STATISTICAL ASSESSMENT OF SUSPECTED CO-MINGLED PLUME AT

TINKER AIR FORCE BASE TO DETERMINE IF MULTIPLE SOURCES EXIST

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2006

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 2007

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CHAPTER I

INTRODUCTION

This investigation is an environmental forensics project performed for Tinker Air Force Base (AFB). The purpose of the project was to determine whether contamination plumes found at the Building 3001 site of Tinker AFB were from only Building 3001 or if there were multiple sources responsible. This chapter provides background information for Tinker AFB, hydraulic and geologic information, information about the contaminants analyzed, and a description of the environmental forensics performed.

1.1 Background Information

General Information about Tinker AFB and the processes performed at Tinker AFB can be found in the following sections.

1.1.1 Tinker Air Force Base

Tinker Air Force Base is located just south of I-40 in the Oklahoma City metropolitan area and covers approximately 220 acres. Figure 1 is an aerial view of the base of concern in this investigation. Labeled are the Industrial Waste Treatment Plant (IWTP) and Building 3001 (B3001), the probable source or sources of the groundwater contamination plumes detailed in this effort. Industrial operations at Tinker AFB began in 1942, and many of the operations produced solutions containing solvents and/or heavy metals. The main function of Tinker Air Force Base is the repair and maintenance of the aircraft of the U.S. Air Force. The base is bordered on the north and northeast by the urban communities of Midwest City and Del City and the south boundary is adjacent to the former General Motors Plant. Lake Stanley Draper is located southeast of the base. The remaining areas to the south and east are primarily agricultural (USACE 1988).

Figure 1: Base Map of Tinker AFB

1.1.2 Building 3001 site

Of particular concern to this effort is Building 3001 (B3001) which, beginning in 1942, served significant Air Force-wide industrial processes, with their associated wastes. Disposal of wastes was completed in accordance with accepted practices at those times; which are not equivalent to what is required today. The industrial activities within B3001 are listed as the following:

a) Disassembly, degreasing, cleaning, and inspection of aircraft and engine parts and components,
b) Plating, painting, heat treating, and testing of metal parts and components,
c) Assembly and repair shops for accessories including electrical systems, valves and governors, gear boxes, tubing and cables, fuel controls, nozzles, pumps, and bearings, and
d) Assembly, testing, and packaging of aircraft and aircraft components (USACE, 1988).

Building 3001 contained several subsurface concrete pits used for degreasing, plating, paint stripping, and solvent storage until the early 1970's. These abandoned pits allowed percolation of contaminants to the upper saturated zone of the Garber Wellington aquifer (USACE, 1991). In November 1984, Building 3001 was extensively damaged by fire. During the post-fire reconstruction, the Tulsa District Core of Engineers (COE) conducted Installation Restoration Program (IRP) investigations discovering high concentrations of trichloroethylene (TCE) and metals within the vicinity of Building 3001 (USACE, 1988). The purpose of this program included the following two objectives:

a) Investigate abandon solvent pits including a geophysical survey and a drilling and sampling program, and

b) Groundwater investigations and monitoring well installation (USACE, 1988).

The Building 3001 site was put on the National Priority List, i.e. the Superfund List, by the Environmental Protection Agency (EPA) in July of 1987. On December 9, 1988, representatives of the Air Force, the Oklahoma Health Department, and the EPA entered into a Federal Facility Agreement (FFA) under the Comprehensive Environmental Response Compensation Liability Act (CERCLA) (USACE, 1991). In 1994 a pump and treat system was installed to treat the contamination under the Building 3001 site. In 2004 the system was shut down and rebound testing was performed to determine if contamination adsorbed to soil would re-contaminate the groundwater (OCALC, 2005). Currently, the pump and treat system remains offline and treatment alternatives are under consideration.

1.1.3 Industrial Waste Treatment Plant

The Industrial Waste Treatment Plant (IWTP) is located northeast of Building 3001 and is included in the Air Force Installation Restoration Program (IRP). The IWTP replaced the use of the industrial waste pit (IWP) in 1965 as the primary means of disposal of hazardous waste from B3001. The IWTP treats waste generated primarily by the paint stripping process and chrome plating (USACE 1988). The area contains groundwater with elevated concentration of not only tetrachloroethene (PCE), trichloroethene (TCE), dichloroethene (1,2 DCE), and chromium (Cr) but also high concentrations of chlorobenzene and vinyl chloride (VC). Chlorobenzene and vinyl chloride were not detected in samples representing building 3001. IWTP is upgradient in the upper and lower saturated zones of the Garber-Wellington, which underlies the base and a substantial amount of central Oklahoma. The IWTP is expected to be a separate source from Building 3001 (USACE 1991).

1.2 Site Geology and Hydrology

The geology and hydrology of the Garber-Wellington aquifer and Hennessey Formation will be discussed in the following sections.

1.2.1 Geology

The Garber Wellington formation is about 900 feet thick in the Tinker area, and consists of lenticular and interbedded sandstone, shale, and siltstone. Sandstone beds ranging from a few feet to about forty feet in thickness make up about 65% of the formation. The Garber-Wellington is overlain by the Hennessey Formation over the southern half of the base. The Hennessey Formation does not reach as far north as Building 3001 or the IWTP (USACE 1988).

1.2.2 Hydrology

The recharge area for the Garber-Wellington covers the eastern half of Oklahoma County including TAFB, and the formation dips to the west about 15 feet per mile. The Garber Sandstone and Wellington Formations are hydrologically interconnected formations which are not easily distinguished from each other based on rock type, key beds, fossils, or hydrologic properties. Groundwater in the Garber-Wellington exists under both water table and confining conditions, depending on the presence of overlying shale beds, and flows to the southwest. The Garber-Wellington aquifer is the single most important source of potable groundwater in the Oklahoma City area (USACE 1988). The formation has been separated into four zones known as the upper saturated zone (USZ), the lower saturated zone (LSZ), the lower, lower saturated zone (LLSZ), and the production zone.

The USZ is located 15 to 30 feet below the ground surface and is an unconfined aquifer. The LSZ is found 50 to 80 feet below ground and is a semi to confined aquifer. The LLSZ is 110 to 175 feet below ground and is a confined aquifer. The production zone is 250 to 700 feet below ground and is a confined aquifer. A summary of the hydrology is presented in Table 1.

Table 1: Summary of Hydraulic Zones

Zone	Depth (ft)	Confining Conditions
USZ	15 to 30	Unconfined
LSZ	50 to 80	Semi to Confined
LLSZ	110 to 175	Confined
Production Zone	250 to 700	Confined

Contour maps of water levels for the USZ, LSZ, and LLSZ are presented in Figures 2 through 5 found below.

Figure 2: Water Level Contour Map for USZ

A more detailed water level contour map from December, 2004, has been provided in Figure 3 for clarification. From Figure 3 it can be seen that B3001 sits above a perched aquifer, or water mound, and that the ground water travels downgradient in essentially every direction away from B3001, except directly towards IWTP, which is approximately the same water level. The USZ does not extend as far as IWTP, and terminates along the western edge of IWTP.

Figure 3: Water Level Contour Map of USZ

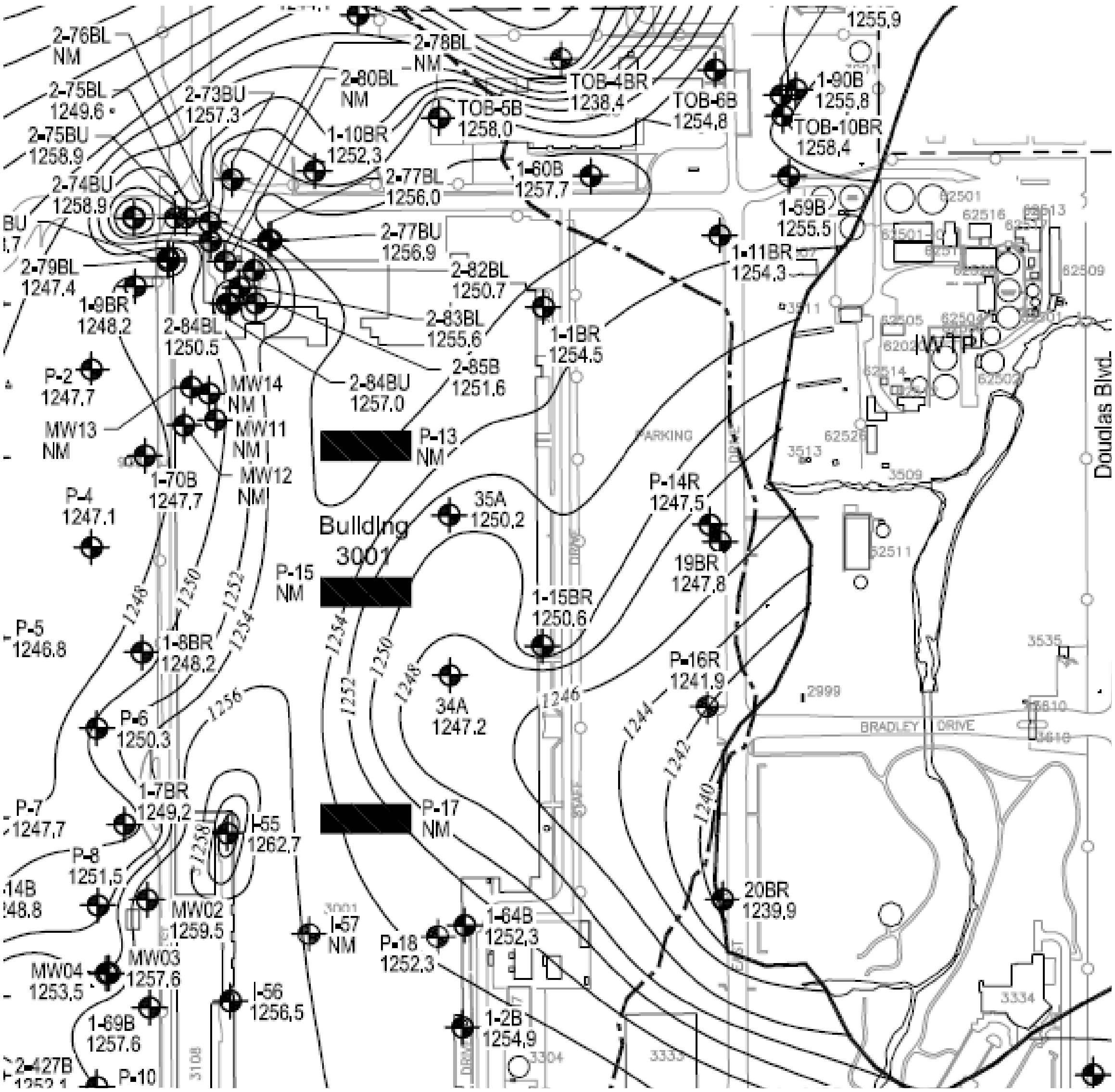


Figure 4 shows the water level contours in the LSZ. The water gradient is traveling downhill in along a north-east to south-west direction, from IWTP to B3001. There are also localized low water areas along the western wall of B3001 where ground water extraction has occurred.

Figure 4: Water Level Contour Map LSZ

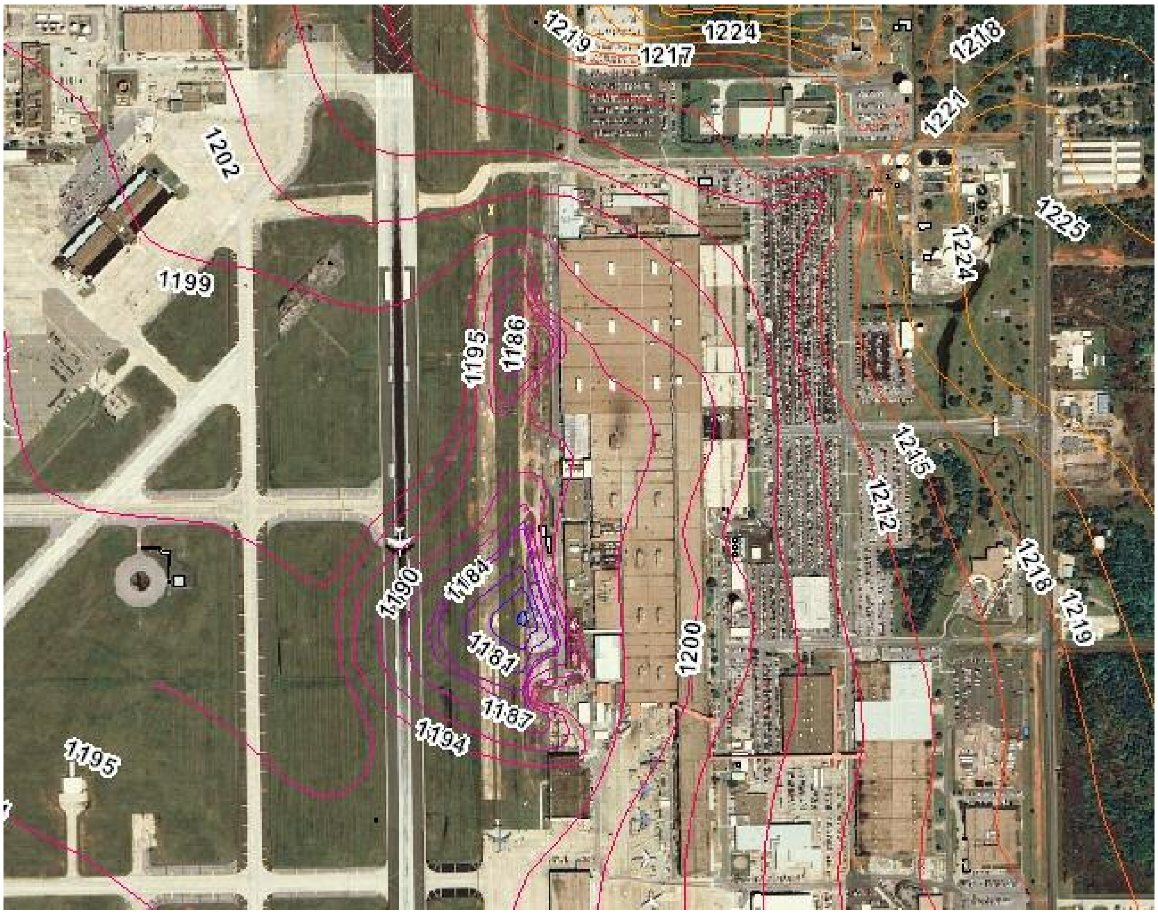


Figure 5 shows the ground water levels in the LLSZ. In Figure 5 it can be seen that the ground water generally travels in a north-east to south-west direction, from the IWTP to B3001. There are also localized low water areas along the western wall of B3001 were ground water extraction has occurred.

Figure 5: Water Level Contour Map for LLSZ

1.3 Description of Contaminants Statistically Analyzed

The following sections provide information on various contaminants found in the vicinity of IWTP and Building 3001. The contaminants analyzed were chlorinated solvents and chromium.

1.3.1 Chlorinated Solvents

The primary chlorinated solvent contaminating the area is trichloroethene (TCE). TCE was used as a degreaser until tetrachloroethene (PCE) began to replace it in the early 1970's. Dichloroethene (DCE), mostly in the form of cis-1,2 DCE, and vinyl chloride (VC) have been detected at the IWTP site and, in the case of DCE, at the Building 3001 site. DCE and VC are suspected of being daughter products of TCE. Tinker AFB has provided concentration contour maps for the four previously mentioned chlorinated solvents and these are found in section 3.3.

1.3.1.1 Dechlorination

Chloroethenes are relatively oxidized compounds, due to the presence of electronegative chlorine atoms, and can act as electron acceptors in microbial metabolism. In the presence of a suitable electron donor and catalyst, hydrogen can replace a chlorine atom on a chlorinated ethene molecule. This microbially catalyzed process is called reductive dechlorination (Chapelle, et al., 2003). The tendency of chlorinated ethenes to undergo reductive dechlorination decreases with decreasing number of chlorine substituents. PCE, with its four chlorine atoms, is a stronger oxidant than all of the naturally occurring electron accepting species found in ground water systems, with the notable exception of oxygen gas (O_2). Thus PCE readily undergoes reductive dechlorination to TCE except in aerobic aquifers. Reductive declorination of TCE to cis-dichloroethene (cis-DCE) occurs under Fe(III)-reducing conditions and in more strongly reducing environments. Reductive dechlorination of cis-DCE to yield VC apparently requires at least sulfate (SO_4)-reducing conditions, but proceeds more readily in methanogenic environments. VC, on the other hand, is the least oxidized of the chloroethenes. Consequently, reductive dechlorination of VC to the nonchlorinated product, ethane, is characteristically slow and significant only under highly reducing, methanogenic conditions. As a result of this decreasing reductive potential with decreasing number of chlorine substituents, reductive dechlorination of chloroethene contaminants is often incomplete in ground water systems and frequently leads to the accumulation of cis-DCE and VC (Chapelle, et al., 2003).

Although the tendency of chloroethenes to undergo reductive dechlorination decreases as the number of chlorine substituents decreases, the tendency to undergo oxidation increases with decreasing number of chlorine substituents. As the least chlorinated of the chloroethenes, VC has the greatest tendency to undergo oxidation. Unfortunately, microbial oxidation of DCE and VC under aerobic conditions is of limited relevance in most ground water systems. In the rare event that VC is directly released to aerobic aquifers, rapid mineralization of VC by aquifer microorganisms can be expected. For the overwhelming majority of sites, however, the presence of DCE and VC in ground water is attributable to the existence of anaerobic conditions and the activity of reductive dechlorinating microorganisms. Aerobic biodegradation of chloroethenes is probably limited to the edge of the contaminant plume where dissolved oxygen (DO) has not been depleted by microbial respiration (Chapelle, et al., 2003).

Oxidation of VC can occur under anaerobic conditions if a sufficiently strong oxidant is available to drive microbial degradation. Fe(III) oxides are strong oxidants that are ubiquitous in ground water systems. In an experiment conducted with sediment from a Fe(III)-reducing aquifer, addition of Fe(III) to anaerobic microcosms resulted in VC mineralization rates comparable to those observed under aerobic conditions (Chapelle, et al., 2003). Low but significant VC mineralization was also observed in anaerobic microcosms under ambient Fe(III) conditions. These results indicated that VC could be mineralized under anaerobic, Fe(III)-reducing conditions, and that the bioavailability of Fe(III) was an important factor affecting the rates of mineralization. More importantly, microbial oxidation of VC under Fe(III)-reducing conditions provided a potential anaerobic alternative to the slow and inefficient reductive dechlorination of VC to ethene (Chapelle, et al., 2003).

Under some redox conditions, all chlorinated ethenes can serve as electron acceptors in microbial metabolism. In this case, microorganisms are respiring the chlorinated ethenes by transferring electrons to them. This process is also called reductive dechlorination. Under other redox conditions, microorganisms can use lightly chlorinated ethenes, such as DCE and VC, as electron donors. In this case microorganisms oxidize the chlorinated ethenes and use them as a source of energy in the form of electrons. Under anoxic conditions, highly chlorinated ethenes, such as PCE and TCE, are subject to reductive dechlorination according to the sequence:

$$PCE \Rightarrow TCE + Cl \Rightarrow DCE + 2Cl \Rightarrow VC + 3Cl \Rightarrow ethene + 4Cl$$

The efficiency of dechlorination, however, differs for different redox conditions. Dechlorination of PCE and TCE to DCE occurs under mildly reducing conditions, such as nitrate (NO_3)- or FE(III)-reduction, whereas the transformation of DCE to VC, or the transformation from VC to ethylene requires the more strongly reducing conditions of methanogenesis or SO_4 reduction. Reductive dechlorination has been shown to be driven by molecular hydrogen (H_2), and the efficiency of reductive dechlorination is directly related to the availability of H_2. The lightly chlorinated ethenes DCE and VC can be oxidized to CO_2 under oxic or Fe(III)-reducing conditions:

DCE $\quad Cl_2C_2H_2 + 2O_2 \Rightarrow 2CO_2 + 2H^+ + 2Cl^-$

VC $\quad ClC_2H_3 + 5/2O_2 \Rightarrow 2CO_2 + H^+ + Cl^-$

Because DCE and VC are usually degradation products of reductive dechlorination, complete degradation of chlorinated ethenes is favored by sequential anoxic-oxic conditions. First, under reducing conditions, PCE and TCE is transformed to DCE and VC. Then, as ground water migrates to more oxic conditions, DCE and VC can be oxidized to CO_2. The efficiency with which chlorinated ethenes are completely degraded, therefore, is directly related to redox conditions present in an aquifer and to the succession of redox processes that chlorinated ethenes are exposed to along particular ground water flowpaths (Chapelle, et al., 2003).

1.3.1.2 Health Effects of Chlorinated Solvents

The Environmental Protection Agency (EPA) has published the known and suspected health effects of chlorinated solvents in the EPA Ground Water and Drinking Water Consumer Factsheet (EPA Consumer Factsheet, 2006). According to the Consumer Factsheet, PCE has the potential to cause detrimental effects to the liver, kidney, and central nervous system at concentrations above 0.005 mg/l. Additionally, there is some evidence that PCE may have the potential to cause cancer from a lifetime exposure at levels above 0.005 mg/l. Some people who drink water containing TCE in excess of 0.005 mg/l over many years could experience problems with their liver and may have an increased risk of getting cancer. The EPA reports that exposure to cis-DCE at concentrations above 0.070 mg/l for relatively short periods of time can cause central nervous system depression. Cis-DCE has the potential to cause liver, circulatory, and nervous system damage from long term exposure to concentrations above 0.070 mg/l. The EPA has found vinyl chloride to potentially cause damage to the central nervous system when people are exposed to it at high levels (40 to 900 mg/l) over short periods of time. Vinyl chloride has the potential to cause cancer and may damage the liver following a lifetime exposure at concentrations above 0.100 mg/l (EPA Consumer Factsheet, 2006).

1.3.2 Chromium

The primary metal contaminant found on site is chromium. The highest concentrations of total chromium are found beneath Building 3001. Lower concentrations are found surrounding Building 3001 (USACE 1988) and IWTP (SAIC, 2006). Abandoned pits investigations conducted in 1985 and 1986 detected high concentrations of lead, cadmium, chromium, and barium in the soil in areas beneath Building 3001 (USACE 1988).

1.3.2.1 Health Effects Associated with Chromium

The Environmental Protection Agency (EPA) has published the known and suspected health effects of chlorinated solvents in the EPA Ground Water and Drinking Water Consumer Factsheet (EPA Consumer Factsheet, 2006). According to the Consumer Factsheet, the EPA has found chromium to potentially cause skin irritation and ulceration when exposed to concentrations above 0.100 mg/l for relatively short periods of time. Chromium has the potential to cause damage to the liver, kidney, circulatory, and nervous tissues, as well as skin irritation, from a lifetime exposure to concentrations above 0.100 mg/l.

1.4 Environmental Forensics

Environmental forensics was performed for contaminants found at the Building 3001 site as well as the IWTP site. The purpose of this investigation was to determine whether Building 3001 is solely responsible for the contamination at the B3001 site or if there is a separate source, such as the IWTP. The following sections will describe various methods of analysis.

1.4.1 Concentration Contour Maps

A qualitative assessment can be performed simply by studying the concentration contour maps presented in the results sections. By comparing concentrations of PCE and daughter products in the lower saturated zone, while accounting for groundwater gradient and reductive dehalogenation, a hypothesis can be formed which will be statistically tested.

1.4.2 Statistical Analysis

The primary methods of performing a statistical analysis on the well data were the one-way, parametric ANOVA, the Kruskal-Wallis test, and the Mann-Whitney test. The ANOVA and Kruskal-Wallis tests were used to test the null hypothesis that all samples are drawn from the same population (Helsel and Hirsch, 2002). In the context of this project, statistical testing will confirm, within the 95% confidence level, whether samples are statistically different. Statistically different samples would suggest that the samples are from separate plumes with separate sources. Statistical testing was performed at the 5% level of significance for chromium concentration, chlorinated solvent concentrations, and chlorinated solvent molar fractions.

1.4.3 Neural Network Modeling

Artificial neural network models were developed to work in conjunction with statistical testing. Statistical methods were utilized to determine differences between locations under the assumption that statistical differences indicate separate sources. Neural networks were utilized for their pattern recognition abilities. The neural network models were utilized to determine patterns in the training data, i.e. the suspected sources Building 3001 and the IWTP, and then applied the recognized patterns to predict which source or sources were responsible for the contamination at each of the twelve well locations individually.

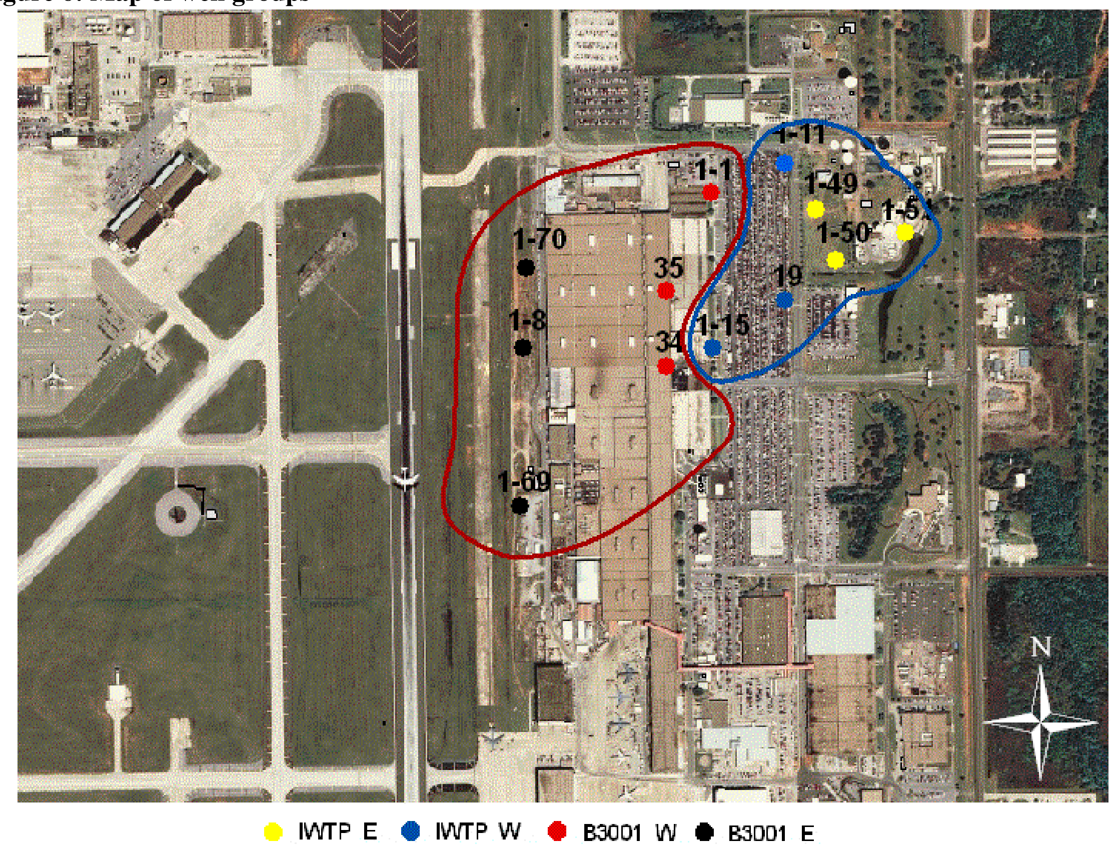
1.5 Well Locations

The wells used for this investigation are listed in Table 2. The location of each well and well group can be seen in Figure 6. A rough representation of the IWTP plume, in blue, and the B3001 plume, in red, can so be seen in Figure 6.

Table 2: List of Well Groups

IWTP E:	IWTP W:	3001 E	3001 W	IWTP		3001	
1*49	1*11	1*1	1*8	1*49	1*11	1*1	1*8
1*50	19	34	1*70	1*50	19	34	1*70
1*51	1*15	35	1*69	1*51	1*15	35	1*69

Figure 6: Map of well groups



CHAPTER II

METHODOLOGY

2.1 Normality Testing

The Anderson-Darling method was used to test data sets for normality. Since many statistical tests assume that the data are normally distributed, normality testing was performed on each data set. The Anderson-Darling method is an empirical cumulative distribution function (ECDF)-based test. The p-value used to determine if a data set is normally distributed is calculated from the Anderson-Darling's A^2 statistic. The A^2 statistic is calculated by the following equation:

$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n}[2i-1][\ln F(Y_i) + \ln(1 - F(Y_{n-i+1}))] \qquad \textbf{Equation 1}$$

Where $F(Y_i) = \Phi((Y_i - \bar{X})/s)$ and s is the standard deviation (D'Agostino and Stephens, 1986).

2.2 Kruskal-Wallis Multiple Comparisons Test

The Kruskal-Wallis test is a non-parametric form of the one-way analysis of variance test. The Kruskal-Wallis test is utilized when the data or the residuals have been found significantly different from normal and when a log transformation fails to adequately normalize the data. The Kruskal-Wallis test does not imply assumptions about the underlying distribution (McBean and Rovers, 1998). Since the collected and processed data were not normally distributed in most cases, the Kruskal-Wallis test was utilized to determine if there were significant differences between the four well groups IWTP W, IWTP E, B3001 W and B3001 E. Differences between well groups are an indication that multiple sources contributed to the contamination at the IWTP and B3001.

In order to be effective for data of any distribution, the data were ranked from lowest to highest. Since the expected rank for any observation is the average rank (N + 1)/2, the expected sum of ranks for n_i observations is n_i (N + 1)/2. Deviation between the expected and observed rank sums indicates disparity between the samples. Multiple comparisons can be made between any two groups by calculating Z_{ij} and transforming it to Z^* using the following equation:

$$Z^* = Z_{\alpha/[k(k-1)]} \qquad \textbf{Equation 2}$$

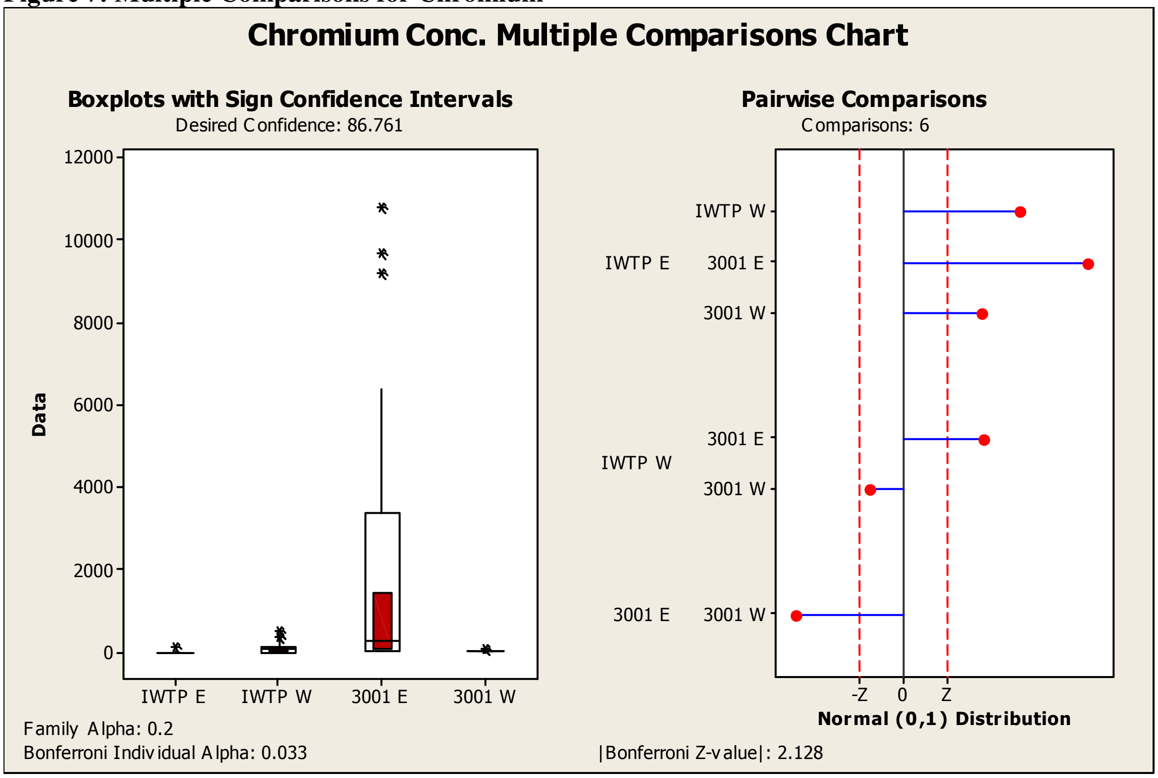
Z_{ij} is calculated by the following equation:

$$Z_{ij} = \frac{\left|\bar{R}_i - \bar{R}_j\right|}{\sqrt{[N(N+1)/12](1/n_i + 1/n_j)}} \qquad \textbf{Equation 3}$$

where $\bar{R}_i$ and $\bar{R}_j$ are the average rank sums of the i^{th} and j^{th} group, respectively. If $Z_{ij} > Z^*$, the groups are said to be significantly different at the α significance level (Gibbons, 2003).

Figure 7 is an example of a Kruskal-Wallis Multiple Comparisons Chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each grouped location. The pariwise comparisons chart shows whether individual comparisons between grouped locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those two wells were significantly different. The well group on the left is compared to each of the well groups to its right. In the example below, the only well groups which were not significantly different were the IWTP W and B3001 W groups.

Figure 7: Multiple Comparisons for Chromium



2.3 One-Way, Parametric Analysis of Variance

The analysis of variance (ANOVA) is a method by which the total variation in a set of data may be reduced to components associated with possible sources of variability, and whose relative importance are of interest. The ANOVA procedure was used to determine if there was a differences in means of at least one of the four locations IWTP E, IWTP W, B3001 E, and B3001 W, for both collected and processed data. The ANOVA was similarly used to test for differences in means between the IWTP and the B3001 locations. The IWTP location was a combination of the IWTP E and IWTP W locations, and the B3001 location was a combination of the B3001 E and B3001 W locations. ANOVA is the name given to a wide variety of flexible and powerful statistical procedures. All of these procedures compare the means of different groups of observations to determine whether there are any significant differences among the groups. If differences are identified, additional procedures may be used to determine where the differences lie (McBean, 1998). This section will focus on the one-way, parametric form of ANOVA. The one-way, parametric ANOVA is best suited for normally distributed data with equal variance amongst sample populations. These criteria can be checked by using normality testing and boxplots, respectively. Boxplots that are symmetric around the median suggest normality, and boxplots of equal length suggest equal variance between locations. Although many of the data sets used in this effort were not normally distributed, the ANOVA is robust against non-normality unless the underlying populations are highly skewed (Lapin, 1990). Therefore, the ANOVA was used in conjunction with the Kruskal-Wallis test and the Mann-Whitney test to identify significant differences between various data sets collected at Tinker AFB. If differences occurred, it was assumed that they resulted from different sources of contamination. The procedure for performing a one-way ANOVA involves the following steps:

The well means are calculated as

$$\bar{X}_i = \frac{\sum_{j=1}^{n} X_{ij}}{n_i} \quad \textbf{Equation 4}$$

The grand mean is calculated as

$$\bar{X} = \frac{\sum_{i=1}^{p} \sum_{j=1}^{n_i} X_{ij}}{N} \quad \textbf{Equation 5}$$

where N is the total number of observations,

$$N = \sum_{i=1}^{p} n_i \quad \textbf{Equation 6}$$

The sum of squares of the difference between well means and the grand mean is computed by the following equation:

$$SS_{factor} = \sum_{i=1}^{p} n_i (\bar{X}_i - \bar{X})^2 \quad \textbf{Equation 7}$$

with (P-1) degrees of freedom.

Compute the corrected total sum of squares using the following equation:

$$SS_{total} = \sum_{i=1}^{p} \sum_{i=1}^{n_i} (X_{ij} - \overline{X})^2$$ **Equation 8**

with (N-P) degrees of freedom.

Compute the error sum of squares as follows:

$$SS_{error} = SS_{total} - SS_{factor}$$ **Equation 9**

The mean squares, MS_{factor} and MS_{error} are computed by dividing the appropriate sum of squares be the appropriate number of degrees of freedom.

To test the hypothesis of equal means for all wells, compute the F statistic as follows:

$$F = \frac{MS_{factor}}{MS_{error}}$$ **Equation 10**

The F statistic is then compared to tabulated critical values with (P-1) and (N-P) degrees of freedom. If the calculated F-statistic exceeds the tabulated value, there is significant difference of means between at least one pair of locations. To determine which locations are significantly different, multiple comparisons must be made (McBean and Rovers, 1998). A statistical difference in concentrations or molar fractions between locations indicates that the locations are either not from the same source, or subjected to dissimilar environments. Since no difference was found in redox potential(see section 3.4.1) it is reasonable to assume that differences in concentrations or molar fractions between locations indicates that said locations represent plumes from separate sources. The method for performing multiple comparisons is explained is section 2.4.

Minitab 14 provides the previously mentioned statistical outputs in a table format (Minitab Inv., 2007). An example of a Minitab ANOVA table is provided below for clarification.

DF (factor) is the number of treatments (grouped well locations) minus one. DF (error) is the total number of observations minus the number of treatments. SS (factor) is the sum of squares, or measure of variance, between treatments. SS (error) is a measure of the variance within treatments. MS (factor) and MS (error) are listed in a similar fashion. The F statistic and P-value determine whether there is at least one significant difference. A P-value below 0.05 indicates that at least one well group is significantly different at a 95% confidence level. S is the pooled standard deviation. R-Sq and R-Sq (adj) values indicate how much of the variation in the response is explained by the model. The higher the R-Sq values, the better the model fits the data (Minitab 14 Help File, 2003).

Example of a Minitab 14 Data Output:

Source	DF	SS	MS	F	P
Factor	3	238923	79641	18.98	0.000
Error	208	872550	4195		
Total	211	1111473			

S = 64.77   R-Sq = 21.50%   R-Sq(adj) = 20.36%

For these hypothetical data, the p-value in this table shows that at least one location was significantly different from another location.

