

N61165.AR.002967
CNC CHARLESTON
5090.3a

ANAEROBIC-AEROBIC SEQUENCING TREATABILITY STUDY REPORT ZONE K SOLID
WASTE MANAGEMENT UNIT 166 CNC CHARLESTON SC
6/2/2000
ENSAFE INC.

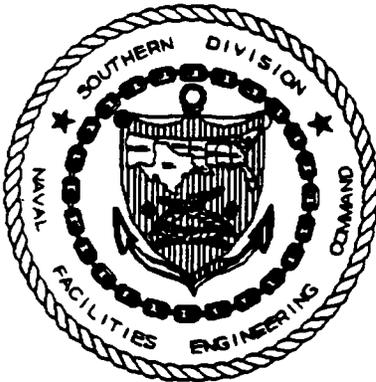


**A-A SEQUENCING TREATABILITY
STUDY REPORT
ZONE K (SWMU 166)**

EnSafe Project Number: 2911-001

Prepared for:

**Department of the Navy
Southern Division
Naval Facilities Engineering Command
North Charleston, South Carolina**



Prepared by:

ENSAFE

**EnSafe Inc.
5724 Summer Trees Drive
Memphis, Tennessee 38134
(901) 372-7962**

June 2, 2000

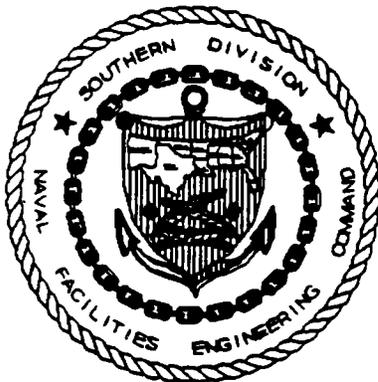


**A-A SEQUENCING TREATABILITY
STUDY REPORT
ZONE K (SWMU 166)**

EnSafe Project Number: 2911-001

Prepared for:

**Department of the Navy
Southern Division
Naval Facilities Engineering Command
North Charleston, South Carolina**



Prepared by:

ENSAFE

**EnSafe Inc.
5724 Summer Trees Drive
Memphis, Tennessee 38134
(901) 372-7962**

June 2, 2000

Table of Contents

1.0	INTRODUCTION	1-1
2.0	REMEDIAL TECHNOLOGY DESCRIPTION	2-1
2.1	Introduction	2-1
2.2	Theory	2-1
2.3	Treatment Process	2-2
2.4	Methodology	2-2
3.0	SITE DESCRIPTION	3-1
3.1	Introduction	3-1
3.2	Site Geology and Hydrogeology of the TCE Investigation Area	3-4
3.3	Nature and Extent of Groundwater Contamination	3-8
4.0	TREATABILITY STUDY OBJECTIVES	4-1
4.1	Primary Objectives	4-1
4.2	Secondary Objectives	4-1
5.0	TREATABILITY SYSTEM SET-UP	5-1
5.1	System Elements	5-1
5.2	Study Area	5-7
6.0	SUMMARY OF FIELD ACTIVITIES	6-1
6.1	System Augmentations	6-1
6.2	Field Monitoring	6-2
6.3	Monthly Ground Water Sampling	6-3
7.0	RESULTS AND ANALYSIS	7-1
7.1	Summary of Data	7-1
7.2	TCE Reduction and Formation of Daughter Products	7-9
7.3	TCE Degradation Rates	7-19
7.4	TCE Degradation Volumes	7-19
7.5	Field Data Interpretation	7-20
7.6	Interpretation of Geochemical Data	7-21
7.7	Hydraulic Evaluation	7-23
8.0	SYSTEM MODIFICATION	8-1
8.1	Summary of Data	8-2
8.2	Analysis of Data	8-6
9.0	CONCLUSIONS AND RECOMMENDATIONS	9-1
10.0	REFERENCES	10-1

List of Figures

Figure 3.1	Groundwater Monitoring Well Location Map, Naval Annex	3-2
Figure 3.2	Treatability Study Area Site Map	3-3
Figure 3.3	Lithostratigraphic Cross-Sections A-A' and B-B' with Monitoring Wells . .	3-5
Figure 3.4	Shallow Groundwater Potentiometric Map, January 1999	3-6
Figure 3.5	Deep Groundwater Potentiometric Map, January 1999	3-7
Figure 3.6	Shallow Zone Total Chlorinated VOCs, March 1999	3-9
Figure 3.7	Deep Zone Total Chlorinated VOCs, March 1999	3-10
Figure 5.1	Process and Instrumentation Diagram	5-2
Figure 5.2	Equipment Layout	5-3
Figure 7.1	October 1999 TCE concentrations	7-11
Figure 7.2	February 2000 TCE concentrations	7-12
Figure 7.3	TCE Concentrations, Treatability Monitoring Wells	7-13
Figure 7.4	TCE Concentrations, Monitoring Wells	7-14
Figure 7.5	October 1999 1,2-DCE concentrations	7-15
Figure 7.6	February 2000 1,2-DCE concentrations	7-16
Figure 7.7	1,2-DCE Concentrations, Treatability Monitoring Wells	7-17
Figure 7.8	1,2-DCE Concentrations, Monitoring Wells	7-18
Figure 7.9	CO ₂ Concentrations	7-22
Figure 7.10	November 4, 1999 Potentiometric Map	7-26
Figure 7.11	November 10, 1999 Potentiometric Map	7-27
Figure 7.12	November 19, 1999 Potentiometric Map	7-28
Figure 7.13	November 24, 1999 Potentiometric Map	7-29
Figure 7.14	December 9, 1999 Potentiometric Map	7-30
Figure 7.15	December 22, 1999 Potentiometric Map	7-31
Figure 7.16	January 5, 2000 Potentiometric Map	7-32
Figure 8.1	April 2000 Potentiometric Map	8-8

List of Tables

Table 6.1	Baseline Groundwater Sampling Protocol	6-3
Table 6.2	Periodic Groundwater Sampling Protocol	6-4
Table 7.1	Treatability Study VOC Data	7-1
Table 7.2	Field Data Summary	7-3
Table 7.3	Treatability Study Inorganic Compound Data	7-5
Table 7.4	Carbon: Nitrogen: Phosphorous Ratio Data	7-6
Table 7.5	TCE Degradation Rates	7-9
Table 7.6	Groundwater Elevations	7-23
Table 8.1	System Modification Volatile Organic Compound Data	8-2
Table 8.2	System Modification Field Data Summary	8-3
Table 8.3	System Modification Inorganic Compound Data	8-3
Table 8.4	System Modification Carbon: Nitrogen: Phosphorous Ratio Data	8-4
Table 8.5	System Modification Groundwater Elevations	8-5

List of Acronyms

A-A	anaerobic-aerobic
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylene
cfm	cubic feet per minute
CLP	Contract Laboratory Program
CMS	Corrective Measures Study
CO ₂	carbon dioxide
DO	dissolved oxygen
DTW	depth to water
ft ²	square feet
gpm	gallons per minutes
hp	horse power
ID	inside diameter
kg	kilogram
mg/L	milligrams per liter
MNA	monitored natural attenuation
msl	mean sea level
mV	millivolts
ORP	oxidation-reduction potential
PCE	perchloroethylene
psi	pounds per square inch
PVC	polyvinyl chloride
QAPP	quality assurance project plan
RFI	RCRA Facility Investigation
SAP	sampling and analysis plan
scfm	standard cubic feet per minute
SITE	Superfund Innovative Technology Evaluation
SU	standard units

SWMU	solid waste management unit
TCE	trichloroethylene
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
USEPA	United States Environmental Protection Agency
VC	vinyl chloride
VOC	volatile organic compound
$\mu\text{g/L}$	micrograms per liter
1,2-DCE	1,2-dichloroethylene

EXECUTIVE SUMMARY

A biological treatability study was conducted at SWMU 166 in the Naval Annex of Zone K of the Charleston Naval Complex between November 1999 and April 2000. SWMU 166 is the chlorinated solvent plume in groundwater that was identified during the investigation of the sanitary sewer line and septic system serving the annex. The treatability study was designed to determine the feasibility of using the anaerobic-aerobic (A-A) sequential system to remediate the chlorinated solvent plume at the site.

The A-A study involved the creation of an anaerobic zone in the upgradient portion of the study area while maintaining aerobic conditions in the downgradient portion. An anaerobic environment was achieved by injecting carbon and nutrients (fructose and ammonium phosphate) into the aquifer, thereby creating conditions in the aquifer that are conducive to degradation of TCE. Groundwater was extracted from downgradient wells to an aboveground amendment system. Fructose and ammonium phosphate were added to the extracted groundwater which was then reinjected upgradient via reinjection wells. The aerobic portion of the system was designed to degrade the daughter products of TCE degradation, namely cis-1,2-DCE and vinyl chloride. Air sparging wells were placed between the extraction wells and reinjection wells to create aerobic conditions in the aquifer.

The feasibility of the technology was evaluated based on field biochemical parameter testing as well as periodic analyses of chlorinated solvents in groundwater monitoring wells. Dissolved oxygen (DO) concentrations and oxidation reduction potential (ORP) values were monitored biweekly to determine effects of the system on the aquifer. Volatile organic compounds were sampled monthly to track the effectiveness of the system.

TCE concentrations in the treatability study wells decreased from a high of 11,000 µg/L to nondetect in most of the treatability study wells. DO and ORP measurements confirmed that an anaerobic environment was created that effectively reduced TCE. Concentrations of cis-1,2-DCE — which is the daughter product of TCE degradation by reductive dechlorination — increased as

the study progressed, strongly supporting biological degradation. Vinyl chloride was not detected in any of the treatability study wells, indicating that this daughter product was being degraded rapidly as it was being formed. However, DO concentrations downgradient of the air sparging wells did not indicate that aerobic conditions were being effectively created to degrade all the 1,2-DCE that was produced.

In March 2000, the treatability system was modified so that air could be injected into the upgradient re-injection wells to increase oxygen concentrations in the aquifer and induce rapid cis-1,2-DCE degradation. The modified system operated for one month before shutdown. During this time, only marginal increases in oxygen concentrations were observed and cis-1,2-DCE concentrations did not decrease. It is likely that a longer time is required to allow for aerobic conditions to re-develop in the aquifer before rapid cis-1,2-DCE degradation can be achieved.

1.0 INTRODUCTION

This SWMU 166 anaerobic-aerobic (A-A) sequential treatability study report is based on the *SWMU 166 A-A Sequencing Treatability Study Work Plan* (March 1999) and the *SWMU 166 A-A Sequencing Treatability Study Design Document* (July 1999). Data presented in the *Monitored Natural Attenuation Interim Report* (March 1999) were also used in this report. The treatability study was conducted in accordance with methods presented in Section 5 of the *Comprehensive Corrective Measures Study Work Plan* (June 1997). The A-A sequential treatment technology is based on enhancing the aquifer to biodegrade volatile organic compounds (VOCs), as described in Section 2. The study's primary purpose was to determine the feasibility of using A-A sequencing to remediate the SWMU 166 VOC groundwater plume. A secondary purpose was to determine the impact of the treatability study on the aquifer's physical, chemical, and biological properties.

Twelve wells were installed for the treatability study in May and June 1999 near well 16610D:

- Two 4-inch inside diameter (ID) extraction wells (166PWA and 166PWB)
- Two 2-inch ID air sparging wells (166AS1 and 166AS2)
- Four 2-inch ID monitoring wells (166TM1, 166TM2, 166TM3, and 166TM4)
- Four 4-inch ID re-injection wells (166IN1, 166IN2, 166IN3, and 166IN4)

Each well was installed to the top of the Ashley Formation, the regional confining layer, which was approximately 36 feet below ground surface (bgs) in the treatability study area. The lower 15 feet of each well were screened with 0.02-inch slotted PVC pipe. The pumps, piping, instrumentation, tanks, electrical wiring, and housing, as described in the design document, were installed in October 1999. Section 5 provides more information on well installation and the system setup.

The system operated from November 9, 1999, until March 16, 2000. During this time, field monitoring data and monthly analytical data were collected, as described in Section 6. Results are presented and analyzed in Section 7. On March 16, the system was modified so that air could be blown into the four upgradient re-injection wells and the two downgradient air sparging wells to create a larger aerobic zone in the aquifer. The modified system ran until April 12, 2000. Section 8 details the modifications made to the system and the impacts of these modifications.

2.0 REMEDIAL TECHNOLOGY DESCRIPTION

2.1 Introduction

Anaerobic-aerobic sequential groundwater treatment, also known as two-zone interception treatment, is designed for enhanced in-situ bioremediation of chlorinated solvent contamination. The U.S. Environmental Protection Agency (USEPA) has demonstrated the technology as an Emerging Technology under the Superfund Innovative Technology Evaluation (SITE) Program.

2.2 Theory

Most chlorinated solvents at contaminated groundwater sites are amenable to biodegradation. However, in contrast to petroleum hydrocarbons, chlorinated solvents are more sensitive to groundwater oxidation-reduction potential (redox), availability of natural organic carbon or anthropogenic organic substrates (benzene, toluene, ethyl benzene, and xylene [BTEX] contamination or other man-made carbon sources), and natural groundwater electron acceptors such as dissolved oxygen, nitrate, sulfate, and carbon dioxide.

While petroleum hydrocarbons can serve as a primary organic substrate (food source that provides energy) or electron donor for microorganisms, chlorinated solvents — particularly the highly chlorinated solvents such as perchlorethylene (PCE) and trichloroethylene (TCE) — are not a direct food or energy source. PCE and TCE serve more as electron acceptors much as oxygen, nitrate, sulfate, and carbon dioxide do in BTEX or natural organic carbon degradation. In other words, anaerobic or reduced conditions (absence of dissolved oxygen) are more suitable to PCE and TCE degradation. Moreover, the more strongly reduced an aquifer is, the more readily PCE and TCE degrade.

The lesser chlorinated solvents such as 1,2-dichloroethylene (1,2-DCE) and vinyl chloride (VC), which are PCE and TCE's biodegradation breakdown products (daughter compounds), are more likely to serve as primary organic substrates or electron donors and are more amenable to biodegradation in the presence of oxygen.

2.3 Treatment Process

An aquifer's anaerobic or aerobic state can be estimated from redox measurements. The lower the aquifer's redox potential (measured in millivolts) the more anaerobic or strongly reducing it is. In general, redox potentials less than +50 millivolts (mVs) represent anaerobic reducing conditions. If redox measurements near the PCE and TCE plume are greater than +50 mVs, nutrients (nitrate and phosphate compounds) and substrate (organic carbon) can be added to consume oxygen drive the system into strongly anaerobic or reducing conditions. Generally, enough carbon is added to create anaerobic conditions and be available as a food source while highly chlorinated solvents such as PCE and TCE are subsequently degraded. Conversely, if redox measurements near 1,2-DCE and VC are less than +50 mVs, air sparging can be used to increase oxygen availability and allow maximum biological consumption of substrates such as 1,2-DCE and VC.

2.4 Methodology

By creating an anaerobic zone upgradient of an aerobic zone within a VOC contaminated groundwater plume, a sequential anaerobic-aerobic zone is established that can degrade PCE and TCE sequentially to innocuous gaseous end-products. Moreover, flow through these zones can be accelerated by placing low-flow extraction wells placed downgradient of the aerobic zone and re-injecting pumped water upgradient of the anaerobic zone.

Anaerobic Zone

An anaerobic zone is created by pumping groundwater from downgradient extraction wells and adding carbon and other nutrients to it aboveground before re-injecting the groundwater into upgradient wells. The groundwater is first pumped to an aboveground chemical amendment system where carbon (fructose) and nutrients (ammonium phosphate) are added before groundwater is re-injected into the aquifer. The carbon and nutrients provide a ready food source that stimulates microbial respiration, which then uses all the available oxygen in the pumped groundwater. This recirculation process (extraction and reinjection) continues until an anaerobic zone is gradually created near the re-injection wells. Highly chlorinated solvents such as PCE and TCE are amenable to reductive dechlorination (biological removal of the chlorine) under anaerobic conditions. In other words, after the anaerobic zone is established, microorganisms will turn to sources other than oxygen, such as chlorinated VOCs, to complete respiration.

Aerobic Zone

Anaerobic reductive dechlorination results in lesser-chlorinated daughter products, namely 1,2, cis-DCE and VC, being formed. However, these compounds break down more readily in an aerobic environment. Therefore, an aerobic zone is created near the downgradient extraction wells by injecting air into the aquifer via sparging wells connected to an aboveground blower. The sparging wells were located approximately 30 feet downgradient of the re-injection wells. Sparging is generally performed intermittently, based on groundwater dissolved oxygen (DO) concentrations in area monitoring wells. Carbon and nutrients can also be added to the air sparging wells to enhance the aerobic degradation of 1,2, cis-DCE and VC. Aerobic degradation of VC forms innocuous end-products such as carbon dioxide and water.

3.0 SITE DESCRIPTION

3.1 Introduction

The U.S. Marine Corps currently uses the Naval Annex as a reserve training center, it houses administrative and classroom type buildings and a heavy vehicle storage and maintenance/small repair facility. In addition to these structures, the surface is covered by grass, asphalt, and concrete. The Naval Annex is part of Zone K, which also includes Clouter Island.

SWMU 166 is the solvent plume identified when the sanitary sewer line and septic system serving the annex were investigated. Initially, the sewer system and the solvent plume were jointly referred to as SWMU 166. However, the sewer system was later designated SWMU 185. Figure 3.1 shows the Zone K Naval Annex area and distribution of buildings and roads, while Figure 3.2 shows the treatability study area in more detail.

During the SWMU 166 RCRA Facility Investigation (RFI), TCE was identified in groundwater at the Naval Annex in an area currently occupied by a U.S. Marine Corps Reserve Training Center. The TCE plume has since migrated east and is discharging offsite into the french drain and storm water sewer system associated with the Interstate 26.

High TCE concentrations in surface soil away from the sanitary sewer line were identified as the probable source for groundwater VOCs. This soil has since been removed by the Environmental Detachment.

10000D ● DEEP MONITORING WELL LOCATION

16303M ● MULTI-LEVEL VERTICAL PROFILE MONITORING WELL LOCATION

166GP003 ◆ GROUNDWATER DPT SAMPLE



ZONE K - SWMU 166
A-A TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX (NAVAL ANNEX)
CHARLESTON, SC

FIGURE 3.1
GROUNDWATER MONITORING WELL LOCATION MAP
NAVAL ANNEX

Dr by: W. FAULK	Tr by: -	
Ck by: R. BRITTO	Appr by: T. HAVERKOST	Sheet 1
Date: 05/30/00	DWG Name: 2911C102	Of 1

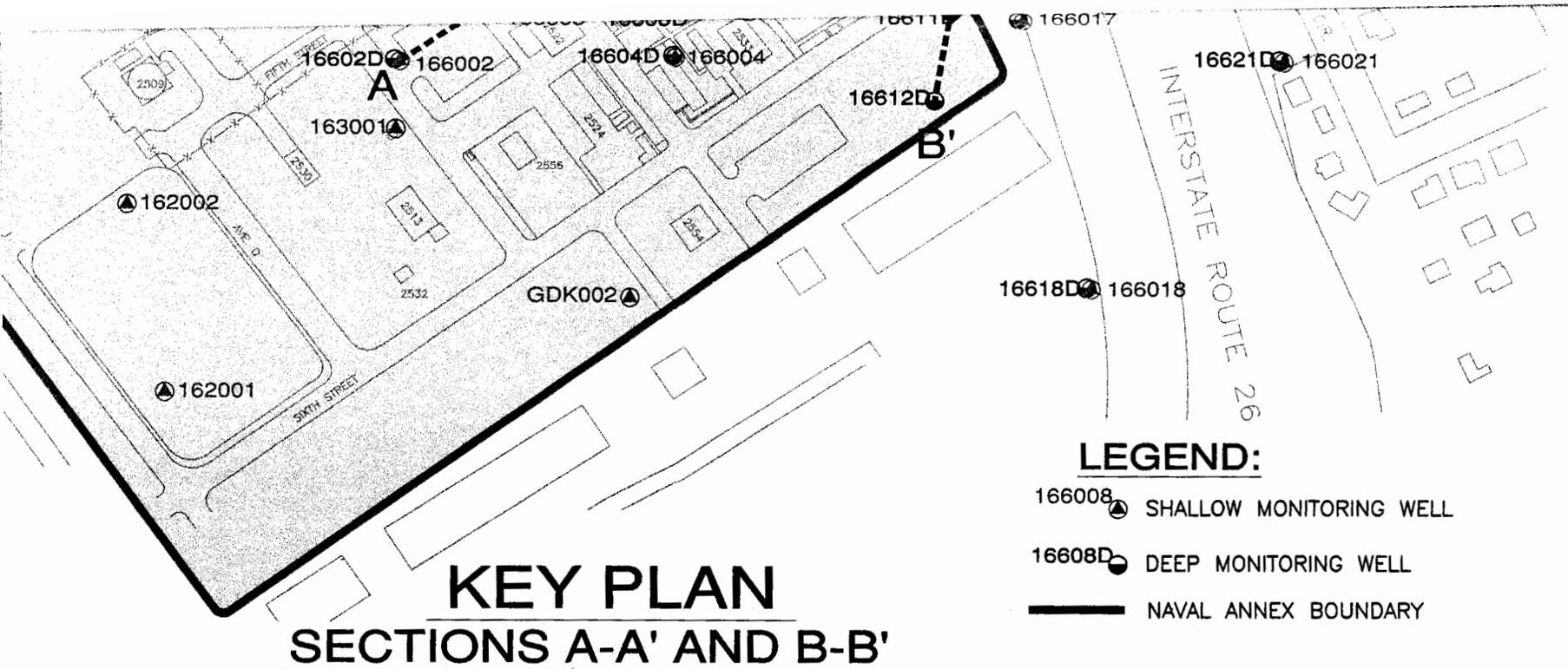
166GP069



ZONE K - SWMU 166
A-A TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX (NAVAL ANNEX)
CHARLESTON, SC

FIGURE 3.2
SWMU 166 - TREATABILITY STUDY AREA
SITE MAP

Dr by: W. FAULK	Tr by: -	
Ck by: R. BRITTO	Appr by: T. HAVERKOST	Sheet 1
Date: 05/30/00	DWG Name: 2911C103	Of 1



LEGEND:

- 166008 SHALLOW MONITORING WELL
- 16608D DEEP MONITORING WELL
- NAVAL ANNEX BOUNDARY

**KEY PLAN
SECTIONS A-A' AND B-B'**



ZONE K - SWMU 166
 A-A TREATABILITY
 STUDY REPORT
 CHARLESTON NAVAL COMPLEX (NAVAL ANNEX)
 CHARLESTON, SC

FIGURE 3.3
 LITHOSTRATIGRAPHIC CROSS-SECTIONS A-A' AND B-B'
 WITH MONITORING WELLS

Dr by: W. FAULK	Tr by: -	
Ck by: R. BRITTO	Appr by: T. HAVERKOST	Sheet 1
Date: 05/30/00	DWG Name: 2911C104	Of 1

