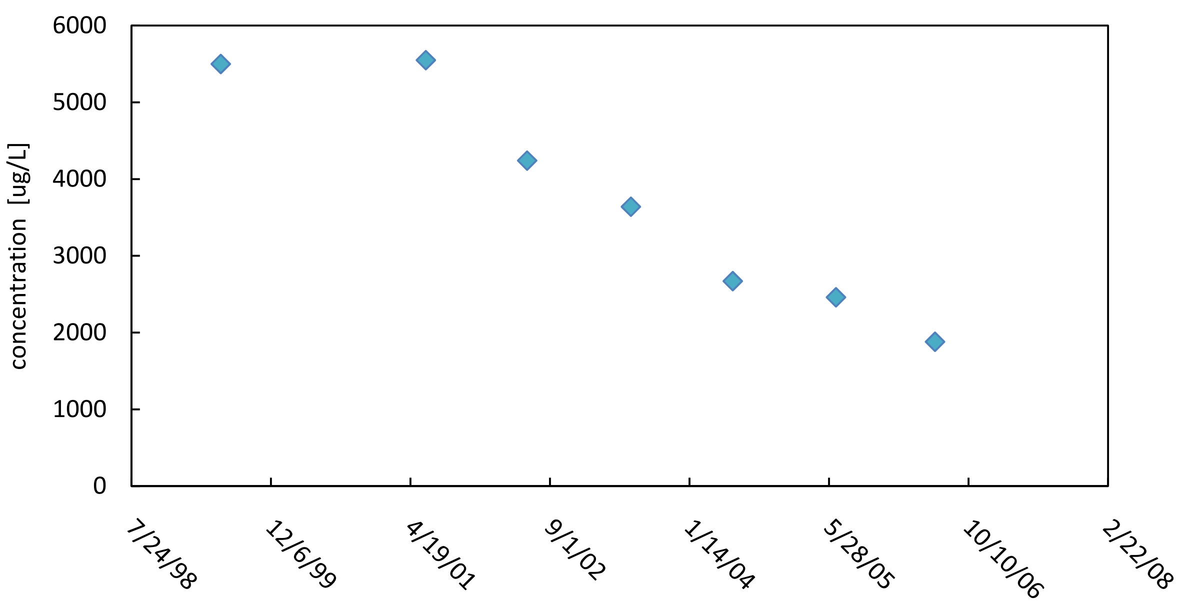

FIGURE 59: TOTAL CHLORINATED ETHENE CONCENTRATIONS AT THE SOURCE, WELL P1-4, OU1 – NORTH PLUME, NBK

Figure 60 corroborates with the determination to assume plume stability and the absence of influences from remedial actions on the sampling data. The different VOCs are decreasing at different rates but show consistent trends, with little or no influence from outside factors. **Table 30** displays the resulting total chlorinated ethene concentrations for the target time period.

TABLE 30: TOTAL CHLORINATED ETHENE CONCENTRATIONS IN MONITORING WELLS, OU1 – NORTH PLUME, NBK

Sampling Event	Concentration Total Chlorinated Ethene (µg/L)		
	P1-4	P1-3	MW1-2
6/9/1999	5500.0	605.0	1387.0
6/13/2001	5550.0	NS	1058.0
6/11/2002	4241.2	125.0	750.0
6/18/2003	3640.0	137.0	1013.0
6/17/2004	2670.0	56.0	752.0
6/22/2005	2460.0	46.0	883.0
6/12/2006	1880.0	20.6	NS

NS – not sampled

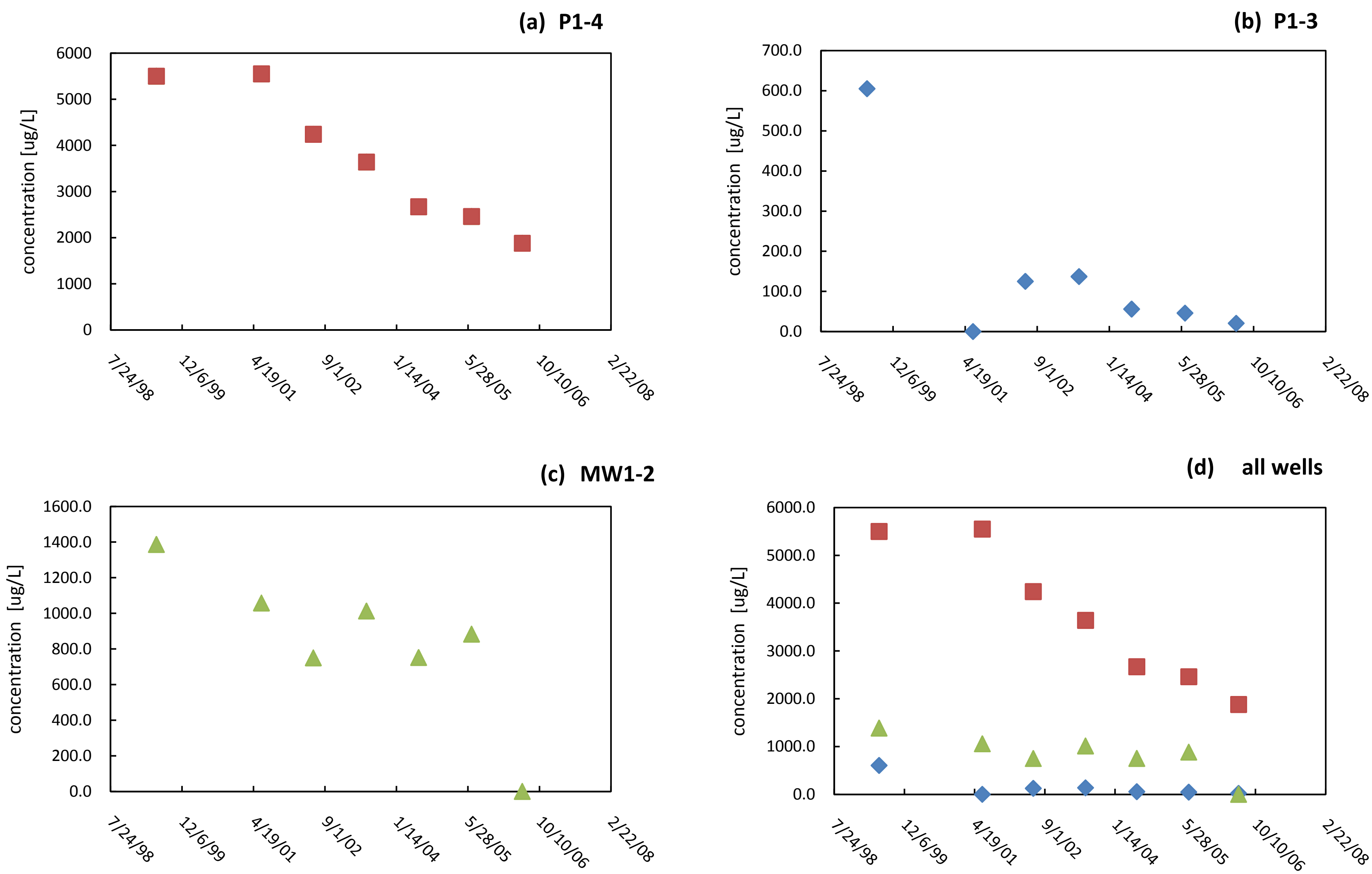

FIGURE 60: TOTAL CHLORINATED ETHENE CONCENTRATIONS IN VARIOUS WELLS ALONG THE PLUME CENTERLINE, OU1 – NORTH PLUME, NBK

4.5.1 *Utilizing NAC as a statistical screening tool*

NAC is determined by finding the slope of the solute concentration profile. **Figure 61** is a solute profile from OU1 of the sampling event on June 17, 2004. The independent variable in the figure is distance along the plume centerline, and the NAC value is highlighted as the slope of the trend. This analysis is completed for each sampling event to find the NAC for total chlorinated ethenes and other dominant chlorinate ethene constituents. The slope of the total chlorinated ethene concentration profile in Figure 61 is -0.0098 [µg/L-ft], corresponding to the NAC value of 0.0098 [1/ft].

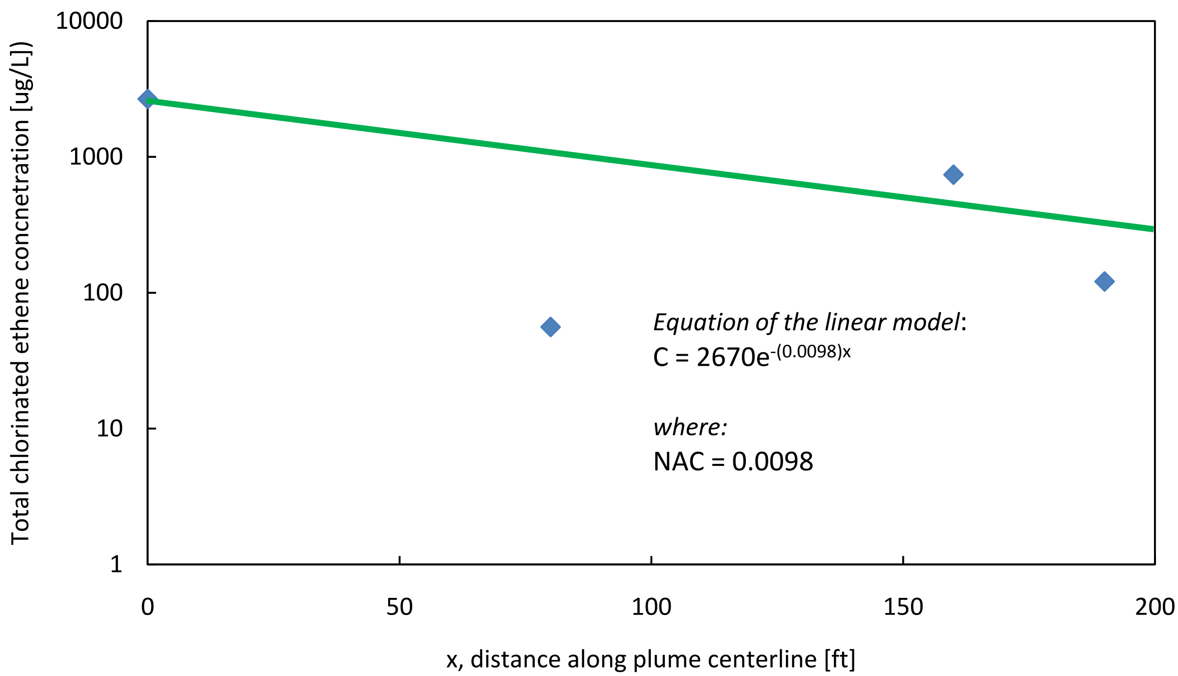

FIGURE 61: SOLUTE CONCENTRATION PROFILE, TOTAL CHLORINATED ETHENE, 6/17/04, OU1 – NORTH PLUME, NBK

The parent compounds TCE and PCE were the actual constituents disposed of at OU1, however; concentrations of cis-DCE and VC are as much as two orders of magnitude greater than TCE and PCE in the time period being evaluated. The total chlorinated ethene concentration is mostly composed of these two daughter compounds. NAC values for cis-DCE and total chlorinated ethene were determined at every sampling event (**Table 31**) and the time trends of NAC for total chlorinated ethene and cis-DCE are displayed in **Figure 62**. TCE was not included in this analysis because NAC values were not possible to be determined given that most of the TCE measurements were below detection limits. The general trend of NAC for total chlorinated ethenes appears to be decreasing with time. The following statistical analysis will evaluate the total chlorinated ethene measurements as a linear trend.

TABLE 31: NAC VALUES, OU1 – NORTH PLUME, NBK

Sampling Event	Total Clor. Ethenes	cis-DCE
6/9/1999	0.00850	0.0086
6/11/2002	0.0108	0.0106
6/18/2003	0.0080	0.0081
6/17/2004	0.00980	0.0092
6/22/2005	0.00640	0.0069

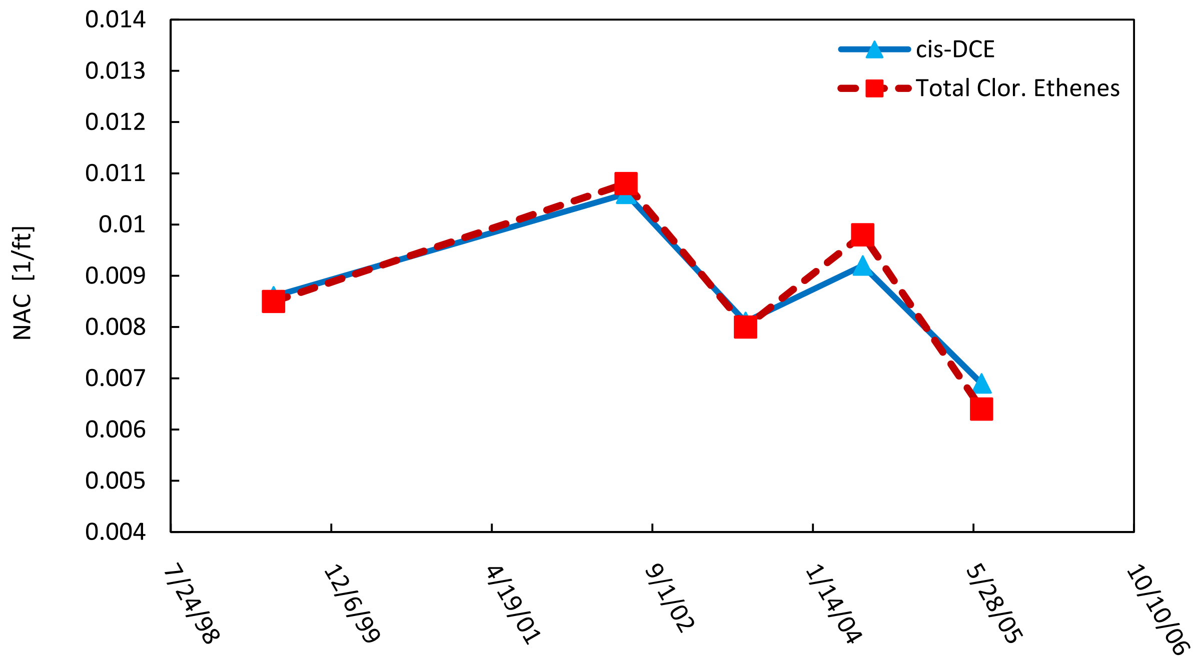

FIGURE 62: NAC AS A FUNCTION OF TIME, OU1 – NORTH PLUME, NBK

4.5.1.1 Linear Regression

A linear regression is performed on the time trend series of NAC values. A thorough explanation of the purpose and description of the linear regression has been provided in **Chapter 2.3**. The hypothesis question is stated, "*Is the slope of the linear regression equal to zero?*" The complete results of the linear regression analysis, which is the statistical tool used to evaluate the hypothesis are contained in **Appendix E**. **Table 32** is a summary of the linear regression results which includes a 90% prediction interval around the predicted model. The mathematic description of the predicted model is **Equation 15**.