2.4 Analysis of Variance with Multiple Comparisons

If a difference in means was detected using the standard ANOVA method, multiple comparisons were made to determine which locations were statistically different. Multiple comparisons were made between each of the four locations IWTP E, IWTP W, B3001 E, and B3001 W. Tukey's method of multiple comparison testing was utilized to determine which individual wells were statistically different. Tukey's method has the same assumptions as the ANOVA; that data within each treatment group are normally distributed, and that each treatment group has equal variance. Violations of these assumptions will result in a loss of power to detect differences which are actually present.

For unequal sample sizes, the computation of Tukey's test is performed as follows:

$$\left|\overline{Y}_i - \overline{Y}_j\right| > q(1-\alpha), k, N-k \bullet \sqrt{MS_{error} \bullet \frac{n_i + n_j}{2n_i n_j}} \qquad \textbf{Equation 11}$$

where q is the studentized range statistic from Neter, Wasserman, and Kutner (1985) (Helsel and Hirsch, 2002).

2.5 Boxplots

Boxplots are a visual tool used to examine characteristics of a sample distribution, such as the mean, the interquartile range, and whether the data are skewed. The means at various locations can visually be compared to determine which locations are similar and which are different. Boxplots have been included in the output of the Kruskal-Wallis multiple comparisons test for the collected and processed data of each of the four locations, IWTP E, IWTP W, B3001 E, and B3001 W. The outer portion of the boxplot represents the interquartile range of the data. The bottom line of the box is the 25% quartile of the sample, the middle line represents the median, and the upper line is the 75% quartile. The quartiles represent the point where 25%, 50%, or 75% of the data are less than that value. The vertical lines are known as whiskers. The upper whisker extends to the highest value within the upper limit. The upper limit is equal to the 75%

quartile + 1.5(75% quartile – 25% quartile). The lower whisker works in a similar manner, representing the lowest value in the lower limit. The asterisks beyond the whisker are known as outliers. The outliers represent data points beyond the upper or lower limit. Within the interquartile range boxplot is another boxplot colored red. This is the confidence interval boxplot. This boxplot represent the upper and lower boundaries of the 95% confidence interval (Minitab 14 Help File, 2003).

2.6 Mann-Whitney

The Mann-Whitney test is a rank-sum test that can be used regardless of how the data are distributed. The Mann-Whitney test compares two data sets to determine if there is a significant difference between the medians of the two samples to determine if they are from the same population (Helsel and Hirsch, 2002). The Mann-Whitney test was applied to the two locations, IWTP and B3001, for both collected and processed data. Differences between IWTP and B3001 are an indication that the two locations are from different sources.

The large scale approximation method was used by first creating a joint rank (R_k) between both samples of size n and m. The smaller of the two ranks is summed to create the test statistic W_{rs} .

The mean (μ_w) and standard deviation (σ_w) are computed as follows:

$\mu_w = n(m+n+1)/2$ **Equation 12**

$\sigma_w = \sqrt{nm(n+m+1)/12}$ **Equation 13**

For two sided testing to determine if the median of sample one is significantly different from the median of sample two, the following equation is used to create a standardized test statistic:

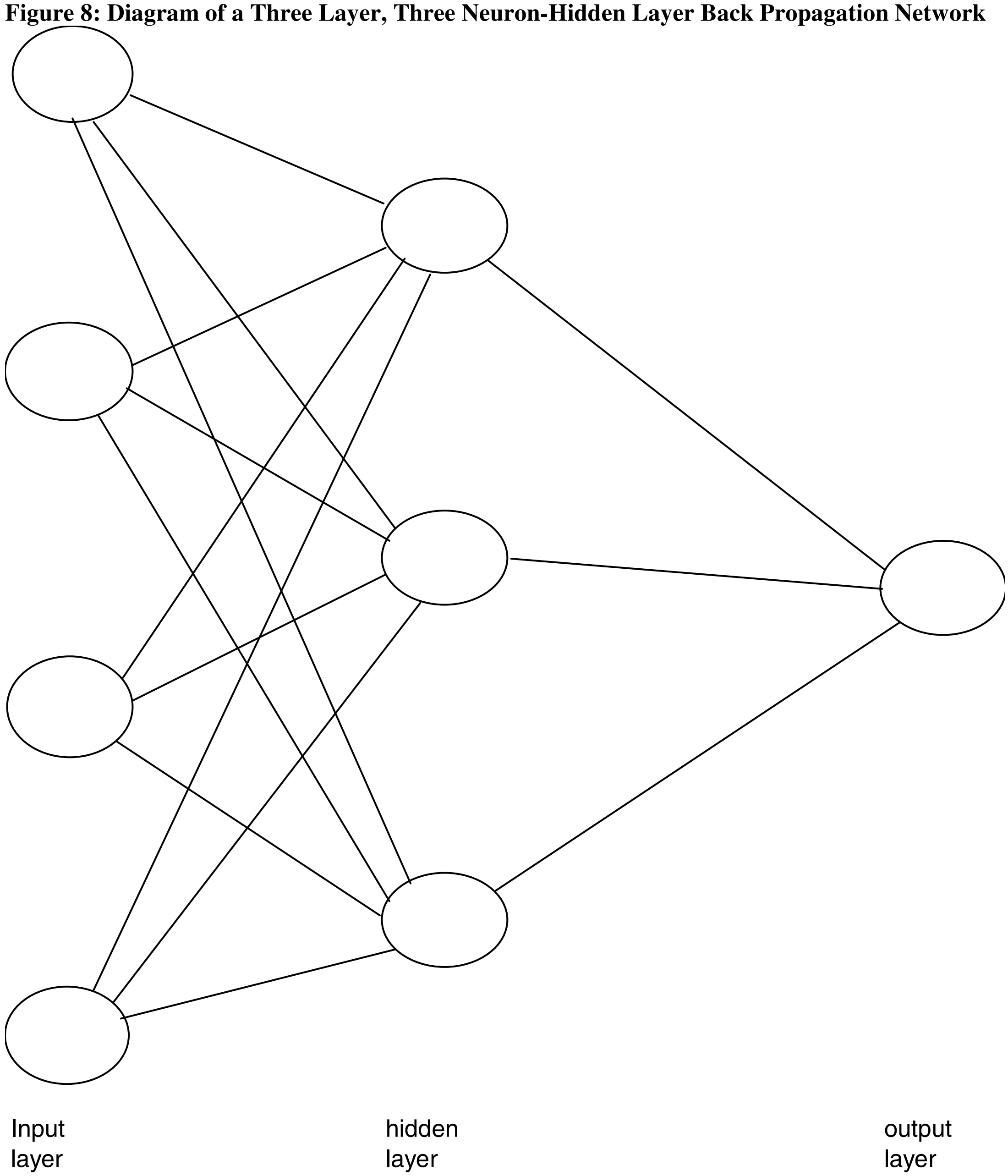
$Z_{rs} = \frac{|W_{rs} - \mu_w| - 0.5}{\sigma_w}$ **Equation 14**

The value of Z_{rs} is compared to a table of standard normal distribution Z values (Hessel, 2002).

2.7 Artificial Neural Network Modeling

Artificial neural network models were developed to work in conjunction with statistical testing. Statistical methods were utilized to determine differences between locations under the assumption that statistical differences indicate separate sources. Neural networks were utilized for their pattern recognition abilities. The neural network models determined patterns in the training data, i.e. the suspected sources Building 3001 and the IWTP, and then applied the recognized patterns to predict which source or sources were responsible for the contamination at each of the twelve well locations individually. Artificial neural network models were developed using the Neuralyst software program (Cheshire Engineering, 1994). Neuralyst provides open ended analysis of spreadsheet data and recognition of associations between data. Neural networks simulate biological neurons to model several aspects of the information combining and pattern recognition abilities of real neurons. Figure 8 (McTernan and Bonnett, 2002) shows the neuron configuration of a neural network comprised of one input layer, one hidden layer with three neurons, and one output layer.

Figure 8: Diagram of a Three Layer, Three Neuron-Hidden Layer Back Propagation Network



Neuralyst uses a structure known as the backpropagation network. The backpropagation network consists of multiple layers arrayed one succeeding the other so that there is an input layer, multiple intermediate layers, and an output layer. Once the neural network is established, the network goes through a process known as training. When training a network, the error between the desired response and actual response of the training inputs is backpropagated through the network to readjust the weights applied to each neuron. This process is repeated until the error is reduced to an acceptable level. The equation which governs weight adjustment process is listed below (Cheshire Engineering, 1994).

$$W_{ij} = W'_{ij} + (1 - M) \bullet LR \bullet e_j \bullet X_j + M \bullet (W'_{ij} - W''_{ij})$$ **Equation 15**

where,

M = Moment Factor

LR = Learning Rate

W'_{ij} = the previous weight

W'' = next to previous weight

e_j = error term

X_j = *i*th input

Table 3 shows the all the input data that was used for training the neural network and testing associations between locations and sources. Not all the input data was used in each model; section 3.6 describes this in more detail.

Table 3: Input Data for Neural Network Model

Location	N-S	E-W	Distance to IWTP	Distance to B3001	TCE Conc. (ug/l)	DCE Conc. (ug/l)	VC Conc. (ug/l)	MF TCE	MF DCE	MF VC
IWTP	14	47	0.00	31.32	100	300	70	15	62	22
3001	23	17	31.32	0.00	1000	10	0	99	1	0
1*50	19	45	23.19	25.08	134	340	161	15	49	34
19	24	36	14.14	14.87	794	2691	169	20	71	6
1*15	21	27	5.10	9.43	173	159	66	34	40	21
1*49	11	44	24.60	28.43	35	57	6	27	58	10
1*51	15	51	29.83	32.20	49	178	43	13	61	22
1*11	7	37	21.21	26.63	65	85	21	23	44	17
1*70	18	5	17.46	20.25	1326	148	21	82	14	3
1*8	28	4	18.97	18.03	2917	208	0	90	9	0
1*69	48	5	31.06	25.50	755	36	0	94	6	0
1*1	11	27	12.08	18.68	332	28	0	79	10	0
35	22	22	0.00	7.00	1942	190	1	83	11	0
34	29	22	7.00	0.00	1035	10	0	97	1	0

The location data was determined using Figure 9 below. Each location is the number of 50 foot increments south and east of the reference point, which is the top left corner of the figure. The numbers across the top and along the left side correspond to the North American Datum (NAD) coordinates used a Tinker AFB. The circles on the figure mark the location of the IWTP and Building 3001 reference points. The inputs for the sources, the IWTP and B3001 concentration and molar fraction data, were determined using the concentration contour maps provided by Tinker. PCE was not used in this model because there was no PCE concentration contours in the LSZ (see Figures 10 through 13).

Figure 9: Map of Well Locations Used in Neural Network Model

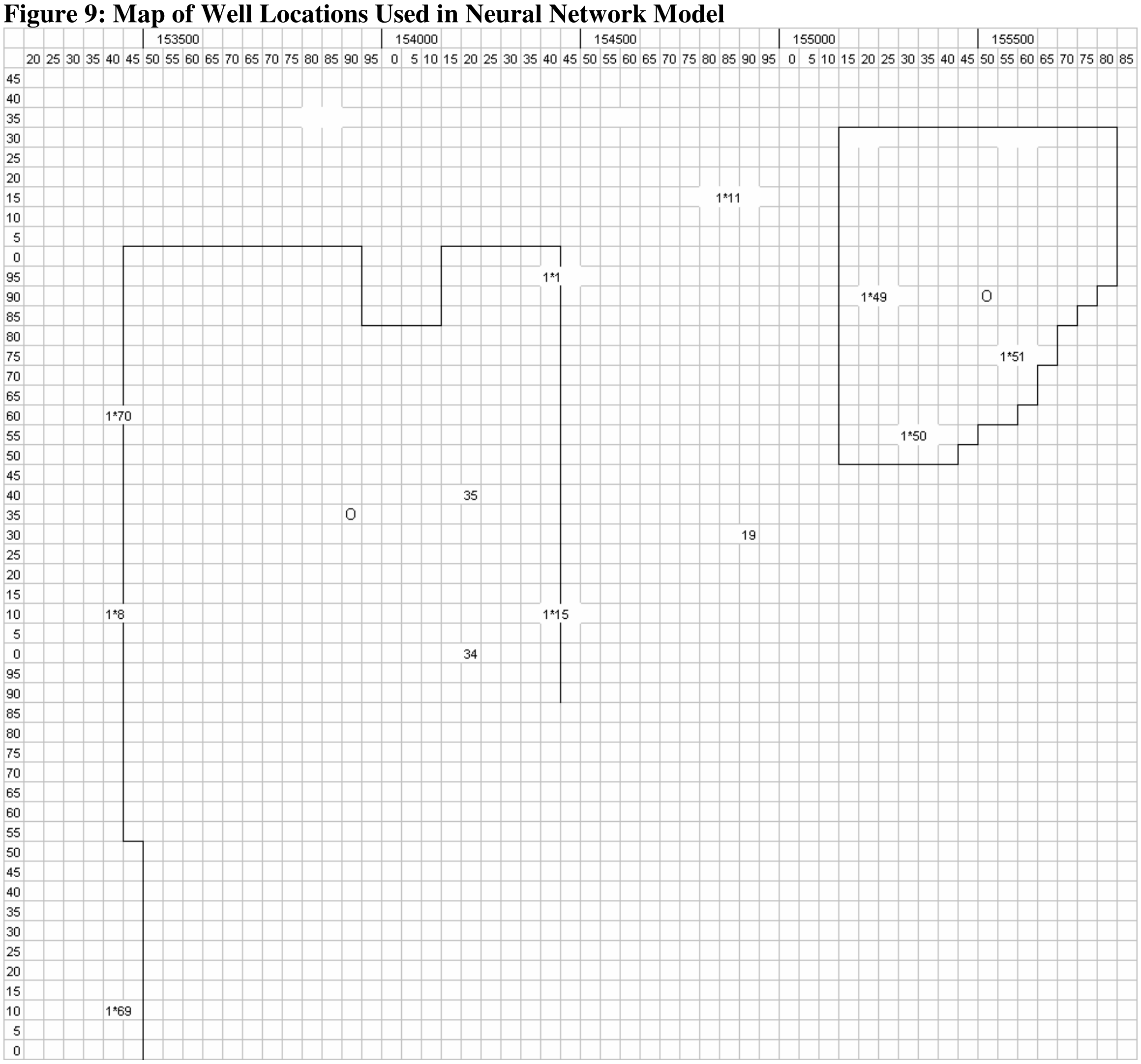


Table 4 shows an example of training and testing a neural network model. The input data for this model were the TCE, DCE, and VC molar fraction data. The source locations, IWTP and B3001, were used to train the neural network. The training data can be identified by the word “Train” in the mode flag column (MF). This was how Neuralyst knew which data was to be used for training and which was to be used for testing. The training data (sources) were given a target value of one for data associated to itself and zero for data corresponding to the other source. For example, IWTP was given a target value of one for data that corresponds to IWTP and a target value of zero for data that corresponds to B3001. The neural network was then trained to recognize patterns in the data that were associated with the IWTP, and adjusts the weight of each variable accordingly. Once these patterns were recognized, the neural network then tested the well location data to determine which source or sources each individual well location was associated with. For example, if a well was associated to the IWTP source then the output in output column one, the IWTP column, will have a value relatively close to one. If that well location was not associated with the IWTP source, it will have an output value relatively close to zero. This procedure was performed three times for three separate models. The first model contains all available data inputs, the second model uses just the concentration data inputs, and the third models uses just the molar fraction data inputs.

Table 4: Example of Training and Testing a Neural Network Model

	Inputs				Target		Output	
Location	MF TCE	MF DCE	MF VC	MF	1	2	1	2
IWTP	15	62	22	Train	1	0	0.896	0.107
3001	99	1	0	Train	0	1	0.103	0.894
1*50	15	49	34	Test			0.902	0.099
19	20	71	6	Test			0.863	0.135
1*15	34	40	21	Test			0.719	0.269
1*49	27	58	10	Test			0.843	0.163
1*51	13	61	22	Test			0.899	0.104
1*11	23	44	17	Test			0.838	0.167
1*70	82	14	3	Test			0.187	0.813
1*8	90	9	0	Test			0.097	0.901
1*69	94	6	0	Test			0.154	0.841
1*1	79	10	0	Test			0.25	0.757
35	83	11	0	Test			0.115	0.88
34	97	1	0	Test			0.101	0.895

2.8 Confidence Intervals

Confidence intervals were included as a tool to quickly gain general information about the collected and processed data at the four locations, IWTP E, IWTP W, B3001 E, and B3001 W. Using the Minitab 14 program, confidence intervals where calculated for the concentration of each of the four chlorinated solvents, as well as chromium. The data tables provide general information including: the number of samples for a specific contaminant at a specific location, the mean concentration of those samples, the standard deviation, the standard error, and the 95% confidence interval. The confidence interval provides a range of concentrations in which there is a 95% probability that the true population mean is contained.

Since the true population mean, μ , is unknown, it is estimated as $\bar{x}$ by calculating Σ x/n, where n is the number of field samples.

The standard deviation, s, of a composite sample is calculated as

$$s=\sqrt{\frac{\Sigma(x-\bar{x})^2}{(n-1)}} \qquad \textbf{Equation 16}$$

The standard error, se, is the standard deviation of a mean, and is calculated using the standard deviation as follows:

$$se = s/\sqrt{n} \qquad \textbf{Equation 17}$$

Using these values, the confidence interval, which assumes a normal distribution, can be calculated using the Student's t distribution with n-1 degrees of freedom using the following equation:

$$\bar{x} \pm t_{(\alpha/2, n-1)} \bullet \sqrt{s^2/n} \quad \textbf{Equation 18}$$

Where α is the probability that the confidence interval does not contain the true population mean (Helsel, 2002).

2.9 Correlation Coefficients

Correlation coefficients were calculated using Excel's correlation function for all four chlorinated solvents using concentration data and molar fraction data, as well as chromium concentration. Correlation coefficients were utilized to indicate similarities or differences between the IWTP and B3001, as well as the area between the two sites. The correlations were computed using the average concentration or molar fraction at each well versus the well's distance from IWTP. A positive correlation value indicated that the concentrations or molar fractions were increasing as the distance from IWTP increased. A negative correlation value indicated that the concentrations or molar fractions were decreasing as the distance from IWTP increased. Correlation values close to one or negative one indicate a strong correlation between the change in concentration or molar fraction and the increase in distance from IWTP. Correlation values close to zero indicate that there is only a slight correlation between the change in concentration or molar fraction versus the increase in distance from IWTP. High correlation coefficients close to one or negative one show not only that there is a strong difference between opposing sides of the plume, but also that the test parameter changes across the center of a co-mingled plume as opposed to a high concentration at the center of a plume that has dispersed outwardly.

Near zero correlation coefficients tend to suggest that a plume is from only one source since both sides of the plume are similar. This is particularly true for the molar fraction data since concentration data can be misleading due to factors such as dilution and dispersion.

Excel uses the following equation to calculate the correlation between two data sets:

$$\textbf{Correlation (X,Y)} = \frac{\Sigma(x-\bar{x})(y-\bar{y})}{\sqrt{\Sigma(x-\bar{x})^2(y-\bar{y})^2}} \qquad \textbf{Equation 19}$$

Where x and y are pairwise comparisons between arrays X and Y, and $\bar{x}$ and $\bar{y}$ are the mean values of array X and Y (Excel help file, 2003).

2.10 Cost Benefit Analysis

A cost benefit analysis was developed utilizing the Remedial Action Cost Engineering and Requirements (RACER) software program developed by Earth Tech (Earth Tech, 2007). The cost benefit analysis compared the cost of remediation of the IWTP plume and the B3001plume as separate plumes to the cost of remediation for the IWTP plume and the B3001 plume treated as only one plume. RACER is a parametric cost modeling system that uses cost technologies based on generic engineering solutions for environmental projects. The generic engineering solutions were derived from historical project information, industry data, government laboratories, construction management agencies, vendors, contractors, and engineering analysis. When creating an estimate in RACER, the generic engineering solutions are tailored by adding site specific parameters to reflect project-specific conditions and requirements. The tailored design is then translated into specific quantities of work, which are priced using current cost data. The RACER cost database is based primarily on the Unit Price Book, which is developed by the Tri-Services Cost Engineering Group (Earth Tech, 2007).

The cost analysis was comprised of four separate phases for each of the three scenarios, i.e. the IWTP plume, the B3001 plume, and the combined IWTP and B3001 plume. These four phases are remedial action, operations and maintenance, long term monitoring, and site close out. The remedial action phase is the capital cost placing ground water extraction wells and setting up a treatment plant. The remedial action phase is the sum of the cost associated with ground water extraction wells, air stripping, residual waste management, professional labor management, metals precipitation, and dewatering. The capital cost of remedial action has already been paid by Tinker AFB but was included for comparison purposes as well as for developing costs associated with operation and maintenance. The operation and maintenance cost for each of the three scenarios was developed by calculating the cost of operating and maintaining the remediation process, described under the remedial action phase, for ten years. The long term monitoring costs were developed by calculating the cost of performing monitoring and reporting monitoring data using an Army reporting technique for twenty years. The site close out cost was developed by calculating the cost associated with closing out the site, such as close out meetings and abandoned pit reports (Earth Tech, 2007).

CHAPTER III

RESULTS

3.1 Introduction to Results

This chapter will present the research findings for the following areas:

- Collected Data Analysis
  1. Chlorinated Solvents
  2. Chromium

- Processed Data Analysis
  1. Chlorinated Solvents

- Statistical Methods for Collected Data
  1. Kruskal-Wallis
  2. Mann-Whitney
  3. ANOVA
  4. Correlation Coefficients

- Statistical Methods for Processed Data
    1. Kruskal-Wallis
    2. Mann-Whitney
    3. ANOVA
    4. Correlation Coefficients

- Artificial Neural Network Models

3.2 Data Sources

As previously mentioned in the methods section of this report, this project employed data collected by and for Tinker AFB. These data were made available via an online data base (SAIC, 2007). This data base includes ground water examination wells throughout the entire base. Isolating the wells pertinent to this investigation involved an examination of the online data base as well as base maps made available by Tinker AFB personnel (Sayler, 2007). The most applicable maps follow.

3.3 Base Maps

Figures 10 through 13 present the location of the various chlorinated solvent plumes in the LSZ. Upon examination of these maps, twelve wells were chosen to represent contamination sources and/or plume boundaries and interfaces between plumes. Table 4 found below lists the twelve wells used in this investigation, as well as listing how wells were grouped according to location. Each well group consists of three wells in similar geographical areas. Wells were grouped to reduce data output into a more understandable, summarized output. There are also two well groups of six wells each. Each of the two well groups represents either the IWTP plume or the B3001 plume.

As seen in Figure 10, PCE concentrations in the LSZ are quite low and no concentration contours are available for PCE in the LSZ.

Figure 10: PCE Concentration in LSZ

Figure 11 shows the concentration contours for TCE in the LSZ. TCE in the LSZ includes not only Building 3001 but also the western portion of the IWTP. It is unknown whether TCE in the USZ traveled towards IWTP before entering the LSZ, or if TCE traveled in the LSZ down gradient from IWTP towards B3001. Since the USZ is a perched aquifer it is possible that contamination in the USZ could travel in nearly any direction relative to B3001. For more information on the hydrology of the area, see section 1.2.2.

Figure 11: TCE Concentration in LSZ

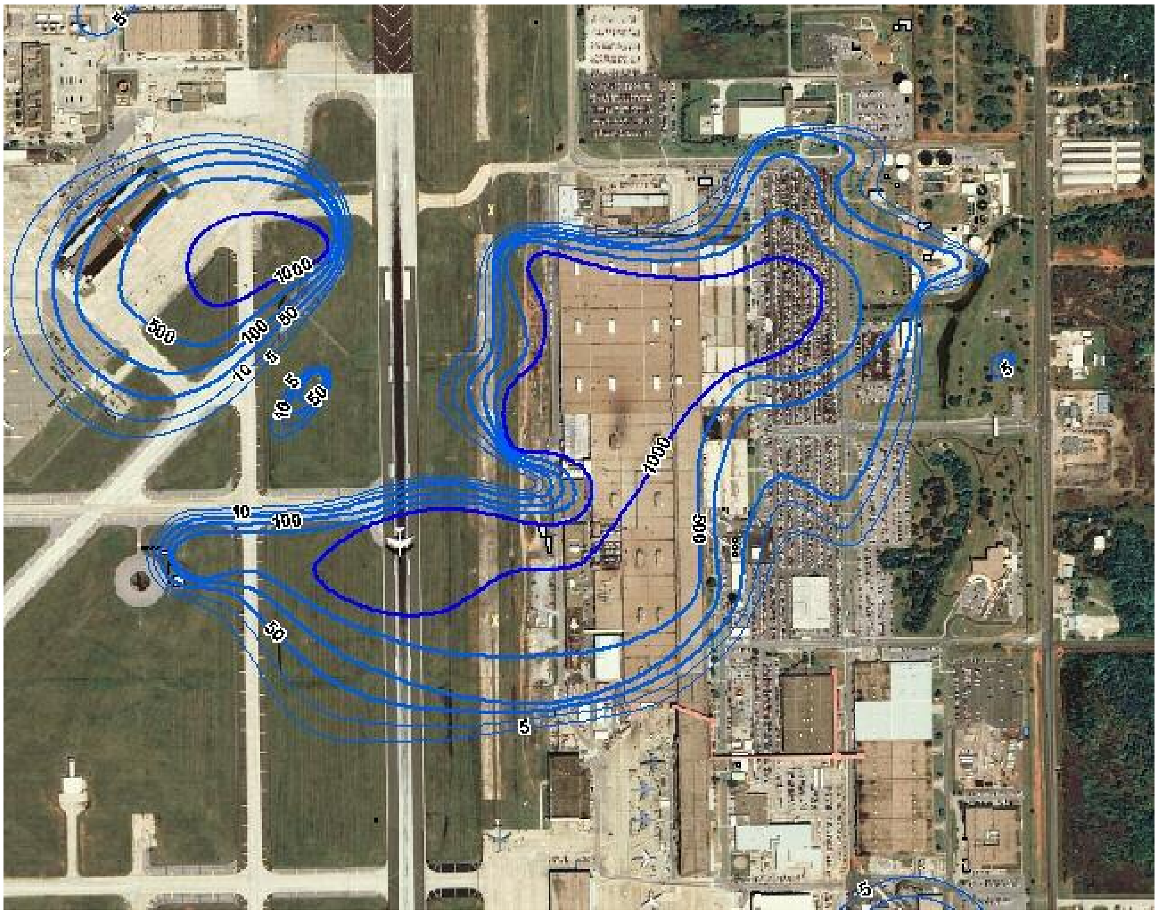


Figure 12 shows the concentration contours for DCE in the LSZ. A small plume of DCE appears to emanate from the IWTP, traveling down gradient towards Building 3001. For more information of the hydrology of the area, see section 1.2.2. The lower concentrations of DCE under Building 3001 could be the result of dispersion of the primary DCE plume. If this is the case, the IWTP would be responsible for a large portion of the DCE contamination around B3001 in the LSZ.

Figure 12: DCE Concentration in LSZ

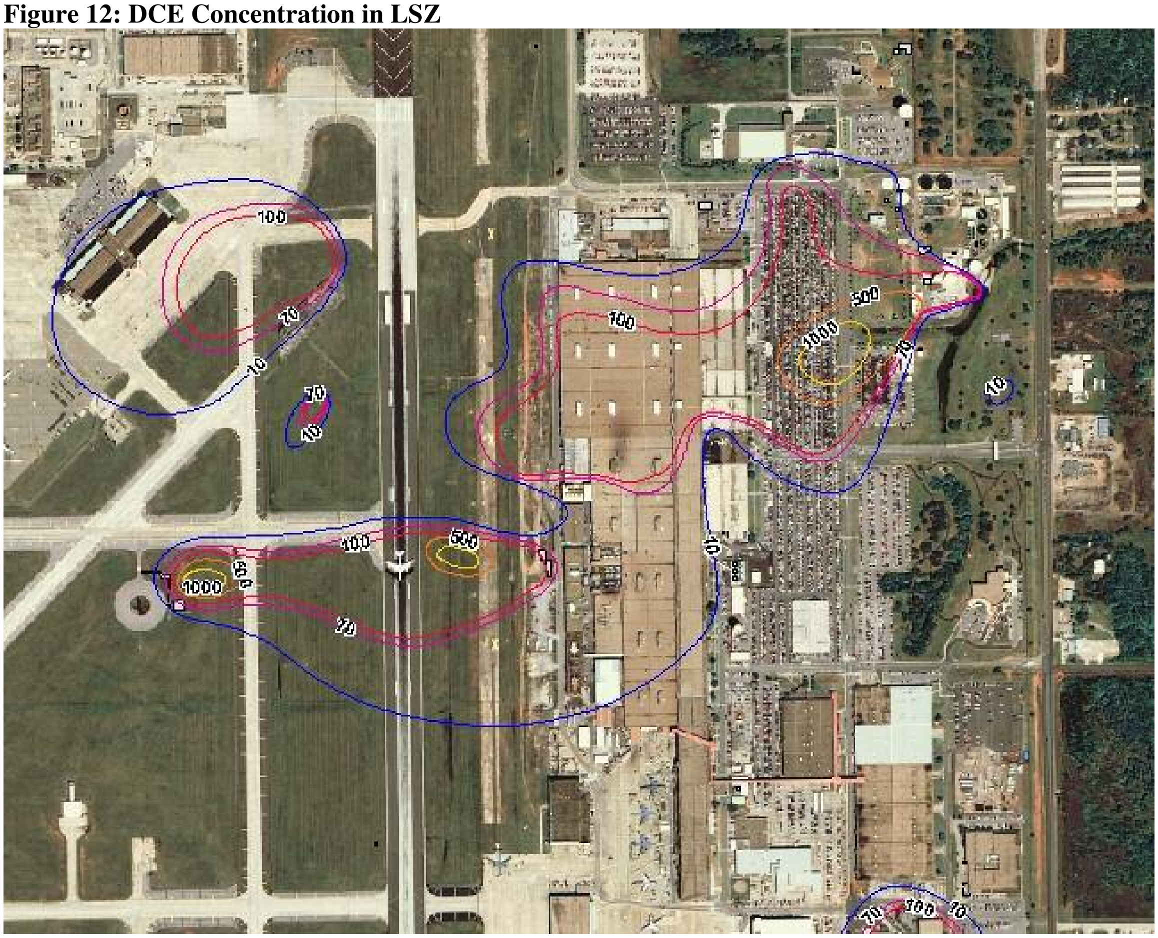
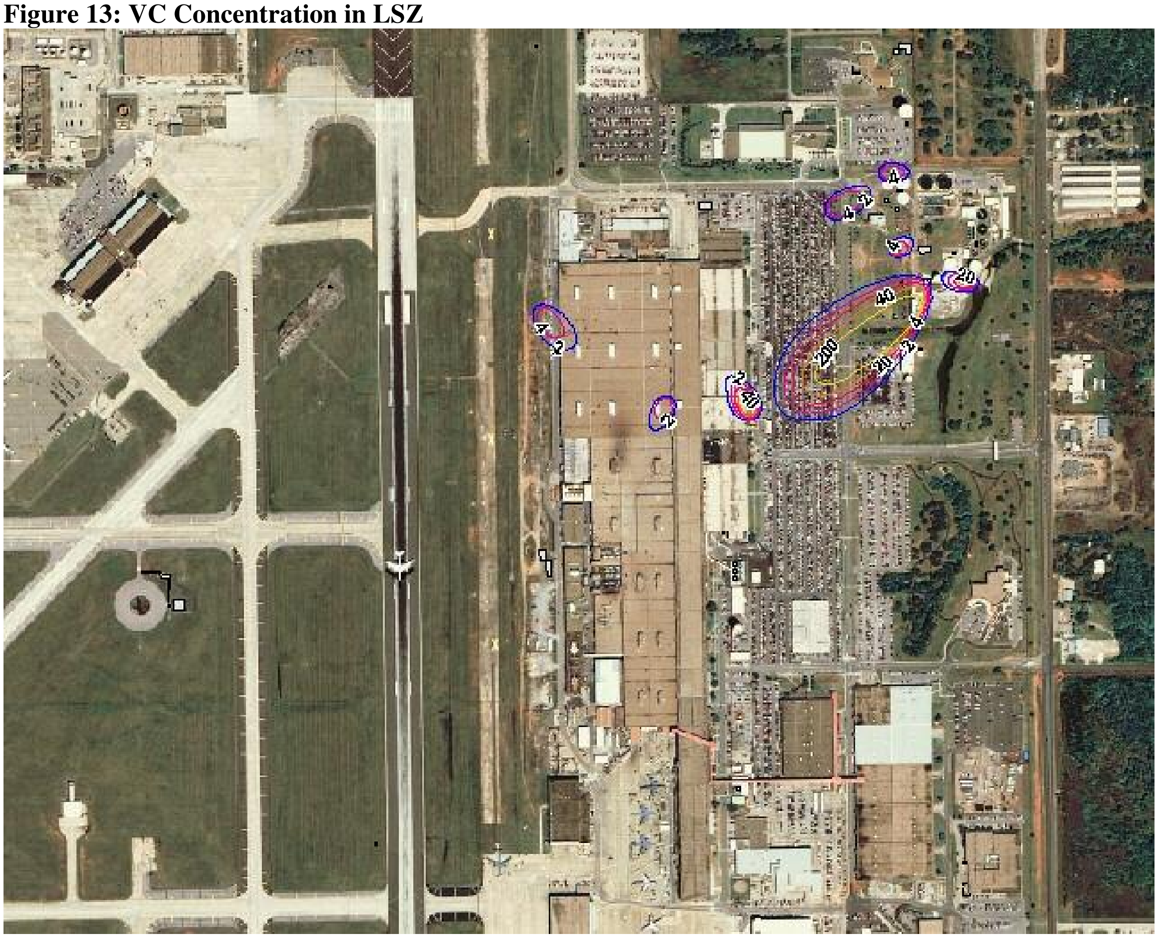


Figure 13 shows the concentration contours for VC in the LSZ. Similar to the DCE contamination, IWTP also appears to be the source of VC contamination in the LSZ, as a small VC plume seems to be traveling down gradient from the IWTP.

Figure 13: VC Concentration in LSZ



3.4 Collected Data Analysis

The collected data used in this effort were the contaminant concentrations provided by Tinker AFB, without modification. Various statistical analyses were applied to the concentration data to analyze tends in data due to location, as well as to assist in suggesting alternative analytical approaches. Tests completed on these data include:

- Chromium
    1. Normality Testing
    2. ANOVA
    3. Kruskal-Wallis
    4. Correlation Coefficients

- Reduction-Oxidation Potential
    1. Normality Testing
    2. ANOVA

- Chlorinated Solvents
    1. Normality Testing
    2. ANOVA
    3. Kruskal-Wallis
    4. Correlation Coefficients

3.4.1 Parametric and Non-Parametric Testing on Chromium Concentration Data

Chromium concentration was used to statistically test for differences between the two IWTP locations, IWTP E and IWTP W, and the two B3001 locations, B3001 E and B3001 W. Statistical testing was also performed between the IWTP plume and the B3001 plume. Statistical testing was performed under the assumption that differences between locations indicates separate sources.

3.4.1.1 Normality Testing on Chromium Concentration Data

Normality testing was performed by employing the Anderson-Darling method (D'Agostino and Stephens, 1986). The results are presented below, which include a probability plot and a p-value. The probability plot is a graphical analysis of the normality of the data. Normally distributed data will lie along a straight line, between the blue lines shown on the probability plot. The p-value is the determining factor as to whether data are normally distributed. For data to be normally distributed with 95% confidence, the p-value must be above 0.05. Since the data analyzed are a composite of three separate locations, the data are rarely normally distributed. Whether or not data are normally distributed affects the strength of an ANOVA and other parametric tests, and determines which types of test are better suited for a given data set. Figures 1A through

3A found in Appendix A show the results of normality tests on chromium concentrations for various well groups. From the probability plots and the p-values of the Anderson-Darling test, it can be seen in Figures 1A through 3A that none of the combined samples were normally distributed with regard to chromium concentration. Although the ANOVA can still be used, non-normality reduces the ANOVA's ability to find significant differences between samples. This suggests the use of non-parametric analysis methods, such as the Kruskal-Wallis test (McBean and Rovers, 1998) and the Mann-Whitney test (Helsel and Hirsch, 2002).

3.4.1.2 ANOVA Performed on Chromium Concentration Data

The results from one-way ANOVA testing on chromium concentration are presented below. The p-value of 0.000 is below 0.05 which means that at least one location was significantly different from the others. When making multiple comparisons, the confidence interval of one well group was subtracted from each other well group individually. The ANOVA shows the difference in the concentration means and 95% confidence intervals for multiple comparison purposes with respect to chromium concentration between each of the four grouped well locations. This procedure was performed to determine which well groups were statistically different with respect to chromium concentration. If zero was between the lower and upper difference in confidence intervals, then the two locations were not significantly different.

```
Source   DF         SS        MS      F      P
Factor    3  132155124  44051708  21.38  0.000
Error   180  370898032   2060545
Total   183  503053157

S = 1435   R-Sq = 26.27%   R-Sq(adj) = 25.04%
                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level    N  Mean  StDev  -------+---------+---------+---------+--
IWTP E  33     7     19  (------*------)
IWTP W  54   108    130     (-----*----)
3001 E  56  1897   2594                             (----*-----)
3001 W  41    29     23   (-----*------)
                         -------+---------+---------+---------+--
                                0       700      1400      2100

Pooled StDev = 1435
```

Tukey 95% Simultaneous Confidence Intervals

All Pairwise Comparisons

Individual confidence level = 98.98%

IWTP E subtracted from:

```
        Lower  Center  Upper  --------+---------+---------+---------+-
IWTP W   -722     101    924              (-----*----)
3001 E   1072    1890   2707                          (-----*----)
3001 W   -849      22    893             (-----*-----)
                              --------+---------+---------+---------+-
                                  -1500         0      1500      3000
IWTP W subtracted from:

        Lower  Center  Upper  --------+---------+---------+---------+-
3001 E   1078    1789   2499                          (----*----)
3001 W   -850     -79    693             (----*-----)
                              --------+---------+---------+---------+-
                                  -1500         0      1500      3000


3001 E subtracted from:

        Lower  Center  Upper  --------+---------+---------+---------+-
3001 W  -2633   -1868  -1102  (-----*----)
                              --------+---------+---------+---------+-
                                  -1500         0      1500      3000
```

Using a one-way ANOVA and Tukey's comparison method, of the four well groups, the only group that was significantly different was the B3001 E group, which had significantly elevated concentrations of chromium. This appears to primarily be due to the high chromium concentrations present at well 34B.

