GROUNDWATER
SERVICES, INC.

# MULCH BIOWALL AND SURFACE AMENDMENT PILOT TEST

Site B301
Offutt AFB, Nebraska

Prepared by

Groundwater Services, Inc.
2211 Norfolk, Suite 1000
Houston, Texas 77098
(713) 522-6300

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**This document describes the results of a field test, which assessed the applicability and feasibility of promoting the in-situ bioremedition of chlorinated solvent compounds (PCE, TCE, etc.) by using a mulch biowall and surface amendment near Building 301 (B301), Offutt Air Force Base, Nebraska. The biowall was installed in the vicinity of MW-9 where the water table is high (i.e., 6 ft bgs) and was filled with mulch produced at the Base. The conceptual model for this technology is that the native organic matter fermented, producing hydrogen to stimulate reductive dechlorination. Similary, a natural organic matter amendment was applied to the ground above the plume in the vicinity of MW-9. This treatement method relies on infiltration to transport soluble organic matter into the subsurface, where the organic matter can then ferment, producing hydrogen to stimulate reductive dechlorination.**

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# TABLE OF CONTENTS

## MULCH BIOWALL AND SURFACE AMENDMENT PILOT TEST

Site B301
Offutt AFB, Nebraska

GSI Job No. G-2050
June 18, 2001

GROUNDWATER
SERVICES, INC.

# TABLE OF CONTENTS

## MULCH BIOWALL AND SURFACE AMENDMENT PILOT TEST

Site B301
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GROUNDWATER
SERVICES, INC.

*June 18, 2001*

# A FIELD TEST OF A MULCH BIOWALL AND SURFACE AMENDMENT FOR THE IN-SITU BIOREMEDIATION OF CHLORINATED HYDROCARBON IMPACTED GROUNDWATER

**Building 301**
**Offutt Air Force Base, Nebraska**

## 1.0 OVERVIEW

This document describes the results of a field test, which assessed the applicability and feasibility of promoting the in-situ bioremediation of chlorinated solvent compounds (PCE, TCE, etc.) by using a mulch biowall and surface amendment near Building 301 (B301), Offutt Air Force Base, Nebraska. The biowall was installed in the vicinity of MW-9 where the water table is high (i.e., 6 ft bgs) and was filled with mulch produced at the Base. The conceptual model for this technology is that the native organic matter fermented, producing hydrogen to stimulate reductive dechlorination. Similarly, a natural organic matter amendment was applied to the ground above the plume in the vicinity of MW-9. This treatment method relies on infiltration to transport soluble organic matter into the subsurface, where the organic matter can then ferment, producing hydrogen to stimulate reductive dechlorination.

This approach effectively simulates a Type 2 plume environment, as described in the "Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents In Ground Water" (Wiedemeier et al., 1998). A Type 2 plume is one where reductive dechlorination is supported by the utilization of a naturally occurring organic carbon source. Type 2 plume behavior has been documented in coastal regions and wetland environments where chlorinated solvents migrate into organic carbon-rich zones. Natural organic biowalls have been used successfully to promote nitrate attenuation by heterotrophic denitrification using 15-100% cellulose solids (Robertson et al., 2000; Schipper and Vojvodic-Vukovic, 1998).

In this work, natural organic matter in the form of mulch is used in a permeable reactive biowall to promote the in situ reductive dechlorination of chlorinated solvents in groundwater. The mulch lowers the dissolved oxygen concentration and oxidation-reduction potential (ORP) in the aquifer by acting as a source of

available carbon to aerobic bacteria. Once anaerobic conditions are created, fermentation of the organic matter generates hydrogen, which can be used to promote biological reductive dechlorination. Because mulch is inexpensive and permeable walls are passive, this technology has the potential to be a cost-effective solution for chlorinated solvent-impacted groundwater.

## 2.0 SITE DESCRIPTION AND HYDROGEOLOGIC SETTING

Offutt AFB is located approximately five miles south of Omaha, Nebraska. Building 301 is located in the eastern part of the Base, approximately 1500 ft from the railway tracks and 4300 ft from Papillion Creek (Figure 1).

B301 is situated on a dissected Pleistocene alluvial terrace remnant of the Missouri River with moderately sloping rolling hills. The area immediately surrounding B301 was leveled prior to its construction. To the west of B301, the ground surface slopes steeply downward into the Papillion Creek alluvial valley. More gradual downward slopes are present to the south and east of the building. Much of the area surrounding B301 is paved for the numerous roadways and parking lots that serve B301.

The pilot test was conducted near MW-9. In this area, the subsurface soil material consists of approximately 1-3 feet of fill, overlying either a stiff, black, low plastic, silty clay (topsoil) or a stiff to very stiff, light to reddish brown, low plastic, silty clay (Peoria and Loveland Loess). Near and west of the Base boundary, depth to groundwater is only 3 to 10 bgs. Depth to groundwater is 6 ft bgs near MW-9S.

The groundwater flow is predominantly westward, toward Papillion Creek and the Missouri River. The hydraulic conductivity in the alluvial silt and clay near MW-9 is 1.8E-3 cm/sec and averaged 3.5 ft/day (mean of 5 slug tests in alluvial silt and clay). The hydraulic gradient is 0.01 ft/ft. Using an assumed effective porosity of 0.15, the computed groundwater seepage velocity is 0.23 ft/day or 85 ft/yr. The Darcy velocity within the alluvial silts and clays of the Papillion Creek alluvial valley is estimated to range from 0.15 to 0.34 ft/day (Parsons Engineering Science, 1997). A summary of key aquifer parameters is provided in Table 1.

# 3.0 AFFECTED ENVIRONMENTAL MEDIA

## 3.1 Affected Soil

During a site investigation performed by WCC (1993), three soil samples were collected from each of six soil boreholes and analyzed for Appendix IX volatile organic compounds (VOC)s, semi-volatile organic compounds (SVOCs), organochlorine pesticides, PCBs, total petroleum hydrocarbons (TPH), total metals, and cyanide. All chlorinated compounds were below reporting limits. During a subsequent remedial investigation (WCC, 1996), nine additional soil samples were collected and analyzed for Appendix IX VOCs. TCE was detected in three of five soil samples collected at MW7I (depths ranging from 25 to 58 bgs) at concentrations ranging from 1.9 μg/kg to 18 μg/kg. TOC concentrations found in soils in the alluvial valley ranged from 0.030 to 0.355 percent.

## 3.2 Affected Groundwater

Groundwater quality data obtained during the RI and TS (Parsons Engineering Science, 1996) indicated that chlorinated aliphatic hydrocarbon (CAH) compounds were the primary contaminants of concern in the groundwater. TCE was the most prevalent CAH in both extent and concentration in the groundwater at B301. The distribution of TCE measured in June-July 1996 is presented in Figure 2. The source of TCE contamination appeared to be located beneath the northwestern corner of B301, as evidenced by the relatively elevated TCE concentration (17,500 μg/L) in the groundwater from MW7I (Figure 2). The plume extended westward approximately 2800 ft from the suspected source area. PCE was not a contaminant of concern, being detected only immediately downgradient of the source area at concentrations close to the quantitation limit (i.e., 1.5, 1.5, and 1.9 μg/L at MW7S, MW14, and MW18).

All three DCE isomers were detected in June-July 1996 groundwater samples, with cis-1,2-DCE being detected most frequently and at the highest concentrations (ranging up to 1,230 μg/L). Relatively low levels of trans-1,2-DCE and 1,1-DCE (ranging up to 9.4 and 28.6 μg/L, respectively) were detected, suggesting that cis-1,2-DCE is an intermediate of reductive dechlorination of TCE. The areal extent of the cis-1,2-DCE plume in June-July 1996 was significantly different than that of the TCE plume. The highest concentration of cis-1,2-DCE was detected at MW7I near the source area. DCE concentrations appeared to decrease west of the source area, but increased substantially near

and west of the Base property boundary. Only two samples contained detectable concentrations of vinyl chloride, a reductive dechlorination product of DCE, and no ethene was detected at quantifiable concentrations. These data suggested that reductive dechlorination was generally not proceeding past the transformation of TCE to DCE.

## 4.0 MULCH BIOWALL AND SURFACE AMENDMENT PILOT TESTS

### 4.1 Characteristics of the Test Location

At Site B301, the area near MW-9 was utilized for the mulch biowall pilot test and the surface amendment test (see Figure 2). This area was selected on the basis of: i) the presence of TCE and degradation products (e.g., cis-1,2-DCE) and ii) shallow depth to groundwater (6 ft bgs) to facilitate the installation of the biowall.

### 4.2 Fill Preparation and Biowall Installation

The fill consisted of a 1:1 by volume mixture of mulch and coarse sand (approximately 850 $ft^3$ mulch and 850 $ft^3$sand). The mulch was generated as part of a severe storm cleanup effort. Fallen tree limb and trunk material was passed through a tub grinder and stockpiled. The mulch contained mostly partially composted leave and twig material as well as some fine wood chips. The mulch was mixed with the sand using a backhoe, as shown in Figure 3a.

A 100 ft x 1 ft biowall was installed to 23 ft near MW-9, using a one-pass trencher, to intercept the groundwater plume. The biowall was simultaneously installed and filled to 2 ft below the surface with the mulch-sand mixture. Based on TCLP characterization of soil cuttings from wells drilled adjacent to the biowall, the soil removed from the biowall was deemed non-hazardous and was used to cap the biowall. A photograph of the continuous trencher is shown in Figure 3b and a cross-section of the mulch biowall is presented in Figure 4. The biowall was installed in January 1999.

### 4.3 Surface Amendment

The surface amendment test involved the application of mulch to the ground surface. This treatment method relied on infiltration to transport soluble organic

compounds in the mulch to the subsurface. Once in the subsurface, these compounds ferment, producing hydrogen needed for reductive dechlorination.

The surface amendment plot was constructed to be 30-ft long by 15-ft wide and approximately 2 ft deep. The plot was filled with mulch and bermed to prevent run-off. The surface amendment was located south of the biowall as shown in Figure 5.

### 4.4 Monitoring Well Installation

Four 2" PVC monitoring wells were installed via hollow stem auger to a depth of 20 ft downgradient of the mulch biowall. The downgradient wells were positioned at 10 and 20 ft intervals as shown in Figure 4. Existing wells (located 15 ft upgradient of the biowall) were used as the upgradient wells to monitor untreated ground water. A representative well construction diagram is shown in Figure 6.

Two 2" monitoring wells were installed to a depth of 20 ft downgradient of the surface amendment plot at 10 ft and 20 ft interval. An existing well (B301-MW22S) was located approximately 8 ft upgradient of the plot.

Two additional monitoring wells were installed within the contaminated plume area, south of the biowall and surface amendment plots, to act as control wells. Samples taken from these wells were used to compare the rate and extent of chlorinated solvent degradation due to natural attenuation versus mulch addition.

### 4.5 Sampling

#### 4.5.1 Analytes

The wells upgradient and downgradient of the mulch biowall and surface amendment plot were sampled for volatile organic compounds (VOCs) (PCE, TCE, cis-1,2-dichloroethylene (c-DCE), 1,1-DCE, and trans-1,2-dichloroethene (t-DCE) and vinyl chloride), alternate electron acceptors/by-products ($NO_3^-$, $SO_4^{2-}$, $Fe^{3+}$, $CH_4$, ethene, and ethane), total organic carbon, alkalinity, chloride, dissolved hydrogen, dissolved oxygen, pH, temperature, redox potential, and specific conductance. Sampling occurred at start-up in January 1999, in June 1999, February 2000 and August 2000. The two wells in the control plot were

sampled for the same analytes as the biowall and surface amendment plot, but only at the beginning and end of the test.

### 4.5.2 Sampling Protocols

Monitoring wells were sampled under low flow using a peristaltic pump. The pump was operated at approximately 300 mL/min. The well was purged until field parameters (i.e., pH, temperature, specific conductivity, ORP, and D.O.) stabilized. A flow-through cell was used to obtain field measurements of dissolved oxygen, redox potential, temperature, pH, and specific conductance. Sulfate, iron, and alkalinity measurements were made using field analytical kits manufactured by HACH Company, Loveland, CO. Headspace gases (hydrogen, methane, ethene, and ethane) were collected using the bubble-strip method. Gas samples were submitted to Microseeps, Inc., Pittsburgh, PA for gas chromatographic analysis. All other analyses were completed by SPL, Houston, TX using standard EPA methods.

### 4.5.3 Static Water Level Measurements

Static water level measurements were taken in all wells at each sampling event. Potentiometric surfaces were drawn for the test areas for each sampling event as shown in Figure 7. These surfaces indicate the direction of groundwater flow did not change appreciably over the life of the test and suggested that groundwater was flowing through the biowall. Furthermore, the potentiometric surfaces indicated that there was no appreciable biofouling or plugging sufficient for water to circumvent the biowall.

## 5.0 BASELINE RESULTS

### 5.1 Chlorinated Solvents and Daughter Products

Baseline data are presented in Table 2. No PCE was detected in the test area. TCE at concentrations ranging from 0.11 to 1.9 mg/L was measured. All three dichloroethene isomers (1,1,-DCE, trans-1,2-dichloroethene, and cis-1,2-dichloroethene) were detected. 1,1-DCE was present at concentrations ranging from <0.001 to 0.006 mg/L; trans-1,2-dichloroethene was present at concentrations ranging from <0.001 to 0.008 mg/L, and cis-1,2-dichloroethene was found at concentrations ranging from <0.001 to 0.27 mg/L. Vinyl chloride

concentrations ranged from <0.001 mg/L to 0.0025 mg/L. No ethene or ethane was detected in any samples. These data suggest that there was some reductive dechlorination of TCE to cis-1,2-dichloroethene, but generally minimal degradation beyond cis-1,2-dichloroethene.

### 5.2 Geochemical Parameters and Water Quality Indicators

The aquifer in the test area was aerobic, as indicated by the dissolved oxygen (1.0 to 3.0 mg/L), and the redox potential (133.2 to 197.5 mV). The total organic carbon in the test area was variable, ranging from <1.0 to 24 mg/L. The chloride concentration ranged from 8 to 19 mg/L. Sulfate was present at 29 mg/L to 74.6 mg/L and nitrate was present at 1.1 to 6.4 mg/L. Low levels of iron were detected (<0.02 to 0.27 mg/L). Methane was measured at <0.0012 to 0.099 mg/L.

## 6.0 MULCH BIOWALL TEST RESULTS

The following section describes the mulch biowall effects on the aquifer geochemistry and its effectiveness for the degradation of chlorinated solvents in groundwater. Compiled data from the three sampling events following the biowall installation can be found in Appendix A.

### 6.1 Water Quality Parameters

Table 3 presents mean water quality parameter values, both upgradient and downgradient of the mulch biowall, along with baseline water quality data and water quality data from the control plot in August 2000. No trends with respect to specific conductance, total organic carbon or chloride concentrations were observed. Chloride concentrations were not observed to increase downgradient because the amount of TCE degraded was not sufficient to generate a measurable amount of chloride. TOC was not observed to increase downgradient. It may have been consumed prior to being measured at the monitoring well 10 ft downgradient.

The groundwater temperature changed seasonally. During the June 1999 and February 2000 sampling events, the groundwater temperature was approximately 2 °F higher downgradient than upgradient. Small increases in temperature may be attributed to microbial heat generation.

## 6.2 Natural Attenuation Parameters

The mean natural attenuation parameter values upgradient and downgradient of the mulch biowall are presented in Table 4. Prior to the installation of the biowall, the aquifer was aerobic. After installation of the biowall, the aquifer became anaerobic due to the consumption of oxygen and natural organic matter by aerobic bacteria. The decline in the dissolved oxygen is shown in Figure 8. Concomitant with a reduction in the dissolved oxygen was a decline in the reduction-oxidation potential. Baseline and control area measurements showed no or less than 10 mV difference in redox potential, while differences of 37-45 mV were noted between upgradient and downgradient biowall wells (Table 4). As oxygen and other alternate electron acceptors are consumed, the redox potential is expected to fall. The optimum redox potential for reductive dechlorination is -100 mV (Weidemeier *et al.*, 1998). Negative redox potentials were not measured in this test, although reductive dechlorination was observed. These higher redox potentials may be the result of mixing of groundwater from different redox zones during sampling or it may be due to measurement inaccuracies in the redox probe.

Alternate electron acceptors, such as nitrate, ferrous iron, and sulfate, have the potential to compete with chlorinated solvents for electron donor. Ferrous iron was not detected throughout the test. Nitrate levels were found to decrease significantly downgradient of the mulch wall, indicating that nitrate reduction was being stimulated by the addition of electron donor to the aquifer. Sulfate reduction did not appear to occur until the February 2000 and August 2000 sampling events.

Another competing electron acceptor is carbon dioxide. Methanogenic bacteria can utilize carbon dioxide as an electron acceptor and hydrogen as an electron donor. In this study, the production of significant quantities of methane (over background conditions) was observed during the February 2000 and August 2000 sampling periods (Figure 8), the same periods where sulfate reduction was first observed. Generally, the methane concentrations were less than 2 mg/L.