TABLE 32: SUMMARY OF SLOPE ESTIMATE FROM LINEAR REGRESSION ANALYSIS OF NAC AS A FUNCTION OF TIME, NAC OF TOTAL CHLORINATED ETHENES, OU1 – NORTH PLUME, NBK

Statistic	Value
*Slope estimate, (β_1)	-6.205E-07
Alpha. (α)	0.10
Standard Error (β_1)	1.097E-06
t Stat (β_1)	-0.5655
P-value	0.6112
Lower Confidence Interval, 90%	-3.203E-06
Upper Confidence Interval, 90%	1.962E-06

**slope of NAC decreasing with respect to time*

$$NAC = -6.205x10^{-7} \left(t^{\text{vii}}\right) + 0.03206$$ **Equation 15**

The linear regression analysis fits the most appropriate linear model to the data set. Assuming that the data can be modeled as a single linear trend, a valid prediction of future measurements is possible. One indicator of a good fit model is relatively similar and small residual values. **Figure 63** shows the residuals, defined as the distance between the prediction value and the actual NAC value at any given sampling event. The residual values are small, relatively similar and randomly placed, which indicates that the single linear trend is a fair assumption for the dataset. A residual plot is provided in **Appendix E**. The primary purpose of the linear regression is to test the hypothesis. The estimated slope of the line is $[-6.205x10^{-7}]$ slightly negative, indicating a decreasing NAC at the site. The p-value (0.6112), a more robust test of the slope sign, is significantly greater than the alpha (0.10) value. The interpretation of a high p-value is that one must accept the null hypothesis of a horizontal trend. The last step is to check the p-value interpretation by verifying that zero fall within the 90% confidence intervals. It does, therefore, the conclusion is to accept the null hypothesis. Although the estimated slope of the NAC trend with respect to time is slightly decreasing, the slope is also not statistically different than zero.

[vii] Time (t) is in days, where day 1 corresponds to January 1, 1900.

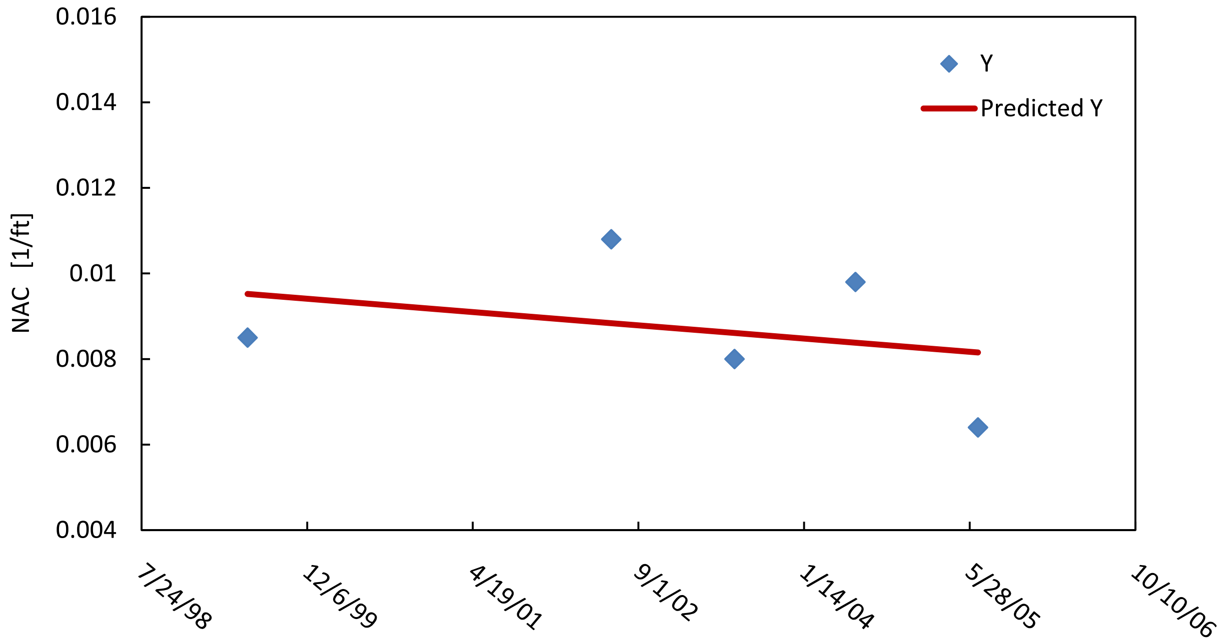

FIGURE 63: PREDICTED LINEAR MODEL AND ACTUAL NAC VALUES, TOTAL CHLORINATED ETHENES, OU1 – NORTH PLUME, NBK

4.5.1.2 Tabular method of determining prediction intervals for the next single measurement

The tabular method of determining prediction intervals for the next single measurement is most appropriate for the Site given that the linear regression slope has been determined to be not different than zero. It involves a process of calculations followed by interpreting the statistical output. The data for the north plume at OU-1 is processed with the help of a statistical program, R. R is used to determine the Student's t value and to conduct the Shapiro-Wilk test of normality on with each new measurement. The Shapiro-Wilk tests on the data confirm that the data is normally distributed with 95% confidence. The results for OU-1 are displayed in **Tables 33** and **34**. Table 33 displays the two-sided prediction interval, which is displayed graphically in **Figure 64**. Table 34 displays the one-sided prediction interval, which is displayed graphically in **Figure 65**. The data set for OU-1 is the smallest set analyzed for any Site in this report. Not surprising is the limited conclusions that can be ascertained from a small dataset. Only two NAC measurements are statistically tested, in Tables 33 and 34, for compliance with the 90% prediction intervals. The sampling event from 6/22/2005 is slightly lower than the one-sided lower prediction interval, but this alarm has limited meaning considering how small the dataset it. Since the residual values are all relatively close, it is possible that that this rogue measurement may be an indication that the slope estimate found through the linear regression is not steep enough. However, without further data any such statements are only speculative.

TABLE 33: DETERMINATION OF TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT AND QUALITATIVE INTERPRETATION, OU1 – NORTH PLUME, NBK

DATE	NAC	Mean	Std. Dev.	Sample No.	Student's t	Shapiro Wilk, p-value	Two-sided, Upper PI	Two-sided, Lower PI	Qualitative Evaluation
6/9/1999	0.0085								
6/11/2002	0.0108								
6/18/2003	0.008	0.00910	0.001493	3	2.91999	0.3212			
6/17/2004	0.0098	0.00928	0.001269	4	2.35336	0.7109	1.414E-02	4.065E-03	The NAC value (0.00980) is within the PI (0.01414, 0.004065), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
6/22/2005	0.0064	0.00870	0.001691	5	2.13185	0.9647	1.261E-02	5.937E-03	The NAC value (0.0064) is within the PI (0.01261, 0.005937), the newest NAC value does NOT reflect a change from the previously established site degradation rate.
Next Value	TBD						1.265E-02	4.751E-03	TBD with next sampling event

TABLE 34: DETERMINATION OF ONE-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT AND QUALITATIVE INTERPRETATION, OU1 – NORTH PLUME, NBK

DATE	NAC	Mean	Std. Dev.	Sample No.	Student's t	Shapiro Wilk, p-value	One-sided, Lower PI	Qualitative Evaluation
6/9/1999	0.0085							
6/11/2002	0.0108							
6/18/2003	0.008	0.00910	0.00149	3	1.88562	0.3212		
6/17/2004	0.0098	0.00928	0.00127	4	1.63774	0.7109	5.85E-03	The NAC value (0.00980) is GREATER than the lower, one-sided PI (0.00585), this newest NAC value does NOT reflect a change in the previously established site degradation trend.
6/22/2005	0.0064	0.00870	0.00169	5	1.53321	0.9647	6.95E-03	The NAC value (0.00640) is NOT GREATER than the lower, one-sided PI (0.006950), this newest NAC value MAY reflect a change in the previously established site degradation trend.
Next Value	TBD						5.86E-03	TBD with next sampling event

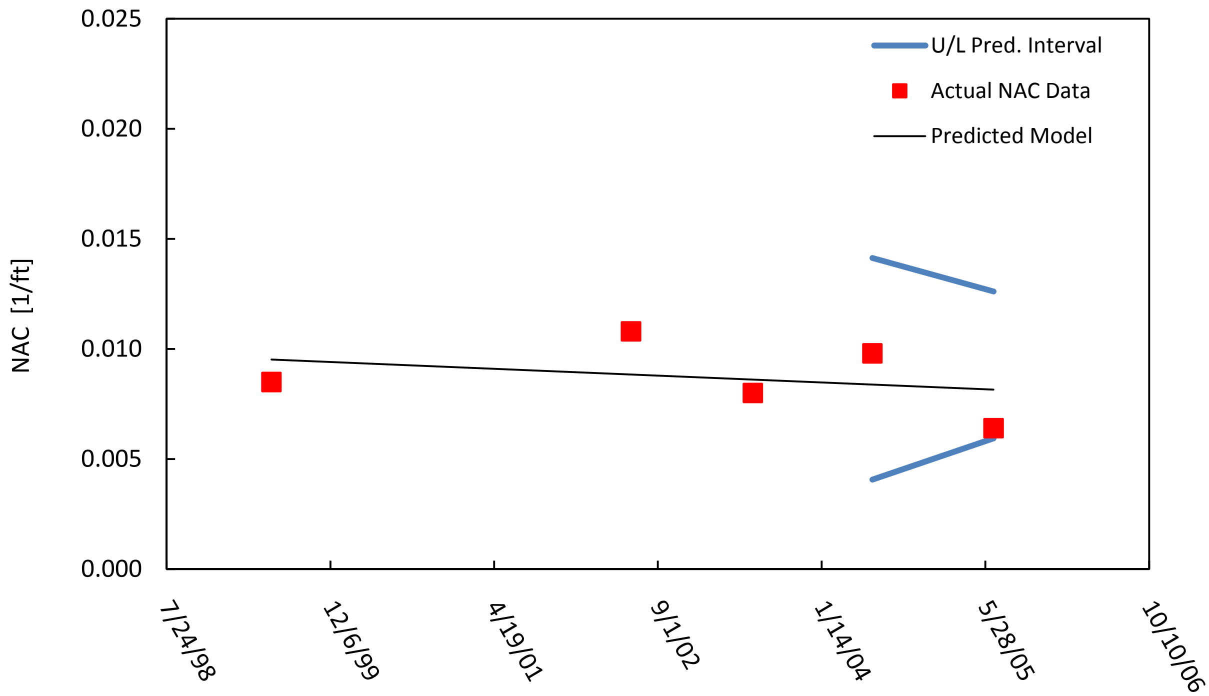

FIGURE 64: TWO-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENE, OU1 – NORTH PLUME, NBK

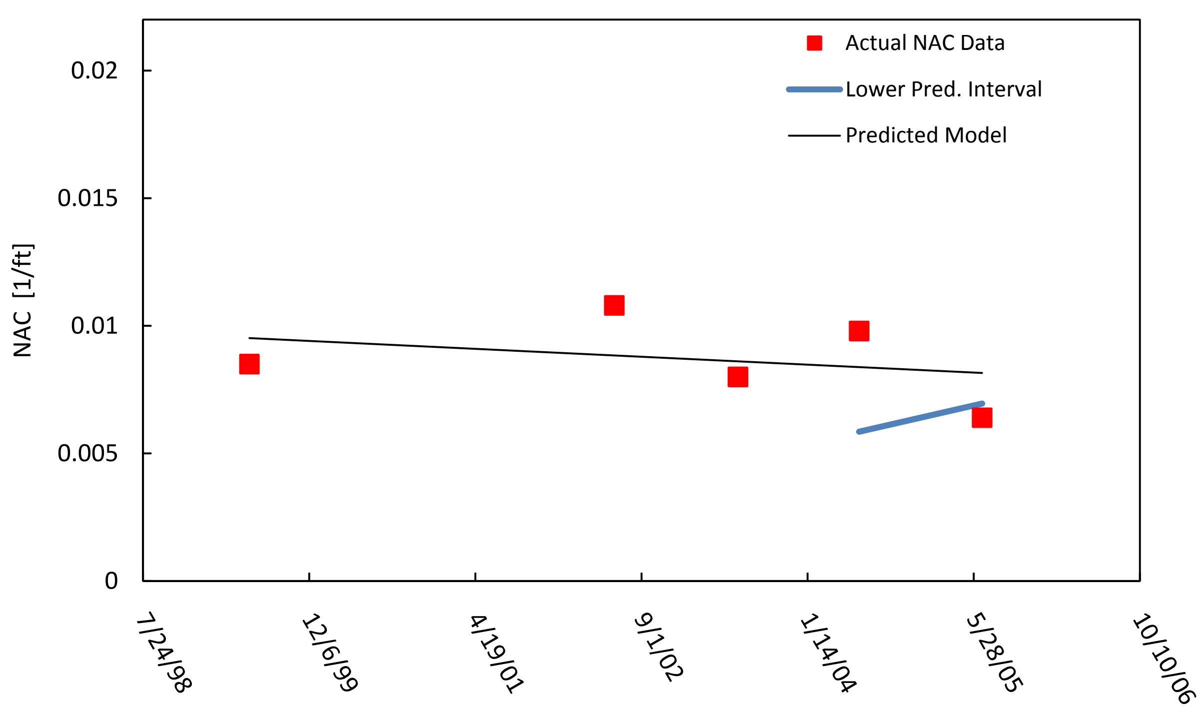

FIGURE 65: ONE-SIDED PREDICTION INTERVAL FOR THE NEXT MEASUREMENT, TOTAL CHLORINATED ETHENE, OU1 – NORTH PLUME, NBK

4.5.2 Summary and Discussion of Key Findings

Measureable natural attenuation is occurring in the north plume of OU-1 at NBK Keyport, Washington. Although due to the limitations of mildly reducing and aerobic conditions at the Site it is unsure how much of the attenuation is a result of reductive dechlorination or other biological processes. Phytoremediation is the only ongoing remedial mechanism being used at the site. The contaminants are in the upper aquifer for a short distance before they interact with surface water under the influence of tidal swells. Rain events also are likely to influence transport rates given the depth of the aquifer (NAVFAC, 2008).