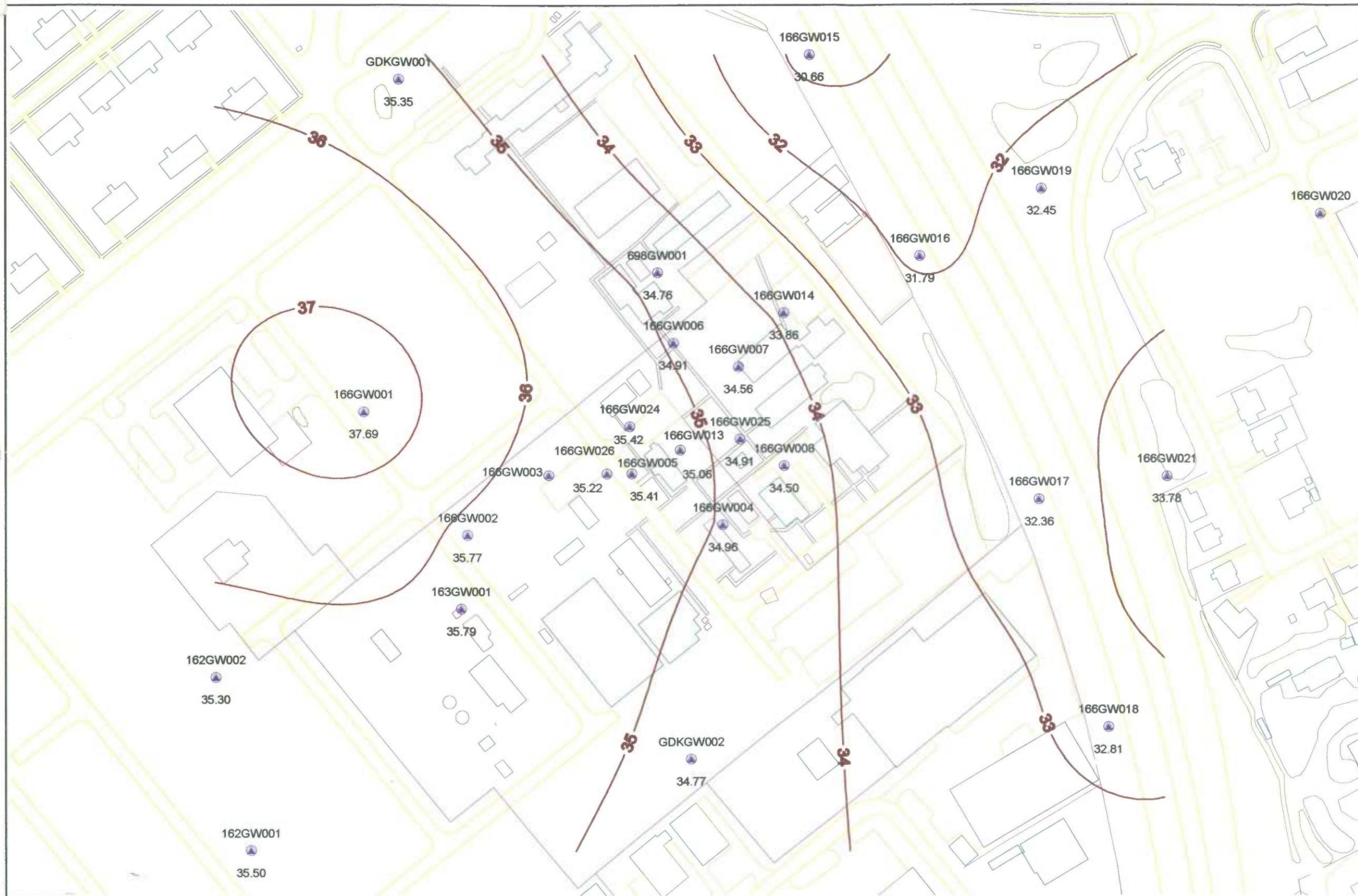
NS	
Rev By:	

3.2 Site Geology and Hydrogeology of the TCE Investigation Area

Figure 3.3 provides geologic profiles of the Naval Annex, Interstate 26, and area between Interstate 26 and Gas Light Square Shopping Center. Three primary lithologies encountered across the investigated area and are identified on the profiles. The uppermost lithologic unit (Qs) is primarily clean, well-sorted, fine-to medium-grained sand with traces of mica. Below this sand unit, another primarily sand unit (Qcs) was encountered; however, this unit contained some silt and clay, along with phosphate nodules and shell hash. In places, clay was the primary texture. The upper sand unit was 20 to 25 feet thick. The lower clayey sand unit was approximately 10 feet thick. The Ashley Formation (Ta) underlies the Qcs throughout the entire study area. A bed of peat was encountered in the upper sand near the Gas Light Square Shopping Center.

Figures 3.4 and 3.5 are January 1999 potentiometric surface maps for the shallow and deep portions of the water table aquifer. They represent potentiometric surfaces before the installation of the A-A sequential treatability study. The shallow potentiometric map encompasses a larger area than the deep potentiometric map due to the broader distribution of shallow wells. Both identify the hydraulic gradient on each side of the interstate to be toward the interstate. The interstate area is a potentiometric low due to the effect of the french drain beneath the interstate. Potentiometric surface maps generated during the treatability study will be compared with pre-treatability surface maps to identify changes that may have occurred as a result of the study.

Slug test and water level data from study area wells 16607D and 16610D indicate that horizontal hydraulic conductivity is approximately 4.0 ft/day and hydraulic gradients are approximately 0.01 ft/ft. Assuming an aquifer porosity of 0.25, groundwater flow velocities through the study area are approximately 0.16 ft/day, or approximately 50 ft/yr.



LEGEND

- SHALLOW MONITORING WELL
- BUILDING
- FENCE
- PAVEMENT
- ROAD
- SIDEWALK
- TREE

Note: All elevations in ft msl



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

Figure 3.4
Shallow Groundwater
Potentiometric Map
January 1999



LEGEND

- DEEP MONITORING WELL
- BUILDING
- FENCE
- PAVEMENT
- ROAD
- SIDEWALK
- TREE

Note: All elevations in ft msl



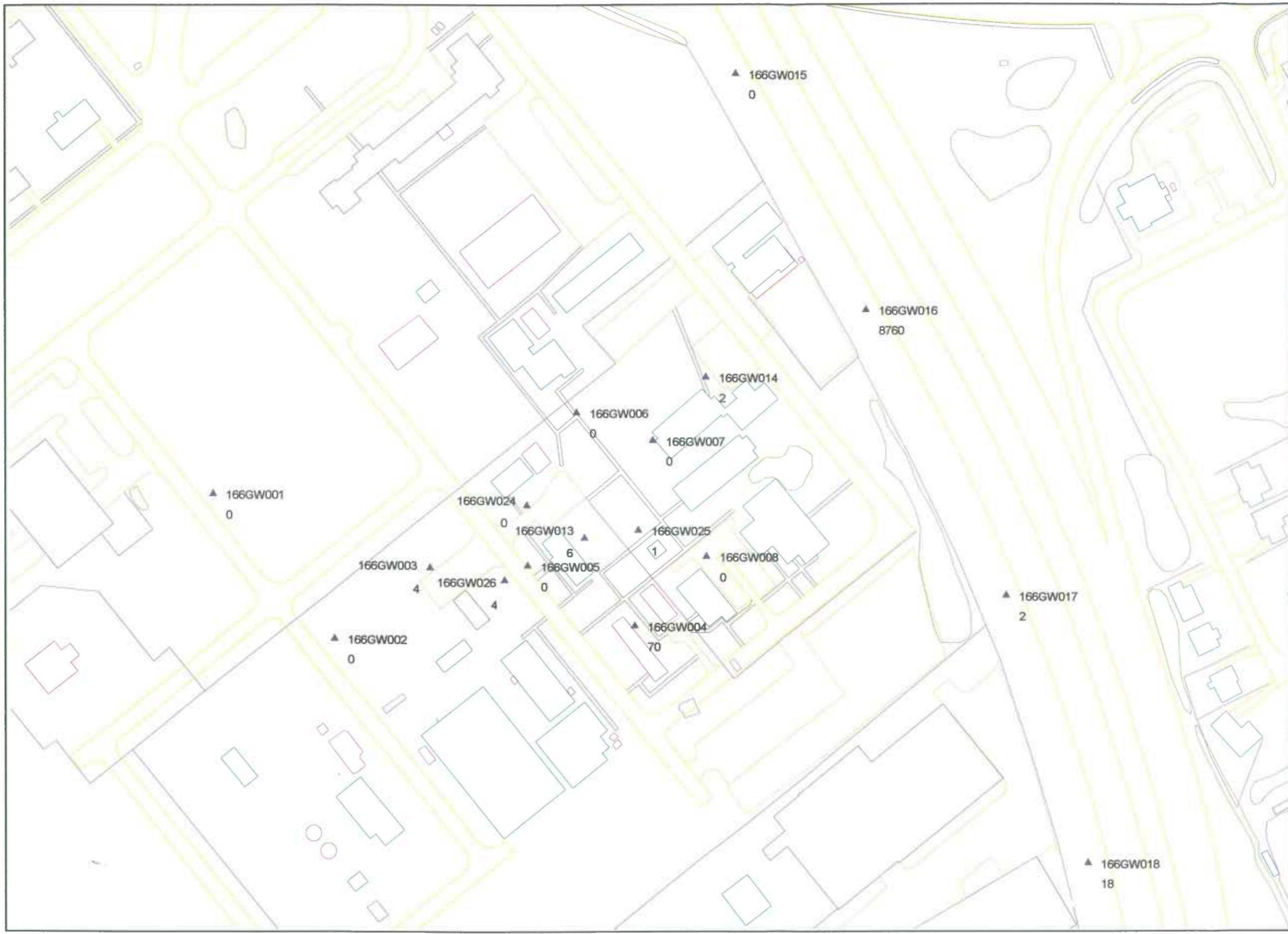
ZONE K - SWMU 166
 A-A SEQUENCING TREATABILITY
 STUDY REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

Figure 3.5
 Deep Groundwater
 Potentiometric Map
 January 1999

A pumping test was performed in January 1999 to determine the sizing and spacing of treatability study wells, piping, and pumps. The average horizontal hydraulic conductivity, as determined by the pumping test, was 9.05 ft/day. Groundwater modeling conducted to support the treatability study design predicted that approximately 50% of the extracted groundwater would be recaptured within six months by the extraction wells. Appendix C of the *SWMU 166 A-A Sequential Treatability Study Design Document* details the pumping tests and modeling effort.

3.3 Nature and Extent of Groundwater Contamination

The RFI identified a chlorinated VOC plume in the shallow and deep portions of the site's surficial aquifer. Figures 3.6 and 3.7 (plume maps) represent TCE concentrations before treatability testing. As shown on the plume maps, the chlorinated VOCs are concentrated in the surficial aquifer's deep zone. The plume originates near the soil source area described above, migrates east toward Interstate 26, extends past the property boundary where it appears to be discharging into the interstate subsurface drainage system, which discharges to a storm sewer running northeast and away from the site. Plume maps generated during the treatability study will be compared with pre-treatability plume maps to identify changes that may have occurred as a result of the study. Chlorinated VOCs identified in groundwater east of the interstate appear to be linked to releases from a former dry cleaning facility on the east side of the interstate.



LEGEND

- ▲ SHALLOW MONITORING WELL
- ▭ BUILDING
- ▭ FENCE
- ▭ PAVEMENT
- ▭ ROAD
- ▭ SIDEWALK
- ▭ TREE

Note: All concentrations in µg/L



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

**Figure 3.6
Shallow Zone Total Chlorinated VOCs
March 1999**



LEGEND

- ▲ DEEP MONITORING WELL
- ▭ BUILDING
- ▭ FENCE
- ▭ PAVEMENT
- ▭ ROAD
- ▭ SIDEWALK
- ▭ TREE

Note: All concentrations in µg/L



ZONE K - SWMU 166
 A-A SEQUENCING TREATABILITY
 STUDY REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

Figure 3.7
 Deep Zone Total Chlorinated VOCs
 March 1999

4.0 TREATABILITY STUDY OBJECTIVES

4.1 Primary Objectives

The main objective of performing a treatability anaerobic-aerobic sequential study at SWMU 166 was to determine the feasibility of using this technology to degrade and remediate the chlorinated VOC groundwater plume. Though it is based on fundamental microbial principles, it has been applied at only a few sites in the United States and is considered an innovative technology. Furthermore, in-situ groundwater technologies are susceptible to inherent chemical, geological and hydrogeological variability that could either enhance or reduce bioremediation. Therefore, a treatability study was needed to assess its effectiveness at SWMU 166 through periodic sampling and analysis of study area groundwater. The treatability study lasted approximately five months.

If the technology is viable, TCE and daughter breakdown compounds (1,2-DCE and VC) were expected to be reduced within the treatability study period. Study results can be used to provide cost and design data for full-scale remediation and to compare this technology with other treatment alternatives.

4.2 Secondary Objectives

Secondary objectives of the treatability study included:

- Measuring and evaluating biochemical operating parameters. These parameters (detailed in Section 7) are dissolved oxygen (DO), pH, oxidation-reduction potential (ORP), heterotrophic plate counts, nutrients (nitrogen and phosphorus), and total organic carbon (TOC). Changes in these values (particularly dissolved oxygen) and when they occurred were noted. These measurements were used to determine how effectively groundwater is being amended to obtain distinct anaerobic and aerobic zones required for chlorinated solvent degradation.

- Measuring groundwater extraction and re-injection rates and changes in groundwater levels in the area monitoring wells as a result of extraction and re-injection. These measurements helped estimate groundwater re-circulation patterns in the test area.
- Measuring of the amounts of carbon (fructose) and nutrients (ammonium phosphate) added to the extracted groundwater. Monitoring the carbon amounts helped maintain the organic carbon's approximate stoichiometric mass balances in the aquifer.
- Monitoring the blower and noting when the blower is used to sparge air to create the downgradient aerobic zone. This data can be used to size blower requirements for full-scale remediation.

5.0 TREATABILITY SYSTEM SET-UP

5.1 System Elements

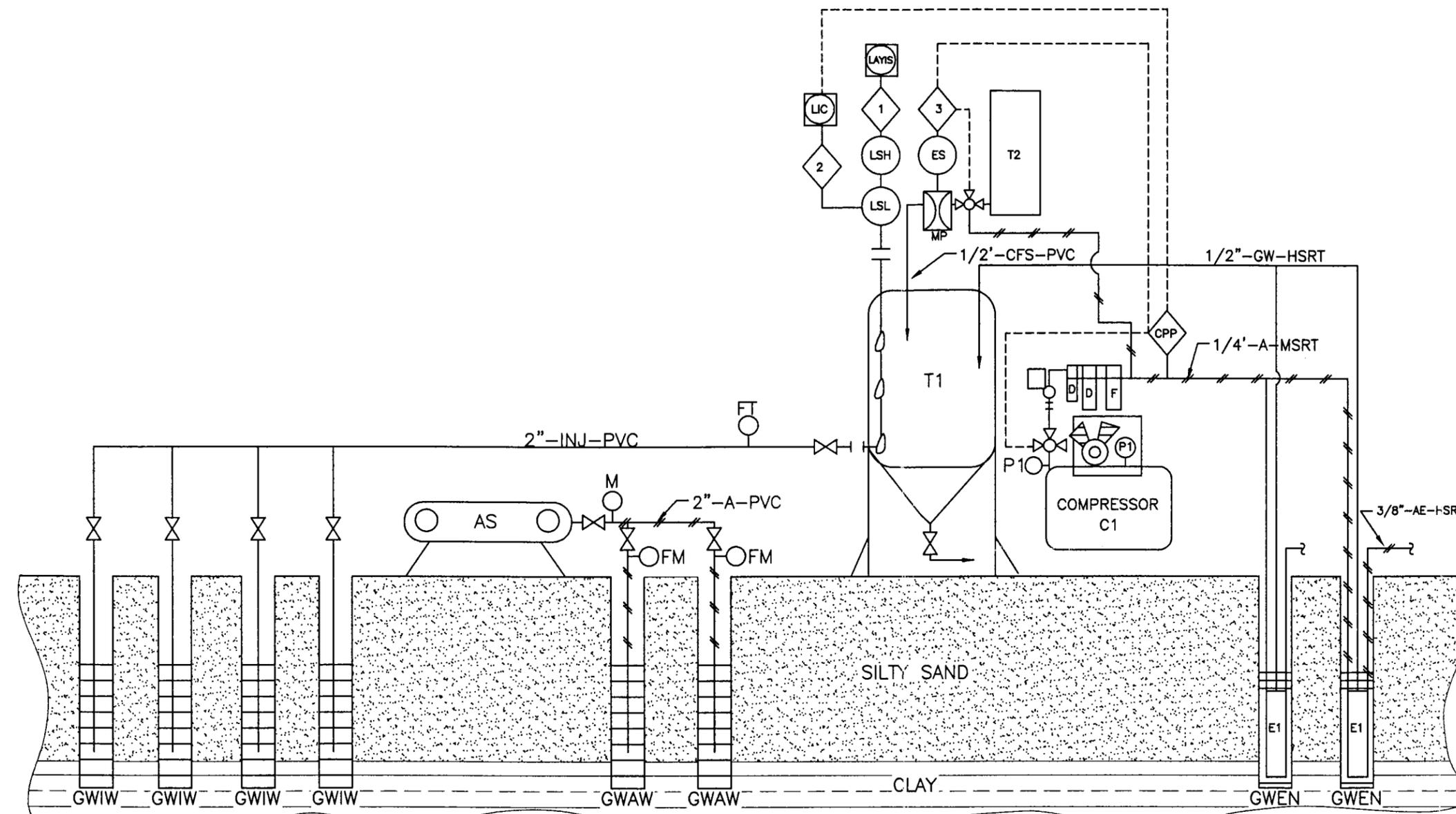
The A-A sequential system included extraction wells, Re-injection wells, an aboveground groundwater chemical amendment system, and air sparging wells. The well locations are shown in Figure 3.2. The process and instrumentation diagram is shown in Figure 5.1. The equipment layout is shown in Figure 5.2. Some modification were made to the system as built that differ slightly from Figures 5.1 and 5.2.

Groundwater Extraction Wells

The two groundwater extraction wells were 4-inch diameter polyvinyl chloride (PVC) wells screened in the deep saturated zone of the surficial aquifer. They were approximately 36 feet in depth and were screened with 0.02-inch slotted PVC screen, 15 feet in length, at the bottom of the well. Each well had a 10 gallon per minute (gpm) capacity submersible pump located at the depth of the screen; each pump was connected by a 3/4-inch hose to an aboveground chemical feed tank. Groundwater was pumped from these wells to a 500-gallon holding tank or a 100-gallon chemical mixing tank.

Groundwater Re-injection Wells

Groundwater from the extraction well was amended with nutrients and substrate in an above ground system. Amended water was then reinjected by gravity flow into the aquifer via four 4-inch ID PVC wells screened in the deep saturated zone of the surficial aquifer. They were approximately 36 feet in depth and were screened with 0.02-inch slotted PVC screen, 15 feet in length, at the bottom of the well.



LEGEND

EQ. NO. T1
 TITLE - GROUNDWATER HOLDING TANK
 TYPE - OPEN TOP CONICAL WITH REMOVABLE COVER, 2" DRAIN (FLANGED)
 MATERIAL - FIBER GLASS OR POLYPROPYLENE
 SIZE - 500 GALLONS
 TEMP - AMB.
 PRESS. - ATMOS.

EQ. NO. T2
 TITLE - CARBON FEED TANK
 TYPE - OPEN TOP WITH COVER (CYLINDRICAL) 1/2" DRAIN FLANGED
 MATERIAL - POLYETHYLENE
 SIZE - 100 GALLONS
 TEMP - AMB.
 PRESS. - ATMOS.

EQ. NO. AS
 TITLE - AIR SPARGING UNIT
 TYPE - REGENERATIVE BLOWER 1 HP
 10 PSI
 TEMP - 225° F
 PRESS. - 10 PSI

EQ. NO. C1
 TITLE - RECIPROCATING AIR COMPRESSOR
 TYPE - STANDARD ELECTRIC - HORIZONTAL 17 CFM, 5 HP, RECIPROCATING PISTON TYPE
 TANK CAPACITY - 80 GALLONS
 PRESSURE - MAX. 125 PSI

EQ. NO. E1
 TITLE - DOWN-WELL (SUBMERSIBLE) AUTO PUMP (PNEUMATIC)
 TYPE - AIR DISPLACEMENT CEE APA OR EQUAL WITH AUTO CONTROL
 MATERIAL - STAINLESS STEEL
 CAPACITY - 4 GPM AT 50' HEAD.
 PRESS - ATMOS
 TEMP - AMB.