Two other natural attenuation parameters that were measured were the hydrogen and alkalinity concentrations. Hydrogen is produced through the fermentation of the mulch and acts as one of the primary electron donors for the reductive dechlorination process. The concentration of hydrogen can indicate the redox potential of the aquifer. In this study, the hydrogen concentrations

were generally on the 1-2 nM level and did not necessarily increase downgradient of the wall. These concentrations are indicative of sulfate-reducing conditions (Wiedemeier et al., 1998).

Alkalinity was also measured as calcium carbonate. Alkalinity reflects the amount of carbon dioxide in the aquifer. When carbon dioxide is formed in the aquifer due to microbial activity, carbonic acid is formed that dissolves carbonate minerals, increasing the alkalinity of the groundwater. Higher alkalinity values are indicative of the production of carbon dioxide associated with microbial activity. Alkalinity was variable over time in the aquifer, but increased downgradient of the wall, as shown in Figure 8. No difference in alkalinity was noted in the control plot. This trend is further evidence of increased microbial activity as the result of the installation of the mulch biowall.

***Key Findings***

The mulch biowall decreased the dissolved oxygen and redox potential of the aquifer, creating conditions conducive to reductive dechlorination. Nitrate and sulfate reduction and methanogenesis were evident after 1 year, but did not prevent the reductive dechlorination of the chlorinated solvents. Hydrogen and TOC did not increase downgradient of the wall, which suggested that they were produced at low levels and/or were being rapidly consumed. Alkalinity increased downgradient of the biowall, indicating increased microbial activity as a result of the introduction of electron donor.

## 6.3 Chlorinated Solvents

Table 4 presents the chlorinated constituent concentration data upgradient and downgradient of the biowall as well as data from the baseline sampling event and the control plot. The following sections discuss TCE removal, and production of daughter and final reduction products as a result of passing through the mulch biowall.

### 6.3.1 TCE Degradation

Comparison of TCE concentrations upgradient and downgradient of the biowall demonstrate that the mulch biowall is effecting a significant removal of TCE, as shown in Figure 9. Mean upgradient TCE concentrations ranged from 0.3 to 2.1 mg/L, while mean downgradient TCE concentrations ranged from 0.1 to 0.5 mg/L 10 ft downgradient and 0.2 to 0.6 mg/L 20 ft downgradient of the biowall. The residence time of the groundwater in the wall is estimated to be 4 days, but

may be longer for chlorinated constituents, which may sorb to the organic matter in the mulch wall. In addition, organic carbon liberated by the mulch wall may travel downgradient with the groundwater allowing additional biological reaction time.

The mean upgradient concentration was 1.3 mg/L and the mean TCE concentration 10 ft downgradient was 0.35 mg/L. Therefore, the biowall was removing an average of 0.95 mg/L. Using a seepage velocity of 85 ft/yr, a porosity of 0.15, a width of 100 ft and a depth of 17 ft (amount of the biowall in the saturated zone), approximately 15.7 kg/yr of TCE was removed by the biowall.

### 6.3.2 Production of Daughter Products

The mulch biowall was clearly enhancing reductive dechlorination because of the production of daughter products (i.e., cis-1,2-dichloroethylene, vinyl chloride, ethane, and ethane) downgradient of the biowall as shown in Figure 9.

c-DCE is a indicator of reductive dechlorination, because it is found in very small quantities in commercially produced dichloroethene. The concentration of c-DCE increased 40 fold as a result of passing through the biowall during the first sampling event. The presence of c-DCE downgradient of the biowall was further indication that the c-DCE was being produced as a result of the reductive dechlorination of TCE. The presence of c-DCE downgradient of the biowall was further evidence that water was passing through the wall. After the June 1999 sampling event, the amount of c-DCE declined, although TCE continued to be removed (Figure 9). Some of the c-DCE was being converted to vinyl chloride, ethene, and ethane, but much of the decline cannot be accounted for by reductive dechlorination end-products (see Section 6.3.4 for further discussion). Some of the c-DCE may have been mineralized in aerobic microenvironments or c-DCE may have sorbed to the aquifer matrix.

Because the TCE concentration in the incoming groundwater changed significantly over the course of the 19 month test, the use of the ratio of c-DCE:TCE is informative. This ratio gives an indication of the extent of reductive dechlorination. Upgradient wells showed mean c-DCE:TCE ratios of 0.01-0.03, while downgradient wells had c-DCE:TCE ratios as high as 28, as shown in Figure 9. An increased c-DCE:TCE ratio is further evidence of reductive dechlorination.

Vinyl chloride can be produced as the result of the reductive dechlorination of c-DCE. Vinyl chloride is a carcinogen and generally degrades more slowly than the other chlorinated constituents under reduced conditions (Vogel et al., 1987). In this study, small amounts of vinyl chloride were produced but the concentrations were less than 3 µg/L. This concentration compares to non-detect or 1 µg/L levels found in the upgradient and control areas. Low concentrations of vinyl chloride may be attributed to rapid degradation of vinyl chloride by a variety of mechanisms including anaerobic oxidation (Bradley and Chapelle, 1996), aerobic mineralization (Hartmans et al., 1985) or cometabolism (Vogel, 1994) in aerobic microenvironments, and reductive dechlorination (Vogel and McCarty, 1985).

The final reduction products of TCE are chloride, ethene, and ethane. Because the concentrations of TCE are low on a molar basis, no increase in chloride was observed. The production of ethene and ethane increased with time, suggesting the growth or adaptation of bacteria capable of reductive dechlorinating vinyl chloride (Figure 9). Production of ethene and ethane also corresponds to when sulfate-reducing and methanogenic conditions were observed in the aquifer. Dechlorination of TCE to DCE can proceed under nitrate or iron (III) reducing conditions (Vogel et al., 1987), while the transformation of DCE to VC and VC to ethene requires more strongly reducing conditions (Freedman and Gossett, 1989; DeStefano et al., 1991; DeBruin et al., 1992).

### 6.3.3 Comparison of the Biowall to the Control

The mean % removals of TCE and of the total chlorinated solvents are shown in Table 5 for both the biowall and the control plot. By averaging the upgradeint concentrations and concentrations 10 ft downgradient, a mean % TCE removal of 73% was calculated. This compares favorably with the natural attenuation control plot that showed an average increase of 20% in TCE concentrations over the course of the test, indicating slight increases in the constituent concentrations. By subtracting the mean total molar concentrations of chlorinated constituents downgradient from the mean total molar concentrations of chlorinated constituents upgradient of the biowall, the % removal of total chlorinated solvents was calculated over the course of the test. The mean % removal of chlorinated constituents was 60%, while the control plot had a mean % increase of 12%. Overall, the mulch biowall achieved significantly greater reductive dechlorination than natural attenuation alone.

### 6.3.4 Molar Balance

To shed some light on the mechanisms of removal, the amount of TCE and total chlorinated solvent removal that could be accounted for in daughter and end-products was calculated as shown in Table 5. Only approximately 25% of the TCE removed could be accounted for by c-DCE, VC, ethene, and ethane. Furthermore, the amount of complete dechlorination (that is the amount of dechlorination that can be accounted for by ethene and ethane) is only 10%. Because of the production of daughter products such as c-DCE and VC, it is clear that reductive dechlorination is occurring. The low molar balances indicate that several other mechanisms are at work. First, the low amount of ethene and ethane recovered could be due to losses to the vadose zone, thus underestimating the amount of complete reductive dechlorination. Also, aerobic microenvironments may have stimulated the aerobic biodegradation of the daughter products. Lastly, it is possible that sorption of TCE and the daughter products occurred in the mulch biowall or to the aquifer matrix. The benefit of sorption of chlorinated constituents to the mulch is increased residence time in close proximity to the carbon and hydrogen source. Future monitoring of the biowall will involve sampling of the mulch to assess the degree of sorption.

***Key Findings***

Significant TCE removal was effected by the mulch biowall (mean of 73%). Reductive dechlorination was stimulated as evidenced by the production of c-DCE, vinyl chloride, ethene, and ethane, well in excess of the concentrations produced in the control plot. Vinyl chloride did not accumulate and was less than 3 □g/L. Ethene and ethane were detected and increased in concentration after sulfate and methanogenic conditions were established in the aquifer. The production of daughter products only accounts for approximately 25% of the removal of TCE. Other removal mechanisms at work may be sorption of the TCE and daughter products to the mulch and/or mineralization of c-DCE, VC, ethene and ethane to carbon dioxide via other biological pathways.

## 7.0 SURFACE AMENDMENT TEST RESULTS

### 7.1 Water Quality Parameters

Table 6 presents mean water quality parameter values, both upgradient and downgradient of the mulch surface amendment, along with baseline water quality data and water quality data from the control plot. No trends with respect

to specific conductance, total organic carbon, temperature, and pH were observed. Chloride concentrations were observed to decrease slightly downgradient of the surface amendment.

## 7.2 Natural Attenuation Parameters

Mean natural attenuation parameter values upgradient and downgradient of the mulch surface amendment are also presented in Table 6. Prior to the installation of the surface amendment, the aquifer was aerobic. After addition of the surface amendment and infiltration of carbon, the aquifer became anaerobic due to the consumption of oxygen and natural organic matter by aerobic bacteria. The decline in the dissolved oxygen is shown in Figure 10. Interestingly, the aquifer remained anaerobic even during the winter when infiltration of carbon rich water would be impeded by surface freezing and snow. Although the dissolved oxygen was seen to decrease during the test, the redox potential remained unaffected.

Alternate electron acceptors, such as nitrate, ferrous iron, and sulfate have the potential to compete with chlorinated solvents for electron donor. Ferrous iron was not detected throughout the test. Nitrate levels were found to decrease downgradient of the mulch surface amendment, indicating that nitrate reduction was being stimulated by the addition of electron donor to the aquifer. Sulfate reduction did not appear to occur until February 2000, but the amount of sulfate degraded was low (on the order of 3-5 mg/L). No sulfate or nitrate reduction was observed in the control plot, indicating that the infiltration of carbon substrate was having an effect on the subsurface environment.

Another competing electron acceptor is carbon dioxide. Methanogenic bacteria can utilize carbon dioxide as an electron acceptor and hydrogen as an electron acceptor. In this study, only low levels of methane were produced (i.e., <72 µg/L). Generally methane concentrations in the surface amendment test area were similar to those measured in the control area.

The concentration of hydrogen is important because it can indicate the redox condition of the aquifer. In this study, the hydrogen concentrations were on the 1-2 nM level, indicating sulfate-reducing conditions. Hydrogen concentrations did not increase downgradient of the surface amendment suggesting that either hydrogen was being consumed as quickly as it was being produced, or limited fermentation was occurring.

Alkalinity as calcium carbonate was also measured. Higher alkalinity values are indicative of the production of carbon dioxide associated with microbial activity. Alkalinity was variable over time in the aquifer, but increased significantly downgradient of the surface amendment in June 1999 only, as shown in Table 6 and Figure 10. No difference in alkalinity concentrations was noted in the control plot. This result indicated a period of increased microbial activity as the result of the application of the surface amendment.

***Key Findings***

The mulch surface amendment caused a depression in the dissolved oxygen due to the infiltration of soluble organic matter. Increased nitrate reduction and some transitory sulfate reduction were observed. Very little methanogenesis occurred. In June 1999, increased alkalinity was measured, indicating increased microbial activity.

## 7.3 Chlorinated Solvents

The chlorinated constituent concentration data upgradient and downgradient of the surface amendment are found in Table 7. The following sections discuss TCE removal, and production of daughter and final reduction products as a result of passing under the mulch surface amendment.

### 7.3.1 TCE Degradation

Comparison of mean upgradient TCE and mean downgradient TCE concentrations indicate that very little TCE is being degraded. Mean upgradient TCE concentrations range from 0.6 to 1.6 mg/L, while downgradient TCE concentrations range from 0.4 to 0.6 as shown in Figure 11. Although there appears to be a reduction in TCE concentration during the August 2000 sampling event, the lag time between the upgradient and downgradient wells must be considered. That is, the upgradient water will take several months to travel from the upgradient well to the downgradient well and therefore samples taken from the same sampling event should not be directly compared.

### 7.3.2 Production of Daughter Products

The production of c-DCE was observed during the first sampling event and then tapered off for the remainder of the test as shown in Figure 11. The ratio of c-DCE to TCE concentrations shows a similar pattern, with a large increase in the ratio observed during the June 1999 sampling event. Vinyl chloride

concentrations were generally low between non-detect and 2 µg/L. A slight increase in vinyl chloride was observed during the June 1999 sampling event, after which vinyl chloride declined to background conditions. Slightly elevated ethene concentrations (i.e., mean concentration of 140 ng/L) during the June 1999 sampling event. No ethane was detected until February 2000.

Limited reductive dechlorination was expected during the February 2000 time frame due to freezing conditions preventing infiltration of organic constituents to the subsurface. However, reductive dechlorination did not commence again in August 2000, suggesting that the available carbon in the mulch had been consumed and/or it was not infiltrating to the subsurface.

### 7.3.3 Comparison of the Surface Amendment to the Control Plot

The mean % removals of TCE and of the total chlorinated solvents are shown in Table 8 for both the surface amendment and the control plot. The mean %TCE removal over the course of the test was 21% and the mean % total chlorinated solvent removal was 5%. Seventy-five percent of the TCE removed could be accounted for by production of daughter products, indicating that reductive dechlorination was the predominant removal mechanism. However, negligible amounts of ethene and ethane were produced. The TCE and Total Chlorinated Solvent concentrations increased slightly within the control plot, indicating no significant removal by natural attenuation. Overall, the reductive dechlorination achieved with the mulch surface amendment was only slightly greater than that from natural attenuation. This technology may be more suited for sandy aquifers with higher rates of infiltration.

***Key Findings***

Some TCE was degraded during the first part of the test, as evidenced by the production of c-DCE measured in the June 1999 sampling event. Very little vinyl chloride, ethene, and ethane were generated. The effect of the surface amendment appeared short-lived and was not observed after the first sampling event. The June 1999 time frame was the only time when methanogenesis was observed, albeit at low levels. Generally the aquifer was under nitrate reducing conditions, which may have precluded the further dechlorination of TCE and c-DCE to VC and end-products.

## 8.0 MULCH BIOWALL ECONOMICS

The attractiveness of this technology is the cheap cost of the mulch (electron donor). In this particular case, mulch was obtained free of charge. Mulch can also be purchased for less than $20/yd^3$ or 1 cent/lb. Mulch is cheaper than other organic electron donors such as hydrogen releasing compound ($6/lb) and molasses and vegetable oil, which cost on the order of $0.20-0.50/lb (Harkness, 2000). Although mulch appears less effective in treating chlorinated constituents than zero valent iron, it is much cheaper than iron, which costs approximately $350/ton or $700/yd$^3$(Peerless, Inc., personal communication). Therefore, potential cost-effective applications of the mulch biowall are as pre- or post-treatment steps, in conjunction with zero valent iron walls, to significantly decrease the amount of iron that is required to achieve clean-up objectives.

A shallow mulch biowall installed using a continuous trencher will cost approximately $140-360/linear foot, depending on the length and contractor. Shorter trenches are more expensive on a linear-foot basis. Mobilization and demobilization will cost an additional $20-40K. Biowalls installed using a continuous trencher are generally limited to a depth of approximately 30 ft. Deeper biowalls can be constructed using conventional excavation, which will be more expensive and time-intensive.

The benefit of a passive biowall is the low operating and maintenance costs. Once installed the biowall requires no energy and very little maintenance. Only monitoring of the groundwater is required. One unknown with respect to maintenance costs is the longevity or replacement frequency of the mulch. Other investigators have installed walls filled with a variety of waste cellulose solids for the treatment of nitrate-contaminated water and have found very little reduction in performance during 7 years of operation (Robertson et al., 2000). Therefore, the mulch biowall can be estimated to last somewhere between 7 and 10 years. Further performance monitoring of the mulch biowall at Offutt AFB will be conducted over the next several years to better estimate mulch longevity.

## 9.0 SUMMARY

A 19-month pilot test of a mulch biowall was performed at Site Building 301 at Offutt AFB. The test was conducted to evaluate the effectiveness of mulch as an electron donor to stimulate the reductive dechlorination of TCE in the groundwater. In January 1999, the mulch biowall was installed using a continuous trencher. The dimensions of the biowall were 100 ft x 1 ft x 23 ft deep. The trench was filled with a 1:1 mixture of sand and mulch. In addition to the mulch biowall, a mulch surface amendment was added to a plot to promote the infiltration of carbon-laden water. Monitoring wells were installed upgradient and gradient of the biowall and surface amendment. In addition, two wells were installed away from the surface amendment and biowall but within the plume to act as controls. Results of the biowall and surface amendment tests are summarized below.

### 9.1 Results of the Mulch Biowall Test

The mulch biowall decreased the dissolved oxygen and redox potential of the aquifer, creating conditions conducive to reductive dechlorination. Nitrate and sulfate reduction and methanogenesis were evident after 1 year, but did not prevent the reductive dechlorination of the chlorinated solvents. Hydrogen and TOC did not increase downgradient of the wall, which suggested that they were produced at low levels and/or were being rapidly consumed. Alkalinity increased downgradient of the biowall, indicating increased microbial activity as a result of the introduction of electron donor.