The data and Site history support the assumption that the plume is stable (Dinicola, 2006). Site data was manipulated into the form of NAC to be used as a screening tool for evaluating the sustainability of natural attenuation processes. A linear regression analysis of NAC with respect to time shows that the slope of the trend is estimated to be slightly decreasing, yet is not statistically different than zero at a confidence of 90%. Further, the prediction interval for the next measurement shows that the fourth and fifth measurements are within the 90% two-sided prediction interval. The historical NAC data can be reasonably represented by a single-linear regression, estimated to be:

$$NAC = -6.205x10^{-7}(t) + 0.03206$$

Of the five measurements tested with a one-side and two-sided 90% prediction interval, only one event falls outside the prediction limits. However, this occurrence is not statistically conclusive. The main limitation of the statistical analysis at NBK Keyport OU-1 is the small amount of data. Five data points in seven years provides a much lower than desired statistical power. Assuming an alpha of 0.05, the desired power is 0.80. However, the small dataset only gives a power of 0.066. A lower than desired power is an indication that the dataset doesn’t provide the ability to see a change in the regression slope if one existed. Caution should be used in interpreting such a small dataset. Future data will allow the linear regression estimate to be re-determined with a higher power and confidence in the data results. The current remedial approach at the Site is continued phytoremediation and MNA, however, more data is needed to determine whether site specific ARARs can be met for the duration of the MNA program at NBK.

In summary of OU-1 at NBK Keyport:

- Efficient reductive dechlorination (short plume) observed at the site
- Assumption of single linear trend fits well (residuals and prediction interval)
- Slope of NAC is statistically zero, estimated at slight decrease
- Complicated site – surface/tidal water interaction, changing redox conditions
- Conclusions are limited by quantity of data: 3 wells, 5 sampling events

4.6 Summary of Site Analysis Results

Five independent DOD installations were selected for this study. Each site shows great variability in site conditions, redox parameters, quantity of contaminants, hydrogeology, historical site use, and remedial approaches. The common thread between these sites is the existence of a mature chlorinated ethene groundwater plume and the use of MNA after other more active measures to remediate the contaminants. The data analysis of each site is briefly summarized below as well as noting significant findings. **Tables 35 and 36** provide site summary information. Table 35 compares the efficiency of reductive dechlorination at each site with other site parameters. Table 35 indicates that the efficiency of reductive dechlorination at a site has no apparent correlation to the slope of the NAC temporal trend. Table 36 provides the ranges of NAC values for each site during the period of time examined.

TABLE 35: COMPARISON OF SITES WITH REGARD TO THE EFFICIENCY OF ONGOING REDUCTIVE DECHLORINATION

Sites with efficient reductive dechlorination				
	Source contaminant	**Most concentrated contaminant during observation period**	**Statistical Slope (90% conf. level)**	**Slope estimate (90% conf. level)**
OU-10, NAS Pensacola	TCE	TCE	Decreasing	-4.04×10^{-6}
IR Site 5, NASNI	TCE/PCE	cis-DCE (and VC)	Increasing	7.712×10^{-6}
Sites with moderately efficient reductive dechlorination				
	Source contaminant	**Most concentrated contaminant during observation period**	**Statistical Slope (90% conf. level)**	**Slope estimate (90% conf. level)**
OU-1, NBK Kitsap	TCE	cis-DCE (and VC)	Not different than zero	-6.205×10^{-7}
Sites with inefficient reductive dechlorination				
	Source/parent contaminant	**Most concentrated contaminant during observation period**	**Statistical Slope (90% conf. level)**	**Slope estimate (90% conf. level)**
Sites I & J, Lakehurst	TCE	cis-DCE	Not different than zero*	-2.291×10^{-7}
OU-2, Hill AFB	TCE	TCE	Not different than zero	-9.669×10^{-8}

* Lakehurst may represent a multi-linear trend

TABLE 36: COMPARISON OF NAC RANGES AT SITES BASED ON TOTAL CHLORINATED ETHENES

Site	Installation	Time Period	Low NAC	High NAC	Avg NAC
OU-10	NAS Pensacola	01/2003 - 05/2008	0.0149	0.0283	0.0194
Sites I&J	NAES Lakehurst	02/2004 - 11/2007	0.0003	0.0009	0.000737
OU-2	Hill AFB	03/1999 - 10/2007	0.0038	0.0046	0.00424
IR Site 5	NAS North Island	10/1997 - 10/2005	0.0005	0.0461	0.0232
OU-1	Naval Base Kitsap	06/1999 - 06/2005	0.0064	0.0108	0.0087

OU10 at NAS Pensacola is the only site where two different methods for determining prediction intervals was demonstrated as well as the comparison of the critical NAC to the actual NAC. It was also shown how the tabular method of determining a prediction interval for the next measurement is a more robust prediction tool than the prediction interval determined from the linear regression model. For this reason, the later method was shown only for NAS Pensacola. At OU10, reductive dechlorination has been ongoing for more than a decade and eleven historical sampling events were chosen to represent current stable conditions at the Site. The NAC trend was shown to be statistically decreasing. By assuming a site specific POC, a hypothetical CNAC was determined to demonstrate how the CNAC can be useful in determining compliance or achievement of ARARs. The CNAC can also be used for negotiating the location of the POC based on set threshold levels. The CNAC analysis completed (based on an assumed POC and potentially outdated ARARs (1999), suggests the compliance threshold levels of TCE would not be met by the last well in the established plume centerline.

The north plume from Sites I&J at NAES Lakehurst demonstrated the ability of the statistical process to collaborate with the Site remediation timeline to determine a cause and effect relationship between natural attenuation measurements and remedial activity. ZVI has been used at the Site between 2002 and 2005, causing unstable conditions in the plume. What also is evident is that the NAC decreases after a ZVI injection is exhausted. Future data measurements will provide a better determination of the new NAC trend with respect to time, which began in the 2006-2007 timeframe.

OU2 at Hill AFB has the least natural attenuation of all five site examined. Conditions are oxic and not favorable for reductive dechlorination as well as other biological processes that reduce chlorinated ethenes. However, approximately 90% of the source has been removed through pump and treat and the remaining contaminants form a long, 1500-foot plume. Most of the natural attenuation at the site is due to non-biological factors such as sorption and dispersion. The plume is stable and the NAC trend with respect to time is not statistically different than zero. The linear regression provides an estimate of the NAC trend that allows for determination of a compliance timeline.

IR Site 5 at NAS North Island has the highest reductive dechlorination rate of all five sites. The source area demonstrates very high concentrations, but the contaminants are quickly reduced to ethene and carbon dioxide within 500 feet of the source. Almost all of the parent compounds have been reduced to the daughter forms of cis-DCE and VC. This is the only site analyzed that demonstrates an increasing NAC with time. Chemical oxidation occurred in the middle of the available data and therefore influences the NAC trend. More data after 2002 is necessary to determine an accurate NAC trend representative of a stable, post-remediation plume.

Naval Base Kitsap in Keyport Washington demonstrates the limitations of having a small dataset to work with. Five sampling events gave the statistical analysis a much lower power than desired, thus increasing the chance that variability in the NAC could go undetected. However, limited data is a reality for many sites with chlorinated ethene contamination and NBK Keyport shows how the statistical process should be used in that scenario. Limited natural attenuation has been measured at the site due to the interaction of tidal surface water with the contaminated aquifer. The NAC was estimated to be slightly decreasing, although the slope is not statistically different than zero. More data is needed to make statistically sound conclusions with regard to past performance and sustainability.

4.7 Conceptual Decision Model

The goal of this thesis is to establish a tool-kit that is statistically powerful yet functional to all parties involved in the decision making process for remediation of contaminant plumes. However, the tools introduced in this thesis must have a conceptual framework to operate within. **Figure 66** outlines a conceptual decision model whereby the question of whether a chlorinated ethene plume is sustainable can be answered. This thesis report outlines in concept how most of the decision model works. The portion of the decision model not included in this report relates to the analysis of changing MNA parameters at a site (outlined in red-dash on Figure 66). The determination of the sustainability of MNA at a site can be separated into two components; past performance of natural attenuation and evaluation of sufficient MNA parameters. The former is the focus of this report and NAC is the screening tool by which past performance of natural attenuation is evaluated. Use of NAC as a screening tool in combination with a specific analysis of MNA parameters within the conceptual decision model allows engineers, regulators, and decision makers to clearly determine whether MNA at a site is sustainable and whether site specific remediation goals will be met.

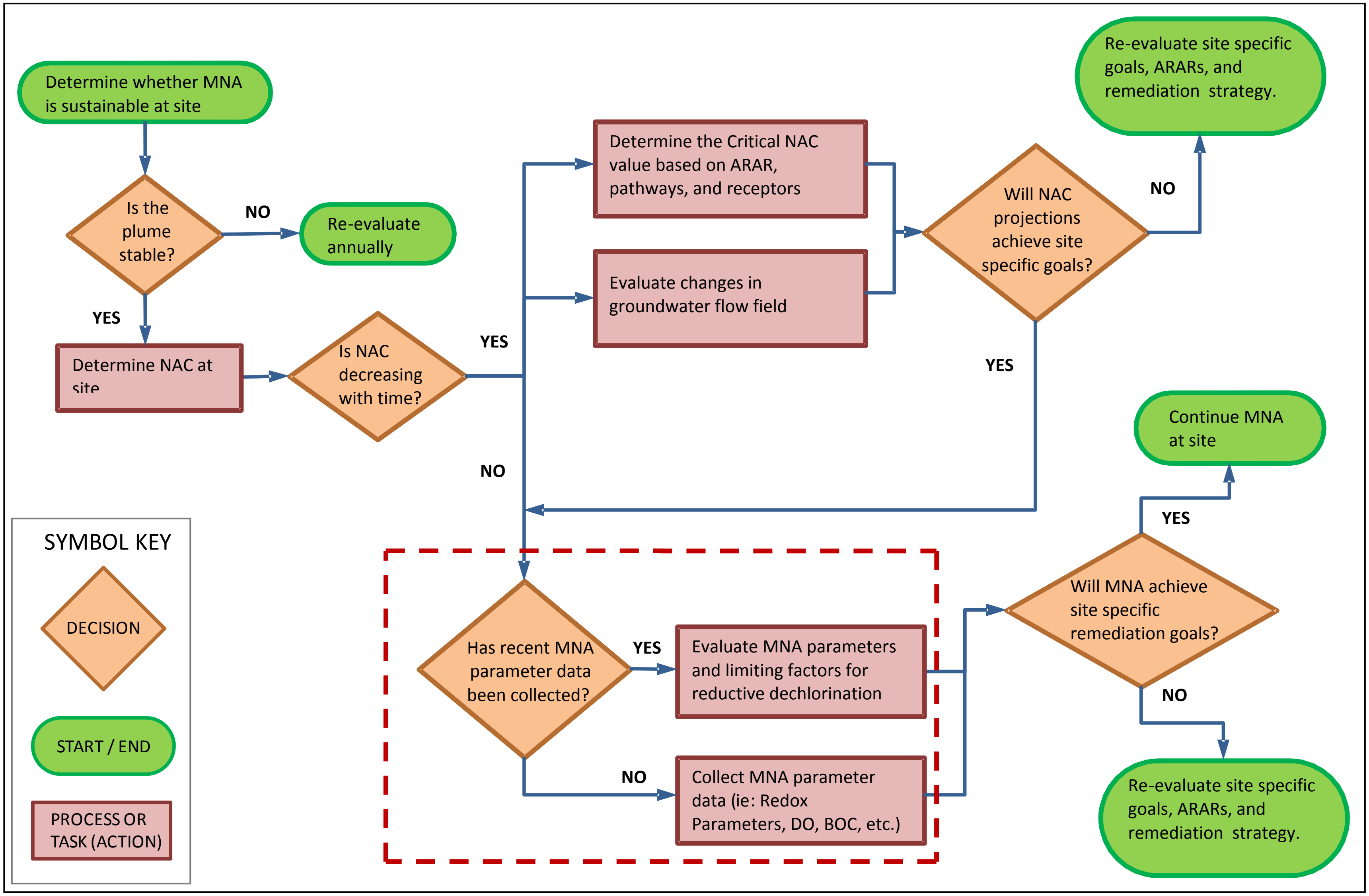

FIGURE 66: CONCEPTUAL DECISION MODEL FOR MNA SUSTAINABILITY EVALUATION USING NAC AND MNA PARAMETERS

5. CONCLUSIONS AND IMPLICATIONS OF RESEARCH

5.1 Conclusions

MNA has been widely used as a remedial strategy, acknowledged by the EPA as a best technology for cost effective remediation within certain site conditions. Despite the widespread use of MNA there are currently no methods of predicting the sustainability of MNA at a site. The primary objective of this thesis is to determine whether NAC is an appropriate quantitative screening tool for determining whether natural attenuation of chlorinated solvents in a groundwater system is sustainable. To achieve this objective, five DoD sites with chlorinated ethene groundwater plumes where selected. Constituent specific NAC values were quantified and statistically examined to determine the past performance of MNA at the sites. This analysis included two methods for evaluating the newest measurement as well as the determination of a site specific CNAC. To fully achieve the primary objective, it was also necessary to define a framework by which a site can be evaluated for sustainable natural attenuation using NAC and other quantitative tools. To that end, a conceptual decision model was developed to be a framework of the statistical tools presented and utilized in this thesis. This decision model enhances the usability of the processes presented as well as simplifies the communication of a site evaluation.