3.4.1.3 Kruskal-Wallis Performed on Chromium Concentration

Kruskal-Wallis testing was performed on chromium concentration for each of the four well groups. The Kruskal-Wallis method is similar to the ANOVA, except that the Kruskal-Wallis method uses ranks, making it better suited for non-normal data. From the data output below, the sample size, median concentration value, average rank, and Z value for each sample is given. The p-value is the determining factor as to whether at least one sample was significantly different. If differences exist, the multiple comparisons chart shows which samples were significantly different from each other.

```
Kruskal-Wallis Test on the data

Group       N   Median  Ave Rank       Z
IWTP E     33    5.000      30.4   -7.39
IWTP W     54   66.650      96.6    0.67
3001 E     56  277.500     136.1    7.34
3001 W     41   20.100      77.6   -2.04
Overall   184               92.5

H = 85.91  DF = 3  P = 0.000
H = 86.10  DF = 3  P = 0.000  (adjusted for ties)
```

From the data output above, the p-value of 0.000 indicates that there is at least one location that was significantly different from another location. Figure 14 shows the output of a multiple comparisons method for determining which locations were significantly different.

Figure 14: Multiple Comparisons for Chromium

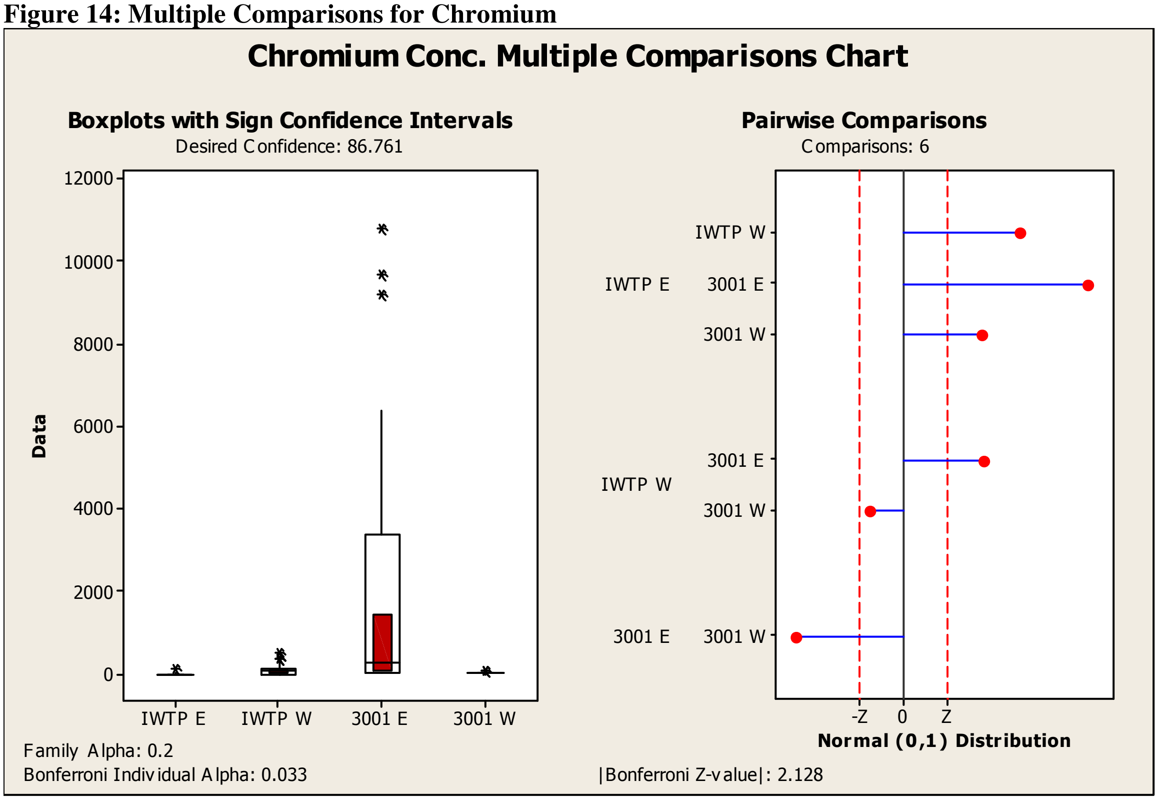


Figure 14 is a Kruskal-Wallis multiple comparisons chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each location. The pairwise comparisons chart shows whether individual comparisons between locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those two wells were significantly different. The well location on the left was compared to each of the locations to its right. Table 5 lists each of locations that were found to be statistically different from each other.

Table 5: Comparisons of Chromium Concentration

Groups	Z-value vs. Critical value	P-value
IWTP E vs. 3001 E	9.05221 >= 2.128	0.0000
IWTP E vs. IWTP W	5.63148 >= 2.128	0.0000
3001 E vs. 3001 W	5.35043 >= 2.128	0.0000
IWTP W vs. 3001 E	3.89168 >= 2.128	0.0001
IWTP E vs. 3001 W	3.79196 >= 2.128	0.0001

From the Kruskal-Wallis pairwise comparisons method it can be seen that the only groups that do not have significant differences were the IWTP E group and the B3001 W group. The box plot shows that the locations IWTP E and B3001 W have very low concentrations of chromium, with increased concentrations at the locations IWTP W and B3001 E. Therefore, it appears that the chromium concentrations are elevated near the interface of the IWTP and B3001 plume. Note that these results were quite different from the parametric ANOVA in terms of differences between well groups. However, these differences are moot when compared to B3001 E, which had a median more than four times greater than the second highest median, IWTP W.

3.4.1.4 Kruskal-Wallis Performed on Chromium Concentration Without Well 34

The Kruskal-Wallis test was performed again on the well groups, but without well 34. Well 34 was excluded due to its high concentration of chromium. Without well 34, a more representative evaluation can be made with respect to the comparisons between the remaining well groups.

```
Kruskal-Wallis Test on the data

Group       N  Median  Ave Rank      Z
IWTP E     33   5.000      30.4  -7.01
IWTP W     54  66.650      96.6   2.90
3001 E     34  42.350     111.9   4.25
3001 W     41  20.100      77.6  -0.62
Overall   162              81.5

H = 59.29  DF = 3  P = 0.000
H = 59.49  DF = 3  P = 0.000  (adjusted for ties)
```

From the data output above, the p-value of 0.000 indicates that there is at least one location that was significantly different from another location. Figure 15 shows the output of the multiple comparisons method for determining which locations were significantly different. The locations that were statistically different are listed in Table 6.

Figure 15: Multiple Comparisons of Chromium without Well 34

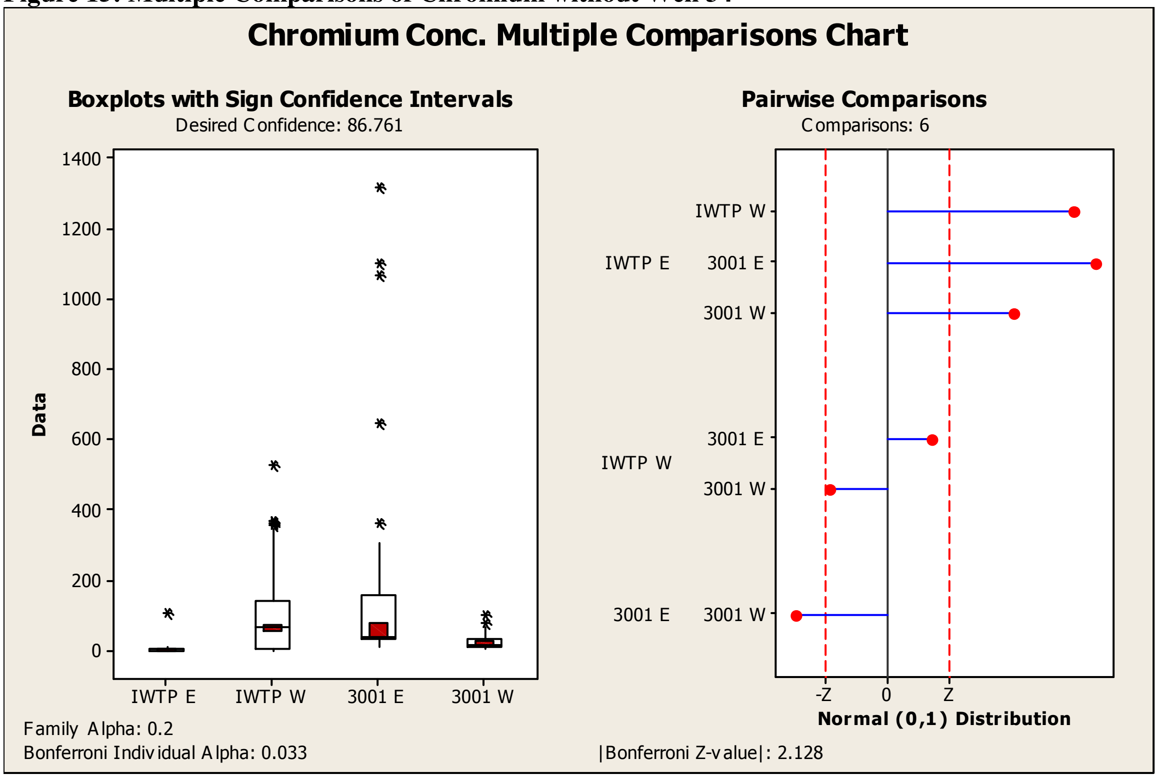


Figure 15 is a Kruskal-Wallis multiple comparisons chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each location. The pariwise comparisons chart shows whether individual comparisons between locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those two locations were significantly different. The well group on the left was compared to each of the locations to its right. Table 6 lists each of locations that were found to be statistically different from each other.

Table 6: Comparisons for Chromium without Well 34

Groups	Z-value vs. Critical value	P-value
IWTP E vs. 3001 E	7.11909 >= 2.128	0.0000
IWTP E vs. IWTP W	6.39722 >= 2.128	0.0000
IWTP E vs. 3001 W	4.30757 >= 2.128	0.0000
3001 E vs. 3001 W	3.15699 >= 2.128	0.0016

The results from the Kruskal-Wallis procedure performed without well 34 showed no significant differences between well groups IWTP W and B3001 E, and between IWTP W and B3001 W. Neglecting well 34, there was no significant difference between the interface of the IWTP plume and the B3001 plume with respect to chromium concentration.

3.4.1.6 ANOVA Performed on IWTP Versus Building 3001 for Chromium Concentration Data

An ANOVA was performed on all the IWTP wells versus all the B3001 wells to test whether IWTP was significantly different than B3001, with respect to chromium concentration. The p-value below 0.05 shows a significant difference between the IWTP plume and B3001 plume. The results of the ANOVA test are presented below.

Source	DF	SS	MS	F	P
Factor	1	49384571	49384571	19.81	0.000
Error	182	453668585	2492685		
Total	183	503053157			

S = 1579   R-Sq = 9.82%   R-Sq(adj) = 9.32%

```
                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level   N  Mean  StDev  -----+---------+---------+---------+----
IWTP   87    70    114  (-----*------)
3001   97  1107   2171                      (-----*-----)
                        -----+---------+---------+---------+----
                             0       500      1000      1500
```

The results of the ANOVA performed on IWTP versus B3001 returned a p-value below 0.05, which shows that there was a significant difference between the IWTP plume and the B3001 plume with respect to chromium concentration. The confidence intervals showed that the B3001 plume had a significantly higher concentration of chromium, as compared to IWTP.

3.4.1.7 Mann-Whitney Performed on IWTP Versus Building 3001 for Chromium Concentration Data

The Mann-Whitney method was used to test whether IWTP was significantly different from B3001. The p-value below 0.05 showed a significant difference between the two plumes. The results of the Mann-Whitney test are presented below.

```
      N  Median
IWTP  87    10.0
3001  97    42.2
```

```
Point estimate for ETA1-ETA2 is -26.8
95.0 Percent CI for ETA1-ETA2 is (-42.0,-17.0)
W = 6219.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000
The test is significant at 0.0000 (adjusted for ties)
```

Since the test is significant at 0.0000, the results of the Mann-Whitney test showed significant differences between the IWTP plume and the B3001 plume.

3.4.2 Results of Testing Redox Potential

Reduction-oxidation potential was tested using an ANOVA to determine if differences in chlorinated solvent concentrations and molar fractions could be the result of significant differences in redox potential between locations. Redox data were first tested for normality then tested for significant differences between locations using an ANOVA.

3.4.2.1 Results of Normality Testing of Redox Potential

From Figures 16 through 18, it can be seen that all well locations had normally distributed data for redox potential; therefore, no non-parametric testing was needed. That is, since the data were shown to be normally distributed, normal theory statistics will be considered satisfactory for analysis.

Figure 16: Probability Plot for Redox Potential for Wells 1-49 Through 1-50

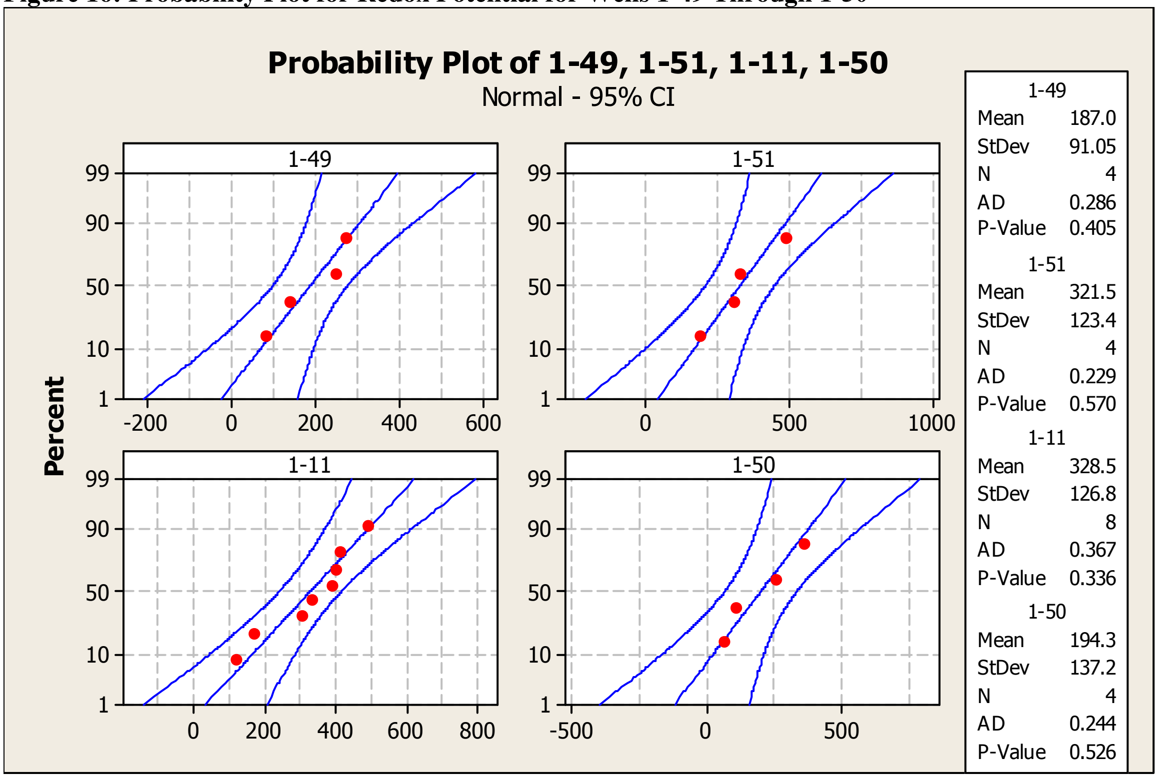


Figure 17: Probability Plot for Redox Potential for Wells 19 Through 1-8

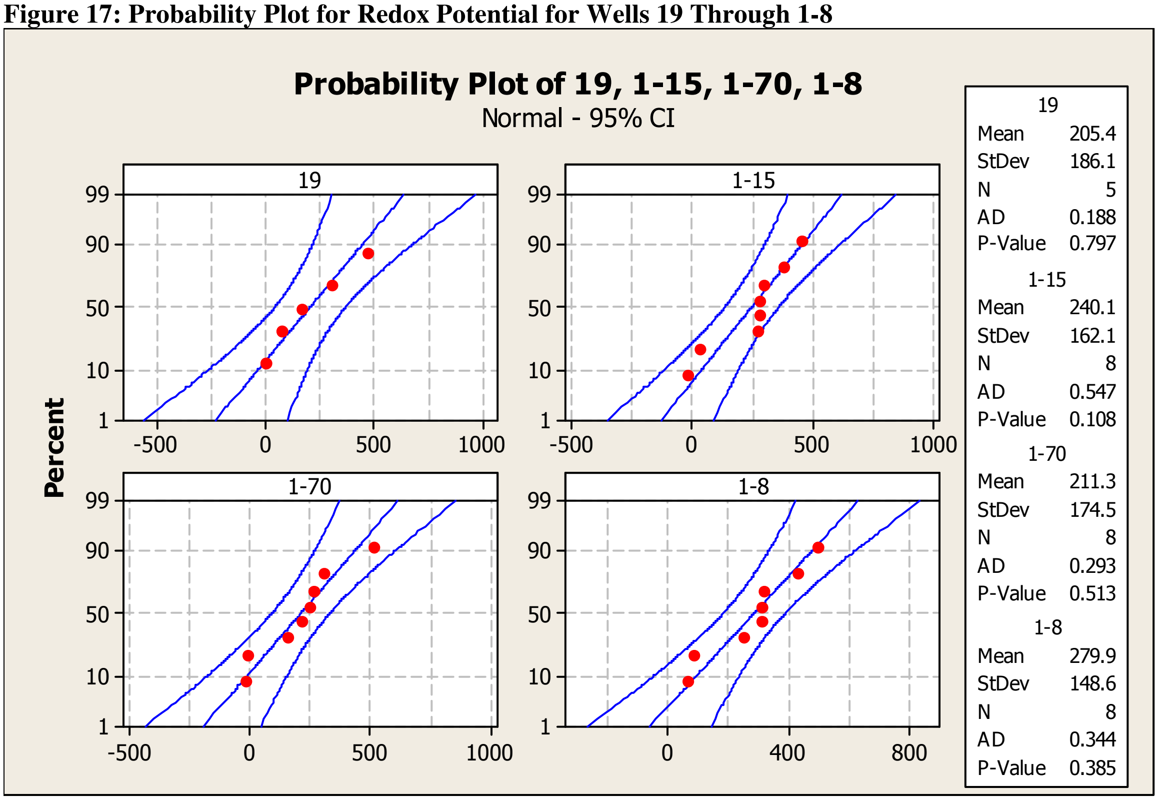
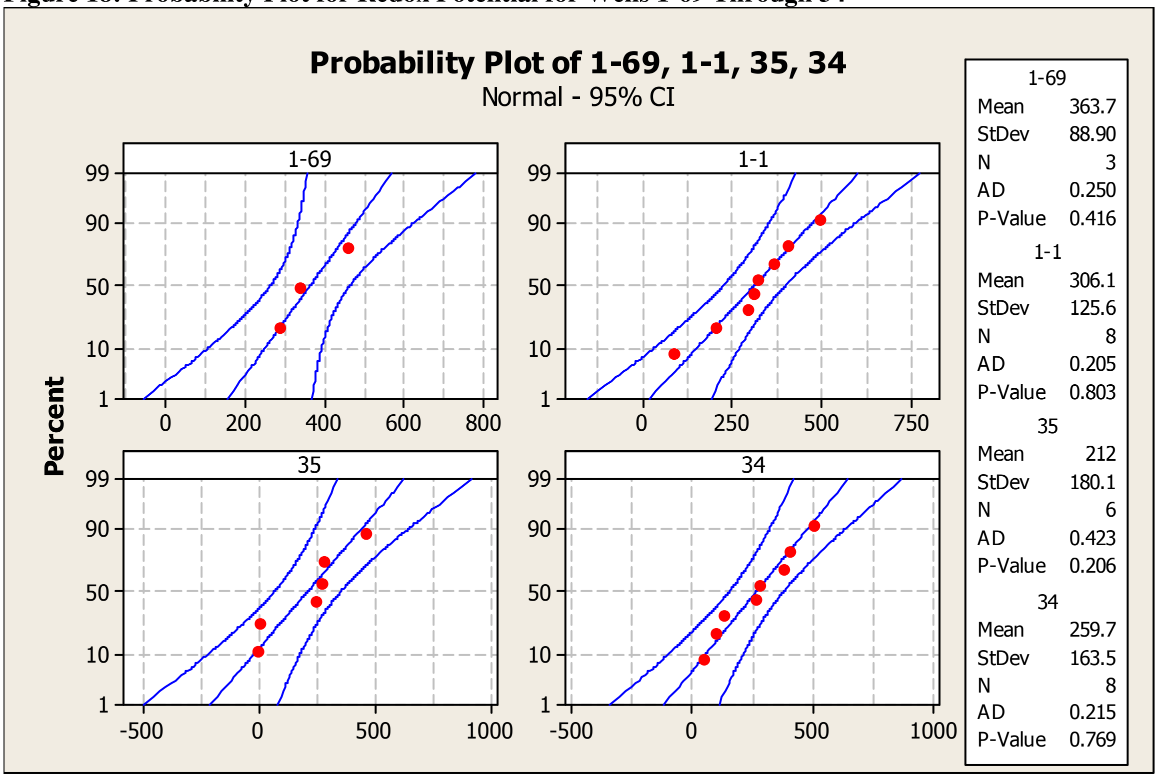


Figure 18: Probability Plot for Redox Potential for Wells 1-69 Through 34



3.4.2.2 ANOVA Performed on Redox Potential

The output of an ANOVA test performed on each individual well with respect to redox potential is shown below.

Source	DF	SS	MS	F	P
Factor	11	194577	17689	0.78	0.658
Error	62	1405378	22667		
Total	73	1599955			

S = 150.6   R-Sq = 12.16%   R-Sq(adj) = 0.00%

3.4.2.3 Results of ANOVA Performed on Redox Potential

The p-value above 0.05 indicates that no well location was significantly different from any other well location with respect to redox potential. Since there were no significant differences, a multiple comparison test was not performed. This output suggests that any differences in chlorinated solvent concentrations or molar fractions between locations were not due to differences in redox potential. This is an indication that any differences between locations, particularly with respect to molar fractions, would be due to separate sources that have statistically different molar fractions of chlorinated solvents.

3.4.3 Results of Parametric and Non-Parametric Testing of Chlorinated Solvents Concentration Data

Parametric and non-parametric testing was performed on the chlorinated solvents according to the concentration at four different locations comprised of three wells each. The testing was performed again using two locations comprised of six wells each. These tests were performed as a means of analyzing trends in the concentrations as a function of location, and to determine statistical differences between locations.

3.4.3.1 Results for Concentration Data Normality Plots

The normality plots, Figures 4A though 15A in Appendix A, showed that none of the six well groups have normally distributed concentration data for any of the four chlorinated solvent species, as indicated by the low p-value from the Anderson-Darling test. Due to non-normality, the non-parametric Kruskal-Wallis and Mann-Whitney tests are better suited for these data sets than the ANOVA.

3.4.4 Results for PCE Concentration Data

The results of the various tests performed, as described below, showed that the well groups IWTP E and B3001 W were not significantly different. Similarly, the IWTP W and B3001 E groups were not significantly different. The IWTP and B3001 groups were not significantly different from each other with respect to PCE concentration.

3.4.4.1 ANOVA Performed on PCE Concentration Data

The output of an ANOVA test performed on the four well groups with respect to PCE is shown below. The p-value of 0.000 showed that at least one location was significantly different from another location. Comparisons were made between each of the locations to determine which locations were significantly different.

Source	DF	SS	MS	F	P
Factor	3	238923	79641	18.98	0.000
Error	208	872550	4195		
Total	211	1111473			

S = 64.77   R-Sq = 21.50%   R-Sq(adj) = 20.36%

```
                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level    N   Mean  StDev  +---------+---------+---------+---------
IWTP E  46  17.48  13.38  (-----*-----)
IWTP W  64  95.43  76.27                            (-----*----)
3001 E  57  77.64  92.00                      (-----*-----)
3001W   45  24.07  23.40    (-----*-----)
                          +---------+---------+---------+---------
                          0        30        60        90
```

Pooled StDev = 64.77

Tukey 95% Simultaneous Confidence Intervals

All Pairwise Comparisons

Individual confidence level = 98.97%

```
IWTP E subtracted from:

         Lower  Center   Upper  -------+---------+---------+---------+--
IWTP W   45.55   77.96  110.36                         (----*----)
3001 E   26.94   60.16   93.38                     (-----*-----)
3001W   -28.55    6.59   41.74             (-----*-----)
                                -------+---------+---------+---------+--
                                     -60         0        60       120
```

```
IWTP W subtracted from:

          Lower  Center   Upper  -------+---------+---------+---------+--
3001 E   -48.33  -17.80   12.73           (----*----)
3001W   -103.97  -71.36  -38.75  (----*-----)
                                 -------+---------+---------+---------+--
                                      -60         0        60       120
```

```
3001 E subtracted from:

        Lower  Center   Upper  -------+---------+---------+---------+--
3001W  -86.99  -53.56  -20.14     (----*-----)
                               -------+---------+---------+---------+--
                                    -60         0        60       120
```

The confidence intervals of the ANOVA showed that the outer well groups, IWTP E and B3001 W, had low concentration of PCE. The interior well groups, IWTP W and B3001

E, had elevated concentration of PCE. The Tukey 95% pairwise comparisons test showed that the well groups IWTP E and B3001 W were not statistically different. Similarly, the IWTP W and B3001 E groups were not significantly different with respect to PCE concentration. However, the inner and outer locations were significantly different from each other, indicating an elevated concentration of PCE at the interface of the IWTP plume and B3001 plume.

3.4.4.2 Kruskal-Wallis Performed on PCE Concentration

The Kruskal-Wallis method of analysis was performed on all four well groups, with comparisons, for PCE concentration data. Table 7 lists the well groups that were significantly different. Figure 19 graphically represents the comparisons between well groups, identifying which groups were significantly different.

```
Kruskal-Wallis Test on the data


Group       N  Median  Ave Rank      Z

IWTP E     46   11.00      59.4  -5.88

IWTP W     64   64.50     145.6   6.11

3001 E     57   43.00     127.7   3.06

3001W      45   13.00      72.1  -4.24

Overall   212             106.5


H = 74.12  DF = 3  P = 0.000

H = 74.13  DF = 3  P = 0.000  (adjusted for ties)
```

From the data output above, the p-value of 0.000 indicates that there is at least one location that was significantly different from another location. Figure 19 shows the output of the multiple comparisons method for determining which locations were significantly different. The locations that were statistically different are listed in Table 7.

Figure 19: Multiple Comparisons for PCE Concentration

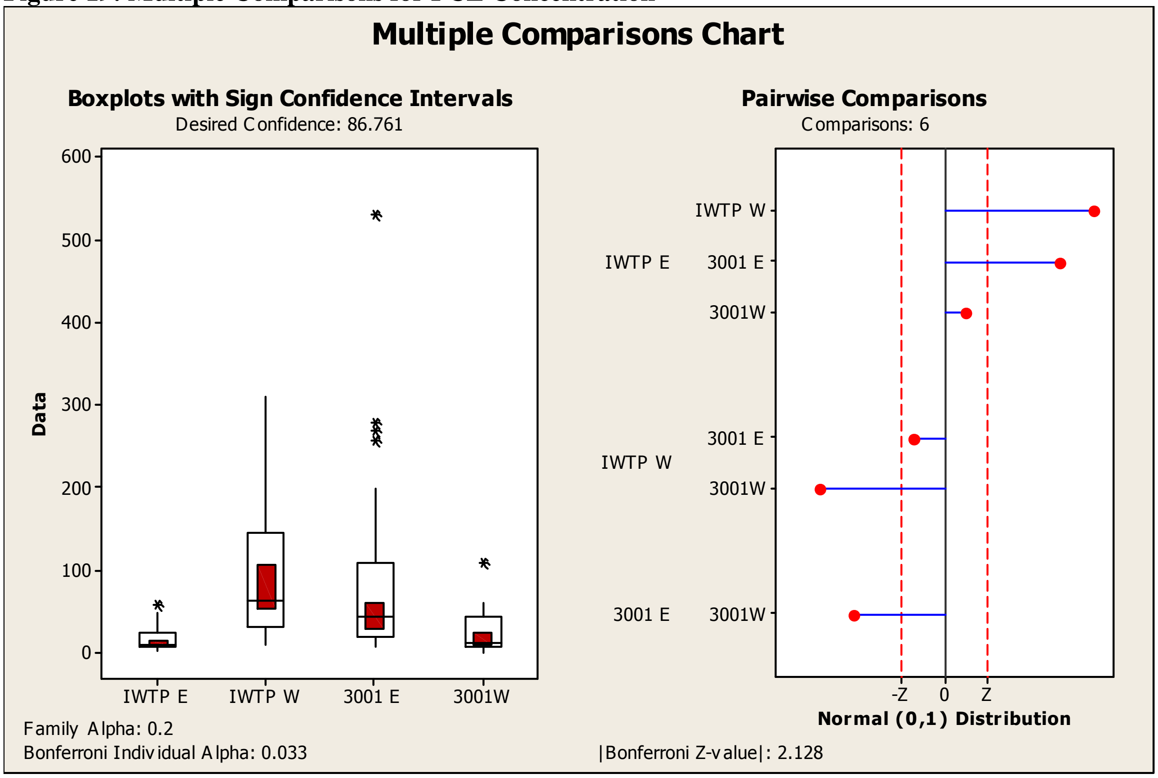


Figure 19 is a Kruskal-Wallis multiple comparisons chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each location. The pairwise comparisons chart shows whether individual comparisons between locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those two locations were significantly different. The location on the left was compared to each of the locations to its right. Table 7 lists each of locations that were found to be statistically different from each other.

Table 7: Comparisons for PCE Concentration

Groups	Z-value vs. Critical value	P-value
IWTP E vs. IWTP W	7.27157 >= 2.128	0.000
IWTP W vs. 3001W	6.16178 >= 2.128	0.000
IWTP E vs. 3001 E	5.61956 >= 2.128	0.000
3001 E vs. 3001W	4.54806 >= 2.128	0.000

The results from the Kruskal-Wallis test agree with the findings provided by the ANOVA. The Kruskal-Wallis test showed that the outer well groups, IWTP E and B3001 W, had low concentration of PCE. The interior well groups, IWTP W and B3001 E, had elevated concentration of PCE. The multiple comparisons test showed that the well groups IWTP E and B3001 W were not significantly different. Similarly, the IWTP W and B3001 E groups were not significantly different with respect to PCE concentration.

3.4.4.3 ANOVA Performed on IWTP Versus Building 3001 for PCE Concentration Data

An ANOVA was performed for all IWTP wells versus all B3001 wells to determine if there were significant differences between the two plumes. The p-value of 0.377

indicates that there was no significant difference between the IWTP plume and the B3001 plume with respect to PCE concentration.

Source	DF	SS	MS	F	P
Factor	1	4126	4126	0.78	0.377
Error	210	1107347	5273		
Total	211	1111473			

S = 72.62   R-Sq = 0.37%   R-Sq(adj) = 0.00%

```
                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level    N   Mean  StDev   +---------+---------+---------+---------
IWTP   110  62.83  70.20            (-------------*------------)
3001   102  54.01  75.13   (-------------*-------------)
                           +---------+---------+---------+---------
                          40        50        60        70
```

Pooled StDev = 72.62

With a p-value of 0.377, the ANOVA test showed no significant differences between the IWTP plume and the B3001 plume with respect to PCE concentration. This does not indicate that the IWTP plume and the B3001 plume are from separate sources with respect to PCE contamination.

3.4.4.4 Mann-Whitney Performed on IWTP Versus Building 3001 for PCE Concentration Data

The Mann-Whitney procedure was also used to test for significant differences between the IWTP plume and the B3001 plume with respect to PCE concentration. Since the test was significant at 0.4495, there was no statistical difference between the IWTP plume and the B3001 plume.

```
        N  Median
IWTP  110   31.00
3001  102   27.50



Point estimate for ETA1-ETA2 is 3.00
95.0 Percent CI for ETA1-ETA2 is (-4.00,10.29)
W = 12053.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.4495
The test is significant at 0.4494 (adjusted for ties)
```

With a p-value of 0.450, the Mann-Whitney test shows no significant differences between the IWTP plume and the B3001 plume with respect to PCE concentration. This indicates that the IWTP plume and the B3001 plume are not from separate sources with respect to PCE contamination.

3.4.4.5 Correlation Coefficients for PCE Concentration as a Function of Distance from IWTP

Table 8 shows the correlation coefficient relating the change in concentration of PCE as a function of increasing distance to IWTP. The correlation coefficient for PCE concentration was a slightly negative coefficient at -0.112. From this it can be seen that there little correlation between PCE concentration and distance from IWTP. Therefore, there does not appear to be a significant change in PCE concentration from the IWTP site to the B3001 site.

Table 8: Correlation Coefficient for PCE Concentration

Well	Distance (ft)	Conc. of PCE (ug/l)	Correlation Coefficient
1*51	188	24.70	-0.112
1*49	312	7.95	
1*50	438	19.64	
1*11	625	62.29	
19	875	156.64	
1*1	1063	54.38	
1*15	1375	31.66	
35	1407	197.80	
34	1625	19.98	
1*70	2188	11.84	
1*8	2313	44.91	
1*69	2781	1.76	

3.4.5 Results for TCE Concentration Data

Parametric and non-parametric testing was performed for TCE concentration data. In general, the testing of TCE concentration data showed that there were significant differences between all locations.

3.4.5.1 ANOVA Performed on TCE Concentration Data

The output of an ANOVA test performed on the four locations with respect to TCE is shown below. The p-value of 0.000 showed that at least one location is statistically different from another location. Comparisons were made between each of the locations to find which locations were significantly different.

```
Source   DF         SS        MS      F      P
Factor    3   91099356  30366452  57.59  0.000
Error   208  109679005    527303
Total   211  200778362

S = 726.2   R-Sq = 45.37%   R-Sq(adj) = 44.59%


                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level     N    Mean   StDev  --+---------+---------+---------+-------
IWTP E   46    74.0    75.7  (--*---)
IWTP W   64   413.1   434.0        (--*--)
3001 E   57  1051.6   764.9                  (---*--)
3001W    45  1893.4  1213.5                                (---*--)
                             --+---------+---------+---------+-------
                               0       600      1200      1800

Pooled StDev = 726.2
```

```
Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons

Individual confidence level = 98.97%


IWTP E subtracted from:

        Lower  Center   Upper  -----+---------+---------+---------+----
IWTP W  -24.1   339.1   702.4              (--*--)
3001 E  605.2   977.6  1350.1                   (--*--)
3001W  1425.4  1819.4  2213.5                          (--*--)
                               -----+---------+---------+---------+----
                                -1200         0      1200      2400


IWTP W subtracted from:

        Lower  Center   Upper  -----+---------+---------+---------+----
3001 E  296.2   638.5   980.8                (--*--)
3001W  1114.7  1480.3  1845.9                       (--*--)
                               -----+---------+---------+---------+----
                                -1200         0      1200      2400
```

```
3001 E subtracted from:

       Lower  Center   Upper  -----+---------+---------+---------+----
3001W  467.0   841.8  1216.6                   (--*--)
                              -----+---------+---------+---------+----
                               -1200         0      1200      2400
```

The confidence intervals provided by the ANOVA showed an increase in TCE concentration as the distance from IWTP increases. Using Tukey's 95% pairwise comparisons showed that there is no significant difference between IWTP E and IWTP W. All other well groups were significantly different, as indicated by the results from the multiple comparisons.

3.4.5.2 Kruskal-Wallis Performed on TCE Concentration Data

The Kruskal-Wallis method of analysis was performed on all four locations, with comparisons, for TCE concentration data. Table 9 lists the well groups that were significantly different. Figure 20 graphically represents the comparisons between locations, identifying which locations were significantly different.

Kruskal-Wallis Test on the data

Group	N	Median	Ave Rank	Z
IWTP E	46	45.00	35.0	-8.93
IWTP W	64	200.00	85.8	-3.24
3001 E	57	904.00	138.5	4.61
3001W	45	1600.00	168.5	7.64
Overall	212		106.5	

H = 131.32 DF = 3 P = 0.000

H = 131.33 DF = 3 P = 0.000 (adjusted for ties)

The p-value of 0.000 shows that at least one location was statistically different from another location. To determine which locations were significantly different, multiple comparisons were performed and are presented in Figure 20 and Table 9.