Significant TCE removal was effected by the mulch biowall (mean of 73% over the test period). Reductive dechlorination was stimulated as evidenced by the production of c-DCE, vinyl chloride, ethene, and ethane, well in excess of the concentrations produced in the control plot. Vinyl chloride did not accumulate and was less than 3 µg/L. Ethene and ethane were detected and increased in concentration after sulfate and methanogenic conditions were established in the aquifer. The production of daughter products only accounts for approximately 25% of the removal of TCE. Other removal mechanisms at work may be sorption of the TCE and daughter products to the mulch and/or mineralization of c-DCE, VC, ethene and ethane to carbon dioxide via other biological pathways.

### 9.2 Results of the Surface Amendment Test

The mulch surface amendment caused a depression in the dissolved oxygen due to the infiltration of soluble organic matter. Increased nitrate reduction and some transitory sulfate reduction were observed. Very little methanogenesis occurred.

Some TCE was degraded during the first 5 months of the test, as evidenced by the production of c-DCE measured in the June 1999 sampling event. Very little vinyl chloride, ethene, and ethane were generated. The effect of the surface amendment appeared short-lived and was not observed after the first sampling event. The June 1999 time frame was the only time when methanogenesis was observed, albeit at low levels. Generally the aquifer was under nitrate reducing conditions, which may have precluded the further dechlorination of TCE to c-DCE,VC and end-products. To facilitate the infiltration of carbon, this technology may be more effective in more temperate climates, with year-round precipitation and no freezing.

## 10.0 FUTURE WORK

A full-scale mulch biowall will be installed in July 2001 at Offutt AFB. The biowall will be 500 ft long to treat the entire width of the plume in the same general area as the pilot test biowall. The full-scale biowall will be constructed in the same way as the pilot biowall, but it will be made 1.5 ft wide to increase the residence time and fermentable carbon available for reductive dechlorination.

## 11.0 REFERENCES

Bradley, P.M. and F.H. Chapelle. 1996. Anaerobic mineralization of vinyl chloride in Fe(III)-reducing aquifer sediments. *Environ. Sci. Technol.* 40:2084-2086.

DeBruin, W.P., M.J.J. Kotterman, M.A. Posthumus, G. Schraa, and A.J.B. Zehnder. 1992. Complete biological reductive transformation of tetrachloroethene to ethane. *Appl. Environ. Microbiol.* 58(6): 1966-2000.

DeStefano, T.D., J.M. Gossett, and S.H. Zinder. 1991. Reductive dehalogenation of high concentration of tetrachloroethene to ethene by an anaerobic enrichment culture in the absence of methanogenesis. *Appl. Environ. Microbiol.* 57(8): 2287-2292.

Freedman, D.L and Gossett, J.M. 1989. Biological reductive dehalogenation of tetrachloroethylene and trichloroethylene to ethylene under methanogenic conditions. *Appl. Environ. Microbiol.*, 55(4): 1009-1014.

Harkness, M.R. 2000. Economic Considerations in Enhanced Anaerobic Biodegradation. Bioremediation and Phytoremediation of Chlorinated and Recalcitrant Compounds. G. B. Wickramanayake, A. R. Gavaskar, B.C. Alleman, and V.S Magar, Eds. *The Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds Conference*. Monterey, California, May 22-25, 2000, Battelle Press, Columbus, Ohio, pg. 9-148.

Hartmans, S., J.A.M. de Bont, J. Tramper, and K. Ch.A.M Luben. 1985 Bacterial degradation of vinyl chloride. *Biotechnol. Lett.*, 7(6)383-388.

Parsons Engineering Science, Inc. 1997. *Remediation by Natural Attenuation Treatability Study for Building 301 Offutt AFB, Nebraska.* Prepared for the Air Force Center for Environmental Excellence, Technology Transfer Division, Brooks AFB, Texas, June 1997.

Robertson, W.D. D.W. Blowes, C.J. Ptacek, and J.A. Cherry. 2000. Long-Term Performance of In Situ Reactive Barriers for Nitrate Remediation. *Ground Water. 38*(5):689-695.

Schipper, L., and M. Vojvodic-Vukovic. 1998. Nitrate Removal from Groundwater Using a Denitrification Wall Amended with Sawdust: Field Trial. *J. Environ. Qual.* 27:664-668.

Vogel, T.M. and P.L. McCarty. 1985. Biotransformation of tetrachloroethylene to trichloroethylene, dichloroethylene, vinyl chloride, and carbon dioxide under methanogenic conditions. *Appl. Environ. Microbiol.* 49(5):1080-1083.

Vogel, T.M., C.S. Criddle, and P.L. McCarty. 1987. Transformation of halogenated aliphatic compounds. *Environ. Sci. Technol.* 21(8): 722-736.

Vogel, T.M. 1994. Natural bioremediation of chlorinated solvents, In Handbook of Bioremediation: Norris, R.D., R.E. Hinchee, R. Brown, P.L. McCarty, L. Semprini, J.T. Wilson, D.H. Kampbell, M. Reinhard, E.J. Bouwer, R.C. Borden, T.M. Vogel, J.M. Thomas, and C.H. Ward, Eds. Lewis Publishers, Boca Raton, FL, p201-225.

Wiedemeier, T.H., M.A. Swanson, D.E. Moutoux, E.K. Gordon, J.T. Wilson, B.H. Wilson, D.H. Kampbell, P.E. Haas, R.N. Miller, J.E. Hansen, and F.H. Chapelle. 1998. *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water*. U.S. EPA. EPA/600/R-98/128.

GSI Job No. G-2050
June 18, 2001

GROUNDWATER SERVICES, INC.

# Mulch Biowall and Surface Amendment Pilot Test

Site B301
Offutt AFB, Nebraska

## TABLES

GROUNDWATER SERVICES, INC.

# TABLE 1
## HYDROGEOLOGICAL CHARACTERISTICS OF TEST SITE

**Building 301**
**Offutt Air Force Base, Nebraska**

| PARAMETER | VALUE |
|---|---|
| Representative Media Type | Alluvial silt and clay |
| Depth to Water (ft, BGS) | 6 |
| Saturated Thickness (ft) | 30 |
| Hydraulic Conductivity, K (ft/d) | 3.5 |
| Groundwater Gradient, i (ft/ft) | 0.01 |
| GW Seepage Velocity (ft/d) | 0.23 |

NOTES
1. Groundwater seepage velocity computed as K*i/n. Effective porosity, n, assumed to be 0.15 (Parsons Engineering Science, 1996).
2. Hydraulic conductivity estimated based on pumping tests completed in nearby wells.

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# TABLE 2
## JANUARY 1999 BASELINE SAMPLING
## BIOWALL AND SURFACE AMENDMENT TESTS AT SITE B301, OFFUTT AFB, NEBRASKA

### Test Program for In-Situ Dechlorination by NOM Addition
### Air Force Center for Environmental Excellence, Brooks AFB, Texas

| | Units | Plume Area Monitoring Wells | | | | | |
|---|---|---|---|---|---|---|---|
| | | Blank | B301-22S | B301-23S | B301-24S | B301-27S | B301-28S |
| **Chlorinated Organics and Reduction By-Products** | | | | | | | |
| PCE | mg/L | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| TCE | mg/L | <0.001 | 0.63 | 0.67 | 1.9 | 0.11 | 0.13 |
| 1,1-DCE | mg/L | <0.001 | 0.0062 | 0.0064 | 0.003 | <0.001 | <0.001 |
| cis-1,2-DCE | mg/L | <0.001 | 0.0078 | 0.0082 | 0.02 | 0.0081 | 0.0029 |
| trans-1,2-DCE | mg/L | <0.001 | <0.001 | 0.0016 | 0.0041 | 0.0075 | 0.0012 |
| Vinyl chloride | mg/L | <0.001 | <0.001 | <0.001 | <0.001 | 0.0012 | <0.001 |
| Ethene | mg/L | <0.0032 | <0.0032 | <0.0032 | <0.0032 | <0.0032 | <0.0032 |
| Ethane | mg/L | <0.0025 | <0.0025 | <0.0025 | <0.0025 | <0.0025 | <0.0025 |
| **Water Quality Parameters** | | | | | | | |
| Temperature | °F | -- | 37.6 | 40.7 | 45.1 | 38.9 | 41.7 |
| pH | pH units | -- | 6.94 | 6.90 | 6.88 | 7.18 | 7.23 |
| Specific conductance | µ mhos/cm | -- | 1,026 | 877 | 1,027 | 453 | 947 |
| Total organic carbon | mg/L | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | 2 |
| Chloride | mg/L | <1.0 | 12 | 13 | 19 | 9 | 8 |
| **Natural Attenuation Parameters** | | | | | | | |
| Dissolved oxygen | mg/L | -- | 1.1 | 1.5 | 1.0 | 1.8 | 3.0 |
| Redox potential | mV | -- | 142.1 | 166.5 | 174.8 | 152.7 | 190.3 |
| Sulfate | mg/L | <0.2 | 31.9 | 35.0 | 45.2 | 29.0 | 32.2 |
| Nitrate | mg/L | <0.1 | 5.2 | 4.9 | 5.7 | 1.1 | 1.6 |
| Ferrous Iron | mg/L | <0.02 | 0.04 | 0.04 | <0.02 | <0.02 | 0.25 |
| Methane | mg/L | 0.0038 | <0.0012 | 0.0028 | <0.0012 | 0.027 | 0.034 |
| Hydrogen | nM | 1.24 | 1.29 | 2.14 | 2.23 | -- | -- |

Notes:
1. All analyses performed at Southern Petroleum Laboratories, Inc., Houston, Texas. Chlorinated organics analyzed by EPA Method 8021; chloride, sulfate, and nitrate by Method 300; iron by Method 6010B; and TOC by Method 9060. Ethene, ethane, and methane were analyzed by GC/FID
2. Additional detections: toluene in well B301-1 at 0.0023 mg/L and chloroethane in well B301-8 at 0.0011 mg/L.
3. -- = Not measured. < = Compound analyzed for but not detected at detection limit indicated.

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## TABLE 2
## JANUARY 1999 BASELINE SAMPLING
## BIOWALL AND SURFACE AMENDMENT TESTS AT SITE B301, OFFUTT AFB, NEBRASKA

**Test Program for In-Situ Dechlorination by NOM Addition**
**Air Force Center for Environmental Excellence, Brooks AFB, Texas**

| | Plume Area Monitoring Wells | | | | | |
|---|---|---|---|---|---|---|
| | B301-29S | B301-30S | B301-31S | B301-32S | B301-33S | B301-34S |
| **Chlorinated Organics and Reduction By-Products** | | | | | | |
| PCE | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| TCE | 0.41 | 0.3 | 0.28 | 0.67 | 1.3 | 1.3 |
| 1,1-DCE | 0.0026 | 0.0018 | 0.0032 | 0.0024 | 0.0023 | 0.0023 |
| cis-1,2-DCE | 0.030 | 0.018 | 0.27 | 0.07 | 0.045 | 0.020 |
| trans-1,2-DCE | 0.0033 | 0.002 | 0.0083 | 0.0068 | 0.0041 | 0.0027 |
| Vinyl chloride | 0.0025 | 0.0011 | 0.0023 | 0.0013 | <0.001 | <0.001 |
| Ethene | <0.0032 | <0.0032 | <0.0032 | <0.0032 | <0.0032 | <0.0032 |
| Ethane | <0.0025 | <0.0025 | <0.0025 | <0.0025 | <0.0025 | <0.0025 |
| **Water Quality Parameters** | | | | | | |
| Temperature | 47.3 | 44.7 | 40.5 | 43.1 | 34.1 | 44.5 |
| pH | 7.09 | 7.10 | 6.89 | 7.64 | 7.91 | 6.97 |
| Specific conductance | 925 | 874 | 1,110 | 973 | 1,075 | 1,078 |
| Total organic carbon | 4 | 2 | 24 | 13 | 15 | 5 |
| Chloride | 11 | 10 | 9 | 10 | 13 | 10 |
| **Natural Attenuation Parameters** | | | | | | |
| Dissolved oxygen | 2.7 | 2.8 | 2.4 | 2.5 | 2.3 | 2.4 |
| Redox potential | 190.2 | 197.5 | 133.2 | 159.6 | 177.1 | 182.6 |
| Sulfate | 38.5 | 34.8 | 57.3 | 53.2 | 74.6 | 59.0 |
| Nitrate | 1.7 | 1.8 | <0.5 | 4.9 | 4.7 | 6.4 |
| Ferrous Iron | 0.03 | 0.27 | 0.03 | 0.05 | <0.02 | 0.06 |
| Methane | 0.0067 | 0.0094 | 0.017 | 0.099 | 0.016 | 0.003 |

Notes:
1. All analyses performed at Southern Petroleum Laboratories, Inc., Houston, TX. Chlorinated organics analyzed by Method 8021; chloride, sulfate, and nitrate by Method 300; iron by Method 6010B; and TOC by Method 9060. Ethene, ethane, and methane were analyzed by GC/FID
2. Additional detections: toluene in well B301-1 at 0.0023 mg/L and chloroethane in well B301-8 at 0.0011 mg/L.
3. -- = Not measured.

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**TABLE 3**
**EFFECT OF MULCH BIOWALL ON WATER QUALITY AND NATURAL ATTENUATION PARAMETERS**
**MULCH BIOWALL TEST AT SITE B301, OFFUTT AFB, NEBRASKA**

**Test Program for In-Situ Dechlorination by NOM Addition**
**Air Force Center for Environmental Excellence, Brooks AFB, Texas**

| | | BASELINE | | BIOWALL | | | | | | CONTROL | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Units | Jan. '99 Mean Upgradient MW23S, MW24S | Jan. '99 Mean Downgradient MWs 31, 32, 33, 34 | Jun. '99 Mean Upgradient MW23S, MW24S | Jun. '99 Mean Downgradient MWs 31, 32, 33, 34 | Feb. '00 Mean Upgradient MW23S, MW24S | Feb. '00 Mean Downgradient MWs 31, 32, 33, 34 | Aug. '00 Mean Upgradient MW23S, MW24S | Aug. '00 Mean Downgradient MWs 31, 32, 33, 34 | Jan. '99 Upgradient MW27S | Jan. '99 Downgradient MW28S | Aug. '00 Upgradient MW27S | Aug. '00 Downgradient MW28S |
| **Water Quality Parameters** | | | | | | | | | | | | | |
| Temperature | °F | 42.9 | 40.6 | 65.1 | 66.9 | 51.2 | 53.3 | 62.4 | 59.0 | 38.9 | 41.7 | 61.3 | 61.5 |
| pH | pH units | 6.89 | 7.35 | 7.10 | 7.05 | 6.21 | 5.73 | 6.41 | 6.44 | 7.18 | 7.23 | 6.71 | 6.64 |
| Specific conductance | µ mhos/cm | 952 | 1059 | 698 | 840 | 801 | 796 | 667 | 711 | 453 | 947 | 645 | 635 |
| Total organic carbon | mg/L | <1.0 | 14.3 | 3.0 | 3.0 | <1.0 | 1.2 | <1.0 | 1.3 | <1.0 | 2.0 | <1.0 | <1.0 |
| Chloride | mg/L | 16 | 11 | 17 | 18 | 20 | 16 | 16 | 16 | 9 | 8 | 7 | 7 |
| **Natural Attenuation Parameters** | | | | | | | | | | | | | |
| Dissolved oxygen | mg/L | 1.3 | 2.4 | 1.1 | 0.50 | 2.2 | 0.21 | 0.02 | 0.03 | 1.80 | 3.00 | 0.01 | 0.03 |
| Redox potential | mV | 170.7 | 163.1 | 128.0 | 88.4 | 199.5 | 162.5 | 214.7 | 169.5 | 152.7 | 190.3 | 220.4 | 220.6 |
| Sulfate | mg/L | 40.1 | 61.0 | 11.0 | 17.8 | 40.0 | 15.5 | 40.00 | 16.75 | 29 | 32.2 | 22 | 22 |
| Nitrate | mg/L | 5.3 | 4.1 | 2.1 | 1.3 | 4.6 | 0.75 | 2.70 | 0.95 | 1.1 | 1.6 | 0.15 | 0.50 |
| Ferrous Iron | mg/L | 0.02[5] | 0.04[5] | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.02 | 0.25 | <0.2 | <0.2 |
| Methane | ug/L | 1.7[6] | 33.8[6] | 0.1 | 43.2 | 0.2 | 1796.6 | 0.81 | 656.915 | 0.027 | 0.034 | 4.335 | 2.403 |
| Hydrogen | nM | 2.2 | -- | 1.1 | 1.1 | 1.3 | 1.9 | 0.8 | 0.6 | -- | -- | 0.8 | 0.5 |
| Alkalinity | mg/L | -- | -- | 320 | 410 | 93 | 121 | 360 | 393 | -- | -- | 400 | 400 |

Notes:

1. The following analyses were performed at Southern Petroleum Laboratories, Inc.(SPL), Houston, Texas: chloride, and nitrate by Method 300, and TOC by Method 9060. Methane was analyzed by GC/FID and hydrogen was analyzed by GC/RGD by Microseeps, Inc., Pittsburgh, PA.
2. Sulfate, Ferrous Iron and Alkalinity were measured in the field using Hach kits. The respective detection limits are 1 mg/L, 0.2 mg/L and 5 mg/L.
3. -- = Not measured.
4. Half the detection limit was used in the calculation of mean values.
5. In Jan. 99, ferrous iron was measured using Method 6010B by SPL. The detection limit is 0.02 mg/L
6. In Jan. 99, methane was measured using GC/FID by SPL. The method detection limit was 0.0012 mg/L.