The determination of the sustainability of MNA at a site can be separated into two components; past performance of natural attenuation and evaluation of current MNA parameters. The process developed has shown to be effective at each site examined, allowing the engineer to determine past performance of MNA. Although in several cases the quantity of data limited the type of statistical conclusions that could be made. With knowledge about the sustainability of MNA at a site, informed decisions can be made about remedial approaches to achieve site specific ARARs.

5.2 Implications of Research on Decision Making

Remediation programs are often driven by factors of risk to populations and natural resources. At sites owned by the DOD a major factor in determining remedial strategy objectives and site specific goals is the delineation of contaminant pathways to receptors. In some cases, land use controls can eliminate pathways between people and sensitive natural resources. MNA has become a widely used remedial approach by the DOD and the EPA when it can be shown to be successful and economical as a long-term remedial strategy (USEPA, 1999). MNA has particularly been used on sites where pathways of contaminants to receptors can be eliminated or do not exist. For this reason, MNA is expected to continue to be used often after source zone remedial actions. The conceptual decision model and the analytical tools used within the model can give greater confidence and clarity to the process of determining if MNA will achieve site specific goals.

5.3 Future Research

The conceptual decision model is used to determine the sustainability at a site by the combined analysis of (1) historical trends in NAC and (2) changes to and biological limitations of MNA parameters related to reductive dechlorination. Evaluating MNA parameters including: field data collection, laboratory analysis methods, and analysis of biological limitations to reductive dechlorination within an aquifer are not covered in this report. These topics are examined in ongoing research at Virginia Tech by Lashaun King and Dr. Mark Widdowson. This ongoing research builds on the NAC tools and conceptual decision model described in this report in order to equip engineers and decision makers with a complete toolkit for analyzing the sustainability of MNA with chlorinated ethene plumes. The expected completion date of King and Widdowson's associated work is May 2011.

The potential for building further on the analysis presented in this thesis exists. One opportunity is to explore a more complex weighted regression analysis. Each NAC value is a slope of a regression which inherently has a standard error. The analysis could be repeated using a weighted time regression analysis. This method could prove to add value and increased accuracy to the determination of MNA sustainability.

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APPENDIX A NAS Pensacola, OU10 – Supporting Documentation

Table A.1: Total chlorinated ethene concentrations, OU10, NAS Pensacola

Well Name	USGS-5	IMW66	USGS-6	USGS-1	USGS-2	33G12
Dist. to Source (ft)	0	30	73	140	225	330
Date	Conc. (ug/L)					
3/24/1997	-	2513.3	-	393.9	15.5	3
7/16/1997	-	3536	-	432.6	29.5	3
11/4/1997	-	4421	-	631	15.3	3
1/23/1998	-	3507	-	834	22.6	3
9/8/1998	1638.2	2958	2094	484.9	32.9	3
12/1/1998	2723	2668	1833	755	25.2	48.9
1/11/1999	2250.7	532.2	1892	905	31.1	3
2/12/1999	2106.9	532.2	1145	0	21.8	3
6/1/1999	89.61	3	52.55	-	-	-
3/23/2000	488.5	-	315.5	530.4	19.1	3
9/20/2000	544.9	109	317.6	574	25.2	2
4/24/2001	1217	53	62.5	540.9	18.2	3
1/24/2002	40.1	29.6	740.3	404	23.6	3
4/11/2002	1871	78.7	999.6	598	18.6	3
7/30/2002	269.2	295.4	600.7	737	15	3
*1/29/2003	3013	183.5	1328.9	616	26.1	1
*8/15/2003	5440	571.1	2939.1	1037	41.9	8.8
*2/16/2004	215	317.5	1351	675.7	28	3.3
*8/10/2004	2815	1080.94	315.37	567	61.2	11.2
*2/7/2005	480	1841	1615	920	54.2	6.5
*8/8/2005	3370	4433.5	884	567	61.2	11.2
*3/22/2006	3180	4890	1147	576	69.8	11
*8/2/2006	3880	4630	1277	635	77	15.1
*4/4/2007	3210	479	986	588	74.1	7.9
*8/13/2007	2500	5350	978	556	62.6	41.53
*5/14/2008	3640	950	1548	521	78.3	-
9/3/2008	-	2954.6	1790	567	58.3	-

(*) indicates data that was used in the statistical analysis

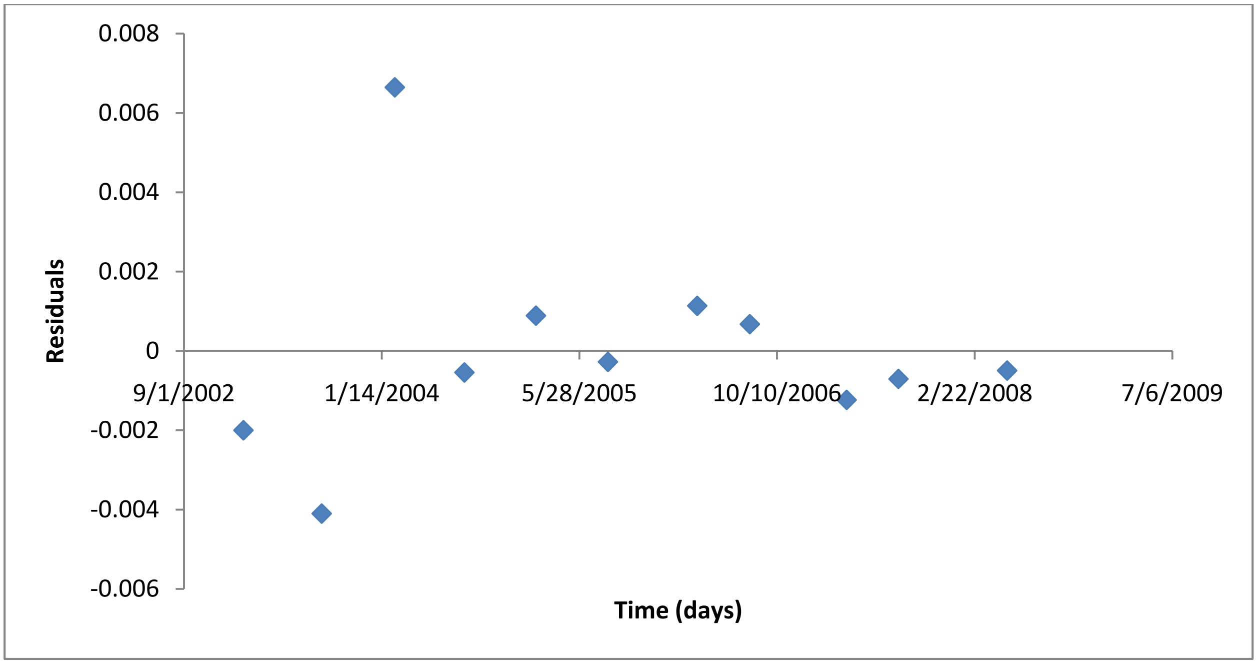

Figure A.1: Residual plot - linear regression, OU10, NAS Pensacola

Table A.2: Residual and predicted model from linear regression, OU10, NAS Pensacola

Observation	*Predicted NAC*	*Residuals*
1	0.0231999	-0.002
2	0.0224	-0.0041
3	0.0216525	0.006647
4	0.0209415	-0.00054
5	0.0202102	0.00089
6	0.0194749	-0.00027
7	0.0185619	0.001138
8	0.0180245	0.000675
9	0.0170347	-0.00123
10	0.0165054	-0.00071
11	0.0153944	-0.00049

Table A.3: Linear regression analysis of NAC with respect to time, NAS Pensacola

Regression Statistics	
Multiple R	0.6911
R Square	0.4776
Adjusted R Sq.	0.4196
Standard Error	0.0028
Observations	11

ANOVA

	df	SS	MS	F	Significance F
Regression	1	6.41633E-05	6.41633E-05	8.228795909	0.01851928
Residual	9	7.01767E-05	7.79741E-06		
Total	10	0.00013434			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 90.0%	Upper 90.0%
Intercept	0.175309785	0.054357231	3.225141908	0.010403307	0.052345185	0.298274385	0.075666842	0.274952728
X Variable 1	-4.0401E-06	1.40839E-06	-2.86858779	0.01851928	-7.2261E-06	-8.54094E-07	-6.62185E-06	-1.45836E-06

Slope +/- standard error	
UCL_se	LCL_se
-2.63171E-06	-5.4485E-06

Slope +/- 90% confidence inter.	
UCL_90%	LCL_90%
-1.45836E-06	-6.6218E-06

+/- Half Range (C.I.)
2.58175E-06

DOES ZERO FALL WITHIN THE 90% CONFIDENCE INTERVAL? NO

P-value (0.0185) is LESS THAN the alpha (0.05), so we REJECT the NULL HYPOTHESIS

NULL HYPOTHESIS - Slope of the linear regression is not different than zero (zero will be with the CI)

ALTERNATIVE HYPOTHESIS - Slope of the linear regression is different than zero

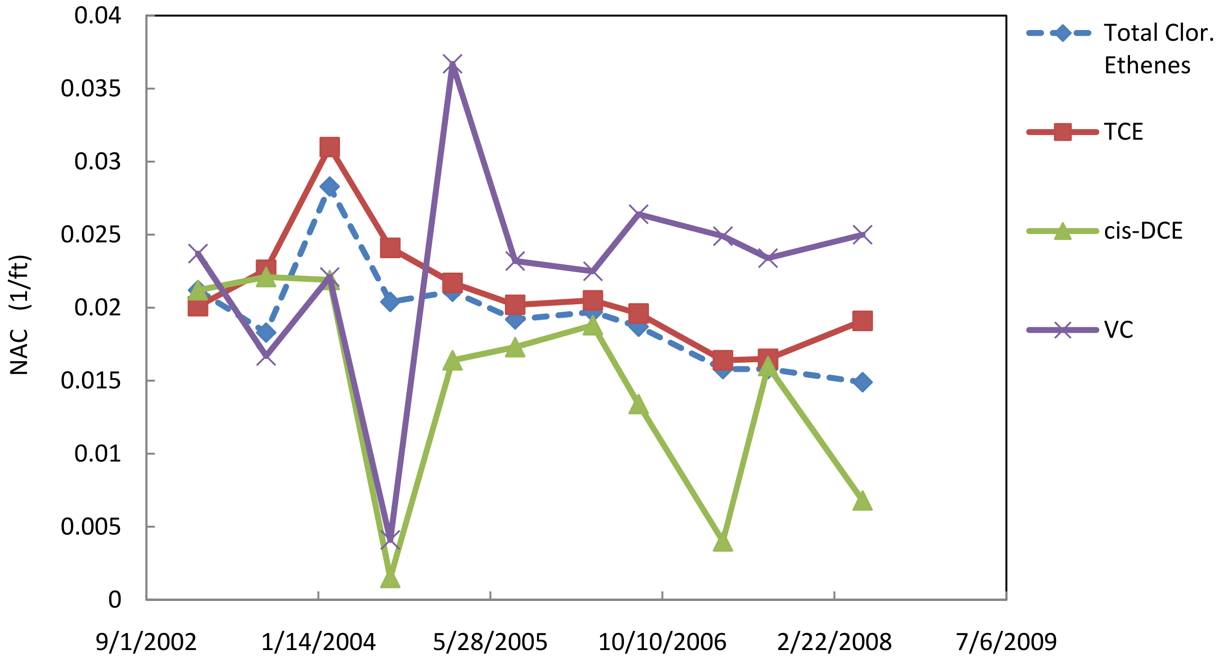

Figure A.2: NAC of all chlorinated ethene constituents, 2003-2008, OU-10, NAS Pensacola

APPENDIX B NAES Lakehurst, Site I&J, North plume - Supporting Documentation

Table B.1: Total chlorinated ethene concentrations by well, north plume, Lakehurst NAES

Well Name	NI	LK	MA	MC	MK
Distance from Source (ft)	0	0 (14)	1530	3060	4940
Date			Conc		
2/16/1996		669.2	0.0	11.9	6.71
5/30/1996		952.0	0.0	8.2	7.61
6/27/1996		325.9	0.0	0.0	0
9/4/1996		571.9	22.8	12.2	10.74
2/28/1997		91.0	2.7	6.4	2.25
9/2/1997		151.8	35.5	5.5	5.12
4/4/1998		465.8	26.1	12.8	6.04
8/7/1998		896.7	26.2	12.8	8.36
1/28/1999		623.9	33.6	11.0	5.69
8/11/1999		475.0	55.0	0.0	5.75
2/29/2000		681.1	46.4	13.0	8.22
9/20/2000		180.6	69.0	0.0	4.023
1/18/2001		180.4	66.3	9.4	4.803
3/4/2002		69.2	47.8	9.3	2.522
8/12/2002		62.5	21.5	6.4	0
3/24/2003		82.2	42.9	11.7	0
8/6/2003		115.6	41.9	10.1	41.82
2/27/2004	510.3	155.5	61.2	11.7	2.63
8/24/2004	336.4	102.8	30.3	9.6	2.113
2/17/2005	427.71	105.2	51.4	9.7	2.025
8/23/2005	358.21	173.4	138.7	8.7	2.073
1/27/2006	331.8	135.7	46.8	8.9	1.964
11/9/2006	348.9	35.1	58.5	0.8	1.744
5/9/2007	249.03	34.0	45.7	0.0	1.45
11/12/2007	291.7	20.2	73.1	9.6	1.52

Table B.2: All concentration data for chlorinated ethenes in plume centerline, north plume, Lakehurst NAES