Figure 20: Multiple Comparisons for TCE Concentration

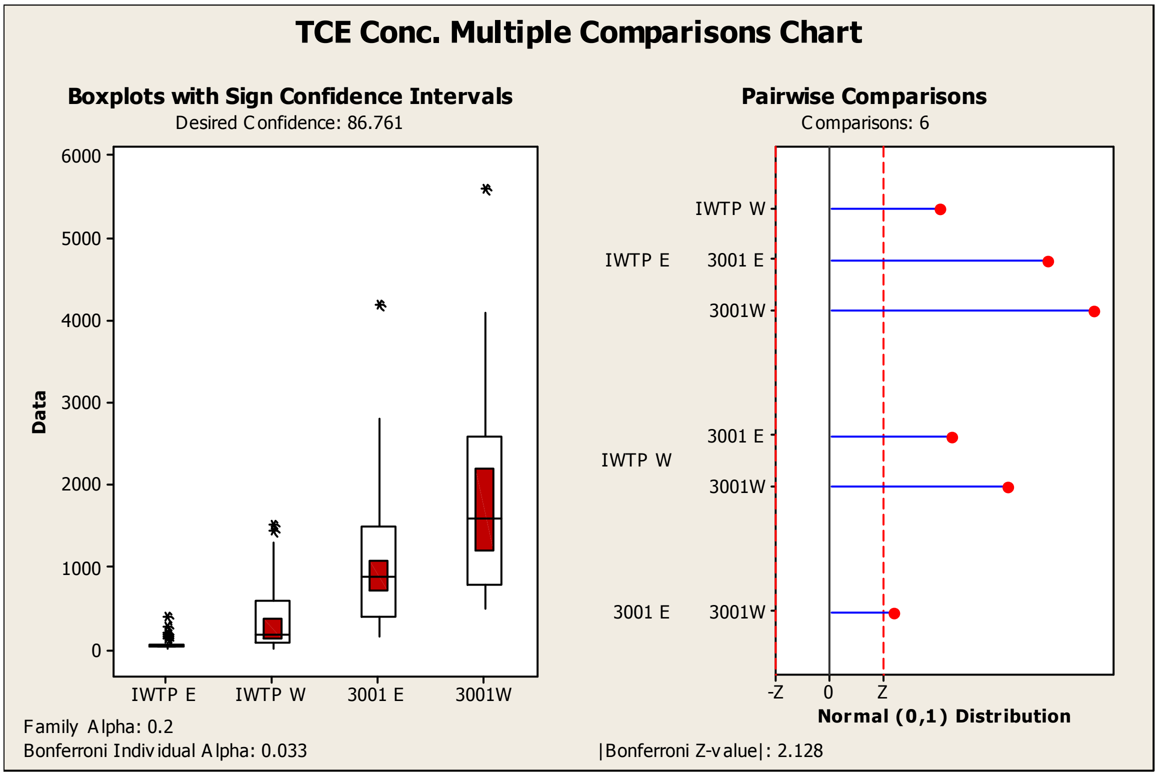


Figure 20 is a Kruskal-Wallis multiple comparisons chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each location. The pairwise comparisons chart shows whether individual comparisons between locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those two locations were significantly different. The location on the left was compared to each of the locations to its right. Table 9 lists each of locations that were found to be statistically different from each other.

Table 9: Comparisons for TCE Concentration

Groups	Z-value vs. Critical value	P-value
IWTP E vs. 3001W	10.3818 >= 2.128	0.0000
IWTP E vs. 3001 E	8.5139 >= 2.128	0.0000
IWTP W vs. 3001W	6.9343 >= 2.128	0.0000
IWTP W vs. 3001 E	4.7205 >= 2.128	0.0000
IWTP E vs. IWTP W	4.2822 >= 2.128	0.0000
3001 E vs. 3001W	2.4537 >= 2.128	0.0141

The results of the Kruskal-Wallis test showed that there were significant differences between all well groups. From the boxplot it can be seen that the concentration of TCE increases as the distance from IWTP increases. From these results, it is reasonable to assume that the source of the TCE contamination is B3001.

3.4.5.3 ANOVA Performed on Building 3001 Versus IWTP for TCE Summarized Concentration Data

An ANOVA was performed for all IWTP wells versus all B3001 wells to determine if there were significant differences between the two plumes. The p-value of 0.000 shows that the two plumes were statistically different. This indicates that the IWTP plume and B3001 plume are the result of different sources.

Source	DF	SS	MS	F	P
Factor	1	70200996	70200996	112.90	0.000
Error	210	130577366	621797		
Total	211	200778362			

S = 788.5   R-Sq = 34.96%   R-Sq(adj) = 34.65%

```
                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level    N    Mean   StDev  -------+---------+---------+---------+--
IWTP   110   271.3   373.5  (---*--)
3001   102  1423.0  1068.8                              (---*--)
                            -------+---------+---------+---------+--
                                 400       800      1200      1600
```

Pooled StDev = 788.5

With a p-value of 0.000, the ANOVA test shows significant differences between the IWTP plume and the B3001 plume. The p-value of 0.000 shows that the two plumes were statistically different. This indicates that the IWTP plume and B3001 plume are the result of different sources.

3.4.5.4 Mann-Whitney Performed on Building 3001 Versus IWTP for TCE Concentration Data

The Mann-Whitney procedure was also used to test for significant differences between the IWTP plume and the B3001 plume. The p-value of 0.000 shows a significant difference between the IWTP plume and the B3001 plume. This indicates that the IWTP plume and B3001 plume are from separate sources.

	N	Median
IWTP	110	94.5
3001	102	1100.0

```
Point estimate for ETA1-ETA2 is -868.2
95.0 Percent CI for ETA1-ETA2 is (-1083.9,-710.0)
W = 7099.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000
The test is significant at 0.0000 (adjusted for ties)
```

With a p-value of 0.000, the Mann-Whitney test shows significant differences between the IWTP plume and the B3001 plume. This indicates that the IWTP plume and B3001 plume are from separate sources.

3.6.3 Correlation Coefficients for TCE Concentration as a Function of Distance from IWTP

Table 10 shows the correlation coefficient relating the change in concentration of TCE as a function of increasing distance to IWTP. The correlation coefficient for TCE concentration showed a strong correlation between increasing TCE concentration and increasing distance from IWTP, with a correlation coefficient of 0.659. This indicates a strong change in TCE concentration from the IWTP site to the B3001 site.

Table 10: Correlation Coefficient for TCE Concentration

Well	Distance (ft)	Conc. of TCE (ug/l)	Correlation Coefficient
1*51	188	49.01	0.659
1*49	312	34.86	
1*50	438	134.06	
1*11	625	65.47	
19	875	794.86	
1*1	1063	331.72	
1*15	1375	172.88	
35	1407	1942.00	
34	1625	1035.04	
1*70	2188	1326.43	
1*8	2313	2916.50	
1*69	2781	754.91	

3.4.6 Results for DCE Concentration Data

The parametric and non-parametric testing provides different results as to which locations for locations tested were significantly different. However, when comparing the IWTP plume to the B3001 plume, parametric and non-parametric testing showed that the IWTP plume and the B3001 plume are significantly different.

3.4.6.1 ANOVA Performed on DCE Concentration Data

The output of an ANOVA test performed on the four well groups with respect to DCE is shown below. The p-value of 0.000 showed that at least one location was statistically different from another location. Comparisons were made between each of the well groups to find which groups were significantly different.

```
Source   DF         SS        MS      F      P
Factor    3   56054936  18684979  24.79  0.000
Error   208  156796858    753831
Total   211  212851794

S = 868.2   R-Sq = 26.34%   R-Sq(adj) = 25.27%


                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level    N    Mean   StDev  ---+---------+---------+---------+------
IWTP E  46   195.0   210.2    (----*----)
IWTP W  64  1245.1  1562.4                        (---*---)
3001 E  57    62.8    95.6  (---*----)
3001 W  45   147.4   107.4   (----*----)
                            ---+---------+---------+---------+------
                               0       500      1000      1500

Pooled StDev = 868.2
```

```
Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons

Individual confidence level = 98.97%


IWTP E subtracted from:

         Lower  Center   Upper      +---------+---------+---------+---------
IWTP W   615.7  1050.0  1484.4                                  (----*-----)
3001 E  -577.5  -132.2   313.2                   (----*-----)
3001 W  -518.8   -47.7   423.5                    (----*-----)
                                    +---------+---------+---------+---------
                                -1600      -800         0       800


IWTP W subtracted from:

          Lower   Center   Upper      +---------+---------+---------+---------
3001 E  -1591.4  -1182.2  -773.0      (----*----)
3001 W  -1534.8  -1097.7  -660.6       (----*-----)
                                      +---------+---------+---------+---------
                                  -1600      -800         0       800
```

```
3001 E subtracted from:

        Lower  Center  Upper      +---------+---------+---------+---------
3001 W  -363.6    84.5  532.6                   (-----*-----)
                                  +---------+---------+---------+---------
                               -1600      -800         0       800
```

The ANOVA test showed that most well groups have moderately low concentrations of DCE, except for group IWTP W, which has significantly higher concentrations of DCE. This was primarily due to well 19, which is a DCE "hotspot". The Tukey's 95% pairwise comparisons test showed that the only well group significantly different from the others was the IWTP W group. These results suggest that the IWTP is the source of the DCE contamination, and that IWTP and B3001 are separate sources.

3.4.6.2 Kruskal-Wallis Performed on DCE Concentration Data

The Kruskal-Wallis method of analysis was performed on all four well groups, with comparisons, for DCE concentration data. Table 11 lists the well groups that were significantly different. Figure 21 graphically represents the comparisons between well groups, identifying which groups were significantly different.

Kruskal-Wallis Test on the data

Group	N	Median	Ave Rank	Z
IWTP E	46	129.50	115.7	1.15
IWTP W	64	190.00	145.4	6.06
3001 E	57	24.00	52.6	-7.76
3001 W	45	130.00	110.1	0.44
Overall	212		106.5	

H = 70.84 DF = 3 P = 0.000

H = 70.85 DF = 3 P = 0.000 (adjusted for ties)

The p-value of 0.000 shows that at least one location was significantly different from another location. Multiple comparisons have been performed to determine which locations were significantly different. The results of the multiple comparisons are presented in Figure 21 and Table 11.

Figure 21: Multiple Comparisons for DCE Concentration

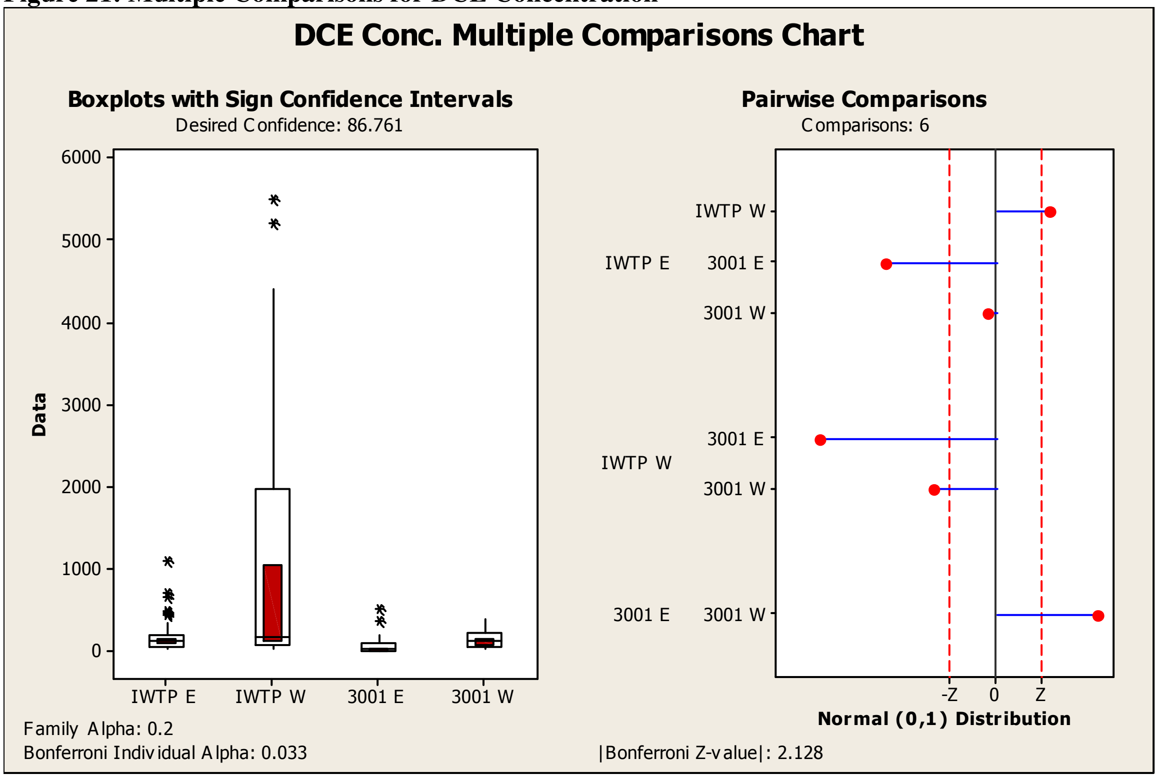


Figure 21 is a Kruskal-Wallis multiple comparisons chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each location. The pairwise comparisons chart shows whether individual comparisons between locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those two locations were significantly different. The location on the left was compared to each of the locations to its right. Table 11 lists each of locations that were found to be statistically different from each other.

Table 11: Comparisons for DCE Concentration

Groups	Z-value vs. Critical value	P-value
IWTP W vs. 3001 E	8.30156 >= 2.128	0.0000
IWTP E vs. 3001 E	5.18794 >= 2.128	0.0000
3001 E vs. 3001 W	4.70066 >= 2.128	0.0000
IWTP W vs. 3001 W	2.95321 >= 2.128	0.0031
IWTP E vs. IWTP W	2.50214 >= 2.128	0.0123

The Kruskal-Wallis test shows that the only locations which were not significantly different were the outermost locations, location IWTP E and B3001 W. Since the Kruskal-Wallis test has more strength for finding significant differences with non-normal data, it is preferable to use the results from the Kruskal-Wallis test as compared to the ANOVA.

3.4.6.3 ANOVA Performed on Building 3001 Versus IWTP for DCE Concentration Data

An ANOVA was performed for all IWTP wells versus all B3001 wells to determine if there were significant differences between the two plumes. The p-value of 0.000 showed that the IWTP plume was significantly different from the B3001 plume. This indicates that the IWTP plume and B3001 plume are from separate sources.

Source	DF	SS	MS	F	P
Factor	1	26366649	26366649	29.69	0.000
Error	210	186485145	888025		
Total	211	212851794			

S = 942.4   R-Sq = 12.39%   R-Sq(adj) = 11.97%

```
                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level    N   Mean   StDev  ---+---------+---------+---------+------
IWTP   110  806.0  1303.8                          (-----*-----)
3001   102  100.1   108.9  (-----*-----)
                           ---+---------+---------+---------+------
                              0       300       600       900
```

Pooled StDev = 942.4

With a p-value of 0.000, the ANOVA showed significant differences between IWTP and B3001. IWTP had significantly higher concentrations of DCE as compared to B3001. These results indicate that the IWTP plume and the B3001 plume are from separate sources.

3.4.6.4 Mann-Whitney Performed on Building 3001 Versus IWTP for DCE Concentration Data

The Mann-Whitney procedure was also used to test for significant differences between the IWTP plume and the B3001 plume. Since the test is significant at 0.0000, these results show that the IWTP plume and the B3001 plume were statistically different. These results indicate that the IWTP plume and the B3001 plume are from separate sources.

```
        N  Median
IWTP  110   150.0
3001  102    43.2

Point estimate for ETA1-ETA2 is 90.0
95.0 Percent CI for ETA1-ETA2 is (59.9,131.3)
W = 14624.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000
The test is significant at 0.0000 (adjusted for ties)
```

With a p-value of 0.000, the Mann-Whitney test shows significant differences between the IWTP plume and the B3001 plume, indicating that the IWTP plume and the B3001 plume are from separate sources.

3.4.6.5 Correlation Coefficients for DCE Concentration as a Function of Distance from IWTP

Table 12 shows the correlation coefficient relating the change in concentration of DCE as a function of increasing distance to IWTP. The correlation coefficient of -0.172 showed only a slight correlation between decreasing DCE concentration and increasing distance from IWTP. Therefore, there does not appear to be a significant change in DCE concentration from the IWTP site to the B3001 site.

Table 12: Correlation Coefficient for DCE Concentration

Well	Distance (ft)	Conc. of DCE (ug/l)		Correlation Coefficient
1*51	188	178.00		-0.172
1*49	312	56.68		
1*50	438	340.69		
1*11	625	85.04		
19	875	2691.43		
1*1	1063	27.98		
1*15	1375	159.29		
35	1407	189.93		
34	1625	9.56		
1*70	2188	147.71		
1*8	2313	208.10		
1*69	2781	36.44		

3.4.7 Results for VC Concentration Data

The results of testing VC concentration showed significant differences between the IWTP locations and the B3001 locations. Both IWTP locations had significantly higher concentrations of VC. Comparing all the IWTP wells to all the B3001 wells showed a significant difference between the two plumes.

3.4.7.1 ANOVA Performed on VC Concentration Data

The output of an ANOVA test performed on the four well groups with respect to VC is shown below. The p-value of 0.000 showed that at least one location was significantly different from another location. Comparisons were made between each of the locations to find which locations were significantly different. The statistical differences between the IWTP locations and the B3001 locations from the multiple comparisons indicate that the IWTP is the source of the VC contamination and that the IWTP plume and the B3001 plume are from separate sources.

Source	DF	SS	MS	F	P
Factor	3	393745	131248	16.33	0.000
Error	208	1671355	8035		
Total	211	2065100			

S = 89.64   R-Sq = 19.07%   R-Sq(adj) = 17.90%

```
                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level     N   Mean   StDev  ------+---------+---------+---------+---
IWTP E   46  74.57  117.35                    (------*-----)
IWTP W   64  97.48  128.50                           (----*-----)
3001 E   57   0.46    0.58  (-----*-----)
3001 W   45   6.94   16.12   (------*-----)
                            ------+---------+---------+---------+---
                                  0        40        80       120

Pooled StDev = 89.64


Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons

Individual confidence level = 98.97%


IWTP E subtracted from:

          Lower  Center   Upper     +---------+---------+---------+---------
IWTP W   -21.93   22.91   67.75                      (-----*------)
3001 E  -120.09  -74.11  -28.13        (-----*------)
3001 W  -116.27  -67.63  -18.99        (------*------)
                                    +---------+---------+---------+---------
                                 -140       -70         0        70
```

```
IWTP W subtracted from:

          Lower   Center   Upper     +---------+---------+---------+---------
3001 E  -139.27   -97.02  -54.77     (-----*-----)
3001 W  -135.67   -90.54  -45.41      (-----*------)
                                     +---------+---------+---------+---------
                                  -140       -70          0        70


3001 E subtracted from:

         Lower   Center  Upper     +---------+---------+---------+---------
3001 W  -39.78    6.48  52.74                   (------*------)
                                   +---------+---------+---------+---------
                                -140       -70          0        70
```

The ANOVA showed significantly higher concentrations of VC at both IWTP locations. The Tukey's 95% pairwise comparisons showed no significant differences between IWTP E and IWTP W or between B3001 E and B3001 W. There were significant differences between the IWTP locations and the B3001 locations. These results indicate that the IWTP is the source of the VC contamination, and that the IWTP plume and B3001 plume are from separate sources.

3.4.7.2 Kruskal-Wallis Performed on VC Concentration Data

The Kruskal-Wallis method of analysis was performed on all four well groups, with comparisons, for VC concentration data. Table 13 lists the well groups that are significantly different. Figure 22 graphically represents the comparisons between well groups, identifying which groups were significantly different.

Kruskal-Wallis Test on the data

Group	N	Median	Ave Rank	Z
IWTP E	46	3.30000E+01	146.4	4.99
IWTP W	64	3.80000E+01	159.2	8.23
3001 E	57	0.000000000	45.2	-8.82
3001 W	45	1.000000000	68.3	-4.71
Overall	212		106.5	

H = 141.18 DF = 3 P = 0.000

H = 143.21 DF = 3 P = 0.000 (adjusted for ties)

The p-value of 0.000 showed that at least one location was significantly different from another location. Multiple comparisons were performed to determine which locations were significantly different. The results of the multiple comparisons are presented in Figure 22 and Table 13.

Figure 22: Multiple Comparisons for VC Concentration

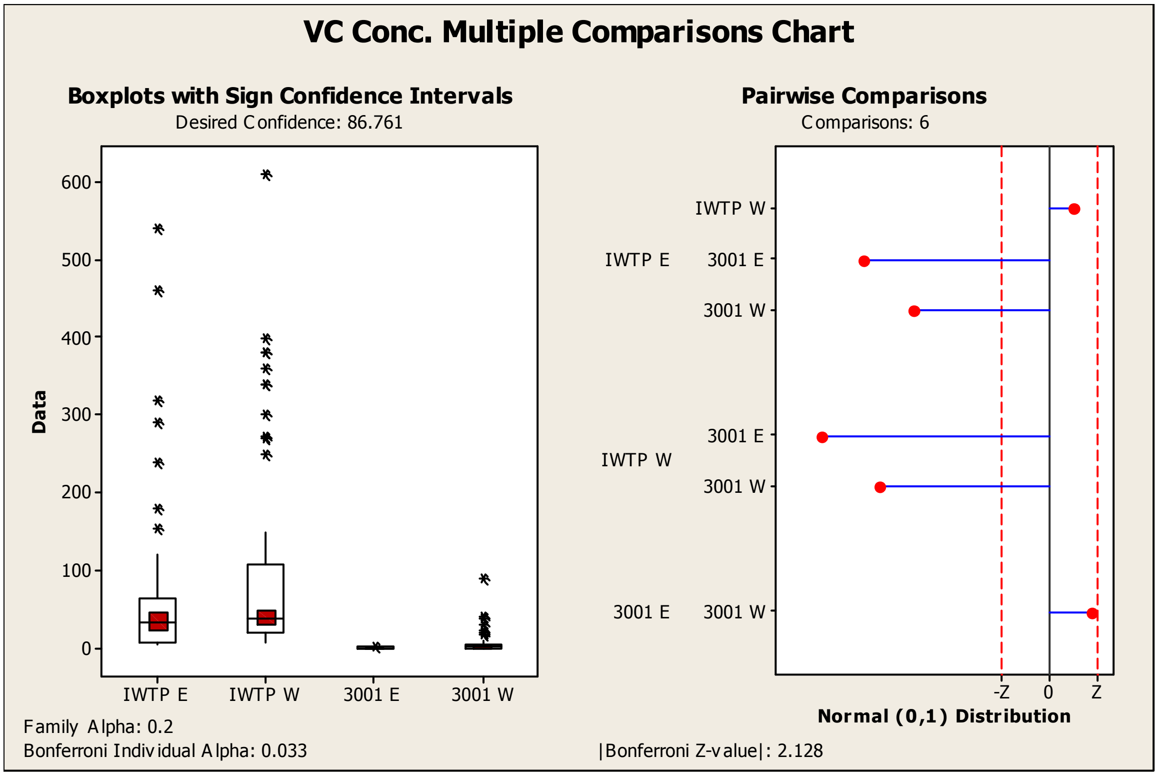


Figure 22 is a Kruskal-Wallis multiple comparisons chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each location. The pairwise comparisons chart shows whether individual comparisons between locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those two locations were significantly different. The location on the left was compared to each of the locations to its right. Table 13 lists each of locations that were found to be statistically different from each other.

Table 13: Comparisons for VC Concentration

Groups	Z-value vs. Critical value	P-value
IWTP W vs. 3001 E	10.2801 >= 2.128	0
IWTP E vs. 3001 E	8.3863 >= 2.128	0
IWTP W vs. 3001 W	7.6761 >= 2.128	0
IWTP E vs. 3001 W	6.1203 >= 2.128	0

There are no differences in the results from the Kruskal-Wallis test as compared to the results from the ANOVA test. The IWTP locations were not significantly different from each other and the B3001 locations were not significantly different from each other. All other comparisons showed significant differences.

3.4.7.3 ANOVA Performed on Building 3001 Versus IWTP for VC Concentration Data

An ANOVA was performed for all IWTP well versus all B3001 wells to determine if there were significant differences between the two plumes. The p-value of 0.000 showed that there was a statistical difference between the IWTP plume and the B3001 plume. These results indicate that the IWTP plume and B3001 plume are from separate locations.

Source	DF	SS	MS	F	P
Factor	1	378640	378640	47.15	0.000
Error	210	1686460	8031		
Total	211	2065100			

S = 89.61   R-Sq = 18.34%   R-Sq(adj) = 17.95%

```
                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level     N   Mean   StDev  -----+---------+---------+---------+----
IWTP    110  87.90  123.93                              (----*-----)
3001    102   3.32   11.13  (-----*-----)
                            -----+---------+---------+---------+----
                                 0        30        60        90
```

Pooled StDev = 89.61

With a p-value of 0.000, the ANOVA shows that the VC concentrations at the IWTP are significantly higher than the concentrations at B3001. This indicates that the IWTP is the source of the VC contamination and that the IWTP plume and the B3001 plume are from separate sources.

3.4.7.4 Mann-Whitney Performed on Building 3001 Versus IWTP for VC Concentration Data

The Mann-Whitney procedure was also used to determine if there where significant differences between the IWTP plume and the B3001 plume. Since the test is significant with a p-value of 0.0000, the IWTP plume and the B3001 plume are statistically different. These results indicate that the IWTP plume and the B3001 plume are from separate sources.

```
        N  Median
IWTP  110   35.00
3001  102    0.47



Point estimate for ETA1-ETA2 is 34.00
95.0 Percent CI for ETA1-ETA2 is (29.99,42.00)
W = 16928.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000
The test is significant at 0.0000 (adjusted for ties)
```

The Mann-Whitney test shows significant differences between the IWTP plume and the B3001 plume, which was significant at 0.000. These results suggest that the IWTP plume and the B3001 plume are from separate sources.

3.4.7.5 Correlation Coefficients for VC Concentration as a Function of Distance from IWTP

Table 14 shows the correlation coefficient relating the change in concentration of VC as a function of increasing distance to IWTP. The VC concentration correlation coefficient showed a decrease in concentration with respect to increasing distance from IWTP. This indicates a difference in VC concentration between the IWTP site and the B3001 site. These results suggest that the IWTP is the source of the VC contamination and that the IWTP plume and the B3001 plume are from separate sources.

Table 14: Correlation Coefficients for VC Concentration

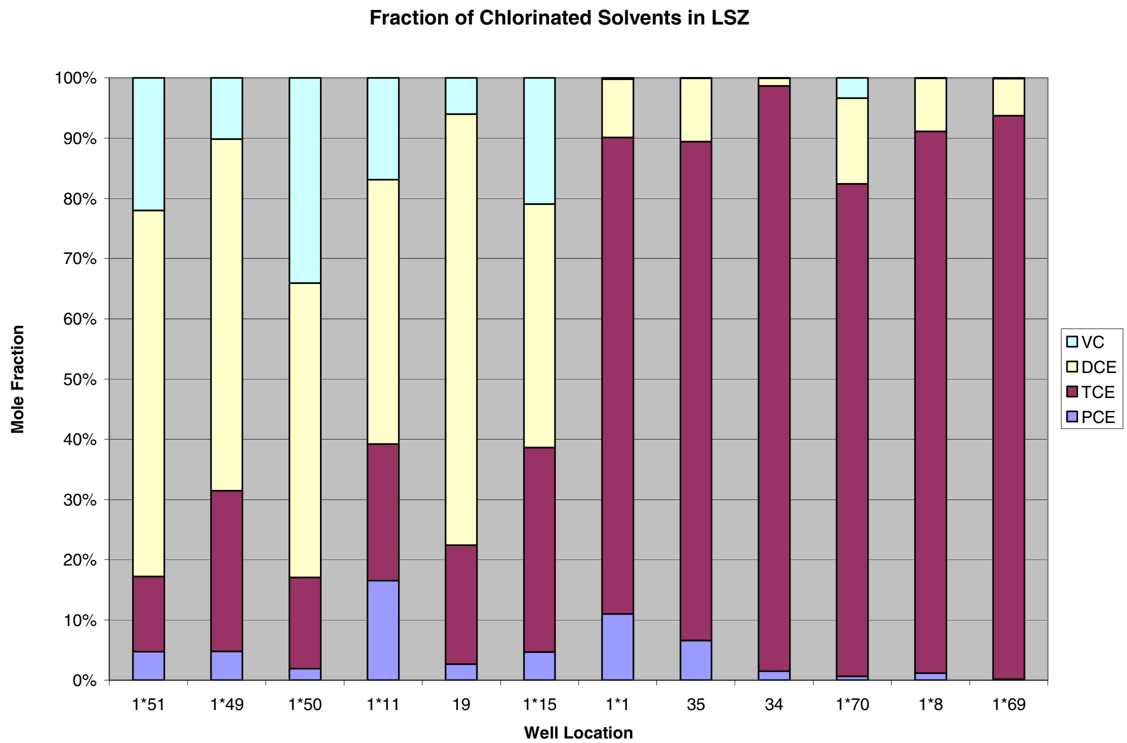
Well	Distance (ft)	Conc. of VC (ug/l)	Correlation Coefficient
1*51	188	43.367	-0.419
1*49	312	6.189	
1*50	438	167.938	
1*11	625	20.966	
19	875	168.693	
1*1	1063	0.510	
1*15	1375	65.718	
35	1407	0.623	
34	1625	0.321	
1*70	2188	21.429	
1*8	2313	0.418	
1*69	2781	0.364	

3.5 Results for Chlorinated Solvents Processed Data

The processed data used in this effort were contaminant molar fractions, developed from the concentration data provided by Tinker AFB. Parametric and non-parametric testing was performed on molar fraction data to determine if there were statistical differences between the IWTP plume and the B3001 plume. Statistical differences in the molar fractions between these locations would be a strong indication that these are separate plumes from separate sources. Molar fractions are generally a better indicator of differences as compared to concentration data. This is because molar fractions are less affected by influences such as dispersion and dilution which result during contaminant migration.

When dealing with PCE and its daughter products, ratios can be an effective way of identifying additional sources. Molar ratios are used so that the numerator and denominator both correspond to number of molecules that are or were formally the parent compound (Morrison and Murphy, 2006). When comparing PCE and TCE to DCE and VC, PCE and TCE will be prevalent in more oxidizing conditions. DCE and VC will be present in more reducing environments. Plotting the molar concentration of all four species versus distance from a source can show correlations between specific locations and suspected sources. In this report, molar fractions of the total moles of the four chlorinated species are used to analyze correlations between wells at B3001 and IWTP. For this analysis, only the LSZ zone was used due to a lack of data for the IWTP area in the USZ. The mole fractions for the LSZ zone have been graphed and are available in Figure 23 found below.

Figure 23: Molar Fractions at Individual Locations



The first six well locations, 1-51 through 1-15, are considered to be representative of the IWTP plume. Each of the six wells had a combined PCE and TCE molar fraction less than 40%, three of the six are below 25%. Conversely, the last six wells, 1-1 through 1-69, were considered to be representative of the B3001 plume. Each of these six wells had a combined PCE and TCE molar fraction greater than 80%. This analysis showed higher molar fractions of VC and DCE near the IWTP area in the LSZ, indicating a reductive environment or some level of reductive dechlorination had taken place prior to release. The three wells west of the IWTP site, 1-11, 19, and 1-15, had molar fractions that were similar to those found at IWTP, indicating a likely correlation between IWTP and the area between IWTP and B3001. All five of the IWTP and "in between" wells had DCE and VC fractions above 50%. Of the seven wells in the B3001 area, only one well, 1-15, had a DCE and VC fraction above 50%. Well 1-15 is directly down gradient of the IWTP site. Four of the seven B3001 wells had DCE and VC fractions below 10%. This showed that a correlation between the B3001 wells is likely, but there is little correlation between IWTP and B3001. This is the foundation of the hypothesis that there are two separate contamination sources; one at B3001 and one at IWTP. In general, testing has shown elevated levels of DCE and VC within the IWTP plume. This is an indication that the hypothesis of IWTP being a separate source is true, since it is reasonable to assume that contamination from the IWTP area would have undergone some level of dechlorination, reducing the TCE found at the B3001 wells to DCE and VC. Statistical testing of the chlorinated solvents molar fraction data is present throughout section 3.5.

3.5.1 Results for Molar Fraction Data Normality Plots

From the various normality plots, Figures 16A through 27A in Appendix A, it can be seen that in most cases the data were not normally distributed. The exceptions to this were the DCE molar fraction for well group IWTP E and the VC molar fraction for well group IWTP W.

3.5.2 Results for PCE Molar Fraction Data

The highest molar fractions of PCE were found at the interface of the IWTP plume and the B3001 plume, at the IWTP W and B3001 E locations. The IWTP E location also showed an elevated percentage of PCE. The B3001 W location had a mean PCE percentage of less than one percent of total chlorinated solvents, and was significantly different from the other three locations.

3.5.2.1 ANOVA Performed on PCE Molar Fraction Data

The output of an ANOVA test performed on the four well groups with respect to PCE molar fractions is shown below. The p-value of 0.000 showed that at least of location was significantly different from another location. Comparisons were made between each of the well groups to find which groups were significantly different.

Source	DF	SS	MS	F	P
Factor	3	0.12539	0.04180	21.02	0.000
Error	208	0.41367	0.00199		
Total	211	0.53906			

S = 0.04460   R-Sq = 23.26%   R-Sq(adj) = 22.15%

```
                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level     N     Mean    StDev  --+---------+---------+---------+-------
IWTP E   46  0.03758  0.01611              (----*----)
IWTP W   64  0.07310  0.06670                             (---*----)
3001 E   57  0.05846  0.04639                       (---*----)
3001W    45  0.00748  0.00528  (----*----)
                               --+---------+---------+---------+-------
                               0.000     0.025     0.050     0.075
Pooled StDev = 0.04460
```

Tukey 95% Simultaneous Confidence Intervals

All Pairwise Comparisons

Individual confidence level = 98.97%

IWTP E subtracted from:

```
           Lower    Center     Upper  --------+---------+---------+---------
IWTP W   0.01321   0.03552   0.05783                    (---*----)
3001 E  -0.00199   0.02089   0.04376                 (---*----)
3001W   -0.05430  -0.03010  -0.00590       (----*----)
                                      --------+---------+---------+---------
                                           -0.050     0.000     0.050
```

```
IWTP W subtracted from:

          Lower    Center     Upper  --------+---------+---------+--------
3001 E  -0.03566  -0.01464   0.00638           (---*---)
3001W   -0.08807  -0.06562  -0.04317  (----*---)
                                     --------+---------+---------+--------
                                          -0.050     0.000     0.050


3001 E subtracted from:

         Lower    Center     Upper  --------+---------+---------+---------
3001W  -0.07400  -0.05098  -0.02797    (----*---)
                                    --------+---------+---------+---------
                                         -0.050     0.000     0.050
```

The results of the ANOVA test showed the highest molar fractions of PCE at the interface between the IWTP plume and the B3001 plume, at the IWTP W and B3001 E locations. IWTP E also had a significantly high molar fraction of PCE. The multiple comparisons showed significant differences between IWTP E and IWTP W, as well as between B3001 W and all other well groups. In contradiction to the results from other chlorinated species, these results do not indicate that IWTP plume and B3001 plume are from separate sources with respect to PCE contamination. Since PCE was not used until the 1970’s, it is reasonable to assume that PCE was not released to the environment in the same manner or quantities that TCE was. This is the likely cause of the difference in statistical results.

3.5.2.2 Kruskal-Wallis Performed on PCE Molar Fraction Data

The Kruskal-Wallis method of analysis was performed on all four well groups, with comparisons, for PCE molar fraction data. Table 15 lists the well groups that were significantly different. Figure 24 graphically represents the comparisons between well groups, identifying which groups are significantly different.

Kruskal-Wallis Test on the data

Group	N	Median	Ave Rank	Z
IWTP E	46	0.041283	116.7	1.27
IWTP W	64	0.042775	137.6	4.85
3001 E	57	0.054639	126.0	2.81
3001W	45	0.007123	27.2	-9.77
Overall	212		106.5	

H = 98.71 DF = 3 P = 0.000

From the data output above, the p-value of 0.000 indicates that there was at least one location that was significantly different from another location. Figure 24 shows the output of the multiple comparisons method for determining which locations were significantly different. The locations that were statistically different are listed in Table 15.

Figure 24: Multiple Comparisons for PCE Molar Fractions

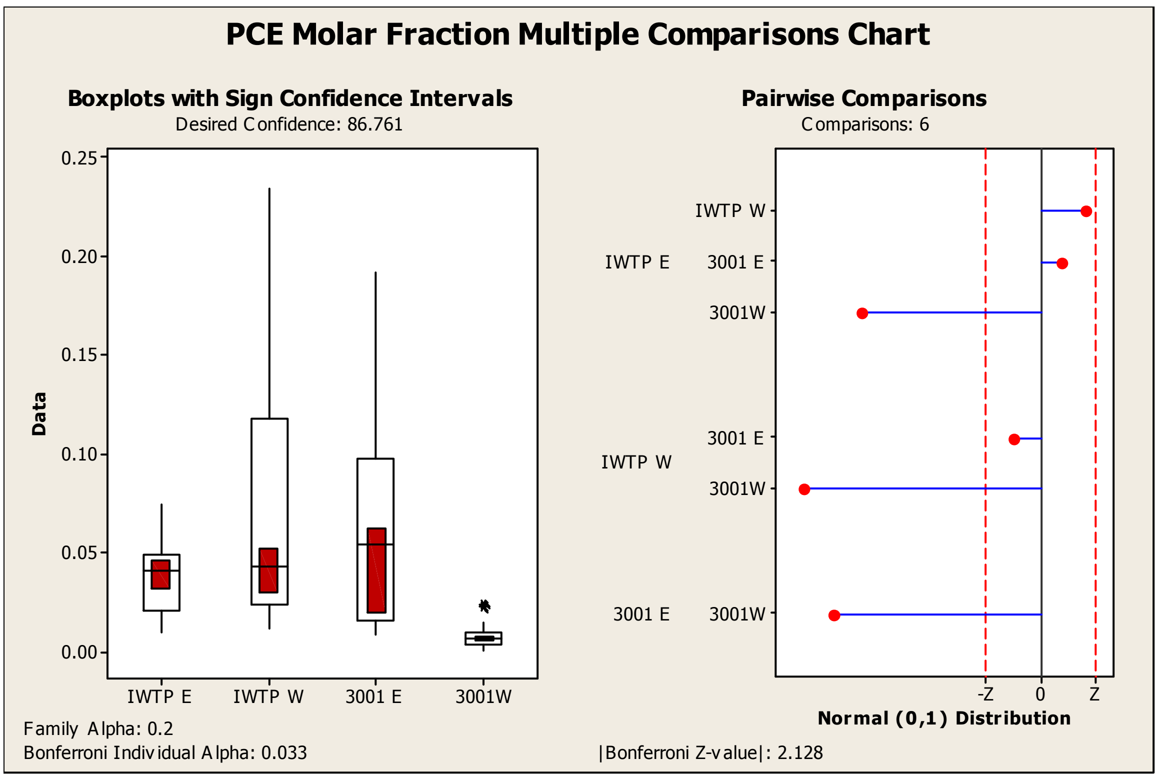


Figure 24 is a Kruskal-Wallis multiple comparisons chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each location. The pairwise comparisons chart shows whether individual comparisons between locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those two locations were significantly different. The location on the left was compared to each of the locations to its right. Table 15 lists each of locations that were found to be statistically different from each other.