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**TABLE 4**
**EFFECT OF MULCH BIOWALL ON CHLORINATED CONSTITUENTS AND END-PRODUCTS**
**BIOWALL TEST AT SITE B301, OFFUTT AFB, NEBRASKA**

**Test Program for In-Situ Dechlorination by NOM Addition**
**Air Force Center for Environmental Excellence, Brooks AFB, Texas**

| | | TCE (mg/L) | c-DCE (mg/L) | VC (mg/L) | Ethene (ng/L) | Ethane (ng/L) | TCE (µmol/L) | c-DCE (µmol/L) | cDCE/TCE ratio (-) | VC (µmol/L) | Ethene (µmol/L) | Ethane (µmol/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **UPGRADIENT MONITORING WELLS** | | | | | | | | | | | | |
| Jan. 99 | B301-MW23S | 0.670 | 0.0082 | <0.001 | <3200[3] | <2500[3] | 5.095 | 0.085 | 0.017 | <0.016 | <0.114[3] | <0.0833[3] |
| Jan. 99 | B301-MW24S | 1.900 | 0.020 | <0.001 | <3200[3] | <2500[3] | 14.449 | 0.206 | 0.014 | <0.016 | <0.114[3] | <0.0833[3] |
| | **Jan 99 Mean** | **1.285** | **0.014** | **<0.001** | **<3200[2]** | **<2500[2]** | **9.772** | **0.145** | **0.015** | **<0.016** | **<0.114[2]** | **<0.0833[2]** |
| Jun. 99 | B301-MW23S | 0.280 | 0.007 | <0.001 | 15.0 | <5 | 2.129 | 0.069 | 0.032 | <0.016 | 0.0005 | <0.0833[3] |
| Jun. 99 | B301-MW24S | 0.250 | 0.007 | <0.001 | 11.0 | <5 | 1.901 | 0.070 | 0.037 | <0.016 | 0.0004 | <0.0833[3] |
| | **Jun 99 Mean** | **0.265** | **0.007** | **<0.001** | **13.0** | **<5** | **2.015** | **0.070** | **0.035** | **<0.016** | **0.0005** | **<0.0833[2]** |
| Feb. 00 | B301-MW23S | 1.200 | 0.008 | <0.001 | 24.0 | 16.0 | 9.125 | 0.080 | 0.009 | <0.016 | 0.0009 | 0.0005 |
| Feb. 00 | B301-MW24S | 2.000 | 0.014 | <0.001 | 14.0 | 8.0 | 15.209 | 0.144 | 0.009 | <0.016 | 0.0005 | 0.0003 |
| | **Feb. 00 Mean** | **1.600** | **0.011** | **<0.001** | **19.0** | **12.0** | **12.167** | **0.112** | **0.009** | **<0.016** | **0.0007** | **0.0004** |
| Aug. 00 | B301-MW23S | 2.200 | 0.029 | <0.001 | 27.0 | <5 | 16.730 | 0.299 | 0.018 | <0.016 | 0.0010 | <0.00017 |
| Aug. 00 | B301-MW24S | 2.000 | 0.039 | <0.001 | 16.0 | <5 | 15.209 | 0.402 | 0.026 | <0.016 | 0.0006 | <0.00017 |
| | **Aug. 00 Mean** | **2.100** | **0.034** | **<0.001** | **21.5** | **<5** | **15.970** | **0.351** | **0.022** | **<0.016** | **0.0008** | **<0.00017** |
| **DOWNGRADIENT MONITORING WELLS** | | | | | | | | | | | | |
| Jan. 99 | B301-MW31S | 0.280 | 0.270 | 0.002 | <3200[3] | <2500[3] | 2.129 | 2.784 | 1.307 | 0.037 | <0.114[3] | <0.0833[3] |
| Jan. 99 | B301-MW33S | 1.300 | 0.045 | <0.001 | <3200[3] | <2500[3] | 9.886 | 0.464 | 0.047 | <0.016 | <0.114[3] | <0.0833[3] |
| | **Jan 99 Mean_10ft** | **0.790** | **0.158** | **0.001** | **<3200[2]** | **<2500[2]** | **6.008** | **1.624** | **0.677** | **0.022** | **<0.114[2]** | **<0.0833[2]** |
| Jan. 99 | B301-MW32S | 0.670 | 0.070 | 0.001 | <3200[3] | <2500[3] | 5.095 | 0.722 | 0.142 | 0.021 | <0.114[3] | <0.0833[3] |
| Jan. 99 | B301-MW34S | 1.300 | 0.020 | <0.001 | <3200[3] | <2500[3] | 9.886 | 0.206 | 0.021 | <0.016 | <0.114[3] | <0.0833[3] |
| | **Jan 99 Mean_20ft** | **0.985** | **0.045** | **0.001** | **<3200[2]** | **<2500[2]** | **7.490** | **0.464** | **0.081** | **0.012** | **<0.114[2]** | **<0.0833[2]** |
| Jun-99 | B301-MW31S | 0.013 | 0.550 | 0.006 | 73.0 | <5 | 0.099 | 5.670 | 57.355 | 0.098 | 0.003 | <0.00017 |
| Jun-99 | B301-MW33S | 0.870 | 0.067 | <0.001 | 34.0 | <5 | 6.616 | 0.691 | 0.104 | <0.016 | 0.001 | <0.00017 |
| | **Jun 99 Mean_10ft** | **0.442** | **0.309** | **0.003** | **53.5** | **<5** | **3.357** | **3.180** | **28.730** | **0.053** | **0.002** | **<0.00017** |
| Jun-99 | B301-MW32S | 0.130 | 0.730 | 0.004 | 166.0 | <5 | 0.989 | 7.526 | 7.613 | 0.066 | 0.006 | <0.00017 |
| Jun-99 | B301-MW34S | 0.600 | 0.040 | <0.001 | 26.0 | <5 | 4.563 | 0.412 | 0.090 | <0.016 | 0.001 | <0.00017 |
| | **Jun 99 Mean_20ft** | **0.365** | **0.385** | **0.002** | **96.0** | **<5** | **2.776** | **3.969** | **3.851** | **0.036** | **0.003** | **<0.00017** |
| Feb. 00 | B301-MW31S | 0.014 | 0.006 | 0.002 | 1272.0 | 8154.0 | 0.106 | 0.065 | 0.610 | 0.032 | 0.045 | 0.272 |
| Feb. 00 | B301-MW33S | 0.215 | 0.091 | 0.003 | 8202.5 | 22698.5 | 1.635 | 0.938 | 0.574 | 0.050 | 0.293 | 0.757 |
| | **Feb. 00 Mean_10ft** | **0.115** | **0.049** | **0.003** | **4737.3** | **15426.3** | **0.871** | **0.502** | **0.592** | **0.041** | **0.169** | **0.514** |
| Feb. 00 | B301-MW32S | 0.011 | 0.019 | 0.002 | 95.0 | 5613.0 | 0.084 | 0.196 | 2.342 | 0.024 | 0.003 | 0.187 |
| Feb. 00 | B301-MW34S | 0.880 | 0.064 | 0.001 | 500.0 | 398.0 | 6.692 | 0.660 | 0.099 | 0.023 | 0.018 | 0.013 |
| | **Feb. 00 Mean_20ft** | **0.247** | **0.046** | **0.002** | **2961.4** | **10458.0** | **0.002** | **0.472** | **251.422** | **0.034** | **0.106** | **0.349** |
| Aug. 00 | B301-MW31S | 0.009 | 0.009 | 0.003 | 796.0 | 17034.0 | 0.068 | 0.094 | 1.371 | 0.048 | 0.028 | 0.568 |
| Aug. 00 | B301-MW33S | 0.960 | 0.098 | 0.001 | 365.0 | 12340.0 | 7.300 | 1.010 | 0.138 | 0.018 | 0.013 | 0.411 |
| | **Aug. 00 Mean_10ft** | **0.485** | **0.054** | **0.002** | **943.5** | **14687.0** | **3.684** | **0.552** | **0.755** | **0.033** | **0.034** | **0.490** |
| Aug. 00 | B301-MW32S | 0.022 | 0.020 | 0.004 | 102.0 | 16948.0 | 0.167 | 0.206 | 1.232 | 0.070 | 0.004 | 0.565 |
| Aug. 00 | B301-MW34S | 1.220 | 0.040 | 0.001 | 717.0 | 587.0 | 9.278 | 0.412 | 0.044 | 0.021 | 0.026 | 0.020 |
| | **Aug. 00 Mean_20ft** | **0.621** | **0.030** | **0.003** | **409.5** | **8767.5** | **4.722** | **0.309** | **0.638** | **0.046** | **0.015** | **0.292** |
| **CONTROL MONITORING WELLS** | | | | | | | | | | | | |
| Jan. 99 | B301-MW27S | 0.110 | 0.0081 | 0.001 | – | – | 0.837 | 0.084 | 0.100 | 0.019 | – | – |
| | B301-MW28S | 0.130 | 0.0029 | <0.001 | – | – | 0.989 | 0.030 | 0.030 | <0.016 | – | – |
| Aug. 00 | B301-MW27S | 0.230 | 0.015 | 0.002 | 35 | 8 | 1.749 | 0.155 | 0.088 | 0.026 | 0.001 | 0.0003 |
| | B301-MW28S | 0.280 | 0.0058 | <0.001 | 20 | 7 | 2 | 0.060 | 0.028 | <0.016 | 0.001 | 0.0002 |

Notes:
1. Chlorinated organics were analyzed by EPA Method 8021 at Southern Petroleum Laboratories, Houston, Texas; Ethene and ethane were analyzed by GC/RGD by Microseeps, Inc., Pittsburgh, PA.
2. < = Compound analyzed for but not detected at detection limit indicated. – = Not Measured
3. These samples were analyzed by SPL instead of Microseeps and thus have higher detection limits.
4. Half the detection limit is assumed for the purposes of calculating the mean.

GROUNDWATER SERVICES, INC.

## TABLE 5
## MULCH BIOWALL PERFORMANCE DATA

**Building 301**
**Offutt Air Force Base, Nebraska**

| | BIOWALL | MNA CONTROL |
|---|---|---|
| Change in Mean TCE Concentrations[1] | -73% | +20% |
| Change in Mean Total Chlorinated Solvent Conc.[2] | -60% | +12% |
| TCE Loss Observed as Daughter Products[3] | +25% | N/A |
| TCE Loss Observed as Ethene and Ethane[4] | +10% | N/A |

NOTES

1. Change in Mean TCE Concentrations was calculated by subtracting the mean TCE concentration 10 ft downgradient from the mean upgradient TCE concentration over the course of the test, dividing by the mean upgradient TCE concentration, and multiplying by 100%. Negative values indicate removal.
2. Change in Mean Total Chlorinated Solvent Conc. is calculated in the same manner as Change in Mean TCE Concentrations, but includes TCE, c-DCE, and VC. Molar concentrations are used.
3. This value is calculated by determining the net mean production of daughter products 10 ft downgradient of the mulch biowall, dividing by the mean amount of TCE removed and multiplying by 100%. This value represents the amount of TCE loss that can be accounted for by c-DCE, VC, ethene, and ethane. This number is a conservative estimate as daugher product mineralization to carbon dioxide and gas losses to the vadose zone can occur.
4. This value is calculated by determining the net mean production of ethene and ethane, dividing by the mean amount of TCE removed, and multiplying by 100%. This value is a conservative estimate as ethene and ethane may be mineralized to carbon dioxide in aerobic microenvironments or be lost to the vadose zone.
5. N/A = not applicable

GROUNDWATER SERVICES, INC.

**TABLE 6**
**EFFECT O F SURFACE AMENDMENT ON WATER QUALITY AND NATURAL ATTENUATION PARAMETERS**
**SURFACE AMENDMENT TEST AT SITE B301, OFFUTT AFB, NEBRASKA**

**Test Program for In-Situ Dechlorination by NOM Addition**
**Air Force Center for Environmental Excellence, Brooks AFB, Texas**

| | | Baseline | | SURFACE AMENDMENT | | | | | | CONTROL | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Units | Jan. '99 Upgradient MW22S | Jan. '99 Mean Downgradient MW 29S, MW30S | Jun. '99 Upgradient MW22S | Jun. '99 Mean Downgradient MW 29S, MW30S | Feb. '00 Upgradient MW22S | Feb. '00 Mean Downgradient MW 29S, MW30S | Aug. '00 Upgradient MW22S | Aug. '00 Mean Downgradient MW 29S, MW30S | Jan. '99 Upgradient MW27S | Jan. '99 Downgradien MW28S | Aug. '00 Upgradient MW27S | Aug. '00 Downgradient MW28S |
| **Water Quality Parameters** | | | | | | | | | | | | | |
| Temperature | °F | 37.6 | 46.0 | 69.9 | 77.5 | 53.4 | 52.8 | 60.1 | 58.8 | 38.9 | 41.7 | 61.3 | 61.5 |
| pH | pH units | 6.94 | 7.1 | 6.98 | 7.1 | 6.22 | 6.16 | 6.49 | 6.66 | 7.18 | 7.23 | 6.71 | 6.64 |
| Specific conductance | µ mhos/cm | 1,026 | 899.5 | 794 | 905.0 | 751 | 781 | 635 | 668 | 453 | 947 | 645 | 635 |
| Total organic carbon | mg/L | <1.0 | 3.0 | 2 | 3.0 | <1 | <1 | <1.0 | <1.0 | <1.0 | 2.0 | <1.0 | <1.0 |
| Chloride | mg/L | 12 | 10.5 | 17.6 | 16.7 | 15 | 12 | 10 | 6.6 | 9 | 8 | 7 | 7 |
| **Natural Attenuation Parameters** | | | | | | | | | | | | | |
| Dissolved oxygen | mg/L | 1.1 | 2.8 | 1.6 | 0.6 | 2.4 | 0.37 | 0.05 | 0.03 | 1.80 | 3.00 | 0.01 | 0.03 |
| Redox potential | mV | 142.1 | 193.9 | 129.5 | 135.6 | 202.5 | 206.1 | 207.1 | 213.3 | 152.7 | 190.3 | 220.4 | 220.6 |
| Sulfate | mg/L | 31.9 | 36.7 | 18 | 18.5 | 24.0 | 21 | 29 | 23.5 | 29 | 32.2 | 22 | 22 |
| Nitrate | mg/L | 5.2 | 1.8 | 6.61 | 0.9 | 3.7 | 1.75 | 2.67 | 0.9475 | 1.1 | 1.6 | 0.15 | 0.50 |
| Ferrous Iron | mg/L | 0.04 | 0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.02 | 0.25 | <0.2 | <0.2 |
| Methane | ug/L | <0.0012 | 0.01 | 0.22 | 71.6 | 0.3 | 5.211 | 0.075 | 0.543 | 0.027 | 0.034 | 4.335 | 2.403 |
| Hydrogen | nM | 1.29 | -- | 1.08 | 1.05 | 1.28 | 1.18 | 0.33 | 0.6 | -- | -- | 0.8 | 0.5 |
| Alkalinity | mg/L | -- | -- | 300 | 410.0 | 90 | 95 | 360 | 360 | -- | -- | 400 | 400 |

Notes:
1. The following analyses were performed at Southern Petroleum Laboratories, Inc., Houston, Texas:
   chloride, and nitrate by Method 300, and TOC by Method 9060. Methane was analyzed by GC/FID and hydrogen was analyzed by GC/RGD by Microseeps, Inc., Pittsburgh, PA
2. Sulfate, Ferrous Iron and Alkalinity were measured in the field using Hach kits. The respective detection limits are 1 mg/L, 0.2 mg/L and 5 mg/L.
3. -- = Not measured.
4. Half the detection limit was used in the calculation of mean values.
5. In Jan. 99, ferrous iron was measured using Method 6010B by SPL. The detection limit is 0.02 mg/L
6. Ferrous iron was measured using Method 6010B by SPL. The detection limit is 0.02 mg/L
7. In Jan. 99, methane was measured using GC/FID by SPL. The method detection limit was 0.0012 mg/L.

GROUNDWATER SERVICES, INC.