Well	Date	Total Chlor. Ethenes	PCE (ug/L)	TCE (ug/L)	cis-DCE (ug/L)	VC (ug/L)
NI	2/27/2004	510.3	54	92	351	13.3
NI	8/24/2004	336.4	17	41	267	11.4
NI	2/17/2005	427.7	46	75.5	297	9.21
NI	8/23/2005	358.2	41.8	68.6	238	9.81
NI	1/27/2006	331.8	23.5	39	246	23.3
NI	11/8/2006	348.9	18.8	51.3	266	12.8
NI	5/9/2007	249.0	5.83	20.2	200	23
NI	11/12/2007	291.7	18.2	55.2	204	14.3
LK	2/16/1996	669.2	125.95	199.5	293.7	50
LK	5/30/1996	952.0	233	291	427.5	0.5
LK	6/27/1996	325.9	68	120	130	7.9
LK	9/4/1996	571.9	125.6	210.8	232	3.46
LK	2/28/1997	91.0	BD	49.1	40.25	1.65
LK	9/2/1997	151.8	23.55	59	68.7	0.5
LK	4/1/1998	465.8	100	168.5	191.6	5.7
LK	8/7/1998	896.7	87.63	281.4	513.7	14
LK	1/28/1999	623.9	146.5	165.5	298.8	13.1
LK	8/11/1999	475.0	62.5	124	276	12.5
LK	2/29/2000	681.1	137	167	371	6.05
LK	9/20/2000	180.6	12	37.4	129	2.17
LK	1/18/2001	180.4	18.95	48	111	2.43
LK	3/4/2002	69.2	6.57	17.5	43	2.1
LK	8/12/2002	62.5	9.59	16.7	36.2	0
LK	3/24/2003	82.2	8.6	15.1	57.3	1.21
LK	8/6/2003	115.6	23.3	15.7	75.8	0.803
LK	2/27/2004	155.5	18.7	28.4	105	3.37
LK	8/24/2004	102.8	10.8	14	75	3.01
LK	2/17/2005	105.2	9.26	20	72.5	3.4
LK	8/23/2005	173.4	10.4	24.2	133	5.75
LK	1/27/2006	135.7	8.45	21.5	94.8	10.9
LK	11/8/2006	35.1	1.75	4.96	26.6	1.81
LK	5/9/2007	34.0	1.89	6.34	23.4	2.38
LK	11/12/2007	20.2	0.94	3.1	13.9	2.24
MA	2/16/1996	0.0	BD	BD	BD	BD

Well	Date	Total Chlor. Ethenes	PCE (ug/L)	TCE (ug/L)	cis-DCE (ug/L)	VC (ug/L)
MA	5/30/1996	0.0	NS	NS	NS	NS
MA	6/27/1996	0.0	NS	NS	NS	NS
MA	9/4/1996	22.8	1.2	7.4	13.1	1.1
MA	2/28/1997	2.7	BD	1.23	1.48	BD
MA	9/2/1997	35.5	1.41	13.7	19.7	0.73
MA	4/1/1998	26.1	1.05	10.7	13.6	0.73
MA	8/7/1998	26.2	1.3	11.71	11.2	1.98
MA	1/28/1999	33.6	1.45	17.42	13.3	1.4
MA	8/11/1999	55.0	3.03	24.9	24.6	2.5
MA	2/29/2000	46.4	3.16	16.4	25.1	1.74
MA	9/20/2000	69.0	1.97	26.2	38.1	2.68
MA	1/18/2001	66.3	2.96	32.8	28.4	2.14
MA	3/4/2002	47.8	3.35	22.9	18.1	3.4
MA	8/12/2002	21.5	BD	11.6	9.87	BD
MA	3/24/2003	42.9	2.25	19.6	19.8	1.26
MA	8/6/2003	41.9	2.12	19.5	18.8	1.52
MA	2/27/2004	61.2	2.52	30.2	26.6	1.85
MA	8/24/2004	30.3	2.11	13.7	13.1	1.38
MA	2/17/2005	51.4	2.2	23.2	24.7	1.3
MA	8/23/2005	138.7	3.98	69.7	62.9	2.08
MA	1/27/2006	46.8	1.86	22.7	20.8	1.4
MA	11/8/2006	58.5	2.93	28.5	26.1	0.932
MA	5/9/2007	45.7	1.62	21.9	21.1	1.08
MA	11/12/2007	73.1	4.34	35.9	31.1	1.78
MC	2/16/1996	11.9	1.56	6.99	3.32	BD
MC	5/30/1996	8.2	1.07	4.61	2.49	BD
MC	6/27/1996	0.0	NS	NS	NS	NS
MC	9/4/1996	12.2	1.9	6.3	4	BD
MC	2/28/1997	6.4	0.77	3.89	1.74	BD
MC	9/2/1997	5.5	1.47	BD	3.98	BD
MC	4/1/1998	12.8	1.21	7.27	4.29	BD
MC	8/7/1998	12.8	1.56	8.01	3.19	BD
MC	1/28/1999	11.0	0.98	7.42	2.63	BD
MC	8/11/1999	0.0	BD	BD	BD	BD
MC	2/29/2000	13.0	1.6	7.38	3.97	BD
MC	9/20/2000	0.0	BD	BD	BD	BD
MC	1/18/2001	9.4	0.96	5.58	2.85	BD
MC	3/4/2002	9.3	0.95	5.08	3.31	BD

Well	Date	Total Chlor. Ethenes	PCE (ug/L)	TCE (ug/L)	cis-DCE (ug/L)	VC (ug/L)
MC	8/12/2002	6.4	BD	4.19	2.16	BD
MC	3/24/2003	11.7	1.16	5.5	5.07	BD
MC	8/6/2003	10.1	0.7	5.61	3.75	BD
MC	2/27/2004	11.7	1.05	6.41	4.21	BD
MC	8/24/2004	9.6	0.816	5.46	3.33	BD
MC	2/17/2005	9.7	0.893	5.6	3.25	BD
MC	8/23/2005	8.7	0.822	5.23	2.61	BD
MC	1/27/2006	8.9	0.761	5.14	2.99	BD
MC	11/8/2006	0.8	BD	0.754	BD	BD
MC	5/9/2007	0.0	BD	BD	BD	BD
MC	11/12/2007	9.6	1.04	5.89	2.64	BD
MK	2/16/1996	6.7	1.02	3.78	1.91	BD
MK	5/30/1996	7.6	1.35	3.55	2.71	BD
MK	6/27/1996	0.0	NS	NS	NS	NS
MK	9/4/1996	10.7	2.32	5.43	2.99	BD
MK	2/28/1997	2.3	BD	BD	2.25	BD
MK	9/2/1997	5.1	0.84	2.62	1.66	BD
MK	4/1/1998	6.0	1.03	3.46	1.55	BD
MK	8/7/1998	8.4	1.77	4.54	2.05	BD
MK	1/28/1999	5.7	0.95	3.31	1.43	BD
MK	8/11/1999	5.8	0.88	3.34	1.53	BD
MK	2/29/2000	8.2	1.43	4.36	2.43	BD
MK	9/20/2000	4.0	0.393	2.1	1.53	BD
MK	1/18/2001	4.8	0.973	2.72	1.11	BD
MK	3/4/2002	2.5	BD	1.55	0.972	BD
MK	8/12/2002	0.0	BD	BD	BD	BD
MK	3/24/2003	0.0	BD	BD	BD	BD
MK	8/6/2003	41.8	2.09	18.9	19.1	1.73
MK	2/27/2004	2.6	BD	1.63	1	BD
MK	8/24/2004	2.1	BD	1.36	0.753	BD
MK	2/17/2005	2.0	BD	1.28	0.745	BD
MK	8/23/2005	2.1	BD	1.34	0.733	BD
MK	1/27/2006	2.0	BD	1.25	0.714	BD
MK	11/8/2006	1.7	BD	1.12	0.624	BD
MK	5/9/2007	1.5	BD	0.95	0.5	BD
MK	11/12/2007	1.5	BD	0.92	0.6	BD

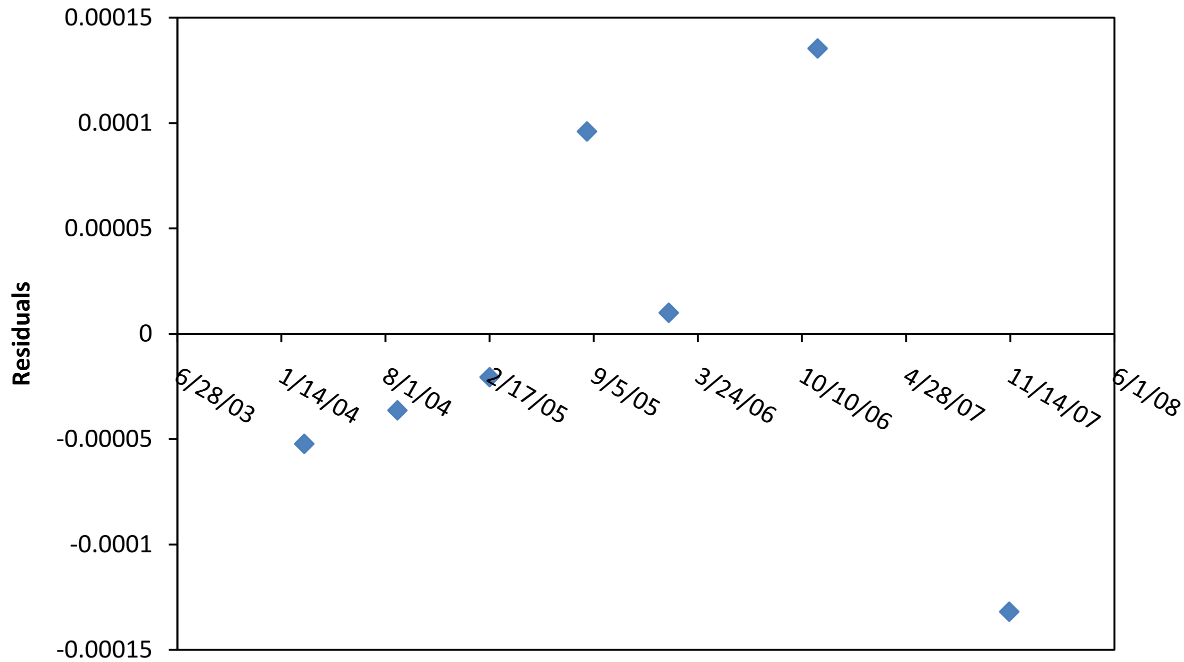

Figure B.1: Residual plot, based on linear regression and predicted model, north plume, Lakehurst NAES

Table B.3: Residual and predicted model from linear regression, north plume, Lakehurst NAES

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
1	0.000852284	-5.22841E-05	-0.575503274
2	0.000836375	-3.63754E-05	-0.400392637
3	0.000820644	-2.06445E-05	-0.227238544
4	0.000804025	9.59752E-05	1.056421909
5	0.000790071	9.92864E-06	0.109286926
6	0.000764653	0.000135347	1.489796278
7	0.000731947	-0.000131947	-1.452370658

`

Table B.4: Linear Regression statistics, north plume, Lakehurst NAES

Regression Statistics	
Multiple R	0.4179
R Square	0.1746
Adjusted R Square	0.0096
Standard Error	0.0001
Observations	7

ANOVA

	df	SS	MS	F	Significance F
Regression	1	1.04784E-08	1.04784E-08	1.057962685	0.35084235
Residual	5	4.95216E-08	9.90432E-09		
Total	6	0.00000006			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 90.0%	Upper 90.0%
Intercept	4.2335E-03	3.3383E-03	1.2682E+00	2.6058E-01	-4.3479E-03	1.2815E-02	-2.4934E-03	1.0960E-02
X Variable 1	-8.8875E-08	8.6406E-08	-1.0286E+00	3.5084E-01	-3.1099E-07	1.3324E-07	-2.6299E-07	8.5238E-08

Slope +/- standard error	
UCL_se	LCL_se
-2.469E-09	-1.753E-07

Slope +/- 90% confidence inter.	
UCL_90%	LCL_90%
8.524E-08	-2.630E-07

+/- Half Range (C.I.)
1.741E-07

DOES ZERO FALL WITHIN THE 90% CONFIDENCE INTERVAL? YES

P-value (0.156) is GREATER THAN the alpha (0.10), so we ACCEPT the NULL HYPOTHESIS

NULL HYPOTHESIS - Slope of the linear regression is not different than zero (zero will be within the CI)

ALTERNATIVE HYPOTHESIS - Slope of the linear regression is different than zero

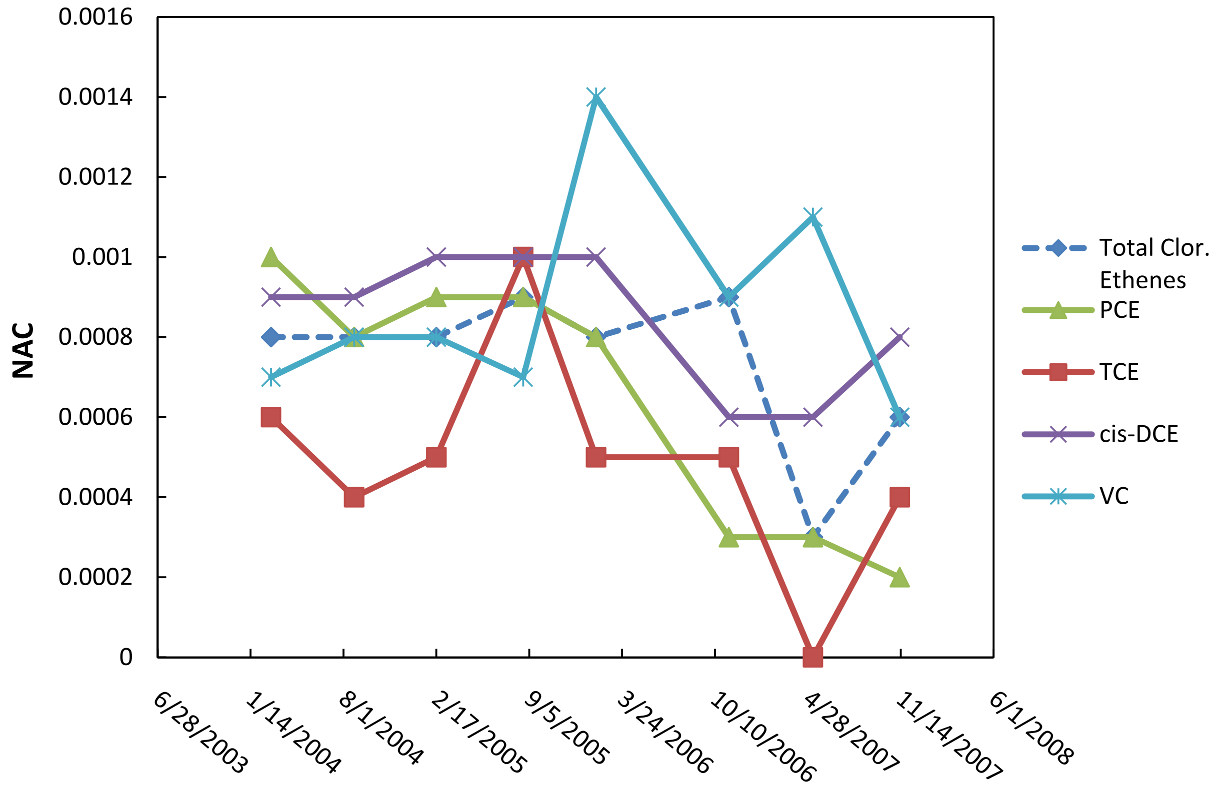

Figure B.2: NAC as a function of time, for all constituents, north plume, Lakehurst NAES