INTERLOCK DESIGNATIONS

- 1 - ON HIGH LEVEL IN HOLDING TANK (T1) STOP ALL GROUNDWATER EXTRACTION WELL PUMPS (E1)
- 2 - ON HIGH LEVEL IN HOLDING TANK (T1) START ALL GROUNDWATER EXTRACTION WELL PUMPS (E1)
- 3 - CARBON FEED PUMP OPERATES WITH GROUNDWATER PUMPS

EQUIPMENT DESIGNATION

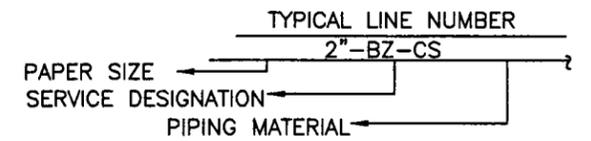
- T1 - GROUNDWATER RECEIVING TANK
- T2 - CARBON FEED TANK
- E1 - PNEUMATIC SUBMERSIBLE PUMP
- AS - AIR SPARGING UNIT
- C1 - AIR COMPRESSOR

LINE LEGEND

- — — — — PROCESS LINE
- - - - - PNEUMATIC LINE
- - - - - ELECTRICAL

SYMBOLS

- MP - METERING PUMP
- FT - FLOW TOTALIZER
- M - MANOMETER
- FM - FLOW METER
- X - BUTTERFLY VALVE
- — — — — FLANGE
- ⊗ - CONTROL VALVE
- ⊕ - AIR FILTER/PRESSURE REGULATOR
- GWEW - GROUNDWATER EXTRACTION WELL
- GWIW - GROUNDWATER INJECTION WELL
- GAWW - GROUNDWATER AIR SPARGING WELL
- PI - PRESSURE GAUGE 0-'74 PSI
- LSL - LIQUID SWITCH LOW LEVEL
- LSH - LIQUID SWITCH HIGH LEVEL
- ES - ELECTRIC SWITCH
- LAHH - LIQUID ALARM HIGH
- LIC - LIQUID INDICATOR CONTROLLER
- CPP - CONTROL PANEL PUMPS
- O - OIL RESERVOIR
- D - DESICANT
- F - FILTER



PIPING SERVICE DESIGNATION

- A - AIR
- GW - GROUNDWATER
- CFS - CARBON FEED
- INJ - INJECTION
- AE - AIR EXHAUST

PIPING MATERIAL DESIGNATION

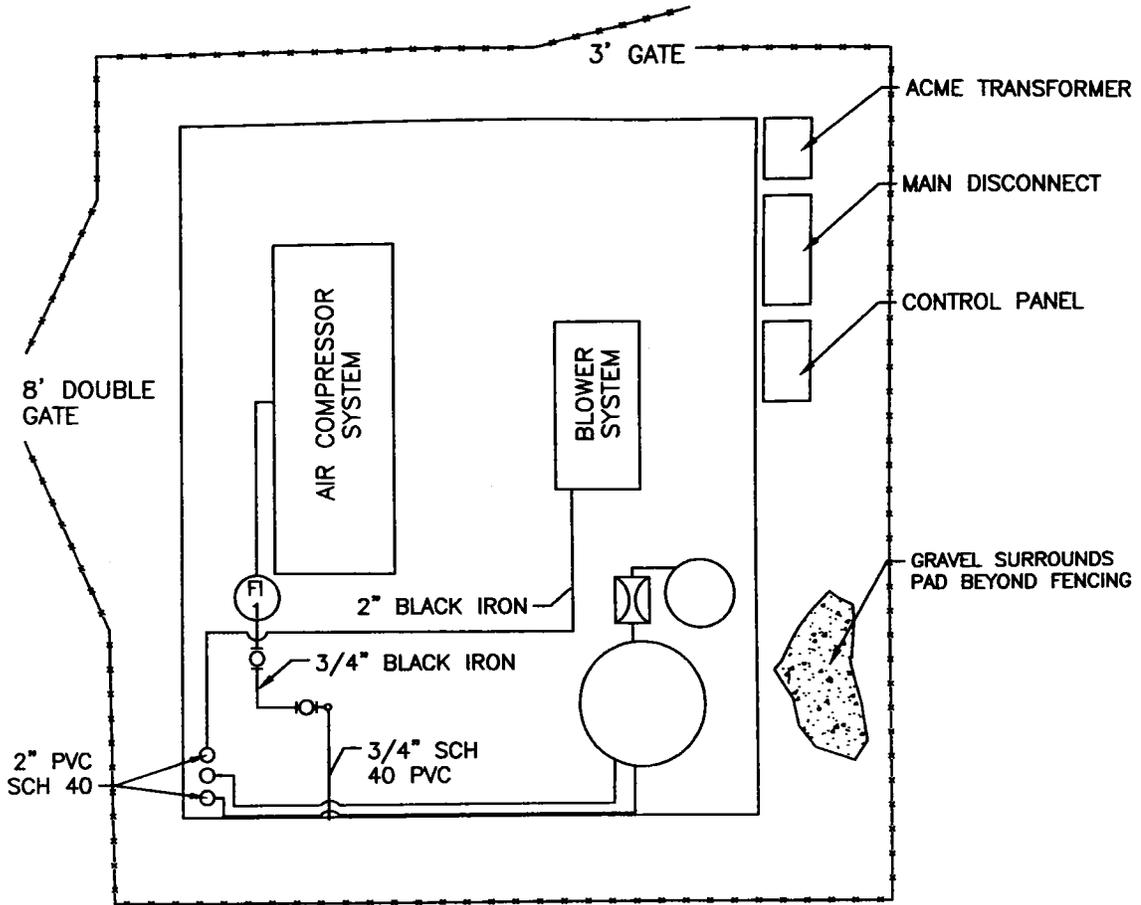
- PVC - POLYVINYL CHLORIDE
- HSRT - HIGH STRENGTH REINFORCED TUBING.

NOT TO SCALE

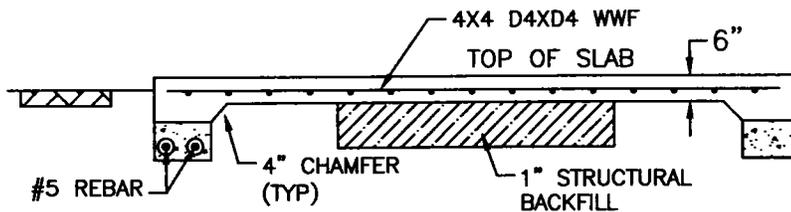


ZONE K - SWMU 166
 A-A TREATABILITY
 STUDY REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 5.1
 PROCESS AND INSTRUMENTATION
 DIAGRAM



FOUNDATION PLAN



SECTION A

NOTES:

1. CONCRETE PAD IS COVERED BY A 14'X10' CANOPY SHELTER.
2. FENCING SURROUNDING PAD AREA CONTAINS GREEN PRIVACY SLATS.
3. ALL PIPING INSIDE COVERED PAD IS BLACK IRON.

NOT TO SCALE



ZONE K - SWMU 166
 A-A TREATABILITY
 STUDY REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 5.2
 EQUIPMENT
 LAYOUT

Groundwater Air Sparging Wells

Air was injected via two 2-inch ID PVC wells screened in the deep saturated zone of the surficial aquifer. They were approximately 36 feet in depth and were screened with 0.02-inch slotted PVC screen, 15 feet in length, at the bottom of the well. The air sparging wells were located downgradient of the Re-injection wells and upgradient of the extraction wells.

Treatability Study Monitoring Wells

Four 2-inch ID PVC wells, screened in the deep saturated zone of the surficial aquifer, were installed to monitor the progress of the treatability system. They were approximately 36 feet in depth and were screened with 0.02-inch slotted PVC screen, 15 feet in length, at the bottom of the well. Three were placed downgradient of the Re-injection wells, but upgradient of the air sparging and extraction wells. One of these was placed south of the treatability study area to monitor the influence of the system on the area just outside the direct flow zone between the Re-injection wells and extraction wells. The other well was placed between the two extraction wells, downgradient of the air sparging wells.

Well Specifications

All wells were installed in a boring drilled to a depth that targeted the deep zone of the aquifer just above the confining Ashley Formation. The wells were flush-mounted at the ground surface and had a well vault. Typical well and vault designs are in Attachment D of the design document. The completed drill holes had outer diameters of 8 to 12 inches, and were large enough to accommodate a 2- or 4-inch inside diameter (ID) well screen and standpipe.

After installation, the wells were thoroughly developed by the drill crew for at least 2 hours, using a combination of pumping, surging, and flushing with potable water. All investigative derived waste (IDW) from drilling and developing the test well were managed as hazardous waste in accordance with the IDW Management Plan presented in the Comprehensive RFI Work Plan for

the Charleston Naval Complex . Development was completed when the engineer or geologist judged the well to be clean and hydraulically responsive.

Air Sparging System

A blower system was installed to supply air to the air sparging wells. The blower was a 1-horsepower (hp), system coupled to an electric motor with the capacity to supply up to 92 standard cubic feet per minute (scfm) at a maximum pressure of 52 inches of water. Power requirements were 230 volts, 3 Φ , and 60 hertz. It was fitted with an air-pressure relief valve, a flow-regulation control valve, and a pressure gauge.

Submersible Pumps

The air-operated submersible pumps placed in the extractions wells were Clean Environmental Equipment (CEE) Standard AP-4 pumps that could extract 4 gpm against a total head of 50 feet. The air supply was regulated by the controllerless total auto pump system. Air requirements, supplied by the compressor system, were 125 pounds per square inch (psi). To prevent overflow of the 500-gallon holding tank, the controllerless total auto pump system was connected to a tank full shut-off system that would block air supply to the submersible pumps if the 500-gallon holding tank became full. Air supply could also be turned on or off manually by check valves.

Chemical Feed Pump

The air-operated diaphragm pump was used to pump water from the 100-gallon chemical mixing tank to the 500-gallon holding tank. The air supply was regulated by the same controllerless total auto pump system as the submersible pumps. The air supply could be turned on or off manually by check valves.

Compressor System

The electrically powered, rotary screw-type compressor supplied 125 psi that powered the submersible pumps and chemical-feed diaphragm pump. The three-phase electrical motor required 230/430 volts at 60 hertz. The compressor was equipped with an air drying system to reduce buildup of condensation in the pressure tank.

Equipment Housing

The blower system, controllerless auto pump system, chemical-feed pump, compressor, air drying system, 500-gallon holding tank, and 100-gallon chemical mixing tank were housed on a fenced 17-foot by 13-foot concrete slab with a metal roof. The housing provided protection for the equipment and controlled access to the system.

Groundwater Recirculation System

The recirculation system was made up of the extraction wells, submersible pumps, 500-gallon holding tank, chemical-feed pump, 100 gallon chemical mixing tank, and Re-injection wells. The 500-gallon polyethylene holding tank had an inlet at the top and a 4-inch outlet at the bottom. The inlet was connected to the groundwater extraction wells via the 3/4-inch hose and a PVC pipe diverted the groundwater influent to the bottom of the tank to avoid aeration and possible volatilization of the VOCs. The outlet was connected to the Re-injection wells by an underground PVC piping network system. Water from the holding tank flowed by gravity to the Re-injection wells. The 100-gallon chemical mixing tank was located adjacent to the 500-gallon holding tank. A 1-inch inlet at the top of the 100-gallon tank allowed groundwater from extraction well 166PWA to be pumped into the tank where carbon and nutrients were mixed into the groundwater. A chemical-feed diaphragm pump was used to transfer the amended groundwater from the mixing tank into the holding tank.

5.2 Study Area

RFI results showed that chlorinated VOC contamination was concentrated primarily in the deeper zone of the surficial aquifer. The maximum total chlorinated VOC concentration in groundwater in the most recent round of sampling was 10,160 micrograms per liter ($\mu\text{g/L}$) (9,700 $\mu\text{g/L}$ TCE; 460 $\mu\text{g/L}$ 1,2-DCE) in well 166GW26D. However, downgradient and near the property line, total chlorinated VOCs began to drop off to more feasible concentrations (2,400 $\mu\text{g/L}$ TCE; 94 $\mu\text{g/L}$ 1,2-DCE in well 166GW10D).

The absence of significant amounts of DCE and VC indicates that drops in TCE concentrations may be attributable to diffusion and dilution more than microbial degradation. This lack of microbial degradation of TCE may be due to a lack of required nutrients and substrate or an abundance of oxygen or other electron acceptors.

The treatability study focused on the area near the property line where total chlorinated VOC concentration are expected to range from about 1,000 to 4,000 $\mu\text{g/L}$ because high concentrations near the source zone may have inhibited microbial activity and because site conditions indicated that there was little microbial degradation occurring within the plume centerline. Study area length (in the direction of groundwater flow) was about 60 feet and study area width was also about 60 feet.

6.0 SUMMARY OF FIELD ACTIVITIES

6.1 System Augmentations

Groundwater was pumped from the two extraction wells (166PWA and 166PWB) to the 500-gallon holding tank in the equipment building. Two to three times a week, groundwater from 166PWA was diverted to the 100-gallon chemical feed tank. When this tank was full, carbon and nutrients (fructose and dibasic ammonium phosphate) were added and mixed with the groundwater in the 100-gallon tank. For every 100 gallons of water, 500 grams of fructose as a carbon source and approximately 40 grams of ammonium phosphate as a nutrient were added. From November 9, 1999, to March 15, 2000, 17.5 kilograms (kg) of fructose and 1.5 kg of ammonium phosphate were added to the system, averaging 1 kg of fructose and 800 grams of ammonium phosphate per week. Typically, 40 to 50 gallons of the carbon and nutrient-enriched groundwater were pumped from the 100-gallon tank per work day into the 500 gallon holding tank. One-inch PVC pipping and a diaphragm pump were used to pump water from the 100-gallon tank to the 500-gallon tank.

More than one million gallons of water were pumped at an average rate of 6 gpm during the four-month study. However, at times the system pumped more than 10 gpm. The volume of groundwater in the area was 166,000 gallons based on estimating the area of the treatability study at 3600 ft², the length of the screened interval of the treatability study wells (15 ft), and the soil porosity 30 to 32 feet bgs at well 16610D (40.9%). It can be estimated that the system recirculated the groundwater almost seven times during the four month period. The system pumped water continuously during the study except

- During monthly groundwater sampling and compressor maintenance
- From November 26, 1999 (afternoon) to December 1, 1999 (16:30) due to low oil in the compressor that resulted in temporary system shut down

- From December 2, 1999 (9:15) to December 3, 1999 (16:00) due to broken compression tubing in the compressor
- From February 3, 2000 (16:00) to February 7, 2000 (10:45) due to high water table around the injection wells
- From February 16, 2000 (12:00) to March 2, 2000 (11:00) due to sediment clogging the extraction well outlet in the 500-gallon tank. However, groundwater from 166PWA was able to be pumped into the 100-gallon chemical feed tank and bypass the 500-gallon tank. This allowed fructose and ammonium phosphate to be added to the groundwater, which was pumped to the 500-gallon holding tank and flowed into the reinjection wells.

6.2 Field Monitoring

Groundwater wells in the test area were monitored for significant field parameters such as pH, DO, ORP, and CO₂. Baseline field monitoring parameters were collected a week before the system was turned on. Wells monitored for baseline field parameters included the two extraction wells, four reinjection wells, two air-sparging wells, four treatability study monitoring wells, and two permanent monitoring wells (16610D and 16616D) near the area of influence of the treatability system. After the system was turned on, field parameters were generally collected weekly for the first two weeks from the four treatability study monitoring wells and the two permanent wells. Field parameters were then collected biweekly from the six wells for the remainder of the study period. Ammonia-nitrogen data were collected after one week of system operation; phosphate data were collected after two weeks of system operation. Standard field meters, instruments, and test kits were used to make these measurements and each was calibrated in accordance with the manufacturer's instructions. Measurements were recorded in field data monitoring sheets.

Compressor temperature and pressure data were noted and recorded. Normal operating pressure was 125 psi. Oil levels were also checked periodically. Groundwater extraction and reinjection rates were also measured or estimated and readings recorded. A totalizer was placed between the 500-gallon holding tank and the injection wells to record the total volume of water (in gallons) that was injected. Volumes and times were recorded so that pumping rates could be calculated. Pumping rates were changed by adjusting the pressure at the pump regulator.

6.3 Monthly Ground Water Sampling

Groundwater samples were collected prior to start up of the treatability study to obtain baseline chemical and biochemical data in the study area. Samples, which were analyzed for parameters listed in Table 6.1, were collected from the extraction wells, re-injection wells, treatability study monitoring wells, and existing monitoring wells near the area of influence of the treatability study. In addition to measuring the contaminants of concern (chlorinated solvents) and biochemical parameters, the samples were also analyzed for metals to examine how geochemical changes in the groundwater resulting from the treatability study may affect metal species distribution and precipitative effects, if any.

**Table 6.1
 Baseline Groundwater Sampling Protocol**

Analyte	Analytical Method	Wells to be sampled	Purpose/Remarks
Volatile Organic Compounds	SW 8260	Extraction wells (2) Reinjection Wells (4) TS Monitoring Wells (4) Existing Monitoring Wells (2) - MW10D and MW16D	The purpose of VOC sampling was to obtain starting concentrations and track decreases in contaminant concentrations during the treatability study.
Metals	Method 6010/7000	Extraction wells (2) and the TS monitoring wells (4)	To examine clogging or solubilization effects on metals such as iron and manganese as a result of the created anaerobic-aerobic zone.

**Table 6.1
Baseline Groundwater Sampling Protocol**

Analyte	Analytical Method	Wells to be sampled	Purpose/Remarks
Biochemical Parameters			
Total Kjeldahl Nitrogen (TKN)	351.1 - 351.4	Extraction wells (2) Reinjection Wells (4) TS Monitoring Wells (4)	Nitrogen, phosphorus and carbon measurements were required to estimate the amount and frequency of nutrient supplementation required to optimize microbial activity. Chlorides are a good indicator parameter for estimating the quantity of chlorinated solvents that were degraded during the treatability study.
Ammonia-nitrogen	350.1	Existing Monitoring Wells (2) - MW10D and MW16D	
Total Phosphorus	365.4		
Orthophosphate	365.2 - 365.3		
Nitrate-nitrogen	352.1		
Total Organic Carbon (TOC)	415.1		
Chloride	325.3		
Total Heterotrophic Counts	SM 9215B		

Note:

TS = treatability study

Groundwater samples were collected monthly during the treatability study operation to track the decreases and changes in chlorinated solvent contamination and daughter product formation and destruction, and to assist in calculating the nutrient supplementation required during the treatability study. Analytical samples were also collected from wells 16608D and 16614D during the last monthly sampling event. The groundwater sampling protocol is detailed in Table 6.2.

**Table 6.2
Periodic Groundwater Sampling Protocol**

Analyte	Analytical Method	Wells to be sampled	Sampling Frequency
Volatille Organic Compounds	SW 8260	Extraction wells (2) TS Monitoring Wells (4) Existing Monitoring Wells (2) - MW10D and MW16D	Monthly and at the conclusion of the study
Metals	Method 6010/7000	Extraction wells (2) and the TS monitoring wells (4)	After one month of treatability system operation

Table 6.2
Periodic Groundwater Sampling Protocol

Analyte	Analytical Method	Wells to be sampled	Sampling Frequency
Biochemical Parameters	351.1 - 351.4	Extraction wells (2)	Monthly and at the conclusion of the study
Total Kjeldahl Nitrogen (TKN)		Reinjection Wells (4) TS Monitoring Wells (4)	
Ammonia-nitrogen	350.1	Existing Monitoring Wells (2) - MW10D and MW16D	
Total Phosphorus	365.4		
Orthophosphate	365.2 - 365.3		
Nitrate-nitrogen	352.1		
Total Organic Carbon (TOC)	415.1		
Chloride	325.3		
Total Heterotrophic Counts	9215B		

All groundwater was sampled in accordance with the RFI Quality Assurance Project Plan (QAPP) and the Sampling and Analysis Program (SAP) developed for this site. Samples to be analyzed were sent to the site-wide selected contracted laboratory. Analytical work was at data quality objective (DQO) III standards, all at standard turnaround times.

7.0 RESULTS AND ANALYSIS

7.1 Summary of Data

Table 7.1 summarizes VOC analytical results for monitoring wells, extraction wells, and reinjection wells in the treatability study area. The table includes VOC data from the first sampling event, which was performed prior to the start of the treatability study and from three events during the study (December 1999, January 1999, and February 1999). Only the VOCs of concern in the pilot study area, TCE, total 1,2-DCE (which was almost entirely cis-1,2-DCE) and VC are included in this table.

Table 7.1
 Treatability Study VOC Data ($\mu\text{g/L}$)

Well	Sampling Round	Date	TCE	1,2-DCE (total)	Vinyl Chloride
166TM1	1	10/7/99	2400 D	170	5 U
	2	12/15/99	29 J	820 D	5 U
	3	1/20/00	3	1200 D	5 U
	4	2/16/00	5 U	860 D	5 U
166TM2	1	10/7/99	4300 D	180	5 U
	2	12/15/99	65	1200 D	5 U
	3	1/19/00	7	1200 D	5 U
	4	2/17/00	2 J	1400 D	5 U
166TM3	1	10/7/99	5600 D	210	5 U
	2	12/15/99	370 D	360 D	5 U
	3	1/20/00	11	1100 D	5 U
	4	2/16/00	5 U	1000 D	5 U
166TM4	1	10/7/99	11000 DJ	180	2 J
	2	12/15/99	350 D	890 D	5 U
	3	1/19/00	40	1700 D	5 U
	4	2/17/00	5	1500 D	5 U
16610D	1	10/7/99	3600 D	140	5 U
	2	12/15/99	320 J	1400 J	5 U
	3	1/20/00	4 J	1200 D	5 U
	4	2/16/00	5 U	1000 D	5 U
166PWA	1	10/7/99	3600 DJ	140 DJ	5 U
	2	12/16/99	540	200	25 U
	3	1/20/00	250 D	660 D	5 U
	4	2/17/00	400 D	1200 D	5 U

Table 7.1
Treatability Study VOC Data (µg/L)

Well	Sampling Round	Date	TCE	1,2-DCE (total)	Vinyl Chloride
166PWB	1	10/6/99	5800 D	140	5 U
	2	12/16/99	3000	1100	120 U
	3	1/21/00	360 D	960 D	5 U
	4	2/17/00	200	470 D	5 U
16616D	1	10/8/99	2600 D	360	57
	2	12/16/99	2700	420	45 J
	3	1/21/00	1900 D	320 D	32
	4	2/23/00	9	14	5 U
166IN1	1	10/8/99	1400 D	190	5 U
166IN2	1	10/8/99	680 D	65	5 U
166IN3	1	10/8/99	11000 D	310	35 U
166IN4	1	10/8/99	5 U	5 U	5 U
	4	2/16/00	290 D	1200 D	5 U
16608D	4	2/23/00	9	5 U	5 U
16614D	4	2/23/00	210 D	22	5 U

Notes:

Qualifiers:

- U — Below detection limits
- D — Dilution
- J — Estimation
- DJ — Dilution and Estimation

Table 7.2 summarizes the field data, which were generally collected on a biweekly basis. These include DO data, ORP, and CO₂ data from the four treatability monitoring wells and permanent monitoring wells 16610D and 16616D. DO data also were periodically measured by direct titration methods to check the accuracy of DO meter readings.

Table 7.2
Field Data Summary

Well	Date	DO (mg/L)		DO (mg/L) Titr.	ORP (mV)	CO ₂ (mg/L)	
		Horiba					
166TM1	11/04/99	0.41		—	-143	28	
	11/10/99	0.3		—	-138	26	
	11/18/99	0.5		—	-113	26	
	11/24/99	0.4		—	-113	34	
	12/09/99	0.4		—	-92	30	
	12/22/99	0.4		—	-114	36	
	01/05/00	0.7		—	-118	34	
	01/20/00	1.1		—	-143	34	
	02/07/00	0.7		—	-161	36	
	02/25/00	3.6		1.2	-79	40	
	Standard Deviation	0.25	±	0.19	NC	NC	NC
	166TM2	11/03/99	—		—	-160	28
		11/10/99	0.3		—	-125	24
11/18/99		0.3		—	-124	24	
11/24/99		0.4		—	-131	24	
12/09/99		0.5		—	-159	34	
12/22/99		0.4		—	-165	36	
01/05/00		0.8		—	-139	40	
01/20/00		0.7		—	-167	36	
02/07/00		0.6		—	-155	44	
02/25/00		6.5		1.0	-105	42	
Standard Deviation		0.19	±	0.15	NC	NC	NC
166TM3	11/04/99	0.06		—	-98	24	
	11/10/99	0.3		—	-140	20	
	11/19/99	0.4		—	-86	18	
	11/24/99	0.6		—	-80	24	
	12/09/99	0.3		—	-91	26	
	12/22/99	0.8		—	-40	36	
	01/05/00	0.9		—	-118	40	
	01/20/00	0.6		—	-87	36	
	02/07/00	0.6		—	-136	30	
	02/25/00	2.7		1.0	-97	58	
	Standard Deviation	0.27	±	0.21	NC	NC	NC
166TM4	11/04/99	0.23		—	-128	30	
	11/10/99	0.3		—	-152	26	
	11/18/99	0.3		—	-148	22	
	11/24/99	0.4		—	-163	28	
	12/09/99	0.3		—	-154	28	
	12/22/99	0.5		—	-166	30	

Table 7.2
Field Data Summary

Well	Date	DO (mg/L) Horiba		DO (mg/L) Titr.	ORP (mV)	CO ₂ (mg/L)
166TM4 (continued)	01/05/00	0.8		—	-166	38
	01/20/00	1.0		—	-158	34
	02/07/00	0.6		—	-147	32
	02/25/00	7.1		0.4	-109	58
	Standard Deviation	0.26	± 0.21	NC	NC	NC
16610D	11/04/99	0.34		—	-104	38
	11/10/99	0.5		—	16	34
	11/18/99	0.4		—	-95	36
	11/24/99	0.3		—	-57	38
	12/09/99	1.2		—	-76	40
	12/22/99	1.3		—	-104	35
	01/05/00	1.6		—	-72	38
	01/20/00	0.8		—	-52	34
	02/07/00	1.4		—	-77	44
	Standard Deviation	0.52	± 0.46	NC	NC	NC
16616D	11/04/99	4.7		—	-69	18
	11/10/99	1.8		—	-59	24
	11/19/99	0.8		—	-88	22
	11/24/99	0.9		—	-102	22
	12/09/99	3.5		—	42	24
	12/22/99	1.2		—	-118	22
	01/05/00	1.8		—	-64	28
	01/20/00	4.2		—	-20	20
	02/07/00	5.4		—	28	20
	Standard Deviation	1.81	± 1.56	NC	NC	NC

Note:

NC — Not Calculated

Table 7.3 (inorganic compound data) summarizes nutrient and geochemical data from treatability monitoring wells and other wells in the pilot study area collected during monthly sampling events. Nutrient measurements include ammonia-N, phosphate, and TKN, while geochemical parameters of significance include total organic carbon, nitrate and chloride.