Table 15: Comparisons for PCE Molar Fractions

Groups	Z-value vs. Critical value	P-value
IWTP W vs. 3001W	9.25095 >= 2.128	0
3001 E vs. 3001W	8.07994 >= 2.128	0
IWTP E vs. 3001W	6.95828 >= 2.128	0

The Kruskal-Wallis test showed statistical differences between the B3001 W location and all other three other locations. Conflicting with the results from the ANOVA, the IWTP E and IWTP W groups were not significantly different. These results do not indicate that the IWTP plume and B3001 plume are from separate sources with respect to PCE contamination.

3.5.2.3 ANOVA Performed on Building 3001 Versus IWTP for PCE Molar Fraction Data

An ANOVA was performed for all IWTP wells versus all B3001 wells to determine if there were significant differences between the two plumes. The p-value of 0.001 shows that the two plumes were statistically different. This indicates that the IWTP plume and B3001 plume are the result of different sources.

Source	DF	SS	MS	F	P
Factor	1	0.02626	0.02626	10.75	0.001
Error	210	0.51281	0.00244		
Total	211	0.53906			

S = 0.04942   R-Sq = 4.87%   R-Sq(adj) = 4.42%

```
                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level    N     Mean    StDev   --------+---------+---------+---------+-
IWTP   110  0.05824  0.05466                     (-------*------)
3001   102  0.03597  0.04304   (-------*-------)
                               --------+---------+---------+---------+-
                                     0.036     0.048     0.060     0.072
```

Pooled StDev = 0.04942

With a p-value of 0.001, there were significant differences between the IWTP plume and the B3001 plume. Note that the PCE concentrations did not show any significant differences between the two plumes. The percentage of PCE in relation to other chlorinated solvents, however, does indicate a significant difference between IWTP and B3001.

3.5.2.4 Mann-Whitney Performed on Building 3001 Versus IWTP for PCE Molar Fraction Data

The Mann-Whitney procedure was also applied to the PCE molar fraction data derived from the IWTP and B3001 monitoring wells to determine if there were statistical differences between IWTP and B3001. Since the test was significant at 0.0000, the results showed that the IWTP plume and the B3001 plume were statistically different. These results indicate that the IWTP plume and B3001 plume are from separate sources.

```
        N  Median
IWTP  110    94.5
3001  102  1100.0

Point estimate for ETA1-ETA2 is -868.2
95.0 Percent CI for ETA1-ETA2 is (-1083.9,-710.0)
W = 7099.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000
The test is significant at 0.0000 (adjusted for ties)
```

With a p-value of 0.0000, the Mann-Whitney test showed a significant difference between the IWTP plume and the B3001 plume. These results indicate that the IWTP plume and the B3001 plume are from separate sources.

3.5.2.5 Correlation Coefficients for PCE Molar Fraction as a Function of Distance from IWTP

Table 16 shows the correlation coefficient relating the change in molar fraction of PCE as a function of increasing distance to IWTP. The PCE molar fraction showed a negative trend with a value of -0.473. From this it can be seen that the PCE molar fraction showed a correlation between the decrease in the molar fraction of PCE with increasing distance from IWTP. This is an indication that there is a difference between the molar fraction of PCE at the IWTP site and the B3001 site. These results suggest that IWTP is the source of PCE contamination.

Table 16: Correlation Coefficient for PCE Molar Fractions

Well	Distance (ft)	Fraction of PCE	Correlation Coefficient
1*51	188	0.0471	-0.473
1*49	312	0.0479	
1*50	438	0.0189	
1*11	625	0.1650	
19	875	0.0267	
1*1	1063	0.1102	
1*15	1375	0.0469	
35	1407	0.0659	
34	1625	0.0150	
1*70	2188	0.0063	
1*8	2313	0.0115	
1*69	2781	0.0018	

3.5.3 Results for TCE Molar Fraction Data

The mean of the molar fraction of TCE in the IWTP well groups was less than 25% of the total moles of chlorinated solvents, whereas the mean for the B3001 well groups was about 88% of the total moles of chlorinated solvents. In general, the IWTP locations and the B3001 locations were not internally different, but did display statistically significant difference when compared to each other. The results of the TCE molar fraction data were an indication that the IWTP plume and the B3001 plume are from separate sources.

3.5.3.1 ANOVA Performed on TCE Molar Fraction Data

The output of an ANOVA test performed on the four well groups with respect to TCE molar fractions is shown below. The p-value of 0.000 showed that there was at least one location that was statistically different from another location. Comparisons were made between each of the well groups to find which groups were significantly different.

Source	DF	SS	MS	F	P
Factor	3	23.30423	7.76808	888.93	0.000
Error	208	1.81765	0.00874		
Total	211	25.12188			

S = 0.09348   R-Sq = 92.76%   R-Sq(adj) = 92.66%

```
                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level     N    Mean    StDev  --+---------+---------+---------+-------
IWTP E   46  0.18038  0.06503  (*)
IWTP W   64  0.24423  0.11096     (*)
3001 E   57  0.87685  0.08785                                   (*)
3001 W   45  0.88293  0.09765                                   (*-)
                              --+---------+---------+---------+-------
                              0.20      0.40      0.60      0.80

Pooled StDev = 0.09348


Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons

Individual confidence level = 98.97%


IWTP E subtracted from:

          Lower   Center    Upper  -------+---------+---------+---------+--
IWTP W  0.01708  0.06384  0.11061                  (-*)
3001 E  0.64852  0.69647  0.74442                                 (*-)
3001 W  0.65182  0.70254  0.75327                                 (-*)
                                   -------+---------+---------+---------+--
                                       -0.40      0.00      0.40      0.80
```

```
IWTP W subtracted from:

          Lower   Center    Upper  -------+---------+---------+---------+--
3001 E  0.58857  0.63263  0.67669                                 (*)
3001 W  0.59163  0.63870  0.68577                                 (*)
                                   -------+---------+---------+---------+--
                                        -0.40      0.00      0.40      0.80


3001 E subtracted from:

          Lower   Center    Upper  -------+---------+---------+---------+--
3001 W -0.04217  0.00607  0.05432                 (*)
                                   -------+---------+---------+---------+--
                                        -0.40      0.00      0.40      0.80
```

The ANOVA shows that the B3001 wells groups had significantly higher molar fractions of TCE as compared to the IWTP well groups. Using the Tukey comparisons method, there was no significant difference within the B3001 locations. The IWTP E and IWTP W groups were significantly different. However, the difference in means between the two groups was only 0.017. The difference in means between IWTP E and both of the B3001 groups was about 0.65. Therefore, although the IWTP groups were significantly different, the ANOVA does show similarities between the two groups as compared to the B3001 groups. These results are an indication that the IWTP plume and the B3001 plume are from separate sources.

3.5.3.2 Kruskal-Wallis Performed on TCE Molar Fraction Data

The Kruskal-Wallis method of analysis was performed on all four well groups, with comparisons, for TCE molar fraction data. Table 17 lists the well groups that are significantly different. Figure 25 graphically represents the comparisons between well groups, identifying which groups are significantly different.

Kruskal-Wallis Test on the data

Group	N	Median	Ave Rank	Z
IWTP E	46	0.1492	43.1	-7.92
IWTP W	64	0.2597	64.5	-6.56
3001 E	57	0.8525	161.2	7.87
3001 W	45	0.9157	161.8	6.82
Overall	212		106.5	

H = 161.06 DF = 3 P = 0.000

From the data output above, the p-value of 0.000 indicates that there was at least one location that was significantly different from another location. Figure 25 shows the output of the multiple comparisons method for determining which locations were significantly different. The locations that were statistically different are listed in Table 17.

Figure 25: Multiple Comparisons for TCE Molar Fractions

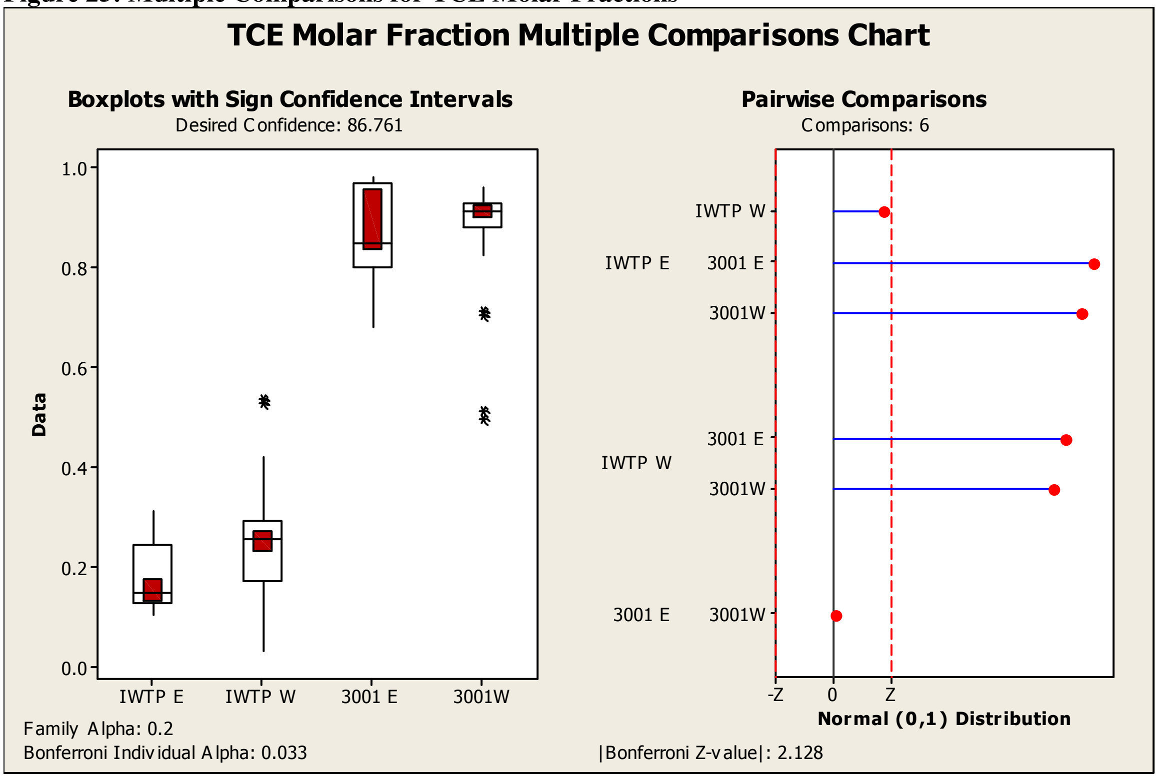


Figure 25 is a Kruskal-Wallis multiple comparisons chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each location. The pairwise comparisons chart shows whether individual comparisons between locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those two locations were significantly different. The location on the left was compared to each of the locations to its right. Table 17 lists each of locations that were found to be statistically different from each other.

Table 17: Comparisons for TCE Molar Fractions

Groups	Z-value vs. Critical value	P-value
IWTP E vs. 3001 E	9.71122 >= 2.128	0
IWTP E vs. 3001 W	9.23333 >= 2.128	0
IWTP W vs. 3001 E	8.65317 >= 2.128	0
IWTP W vs. 3001 W	8.15825 >= 2.128	0

The results from the Kruskal-Wallis test were similar to those from the ANOVA test with the exception that the IWTP well groups were not significantly different. All other results agree with the results from the ANOVA. From the boxplot and pairwise comparisons, the difference between the IWTP locations and the B3001 locations suggests that the IWTP plume and the B3001 plume are from separate sources.

3.5.3.3 ANOVA Performed on Building 3001 Versus IWTP for TCE Molar Fraction Data

An ANOVA was performed for all IWTP well versus all B3001 wells to determine if there were significant differences between the two plumes. The p-value of 0.000 shows that the two plumes were statistically different. This indicates that the IWTP plume and B3001 plume are the result of different sources.

```
Source    DF         SS         MS         F      P
Factor     1  23.19421  23.19421  2526.78  0.000
Error    210   1.92767   0.00918
Total    211  25.12188

S = 0.09581   R-Sq = 92.33%   R-Sq(adj) = 92.29%

                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level     N      Mean     StDev    +---------+---------+---------+---------
IWTP   110  0.21753  0.09931    (*)
3001   102  0.87953  0.09188                                   (*)
                                   +---------+---------+---------+---------
                                 0.20      0.40      0.60      0.80

Pooled StDev = 0.09581
```

An ANOVA performed on IWTP and B3001 showed that there was a significant difference between the two plumes with respect to TCE molar fractions. With a p-value of 0.000, the B3001 plume had a significantly higher molar fraction of TCE. These results suggest that the IWTP plume and the B3001 plume are from separate sources.

3.5.3.4 Mann-Whitney Performed on Building 3001 Versus IWTP for TCE Molar Fraction Data

The Mann-Whitney procedure was also applied to the IWTP group and the B3001 group to determine if there are statistical differences between IWTP and B3001. Since the test was significant at 0.0000, the results indicate that the IWTP plume and the B3001 plume are from separate sources.

```
        N   Median
IWTP  110  0.22678
3001  102  0.90245



Point estimate for ETA1-ETA2 is -0.67362
95.0 Percent CI for ETA1-ETA2 is (-0.69509,-0.64993)
W = 6109.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000
```

The results from the Mann-Whitney test agreed with those from the ANOVA which showed a significant difference between the IWTP plume and the B3001 plume. These results indicate that the IWTP plume and the B3001 plume are from separate sources.

3.5.3.5 Correlation Coefficients for TCE Molar Fraction as a Function of Distance from IWTP

Table 18 shows the correlation coefficient relating the change in molar fraction of TCE as a function of increasing distance to IWTP. The TCE molar fraction coefficient of 0.840 showed a strong correlation between increasing TCE molar fraction and increasing distance from IWTP. This verifies the statistical testing performed on TCE molar fraction data and indicates a significant difference between the molar fraction of TCE at the IWTP site and the B3001 site.

Table 18: Correlation Coefficient for TCE Molar Fractions

Well	Distance (ft)	Fraction of TCE	Correlation Coefficient
1*51	188	0.1252	0.840
1*49	312	0.2665	
1*50	438	0.1514	
1*11	625	0.2273	
19	875	0.1978	
1*1	1063	0.7908	
1*15	1375	0.3397	
35	1407	0.8284	
34	1625	0.9717	
1*70	2188	0.8179	
1*8	2313	0.8995	
1*69	2781	0.9355	

3.5.4 Results for DCE Molar Fraction Data

Although the conclusion is the same, the results of testing DCE molar fraction data appear to be the opposite of the results obtained from testing TCE molar fraction data. The IWTP locations had elevated molar fractions of DCE while the B3001 locations had comparably low molar fractions of DCE. The results of these test suggests that the IWTP plume and the B3001 plume are from separate sources.

3.5.4.1 ANOVA Performed on DCE Molar Fraction Data

The output of an ANOVA test performed on the four well groups with respect to DCE molar fractions is shown below. The p-value of 0.000 showed that at least one location was statistically different from another location. Comparisons were made between each of the well groups to find which groups were significantly different.

```
Source   DF       SS      MS       F      P
Factor    3  11.9693  3.9898  361.09  0.000
Error   208   2.2983  0.0110
Total   211  14.2675

S = 0.1051   R-Sq = 83.89%   R-Sq(adj) = 83.66%


                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level    N    Mean   StDev  --------+---------+---------+---------+-
IWTP E  46  0.5587  0.0665                                (-*-)
IWTP W  64  0.5506  0.1661                                (-*)
3001 E  57  0.0635  0.0466  (-*-)
3001 W  45  0.0988  0.0739     (-*-)
                            --------+---------+---------+---------+-
                                 0.15      0.30      0.45      0.60
Pooled StDev = 0.1051
```

```
Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons

Individual confidence level = 98.97%


IWTP E subtracted from:

          Lower   Center    Upper  --------+---------+---------+---------+-
IWTP W  -0.0607  -0.0081   0.0445                  (-*)
3001 E  -0.5491  -0.4951  -0.4412  (*-)
3001 W  -0.5169  -0.4599  -0.4029   (-*-)
                                   --------+---------+---------+---------+-
                                        -0.30      0.00      0.30      0.60


IWTP W subtracted from:

          Lower   Center    Upper  --------+---------+---------+---------+-
3001 E  -0.5366  -0.4871  -0.4375  (-*)
3001 W  -0.5048  -0.4518  -0.3989   (-*-)
                                   --------+---------+---------+---------+-
                                        -0.30      0.00      0.30      0.60
```

```
3001 E subtracted from:

         Lower  Center   Upper  --------+---------+---------+---------+-
3001 W  -0.0190  0.0352  0.0895                  (-*-)
                                --------+---------+---------+---------+-
                                    -0.30      0.00      0.30      0.60
```

The results from the ANOVA test showed significantly higher molar fractions of DCE in the IWTP locations compared to the B3001 locations. The IWTP locations and B3001 locations were not internally different, but did showed statistically significant differences when compared to each other. These results are an indication that the IWTP plume and the B3001 plume are from separate sources.

3.5.4.2 Kruskal-Wallis Performed on DCE Molar Fraction Data

The Kruskal-Wallis method of analysis was performed on all four well groups, with comparisons, for DCE molar fraction data. Table 19 lists the well groups that were significantly different. Figure 26 graphically represents the comparisons between well groups, identifying which groups were significantly different.

```
Kruskal-Wallis Test on the data

Group       N   Median  Ave Rank      Z
IWTP E     46  0.56483     161.5   6.87
IWTP W     64  0.49128     154.3   7.46
3001 E     57  0.08153      47.4  -8.51
3001 W     45  0.07569      57.2  -6.07
Overall   212              106.5

H = 157.86  DF = 3  P = 0.000
```

From the data output above, the p-value of 0.000 indicates that there was at least one location that was significantly different from another location. Figure 26 shows the output of the multiple comparisons method for determining which locations were significantly different. The locations that were statistically different are listed in Table 19.

Figure 26: Multiple Comparisons for DCE Molar Fractions

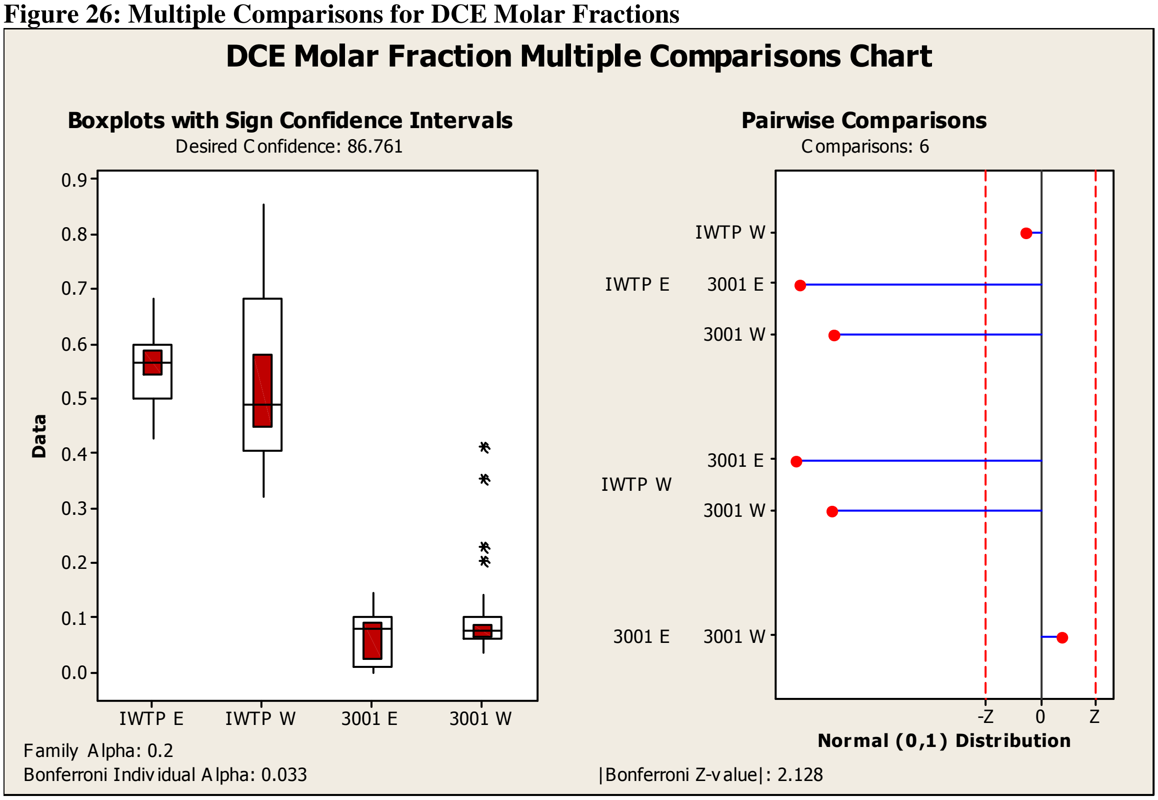


Figure 26 is a Kruskal-Wallis multiple comparisons chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each location. The pairwise comparisons chart shows whether individual comparisons between locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those locations were significantly different. The location on the left is compared to each of the locations to its right. Table 19 lists each of locations that were found to be statistically different from each other.

Table 19: Comparisons for DCE Molar Fractions

Groups	Z-value vs. Critical value	P-value
IWTP W vs. 3001 E	9.57405 >= 2.128	0
IWTP E vs. 3001 E	9.38686 >= 2.128	0
IWTP W vs. 3001 W	8.13564 >= 2.128	0
IWTP E vs. 3001 W	8.10585 >= 2.128	0

The results from the Kruskal-Wallis analysis were similar to those from the ANOVA test. The IWTP locations were internally similar and the B3001 locations were internally similar. The only significant differences were from comparing the IWTP locations to the B3001 locations. This is an indication that the IWTP plume and the B3001 plume are from separate sources.

3.5.4.3 ANOVA Performed on Building 3001 Versus IWTP for DCE Molar Fraction Data

An ANOVA was performed for all IWTP wells versus all B3001 wells to determine if there were significant differences between the two plumes. The p-value of 0.000 showed a statistical difference between the IWTP plume and the B3001 plume. This is an indication that the IWTP plume and the B3001 plume are from separates sources.

Source	DF	SS	MS	F	P
Factor	1	11.9363	11.9363	1075.23	0.000
Error	210	2.3312	0.0111		
Total	211	14.2675			

S = 0.1054   R-Sq = 83.66%   R-Sq(adj) = 83.58%

```
                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level    N    Mean   StDev  ------+---------+---------+---------+---
IWTP   110  0.5540  0.1334                                (*)
3001   102  0.0791  0.0624  (*-)
                            ------+---------+---------+---------+---
                                0.15      0.30      0.45      0.60
```

The results from the ANOVA show a significantly higher molar fraction of DCE within the IWTP plume compared to the B3001 plume. This was significant with a p-value of 0.0000. These results indicate that the IWTP plume and the B3001 plume are from separate sources.

3.5.4.4 Mann-Whitney Performed on Building 3001 Versus IWTP for DCE Molar Fraction Data

The Mann-Whitney procedure was also applied to the IWTP group and the B3001 group to determine if there were statistical differences between IWTP and B3001. The p-value of 0.0000 showed that the IWTP plume and the B3001 plume were statistically different. This is an indication that the IWTP plume and the B3001 plume are from separate sources.

	N	Median
IWTP	110	0.54686
3001	102	0.07887

```
Point estimate for ETA1-ETA2 is 0.47094
95.0 Percent CI for ETA1-ETA2 is (0.43769,0.49884)
W = 17304.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000
```

With a p-value of 0.000, the results from the Mann-Whitney analysis agreed with the results from the ANOVA, which showed that the IWTP plume and the B3001 plume were statistically different. This is an indication that the IWTP plume and the B3001 plume are from separate sources.

3.5.4.5 Correlation Coefficients for DCE Molar Fraction as a Function of Distance from IWTP

Table 20 shows the correlation coefficient relating the change in molar fraction of DCE as a function of increasing distance to IWTP. The DCE molar fraction correlation coefficient showed a strong correlation between decreasing DCE molar fraction and increasing distance from IWTP. This verifies the statistical testing performed on DCE molar fraction data. The negative correlation coefficient suggests that the IWTP is the source of the DCE contamination. The correlation coefficient is an indication that there is a significant difference between the IWTP site and the B3001 site and suggests that the IWTP plume and the B3001 plume are from separate sources.

Table 20: Correlation Coefficient for DCE Molar Fractions

Well	Distance (ft)	Fraction of DCE	Correlation Coefficient
1*51	188	0.6076	-0.779
1*49	312	0.5840	
1*50	438	0.4890	
1*11	625	0.4387	
19	875	0.7155	
1*1	1063	0.0965	
1*15	1375	0.4042	
35	1407	0.1051	
34	1625	0.0128	
1*70	2188	0.1421	
1*8	2313	0.0888	
1*69	2781	0.0618	

3.5.5 Results for VC Molar Fraction Data

The results from of testing VC molar fraction data showed an elevated VC fraction of at the IWTP E group, with decreasing molar fractions of VC as the distance from IWTP increases. Since contamination from IWTP would likely have undergone at least some level of reductive dechlorination, the elevated molar fraction of VC at IWTP E is an indication that IWTP is a source of contamination, separate from B3001. VC contamination as well as molar fractions can be considered a "tracer" for contamination from the IWTP. This is further supported by the results of the redox analyses which showed no significant difference in reductive dechlorination potential at these monitored locations. Since there was no significant difference in redox potential, there is no statistical basis to believe that differences in VC concentrations or molar fractions would be the result of difference in geological environments.

3.5.5.1 ANOVA Performed on VC Molar Fraction Data

The output of an ANOVA test performed on the four well groups with respect to VC molar fractions is shown below. The p-value of 0.000 showed that at least one location was statistically different from another location. Comparisons were made between each of the well groups to determine which groups were significantly different.

Source	DF	SS	MS	F	P
Factor	3	1.66327	0.55442	114.39	0.000
Error	208	1.00811	0.00485		
Total	211	2.67138			

S = 0.06962   R-Sq = 62.26%   R-Sq(adj) = 61.72%

```
                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level    N     Mean    StDev  --+---------+---------+---------+-------
IWTP E  46  0.22337  0.11052                                (--*--)
IWTP W  64  0.13207  0.08233                   (--*-)
3001 E  45  0.01082  0.02665   (--*-)
3001 W  57  0.00116  0.00184  (-*--)
                              --+---------+---------+---------+-------
                              0.000     0.070     0.140     0.210

Pooled StDev = 0.06962


Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons

Individual confidence level = 98.97%
```

```
IWTP E subtracted from:

          Lower    Center     Upper
IWTP W  -0.12612  -0.09130  -0.05647
3001 E  -0.25032  -0.21254  -0.17477
3001 W  -0.25792  -0.22221  -0.18650

          -+---------+---------+---------+--------
IWTP W             (--*--)
3001 E    (--*--)
3001 W    (-*--)
          -+---------+---------+---------+--------
        -0.24     -0.12      0.00      0.12


IWTP W subtracted from:

          Lower    Center     Upper
3001 E  -0.15630  -0.12125  -0.08619
3001 W  -0.16373  -0.13091  -0.09810

          -+---------+---------+---------+--------
3001 E           (--*--)
3001 W          (--*--)
          -+---------+---------+---------+--------
        -0.24     -0.12      0.00      0.12
```

```
3001 E subtracted from:

          Lower     Center     Upper     -+---------+---------+---------+-----
3001 W  -0.04560  -0.00967  0.02626                   (--*--)
                                         -+---------+---------+---------+-----
                                       -0.24     -0.12      0.00      0.12
```

The results from the ANOVA test showed the highest molar fraction of VC at the IWTP E well group. With a difference in means of -0.091, the IWTP W location was significantly lower than IWTP E. However, the IWTP W location was significantly higher than the B3001 E location and the B3001 W location by a difference in means of -0.121 and -0.131, respectively. Comparison testing shows that there was no significant difference between the B3001 locations B3001 E and B3001 W, both of which had a mean VC fraction of about 0% to 1%. From these results, it is reasonable to assume that contamination was released from the IWTP area after receiving some level of reductive dechlorination. These results suggest that the IWTP plume and the B3001 plume are from separate sources.

3.5.5.2 Kruskal-Wallis Performed on VC Molar Fraction Data

The Kruskal-Wallis method of analysis was performed on all four well groups, with comparisons, for VC molar fraction data. Table 21 lists the well groups that were significantly different. Figure 27 graphically represents the comparisons between well groups, identifying which groups were significantly different.

Kruskal-Wallis Test on the data

Group	N	Median	Ave Rank	Z
IWTP E	46	0.220793765	171.8	8.17
IWTP W	64	0.136088680	145.1	6.02
3001 E	45	0.000494434	59.5	-5.79
3001 W	57	0.000000000	47.5	-8.49
Overall	212		106.5	

H = 156.62 DF = 3 P = 0.000

H = 158.46 DF = 3 P = 0.000 (adjusted for ties)

From the data output above, the p-value of 0.000 indicates that there was at least one location that was significantly different from another location. Figure 27 shows the output of the multiple comparisons method for determining which locations were significantly different. The locations that were statistically different are listed in Table 21.

Figure 27: Multiple Comparisons for VC Molar Fractions

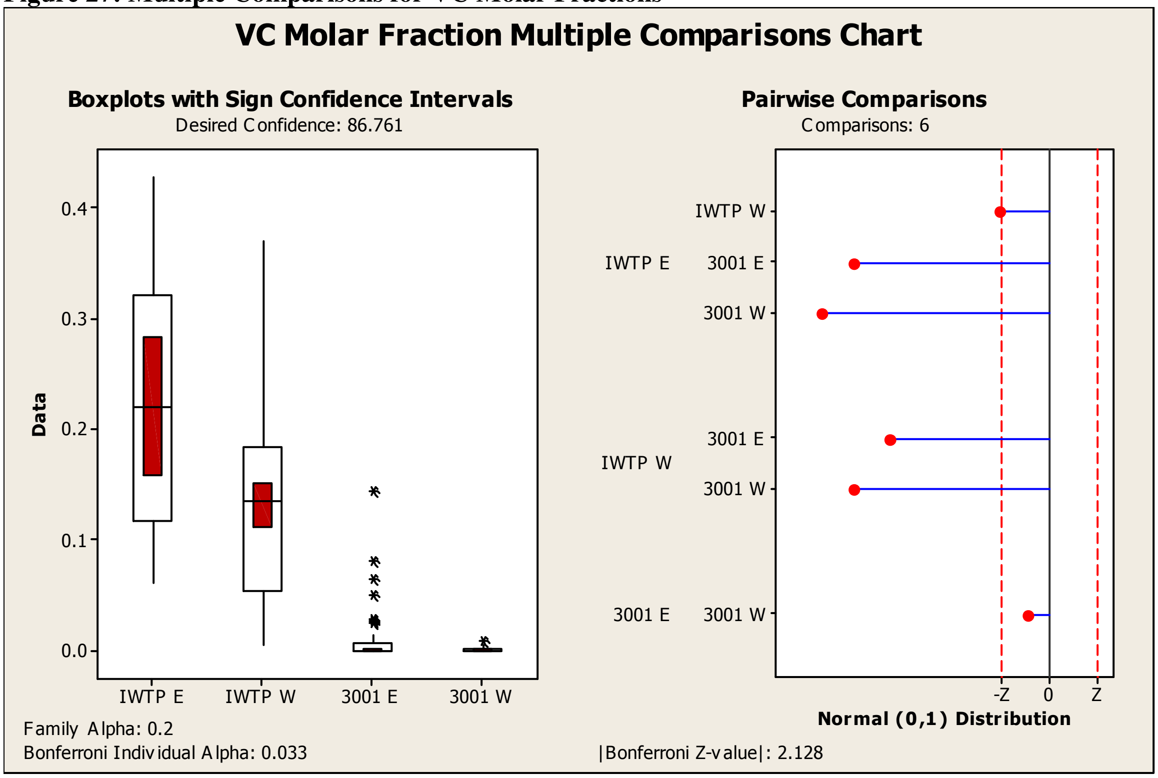


Figure 27 is a Kruskal-Wallis multiple comparisons chart. This chart contains both a boxplot for each location, and a pairwise comparisons chart. The boxplot shows the confidence interval for each location. The pairwise comparisons chart shows whether individual comparisons between locations were significantly different. If the horizontal blue line extends past the vertical red, dotted line, then those two locations were significantly different. The location on the left is compared to each of the locations to its right. Table 21 lists each of locations that were found to be statistically different from each other.

Table 21: Comparisons for VC Molar Fractions

Groups	Z-value vs. Critical value	P-value
IWTP E vs. 3001 W	10.2852 >= 2.128	0.0000
IWTP E vs. 3001 E	8.7852 >= 2.128	0.0000
IWTP W vs. 3001 W	8.7843 >= 2.128	0.0000
IWTP W vs. 3001 E	7.2133 >= 2.128	0.0000
IWTP E vs. IWTP W	2.2695 >= 2.128	0.0232

The Kruskal-Wallis test showed the highest molar fraction of VC at the IWTP E location, with decreasing molar fractions with increasing distance from the IWTP. The multiple comparisons test showed that the only well groups that were not significantly different were the B3001 E and B3001 W groups.

3.5.5.3 ANOVA Performed on Building 3001 Versus IWTP for VC Molar Fraction Data

An ANOVA was performed for the IWTP location versus the B3001 location to determine if there were significant differences between the two plumes. The p-value of 0.000 showed that the IWTP plume and B3001 plume were statistically different. These results suggest that the IWTP plume and the B3001 plume are from separate sources.

```
Source    DF        SS        MS       F      P
Factor     1   1.43784   1.43784  244.78  0.000
Error    210   1.23354   0.00587
Total    211   2.67138

S = 0.07664   R-Sq = 53.82%   R-Sq(adj) = 53.60%


                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level     N      Mean     StDev  --+---------+---------+---------+-------
IWTP   110   0.17025   0.10491                                  (--*--)
3001   102   0.00542   0.01829  (--*--)
                                 --+---------+---------+---------+-------
                                 0.000     0.050     0.100     0.150

Pooled StDev = 0.07664
```

With a p-value of 0.000, the ANOVA showed that the IWTP plume had a significantly higher molar fraction of VC than B3001. This suggests that the IWTP plume and B3001 plume are from separate sources. Furthermore, the mean of the molar fractions at the IWTP, 0.170, compared to the mean of the molar fractions at the B3001 location, 0.005, suggests that the IWTP is the source of the VC contamination.

3.5.5.4 Mann-Whitney Performed on Building 3001 Versus IWTP for VC Molar Fraction Data

The Mann-Whitney procedure was also applied to the IWTP location and the B3001 location to determine if there were statistical differences between the IWTP plume and the B3001 plume. The p-value of 0.0000 showed that the IWTP plume and the B3001 plume were statistically different. This result indicates that the IWTP plume and the B3001 plume are from separate sources.

```
        N   Median
IWTP  110  0.15081
3001  102  0.00041



Point estimate for ETA1-ETA2 is 0.14758
95.0 Percent CI for ETA1-ETA2 is (0.12829,0.16385)
W = 17191.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000
The test is significant at 0.0000 (adjusted for ties)
```

The Mann-Whitney test shows a significant difference between the IWTP plume and the B3001 plume with a p-value of 0.000. This result indicates that the IWTP plume and the B3001 plume are from separate sources.

3.5.5.6 Correlation Coefficients for VC Molar Fraction as a Function of Distance from IWTP

Table 22 shows the correlation coefficient relating the change in molar fraction of VC as a function of increasing distance to IWTP. The VC molar fraction data also showed a strong correlation between decreasing molar fraction of VC with respect to distance from IWTP. This verifies the statistical testing performed on VC molar fraction data, and is an indication that there is a significant difference between the IWTP site and the B3001 site.

Table 22: Correlation Coefficient for VC Molar Fraction

Well	Distance (ft)	Fraction of VC	Correlation Coefficient
1*51	188	0.2201	-0.655
1*49	312	0.1016	
1*50	438	0.3406	
1*11	625	0.1691	
19	875	0.0601	
1*1	1063	0.0024	
1*15	1375	0.2093	
35	1407	0.0005	
34	1625	0.0006	
1*70	2188	0.0338	
1*8	2313	0.0002	
1*69	2781	0.0009	

3.6 Results for Artificial Neural Network Modeling

Three neural network models were developed from the data inputs listed in Table 23 found below. These were well location, distance to source, concentration data, and molar fraction data. One model used all available data inputs, one model used only concentration data, and one model used only molar fraction data. The concentration-only and molar-fraction-only models were used to determine if a pattern between wells and source would result, independent of well location. This pattern could then be employed to identify a source or sources for the respective concentrations. In addition to the output data, the parameters used to run the network are also listed. The network parameters used for these models were generally the default parameters presented with the artificial neural network code.