APPENDIX C Hill AFB, Site OU-2 - Supporting Documentation

Table C.1: Concentration data for chlorinated ethene constituents, wells in the plume centerline, OU2, Hill AFB

Well	Date	Total Chlorinated Ethene (ug/L)	PCE (ug/L)	TCE (ug/L)	cis-DCE (ug/L)	VC (ug/L)
U2-085	2/6/1998	20571	63	20500	8	NS
U2-085	9/24/1998	8091.22	74.42	8016.8	0	0
U2-085	3/25/1999	40774.3	0	40774.3	0	0
U2-085	6/14/1999	24062	55	24000	7	0
U2-085	7/14/2000	35200	0	35200	0	0
U2-085	4/30/2001	37093	76.4	37000	16	0.6
U2-085	1/11/2002	35176.4	52.3	35100	21.6	2.5
U2-085	7/8/2002	32458.4	58.4	32400	0	0
U2-085	10/10/2002	24046	46	24000	0	0
U2-085	9/16/2003	21960.9	44.3	21900	14.1	2.5
U2-085	11/19/2003	20754.7	27.5	20680	47.2	0
U2-085	5/11/2004	35160.7	45.8	35100	14.1	0.8
U2-085	11/3/2004	27048	36.6	27000	11.4	0
U2-085	5/6/2005	35654.6	54.6	35600	0	0
U2-085	10/14/2005	24442.2	42.2	24400	0	0
U2-085	5/11/2006	22156.3	43.1	22100	13.2	0
U2-085	10/17/2006	19846.9	32.6	19800	10.7	3.6
U2-085	5/4/2007	15643.4	32.2	15600	11.2	0
U2-085	10/3/2007	13745.1	31.3	13700	13.8	0
U2-021R	5/26/1994	6133	33	6100	NS	0
U2-021R	8/9/1994	5800	0	5800	NS	0
U2-021R	11/15/1994	7632	32	7600	NS	0
U2-021R	2/8/1995	7749	49	7700	NS	0
U2-021R	8/30/1995	9433	33	9400	NS	0
U2-021R	2/21/1996	9238	38	9200	NS	0
U2-021R	9/25/1996	13270	0	13000	270	0
U2-021R	3/27/1997	9049	29	8700	320	0
U2-021R	9/23/1997	6956	26	6600	330	0
U2-021R	3/25/1998	6683	23	6400	260	0
U2-021R	9/24/1998	4247.21	19.88	4018.4	208.93	0
U2-021R	3/24/1999	7012.7	0	6710	302.7	0
U2-021R	6/14/1999	3666	16	3500	150	0
U2-021R	7/18/2000	4362.2	24.2	4090	248	0
U2-021R	4/30/2001	4787.4	28.3	4530	229	0.1
U2-021R	1/10/2002	4710.4	34.4	4480	196	0
U2-021R	6/27/2002	4604.9	21.9	4380	203	0

Well	Date	Total Chlorinated Ethene (ug/L)	PCE (ug/L)	TCE (ug/L)	cis-DCE (ug/L)	VC (ug/L)
U2-021R	10/3/2002	5004	27	4800	177	0
U2-021R	7/9/2003	3193	19	3040	134	0
U2-021R	11/19/2003	3176.2	26.4	3050	99.8	0
U2-021R	5/7/2004	4322.3	27.1	4140	155	0.2
U2-021R	10/18/2004	2589.6	18.6	2450	121	0
U2-021R	5/25/2005	2319.7	17.7	2180	122	0
U2-021R	10/26/2005	1656.1	15.7	1550	90.4	0
U2-021R	5/18/2006	1735.9	13.9	1590	132	0
U2-021R	10/19/2006	2227	13	2090	124	0
U2-021R	4/26/2007	1812.4	12.4	1690	110	0
U2-021R	10/4/2007	1902.2	15.2	1780	107	0
U2-021R	4/22/2008	2063.6	13.6	1950	100	0
U2-039	9/23/1998	3158.22	17.62	3021	119.6	0
U2-039	3/24/1999	2017.6	0	2017.6	0	0
U2-039	1/10/2002	1079.8	9.1	972	87.7	11
U2-039	6/27/2002	1625.5	6.7	1520	98.8	0
U2-039	10/2/2002	1374.35	4.51	1210	157	2.84
U2-039	6/5/2003	654.44	0.14	117	519	18.3
U2-039	10/16/2003	976.7	0	408	562	6.7
U2-039	4/26/2004	666.6	0.5	373	263	30.1
U2-039	10/14/2004	1401.6	0.8	854	540	6.8
U2-039	5/4/2005	406.2	0	3.1	343	60.1
U2-039	10/21/2005	829.7	0	93	638	98.7
U2-039	5/22/2006	677.6	0	0.6	361	316
U2-039	10/13/2006	961.6	0.6	266	561	134
U2-039	4/23/2007	727.6	0	63.4	602	62.2
U2-039	10/5/2007	477.8	0	17.8	338	122
U2-039	4/21/2008	712.4	0.3	59.1	517	136
U2-043	9/28/1995	624.9	3.8	620	NS	1.1
U2-043	2/20/1996	1710.5	8.1	1700	NS	2.4
U2-043	9/25/1996	1730	0	1700	30	0
U2-043	3/26/1997	1847.9	4.9	1800	43	0
U2-043	9/23/1997	1859.2	8.4	1800	49	1.8
U2-043	3/24/1998	457.2	8.2	400	49	0
U2-043	6/15/1998	2253.05	11.65	2183.16	58.24	0
U2-043	9/23/1998	2968.84	0	2968.84	0	0
U2-043	12/8/1998	2774	0	2774	0	0

Well	Date	Total Chlorinated Ethene (ug/L)	PCE (ug/L)	TCE (ug/L)	cis-DCE (ug/L)	VC (ug/L)
U2-043	3/24/1999	2834.4	0	2768.4	66	0
U2-043	6/25/1999	2362	12	2300	48	2
U2-043	7/18/2000	2186	11.1	2120	52.6	2.3
U2-043	1/10/2002	1315.9	13	1270	29.9	3
U2-043	6/27/2002	1570.6	8.8	1530	31.8	0
U2-043	10/2/2002	1582.06	11.3	1530	37.8	2.96
U2-043	6/9/2003	1448.9	10.3	1400	37	1.6
U2-043	10/16/2003	1383.1	11.9	1330	36.2	5
U2-043	4/27/2004	1424.3	12	1370	38.5	3.8
U2-043	10/14/2004	1408.4	9.5	1370	26.2	2.7
U2-043	5/4/2005	1429.6	11	1380	36.1	2.5
U2-043	10/25/2005	1057.5	8.6	1020	26.6	2.3
U2-043	5/16/2006	1084.4	10.2	1040	32	2.2
U2-043	10/13/2006	1236.3	8.5	1200	25.7	2.1
U2-043	4/23/2007	1225.8	8.2	1190	26.5	1.1
U2-043	10/5/2007	860.8	9	827	23.4	1.4
U2-043	4/21/2008	912.5	3.8	884	24.6	0.1
U2-082	1/15/1998	1605.6	7.7	1520	77.9	NS
U2-082	9/23/1998	2281.2	0	2221.58	59.62	0
U2-082	3/24/1999	2400.8	0	2335	65.8	0
U2-082	6/28/1999	1858	4	1800	52	2
U2-082	7/13/2000	1414.3	3.9	1370	39.2	1.2
U2-082	1/8/2002	1477.7	3.4	1440	33.5	0.8
U2-082	6/25/2002	1554.7	2.9	1500	51.8	0
U2-082	10/4/2002	2037.5	0	1980	57.5	0
U2-082	6/17/2003	1745.25	4.95	1690	50.3	0
U2-082	11/18/2003	1685.8	4	1633	48.3	0.5
U2-082	5/11/2004	2291.6	5.5	2220	64.5	1.6
U2-082	11/5/2004	2184.4	6	2100	77	1.4
U2-082	5/6/2005	2171.3	6.3	2110	53.3	1.7
U2-082	10/26/2005	1663.7	5.7	1600	57.3	0.7
U2-082	5/16/2006	1792.9	4.9	1680	108	0
U2-082	10/19/2006	2025.5	6.2	1930	88.5	0.8
U2-082	5/4/2007	1628.1	5.7	1570	52.4	0
U2-082	10/16/2007	1222.4	3.4	1160	59	0
U2-086	1/7/1998	47.8	2	44.3	1.5	NS
U2-086	9/22/1998	106.01	0	103.45	2.56	0

Well	Date	Total Chlorinated Ethene (ug/L)	PCE (ug/L)	TCE (ug/L)	cis-DCE (ug/L)	VC (ug/L)
U2-086	3/23/1999	69.48	0	66.57	2.91	0
U2-086	6/24/1999	64	0	63	1	0
U2-086	7/17/2000	71.4	0	68.4	3	0
U2-086	4/27/2001	83.8	0	80.9	2.9	0
U2-086	12/6/2001	62.3	0	59.2	3.1	0
U2-086	6/24/2002	74.2	0	72.4	1.8	0
U2-086	9/30/2002	62.2	0	59.7	2.5	0
U2-086	5/29/2003	55.22	0	52.7	2.52	0
U2-086	11/18/2003	56.9	0	54.7	2.2	0
U2-086	5/3/2004	67.9	0	65.2	2.7	0
U2-086	10/13/2004	46.3	0	44.2	2.1	0
U2-086	5/3/2005	48.9	0	46.8	2.1	0
U2-086	10/21/2005	65.9	0	63.2	2.7	0
U2-086	5/17/2006	51.1	0	48.7	2.4	0
U2-086	10/9/2006	48.4	0	46.2	2.2	0
U2-086	4/30/2007	40.8	0	39	1.8	0
U2-086	10/8/2007	34.8	0	33.3	1.5	0

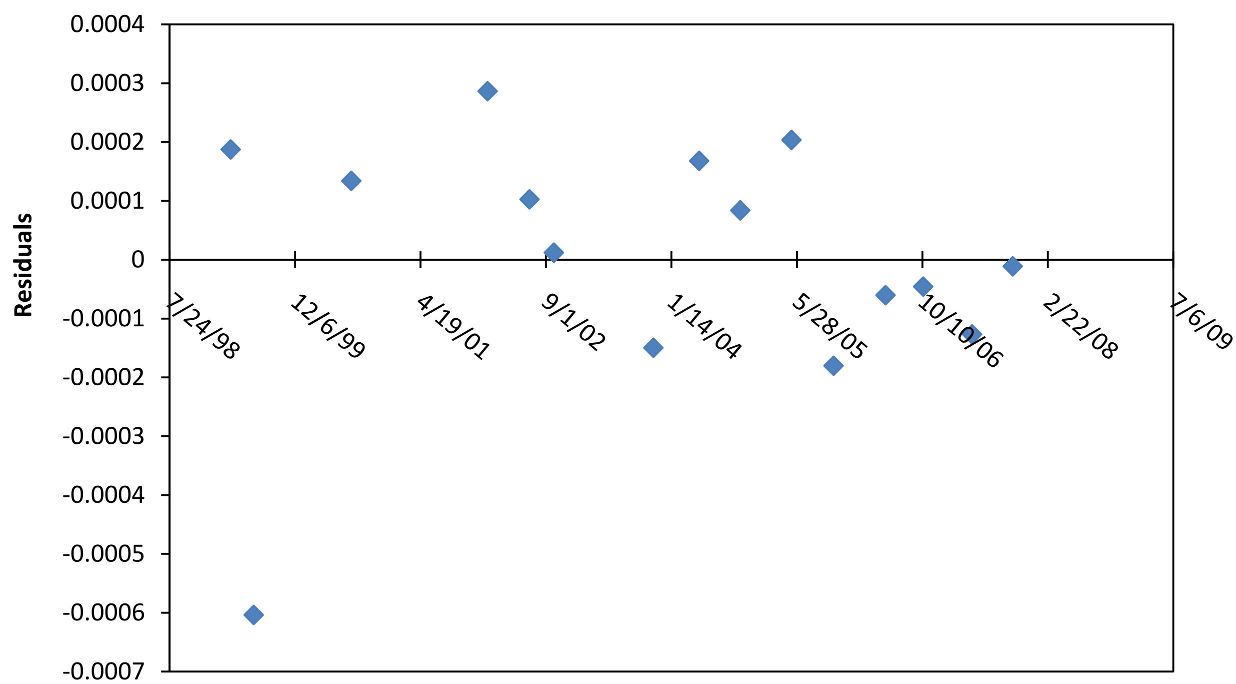

Figure C.1: Residual plot, OU2, Hill AFB

Table C.2: Residuals and predicted model from linear regression, OU2, Hill AFB

Observation	*Predicted Y*	*Residuals*
1	0.004412585	0.000187415
2	0.004403689	-0.000603689
3	0.004366076	0.000133924
4	0.004313572	0.000286428
5	0.004297424	0.000102576
6	0.004288045	1.19553E-05
7	0.004249658	-0.000149658
8	0.00423206	0.00016794
9	0.004216202	8.3798E-05
10	0.004196477	0.000203523
11	0.004180232	-0.000180232
12	0.004160217	-6.02169E-05
13	0.004145713	-4.57129E-05
14	0.004126858	-0.000126858
15	0.004111194	-1.11936E-05