Table 7.3
Treatability Study Inorganic Compound Data (mg/L)

Well	Sampling Round	Date	Ammonia	o-Phosphate	Nitrate-Nitrite-N	TKN	Chloride	TOC
166TM1	1	10/7/99	1.0 U	0.10 U	0.1 U	1.3	6.8	1.0 U
	2	12/15/99	2.0	0.30	0.1 U	1.4	5.7	1.0 U
	3	1/20/00	1.0 U	0.43	0.1 U	1.0 U	5.4	1.5
	4	2/16/00	0.1 U	0.69	0.1 U	1.0 U	5.1	1.0 U
166TM2	1	10/7/99	1.0 U	0.10 U	0.1 U	1.7	5.7	1.0 U
	2	12/15/99	1.0 U	0.30	0.1 U	1.4	5.7	1.0
	3	1/19/00	1.4	0.10 U	0.1 U	1.7	5.4	1.7
	4	2/17/00	0.1 U	0.10 U	0.1 U	2.2	5.1	1.4
166TM3	1	10/7/99	1.0 U	0.10 U	0.1 U	1.0 U	4.9	1.0 U
	2	12/15/99	1.7	0.30	0.1 U	1.4	4.5	1.0 U
	3	1/20/00	1.0 U	0.24	0.1 U	1.0 U	5.1	1.1
	4	2/16/00	0.1 U	0.52	0.1 U	1.0 U	5.5	1.0 U
166TM4	1	10/7/99	1.0 U	0.10 U	0.1 U	2.8	5.5	1.0 U
	2	12/15/99	3.9	0.20	0.1 U	2.5	5.7	1.0 U
	3	1/19/00	2.2	0.17	0.1 U	1.4	5.2	1.6
	4	2/17/00	0.1 U	0.20	0.1 U	2.0	5.7	1.0 U
16610D	1	10/7/99	1.0 U	0.20	0.1 U	1.0 U	5.3	1.0 U
	2	12/15/99	1.7	0.69	0.1 U	1.7	5.5	1.0 U
	3	1/20/00	1.0 U	0.63	0.1 U	1.0 U	5.4	1.3
	4	2/16/00	0.1 U	0.13	0.1 U	2.8	6.1	1.0 U
166PWA	1	10/7/99	1.0 U	0.10 U	0.1 U	3.9	5.9	1.0 U
	2	12/16/99	2.2	0.60	0.1 U	4.2	6.5	1.7
	3	1/20/00	2.5	2.80	0.1 U	2.2	4.7	70.3
	4	2/17/00	0.1 U	0.32	0.1 U	1.0 U	5.3	1.6
166PWB	1	10/6/99	1.0 U	0.10 U	0.1 U	1.0 U	5.7	1.0 U
	2	12/16/99	1.0 U	0.40	0.22	1.4	5.9	1.8
	3	1/21/00	1.0 U	0.54	0.1 U	1.0 U	5.1	1.8
	4	2/17/00	0.1 U	0.11	0.1 U	1.4	5.3	1.0 U
16616D	1	10/8/99	1.0 U	0.26	0.1 U	2.8	6.3	1.0 U
	2	12/16/99	6.2	0.30	0.1 U	5.0	6.9	1.5
	3	1/21/00	1.0 U	0.27	0.1 U	1.0 U	5.3	1.5
	4	2/23/00	1.1	0.22	0.1 U	1.0 U	6.4	1.0 U
166IN1	1	10/8/99	1.0 U	0.40	0.1 U	1.0 U	6.1	1.0 U
	2	12/16/99	1.0 U	0.60	0.1 U	3.9	6.1	1.6
	3	1/20/00	1.0 U	1.60	0.1 U	2.0	5.1	42.6
	4	2/22/00	1.0	1.00	0.1 U	6.7	5.4	5.6
166IN2	1	10/8/99	1.0 U	0.58	0.1 U	1.0 U	3.8	1.0 U
	2	12/16/99	1.0 U	0.70	9.3	3.1	6.1	1.5
	3	1/20/00	1.0 U	2.40	0.1 U	2.5	5.2	55.8
	4	2/22/00	4.3	18.4	0.1 U	5.9	8.8	204

Table 7.3
Treatability Study Inorganic Compound Data (mg/L)

Well	Sampling Round	Date	Ammonia	o-Phosphate	Nitrate-Nitrite-N	TKN	Chloride	TOC
166IN3	1	10/8/99	1.0 U	0.12	0.1 U	3.4	4.2	1.8
	2	12/16/99	3.9	0.60	0.1 U	4.8	5.9	1.7
	3	1/20/00	1.0 U	2.40	0.1 U	1.7 U	6.2	33.9
	4	2/17/00	1.6	3.90	0.1 U	1.0	6.4	85.9
166IN4	1	10/8/99	1.0 U	0.14	0.1 U	1.0 U	5.9	1.0 U
	2	12/16/99	1.0 U	0.40	0.1 U	1.4	5.7	1.5
	3	1/20/00	1.0 U	2.80	0.1 U	2.0	5.9	44.3
	4	2/16/00	0.1 U	0.17	0.1 U	2.0	5.5	1.1
16608D	4	2/23/00	0.1	0.34	0.1 U	1.0 U	4.8	1.2
16614D	4	2/23/00	1.1	0.13	0.1 U	2.0	5.6	1.0 U

Notes:

Qualifiers:

- U — Below detection limits
- D — Dilution
- J — Estimation
- DJ — Dilution and Estimation

Table 7.4 summarizes calculated ratios of total organic carbon: TKN: total phosphorus based on monthly sampling events. This computation was performed to check the adequacy of nitrogen and phosphorus as microbial nutrients in the groundwater.

Table 7.4
Carbon: Nitrogen: Phosphorous Ratio Data

Well	Sampling Round	Date	TOC (mg/L)	TKN (mg/L)	Total Phosphorous (mg/L)	C:N:P Ratio
166TM1	1	10/7/99	1.0 U	1.3	0.36	100:260:72
	2	12/15/99	1.0 U	1.4	1.00	100:280:200
	3	1/20/00	1.5	1.0 U	0.76	100:33:51
	4	2/16/00	1.0 U	1.0 U	0.74	100:100:148
166TM2	1	10/7/99	1.0 U	1.7	0.16	100:340:32
	2	12/15/99	1.0	1.4	0.30	100:140:30
	3	1/19/00	1.7	1.7	0.27	100:100:16
	4	2/17/00	1.4	2.2	0.43	100:157:31

A-A Sequential Study Treatability Report
 SWMU 166 — Zone K
 Charleston Naval Complex
 Charleston, South Carolina

Table 7.4
Carbon: Nitrogen: Phosphorous Ratio Data

Well	Sampling Round	Date	TOC (mg/L)	TKN (mg/L)	Total Phosphorous (mg/L)	C:N:P Ratio
166TM3	1	10/7/99	1.0 U	1.0 U	0.16	100:100:32
	2	12/15/99	1.0 U	1.4	0.51	100:280:102
	3	1/20/00	1.1	1.0 U	0.38	100:45:35
	4	2/16/00	1.0 U	1.0 U	0.57	100:100:114
166TM4	1	10/7/99	1.0 U	2.8	0.28	100:560:56
	2	12/15/99	1.0 U	2.5	0.55	100:500:110
	3	1/19/00	1.6	1.4	0.21	100:88:13
	4	2/17/00	1.0 U	2.0	0.43	100:400:86
16610D	1	10/7/99	1.0 U	1.0 U	0.30	100:100:60
	2	12/15/99	1.0 U	1.7	0.41	100:340:82
	3	1/20/00	1.3	1.0 U	0.38	100:38:29
	4	2/16/00	1.0 U	2.8	0.65	100:560:130
166PWA	1	10/7/99	1.0 U	3.9	0.30	100:780:60
	2	12/16/99	1.7	4.2	2.00	100:247:118
	3	1/20/00	70.3	2.2	2.90	100:3:4
	4	2/17/00	1.6	1.0 U	1.10	100:31:69
166PWB	1	10/6/99	1.0 U	1.0 U	0.59	100:100:118
	2	12/16/99	1.8	1.4	0.71	100:78:39
	3	1/21/00	1.8	1.0 U	0.38	100:28:21
	4	2/17/00	1.0 U	1.4	0.21	100:280:42
16616D	1	10/8/99	1.0 U	2.8	0.24	100:560:48
	2	12/16/99	1.5	5.0	0.34	100:333:23
	3	1/21/00	1.5	1.0 U	0.15	100:33:10
	4	2/23/00	1.0 U	1.0 U	0.22	100:100:44
166IN1	1	10/8/99	1.0 U	1.0 U	0.57	100:100:114
	2	12/16/99	1.6	3.9	1.30	100:244:81
	3	1/20/00	42.6	2.0	1.90	100:5:4
	4	2/22/00	5.6	6.7	1.90	100:120:34
166IN2	1	10/8/99	1.0 U	1.0 U	0.59	100:100:118
	2	12/16/99	1.5	3.1	1.20	100:207:80
	3	1/20/00	55.8	2.5	3.20	100:4:6
	4	2/22/00	204	5.9	23.10	100:3:11
166IN3	1	10/8/99	1.8	3.4	0.11	100:189:6
	2	12/16/99	1.7	4.8	0.97	100:282:57
	3	1/20/00	33.9	1.7	2.50	100:5:7
	4	2/17/00	85.9	1.0 U	6.90	100:1:8
166IN4	1	10/8/99	1.0 U	1.0 U	0.10 U	100:100:10
	2	12/16/99	1.5	1.4	1.20	100:93:80
	3	1/20/00	44.3	2.0	2.80	100:5:6
	4	2/16/00	1.1	2.0	0.86	100:182:78

Table 7.4
Carbon: Nitrogen: Phosphorous Ratio Data

Well	Sampling Round	Date	TOC (mg/L)	TKN (mg/L)	Total Phosphorous (mg/L)	C:N:P Ratio
16608D	4	2/23/00	1.2	1.0 U	0.19	100:42:16
16614D	4	2/23/00	1.0 U	2.0	0.27	100:400:54

Notes:

Qualifier:

- U — Below detection limits
- TOC — Total organic carbon
- TKN — Total kjeldahl nitrogen

Table 7.5 summarizes microbial degradation rates of TCE in the treatability study area well, which were calculated based on the assumption that TCE decreases followed a first-order or asymptotic equation. The first-order degradation equation is provided below:

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

where:

- C_e = TCE concentration in mg/L at time "t"
- C_0 = TCE concentration in mg/L before treatability study start-up
- t = time in days
- k = first-order degradation rate in day⁻¹ (1/day)

Four sampling events (one before and three after treatability study start-up) were used to estimate degradation rates. Each well was separately considered when calculating degradation rates.

Table 7.5
TCE Degradation Rates

Well	k (day ⁻¹)
166TM1	0.0510
166TM2	0.0587
166TM3	0.0558
166TM4	0.0572
16610D	0.0552
166PWA	0.0186
166PWB	0.0262
16616D	0.0332

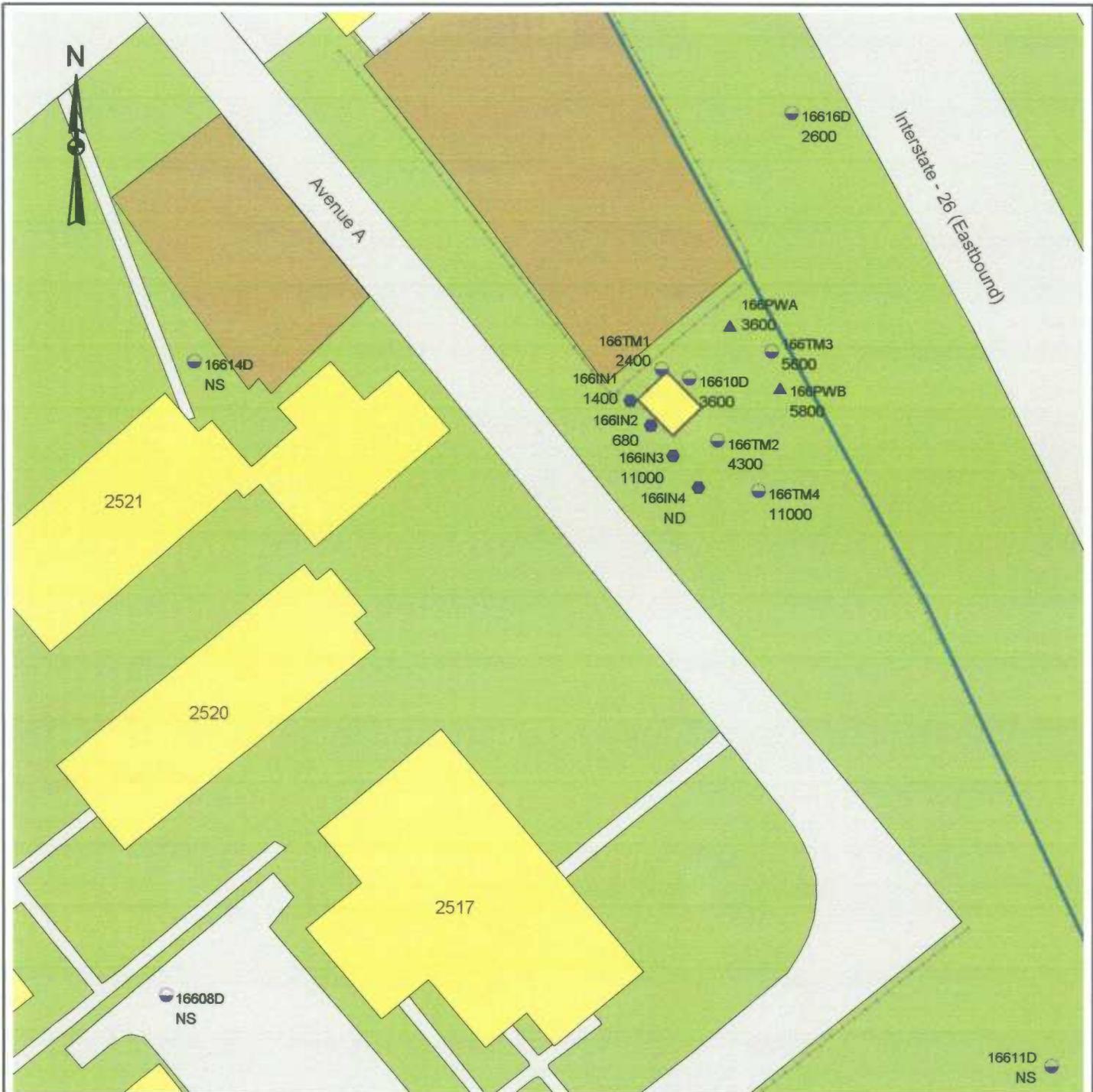
7.2 TCE Reduction and Formation of Daughter Products

Table 7.1 (VOC data) shows that the introduction of a carbon source (fructose) and nutrients (nitrogen and phosphorus) resulted in a rapid decrease in TCE concentrations. In particular, the TCE concentration at monitoring well 166TM4 decreased from 11,000 $\mu\text{g/L}$ to 350 $\mu\text{g/L}$ one month after system start up, a decrease of 97%. TCE in all other wells (166TM1, 166TM2, 166TM3, and 16610D) impacted by the A-A system also decreased substantially during the first month of system operation. During this same period, the concentration of cis-1,2-DCE (reported in the table as total 1,2-DCE because most of it was in the cis-form) increased in all of these wells. Because, cis-1,2-DCE is a known biological daughter breakdown product of TCE, decreases in concentration of TCE can be largely attributed to microbial activity induced by the A-A system. The injection of fructose in the aquifer created the proper anaerobic environment for native microorganisms to begin degrading the TCE very rapidly.

TCE concentrations continued to decrease after the first month of operation and eventually reduced to 5 $\mu\text{g/L}$ or less in all four treatability study monitoring wells and 16610D. TCE concentrations in the extraction wells also decreased during the study, but at a lower rate than the monitoring wells, indicating that the anaerobic zone was more prevalent in the vicinity of the reinjection wells

and monitoring wells, while downgradient wells were impacted less by fructose injection. Figure 7.1 shows TCE concentrations of the treatability study wells and surrounding wells in October 1999, while Figure 7.2 shows TCE concentrations in February/March 2000. Figure 7.3 shows the change in TCE concentrations in the treatability study monitoring wells over time. Figure 7.4 shows the change in TCE concentrations in the monitoring wells over time. Figures 7.5 and 7.6 show 1,2-DCE concentrations in October 1999 and February 2000, respectively. Figure 7.7 shows the change in 1,2-DCE concentrations in the treatability study monitoring wells over time. Figure 7.8 shows the change in 1,2-DCE concentrations in the monitoring wells over time.

Vinyl chloride was not detected in the aquifer in any of the area wells sampled, except 16616D, which has had a history of vinyl chloride detections. Vinyl chloride is generally a daughter product of the further reductive dechlorination of cis-1,2-DCE. The absence of vinyl chloride probably indicates that if it was being formed from its parent compound, no accumulation occurred. In other words, the sparging of the aquifer in downgradient locations with the blower degraded the vinyl chloride aerobically before it accumulated in the aquifer. Concentrations of cis-DCE however remained elevated after three months into the study, indicating that the anaerobic zone was probably not reducing enough to drive reductive dechlorination rapidly enough all the way to ethylene. Also, the continuous presence of cis-DCE in the aquifer indicated that the downgradient zone may have degraded only a percentage of the cis-DCE formed from TCE reduction.



LEGEND

- Deep Monitoring Well
- Re-Injection Well
- ▲ Extraction Well
- NS Not Sampled
- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

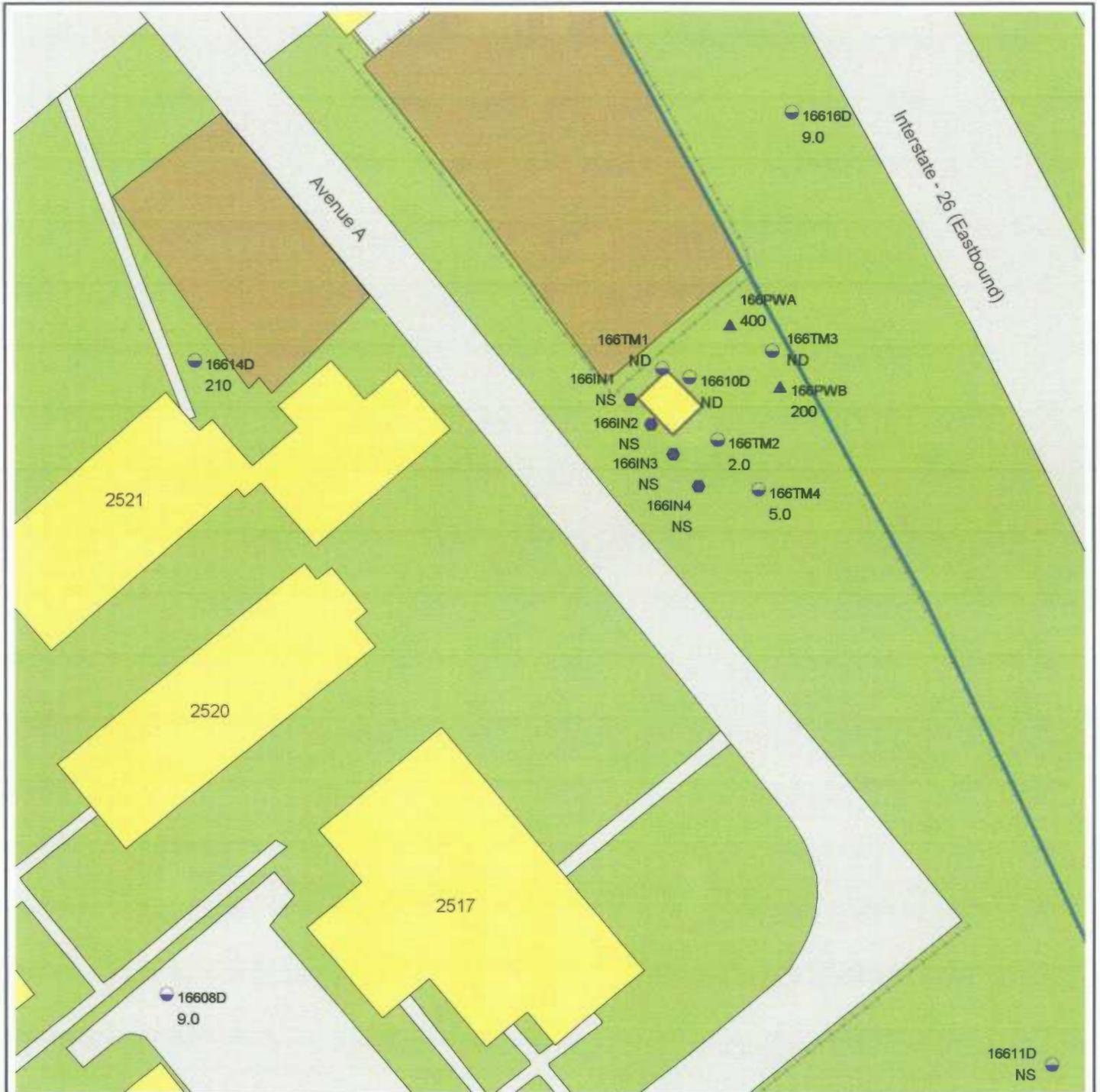
Note: All concentrations in $\mu\text{g/L}$



ZONE K - SWMU 166
 A-A SEQUENCING TREATABILITY
 STUDY REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

Figure 7.1
 SWMU 166

TCE
 October 1999
 Groundwater Concentrations



LEGEND

- Deep Monitoring Well
- Re-Injection Well
- ▲ Extraction Well
- NS Not Sampled

- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

Note: All concentrations in µg/L.