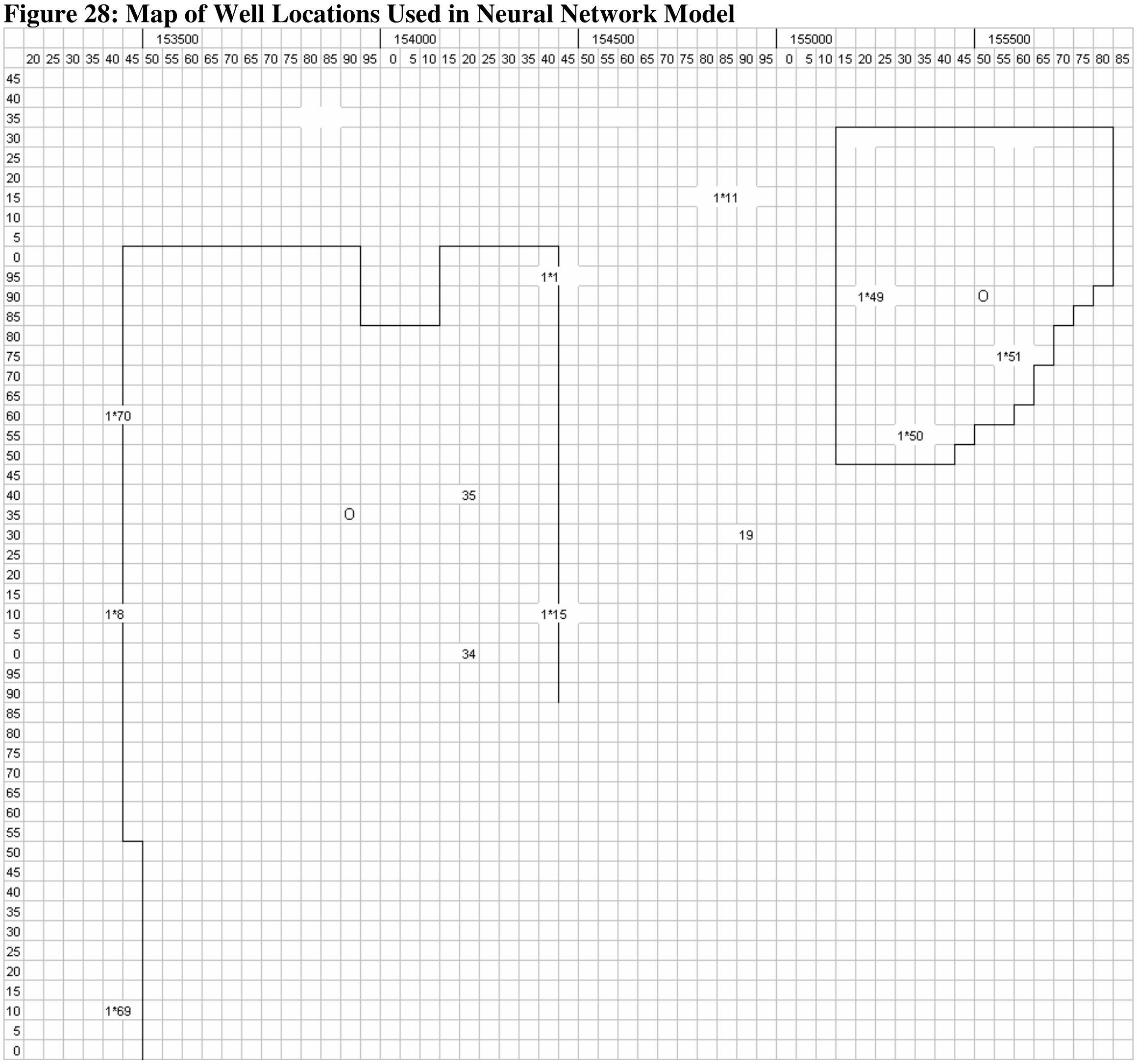
3.6.1 Neural Network Inputs

Table 23 shows all of the neural network inputs that were available for use in the neural network models. The location data were determined using Figure 28 found below. Each location is the number of 50 foot increments south and east of the reference point, which is the top left corner of the figure. The circles on the figure mark the location of the IWTP and Building 3001 reference points. The numbers across the top and along the left side correspond to NAD coordinates used at Tinker AFB. The circles on the figure mark the location of the IWTP and Building 3001 reference points. The inputs for the sources, the IWTP and B3001 concentration and molar fraction data, were determined using the concentration contour maps provided by Tinker. PCE was not used in this model because there were no PCE concentration contours in the LSZ (see Figures 9 through 12).

Table 23: Data Inputs for Neural Network Model

Location	N-S	E-W	Distance to IWTP	Distance to B3001	TCE	DCE	VC	MF TCE	MF DCE	MF VC
IWTP	14	47	0.00	31.32	100	300	70	15	62	22
3001	23	17	31.32	0.00	1000	10	0	99	1	0
1*50	19	45	23.19	25.08	134	340	161	15	49	34
19	24	36	14.14	14.87	794	2691	169	20	71	6
1*15	21	27	5.10	9.43	173	159	66	34	40	21
1*49	11	44	24.60	28.43	35	57	6	27	58	10
1*51	15	51	29.83	32.20	49	178	43	13	61	22
1*11	7	37	21.21	26.63	65	85	21	23	44	17
1*70	18	5	17.46	20.25	1326	148	21	82	14	3
1*8	28	4	18.97	18.03	2917	208	0	90	9	0
1*69	48	5	31.06	25.50	755	36	0	94	6	0
1*1	11	27	12.08	18.68	332	28	0	79	10	0
35	22	22	0.00	7.00	1942	190	1	83	11	0
34	29	22	7.00	0.00	1035	10	0	97	1	0

Figure 28: Map of Well Locations Used in Neural Network Model



3.6.2 Neural Network Model Developed Using All Inputs

A neural network model was developed using all available input data as listed in Table 23. The network consists of a ten neuron input layer, a two neuron hidden layer, and a two neuron output layer. Table 24 shows the network parameters used in Neuralyst to develop the neural network using all available inputs. Table 25 shows the output generated from the neural network.

Table 24: Parameters used in Neural Network Model with All Input Variables

Network Run Statistics	
0.078841	RMS Error
4	Number of Data Items
4	Number Right
0	Number Wrong
100%	Percent Right
0%	Percent Wrong
100	Training Epochs
Network Parameters	
1	Learning rate
0.9	Momentum
0	Input Noise
0.1	Training Tolerance
0.3	Testing Tolerance
20	Epochs per Update
0	Epoch Limit
0	Time Limit (Hrs)
0	Error Limit (Increase)

Table 25: Output From Neural Network Model with All Input Variables

Input												Target		Output	
Location	N-S	E-W	Distance to IWTP	Distance to B3001	TCE	DCE	VC	MF TCE	MF DCE	MF VC	MF	IWTP	B3001	IWTP	B3001
IWTP	14	47	0.00	31.32	100	300	70	15	62	22	Train	1	0	0.896	0.107
3001	23	17	31.32	0.00	1000	10	0	99	1	0	Train	0	1	0.103	0.894
1*50	19	45	23.19	25.08	134	340	161	15	49	34	Test			0.902	0.099
19	24	36	14.14	14.87	794	2691	169	20	71	6	Test			0.863	0.135
1*15	21	27	5.10	9.43	173	159	66	34	40	21	Test			0.719	0.269
1*49	11	44	24.60	28.43	35	57	6	27	58	10	Test			0.843	0.163
1*51	15	51	29.83	32.20	49	178	43	13	61	22	Test			0.899	0.104
1*11	7	37	21.21	26.63	65	85	21	23	44	17	Test			0.838	0.167
1*70	18	5	17.46	20.25	1326	148	21	82	14	3	Test			0.187	0.813
1*8	28	4	18.97	18.03	2917	208	0	90	9	0	Test			0.097	0.901
1*69	48	5	31.06	25.50	755	36	0	94	6	0	Test			0.154	0.841
1*1	11	27	12.08	18.68	332	28	0	79	10	0	Test			0.25	0.757
35	22	22	0.00	7.00	1942	190	1	83	11	0	Test			0.115	0.88
34	29	22	7.00	0.00	1035	10	0	97	1	0	Test			0.101	0.895

Pattern recognition was computed using a neural network and all ten input parameters for the twelve LSZ well locations versus the ten input parameters for the IWTP plume and the B3001 plume. Training was performed using input data for the sources to train the data against the target numbers zero and one. During training the weights of each input variable were adjusted by Neuralyst to better represent the relationship between the input variables and the sources. Once training was complete, the input data of each individual well was tested by Neuralyst and given a value between zero and one to represent each well's association to the IWTP and/or B3001. Values close to one represent a strong association between a given well and source while values close to zero represent little or no association between a given well and source. The results showed a strong association between IWTP wells and the IWTP plume with association coefficients between 0.719 and 0.902. Conversely, there was very little association between the IWTP wells and the

B3001 plume, with association coefficients between 0.099 and 0.269. Similarly, there was a strong association between the B3001 wells and the B3001 plume, with association coefficients between 0.757 and 0.901. There was very little association between B3001 wells and the IWTP plume, with association coefficients between 0.097 and 0.250. These results show that there are strong associations between the IWTP wells and the IWTP plume, as well as strong associations between the B3001 wells and the B3001 plume. Additionally, these results show that there is very little association between the IWTP wells and the B3001 plume, as well as very little association between the B3001 wells and the IWTP plume. Summarizing, this analysis suggests that there are two separate plumes with two separate sources, one from B3001 and one from IWTP.

3.6.3 Neural Network Model Developed Using Concentration Data

Table 26 shows the network parameters used in Neuralyst to develop the neural network using only concentration data. The neural network model consisted of a three neuron input layer, a two neuron hidden layer, and a two neuron output layer. Table 27 shows the output generated from the neural network.

Table 26: Parameters Used in Neural Network Model Using Concentration Inputs

Network Run Statistics

0.088921	RMS Error
4	Number of Data Items
4	Number Right
0	Number Wrong
100%	Percent Right
0%	Percent Wrong
323	Training Epochs

Network Parameters

1	Learning rate
0.9	Momentum
0	Input Noise
0.1	Training Tolerance
0.3	Testing Tolerance
1	Epochs per Update
0	Epoch Limit
0	Time Limit (Hrs)
0	Error Limit (Increase)

Table 27: Output from Neural Network Model Using Concentration Inputs

Input					Target		Output	
Location	TCE	DCE	VC	MF	IWTP	B3001	IWTP	B3001
IWTP	100	300	70	Train	1	0	0.893	0.109
3001	1000	10	0	Train	0	1	0.085	0.913
1*50	134	340	161	Test			0.976	0.026
19	794	2691	169	Test			0.975	0.027
1*15	173	159	66	Test			0.867	0.136
1*49	35	57	6	Test			0.425	0.574
1*51	49	178	43	Test			0.781	0.221
1*11	65	85	21	Test			0.58	0.421
1*70	1326	148	21	Test			0.122	0.876
1*8	2917	208	0	Test			-0.01	1.011
1*69	755	36	0	Test			0.128	0.869
1*1	332	28	0	Test			0.243	0.755
35	1942	190	1	Test			0.012	0.987
34	1035	10	0	Test			0.08	0.918

Pattern recognition was computed using a neural network and concentration input variables for the twelve LSZ well locations versus the concentration input variables for the IWTP plume and the B3001 plume. Training was performed using input data for the sources to train the data against the target numbers zero and one. During training the weights of each input variable were adjusted by Neuralyst to better represent the relationship between the input variables and the sources. Once training was complete, the input data of each individual well was tested and given a value between zero and one to represent each wells association to the IWTP and/or B3001. Values close to one represent a strong association between a given well and source while values close to zero represent little or no association between a given well and source. In general, the results from the neural network analysis using just the concentration inputs show that there is a strong association between the IWTP wells and the IWTP plume and little association between the IWTP wells and the B3001 plume. In addition, the results show a strong association between the B3001 and the B3001 plume and little association between the B3001 wells and the IWTP plume. The exceptions are the IWTP wells 1-49 and 1-11 which show a moderate association to both the IWTP plume and the B3001 plume.

3.6.4 Neural Network Model Developed Using Molar Fraction Data

Table 28 shows the network parameters used in Neurayst to develop the neural network using only molar fraction data. The neural network consisted of a three neuron input layer, a two neuron hidden layer, and a two neuron output layer. Table 29 shows the output generated from the neural network.

Table 28: Parameters Used in Neural Network Model Using Molar Fraction Inputs

Network Run Statistics	
0.087771	RMS Error
4	Number of Data Items
4	Number Right
0	Number Wrong
100%	Percent Right
0%	Percent Wrong
183	Training Epochs
Network Parameters	
1	Learning rate
0.9	Momentum
0	Input Noise
0.1	Training Tolerance
0.3	Testing Tolerance
1	Epochs per Update
0	Epoch Limit
0	Time Limit (Hrs)
0	Error Limit (Increase)

Table 29: Output from Neural Network Model Using Molar Fractions Inputs

Input					Target		Output	
Location	MF TCE	MF DCE	MF VC	MF	IWTP	B3001	IWTP	B3001
IWTP	15	62	22	Train	1	0	0.918	0.084
3001	99	1	0	Train	0	1	0.106	0.891
1*50	15	49	34	Test			0.916	0.085
19	20	71	6	Test			0.906	0.1
1*15	34	40	21	Test			0.817	0.186
1*49	27	58	10	Test			0.873	0.133
1*51	13	61	22	Test			0.919	0.084
1*11	23	44	17	Test			0.857	0.146
1*70	82	14	3	Test			0.156	0.839
1*8	90	9	0	Test			0.124	0.872
1*69	94	6	0	Test			0.115	0.881
1*1	79	10	0	Test			0.144	0.851
35	83	11	0	Test			0.139	0.857
34	97	1	0	Test			0.107	0.889

Pattern recognition was computed using a neural network and the molar fraction input variables for the twelve LSZ well locations versus the molar fraction input variables for the IWTP plume and the B3001 plume. Training was performed using input data for the sources to train the data against the target numbers zero and one. During training the weights of each input variable were adjusted by Neuralyst to better represent the relationship between the input variables and the sources. Once training was complete, the input data of each individual well was tested by Neuralyst and given a value between zero and one to represent each wells association to the IWTP and/or B3001. Values close to one represent a strong association between a given well and source while values close to zero represent little or no association between a given well and source. The Neuralyst program recognized a pattern between the IWTP wells and the IWTP plume, but did not recognize a pattern between the IWTP wells and the B3001 plume. The analysis also shows that there is a strong association between the B3001 wells and the B3001 plume, but little association between the B3001 wells and the IWTP plume. These results suggest that based solely on the molar fractions of the chlorinated solvents there are two separate plumes with separate sources, IWTP and B3001. The results of the molar-fraction-only neural network showed stronger associations between each well and its respective source than the concentration-only neural network.

3.7 Cost Benefit Analysis

A cost benefit analysis was performed using the Racer software package. This analysis was performed to determine the cost difference of treating the IWTP plume and B3001 plume separately or treating the IWTP plume and B3001 plume as one plume.

3.7.1 Cost Analysis of the IWTP Plume

The cost analysis of individual site remediation for the IWTP plume has been performed and the results are presented in Table 30. The cost analysis showed a total remediation cost of approximately 23.3 million dollars.

Table 30: Cost Analysis of the IWTP Plume

Phase	Direct Cost	Markups	Total Cost
Remedial Action (Capital)	$3,039,949	$2,022,177	$5,062,126
Operations and Maintenance	$4,491,901	$3,069,484	$7,561,385
Long Term Monitoring	$7,004,373	$3,655,994	$10,660,367
Site Close Out	$9,959	$22,377	$32,336
Total Site Cost	$14,546,183	$8,770,030	$23,316,213

3.7.2 Cost Analysis of the B3001 Plume

The cost analysis of individual site remediation for the B3001 plume has been performed and the results are presented in Table 31. The cost analysis showed a total remediation cost of approximately 87.0 million dollars.

Table 31: Cost Analysis of the B3001 Plume

Phase	Direct Cost	Markups	Total Cost
Remedial Action (Capital)	$5,323,565	$3,550,312	$8,873,877
Operations and Maintenance	$5,754,246	$5,802,185	$11,556,431
Long Term Monitoring	$43,677,279	$22,782,781	$66,460,060
Site Close Out	$23,689	$50,528	$74,217
Total Site Cost	$54,778,779	$32,185,806	$86,964,585

3.7.3 Cost Analysis of the Combined IWTP and B3001 Plume

The cost analysis of combined site remediation for the IWTP plume and B3001 plume has been performed and the results are presented in Table 32. The cost analysis showed a total remediation cost of approximately 103.6 million dollars.

Table 32: Cost Analysis of the Combined IWTP and B3001 Plume

Phase	Direct Cost	Markups	Total Cost
Remedial Action (Capital)	$8,304,421	$5,084,433	$13,388,854
Operations and Maintenance	$7,388,611	$6,833,204	$14,221,815
Long Term Monitoring	$50,318,498	$25,706,400	$76,024,898
Site Close Out	$25,816	$53,593	$79,409
Total Site Cost	$66,037,346	$37,677,630	$103,714,976

These analyses compare only similar treatment approaches, showing that if active remediation is pursued then cost savings should result when the co-mingled plume is remediated in its entirety. Given the lower concentration of chromium in the IWTP plume as well as partial dechlorination of chlorinated solvents in the IWTP plume, it is possible that a natural attenuation approach for the IWTP plume combined with the active restoration of the contamination which came from the B3001 plume could prove more cost effective. Additional analysis addressing this type of alternative is presented in the discussion section of this thesis.

CHAPTER IV

DISCUSSION

4.1 Introduction to Discussion

This chapter will explain the results and discuss the findings with respect to the problem statement and general focus of this investigation. The discussion will be presented in four main sections; chromium concentration, chlorinated solvent concentrations, chlorinated solvent molar fractions, and neural networks.

4.2 Discussion of Testing Performed on Chromium Concentration

Figure 14 shows elevated concentrations of chromium at the IWTP W and B3001 E well groups, essentially the center of the co-mingled plume. Testing also showed very low concentrations of chromium, with a mean concentration of 7.0 $\mu g / l$, at the IWTP E wells groups. These results suggest that B3001 is the sole source of chromium contamination, and that the contamination had dispersed radially away from the source. Testing of all IWTP wells versus all B3001 wells showed that there were significant differences between the two locations, indicating that these areas represent contamination from separate sources. A summary of results is presented in Table 33.

Table 33: Summary of Comparisons Between Locations for Chromium Concentration

Groups	Statistically Different	Difference of Means
IWTP E Vs. IWTP W	Yes	101
IWTP E Vs. B3001 E	Yes	1890
IWTP E Vs. B3001 W	Yes	22
IWTP W Vs. B3001 E	Yes	1789
IWTP W Vs. B3001 W	No	-79
B3001 E Vs. B3001 W	Yes	-1868
IWTP Vs. B3001	Yes	1037

4.3 Discussion of Testing Performed on Chlorinated Solvents

Testing of the four chlorinated solvents showed statistical differences between the IWTP and B3001 for TCE, DCE, and VC. TCE was statistically higher at B3001 whereas DCE and VC were statistically higher at IWTP. This was the original hypothesis, since it was expected that contamination from IWTP would be in a reduced form due to treatment. It appears that contamination from IWTP has migrated down-gradient as well as towards ground water extraction wells. This migration has continued past well 1-15 until reaching the B3001 plume. There is an interface were the IWTP and B3001 plume meet, located between well 1-15 and wells 34 and 35. There is a similar interface between the IWTP well 1-11 and the B3001 well 1-1, shown in Figure 1. The results of the chlorinated solvents testing will be discussed individually for each contaminant throughout the next four subsections.

4.3.1 Discussion of Testing Performed on PCE

Testing of PCE concentration showed elevated concentrations of PCE at the two locations IWTP W and B3001 E. From the boxplots in Figure 16, it can be seen that PCE concentrations decrease as the distance from IWTP increases, starting at IWTP W. The decrease in PCE concentration was not enough to cause a significant difference between the IWTP plume and the B3001 plume with respect to PCE concentration as shown in Table 34.

Table 34: Summary of Comparisons Between Locations for PCE Concentration

Groups	Statistically Different	Difference of Means
IWTP E Vs. IWTP W	Yes	78
IWTP E Vs. B3001 E	Yes	60.2
IWTP E Vs. B3001 W	No	6.6
IWTP W Vs. B3001 E	No	-17.8
IWTP W Vs. B3001 W	Yes	-71.4
B3001 E Vs. B3001 W	Yes	-53.6
IWTP Vs. B3001	No	-8.8

Testing of PCE molar fractions showed similar results, except that the IWTP area had a significantly higher molar fraction than B3001, as shown in Table 35. However, it seems unlikely that IWTP would be the source of PCE contamination. Since PCE concentrations are similar at the IWTP and B3001 locations, the lower molar fractions at B3001 are likely due to the high concentrations of TCE dwarfing the minute concentrations of PCE, since molar fractions are essentially a ratio. Due to the lack of statistical differences between the IWTP plume and the B3001 plume, the results of PCE testing remain inconclusive as to where the source of the PCE contamination was, or if there were multiple sources.

Table 35: Summary of Comparisons Between Locations for PCE Molar Fractions

Groups	Statistically Different	Difference of Means
IWTP E Vs. IWTP W	No	0.036
IWTP E Vs. B3001 E	No	0.021
IWTP E Vs. B3001 W	Yes	-0.03
IWTP W Vs. B3001 E	No	-0.015
IWTP W Vs. B3001 W	Yes	-0.066
B3001 E Vs. B3001 W	Yes	-0.051
IWTP Vs. B3001	Yes	-0.022

4.3.2 Discussion of Testing Performed on TCE

From the TCE concentration boxplots and correlation coefficient of 0.659, Figure 20 and Table 9, it is evident that TCE concentration is increasing with increasing distance from IWTP, indicating that B3001 is the source of TCE contamination. From east to west, each well group had a significantly higher concentration of TCE than the group preceding it. For example, B3001 E had a significantly higher concentration of TCE than IWTP W. The results of testing between the IWTP area and the B3001 area showed B3001 to be significantly higher in TCE concentration than the IWTP, as shown in Table 36. This indicates that B3001 is the source of TCE contamination and that the IWTP plume and the B3001 plume are separate sources.

Table 36: Summary of Comparisons Between Locations for TCE Concentrations

Groups	Statistically Different	Difference of Means
IWTP E Vs. IWTP W	Yes	339.1
IWTP E Vs. B3001 E	Yes	977.6
IWTP E Vs. B3001 W	Yes	1819.4
IWTP W Vs. B3001 E	Yes	638.5
IWTP W Vs. B3001 W	Yes	1480.3
B3001 E Vs. B3001 W	Yes	841.8
IWTP Vs. B3001	Yes	1151.7

Testing performed on TCE molar fractions produced similar results. Figure 25 shows that the B3001 E and B3001 W well groups both had elevated molar fraction which were not significantly different from each other. The IWTP E and IWTP W well groups both had low TCE molar fractions which were not significantly different from each other. As shown in Table 37, testing TCE molar fractions between IWTP and B3001 showed that the two areas were significantly different. From this it is reasonable to believe that the B3001 site is the sole source of TCE contamination and that the IWTP plume and the B3001 plume are from separate sources.

Table 37: Summary of Comparisons Between Locations for TCE Molar Fractions

Groups	Statistically Different	Difference of Means
IWTP E Vs. IWTP W	No	0.064
IWTP E Vs. B3001 E	Yes	0.696
IWTP E Vs. B3001 W	Yes	0.703
IWTP W Vs. B3001 E	Yes	0.633
IWTP W Vs. B3001 W	Yes	0.639
B3001 E Vs. B3001 W	No	0.006
IWTP Vs. B3001	Yes	0.662

4.3.3 Discussion of Testing Performed on DCE

The results of DCE concentration testing were strikingly different from the results of testing TCE contamination. As shown in Figure 20, the highest level of DCE concentration was found to be in the IWTP W area, centered at well 19. As shown in Table 38, testing between IWTP and B3001 showed the IWTP to have significantly higher concentrations of DCE. These results indicate that the DCE contamination is from IWTP and that the IWTP plume and the B3001 plume are from separate sources.

Table 38: Summary of Comparisons Between Locations for TCE Concentration

Groups	Statistically Different	Difference of Means
IWTP E Vs. IWTP W	Yes	1050
IWTP E Vs. B3001 E	Yes	-132.2
IWTP E Vs. B3001 W	No	-47.7
IWTP W Vs. B3001 E	Yes	-1182.2
IWTP W Vs. B3001 W	Yes	-1097.7
B3001 E Vs. B3001 W	Yes	84.5
IWTP Vs. B3001	Yes	-705.9

The results of testing DCE molar fractions were opposite of the results from testing TCE molar fractions, as expected. Figure 26 shows that the IWTP E and IWTP W groups showed elevated DCE molar fraction values which were not significantly different. The B3001 E and B3001 W groups had low molar fractions of DCE which were not significantly different. As shown in Table 39, testing DCE molar fractions between IWTP and B3001 showed that the two areas were significantly different. These results indicate that the DCE contamination is from IWTP and that the IWTP plume and the B3001 plume are from separate sources. The results of the reduction-oxidation potential testing reinforce this conclusion since there were no statistical differences between locations with respect to redox potential. Since the locations were not statistically different, there is no statistical basis to believe that differences in DCE molar fractions are the result of differences in geological conditions. Therefore, this reinforces the hypothesis that the differences in DCE molar fractions were the result of separate sources for the IWTP plume and B3001 plume. Although the correlation coefficient for DCE concentration was weak due to low concentrations at the IWTP E area, the correlation coefficient for molar fractions showed a strong relationship between decreasing molar fractions and increasing distance from IWTP.

Table 39: Summary of Comparisons Between Locations for DCE Molar Fractions

Groups	Statistically Different	Difference of Means
IWTP E Vs. IWTP W	No	-0.008
IWTP E Vs. B3001 E	Yes	-0.495
IWTP E Vs. B3001 W	Yes	-0.46
IWTP W Vs. B3001 E	Yes	-0.487
IWTP W Vs. B3001 W	Yes	-0.452
B3001 E Vs. B3001 W	No	0.035
IWTP Vs. B3001	Yes	-0.475

Since DCE is a reduced form of the TCE used at the B3001 site, it is reasonable to believe that TCE was dechlorinated at the IWTP site where it was reduced to DCE prior to its release to the environment. The DCE contamination then likely traveled from the IWTP E area into the IWTP W area, which is not only down gradient but also towards ground water extraction wells.

4.3.4 Discussion of Testing Performed on VC

The results of testing performed on VC concentration were similar to the results of testing DCE concentration. Since VC is also a reduced form of TCE, these results were expected. The correlation coefficients for both concentration and molar fractions showed a moderate relationship between decreasing concentration/molar fraction and increasing distance from IWTP. Figure 22 shows that the IWTP W and IWTP E well groups both showed elevated concentrations of VC which were not significantly different. The B3001 E and B3001 W wells groups showed low concentrations of VC which were not significantly different. As shown in Table 40, testing between IWTP and B3001 showed that there was a significant difference between the two areas. These results indicate that IWTP is the source of VC contamination and that the IWTP plume and the B3001 plume are from separate sources.

Table 40: Summary of Comparisons Between Locations for VC Concentration

Groups	Statistically Different	Difference of Means
IWTP E Vs. IWTP W	No	22.9
IWTP E Vs. B3001 E	Yes	-74.1
IWTP E Vs. B3001 W	Yes	-67.6
IWTP W Vs. B3001 E	Yes	-97
IWTP W Vs. B3001 W	Yes	-90.5
B3001 E Vs. B3001 W	No	6.5
IWTP Vs. B3001	Yes	-84.6

Testing of VC molar fractions produced results similar to those found testing VC concentration. The difference was that the IWTP E and IWTP W groups were significantly different at the 95% confidence level, but not significantly different at the 99% confidence level. A summary of the results of VC molar fraction comparisons between locations are presented in Table 41. These results indicate that the VC was released from the IWTP site, having previously undergone some degree of treatment resulting in its reduced form and that the IWTP plume and the B3001 plume are from separate sources.

Table 41: Summary of Comparisons Between Locations for VC Molar Fractions

Groups	Statistically Different	Difference of Means
IWTP E Vs. IWTP W	Yes	-0.091
IWTP E Vs. B3001 E	Yes	-0.213
IWTP E Vs. B3001 W	Yes	-0.222
IWTP W Vs. B3001 E	Yes	-0.121
IWTP W Vs. B3001 W	Yes	-0.131
B3001 E Vs. B3001 W	No	-0.01
IWTP Vs. B3001	Yes	-0.165

4.3.5 Discussion of Neural Network Models

The neural network models proved to be a powerful tool for finding differences and similarities between wells and sources. All three models showed that the wells used to represent the IWTP and B3001 plumes in the previous statistical models were representative of their respective sources. The only exceptions were for two IWTP wells, well 1-49 which had values of 0.425 for IWTP and 0.574 for B3001 and well 1-11 which had values of 0.580 for IWTP and 0.421 for B3001, in the concentrations only model. The results of the neural network model indicate that the IWTP wells were representative of the IWTP plume and that the B3001 wells were representative of the B3001 plume. Furthermore, these results indicate that the IWTP plume and the B3001 plume are from separate sources.

4.3.6 Cost Benefit Analysis

The total costs, the sum of the direct costs and markups, has been included in Table 42 for the IWTP plume, the B3001 plume, and the combination of the IWTP and B3001 plumes treated as one plume. The costs were determined using the Racer software program.

Table 42: Total Costs for the IWTP, B3001, and Combined Plume

Phase	IWTP Plume	B3001 Plume	Combined Plume
Remedial Action (Capital)	$5,062,126	$8,873,877	$13,388,854
Operations and Maintenance	$7,561,385	$11,556,431	$14,221,815
Long Term Monitoring	$10,660,367	$66,460,060	$76,024,898
Site Close Out	$32,336	$74,217	$79,409
Total Site Cost	$23,316,213	$86,964,585	$103,635,567

The combined cost of each phase is less expensive than the sum of the IWTP plume and B3001 plume. In each case, the Racer software estimates that it would be less expensive to treat the IWTP plume and B3001 plume as one combined plume. The cost estimate of treating the IWTP plume and B3001 plume as one combined plume is approximately 16.7 million dollars less expensive. This estimate was developed by treating the IWTP plume, the B3001 plume, and the combined plume with identical treatment techniques, as detailed in section 2.9. Since the contaminants at each plume have been shown to be statistically different, a remediation feasibility study is suggested to determine the most reasonable treatment for each plume individually. For example, since the IWTP plume contains partially dechlorinated forms of chlorinated ethenes, i.e. DCE and VC, as well as statistically lower concentrations of chromium, it may be possible to perform long term monitoring at IWTP as opposed to performing pump and treat efforts. This would allow approximately 7.5 million dollars, the cost of performing pump and treat remediation, to be saved. The combined costs for remediation of both plumes under this scenario, while improved, still do not offer improvements over a program of total plume restoration.

CHAPTER V

CONCLUSIONS

5.1 Introduction to Conclusions

This chapter will summarize the statistical methods and analysis utilized, the constituents which were tested, and results found throughout this report, with respect to the problem statement and general focus of this investigation.

5.2 Tests Performed Which Showed Statistical Differences Between Plumes

The results of statistically testing the concentration of chlorinated solvents showed statistical trends in concentration data and statistical differences between well groups, indicating that the IWTP plume and B3001 plume are from separate sources. The following statistical concentration tests produced statistically defensible evidence that the Tinker collected data from wells in proximity to the IWTP site and B3001 site are an indication that the IWTP plume and B3001 plume are from separate sources:

- Chromium
    1. ANOVA
    2. Kruskal-Wallis
    3. Mann-Whitney

- TCE
    1. ANOVA
    2. Kruskal-Wallis
    3. Mann-Whitney
    4. Correlation Coefficients

- DCE
    1. ANOVA
    2. Kruskal-Wallis
    3. Mann-Whitney
    4. Correlation Coefficients

- VC
    1. ANOVA
    2. Kruskal-Wallis
    3. Mann-Whitney
    4. Correlation Coefficients

- Neural Network Models

5.3 Conclusions

Analysis of the tests listed above led to the following conclusions:

1. Activities in or near B3001 are the source of Chromium contamination.
2. TCE concentration and molar fractions are increasing as the distance from the IWTP increases, indicating that IWTP plume and B3001 plume are from separate sources.
3. The B3001 plume is significantly different from IWTP with respect to TCE concentration and molar fractions, indicating that IWTP plume and B3001 plume are from separate sources.
4. Activities in or near B3001 are the source of TCE contamination.
5. The molar fractions of DCE are decreasing as distance from IWTP increases, indicating that IWTP plume and B3001 plume are from separate sources.

6. IWTP shows elevated concentrations and molar fractions of DCE which are significantly different from B3001, indicating that IWTP plume and B3001 plume are from separate sources.
7. Activities in or near IWTP are the source of the DCE contamination.
8. VC concentrations and molar fractions are decreasing as the distance from IWTP increases, indicating that IWTP plume and B3001 plume are from separate sources.
9. IWTP has elevated concentrations and molar fractions of VC which are significantly different from B3001, indicating that IWTP plume and B3001 plume are from separate sources.
10. Activities in or near IWTP are the source of VC contamination.
11. Neural network modeling has detected associations between the IWTP wells and the IWTP source using the following data:
    a. Location
    b. TCE, DCE, and VC concentration data
    c. TCE, DCE, and VC molar fraction data
12. Neural network modeling has detected associations between the B3001 wells and the B3001 source using the following data:
    a. Location
    b. TCE, DCE, and VC concentration data
    c. TCE, DCE, and VC molar fraction data

13. Cost benefit analysis predicted the following approximate costs:

   a. Multiple plume remediation: 110.3 million dollars

   b. Single plume remediation: 103.6 million dollars

   c. Active remediation of the B3001 plume coupled with natural attenuation of the IWTP plume: 102.7

REFERENCES

D'Agostino, R. B., and Stephens, M. A. 1986. *Goodness-of-Fit Techniques*. New York: Marcel Dekker, Inc.

Earth Tech. 2006. *Racer Quick Reference Guide*.

Gibbions, J. D., and Chakraborti, S. 2003. *Nonparametric Statistical Inference*. 4th ed. New York: Marcel Dekker, Inc.

Helsel, D. R., and Hirsch, R. M. 2002. *Statistical Methods in Water Resources*. U.S. Geological Survey

Lapin, L. L. 1990. *Probability and Statistics for Modern Engineering*. 2nd ed. Prospect Heights, Il.: Waveland Press

McBean, E. A., and Rovers, F. A. 1998. *Statistical Procedures for Analysis of Environmental Monitoring Data and Risk Assessment*. 3rd ed. Upper Saddle River, NJ: Pretice Hall

McTernan, W. F., and Bonnett, B. V. 2002. *Using Artificial Neural Network Models to Determine Contaminant Sources*. Report Submitted to CACI EA TIET 02-003. Stillwater, Ok: Civil and Environmental Engineering Department, Oklahoma State University

Minitab Inc., 2003. Minitab Release 14 Help File

Morrison, R., and Murphy, B. 2006. *Environmental Forensics Contaminant Specific Guide.* Amsterdam: Academic Press.

Murphy, B., and Morrison, R. 2002 *Introduction to Environmental Forensics.* London: Academic Press.

Oklahoma City Air Logistics Center (OCALC) (2005) Groundwater Treatment Plant Technical Assessment Report. Department of the Air Force. Oklahoma City Air Logistics Center. Tinker Air Force Base, Oklahoma. October 2005.

Shih, Y. 1994. *Neuralyst User's Guide*. 1.4 ed. United States of America: Cheshire Engineering Corporation

Tinker Air Force Base Data Management Tool (SAIC). 2006. http://tinker.saiceemg.com/

Thode, H. C. Jr. 2002. *Testing for Normality*. New York: Marcel Dekker, Inc.

U.S. Army Corps of Engineers Tulsa District (USACE). 1988. *Building 3001 Remedial Investigations Volume I*. January 1988.

U.S. Army Corps of Engineers Tulsa District (USACE). 1988. *Building 3001 Remedial Investigations Volume II*. January 1988.

U.S. Army Corps of Engineers Tulsa District (USACE). 1990. *Building 3001 (NPL Site) Record of Decision Tinker Air Force Base*. August 1990.

U.S. Army Corps of Engineers Tulsa District (USACE). 1991. *Building 3001 Remedial Investigations Report*. October 1991.