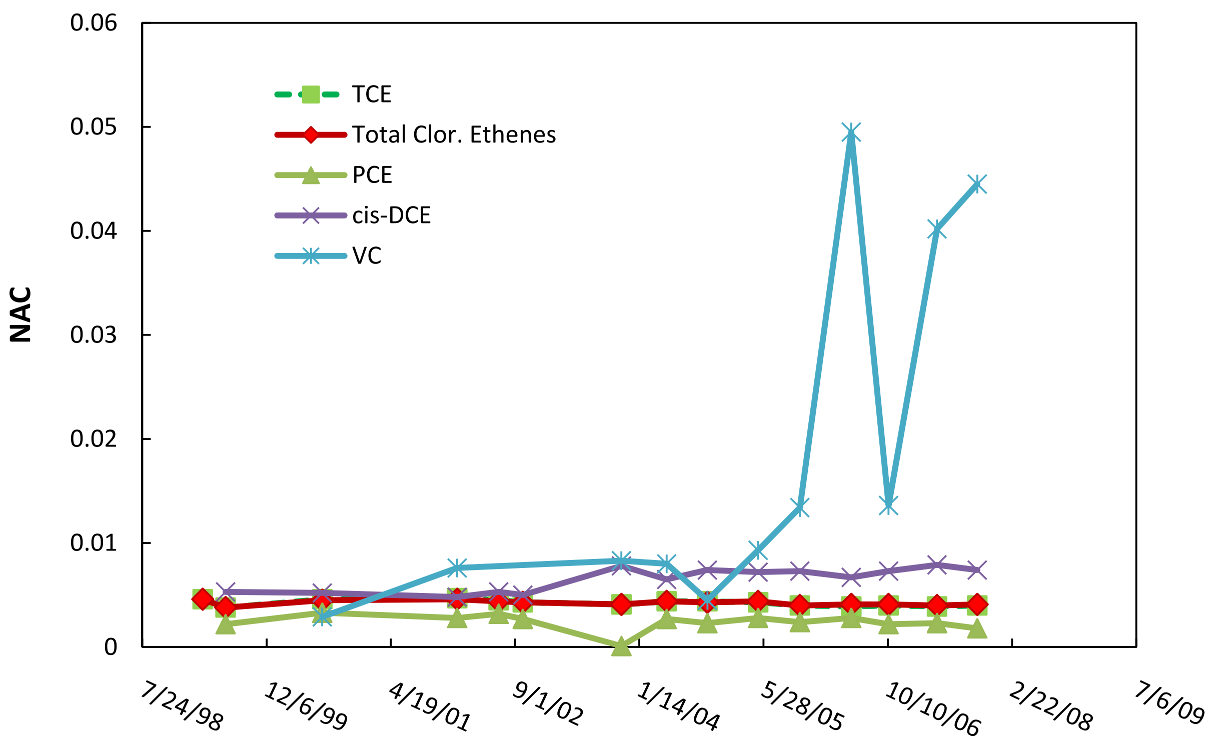

Figure C.2: NAC for each chlorinated ethene constituent

Table C.3: Linear regression statistics, OU2, Hill AFB

Regression Statistics	
Multiple R	0.4094
R Square	0.1676
Adjusted R Square	0.1036
Standard Error	0.0002
Observations	15

ANOVA

	df	SS	MS	F	Significance F
Regression	1	1.33664E-07	1.33664E-07	2.618210665	0.129638453
Residual	13	6.6367E-07	5.10515E-08		
Total	14	7.97333E-07			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 90.0%	Upper 90.0%
Intercept	7.9170E-03	2.2691E-03	3.4891E+00	3.9968E-03	3.0150E-03	1.2819E-02	3.8986E-03	1.1935E-02
X Variable 1	-9.6693E-08	5.9757E-08	-1.6181E+00	1.2964E-01	-2.2579E-07	3.2405E-08	-2.0252E-07	9.1336E-09

Slope +/- standard error	
UCL_se	LCL_se
-3.694E-08	-1.565E-07

Slope +/- 90% confidence inter.	
UCL_90%	LCL_90%
9.134E-09	-2.025E-07

+/- Half Range (C.I.)
1.058E-07

DOES ZERO FALL WITHIN THE 90% CONFIDENCE INTERVAL? **YES**

P-value (0.1296) is GREATER THAN the alpha (0.10), so we ACCEPT the NULL HYPOTHESIS

NULL HYPOTHESIS - Slope of the linear regression is not different than zero (zero will be within the CI)

ALTERNATIVE HYPOTHESIS - Slope of the linear regression is different than zero

APPENDIX D NAS North Island, IR Site 5 - Supporting Documentation

Table D.1: Concentrations of constituents, IR Site 5, NASNI

Well	Date	Total Chlor. Ethenes	PCE (ug/L)	TCE (ug/L)	cis-DCE (ug/L)	VC (ug/L)
S5-MW-21	10/9/1997	250,000	<5000	<5000	140,000	110,000
S5-MW-21	1/8/1998	240,000	<2000	<2000	130,000	110,000
S5-MW-21	4/16/1998	248,061	<13	61	180,000	68,000
S5-MW-21	7/9/1998	561,180	<13	180	550,000	11,000
S5-MW-21	4/18/2000	93,000	<1000	<1000	46,000	47,000
S5-MW-21	8/29/2000	69,000	<1200	<1200	19,000	50,000
S5-MW-21	1/4/2001	51,000	<500	<500	16,000	35,000
S5-MW-21	5/20/2002	112,000	<1000	<1000	61,000	51,000
S5-MW-21	8/13/2002	35,000	<500	<500	13,000	22,000
S5-MW-21	10/24/2002	46,000	<500	<500	27,000	19,000
S5-MW-21	1/7/2003	59,500	<10000	<10000	27,300	32,200
S5-MW-21	3/26/2003	24,100	<1000	<1000	23,000	1,100
S5-MW-21	4/9/2003	112,300	<2500	<2500	110,000	2,300
S5-MW-21	6/5/2003	88,500	<2500	<2500	82,000	6,500
S5-MW-21	7/9/2003	124,000	<2500	<2500	110,000	14,000
S5-MW-21	1/19/2005	117,000	<2000	<10000	49,000	68,000
S5-MW-21	4/5/2005	239,000	<10000	<50000	190,000	49,000
S5-MW-21	7/26/2005	587,000	<25000	<120000	500,000	87,000
S5-MW-21	10/6/2005	152,000	<5000	<25000	110,000	42,000
S5-MW-26	10/9/1997	0	NS	NS	NS	NS
S5-MW-26	1/8/1998	0	NS	NS	NS	NS
S5-MW-26	4/16/1998	0	NS	NS	NS	NS
S5-MW-26	7/9/1998	0	NS	NS	NS	NS
S5-MW-26	4/18/2000	19,900	<120	<120	8,900	11,000
S5-MW-26	8/29/2000	4,960	BD	BD	460	4,500
S5-MW-26	1/4/2001	0	NS	NS	NS	NS
S5-MW-26	5/20/2002	13,400	<250	<250	1,400	12,000
S5-MW-26	8/13/2002	13,980	<500	<500	980	13,000
S5-MW-26	10/24/2002	26,200	<250	<250	2,200	24,000
S5-MW-26	1/7/2003	60,500	<10,000	<10,000	<10,000	60,500
S5-MW-26	3/26/2003	0	NS	NS	NS	NS
S5-MW-26	4/9/2003	0	NS	NS	NS	NS
S5-MW-26	6/5/2003	0	NS	NS	NS	NS
S5-MW-26	7/9/2003	0	NS	NS	NS	NS
S5-MW-26	1/19/2005	91,000	<2,000	<10,000	25,000	66,000

S5-MW-26	4/5/2005	89,010	<25	10	25,000	64,000
S5-MW-26	7/26/2005	87,000	<2500	<12,000	16,000	71,000
S5-MW-26	10/6/2005	93,000	<25,000	<120,000	26,000	67,000
S5-MW-20	10/9/1997	157,000	<2000	<2000	110,000	47,000
S5-MW-20	1/8/1998	220,000	<2000	<2000	160,000	60,000
S5-MW-20	4/16/1998	184,000	<13	<17	140,000	44,000
S5-MW-20	7/9/1998	101,000	<13	<17	69,000	32,000
S5-MW-20	4/18/2000	0	NS	NS	NS	NS
S5-MW-20	8/29/2000	0	NS	NS	NS	NS
S5-MW-20	1/4/2001	1,490	<50	<50	190	1,300
S5-MW-20	5/20/2002	38	<12	14	BD	24
S5-MW-20	8/13/2002	13.6	<10	<10	3.6	10
S5-MW-20	10/24/2002	0	NS	NS	NS	NS
S5-MW-20	1/7/2003	0	NS	NS	NS	NS
S5-MW-20	3/26/2003	0	NS	NS	NS	NS
S5-MW-20	4/9/2003	7	<12	<12	<12	6.6
S5-MW-20	6/5/2003	0	NS	NS	NS	NS
S5-MW-20	7/9/2003	7	<10	<10	<10	6.6
S5-MW-20	1/19/2005	25	<10	<50	12	13
S5-MW-20	4/5/2005	47	BD	<5	13	34
S5-MW-20	7/26/2005	801	<25	<120	41	760
S5-MW-20	10/6/2005	445	<10	<50	15	430
S5-MW-12	10/9/1997	0	BD	BD	BD	BD
S5-MW-12	1/8/1998	0	BD	BD	BD	BD
S5-MW-12	4/16/1998	44	BD	BD	40	3.6
S5-MW-12	7/9/1998	0	BD	BD	0	BD
S5-MW-12	4/18/2000	0	NS	NS	NS	NS
S5-MW-12	8/29/2000	0	NS	NS	NS	NS
S5-MW-12	1/4/2001	0	BD	BD	BD	BD
S5-MW-12	5/20/2002	0	NS	NS	NS	NS
S5-MW-12	8/13/2002	0	NS	NS	NS	NS
S5-MW-12	10/24/2002	0	NS	NS	NS	NS
S5-MW-12	1/7/2003	0	NS	NS	NS	NS
S5-MW-12	3/26/2003	0	NS	NS	NS	NS
S5-MW-12	4/9/2003	5	BD	BD	4.7	0.7
S5-MW-12	6/5/2003	0	NS	NS	NS	NS
S5-MW-12	7/9/2003	0	NS	NS	NS	NS
S5-MW-12	1/19/2005	2	BD	<5	2.3	BD
S5-MW-12	4/5/2005	25	BD	2	15	7.9

S5-MW-12	7/26/2005	45	BD	<5	18	27
S5-MW-12	10/6/2005	3	BD	<5	3	BD
S5-MW-19	10/9/1997	0	BD	BD	BD	BD
S5-MW-19	1/8/1998	0	BD	BD	BD	BD
S5-MW-19	4/16/1998	0	BD	BD	BD	BD
S5-MW-19	7/9/1998	0	BD	BD	BD	BD
S5-MW-19	4/18/2000	0	NS	NS	NS	NS
S5-MW-19	8/29/2000	0	NS	NS	NS	NS
S5-MW-19	1/4/2001	0	BD	BD	BD	BD
S5-MW-19	5/20/2002	0	NS	NS	NS	NS
S5-MW-19	8/13/2002	0	NS	NS	NS	NS
S5-MW-19	10/24/2002	0	NS	NS	NS	NS
S5-MW-19	1/7/2003	0	NS	NS	NS	NS
S5-MW-19	3/26/2003	0	NS	NS	NS	NS
S5-MW-19	4/9/2003	0	BD	BD	BD	BD
S5-MW-19	6/5/2003	0	NS	NS	NS	NS
S5-MW-19	7/9/2003	0	NS	NS	NS	NS
S5-MW-19	1/19/2005	0	NS	NS	NS	NS
S5-MW-19	4/5/2005	4	BD	1.2	2.7	BD
S5-MW-19	7/26/2005	0	BD	BD	BD	BD
S5-MW-19	10/6/2005	0	BD	BD	BD	BD

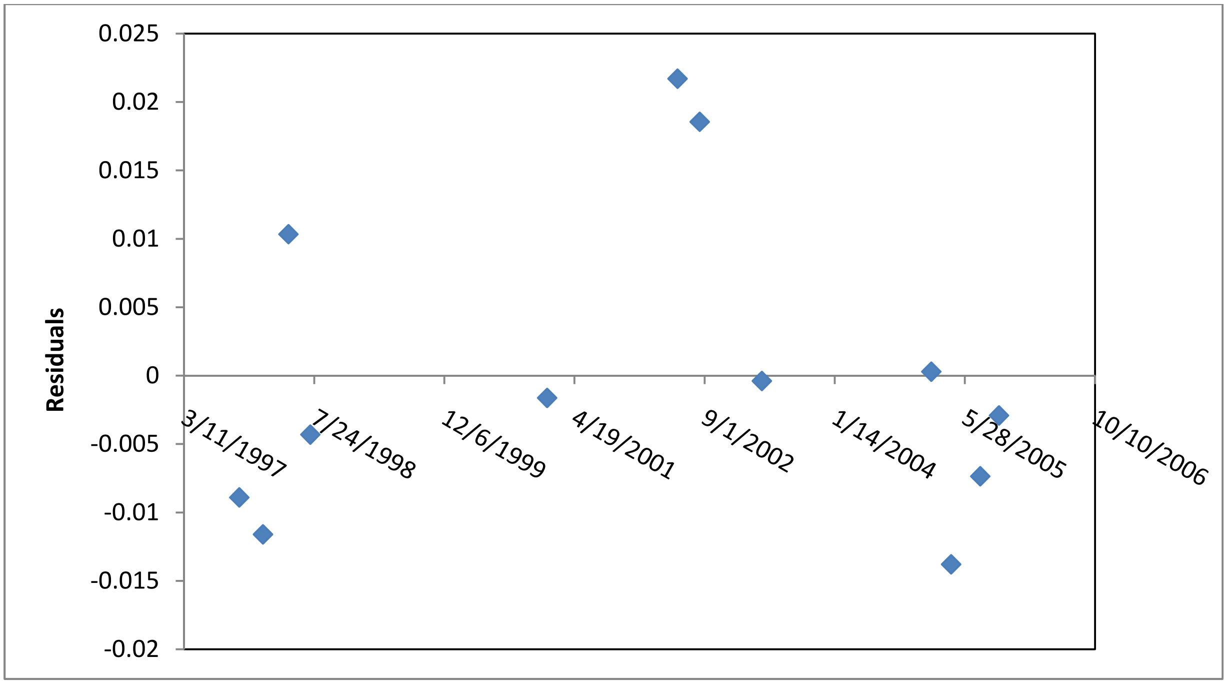

Figure D.1: Residual plot, IR Site 5, NASNI

Table D.2: Residuals and predicted model from linear regression, IR Site 5, NASNI