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

**Figure 7.2
SWMU 166**

**TCE
March 2000
Groundwater Concentrations**

Figure 7.3
TCE Concentrations
Treatability Study Monitoring Wells

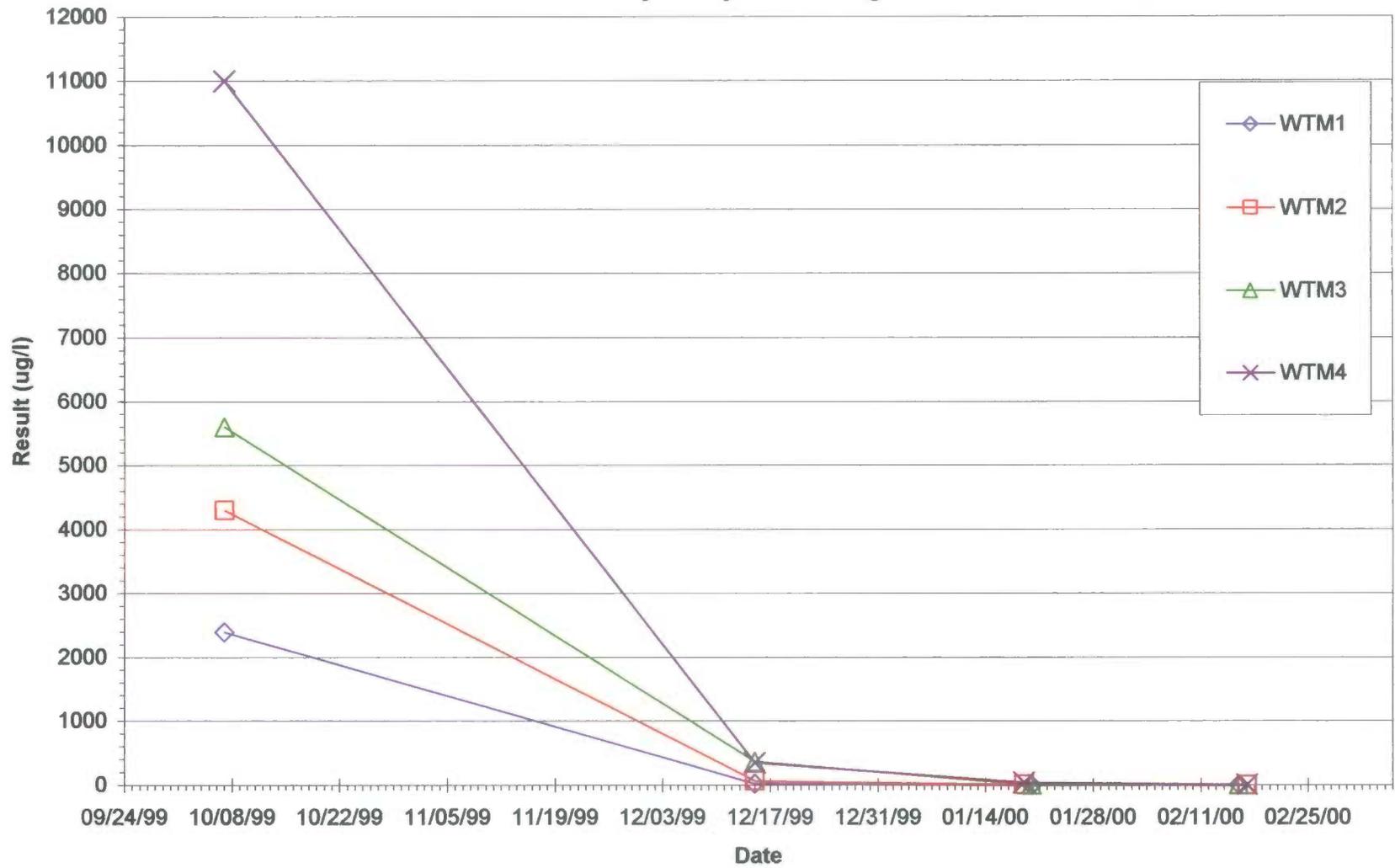
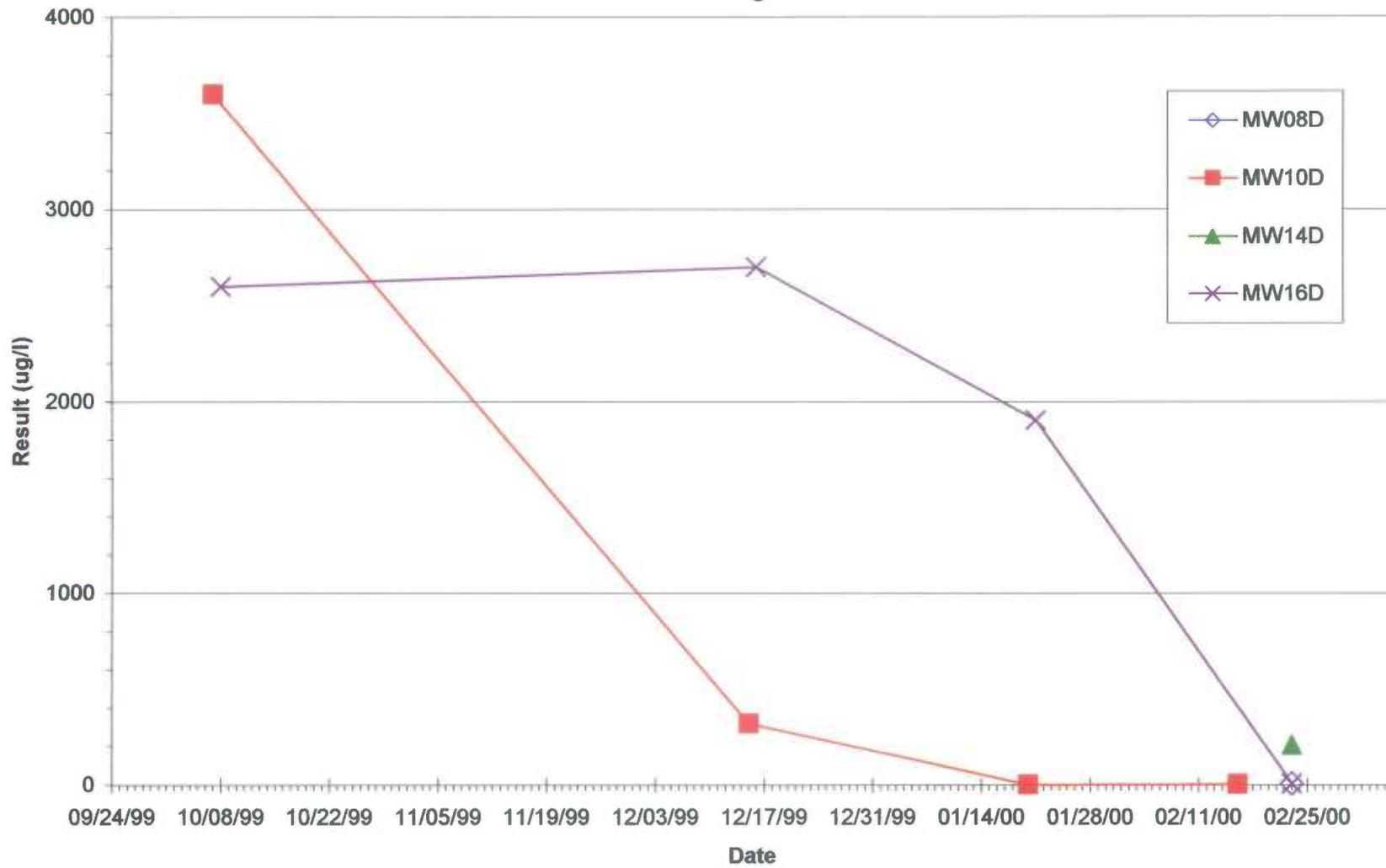
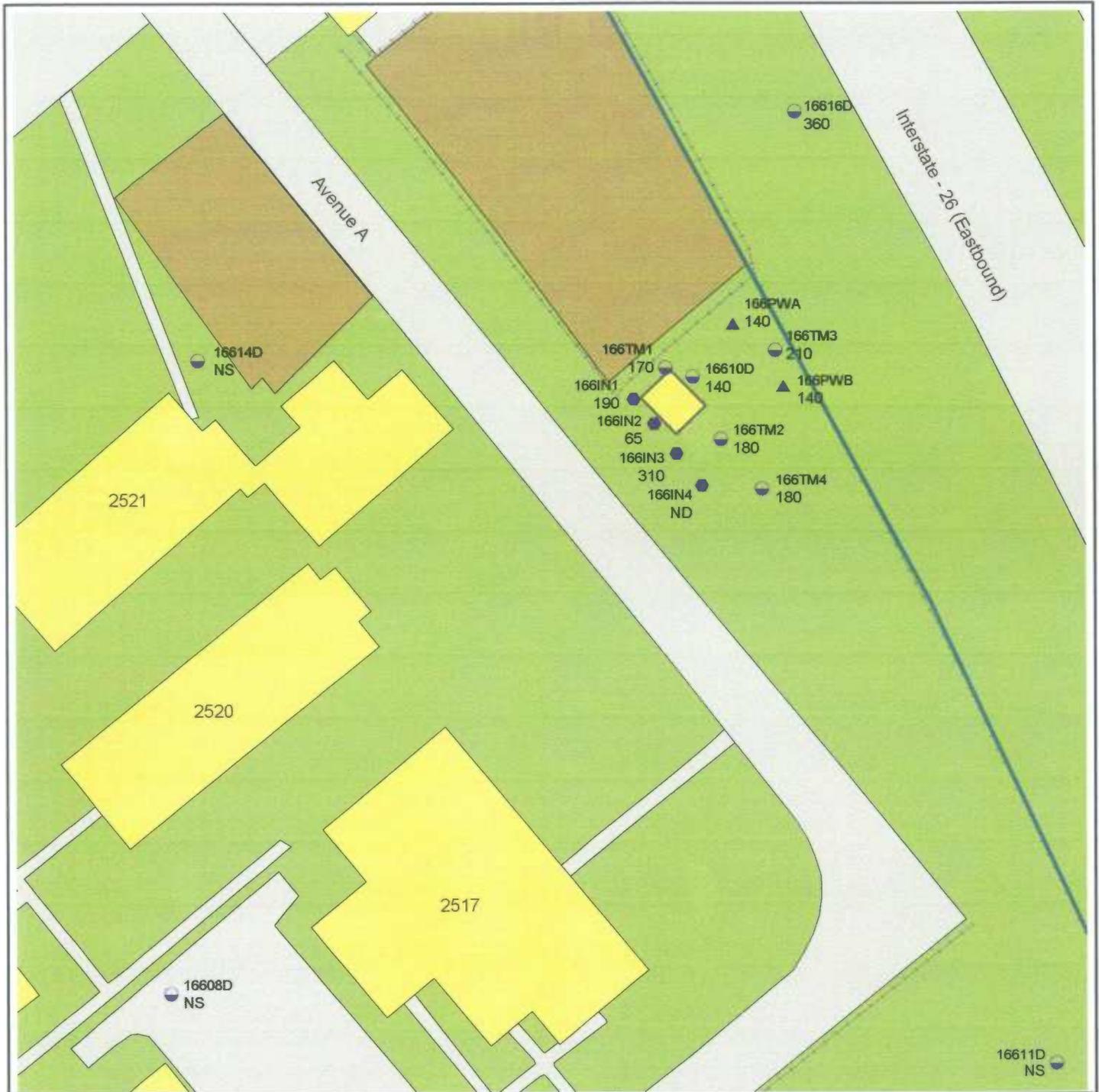


Figure 7.4
TCE Concentrations
Monitoring Wells





LEGEND

- Deep Monitoring Well
- Re-Injection Well
- ▲ Extraction Well
- NS Not Sampled
- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

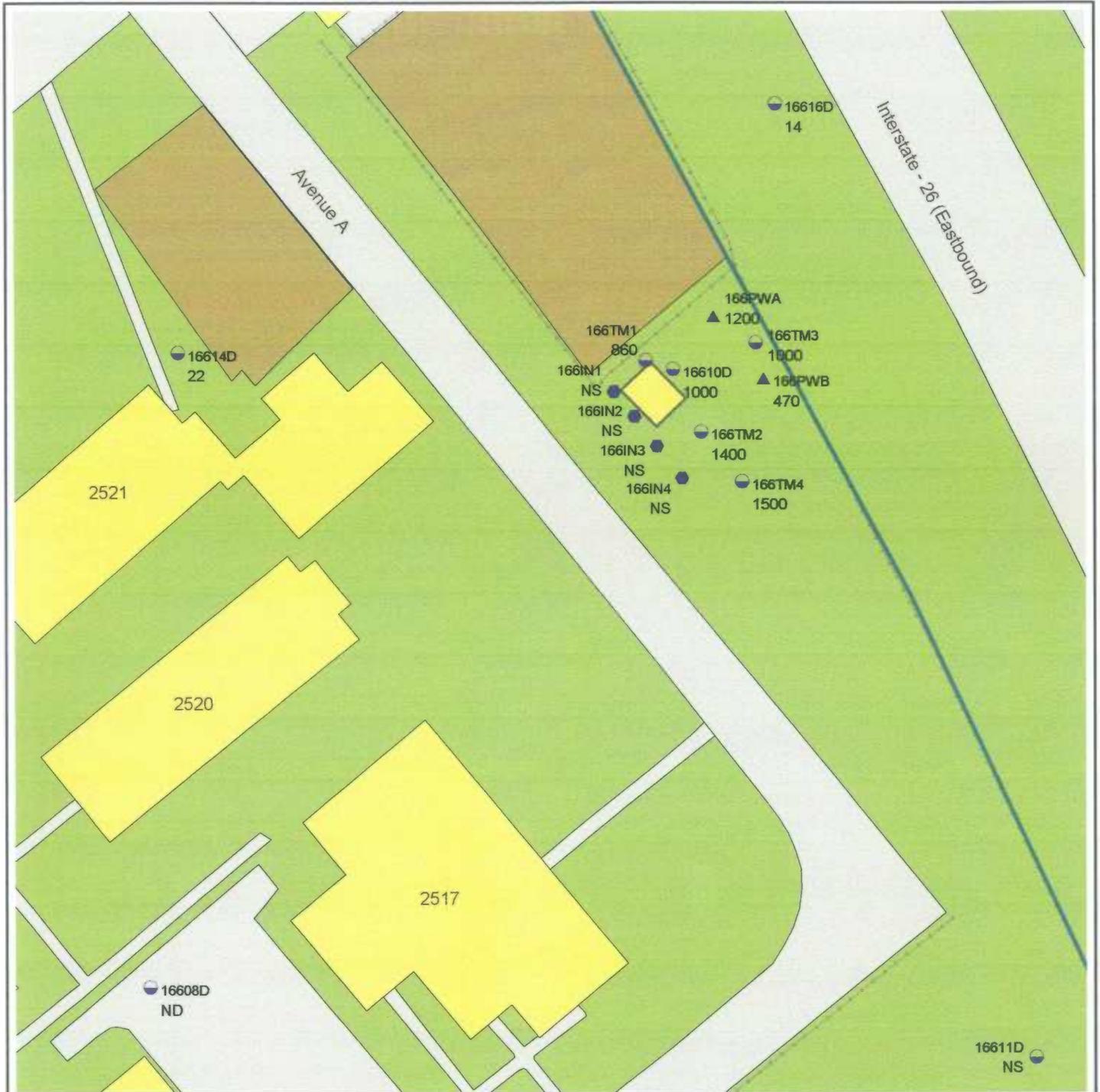
Note: All concentrations in µg/L



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

**Figure 7.5
SWMU 166**

**1,2-DCE (total)
October 1999
Groundwater Concentrations**



LEGEND

- Deep Monitoring Well
- Re-Injection Well
- ▲ Extraction Well
- NS Not Sampled
- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

Note: All concentrations in µg/L



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

**Figure 7.6
SWMU 166**

**1,2-DCE (total)
March 2000
Groundwater Concentrations**

Figure 7.7
1,2-DCE (total) Concentrations
Treatability Study Monitoring Wells

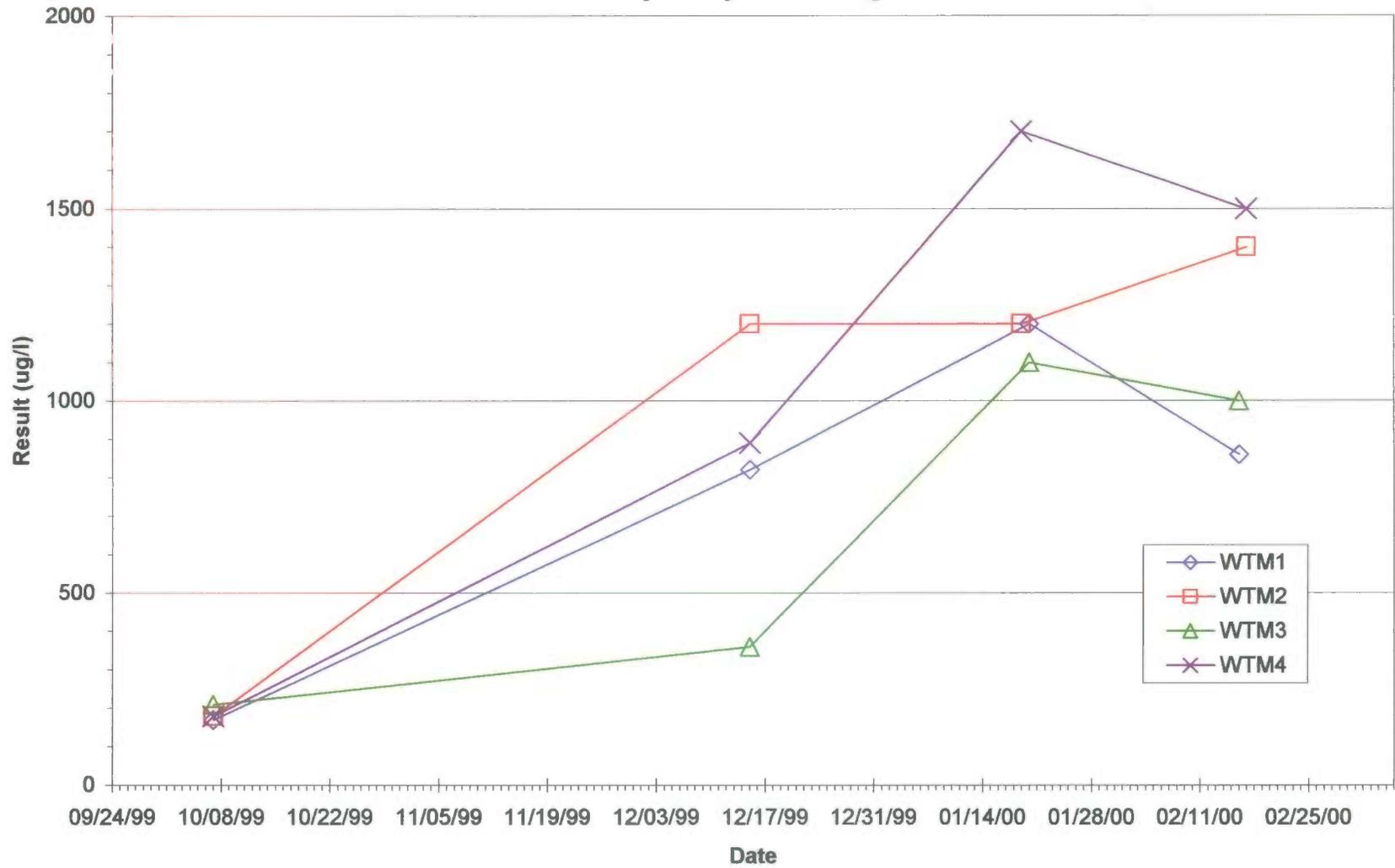
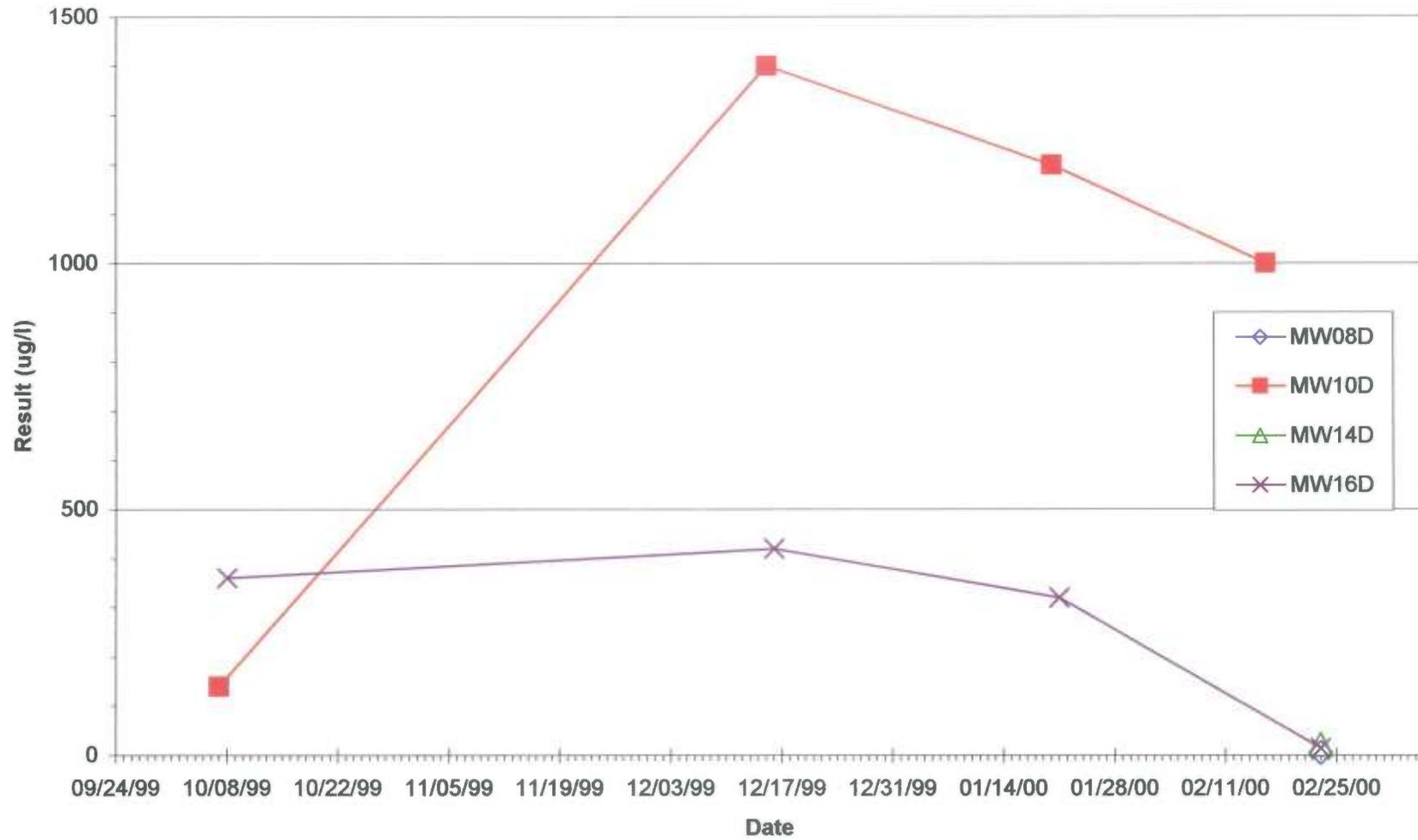


Figure 7.8
1,2-DCE (total) Concentrations
Monitoring Wells



7.3 TCE Degradation Rates

TCE degradation rates summarized in Table 7.5 indicate a first-order value between 0.05 and 0.059 day⁻¹, a relatively high value for in-situ remediation of TCE and more than two orders of magnitude of most rates noted in the literature for natural attenuation of TCE (Wilson 1996). TCE degradation rates at the extraction wells and at well 16616D, which is downgradient and away from the influence of the A-A system, were much lower and ranged from 0.01 to 0.033 day⁻¹.