**TABLE 7**
**EFFECT OF SURFACE AMENDMENT ON CHLORINATED CONSTITUENTS AND END-PRODUCTS**
**SURFACE AMENDMENT TEST AT SITE B301, OFFUTT AFB, NEBRASKA**

**Test Program for In-Situ Dechlorination by NOM Addition**
**Air Force Center for Environmental Excellence, Brooks AFB, Texas**

| | | TCE (mg/L) | c-DCE (mg/L) | VC (mg/L) | Ethene (ng/L) | Ethane (ng/L) | TCE (µmol/L) | c-DCE (µmol/L) | c-DCE/TCE ratio (-) | VC (µmol/L) | Ethene (µmol/L) | Ethane (µmol/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **UPGRADIENT MONITORING WELLS** | | | | | | | | | | | | |
| Jan. 99 | B301-MW22S | 0.630 | 0.0078 | <0.001 | <3200[3] | <2500[3] | 4.791 | 0.080 | 0.017 | <0.016 | <0.114[3] | <0.0833[3] |
| Jun. 99 | B301-MW22S | 0.420 | 0.0100 | <0.001 | 11.0 | <5 | 3.194 | 0.103 | 0.032 | <0.016 | 0.0004 | <0.00017 |
| Feb. 00 | B301-MW22S | 0.600 | 0.0074 | <0.001 | 24.0 | 9.0 | 4.563 | 0.076 | 0.017 | <0.016 | 0.0009 | 0.00030 |
| Aug. 00 | B301-MW22S | 1.600 | 0.0160 | <0.001 | 7.0 | <5 | 12.167 | 0.165 | 0.014 | <0.016 | 0.0003 | <0.00017 |
| **DOWNGRADIENT MONITORING WELLS** | | | | | | | | | | | | |
| Jan. 99 | B301-MW29S | 0.410 | 0.0300 | 0.003 | <3200[3] | <2500[3] | 3.118 | 0.309 | 0.099 | 0.040 | <1.14[3] | <0.0833[3] |
| Jan. 99 | B301-MW30S | 0.300 | 0.0180 | 0.001 | <3200[3] | <2500[3] | 2.281 | 0.186 | 0.081 | 0.018 | <1.14[3] | <0.0833[3] |
| | **Mean Jan. 99** | **0.355** | **0.024** | **0.002** | **<3200[3]** | **<2500[3]** | **2.700** | **0.247** | **0.090** | **0.029** | **<1.14[3]** | **<0.0833[3]** |
| Jun-99 | B301-MW29S | 0.630 | 0.2600 | 0.003 | 208.0 | <5 | 4.791 | 2.680 | 0.559 | 0.042 | 0.0074 | <0.00017 |
| Jun-99 | B301-MW30S | 0.480 | 0.1400 | 0.002 | 77.0 | <5 | 3.650 | 1.443 | 0.395 | 0.037 | 0.0028 | <0.00017 |
| | **Mean Jun-99** | **0.555** | **0.200** | **0.002** | **142.5** | **<5** | **4.221** | **2.062** | **0.477** | **0.039** | **0.0051** | **<0.00017** |
| Feb. 00 | B301-MW29S | 0.370 | 0.0069 | <0.001 | 65.0 | 37.0 | 2.814 | 0.071 | 0.025 | <0.016 | 0.0023 | 0.00123 |
| Feb. 00 | B301-MW30S | 0.340 | 0.0043 | <0.001 | 37.0 | 65.0 | 2.586 | 0.044 | 0.017 | <0.016 | 0.0013 | 0.00217 |
| | **Mean Feb. 00** | **0.355** | **0.006** | **<0.001** | **51.0** | **51.0** | **2.700** | **0.058** | **0.021** | **<0.016** | **0.0018** | **0.00170** |
| Aug. 00 | B301-MW29S | 0.410 | 0.0082 | <0.001 | 21 | <5 | 3.118 | 0.085 | 0.027 | <0.016 | 0.0008 | <0.00017 |
| Aug. 00 | B301-MW30S | 0.380 | 0.0062 | <0.001 | 19 | 5 | 2.890 | 0.064 | 0.022 | <0.016 | 0.0007 | 0.00017 |
| | **Mean Aug. 00** | **0.395** | **0.007** | <0.001 | **20.0** | 3.75 | **3.004** | **0.074** | **0.025** | **<0.016** | **0.0007** | **0.00013** |

Notes:
1. Chlorinated organics were analyzed by EPA Method 8021 at Southern Petroleum Laboratories (SPL), Houston, TX; Ethene and ethane were analyzed by GC/RGD by Microseeps, Inc., Pittsburgh, PA.
2. < = Compound analyzed for but not detected at detection limit indicated.
3. These samples were analyzed by SPL instead of Microseeps and thus have higher detection limits.

GROUNDWATER SERVICES, INC.

**TABLE 8**
**MULCH SURFACE AMENDMENT PERFORMANCE DATA**

**Building 301**
**Offutt Air Force Base, Nebraska**

| | BIOWALL | MNA CONTROL |
|---|---|---|
| Change in Mean TCE Concentration[1] | -21% | +20% |
| Change in Mean Total Chlorinated Solvent Conc.[2] | -5% | +12% |
| TCE Loss Observed as Daughter Products[3] | +75% | N/A |
| TCE Loss Observed as Ethene and Ethane[4] | +0.3% | N/A |

NOTES

1. Change in Mean TCE Concentration was calculated by subtracting the mean TCE concentration 10 ft downgradient from the mean upgradient TCE concentration over the course of the test, dividing by the mean upgradient TCE concentration, and multiplying by 100%. Negative values indicate removal. August 2000 upgradient TCE data was not included in the calculation because its inclusion increased the amount of removal, although none was occurring in that time frame.
2. Change in Mean Total Chlorinated Solvent Conc. is calculated in the same manner as Change in Mean TCE Concentration, but includes TCE, c-DCE, and VC. Molar concentrations are used.
3. This value is calculated by determining the net mean production of daughter products 10 ft downgradient of the mulch amendment, dividing by the mean amount of TCE removed and multiplying by 100%. This value represents the amount of TCE loss that can be accounted for by c-DCE, VC, ethene, and ethane. This number is a conservative estimate as daugher product mineralization to carbon dioxide and gas losses to the vadose zone can occur.
4. This value is calculated by determining the net mean production of ethene and ethane, dividing by the mean amount of TCE removed, and multiplying by 100%. This value is a conservative estimate as ethene and ethane may be mineralized to carbon dioxide in aerobic microenvironments or be lost to the vadose zone.
5. N/A = not applicable

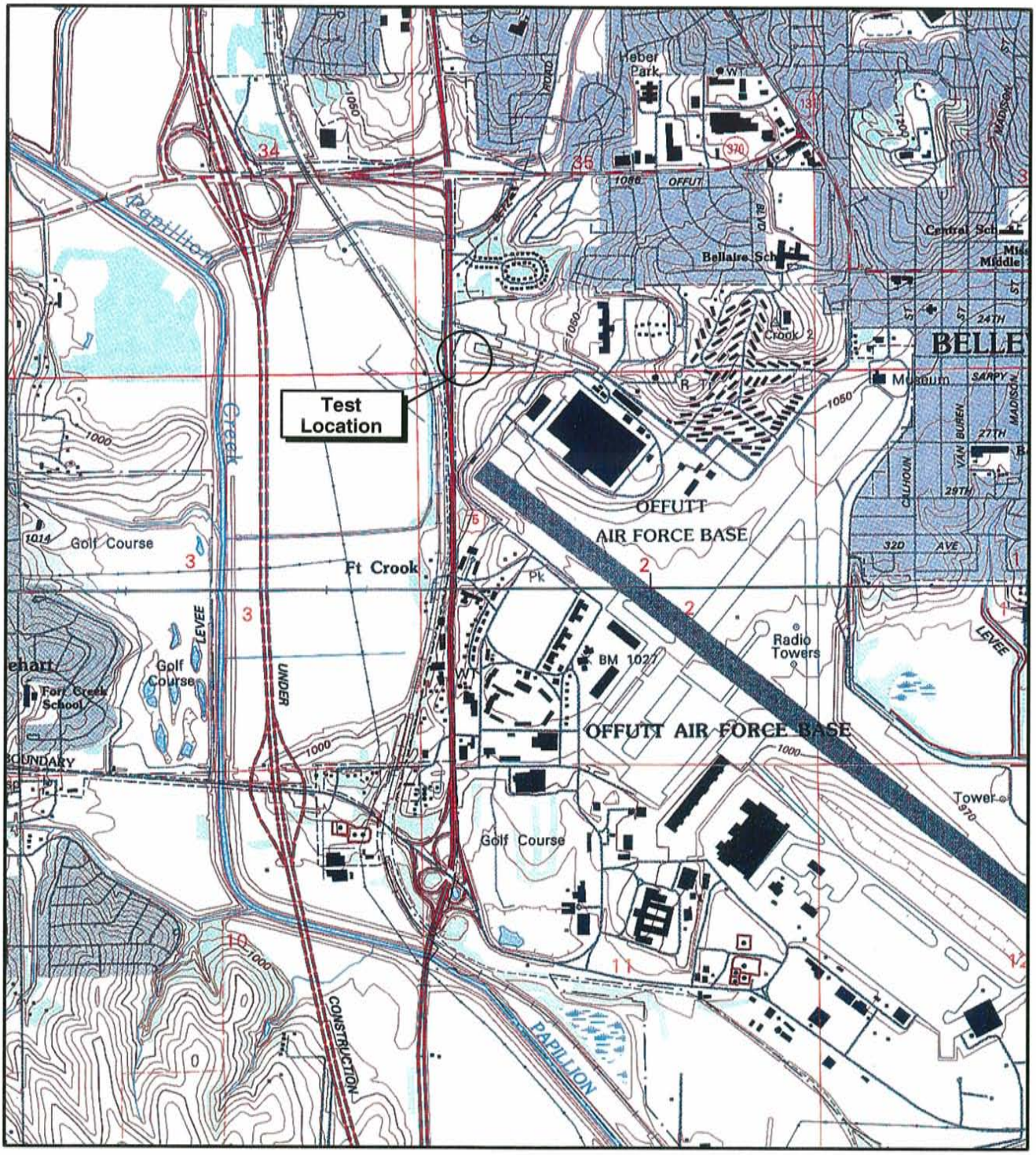
GSI Job No. G-2050
June 18, 2001

GROUNDWATER SERVICES, INC.

# Mulch Biowall and Surface Amendment Pilot Test

Site B301
Offutt AFB, Nebraska

## FIGURES




U.S. Geological Survey Map
Omaha, Nebr.-Iowa (1994)
Plattsmouth, Nebr.-Iowa (1994)
Quadrangle, 7.5 minute

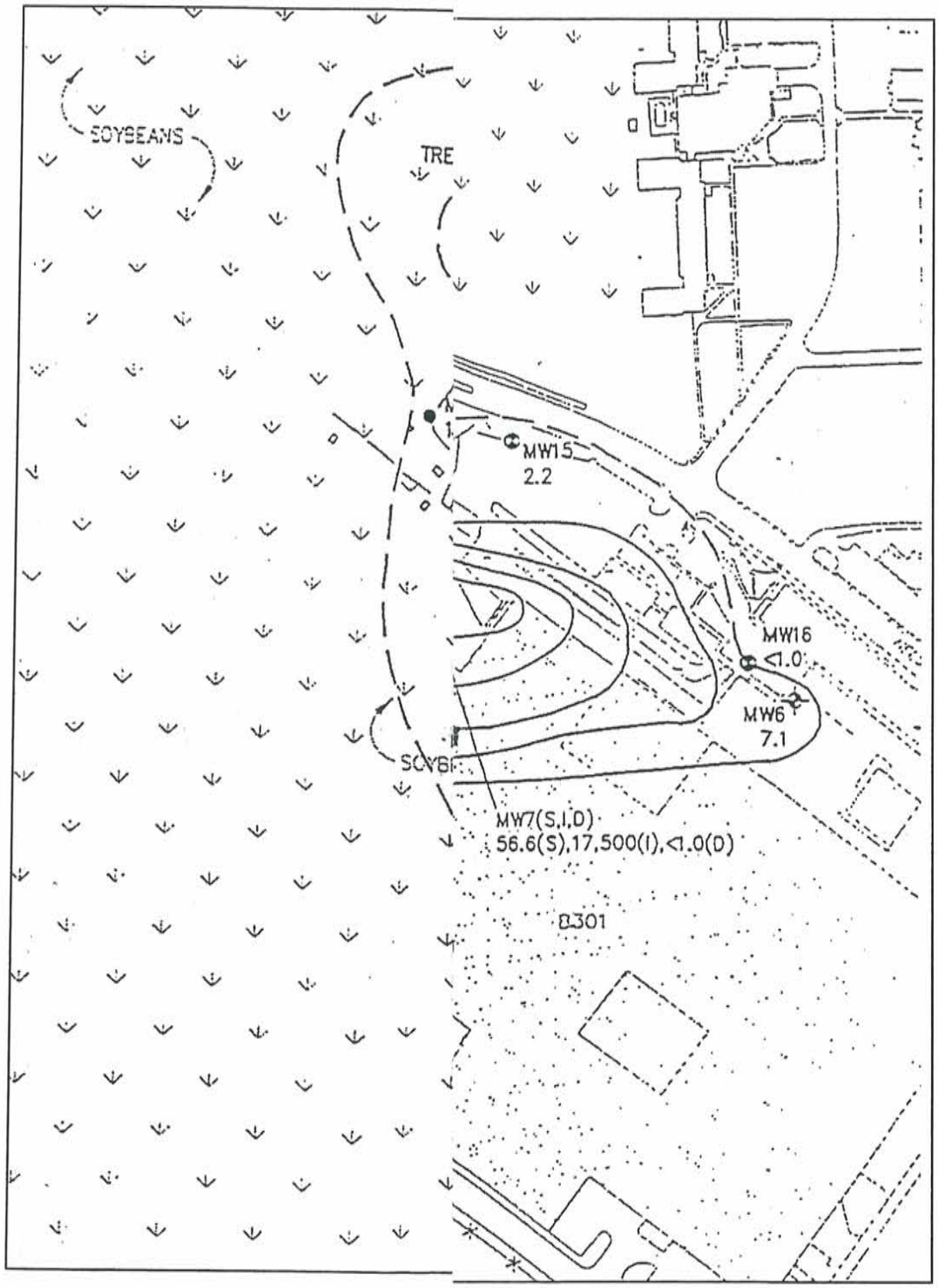
SCALE (ft.)
0 1000 2000

GROUNDWATER SERVICES, INC.

## SITE LOCATION MAP

Site B301
Offutt AFB, Nebraska

| | | | | |
|---|---|---|---|---|
| GSI Job No.: | G-2050 | Scale: | As Shown | FIGURE 1 |
| Drawn by: | CCJ | Approved by: | CEA | |
| Revised: | | Date: | 6/18/01 | |




LEGEND

| | |
|---|---|
| MW9(S) | PRE-EXISTING MONITORING WELL OR WELL C |
| MW13 | NEW MONITORING WELL |
| MP1 | MONITORING POINT |
| 10 | LINE OF EQUAL TCE CONCENTRATION (µg/L) DASHED WHERE INFERRED |
| SW2 | SURFACE WATER SAMPLING LOCATION |
| TW1 | TEMPORARY MONITORING WELL |
| 9.0(S),201(I),1.6(D) | TCE CONCENTRATION (µg/L) (S=SHALLOW, I= |