Observation	*Predicted Y*	*Residuals*
1	0.011403324	-0.008903324
2	0.012105071	-0.011605071
3	0.012860799	0.010339201
4	0.013508565	-0.004308565
5	0.020526035	-0.001626035
6	0.0243895	0.0217105
7	0.025044978	0.018555022
8	0.026888027	-0.000388027
9	0.031908218	0.000291782
10	0.032494292	-0.013794292
11	0.033357981	-0.007357981
12	0.033913209	-0.002913209

Table D.3: Linear regression statistics, IR Site 5, NASNI

Regression Statistics	
Multiple R	0.6174
R Square	0.3811
Adjusted R Square	0.3192
Standard Error	0.0119
Observations	12

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.000868827	0.000868827	6.158253037	0.032454734
Residual	10	0.001410833	0.000141083		
Total	11	0.00227966			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 90.0%	Upper 90.0%
Intercept	-2.6399E-01	1.1578E-01	-2.2801E+00	4.5777E-02	-5.2196E-01	-6.0175E-03	-4.7384E-01	-5.4144E-02
X Variable 1	7.7115E-06	3.1075E-06	2.4816E+00	3.2455E-02	7.8758E-07	1.4635E-05	2.0793E-06	1.3344E-05

Slope +/- standard error	
UCL_se	LCL_se
1.082E-05	4.604E-06

Slope +/- 90% confidence inter.	
UCL_90%	LCL_90%
1.334E-05	2.079E-06

+/- Half Range (C.I.)
5.632E-06

DOES ZERO FALL WITHIN THE 90% CONFIDENCE INTERVAL? **NO**

P-value (0.0324) is LESS THAN the alpha (0.10), so we REJECT the NULL HYPOTHESIS

NULL HYPOTHESIS - Slope of the linear regression is not different than zero (zero will be within the CI)

ALTERNATIVE HYPOTHESIS - Slope of the linear regression is different than zero

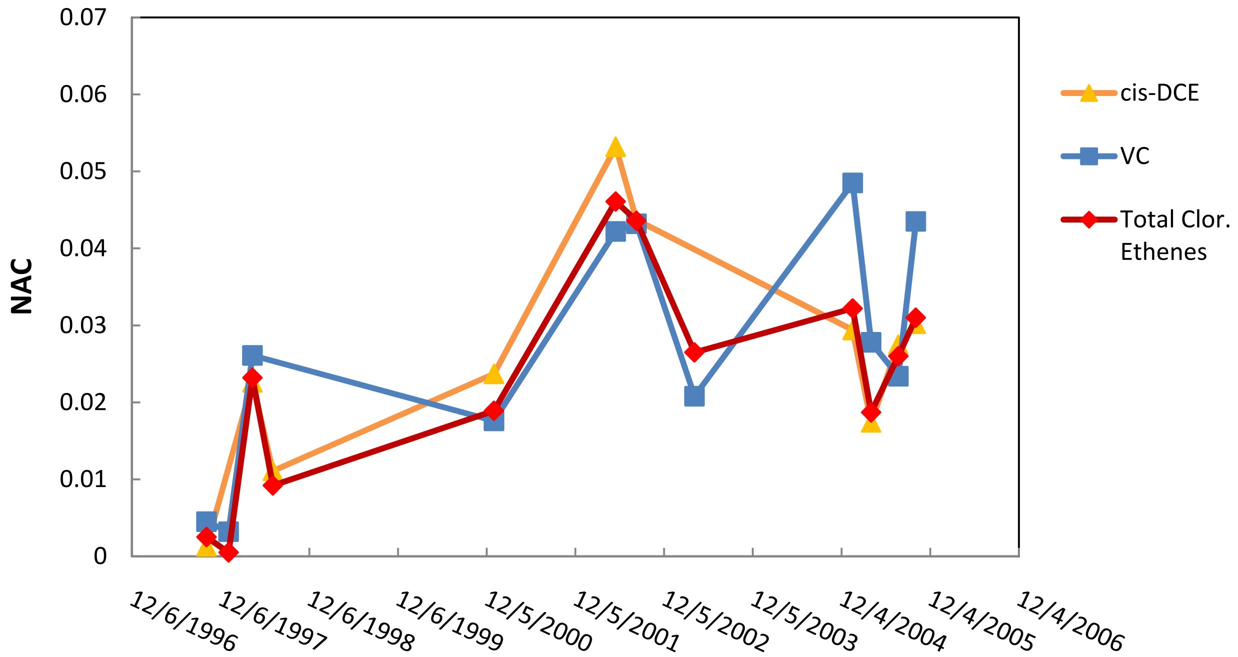

Figure D.2: NAC for three constituents with sufficient data, IR Site 5, NASNI

APPENDIX E NBK Keyport, OU-1, North plume - Supporting Documentation

Table E.1: Concentrations of constituents in plume centerline, OU1, NBK

Well	Date	Total Chlor. Ethenes	PCE (ug/L)	TCE (ug/L)	cis-DCE (ug/L)	VC (ug/L)
P1-4	6/9/1999	5500	<130	160	4800	540
P1-4	6/13/2001	5550	<20	<20	4900	650
P1-4	6/11/2002	4241.2	<.2	1.2	3600	640
P1-4	6/18/2003	3640	<100	<100	3200	440
P1-4	6/17/2004	2670	<130	<130	2300	370
P1-4	6/22/2005	2460	<67	<67	2100	360
P1-4	6/12/2006	1880	<50	<50	1600	280
P1-3	6/9/1999	605	<16	35	450	120
P1-3	6/13/2001	0	NS	NS	NS	NS
P1-3	6/11/2002	125	<.2	<.2	53	72
P1-3	6/18/2003	137	<2	<2	58	79
P1-3	6/17/2004	56	<1	<1	15	41
P1-3	6/22/2005	46	<1	<1	11	35
P1-3	6/12/2006	20.6	<1	<1	4.6	16
MW1-2	6/9/1999	1387	BD	27	1200	160
MW1-2	6/13/2001	1058	BD	19	950	89
MW1-2	6/11/2002	750	BD	15	660	75
MW1-2	6/18/2003	1013	BD	13	870	130
MW1-2	6/17/2004	752	<50	12	630	110
MW1-2	6/22/2005	883	BD	13	690	180
MW1-2	6/12/2006	0	NS	NS	NS	NS
N-2	6/17/2004	122.6	BD	1.6	83	38

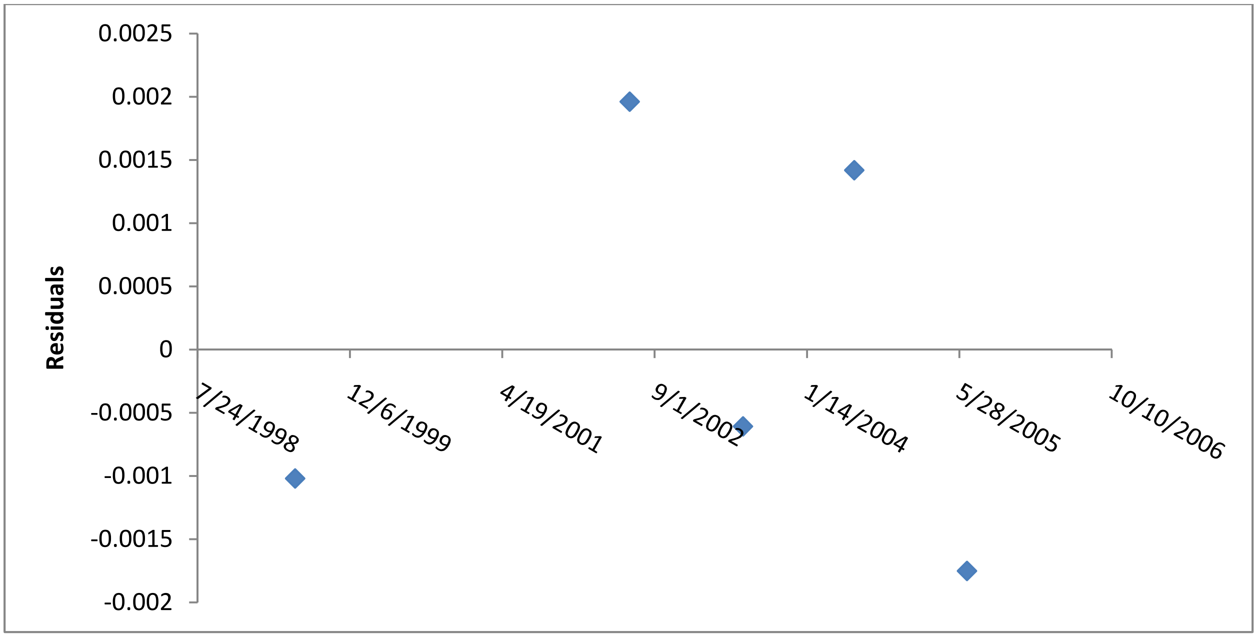

Figure E.1: Residual plot, OU1, NBK

Table E.2: Residuals and predicted model from linear regression, OU1, NBK

Observation	*Predicted Y*	*Residuals*
1	0.009520027	-0.001020027
2	0.008838739	0.001961261
3	0.008607921	-0.000607921
4	0.008381445	0.001418555
5	0.008151868	-0.001751868

Table E.3: Linear regression statistics, OU1, NBK

Regression Statistics	
Multiple R	0.3104
R Square	0.0963
Adjusted R Square	-0.2049
Standard Error	0.0019
Observations	5

ANOVA

	df	SS	MS	F	Significance F
Regression	1	1.1021E-06	1.1021E-06	0.319822234	0.61124928
Residual	3	1.03379E-05	3.44597E-06		
Total	4	0.00001144			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 90.0%	Upper 90.0%
Intercept	3.2056E-02	4.1308E-02	7.7603E-01	4.9429E-01	-9.9403E-02	1.6351E-01	-6.5156E-02	1.2927E-01
X Variable 1	-6.2048E-07	1.0972E-06	-5.6553E-01	6.1125E-01	-4.1122E-06	2.8712E-06	-3.2025E-06	1.9616E-06

Slope +/- standard error	
UCL_se	LCL_se
4.767E-07	-1.718E-06

Slope +/- 90% confidence inter.	
UCL_90%	LCL_90%
1.962E-06	-3.203E-06

+/- Half Range (C.I.)
2.582E-06

DOES ZERO FALL WITHIN THE 90% CONFIDENCE INTERVAL? **YES**

P-value (0.0324) is LESS THAN the alpha (0.10), so we REJECT the NULL HYPOTHESIS

NULL HYPOTHESIS - Slope of the linear regression is not different than zero (zero will be within the CI

ALTERNATIVE HYPOTHESIS - Slope of the linear regression is different than zero

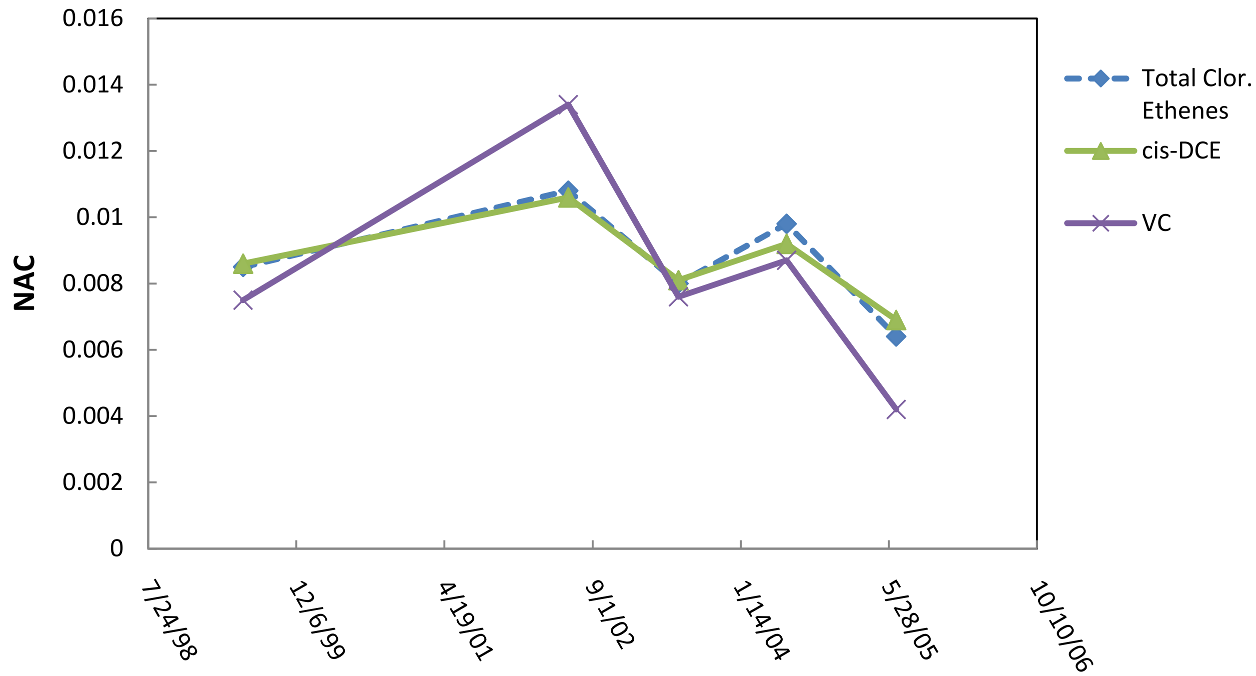

Figure E.2: NAC for constituents with sufficient data, OU1, NBK