7.4 TCE Degradation Volumes

The estimated area affected by the A-A treatability study is approximately 3600 ft² and each of the wells installed for the treatability study had screened intervals of 15 feet, resulting in an approximate affected volume of 54,000 ft³. Based on geotechnical data from well 16610D (30 to 32 feet bgs), the water-filled porosity in the deep aquifer is 41%. Based on this data, the affected volume yields approximately 627,000 liters or 166,000 gallons of groundwater.

The average TCE concentration from the 11 area wells during the baseline sampling event in October 1999 was approximately 4,490 µg/L. Therefore, approximately 2.81 kg (6.20 pounds) of TCE was in the deep zone of the shallow aquifer. In February 2000, the average TCE concentration from the seven wells in the treatability study area was 87.8 µg/L, resulting in 0.055 kg (0.121 pounds) of TCE in the deep zone aquifer (the four injection wells were not sampled). The mass of TCE decreased 2.76 kg (6.07 pounds), a 98% reduction of the original mass after three months of system operation.

The average 1,2-DCE concentration during baseline sampling event was 157 µg/L; during fourth sampling event, the average concentration was 1060 µg/L, equaling 1,2-DCE masses of 0.098 kg (0.217 pounds) and 0.665 kg (1.47 pounds), respectively. The mass of 1,2-DCE increased 85%, adding about 0.567 kg (1.25 pounds) of 1,2-DCE to the deep zone aquifer.

The ratio of atomic masses for TCE to 1,2-DCE is 1.36, meaning a molecule of TCE has 1.36 times more mass than a molecule of 1,2-DCE. The reduction of 2.76 kg (6.07 pounds) of TCE by reductive dechlorination would result in the formation of 2.03 kg (4.46 pounds) of 1,2-DCE. However, there was only a 0.567 kg (1.25 pounds) increase of 1,2-DCE. It is possible that under the anaerobic conditions of the aquifer, much of the 1,2-DCE degraded to vinyl chloride, which then degraded further to end-products. Vinyl chloride has also been shown to oxidize directly to carbon dioxide and water in anaerobic conditions (USEPA 1998). However, vinyl chloride reduces most efficiently in aerobic conditions, which were not produced by the treatability system. The degradation of 1,2-DCE to vinyl chloride is not occurring as rapidly as the degradation of TCE to 1,2-DCE, causing 1,2-DCE to accumulate in the aquifer.

7.5 Field Data Interpretation

Field data are summarized in Table 7.2. The most significant measuring parameters in the field were ORP and DO. ORP values remained negative throughout the study and in most wells, values were below -100 mVs. ORP values measured from 16610D during MNA sampling in March and September 1998 were considerably higher (-8 mV and 49 mV, respectively). Negative ORPs generally indicate highly reducing conditions that are very conducive to TCE degradation, as reflected in the rapid decrease in TCE concentrations in the area. Generally, reductive dechlorination of TCE all the way through cis-DCE, VC, and the final end-product, ethylene, occurs when the ORP drops further to less than below -200 mV. However, cis-DCE remained elevated after being generated as a daughter product until the February 2000 sampling event, indicating that the ORP could not be reduced to the levels necessary for their reduction by the mechanisms employed. Alternatively, the treatability study area (approximately 60 feet by 60 feet) and the time of study may have been too small to observe noticeable changes in cis-DCE concentrations.

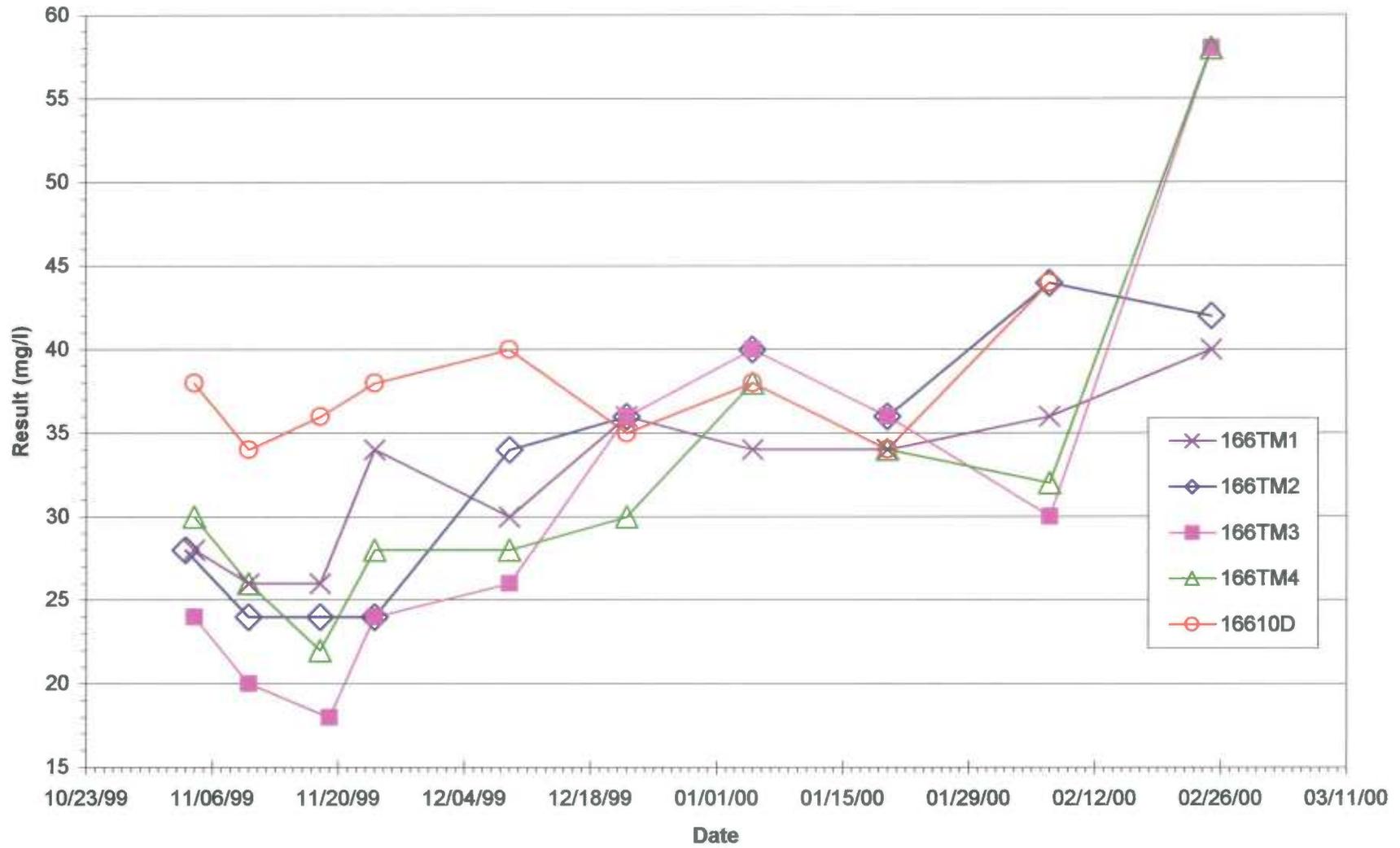
Dissolved oxygen concentrations in the area remained low throughout the study in the four treatability study monitoring wells and well 16610D. The DO concentration in all of these wells was generally far below 0.5 mg/L, the concentration at which reduced or anaerobic conditions have been established in the aquifer. Therefore, the objective of attaining a low DO concentration in the treatability study area — a condition essential for reductive dechlorination of TCE — was achieved by augmenting the system with fructose and other nutrients. By comparison, DO concentrations at downgradient well 16616D remained elevated throughout the study because this vicinity was not impacted by the treatability study.

Carbon dioxide concentrations in three treatability study monitoring wells (166TM1, 166TM2, and 166TM3) immediately downgradient of the injection wells increased as the study progressed. CO₂ concentrations over the length of the treatability study are represented in Figure 7.9. CO₂ concentrations often increase in areas where microbial activity has increased because it is an end-product of some respiratory mechanisms. Therefore, this increase reflects a response of the microbial population to the added fructose and nutrients during TCE degradation.

7.6 Interpretation of Geochemical Data

Geochemical data analyzed in the laboratory including nutrients (total nitrogen, ammonia and phosphorus), total organic carbon, and chloride were previously summarized in Table 7.3, while TOC:TKN:Phosphorus (C:N:P) ratios were summarized in Table 7.4. These ratios for most of the events and all of the sampled wells show that nitrogen and phosphorus (the two most essential nutrients for microbial activity) are not limiting in the aquifer. Generally, C:N:P ratios of 100:10:2 to 100:5:1 are considered sufficient for optimal microbial activity. Ratios shown in Table 7.4 far exceeded typical values. Therefore, microbial nutrients were always available in the aquifer for TCE degradation during the treatability study.

Figure 7.9
CO₂ Concentrations



Chloride concentrations did not vary much during the study. Chloride is generally a conservative end-product of TCE degradation and an increase in its concentration often signifies a decrease in the contaminant concentration. However, the starting TCE concentrations (2.4 mg/L to 11 mg/L) were not high enough to observe a measurable increase in chloride concentrations in the aquifer.

7.7 Hydraulic Evaluation

Based on groundwater elevations measured at Zone K during the RFI, groundwater flows east-northeast toward Interstate 26 and the storm water sewer system below the interstate. January 1999 water level measurements show this pattern (Figure 3.5). Groundwater elevations measured during the treatability study are shown in Table 7.6.

Table 7.6
Groundwater Elevations

Well	TOC Elev (msl)	Date	DTW (ft)	Elev (msl)		
166TM1	40.87	10/07/99*	8.14	32.73		
		11/04/99	7.89	32.98		
		11/10/99	6.82	34.05		
		11/19/99	6.19	34.68		
		11/24/99	4.1	36.77		
		12/09/99	6.69	34.18		
		12/15/99*	8.46	32.41		
		12/22/99	6.33	34.54		
		01/05/00	7.72	33.15		
		01/19/00*	6.52	34.35		
		02/15/00*	7.54	33.33		
		166TM2	40.56	10/07/99*	7.76	32.8
				11/04/99	7.59	32.97
11/10/99	6.96			33.6		
11/19/99	5.91			34.65		
11/24/99	5.75			34.81		
12/09/99	6.48			34.08		
12/15/99*	7.3			33.26		
12/22/99	6.47			34.09		
01/05/00	6.92			33.64		
01/18/00*	6.75			33.81		
02/16/00*	6.65			33.91		

Table 7.6
Groundwater Elevations

Well	TOC Elev (msl)	Date	DTW (ft)	Elev (msl)
166TM3	40.69	10/07/99*	8.07	32.62
		11/04/99	7.93	32.76
		11/10/99	10.01	30.68
		11/19/99	9.17	31.52
		11/24/99	9.21	31.48
		12/09/99	9.35	31.34
		12/15/99*	8.52	32.17
		12/22/99	8.95	31.74
		01/05/00	9.62	31.07
		01/19/00*	8.5	32.19
		02/15/00*	8.31	32.38
		166TM4	40.53	10/07/99*
11/04/99	7.52			33.01
11/10/99	7.53			33
11/19/99	7.15			33.38
11/24/99	7.16			33.37
12/09/99	6.8			33.73
12/15/99*	8.07			32.46
12/22/99	7.07			33.46
01/05/00	7.37			33.16
01/18/00*	7			33.53
02/16/00*	6.79			33.74
16610D	43.01			10/07/99*
		11/04/99	10.55	32.46
		11/10/99	10.52	32.49
		11/19/99	9.72	33.29
		11/24/99	8.9	34.11
		12/09/99	10.35	32.66
		12/15/99*	11.21	31.8
		12/22/99	9.99	33.02
		01/05/00	10.92	32.09
		01/19/00*	10.05	32.96
		02/15/00*	10.38	32.63
		16616D	33.73	10/07/99*
11/04/99	1.63			32.1
11/10/99	2.35			31.38
11/19/99	2.16			31.57
11/24/99	2.17			31.56
12/09/99	2.34			31.39
12/16/99*	2.34			31.39
12/22/99	2.05			31.68
01/05/00	2.48			31.25
01/20/00*	2.15			31.58
02/22/00*	1.62			32.11

Table 7.6
Groundwater Elevations

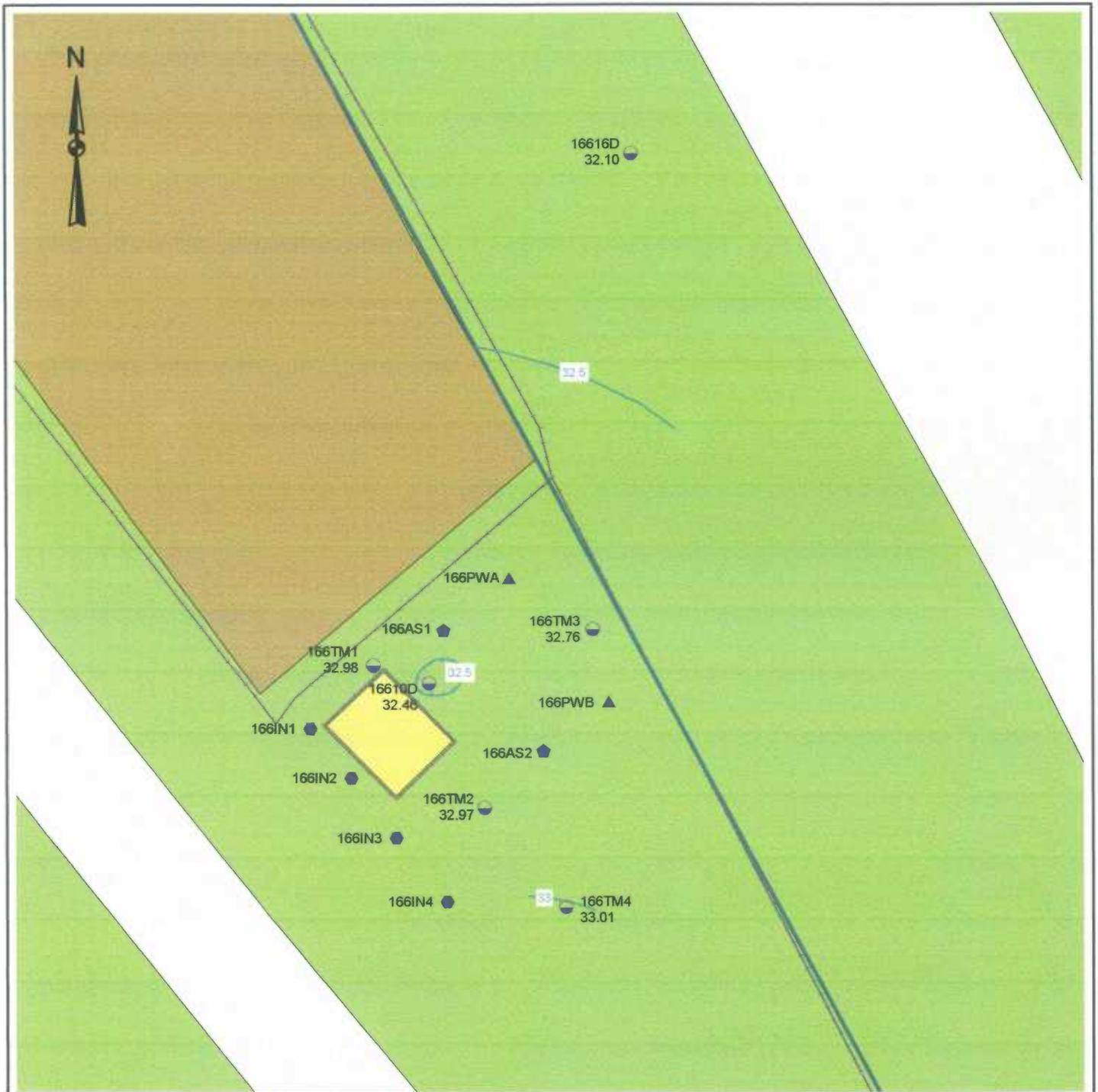
Well	TOC Elev (msl)	Date	DTW (ft)	Elev (msl)
16608D	40.34	02/22/00*	6.2	34.14
16614D	40.34	02/22/00*	6.88	33.46

Notes:

- TOC — Top of (well) casing
- DTW — Depth to water
- msl — Mean sea level
- * — Depth to water measurement were not taken synoptically with other wells

Before system startup, water levels were measured at the four treatability study monitoring wells and wells 16610D and 16616D. Based on these measurements, groundwater flowed northeast toward 16616D and there was a slight depression around 16610D. This may be due to the fact that 16610D has a 5-foot screen while the four treatability study wells have 15-foot screens (Figure 7.10). Water levels measured the day after the system startup showed that groundwater flowed northwest, with a high near 166TM1 and a low near 166TM3, which was located between extraction wells 166PWA and 166PWB (Figure 7.11). This pattern was expected due to pumping at the extraction wells and reinjection of the water upgradient of the wells. Water levels measured nine days later showed the same general pattern, except the low was near 16616D (Figure 7.12). This pattern prevailed throughout the study period, with water levels at 166TM3 and 16616D almost equal after the initial low at 166TM3 (Figures 7.13 through 7.16).

Changes in aquifer water levels due to the system were almost immediate. After one day of pumping and reinjection, the water level increased more than 1 foot at 166TM1 and decreased more than 2 ft at 166TM3. The greatest increase of water levels for upgradient wells 166TM1, 166TM2, 166TM4, and 16610D was on November 24, 1999. The system had been running for almost two weeks at an average of more than 8 gpm. After this time, water levels decreased at these wells. The average increase in the water levels of upgradient wells was 0.92 foot. The average decrease in downgradient well 166TM3 was 1.5 foot and the average water level decrease in 16616D was 0.63 foot. These water level changes were not expected to alter regional groundwater flow patterns.



LEGEND

- Deep Monitoring Well
- Re-Injection Well
- Air Sparging Well
- Extraction Well

- Groundwater Elevation Contour Line
- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

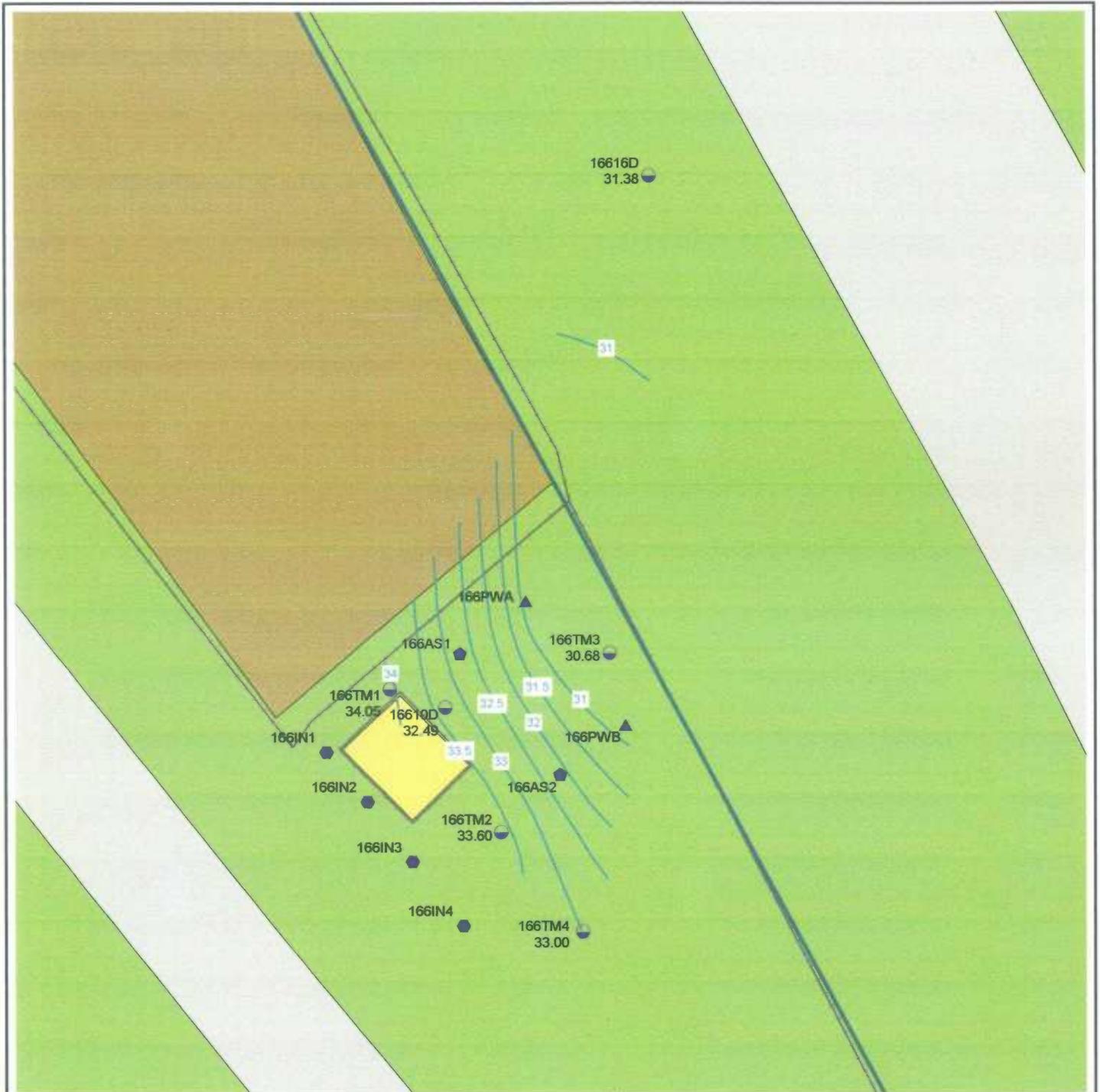
Note: All elevations in ft msl



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

**Figure 7.10
SWMU 166**

**November 4, 1999
Groundwater Elevations**



LEGEND

- Deep Monitoring Well
- Re-Injection Well
- ◆ Air Sparging Well
- ▲ Extraction Well

- 33 Groundwater Elevation Contour Line
- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