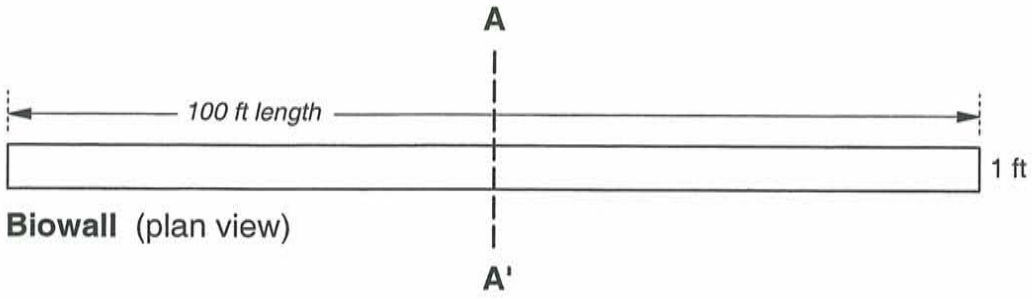
**FIGURE 2**

**DISTRIBUTION OF TCE IN GROUNDWATER AND SURFACE WATER JUNE-JULY 1996**

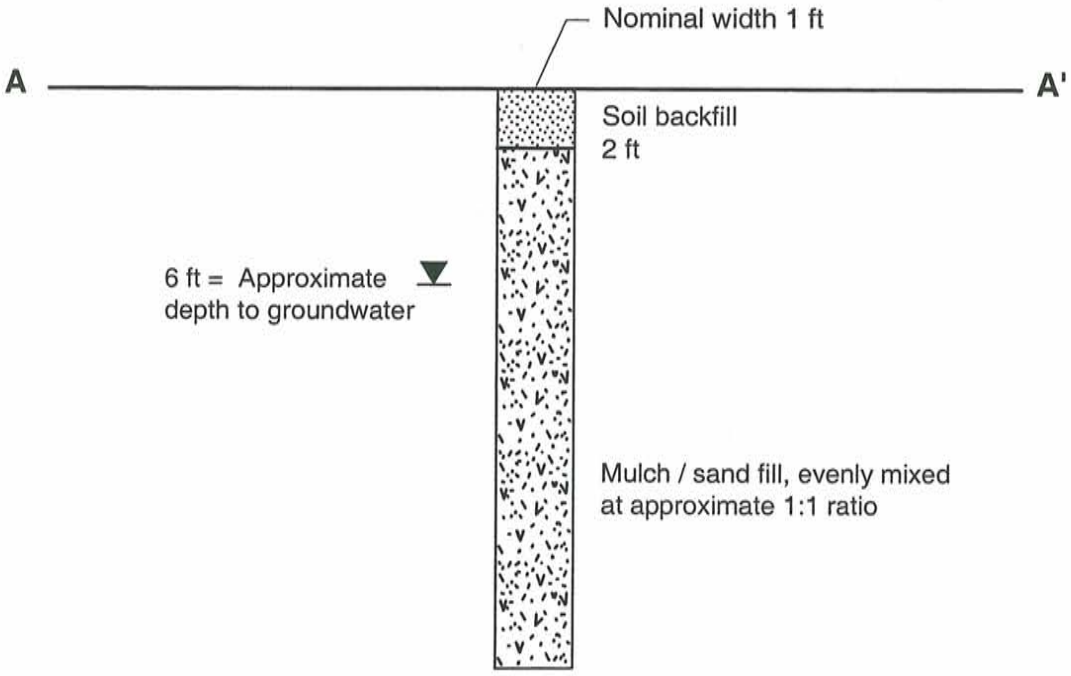
Site B301
Offutt AFB, Nebraska


Figure 3a) Mixing of Mulch with Concrete Sand

Figure 3b) Installation of the Biowall Using a Continuous Trencher

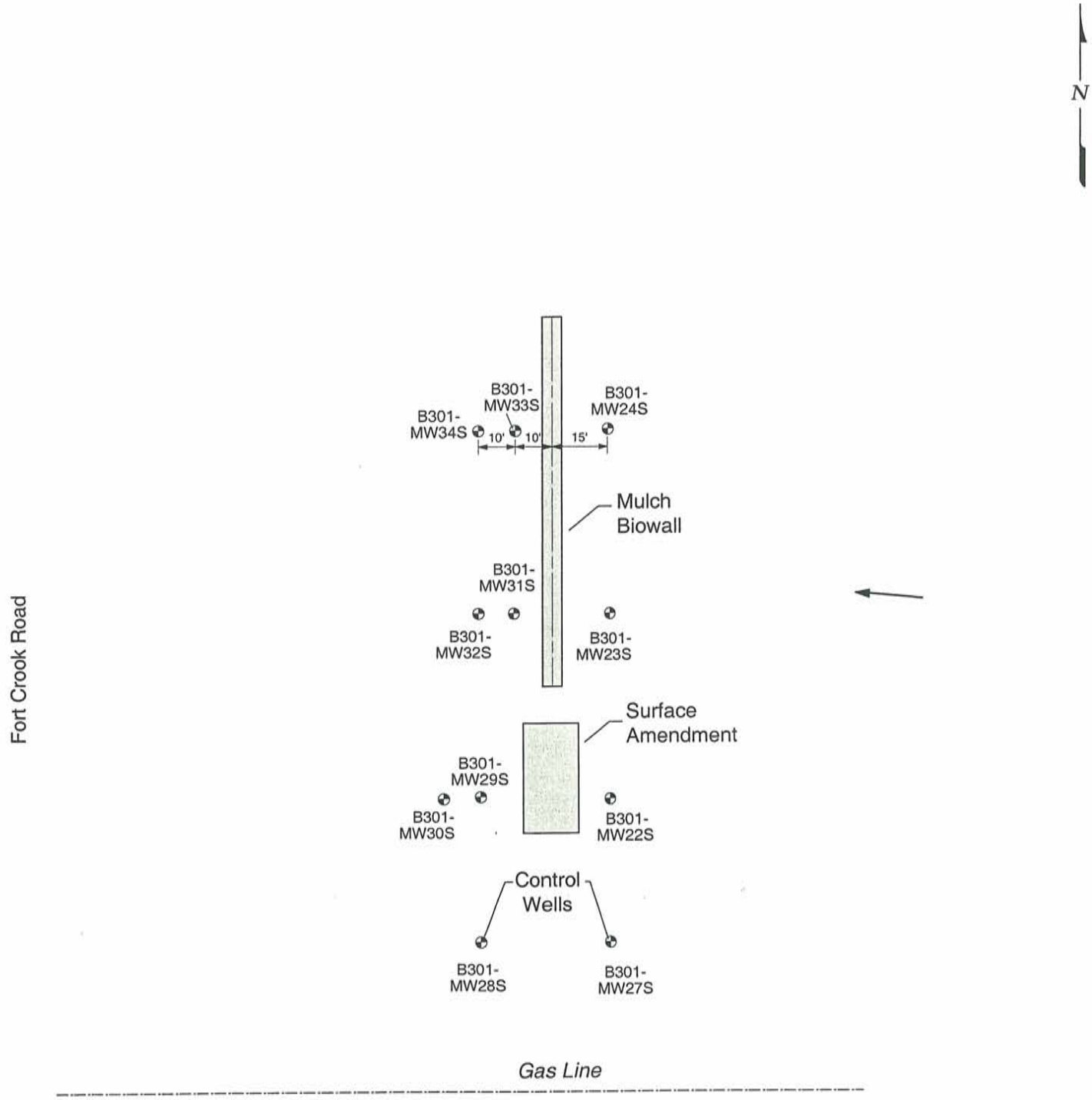



**Biowall** (plan view)




23 ft = Total depth

| | | | |
|---|---|---|---|
| GROUNDWATER SERVICES, INC. | GSI Job No. G-2050 | Drawn By: DLB/CCJ | **MULCH BIOWALL CROSS-SECTION** |
| | Issued: 6/18/01 | Chk'd By: CEA | Site B301 |
| | Revised: _____ | Aprv'd By: | Offutt AFB, Nebraska |
| | Scale: Not to scale | **FIGURE 4** | |




**LEGEND**

- Monitoring well location
- Groundwater flow direction

SCALE (ft.)

0 20 40

GROUNDWATER SERVICES, INC.

| | | | |
|---|---|---|---|
| GSI Job No. G-2050 | | Drawn By: CCJ | **MONITORING WELL NETWORK** |
| Issued: | | Chk'd By: CEA | Site B301<br>Offutt AFB, NB |
| Revised: | | Aprv'd By: | |
| Scale: As Shown | | **FIGURE 5** | |

GEOLOGIST: Mark Hampton
DRILLER: Professional Service Industries
DRILLING METHOD: Flight Auger
HOLE DIAMETER: 6.0 in

COMPLETION DATE: 11/12/98
SURFACE ELEVATION: NOT MEASURED

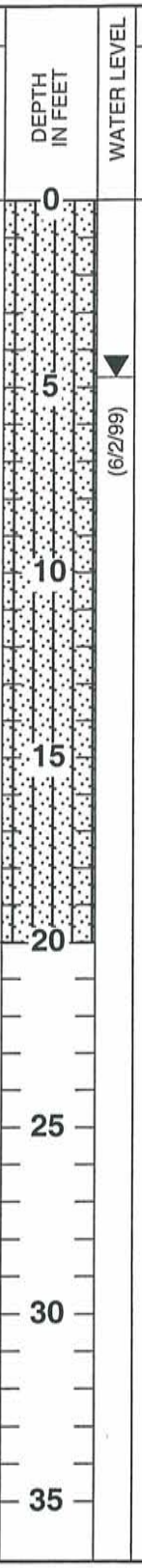
**SOIL DESCRIPTION**

GROUND SURFACE

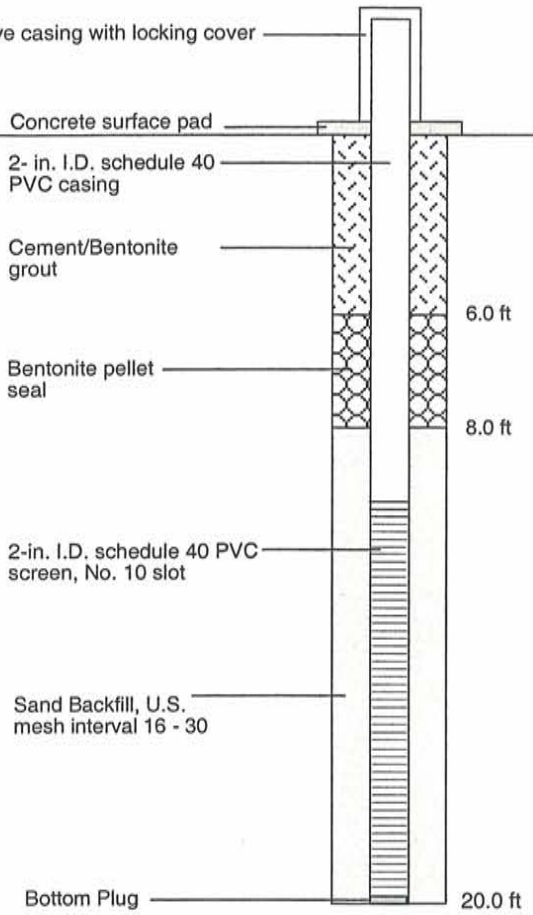
Grayish-brown clayey SILT (ML)

Total Depth = 20.0 ft

Notes:
1. Groundwater seepage encountered at approximately 5 feet during drilling.
2. Water level elevations are approximate.
3. Stratigraphy based on observation of drill cuttings.




**WELL CONSTRUCTION**



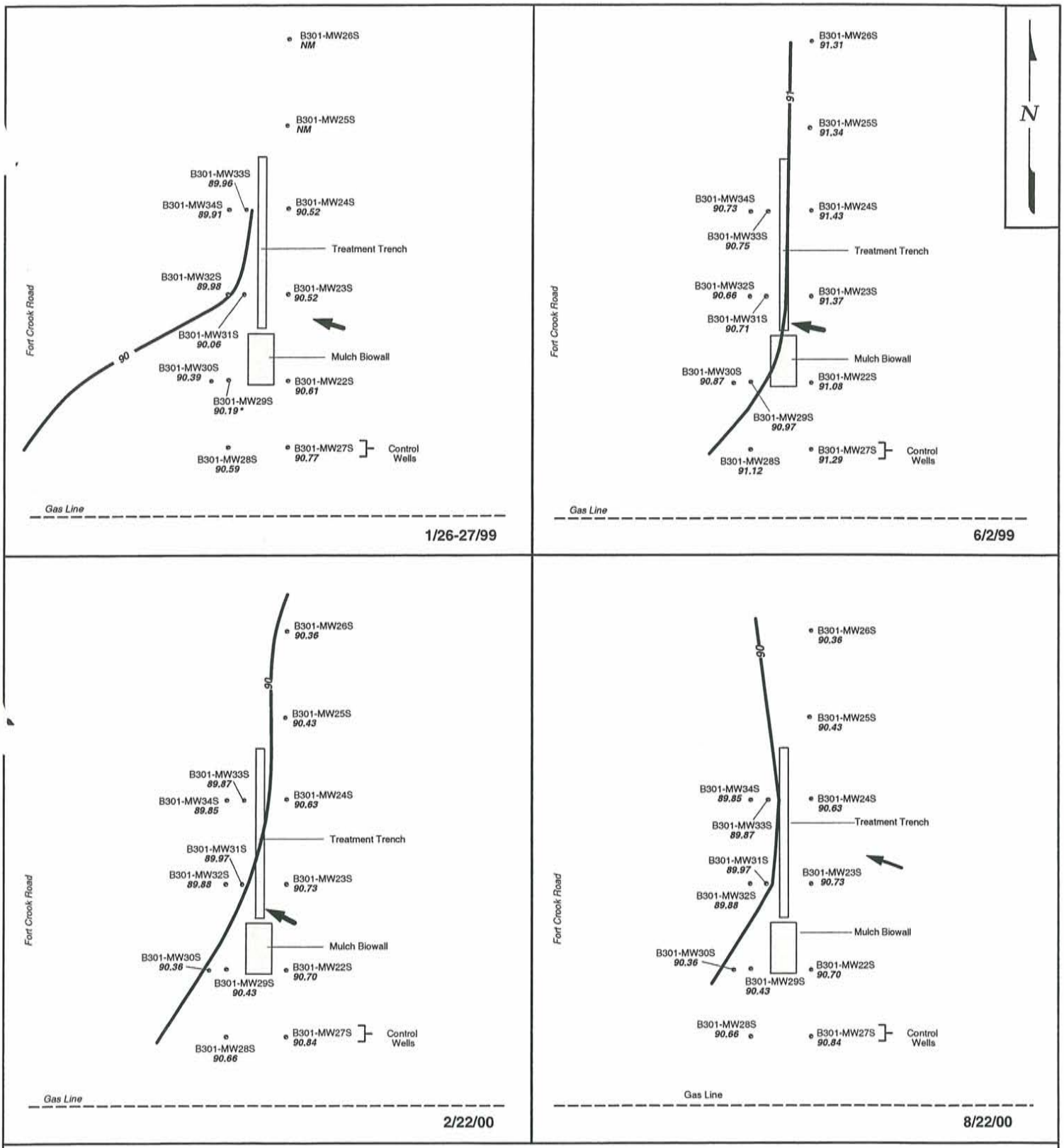

GROUNDWATER SERVICES, INC.

**LOG FOR B301-MW22S & REPRESENTATIVE AS-BUILT DIAGRAM**

Site B301
Offutt Air Force Base, Nebraska

GSI Job No. G-2050
Page 1 of 1
Issued: 6/18/01

**FIGURE 6**




## LEGEND

| | | | |
|---|---|---|---|
| ⊙ | Monitoring well location | *NM* | Not measured |
| *90.61* | Groundwater elevation in Upper Silt | * | Value not used in contouring |
| *– 90 –* | Groundwater elevation contour | ← | Groundwater flow direction |

SCALE (ft.)

0 40 80

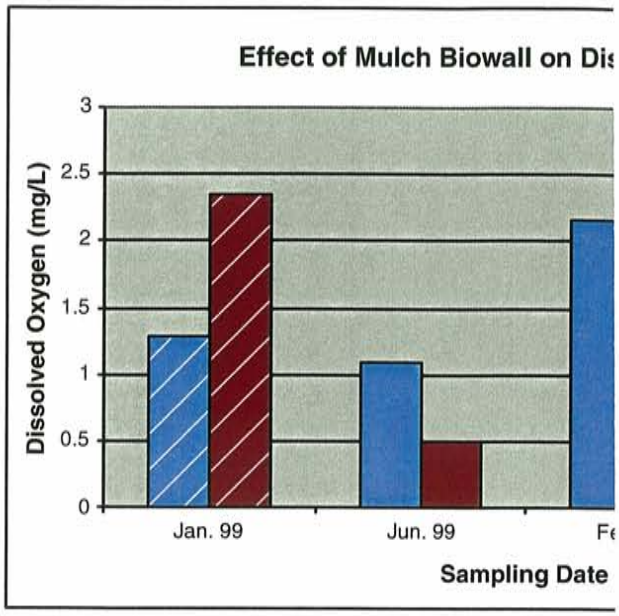
GROUNDWATER SERVICES, INC.