APPENDIX A

Figure 29A: Probability Plot for Chromium at IWTP E and IWTP W

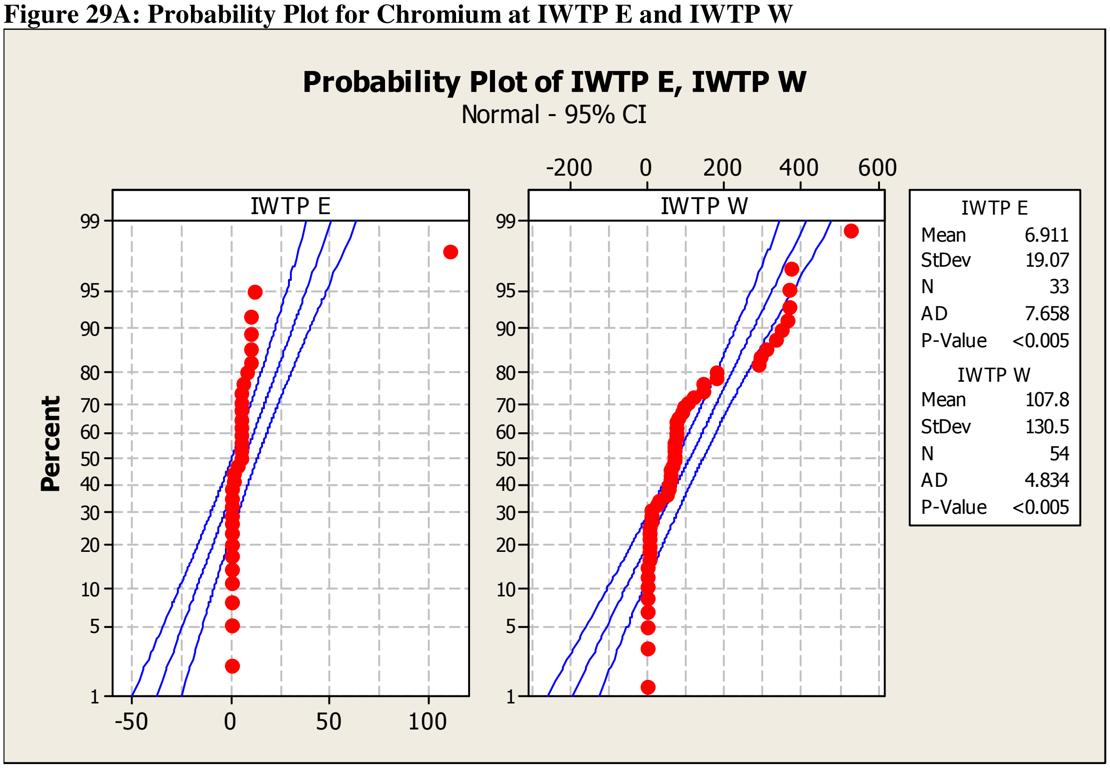


Figure 30A: Probability Plot for Chromium at B3001 E and B3001 W

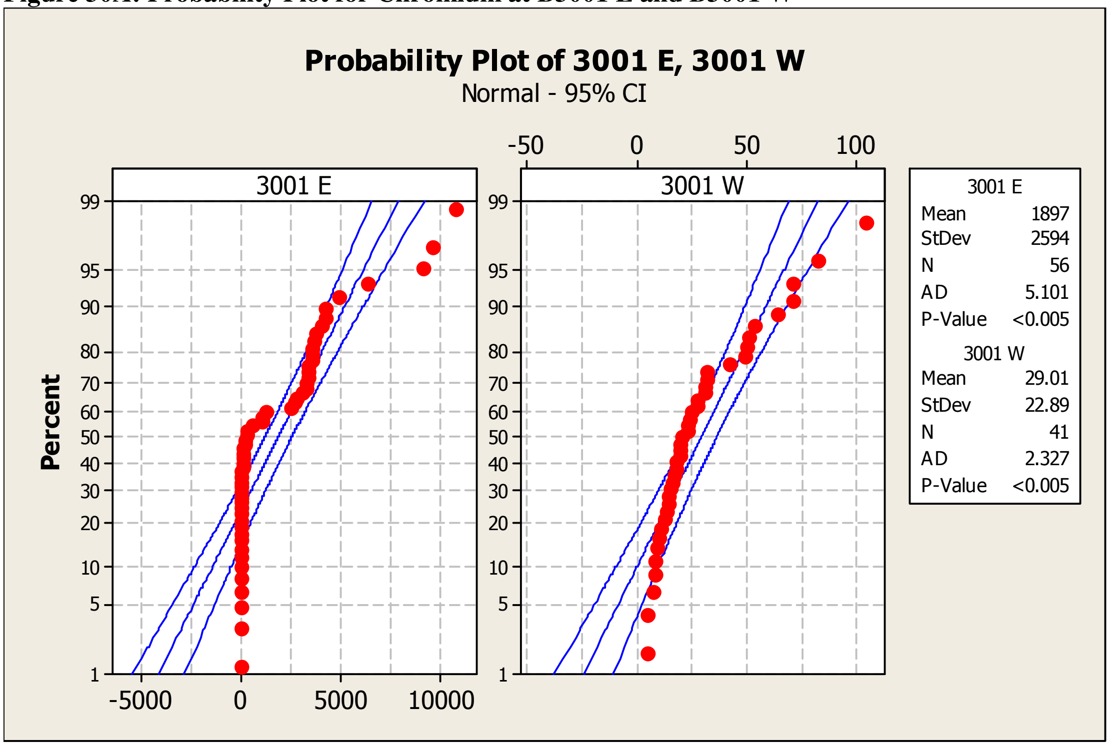


Figure 31A: Probability Plot for Chromium at IWTP and B3001

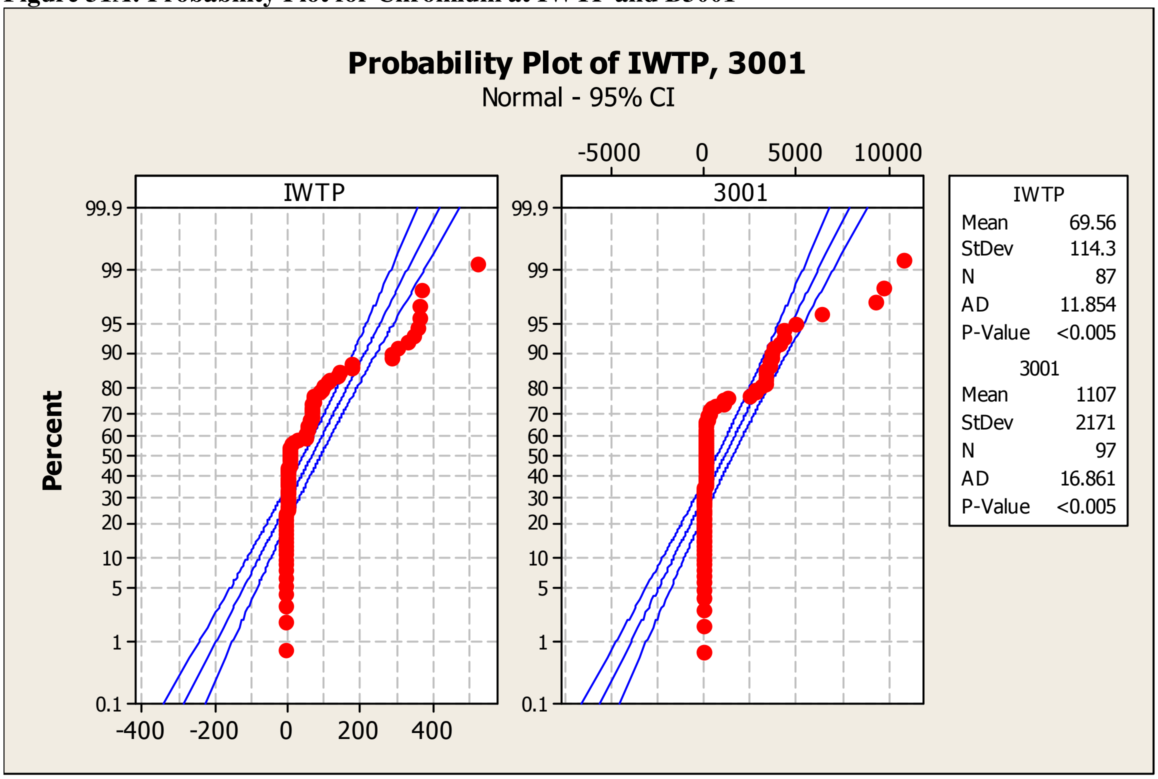


Figure 32A: Probability Plot for PCE at IWTP E and IWTP W

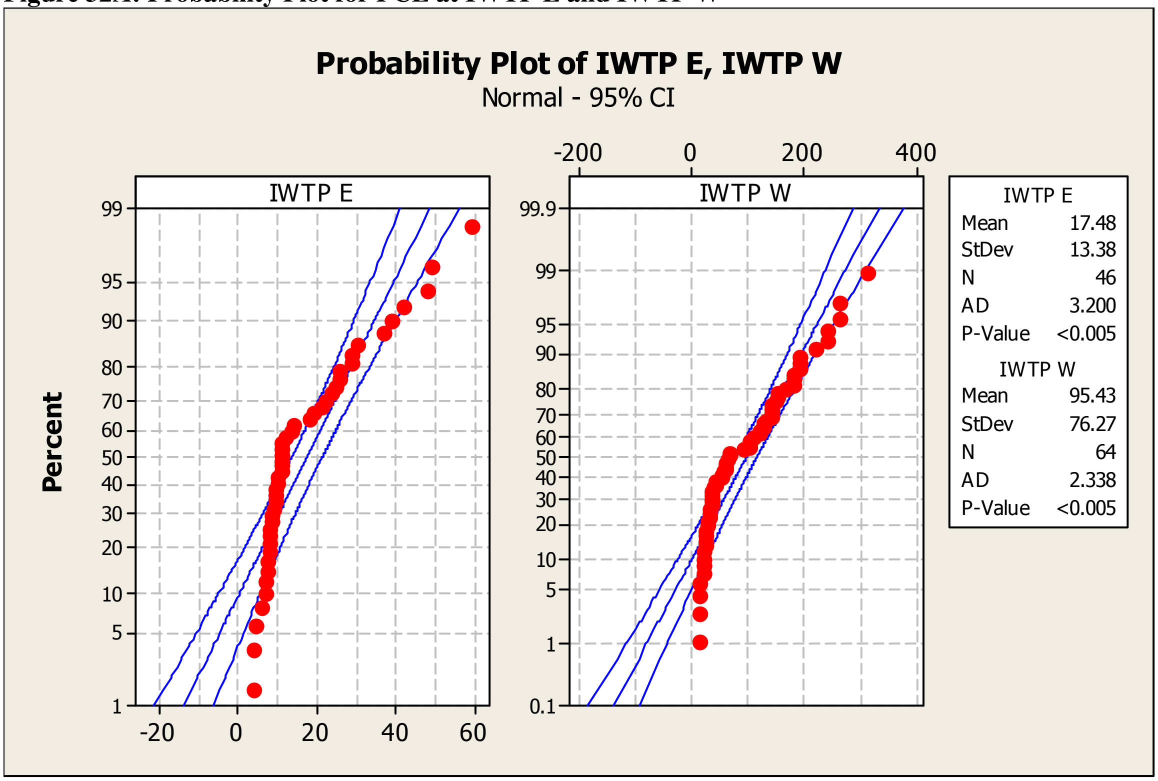


Figure 33A: Probability Plot for PCE at B3001 E and B3001 W

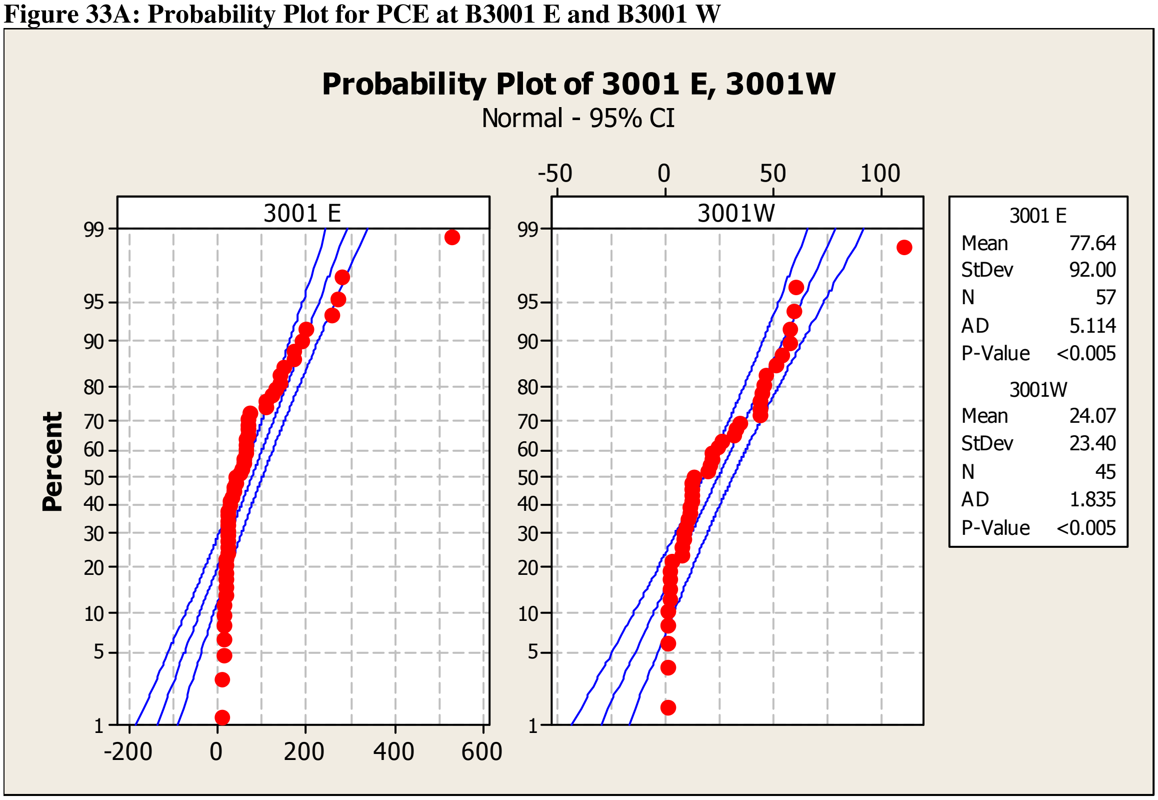


Figure 34A: Probability Plot for PCE at IWTP and B3001

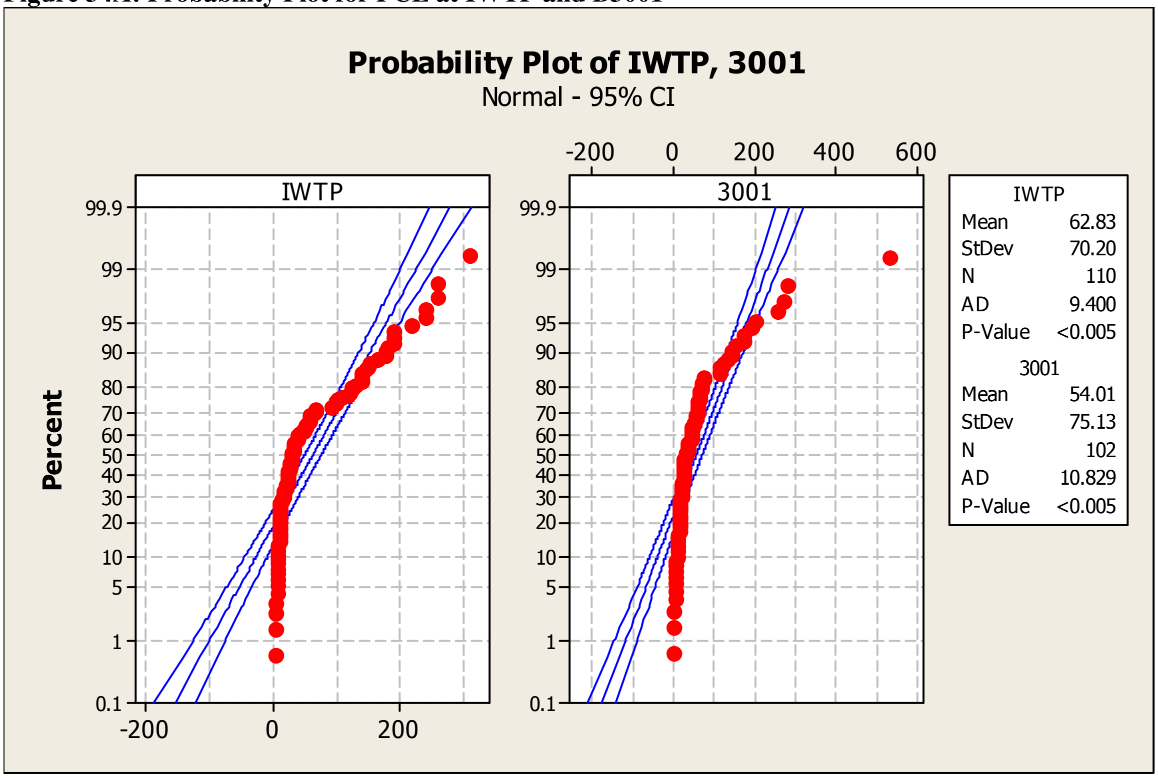


Figure 35A: Probability Plot for TCE at IWTP E and IWTP W

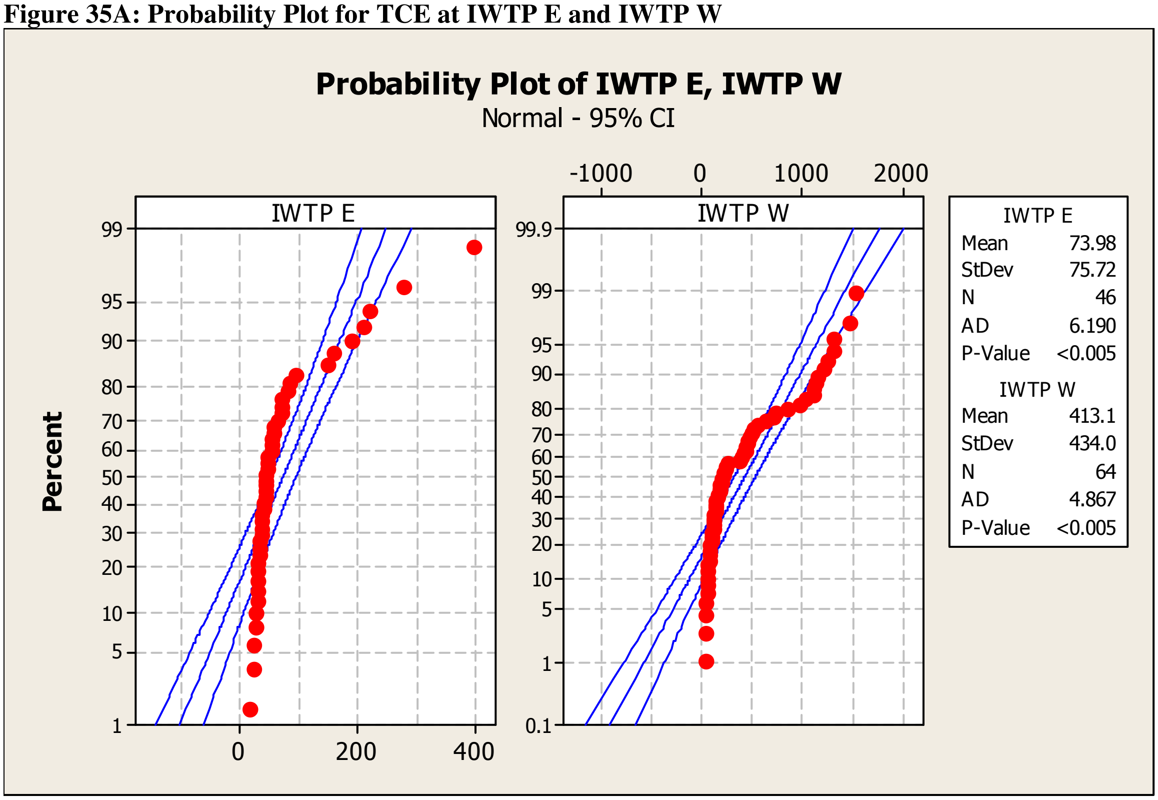


Figure 36A: Probability Plot for TCE at B3001 E and B3001 W

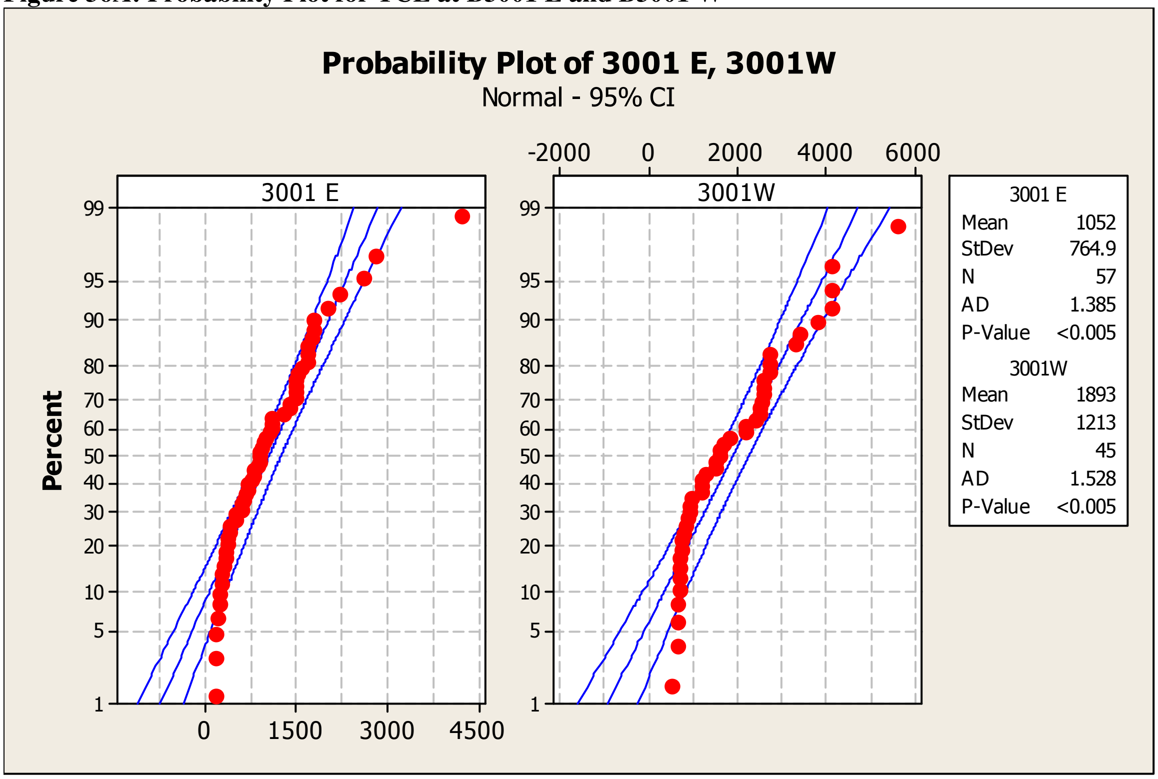


Figure 37A: Probability Plot for TCE at IWTP and B3001

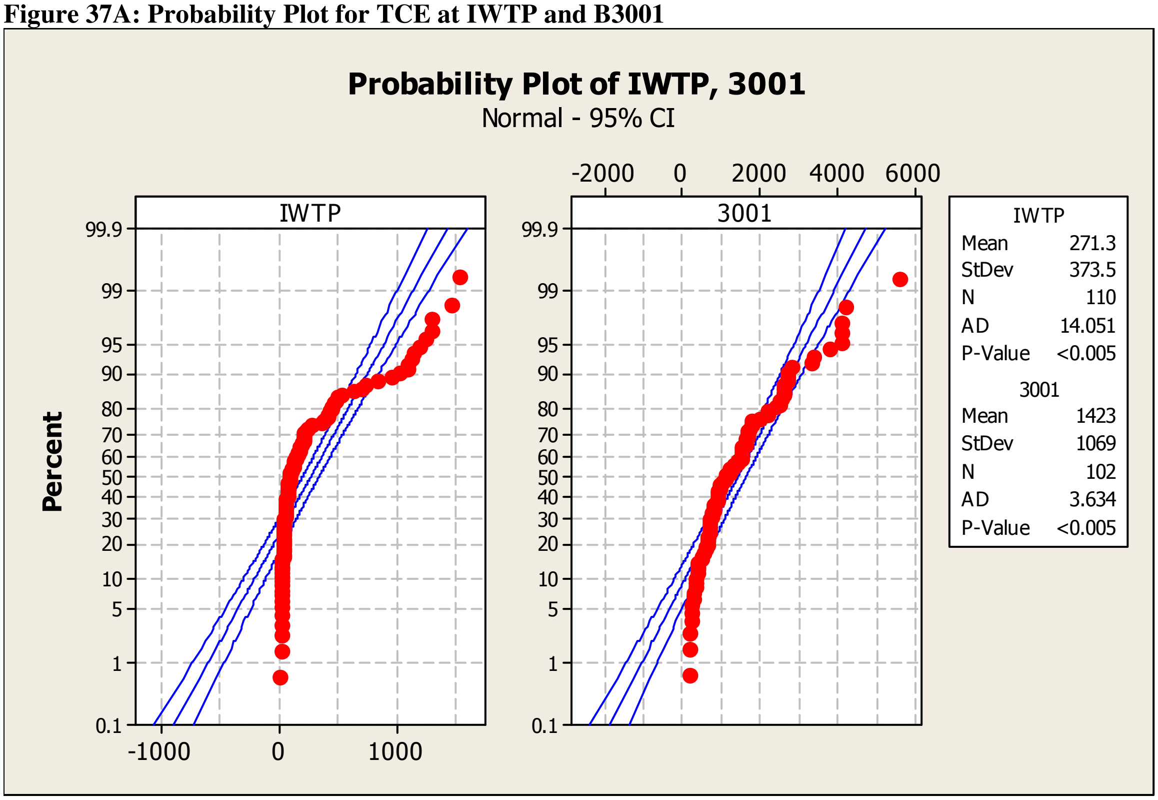


Figure 38A: Probability Plot for DCE at IWTP E and IWTP W

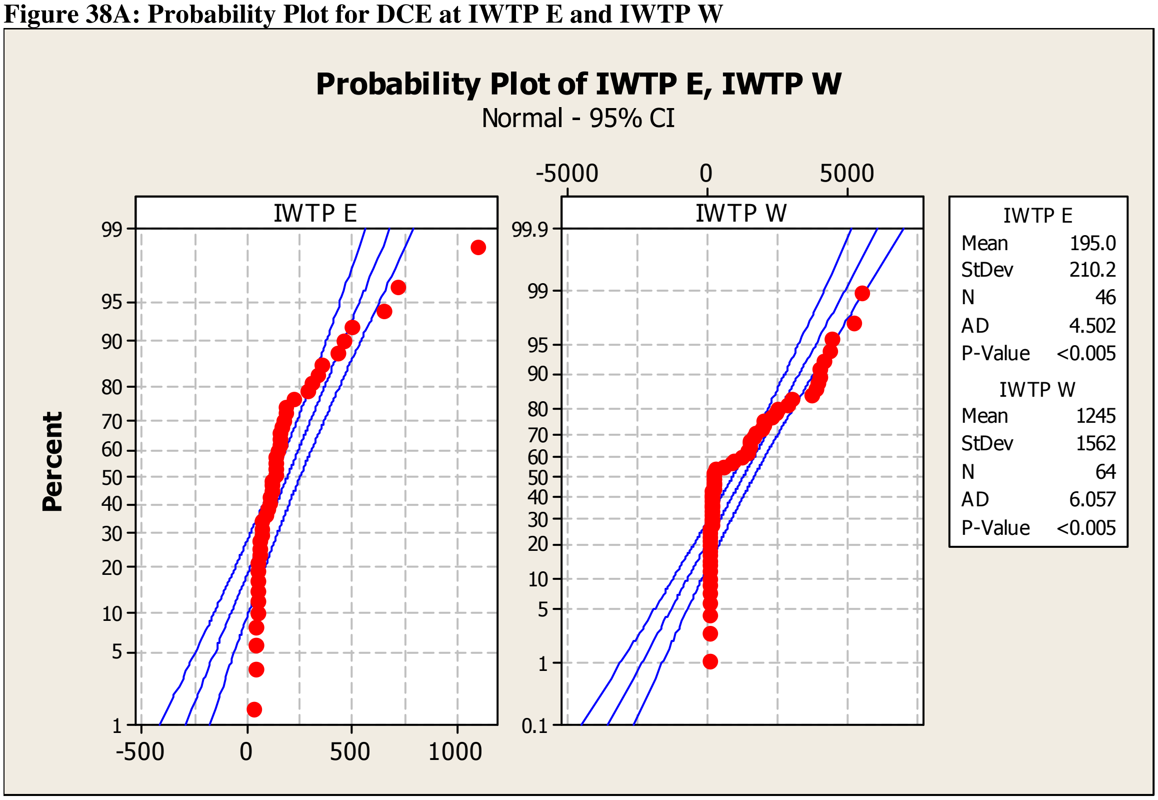


Figure 39A: Probability Plot for DCE at B3001 E and B3001 W

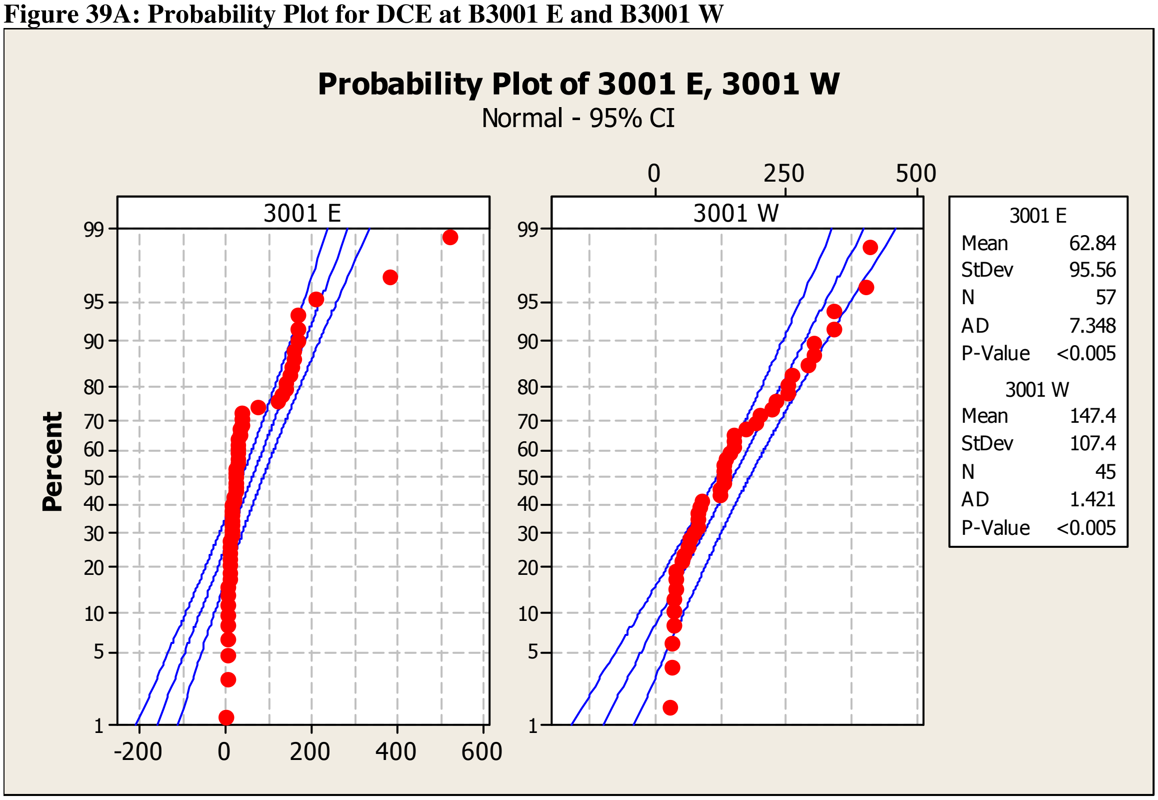


Figure 40A: Probability Plot for DCE at IWTP and B3001

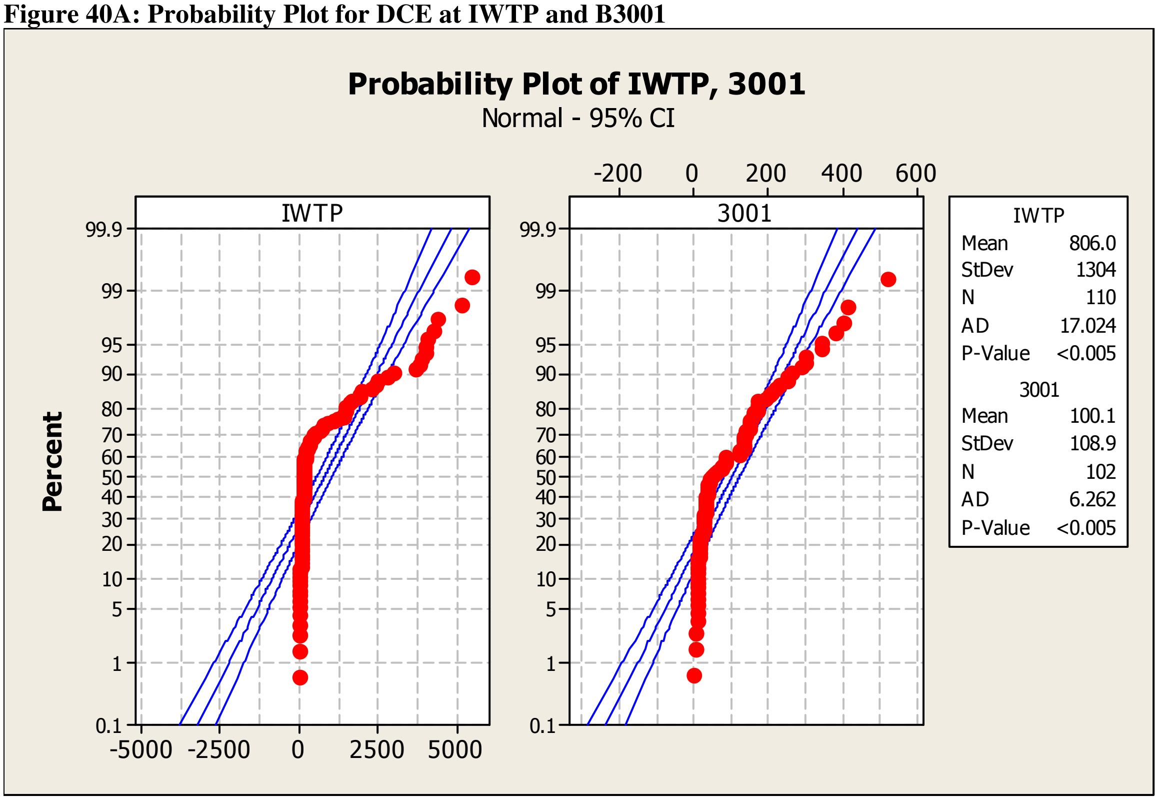


Figure 41A: Probability Plot for VC at IWTP E and IWTP W

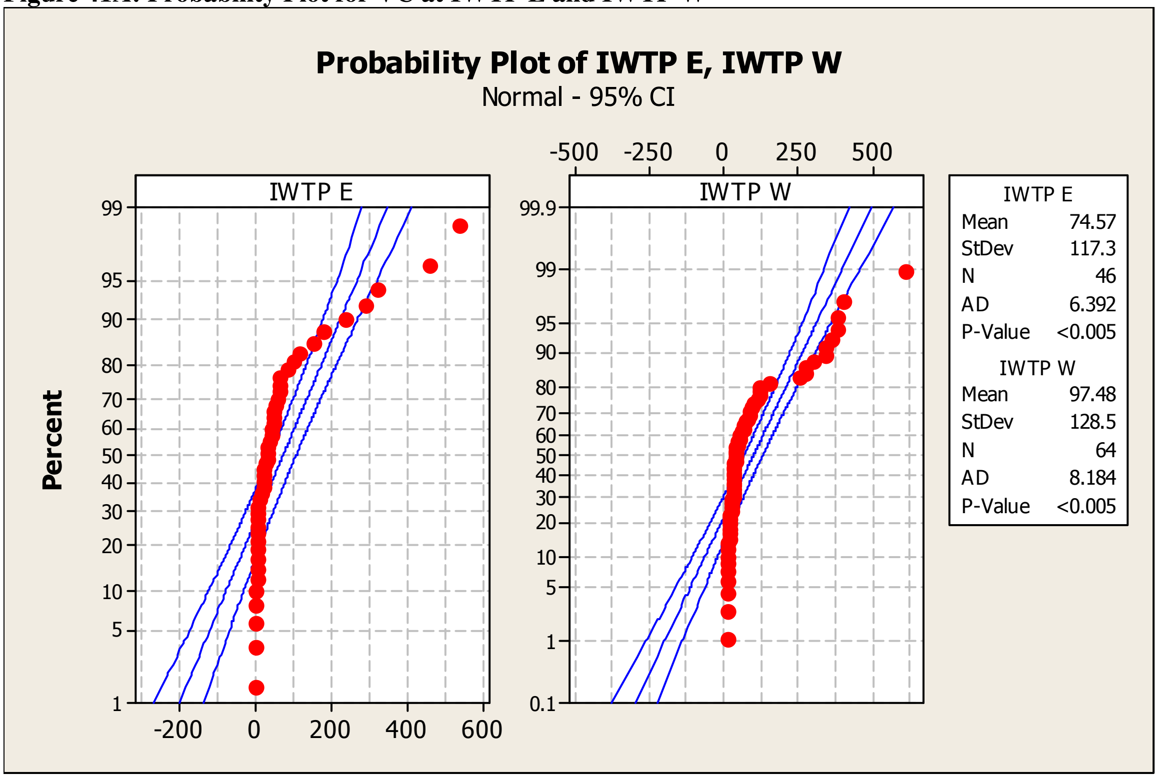


Figure 42A: Probability Plot for VC at B3001 E and B3001 W

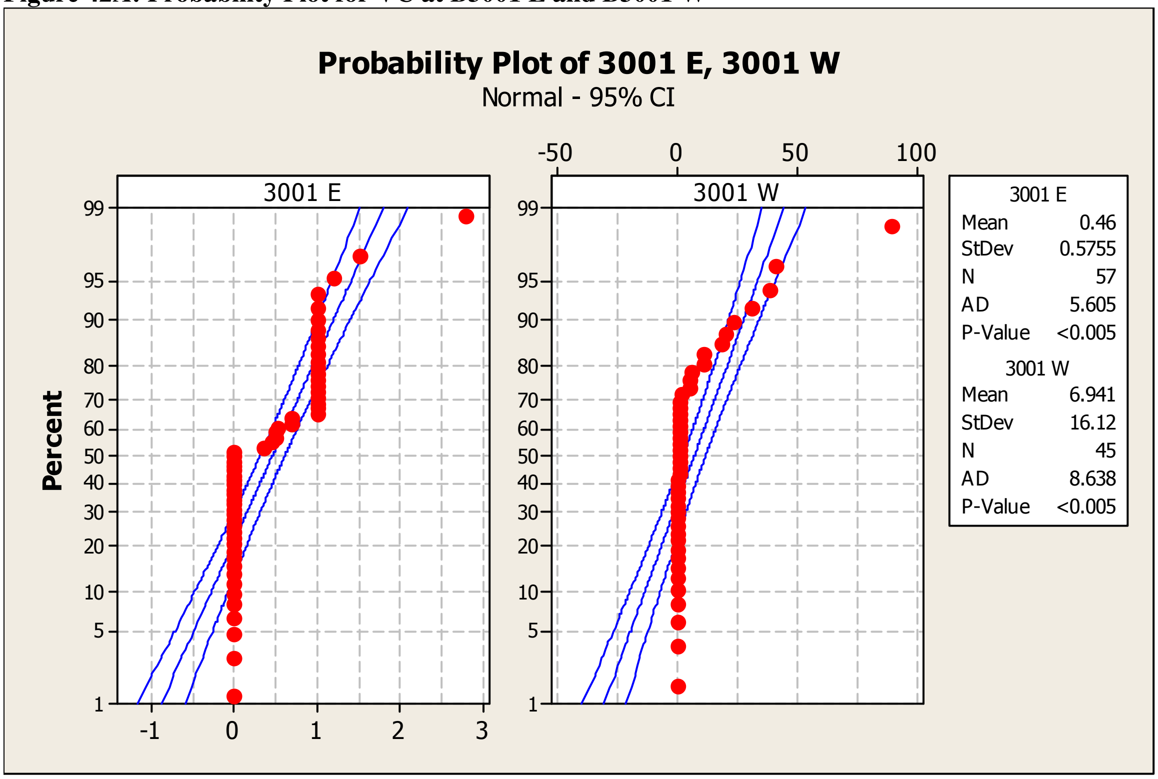


Figure 43A: Probability Plot for VC at IWTP and B3001

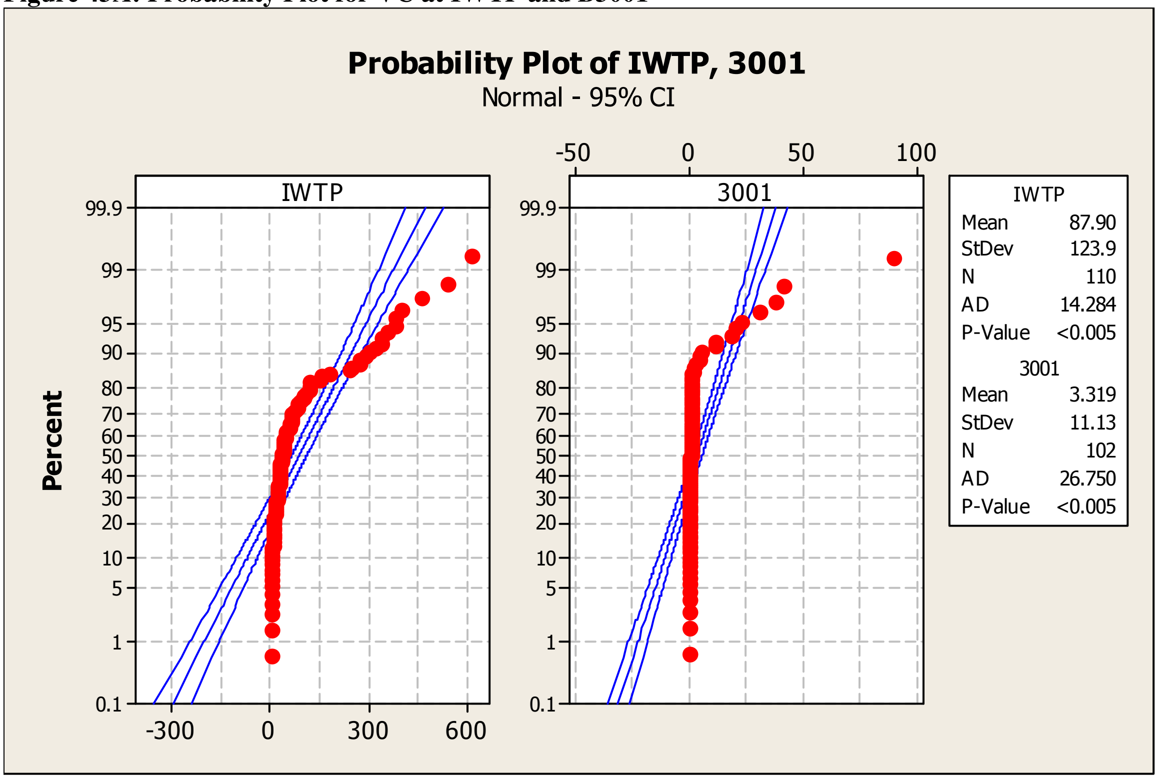


Figure 44A: Probability Plot for PCE Molar Fractions at IWTP E and IWTP W

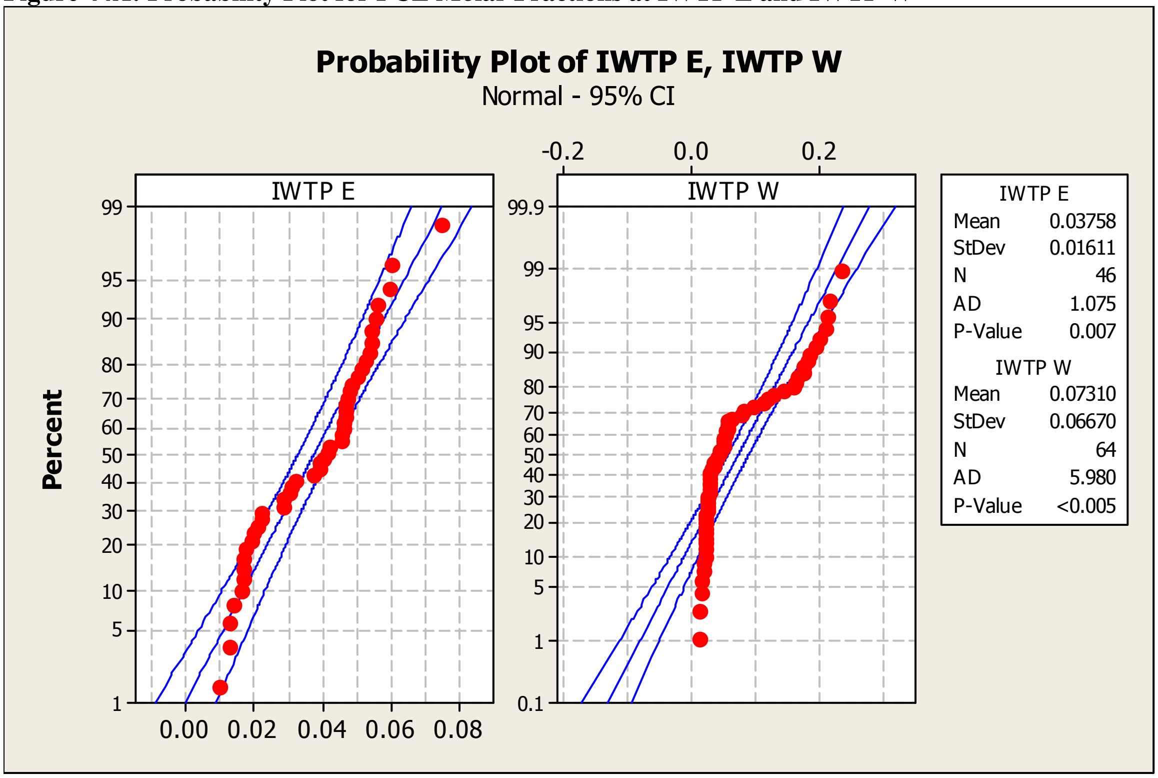


Figure 45A: Probability Plot for PCE Molar Fraction at B3001 E and B3001 W

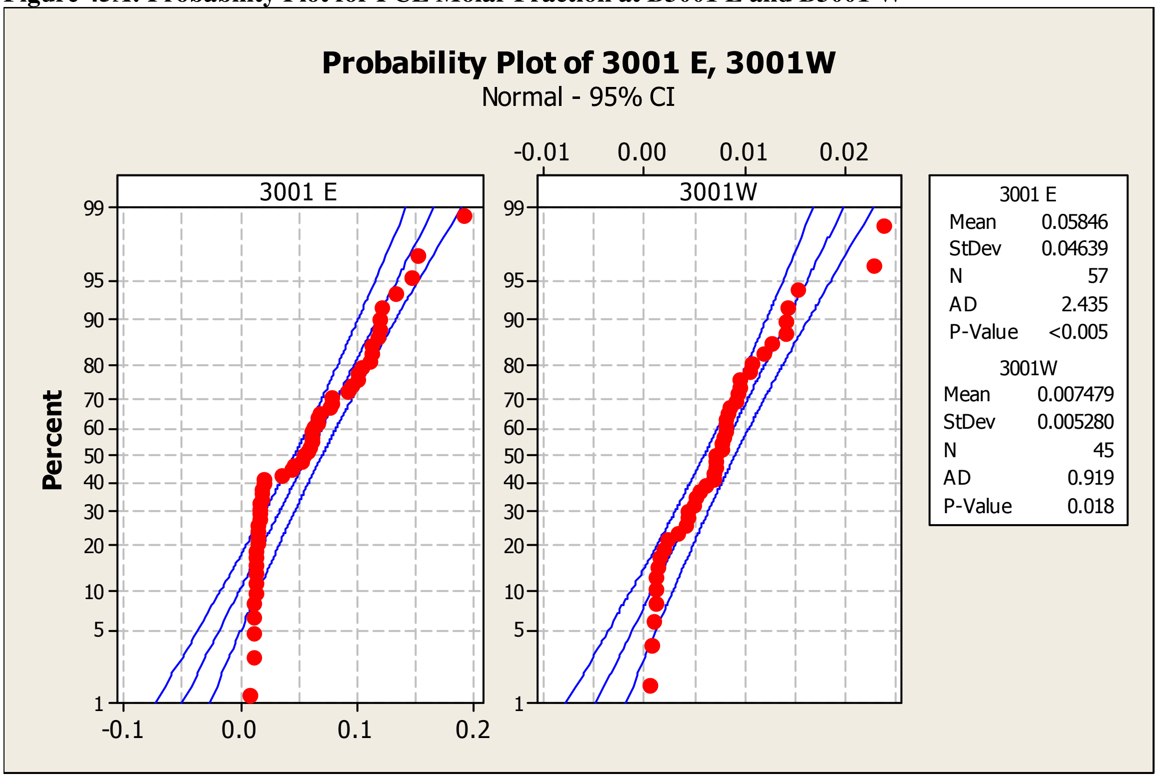


Figure 46A: Probability Plot for PCE Molar Fractions at IWTP and B3001

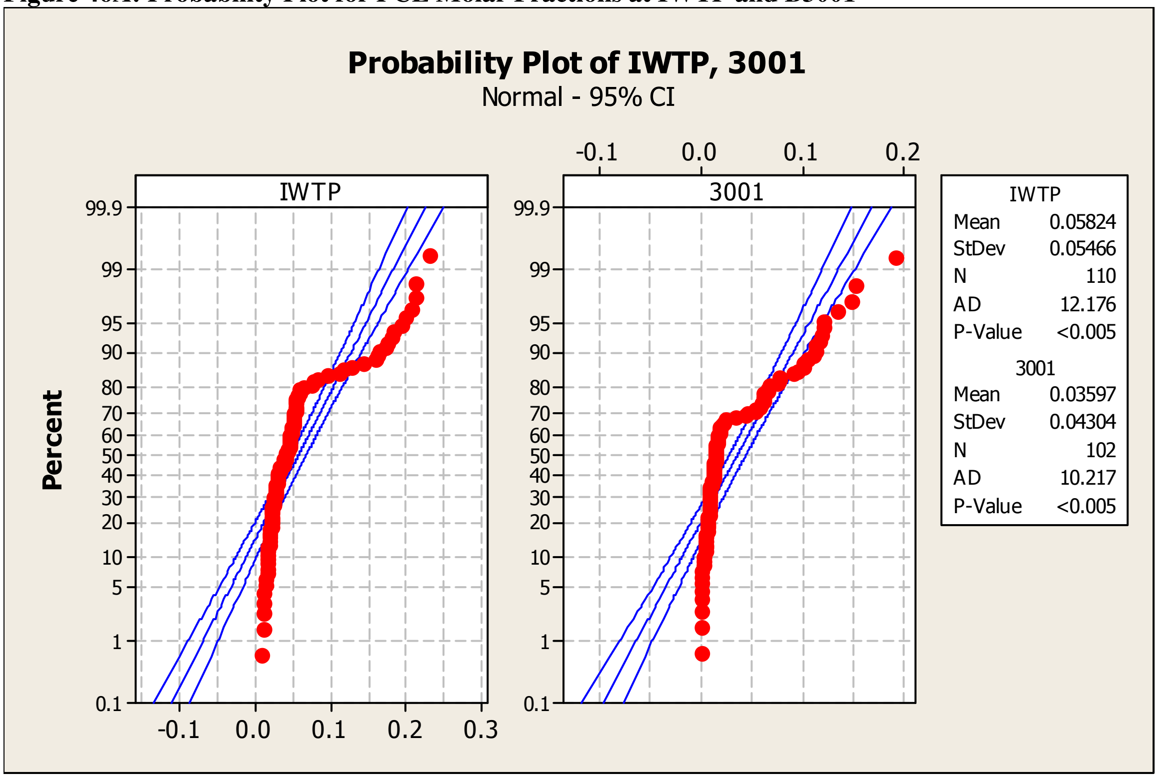


Figure 47A: Probability Plot for TCE Molar Fractions at IWTP E and IWTP W

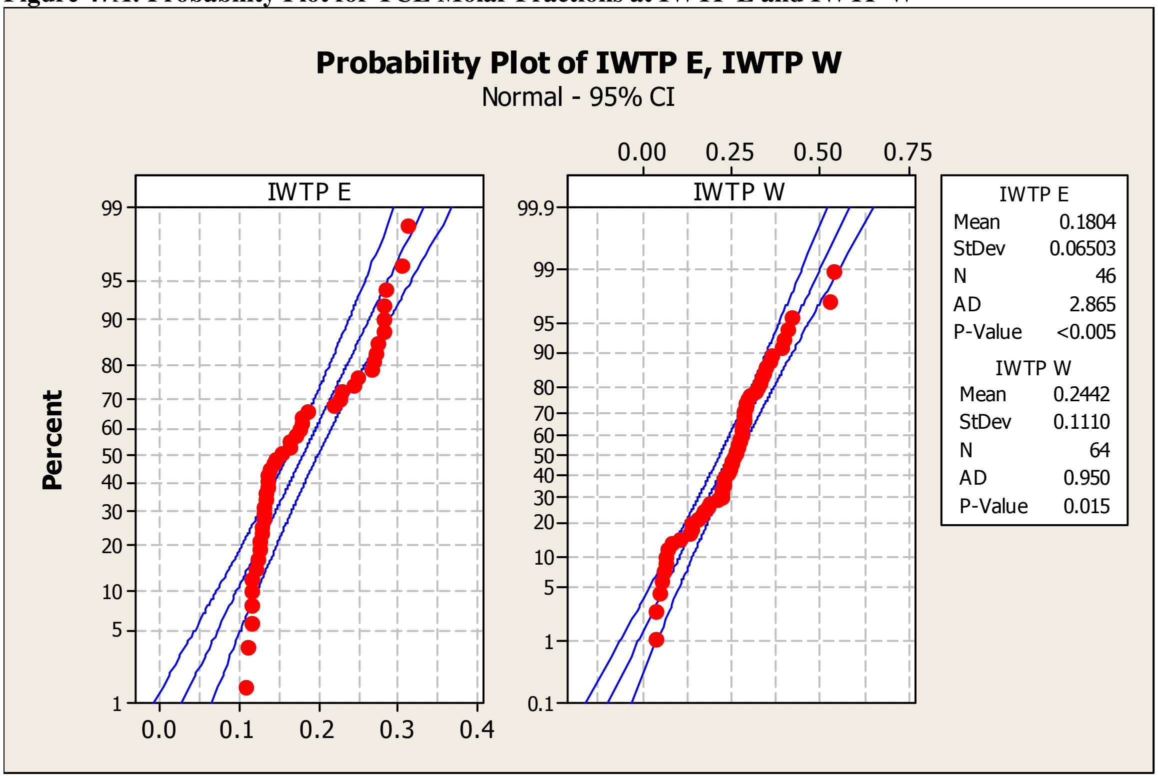


Figure 48A: Probability Plot for TCE Molar Fractions at B3001 E and B3001 W

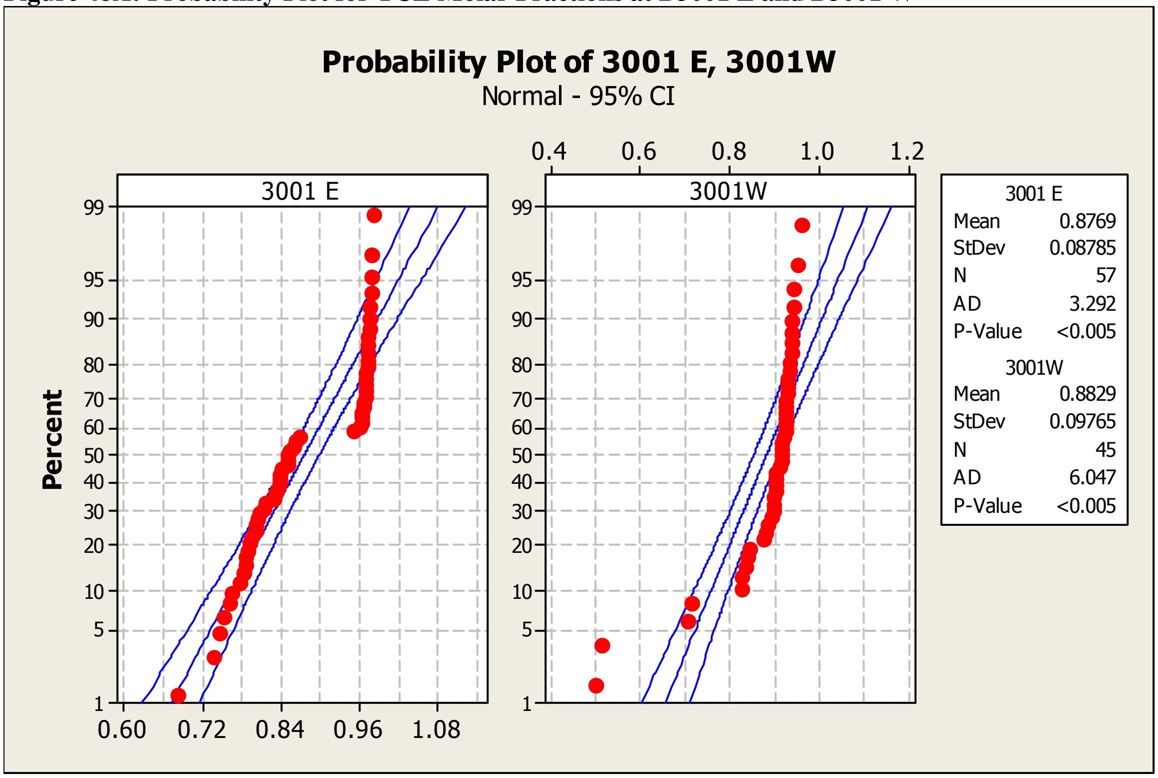


Figure 49A: Probability Plot for TCE at IWTP and B3001

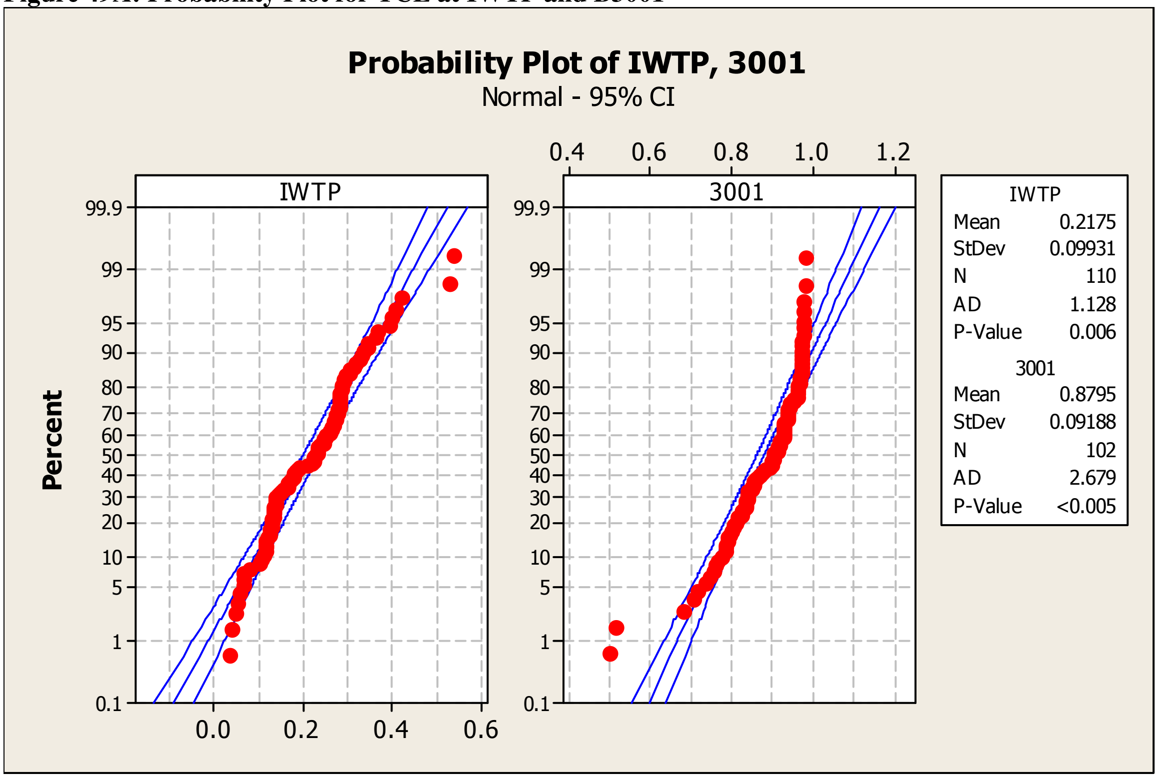


Figure 50A: Probability Plot for DCE Molar Fractions at IWTP E and IWTP W

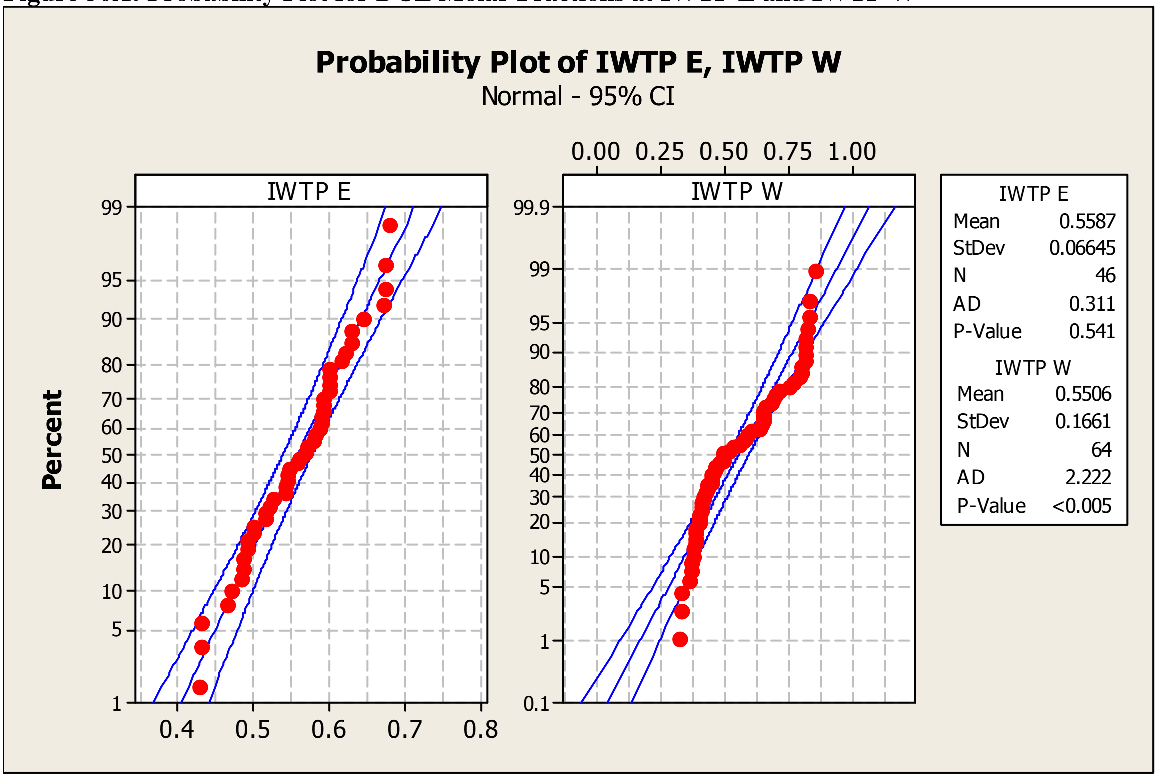


Figure 51A: Probability Plot for DCE Molar Fractions at IWTP and B3001

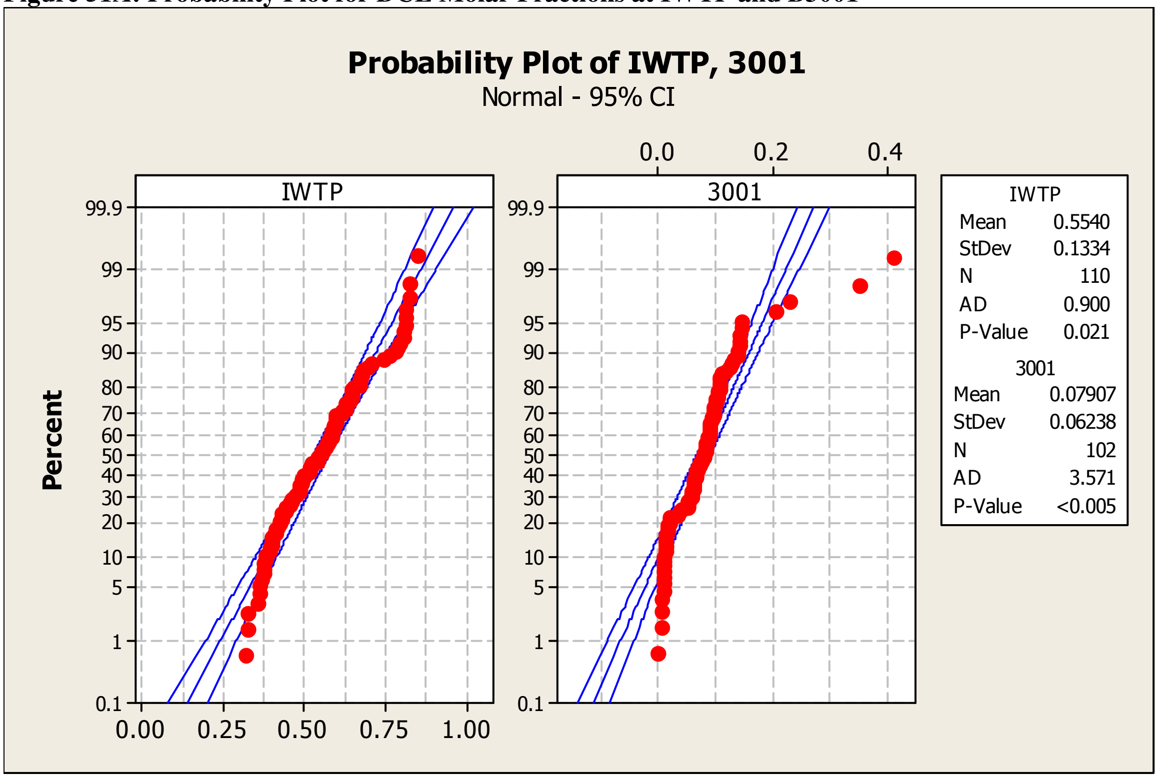


Figure 52A: Probability Plot for VC Molar Fractions at IWTP E and IWTP W

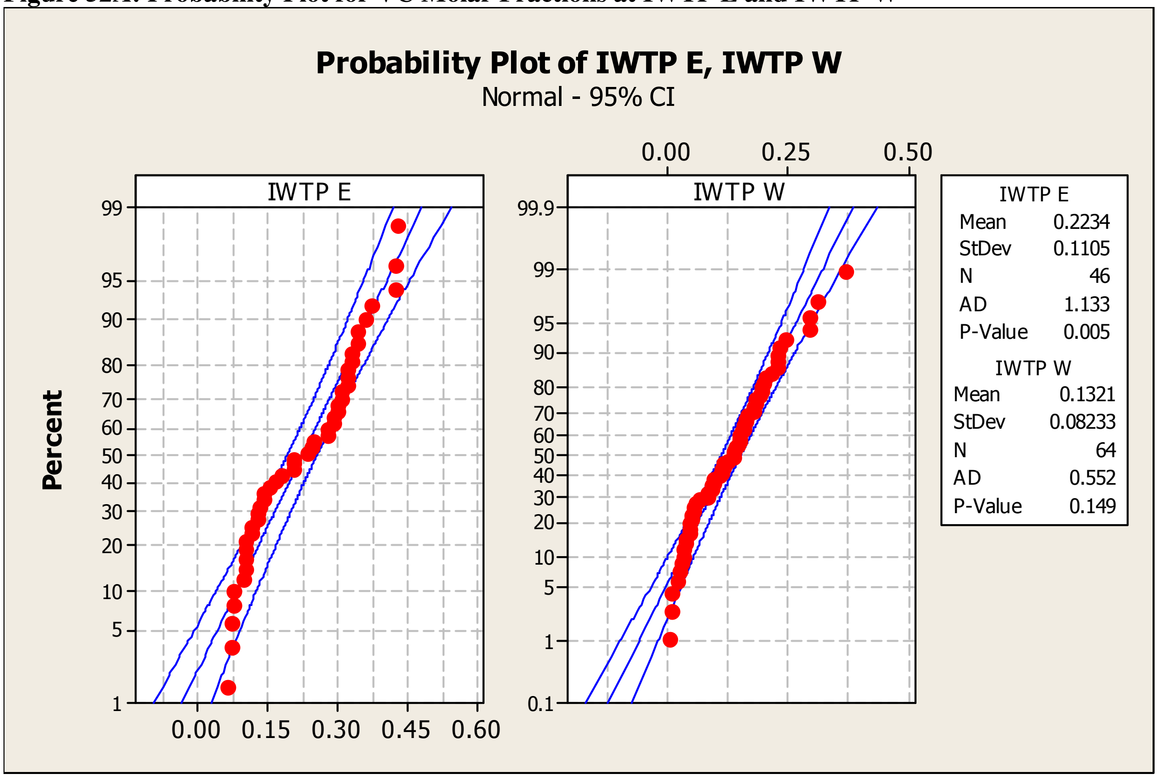


Figure 53A: Probability Plot for VC Molar Fractions at B3001 E and B3001 W

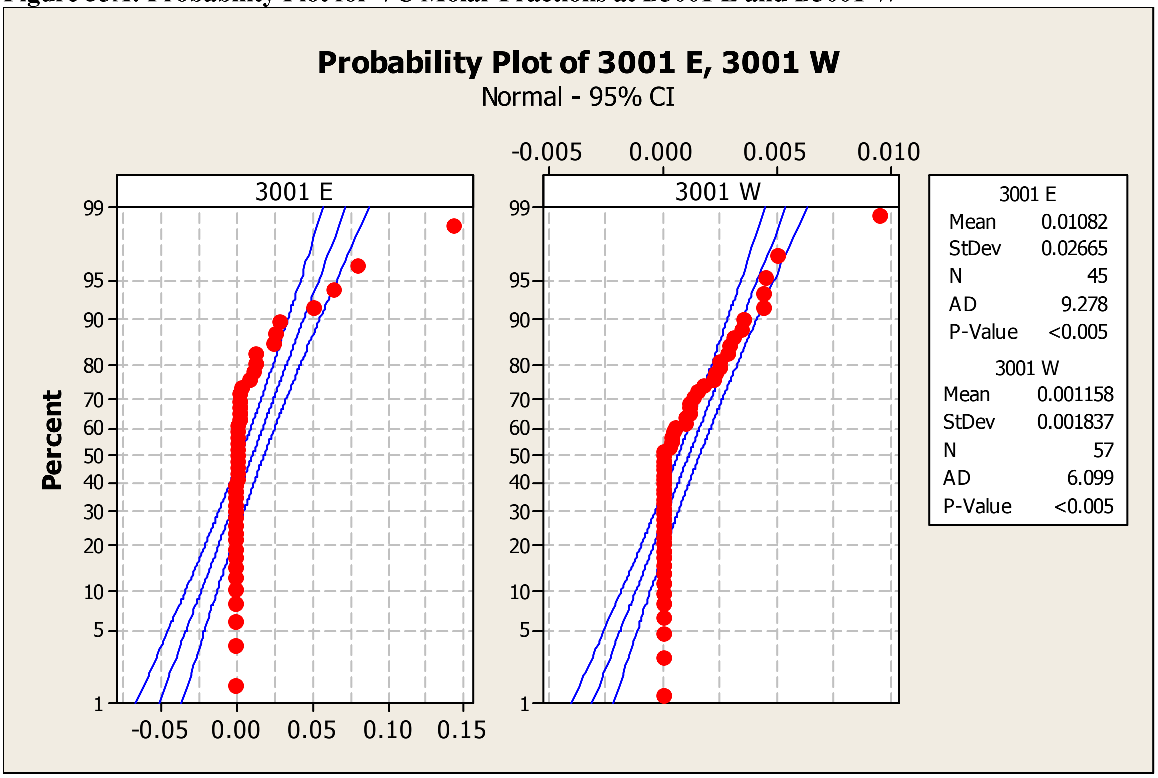
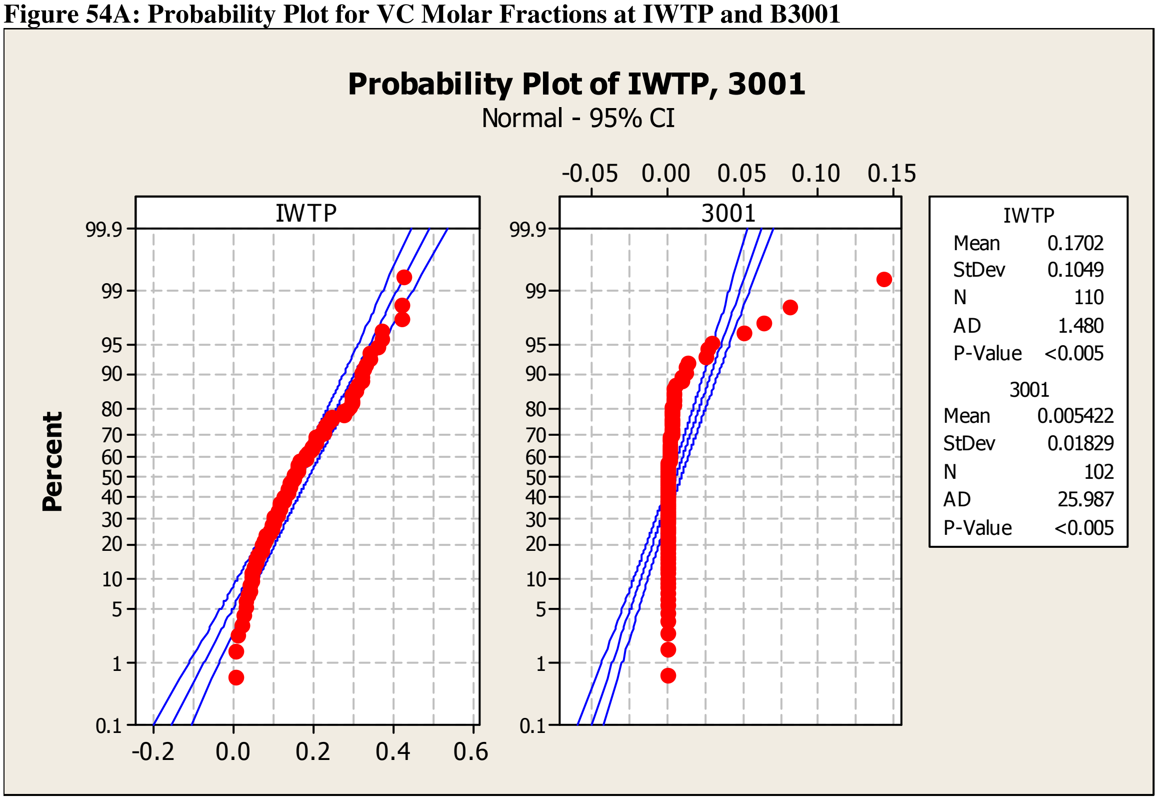