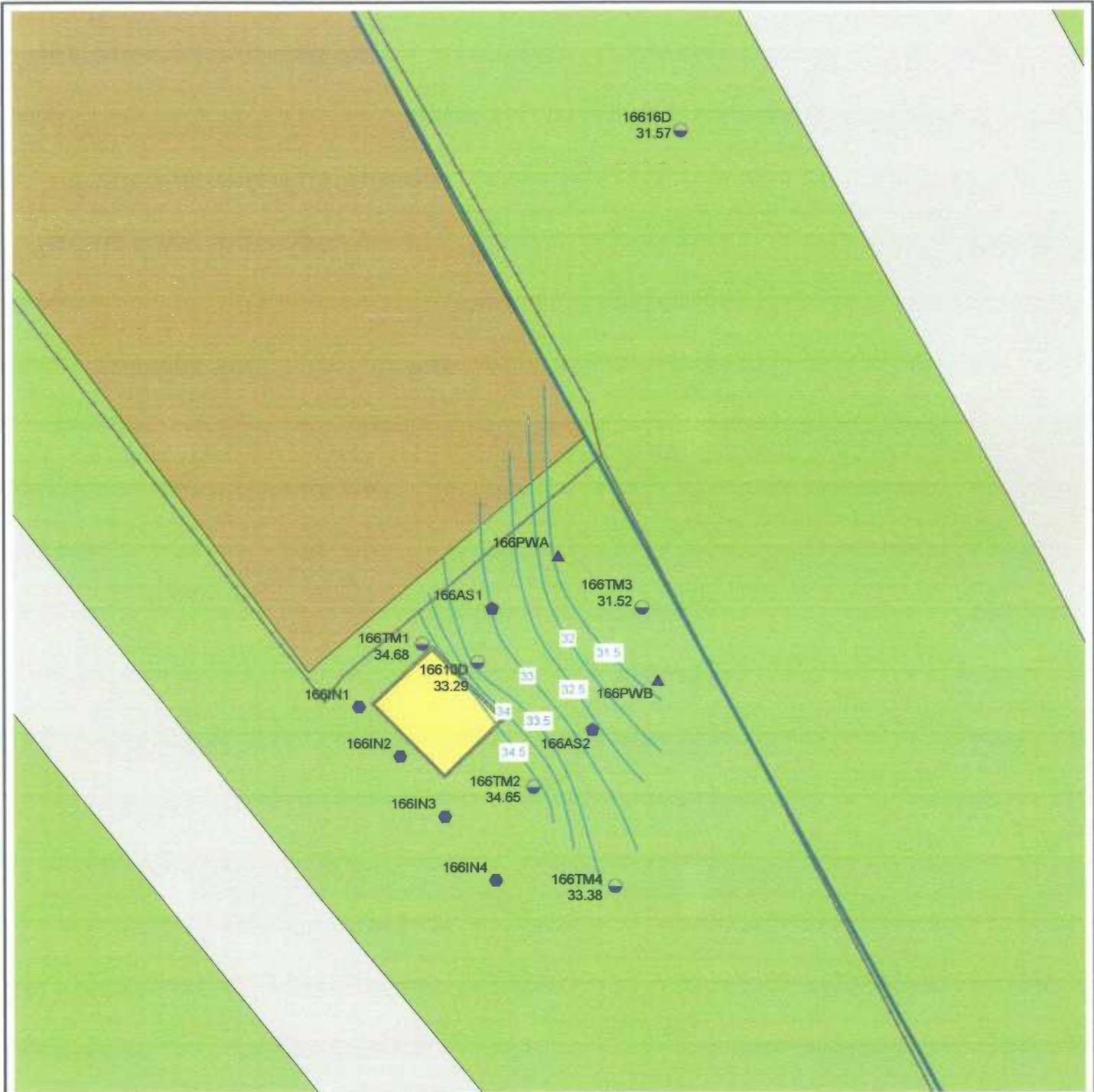
Note: All elevations in ft msl



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

**Figure 7.11
SWMU 166**

**November 10, 1999
Groundwater Elevations**



LEGEND

- Deep Monitoring Well
- Re-Injection Well
- Air Sparging Well
- ▲ Extraction Well

- 33 Groundwater Elevation Contour Line
- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

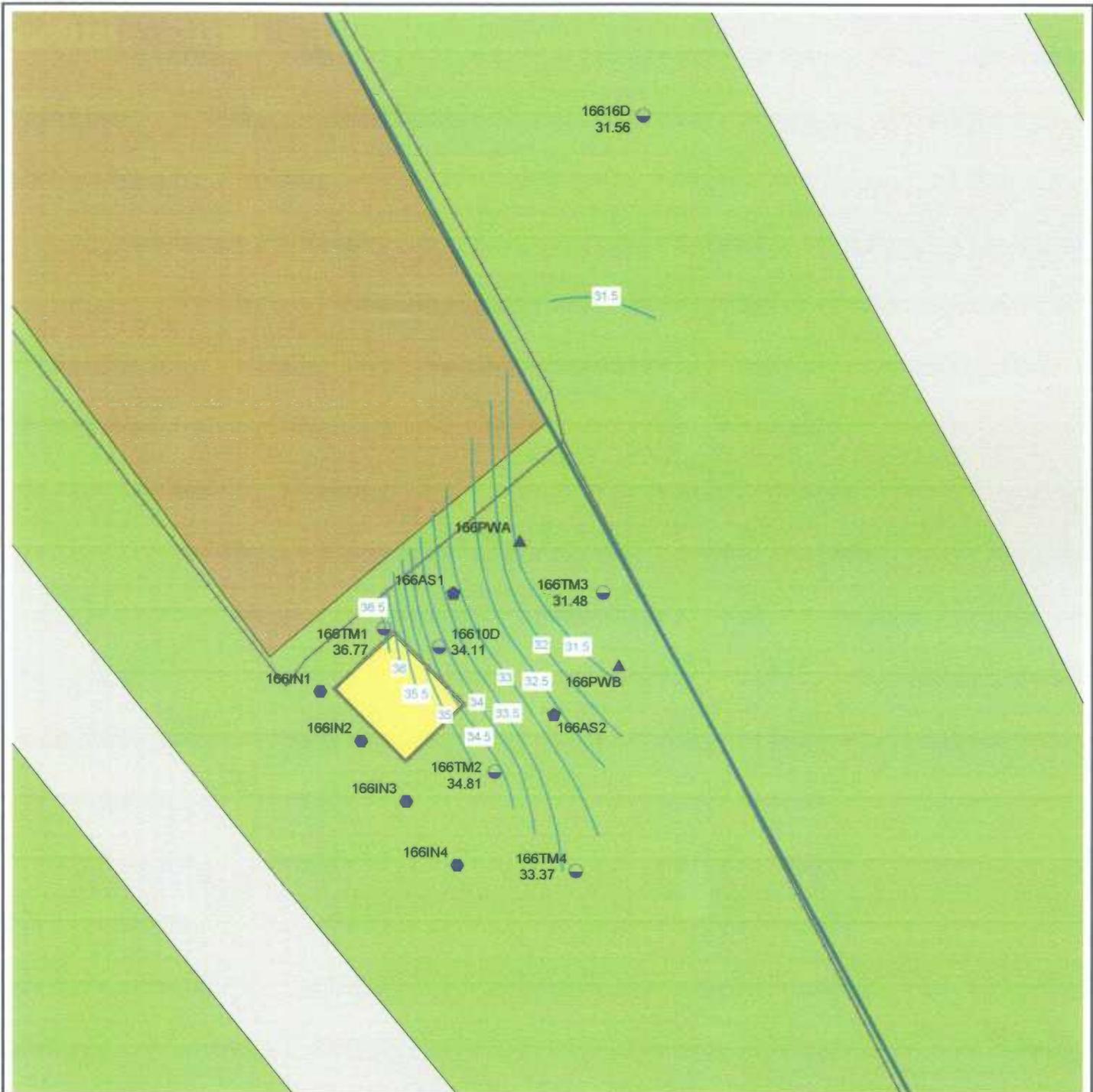
Note: All elevations in ft msl



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

**Figure 7.12
SWMU 166**

**November 19, 1999
Groundwater Elevations**



LEGEND

- Deep Monitoring Well
- ◆ Re-Injection Well
- Air Sparging Well
- ▲ Extraction Well

- 33 Groundwater Elevation Contour Line
- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

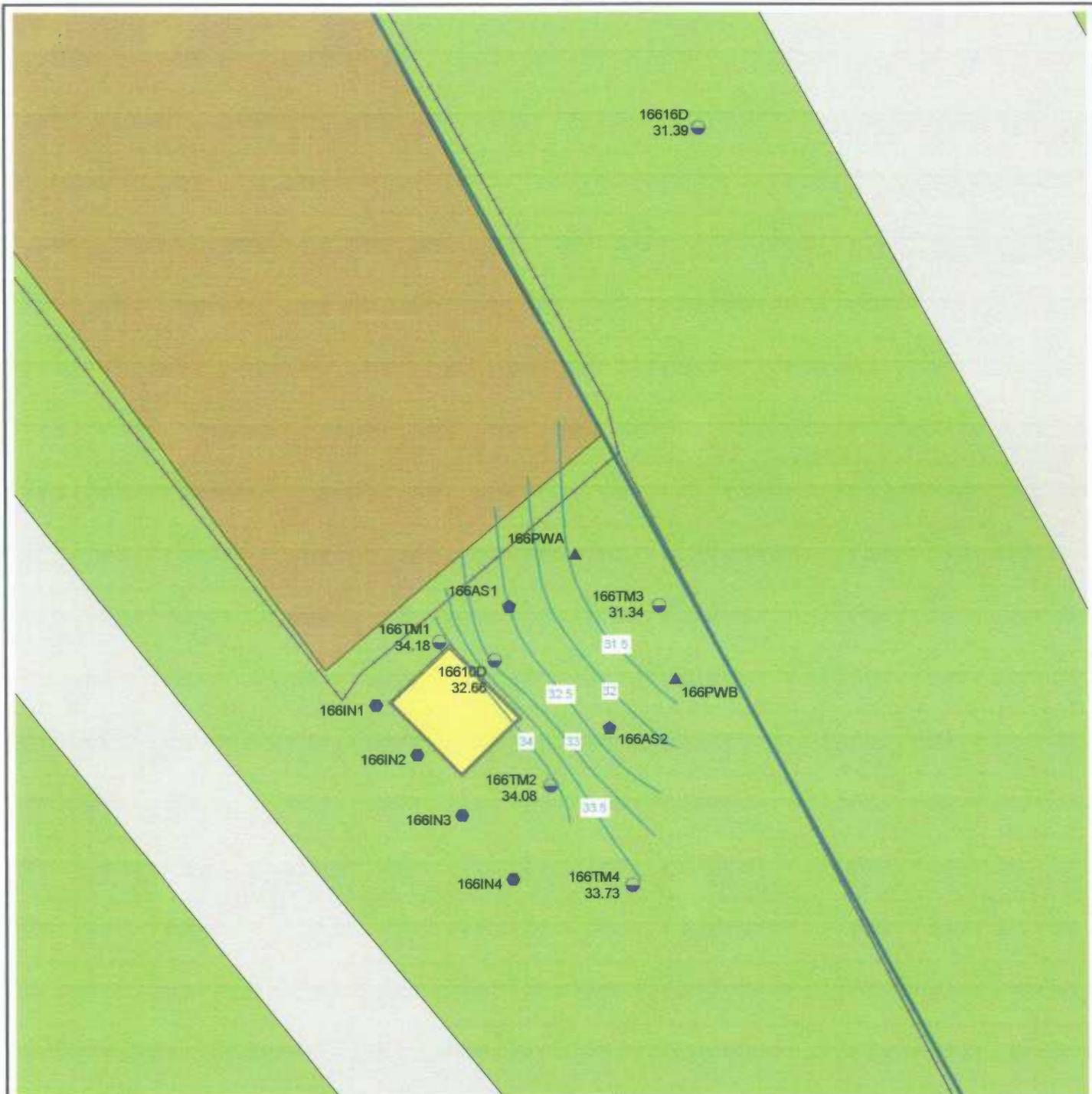
Note: All elevations in ft msl



ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC

Figure 7.13
SWMU 166

November 24, 1999
Groundwater Elevations



LEGEND

- Deep Monitoring Well
- Re-Injection Well
- ◆ Air Sparging Well
- ▲ Extraction Well

- Groundwater Elevation Contour Line
- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

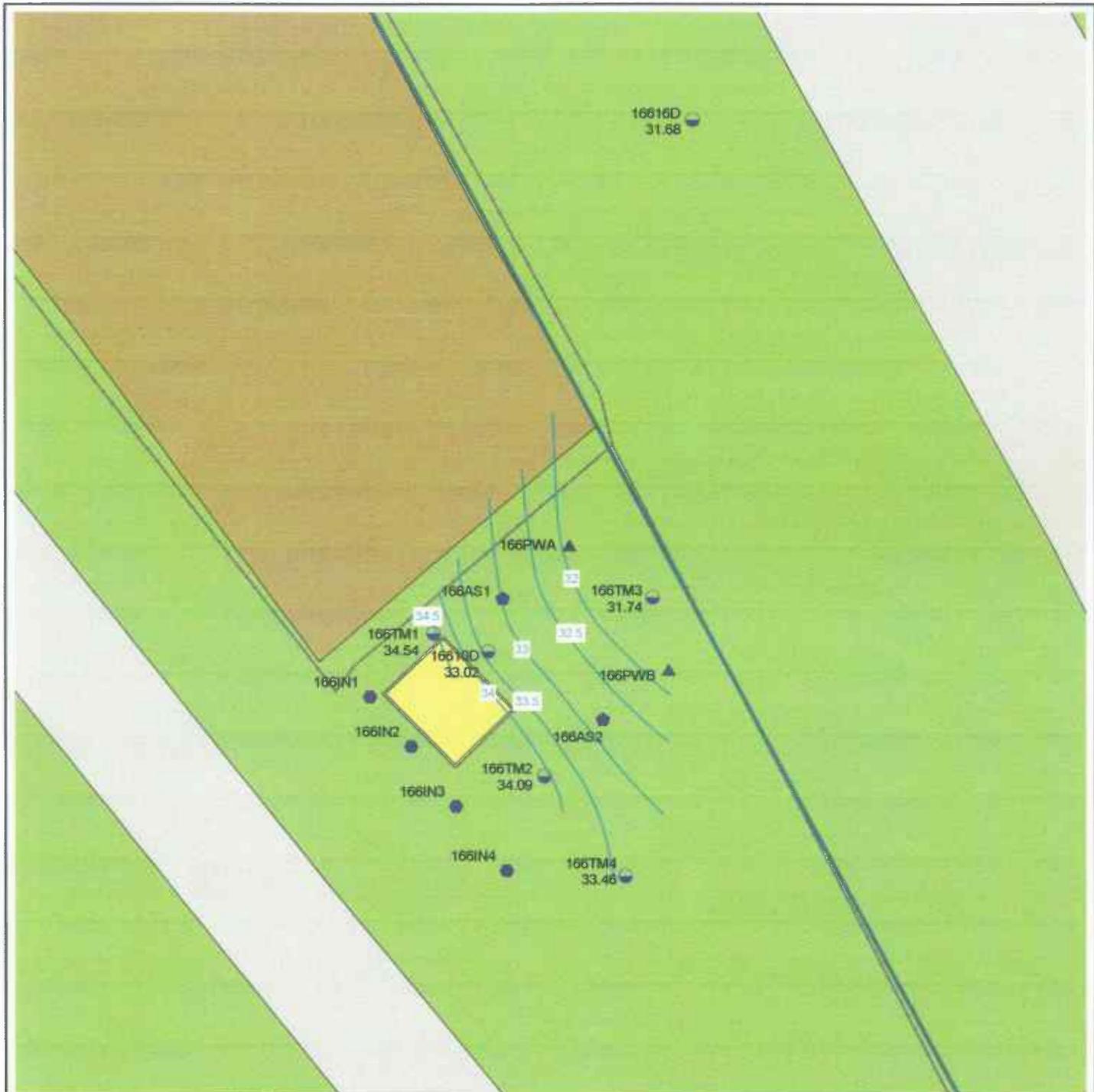
Note: All elevations in ft msl



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

**Figure 7.14
SWMU 166**

**December 9, 1999
Groundwater Elevations**



LEGEND

- Deep Monitoring Well
- Re-Injection Well
- ◆ Air Sparging Well
- ▲ Extraction Well

- Groundwater Elevation Contour Line
- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

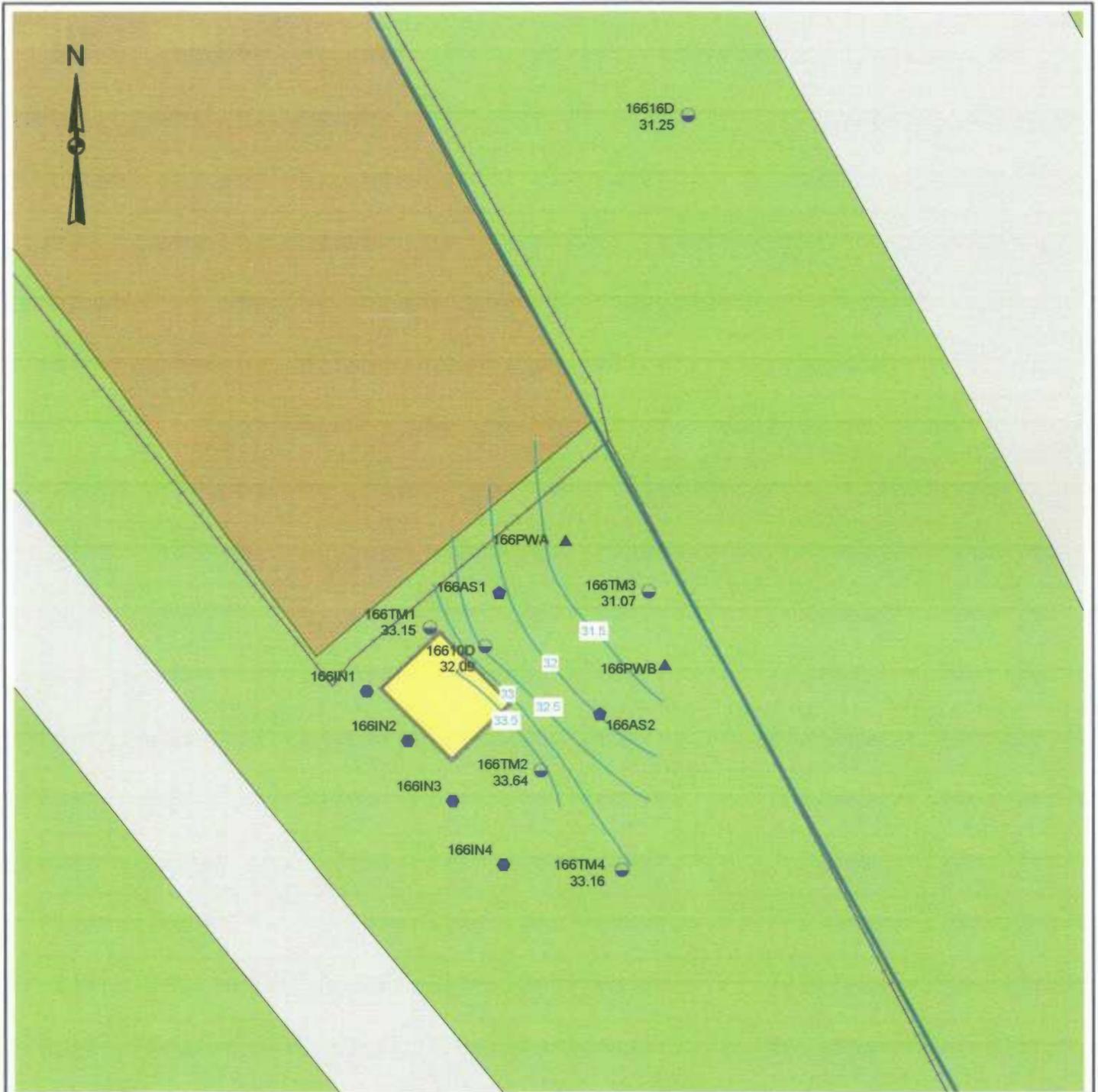
Note: All elevations in ft msl



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

**Figure 7.15
SWMU 166**

**December 22, 1999
Groundwater Elevations**



LEGEND

- Deep Monitoring Well
- Re-injection Well
- Air Sparging Well
- ▲ Extraction Well

- 33 Groundwater Elevation Contour Line
- Building
- Gravel or Porous Material
- Street / Pavement
- Grass and/or Soil Cover
- Fence
- Zone Boundary

Note: All elevations in ft msl



**ZONE K - SWMU 166
A-A SEQUENCING TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC**

**Figure 7.16
SWMU 166**

**January 5, 2000
Groundwater Elevations**

8.0 SYSTEM MODIFICATION

After three months of treatability testing, VOC results from the monthly sampling of treatability study wells and surrounding site wells showed sharp decreases in TCE concentrations and increases in 1,2-DCE concentrations (Table 7.1). The air sparging wells downgradient of the injection wells were installed to inject air into the aquifer to create an aerobic zone so that 1,2-DCE and vinyl chloride could be biodegraded. However, results from the weekly field monitoring and monthly sampling did not show that an adequate aerobic zone for the biodegradation of 1,2-DCE was being created by the A-A sequencing system.

On March 16, 2000, after four months of operation, the A-A system was modified so that air could be injected from the blower directly to the four upgradient injection wells and to the two downgradient air sparging wells to create a larger aerobic zone in the aquifer. New piping was connected the blower system to the reinjection well piping. A ball valve was installed on the new piping so that air could be injected only to the two downgradient air sparging wells if required during groundwater pumping. During air sparging of all six wells, the ball valve to the 500-gallon tank was closed so that air would flow to the injection wells and not in the 500 gal tank.

The modified system operated for four weeks until April 12, 2000. During the first two weeks, a pattern of five days of air sparging and two days of groundwater pumping was followed. That is, air was blown into the four injection wells and the two air sparging for five days, then groundwater was pumped from the pumping wells to the four injection wells for two days. For the final two weeks, groundwater was pumped only on April 6, 2000. The blower was capable of blowing 92 cfm, although the ball valve to the two air sparging wells was not fully open when groundwater was being pumped, therefore it was blowing less than 92 cfm.

8.1 Summary of Data

VOC data (Table 8.1), field data (Table 8.2), and inorganic data (Tables 8.3 and 8.4) were collected after modifications to the A-A system were made. Groundwater levels were also measured two weeks after the modifications were made (Table 8.5).