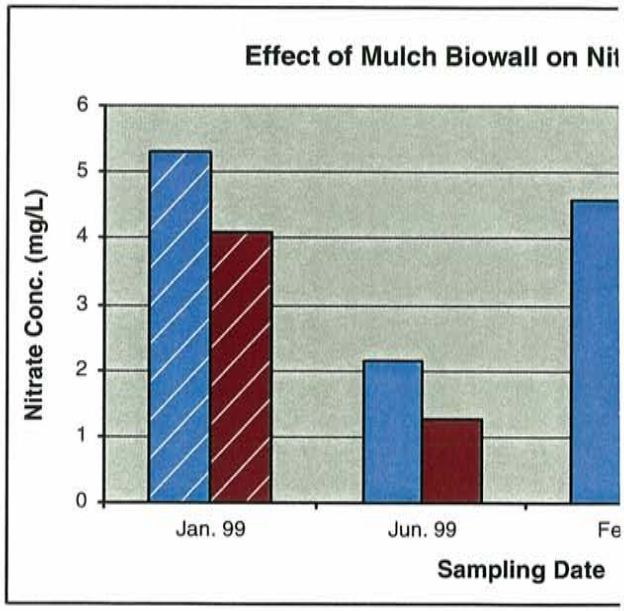
| | | | |
|---|---|---|---|
| GSI Job No. | G-2050 | Drawn By: | CCJ |
| Issued: | 5/18/01 | Chk'd By: | CEA |
| Revised: | _____ | Aprv'd By: | |
| Scale: | As Shown | **FIGURE 7** | |

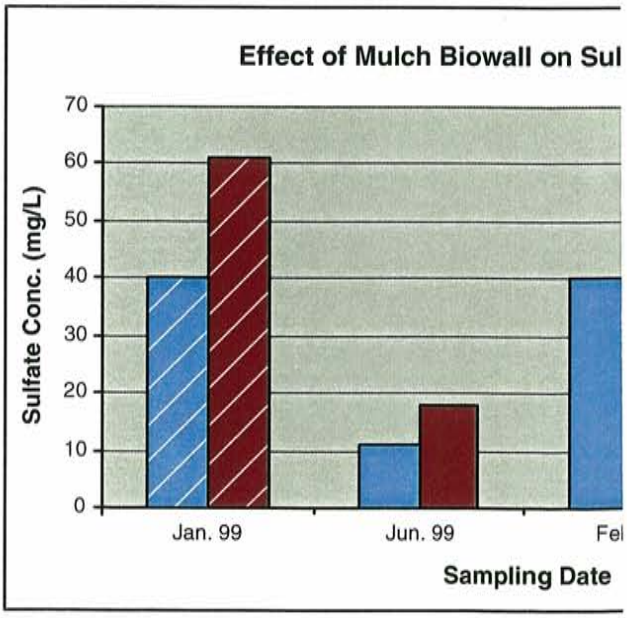
# GROUNDWATER ELEVATIONS IN UPPER SILT STRATUM

**Site B301**

**Offutt AFB, Nebraska**



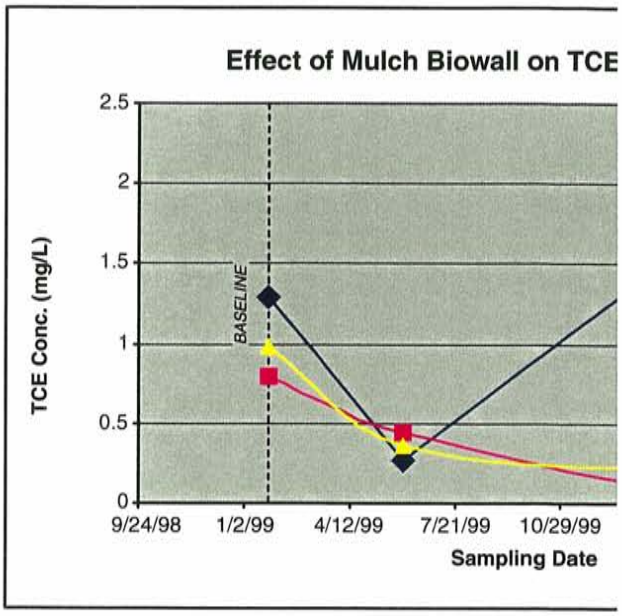

**NOTES:** NM = not measured
NA = not available
Striped bars indicate baseline conditions, prior to biowall installation.

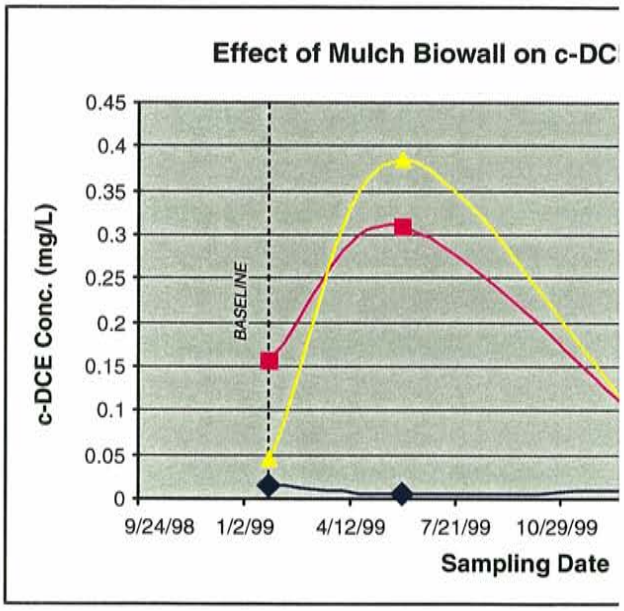
GROUNDWATER SERVICES, INC.

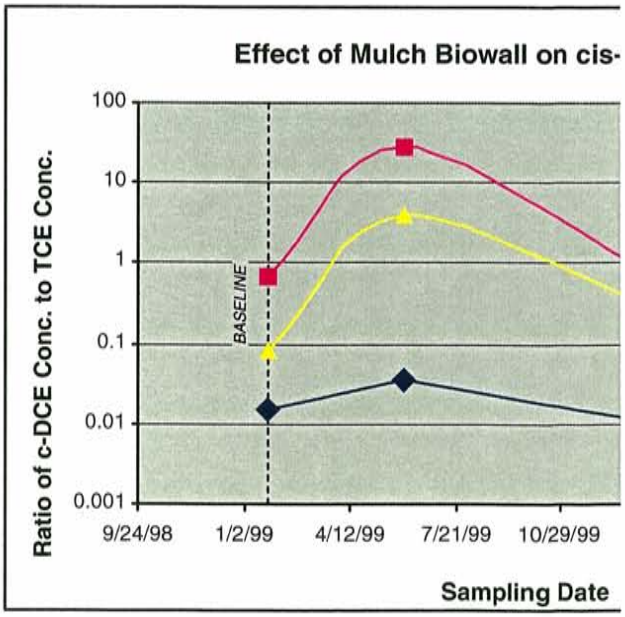
# EFFECT OF MULCH BIOWALL ON ELECTRON ACCEPTORS, METHANE, AND ALKALINITY

Site B301
Offutt AFB, Nebraska

| | | | |
|---|---|---|---|
| GSI Job No. | G-2050 | Drawn By: | CCJ |
| Issued: | 6/18/01 | Chk'd By: | CEA |
| Revised: | _____ | Apprv'd By: | |
| Scale: | As Shown | **FIGURE 8** | |




**LEGEND**

- Mean Concentration Upgradient
- Mean Concentration 10 ft. Downgradient
- Mean Concentration 20 ft. Downgradient

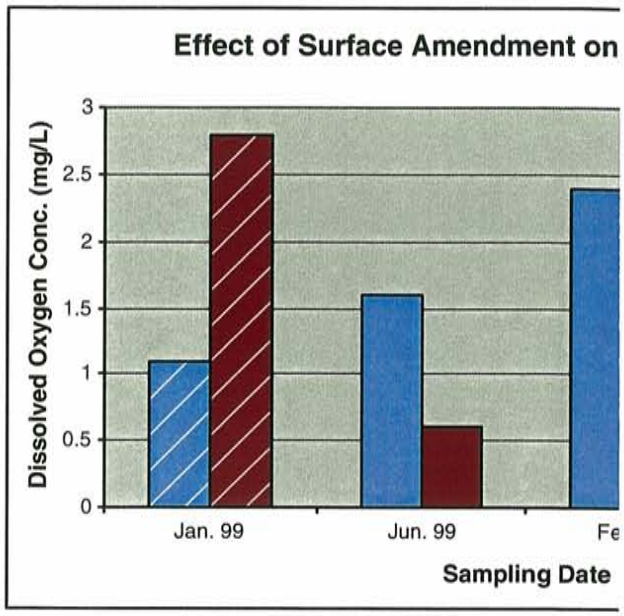
**NOTE:** **Ethene and ethane concentrations were measured prior to start-up and were non-detect.**

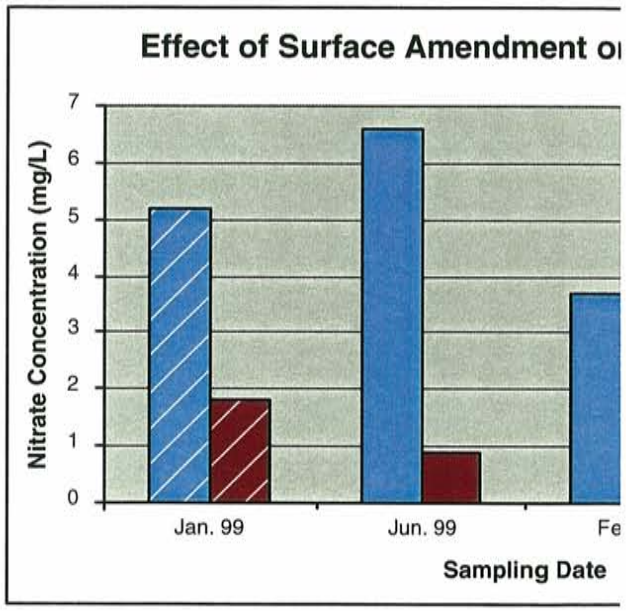
GROUNDWATER SERVICES, INC.

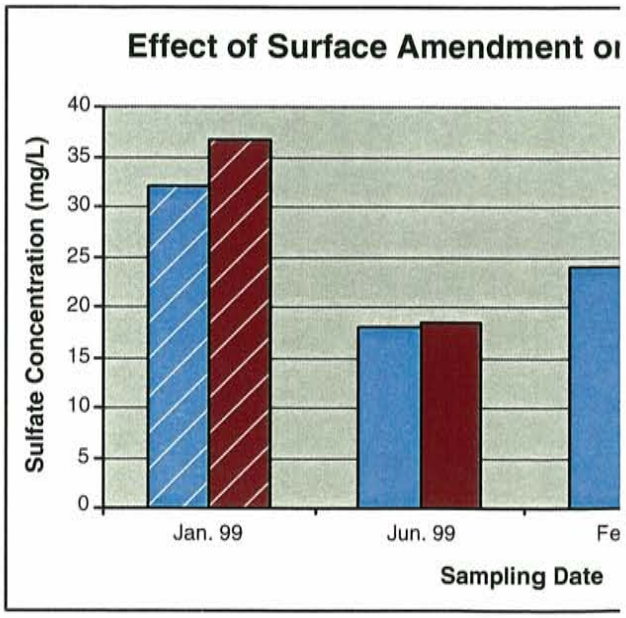
# EFFECT OF MULCH BIOWALL ON TCE AND DAUGHTER PRODUCTS

Site B301
Offutt AFB, Nebraska

| | | | |
|---|---|---|---|
| GSI Job No. | G-2050 | Drawn By: | CCJ |
| Issued: | 6/18/01 | Chk'd By: | CEA |
| Revised: | ——— | Apprv'd By: | |
| Scale: | As Shown | **FIGURE 9** | |



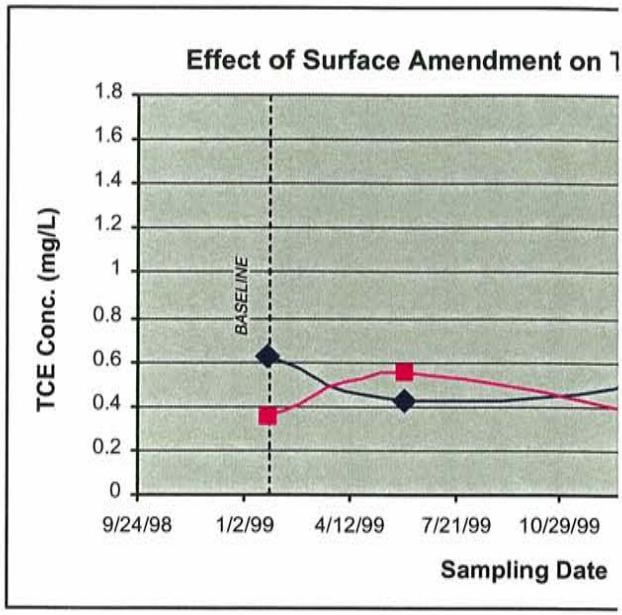

**NOTES:** NM = not measured
NA = not available
Striped bars indicate baseline conditions, prior to biowall installation.

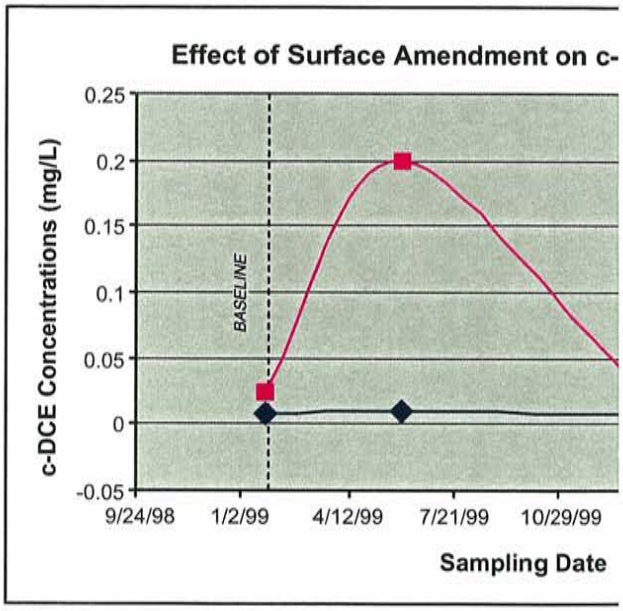
GROUNDWATER SERVICES, INC.

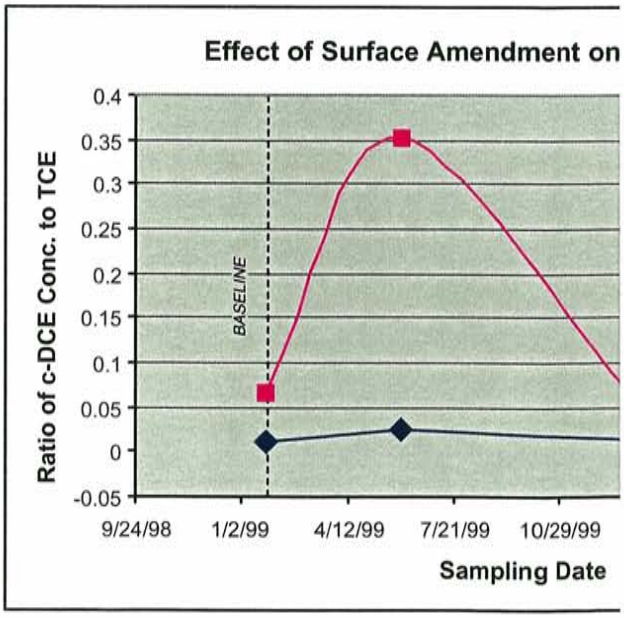
# EFFECT OF SURFACE AMENDMENT ON ELECTRON ACCEPTORS, METHANE, AND ALKALINITY

Site B301
Offutt AFB, Nebraska

| | | | |
|---|---|---|---|
| GSI Job No. | G-2050 | Drawn By: | CCJ |
| Issued: | 6/18/01 | Chk'd By: | CEA |
| Revised: | ——— | Apprv'd By: | |
| Scale: | As Shown | **FIGURE 10** | |




**LEGEND**

- Upgradient Concentrations
- Mean Downgradient Concentrations

**NOTE:** **Ethene and ethane concentrations were measured prior to start-up and were non-detect.**

GROUNDWATER SERVICES, INC.

# EFFECT OF SURFACE AMENDMENT ON TCE AND DAUGHTER PRODUCTS

Site B301
Offutt AFB, Nebraska

| | | | |
|---|---|---|---|
| GSI Job No. | G-2050 | Drawn By: | CCJ |
| Issued: | 6/18/01 | Chk'd By: | CEA |
| Revised: | _____ | Apprv'd By: | |
| Scale: | As Shown | **FIGURE 11** | |

GSI Job No. G-2050
June 18, 2001

GROUNDWATER
SERVICES, INC.

# Mulch Biowall and Surface Amendment Pilot Test

Site B301
Offutt AFB, Nebraska

## APPENDIX

GSI Job No. G-2050
June 18, 2001

GROUNDWATER
SERVICES, INC.

# Mulch Biowall and Surface Amendment Pilot Test

Site B301
Offutt AFB, Nebraska

## APPENDIX

Appendix A: Groundwater Sampling Results

GSI Job No. G-2050
Issued: 6/18/01

GROUNDWATER SERVICES, INC.