Figure 54A: Probability Plot for VC Molar Fractions at IWTP and B3001



VITA

Derek Adam Henderson

Candidate for the Degree of

Master of Science

Thesis: STATISTICAL ASSESSMENT OF SUSPECTED CO-MINGLED PLUME AT TINKER AIR FORCE BASE TO DETERMINE IF MULTIPLE SOURCES EXIST

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Personal Data: Born in Perry, Oklahoma, on January 23, 1980, the son of Roger and Suzanne Henderson. Husband on Min Cai Henderson.

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Name: Derek A. Henderson Date of Degree: July, 2007

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: STATISTICAL ASSESSMENT OF SUSPECTED CO-MINGLED PLUME AT TINKER AIR FORCE BASE TO DETERMINE IF MULTIPLE SOURCES EXIST

Pages in Study: 212 Candidate for the Degree of Master of Science

Major Field: Environmental Engineering

Scope and Method of Study: Contamination of the groundwater at Tinker AFB in the Building 3001 area was suspected of coming from multiple sources. In particular, the Industrial Waste Treatment Plant was a suspected second source of contamination. Various statistical analyses were performed to find statistical differences between various locations at the Building 3001 area and the Industrial Waste Treatment Plant area. Statistical methods included one-way, parametric analysis of variance testing, the Kruskal-Wallis method, the Mann-Whitney method, and correlation coefficients. Neural network models were also developed to determine associations between locations and sources. The statistical analyses and neural network models used chromium concentration and the concentration and molar fractions of four chlorinated solvents to determine statistical differences between locations representative of the Building 3001 plume and the Industrial Waste Treatment Plant plume. The hypothesis was that the Industrial Waste Treatment Plant plume would have statistically higher concentrations and molar fractions of dichloroethene and vinyl chloride, while the Building 3001 plume would have statistically higher concentrations and molar fractions of trichloroethene.

Findings and Conclusions: The statistical analyses showed statistically higher concentrations and molar fractions of dichloroethene and vinyl chloride at the Industrial Waste Treatment Plant plume. Statistical analyses also showed statistically higher concentrations and molar fractions of trichloroethene in the Building 3001 plume. The neural network models showed strong associations between the locations in the Industrial Waste Treatment Plant plume and the Industrial Waste Treatment Plant source. The neural network model also showed strong associations between locations within the Building 3001 plume and the Building 3001 source.

ADVISER'S APPROVAL: Dr. William F. McTernan