**TABLE A-1**
**MULCH BIOWALL AND SURFACE AMENDMENT TEST AT SITE B301, OFFUTT AFB, NEBRASKA**
**Groundwater Sampling Results: June 1999**

**Test Program for In-Situ Dechlorination by NOM Addition**
**Air Force Center for Environmental Excellence, Brooks AFB, Texas**

| | | PLUME AREA MONITORING WELLS | | | | | | | | | | | Biowall Well[6] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Units | Blank | B301-MW22S | B301-MW23S | B301-MW24S | B301-MW29S | B301-MW30S | B301-MW31S | B301-MW32S | B301-MW33S | B301-MW34S | DUPLICATE B301-MW34A | B301-MW35 |
| **Chlorinated Organics and Reduction By-Products** | | | | | | | | | | | | | |
| PCE | mg/L | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| TCE | mg/L | <0.001 | 0.420 | 0.280 | 0.250 | 0.630 | 0.480 | 0.013 | 0.130 | 0.870 | 0.600 | 0.600 | 0.28 |
| 1,1-DCE | mg/L | <0.001 | <0.001 | <0.001 | <0.001 | 0.0032 | 0.0031 | 0.0012 | 0.0026 | <0.001 | <0.001 | <0.001 | <0.001 |
| cis-1,2-DCE | mg/L | <0.001 | 0.010 | 0.0067 | 0.0068 | 0.260 | 0.140 | 0.550 | 0.73 | 0.067 | 0.040 | 0.044 | 0.0063 |
| trans-1,2-DCE | mg/L | <0.001 | 0.0015 | 0.0011 | 0.001 | 0.0046 | 0.0032 | 0.0045 | 0.0064 | 0.0033 | 0.0022 | 0.0023 | 0.0011 |
| Vinyl chloride | mg/L | <0.001 | <0.001 | <0.001 | <0.001 | 0.0026 | 0.0023 | 0.0061 | 0.0041 | <0.001 | <0.001 | <0.001 | <0.001 |
| Ethene | ng/L | 9 | 11 | 15 | 11 | 208 | 77 | 73 | 166 | 34 | 26 | 27 | <3200[4] |
| Ethane | ng/L | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | 5 | <5 | <5 | <2500[4] |
| **cDCE/TCE ratio** | | --- | **0.02** | **0.02** | **0.03** | **0.41** | **0.29** | **42.31** | **5.62** | **0.08** | **0.07** | **0.07** | |
| **Water Quality Parameters** | | | | | | | | | | | | | |
| Temperature | °F | -- | 69.9 | 69.1 | 61.1 | 77.9 | 77.1 | 72.5 | 68.9 | 69.3 | 56.8 | -- | 73.4 |
| pH | pH units | -- | 6.98 | 7.14 | 7.05 | 7.04 | 7.09 | 7.07 | 7.06 | 7.05 | 7.03 | -- | 7.03 |
| Specific conductance | µ mhos/cm | -- | 794 | 752 | 643 | 880 | 930 | 890 | 880 | 900 | 690 | -- | 980 |
| Total organic carbon | mg/L | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Chloride | mg/L | <0.2 | 17.6 | 17.6 | 17.2 | 17.9 | 15.4 | -- | 17.4 | 18.6 | 19.1 | 18.9 | -- |
| **Natural Attenuation Parameters** | | | | | | | | | | | | | |
| Dissolved oxygen | mg/L | -- | 1.6 | 1.1 | 1.1 | 0.6 | 0.5 | 0.4 | 0.3 | 0.5 | 0.8 | -- | 0.9 |
| Redox potential | mV | -- | 129.5 | 127.2 | 128.8 | 131.4 | 139.7 | 30.6 | 79.9 | 159.1 | 84 | -- | 97.4 |
| Sulfate | mg/L | -- | 18 (17 ) | 13 | 9 | 18 | 19 | 2 (11.8) | 16 (23.3) | 30 | 23 (27.4) | -- | 17 |
| Nitrate | mg/L | 0.11 | 6.61 | 2.06 | 2.22 | 0.64 | 1.18 | -- | <0.1 | 2.05 | 1.69 | 1.67 | -- |
| Ferrous Iron | mg/L | -- | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 (0.25) | <0.2 (0.07) | <0.2 | <0.20 (<0.02) | -- | <0.20 |
| Methane | ug/L | 0.055 | 0.22 | 0.077 | 0.121 | 111.8 | 31.31 | 55.91 | 111.8 | 3.6 | 1.324 | 0.924 | <1200[4] |
| Hydrogen | nM | 0.92 | 1.08 | 1.15 | 1.02 | 0.93 | 1.16 | 1.03 | 1.13 | 0.85 | 1.32 | 1.59 | -- |
| Alkalinity | mg/L | -- | 300 (420 ) | 340 | 300 | 400 | 420 | 440 (360) | 400 (362) | 400 | 400 (298) | -- | 380 |

Notes:
1. The following analyses were performed at Southern Petroleum Laboratories (SPL), Inc., Houston, Texas: Chlorinated organics analyzed by EPA Method 8021; chloride and nitrate by Method 300, and TOC by Method 9060.
Ethene, ethane, and methane were analyzed by GC/FID and hydrogen was analyzed by GC/RGD by Microseeps, Inc.
2. Sulfate, Ferrous Iron, and Alkalinity were measured in the field using Hach kits. The respective detection limits are 1 mg/L, 0.2 mg/L and 5 mg/L. Bracketed values represent laboratory measurements for comparison to Hach tests, with sulfate analysis by Method 300 or iron analysis by Method 6010B.
3. -- = Not measured.
4. These samples were analyzed by SPL instead of Microseeps and thus have higher detection limits.
5. Samples from B301-MW35 was analyzed at T>4°C, compromising the reliability of VOC measurements.
6. B301-MW35 was a temporary well installed in the biowall.

GSI Job No. G-2050
Issued: 6/18/01

GROUNDWATER SERVICES, INC.

**TABLE A-2**
**MULCH BIOWALL AND SURFACE AMENDMENT TEST AT SITE B301, OFFUTT AFB, NEBRASKA**
**Groundwater Sampling Results: February 2000**

**Test Program for In-Situ Dechlorination by NOM Addition**
**Air Force Center for Environmental Excellence, Brooks AFB, Texas**

| | | PLUME AREA MONITORING WELLS | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Units | Blank | B301-MW22S | B301-MW23S | B301-MW24S | B301-MW27S | B301-MW28S | B301-MW29S | B301-MW30S | B301-MW31S | B301-MW32S | B301-MW33S | DUPLICATE B301-MW33A | B301-MW34S | DUPLICATE B301-MW34A |
| **Chlorinated Organics and Reduction By-Products** | | | | | | | | | | | | | | | |
| PCE | mg/L | <0.001 | 0.0011 | 0.0011 | 0.0012 | <0.001 | 0.0011 | 0.0011 | 0.0071 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| TCE | mg/L | <0.001 | 0.6 | 1.2 | 2.0 | 0.150 | 0.17 | 0.37 | 0.34 | 0.014 | 0.011 | 0.22 | 0.21 | 0.84 | 0.92 |
| 1,1-DCE | mg/L | <0.001 | 0.0052 | 0.0047 | 0.0032 | 0.001 | <0.001 | 0.0014 | 0.0015 | <0.001 | <0.001 | <0.001 | <0.001 | 0.0029 | 0.003 |
| cis-1,2-DCE | mg/L | <0.001 | 0.0074 | 0.0078 | 0.014 | 0.015 | 0.003 | 0.0069 | 0.0043 | 0.0063 | 0.019 | 0.09 | 0.092 | 0.065 | 0.062 |
| trans-1,2-DCE | mg/L | <0.001 | 0.0015 | 0.0027 | 0.0039 | 0.012 | 0.0015 | 0.001 | <0.001 | 0.0033 | 0.0034 | 0.0055 | 0.0055 | 0.0036 | 0.0034 |
| Vinyl chloride | mg/L | 0.0015 | <0.001 | <0.001 | <0.001 | 0.0023 | <0.001 | <0.001 | <0.001 | 0.002 | 0.0015 | 0.003 | 0.0033 | 0.0014 | 0.0015 |
| Ethene | ng/L | 15 | 24 | 24 | 14 | 121 | 19 | 65 | 37 | 1272 | 95 | 8162 | 8243 | 857 | 143 |
| Ethane | ng/L | <5 | 9 | 16 | 8 | 52 | 10 | 37 | 65 | 8154 | 5613 | 22587 | 22810 | 686 | 110 |
| **cDCE/TCE ratio** | | --- | **0.01** | **0.01** | **0.01** | **0.10** | **0.02** | **0.02** | **0.01** | **0.45** | **1.73** | **0.41** | 0.44 | 0.08 | 0.07 |
| **Water Quality Parameters** | | | | | | | | | | | | | | | |
| Temperature | °F | -- | 53.4 | 52.0 | 50.4 | 51.3 | 50.9 | 52.9 | 52.7 | 52.2 | 54 | 53.6 | 53.6 | 53.4 | 53.4 |
| pH | pH units | -- | 6.22 | 6.21 | 6.21 | 6.42 | 6.33 | 6.18 | 6.14 | 5.96 | 5.42 | 5.36 | 5.36 | 6.18 | 6.18 |
| Specific conductance | µ mhos/cm | -- | 751 | 792 | 810 | 729 | 710 | 733 | 828 | 830 | 662 | 862 | 862 | 828 | 828 |
| Total organic carbon | mg/L | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | 1.67 | 1.08 | <1 | -- | 1.36 | <1 |
| Chloride | mg/L | 4.8 | 15 | 19 | 20 | 11 | 10 | 12 | 12 | 13 | 13 | 19 | -- | 20 | 20 |
| **Natural Attenuation Parameters** | | | | | | | | | | | | | | | |
| Dissolved oxygen | mg/L | -- | 2.42 | 2.10 | 2.24 | 0.29 | 0.34 | 0.25 | 0.49 | 0.3 | 0.1 | 0.12 | 0.12 | 0.3 | 0.3 |
| Redox potential | mV | -- | 202.5 | 199.3 | 199.6 | 206.4 | 206.1 | 206.7 | 205.5 | 202.8 | 146.7 | 150.3 | 150.3 | 150.2 | 150.2 |
| Sulfate | mg/L | -- | 24 | 33 | 47 | 20 | 18 | 21 | 21 | 13 | 2 | 14 | 14 | 33 | 33 |
| Nitrate | mg/L | <0.1 | 3.7 | 4.4 | 4.8 | 0.76 | 1.3 | 1.7 | 1.8 | <0.1 | <0.1 | 0.3 | -- | 2.6 | 2.6 |
| Ferrous Iron | mg/L | -- | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 |
| Methane | ug/L | 0.118 | 0.283 | 0.267 | 0.149 | 58.15 | 0.526 | 3.923 | 6.498 | 1373 | 1154.0 | 4477 | 4531 | 174.4 | 30.16 |
| Hydrogen | nM | 0.71 | 1.28 | 1.54 | 1.02 | 0.75 | 0.61 | 1.02 | 1.34 | 1.28 | 1.89 | 2.54 | 1.39 | 1.72 | 1.44 |
| Alkalinity | mg/L | -- | 90 | 90 | 95 | 95 | 90 | 95 | 95 | 110 | 138 | 125 | 125 | 110 | 110 |

Notes:
1. The following analyses were performed at Southern Petroleum Laboratories, Inc., Houston, Texas: Chlorinated organics analyzed by EPA Method 8021; chloride, and nitrate by Method 300, and TOC by Method 9060. Ethene, ethane, and methane were analyzed by GC/FID and hydrogen was analyzed by GC/RGD by Microseeps Laboratory, Pittsburgh, Pennsylvania.
   Temperature, pH, specific conductance, and dissolved oxygen measured in the field with a Horriba water quality checker. Redox potential measured in the field with a Cole-Parmer multimeter.
2. Sulfate, Ferrous Iron and Alkalinity were measured in the field using Hach kits. The respective detection limits are 1 mg/L, 0.2 mg/L and 5 mg/L.
3. -- = not measured.
4. Hydrogen measurements may have been compromised in the February 2000 sampling episode as the lab supplied vials with the wrong type of septum.

GSI Job No. [illegible]
Issued: 6/18/01

GROUNDWATER SERVICES, INC.

**TABLE A-3**
**MULCH BIOWALL AND SURFACE AMENDMENT TEST AT SITE B301, OFFUTT AFB, NEBRASKA**
**Groundwater Sampling Results: August 2000**

**Test Program for In-Situ Dechlorination by NOM Addition**
**Air Force Center for Environmental Excellence, Brooks AFB, Texas**

| | | PLUME AREA MONITORING WELLS | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Units | Blank | B301-MW22S | B301-MW23S | B301-MW24S | B301-MW27S | B301-MW28S | B301-MW29S | B301-MW30S | B301-MW31S | B301-MW32S | Duplicate B301-MW32A | B301-MW33S | Duplicate B301-MW33A | B301-MW34S |
| **Chlorinated Organics and Reduction By-Products** | | | | | | Control | Control | | | | | | | | |
| PCE | mg/L | <0.001 | 0.001 | 0.0012 | <0.001 | <0.001 | 0.0011 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| TCE | mg/L | <0.001 | 1.6 | 2.2 | 2.0 | 0.230 | 0.28 | 0.41 | 0.38 | 0.009 | 0.022 | 0.02 | 0.96 | 0.99 | 1.2 |
| 1,1-DCE | mg/L | <0.001 | 0.0039 | 0.0024 | 0.0019 | 0.001 | 0.0011 | 0.0014 | 0.0014 | <0.001 | <0.001 | <0.001 | 0.0021 | 0.002 | 0.0019 |
| cis-1,2-DCE | mg/L | <0.001 | 0.016 | 0.0290 | 0.039 | 0.015 | 0.0058 | 0.0082 | 0.0062 | 0.0091 | 0.02 | 0.019 | 0.098 | 0.085 | 0.04 |
| trans-1,2-DCE | mg/L | <0.001 | 0.0031 | 0.0051 | 0.0059 | 0.014 | 0.0026 | <0.001 | 0.0012 | 0.0081 | 0.0068 | 0.0061 | 0.0046 | 0.0046 | 0.0039 |
| Vinyl chloride | mg/L | <0.001 | <0.001 | <0.001 | <0.001 | 0.0016 | <0.001 | <0.001 | <0.001 | 0.003 | 0.0044 | 0.0036 | 0.0011 | 0.001 | 0.0013 |
| Ethene | ng/L | <5 | 7.0 | 27.0 | 16 | 35 | 20 | 21 | 19 | 796 | 102 | 76 | 365 | 483 | 717 |
| Ethane | ng/L | <5 | <5 | <5 | <5 | 8.0 | 7.0 | <5 | 5.0 | 17034 | 16948 | 12340 | 750 | 1006 | 587 |
| **cDCE/TCE ratio** | | --- | **0.01** | **0.01** | **0.02** | **0.07** | **0.02** | **0.02** | **0.02** | **0.99** | **0.91** | **0.95** | **0.10** | **0.09** | **0.03** |
| **Water Quality Parameters** | | | | | | | | | | | | | | | |
| Temperature | °C | -- | 15.6 | 16.6 | 17.2 | 16.3 | 16.4 | 15.5 | 14.3 | 16.1 | 14.6 | -- | 14.4 | -- | 14.9 |
| pH | pH units | -- | 6.49 | 6.36 | 6.46 | 6.71 | 6.64 | 6.69 | 6.64 | 6.41 | 6.46 | -- | 6.49 | -- | 6.39 |
| Specific conductance | µ µηοσ/χµ | -- | 635 | 662 | 671 | 645 | 635 | 710 | 627 | 781 | 713 | -- | 673 | -- | 677 |
| Total organic carbon | mg/L | -- | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | <1.0 | 1.6 | 1.93 | -- | <1.0 | <1.0 | 1.25 |
| Chloride | mg/L | <1 | 10 | 15 | 17 | 6.5 | 6.7 | 6.7 | 6.5 | 17 | 16 | -- | 16 | 15 | 16 |
| **Natural Attenuation Parameters** | | | | | | | | | | | | | | | |
| Dissolved oxygen | mg/L | -- | 0.05 | 0.04 | 0.00 | 0.01 | 0.03 | 0.04 | 0.02 | 0.05 | 0.04 | -- | 0.02 | -- | 0.02 |
| Redox potential | mV | -- | 207.1 | 216.0 | 213.4 | 220.4 | 220.6 | 222.9 | 203.7 | 172.0 | 143.5 | -- | 178.5 | -- | 184.1 |
| Sulfate | mg/L | -- | 29 | 40 | 40 | 22 | 22 | 23 | 24 | ND | ND | -- | 33 | -- | 33 |
| Nitrate | mg/L | <0.1 | 2.67 | 2.83 | 2.63 | 0.145 | 0.498 | 0.948 | 0.947 | ND | ND | -- | 1.9 | 1.9 | 1.8 |
| Ferrous Iron | mg/L | -- | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | -- | <0.2 | - | <0.2 |
| Methane | ug/L | 0.048 | 0.075 | 0.973 | 0.650 | 4.335 | 2.403 | 0.450 | 0.635 | 1162 | 1251 | 895 | 120.4 | 172.8 | 94.3 |
| Hydrogen | nM | 0.5 | 0.330 | 0.500 | 1.190 | 0.770 | 0.540 | 0.600 | 0.690 | 0.940 | 0.650 | 0.770 | 0.440 | 0.380 | 0.480 |
| Alkalinity | mg/L | -- | 360 | 360 | 360 | 400 | 400 | 360 | 360 | 420 | 400 | -- | 390 | -- | 360 |

Notes:

1. The following analyses were performed at Southern Petroleum Laboratories, Inc., Houston, Texas: Chlorinated organics analyzed by EPA Method 8021; chloride, and nitrate by Method 300, and TOC by Method 9060. Ethene, ethane, and methane were analyzed by GC/FID and hydrogen was analyzed by GC/RGD by Microseeps Laboratory, Pittsburgh, Pennsylvannia. Temperature, pH, specific conductance, and dissolved oxygen measured in the field with a Horriba water quality checker. Redox potential measured in the field with a Cole-Parmer multimeter.
2. Sulfate, Ferrous Iron and Alkalinity were measured in the field using Hach kits. The respective detection limits are 1 mg/L, 0.2 mg/L and 5 mg/L.
3. -- = not measured.