Table 8.1
System Modification
Volatile Organic Compound Data (µg/L)

Well	Sampling Round	Date	TCE	1,2-DCE (total)	Vinyl Chloride
166TM1	5	4/13/00	100 U	1800	100 U
166TM2	5	4/13/00	100 U	1800	100 U
166TM3	5	4/14/00	150	2200	120 U
166TM4	5	4/14/00	100 U	2100	100 U
16610D	5	4/13/00	100 U	1900	100 U
16616D	5	4/17/00	1600 D	920 D	31
166PWA	5	4/17/00	97	1600 D	5 U
166PWB	5	4/17/00	7	1600 D	5 U

Notes:

Qualifiers:

U — Below detection limits
 D — Dilution

Table 8.2
System Modification
Field Data Summary

Well	Date	DO (mg/L)		ORP (mV)	CO ₂ (mg/L)	Ammonia Nitrate	Phosphate (mg/L)	pH (SU)
		Horiba U-22	Titration					
166TM1	3/30/00	0.1	0	-37	NT	NT	NT	5.33
	4/06/00	0.5	0.2	-118	NT	0.4	5.0	6.28
	4/12/00	0.5	0.4	-66	40	0.4	2.5	5.88
166TM2	3/30/00	0.1	0	-94	NT	NT	NT	5.86
	4/06/00	0.6	0.2	-107	NT	0.5	1.8	6.21
	4/12/00	0.5	0.2	-99	40	0.7	1.8	5.95
166TM3	3/30/00	0.1	0	-80	NT	NT	NT	5.57
	4/06/00	0.5	0.4	-83	NT	0.4	4.9	6.14
	4/12/00	0.5	0.4	-95	30	0.4	1.9	6.21
166TM4	3/30/00	NT	NT	NT	NT	NT	NT	NT
	4/06/00	0.6	0.4	-97	NT	0.5	1.7	6.07
	4/12/00	0.5	0.2	-98	40	0.5	2.6	6.01
16610D	3/30/00	NT	NT	NT	NT	NT	NT	NT
	4/06/00	0.9	0.2	-63	NT	0.6	2.0	6.06
	4/12/00	0.6	0.4	-40	50	0.3	1.8	5.87
16616D	3/30/00	NT	NT	NT	NT	NT	NT	NT
	4/06/00	NT	NT	NT	NT	NT	NT	NT
	4/12/00	2.3	2.2	-24	20	0.7	0.6	7.18

Notes:

- DO — Dissolved oxygen
- mg/L — milligrams per liter
- ORP — Oxidation-reduction potential
- mV — millivolts
- CO₂ — Carbon dioxide
- SU — Standard units
- NT — Not taken

Table 8.3
System Modification
Inorganic Compound Data (mg/L)

Well	Sampling Round	Date	Ammonia	o-Phosphate	Nitrate-Nitrite-N	TKN	Chloride	TOC
166TM1	5	4/13/00	0.1 U	0.5	0.1 U	1.0 U	5.2	1.0 U
166TM2	5	4/13/00	0.1 U	0.1 U	0.1 U	1.0 U	5.4	1.0 U
166TM3	5	4/14/00	1.0 U	0.26	0.1 U	1.4	5.8	1.0 U
166TM4	5	4/14/00	1.0 U	0.54	0.1 U	1.0 U	5.8	1.0 U
16610D	5	4/13/00	0.1 U	0.63	0.1 U	1.1	5.0	1.0 U
16616D	5	4/17/00	1.0 U	0.17	0.1 U	1.0 U	5.8	1.0 U
166IN1	5	4/12/00	1.0 U	0.78	0.1 U	1.0 U	5.0	1.0 U
166IN2	5	4/12/00	1.0 U	1.1	0.1 U	2	6.0	7.4
166IN3	5	4/13/00	0.1 U	1.3	0.1 U	1.0 U	5.6	1.1
166IN4	5	4/17/00	1.4	1.5	0.1 U	1.7	5.4	1.4
166PWA	5	4/17/00	1.0 U	0.84	0.1 U	1.0 U	6.2	1.5
166PWB	5	4/17/00	1.0 U	0.41	0.1 U	1.4	6.0	1.0

Notes:

Qualifiers:

- U — Below detection limit
- TKN — Total Kjeldahl Nitrogen
- TOC — Total organic carbon

Table 8.4
System Modification
Carbon:Nitrogen:Phosphorous Ratio Data

Well	Sampling Round	Date	TOC (mg/L)	TKN (mg/L)	Total Phosphorous (mg/L)	C:N:P Ratio
166TM1	5	4/13/00	1.0 U	1.0 U	0.85	100:100:170
166TM2	5	4/13/00	1.0 U	1.0 U	0.62	100:100:124
166TM3	5	4/14/00	1.0 U	1.4	0.65	100:280:130

Table 8.4
System Modification
Carbon:Nitrogen:Phosphorous Ratio Data

Well	Sampling Round	Date	TOC (mg/L)	TKN (mg/L)	Total Phosphorous (mg/L)	C:N:P Ratio
166TM4	5	4/14/00	1.0 U	1.0 U	0.66	100:100:132
16610D	5	4/13/00	1.0 U	1.1	0.59	100:220:118
16616D	5	4/17/00	1.0 U	1.0 U	0.27	100:100:54
166IN1	5	4/12/00	1.0 U	1.0 U	1.2	100:100:240
166IN2	5	4/12/00	7.4	2.0	1.8	100:27:24
166IN3	5	4/13/00	1.1	1.0 U	2.3	100:45:209
166IN4	5	4/17/00	1.4	1.7	4.4	100:121:314
166PWA	5	4/17/00	1.5	1.0 U	0.91	100:33:61
166PWB	5	4/17/00	1.0	1.4	0.69	100:140:69

Notes:

Qualifiers:

U — Below detection limit

Table 8.5
System Modification
Groundwater Elevations

Well	TOC Elevation (msl)	Date	DTW (ft)	Groundwater Elevation (msl)
166TM1	40.87	4/05/00	8.31	32.56
166TM2	40.56	4/05/00	8.03	32.53
166TM3	40.69	4/05/00	8.33	32.36
166TM4	40.53	4/05/00	7.93	32.60
16607D	40.46	4/05/00	6.98	33.48
16608D	40.34	4/05/00	6.81	33.53
16610D	43.01	4/05/00	10.98	32.03

Table 8.5
System Modification
Groundwater Elevations

Well	TOC Elevation (msl)	Date	DTW (ft)	Groundwater Elevation (msl)
16611D	42.46	4/05/00	10.22	32.24
16614D	40.34	4/05/00	7.40	32.94
16616D	33.73	4/05/00	1.96	31.77
16625D	39.97	4/05/00	6.15	33.82

Notes:

TOC — Top of (well) casing
 DTW — Depth to water
 msl — Mean sea level

8.2 Analysis of Data

Wells were sampled for VOCs and biochemical parameters after the four weeks of air sparging. Results were similar to those of the previous sampling round in February (see Tables 7.1, 7.3, and 7.4), although there were a few exceptions:

- Downgradient wells 166TM3 and 16616D showed higher concentrations of TCE.
- Each well had higher concentrations of 1,2-DCE (total).
- Vinyl chloride was detected in 16616D.
- Ammonia was not detected in wells 16616D, 166IN1, 166IN2, and 166IN3, but was detected in 166IN4.

1,2-DCE concentrations did not decrease after increased air sparging and vinyl chloride was not detected in any wells, except 16616D, which has a history of vinyl chloride detections. Carbon

and nutrients were added to the system up until March 10, 2000, less than a week before the system was modified. It is likely that the four-week period of air sparging was not long enough to significantly increase oxygen levels in the aquifer. It is likely that the fructose added in the first three months of the study consumed most of the oxygen injected in the aquifer. This is consistent with findings from a similar treatability study conducted in Watertown, MA. Aerobic conditions were not established in this system until approximately one month after similar modifications were made to the system to increase oxygen concentrations in the aquifer (Lewis 1998). Increased air sparging time would likely increase oxygen levels in the aquifer enough to create aerobic conditions and initiate the degradation of cis-1,2-DCE.

Field parameters were collected after the first two weeks of operating the modified system from wells 166TM1, 166TM2, and 166TM3. Dissolved oxygen concentrations had decreased from the previous time field parameters were collected (See Table 7.2) and showed that the aquifer was under anaerobic conditions. When field parameters were collected a week later, dissolved oxygen concentrations had risen, but were still less than 0.5 mg/L in most wells. Field parameters were again collected a week later, and dissolved oxygen concentrations had only risen slightly. Dissolved oxygen concentrations were measured using a titration kit and a Horiba U-22 water quality meter that was lowered into the wells. Generally, concentrations collected using the titration method were slightly lower. Other field parameters showed little change from previous results.

Water levels were measured after the first two weeks of air sparging on April 5, 2000 from the treatability study wells and surrounding deep monitoring wells (Figure 8.1). Water levels decreased slightly in all the treatability study wells from measurements taken on November 4, 1999, which was expected due to increased air sparging. However, results showed the sparging did not affect the regional groundwater flow pattern.



9.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The main objective of performing a treatability anaerobic-aerobic sequential study at SWMU 166 was to determine the feasibility and effectiveness of using enhanced in-situ bioremediation to degrade and remediate a chlorinated VOC groundwater plume. Introducing a carbon source (fructose) and nutrients (nitrogen and phosphorus) into the system achieved this objective. The result was a rapid decrease in TCE concentrations during the first month of system operation. During this same period, the concentration of cis-1,2-DCE increased in all of wells. Because, cis-1,2-DCE is a known biological daughter breakdown product of TCE, the decrease in concentration of TCE can be largely attributed to microbial activity induced by the A-A system. The injection of fructose into the aquifer created the proper anaerobic environment for native microorganisms to begin degrading the TCE very rapidly. Concentrations of cis-DCE however remained elevated after three months of the study, indicating that the anaerobic zone was probably not reducing enough to drive reductive dechlorination rapidly enough all the way to ethylene.

Dissolved oxygen concentrations in the area remained low throughout the study in the four monitoring wells and well 16610D. ORP values remained negative throughout the study and in most wells, values were below -100 mV. Both conditions indicate that the aquifer is highly reducing.

CO₂ concentrations in three monitoring wells (166TM1, 166TM2, and 166TM3), which are immediately downgradient of the injection wells, increased as the study progressed. CO₂ concentrations often increase in areas where microbial activity has increased because it is an end-product of some respiratory mechanisms. Therefore, the increase in CO₂ and the decreases in DO and ORP reflect a response of the microbial population to the added fructose and nutrients during TCE degradation.

Increased air sparging for one month did not decrease 1,2-DCE concentrations, increase vinyl chloride concentrations, or significantly increase DO concentrations. However, because carbon and nutrients were added to the system shortly before air sparging increased, a longer period of increased air sparging would have likely increased DO concentrations, creating conditions more conducive to degrade 1,2-DCE and vinyl chloride.

Recommendations

The A-A sequential study at SWMU 166 has successfully reduced the concentrations of TCE in the groundwater contamination plume. The addition of fructose and nutrients created the necessary anaerobic conditions and increased the degradation of TCE. Fructose addition is more economical, feasible, and safer to work with than methane (Ludvigsen 1999) and methanol (Litherland 1999), which were used as a carbon sources in other similar studies.

As evident from an earlier treatability study, increased time of air sparging would likely increase oxygen level in the aerobic zone enough to create greater aerobic conditions and initiate the degradation of cis-1,2-DCE (Lewis 1998). Variations in size of the aerobic zone and the placement of the air spargers, which were limited at this site, may be an option for future studies or in full-scale remediation. Variations in pumping and sparging cycles may also be an option during full-scale remediation. An increased time period for the degradation of cis-1,2-DCE is also recommended.

10.0 REFERENCES

EnSafe Inc. *Comprehensive Corrective Measures Study Work Plan and Project Management Plans*. Prepared for Department of the Navy, Southern Division Naval Facilities Engineering Command: Charleston, SC. Contract N62467-89-D-0318. June 27, 1997.

EnSafe Inc. *Monitored Natural Attenuation Interim Report*. Prepared for Department of the Navy, Southern Division Naval Facilities Engineering Command: Charleston, SC. Contract N62467-89-D-0318. March, 1999.

EnSafe Inc. *SWMU 166 A-A Sequencing Treatability Study Work Plan*. Prepared for Department of the Navy, Southern Division Naval Facilities Engineering Command: Charleston, SC. Contract N62467-89-D-0318. March, 1999.

EnSafe Inc. *SWMU 166 A-A Sequencing Treatability Study Design Document*. Prepared for Department of the Navy, Southern Division Naval Facilities Engineering Command: Charleston, SC. Contract N62467-89-D-0318. July, 1999.

Lewis, Ronald F., Dooley, M. A., Johnson, J. C., and W. A. Murray. "Sequential Anaerobic/Aerobic Biodegradation of Chlorinated Solvents: Pilot-Scale Field Demonstration." *First International Conference on Remediation of Chlorinated and Recalcitrant Compounds*. Vol. C1-6. May, 1998.

Litherland, Susan Tighe, Anderson, D. W., and B. A. Dinwiddie. "Full-Scale Bioremediation at a Chlorinated Solvents Site: Project Update." *Fifth International In Situ and On-Site Bioremediation Symposium*. Vol 5(2). April, 1999.

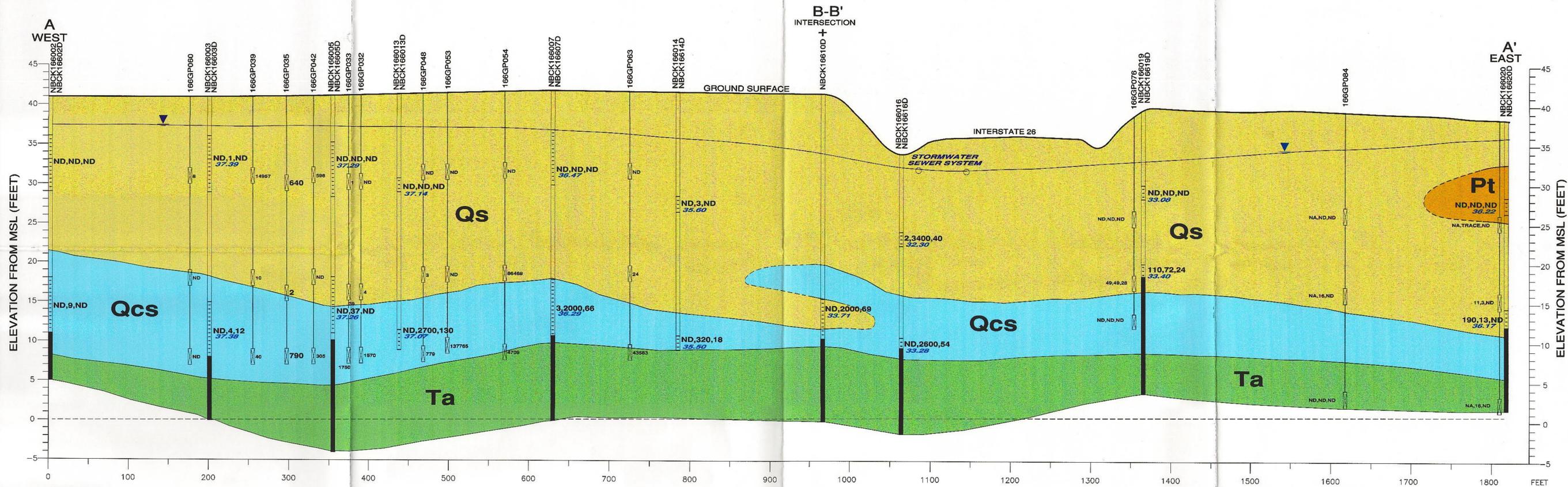
Ludvigsen, Liselotte, Kiillerich, O., Broholm, K, and L. Deigaard. “Aerobic Biodegradation of Vinyl Chloride and cis-1,2-Dichloroethylene: Laboratory and Field Studies.” *Fifth International In Situ and On-Site Bioremediation Symposium*. Vol 5(2). April, 1999.

Saberian, Amireh G., Schmid, H., Spadaro, J. T., and John Kuiper. “Comparison of PCE Biodegradation Rate Under Natural Versus Enhanced Conditions.” *Fourth International In Situ and On-Site Bioremediation Symposium*. Vol. 4(3). May, 1997.

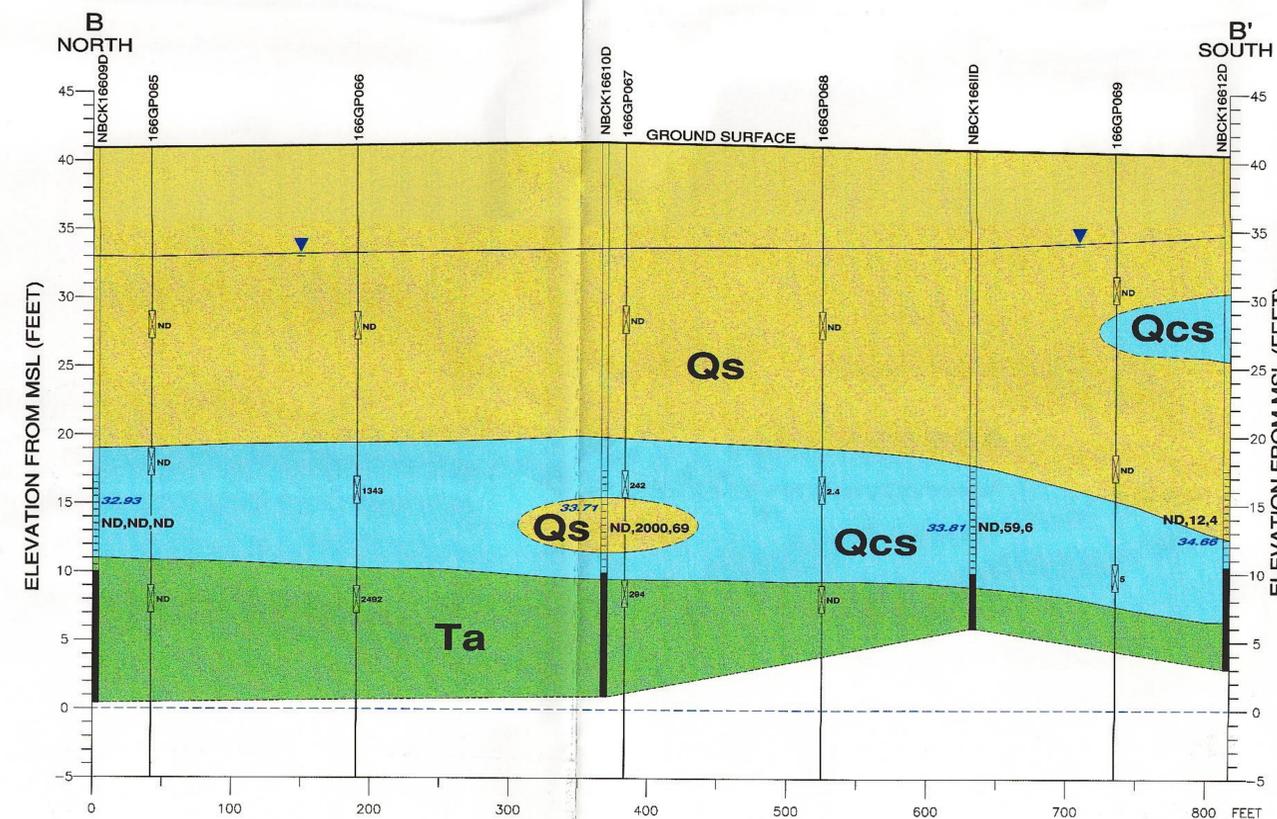
Wilson, John T., Kampbell, D. H., and J. A. Weaver. “Environmental Chemistry and the Kinetics of Biotransformation of Chlorinated Organic Compounds in Ground Water.” *Symposium on Natural Attenuation of Chlorinated Organics in Ground Water*. EPA/540/R-96/509. September 1996.

USEPA. *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water*. Office of Research and Development, Washington, DC. 1998.

EnSafe Inc. (July 1998). *Zone A RCRA Facility Investigation Report NAVBASE Charleston*. Prepared for Department of the Navy, Southern Division Naval Facilities Engineering Command: Charleston, SC. Contract N62467-89-D-0318. July.



CROSS-SECTION A - A'



CROSS-SECTION B - B'

LEGEND:

- EQUIPOTENTIAL LINE (0.2 FOOT INTERVALS)
- FLOW LINE
- WATER TABLE SURFACE
- SCREENED INTERVAL OF MONITORING WELL - INCLUDING FILTER PACK WITH PCE, TCE, AND DCE CONCENTRATIONS IN $\mu\text{g/L}$ AND WATER LEVEL ELEVATION
- BENTONITE
- DPT SAMPLE LOCATION WITH COMBINED TCE/DCE CONCENTRATIONS (ONE NUMBER) OR PCE, TCE, AND DCE CONCENTRATIONS (THREE NUMBERS)
- GEOLOGIC CONTACTS - DASHED WHERE INFERRED
- MEAN SEA LEVEL (MSL) DATUM
- VERTICAL SCALE: 1" = 5'-0"
- HORIZONTAL SCALE: 1" = 50'-0"

LITHOSTRATIGRAPHIC UNITS

QUATERNARY AGE

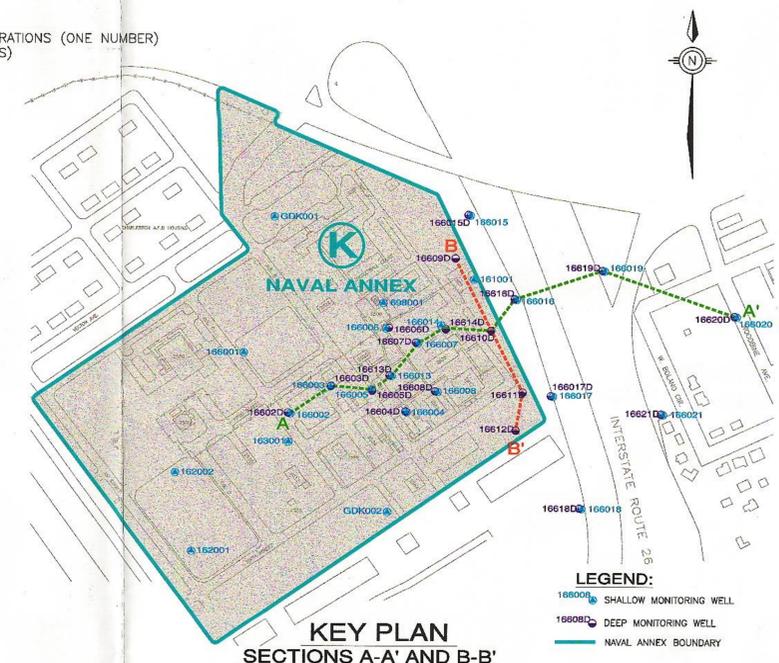
Qs SAND: TYPICALLY GRAY, GREEN, ORANGE, OR BROWN; FINE TO MEDIUM SLIGHTLY SILTY; MICACEOUS.

Pt PEAT: DARK BROWN; WOODY FRAGMENTS; DECOMPOSING GRASSES; SPONGY

Qcs CLAYEY SAND TO CLAY; TYPICALLY GREEN TO GRAY-GREEN; FINE TO COARSE; CLAYEY; VARYING AMOUNTS OF SILT; PHOSPHATE NODULES AND SHELL CLAY GENERALLY FIRM TO STIFF AND PLASTIC

TERTIARY AGE

Ta SILT: TYPICALLY OLIVE BROWN; CLAYEY, DENSE, CALCAREOUS, ASHLEY FORMATION



KEY PLAN SECTIONS A-A' AND B-B'

REVISIONS		
Rev Number	Rev Date	Rev By

ZONE K - SWMU 166
 A-A TREATABILITY
 STUDY REPORT
 CHARLESTON NAVAL COMPLEX (NAVAL ANNEX)
 CHARLESTON, SC

FIGURE 3.3
 LITHOSTRATIGRAPHIC CROSS-SECTIONS A-A' AND B-B'
 WITH MONITORING WELLS

Dr by: W. FAULK Tr by: -
 Ck by: R. BRITTO Appr by: T. HAVERKOST Sheet 1
 Date: 05/30/00 DWG Name: 2911C104 Of 1



LEGEND:

- 166TM1 SWMU 166 TREATABILITY STUDY DEEP MONITORING WELL
- 161001 ZONE K RFI SHALLOW MONITORING WELL W/ ID NUMBER
- 16611D ZONE K RFI DEEP MONITORING WELL W/ ID NUMBER
- 166GP006 ZONE K RFI DPT SAMPLE W/ ID NUMBER
- DIRECTION OF FLOW - STORMWATER RUNOFF
- DIRECTION OF FLOW - GROUNDWATER (BASED ON 10 NOV 98 ELEVATION DATA)
- FENCE
- SEWER LINE (SWMU 185)
- STUDY ZONE BOUNDARY
- BUILDING
- GRASS/SOIL OR OTHER POROUS GROUNDCOVER
- OPEN WATER
- MARSH OR OTHER WETLANDS
- GRAVEL OR OTHER POROUS PAVING MATERIAL
- ASPHALT OR OTHER NON-POROUS PAVING MATERIAL

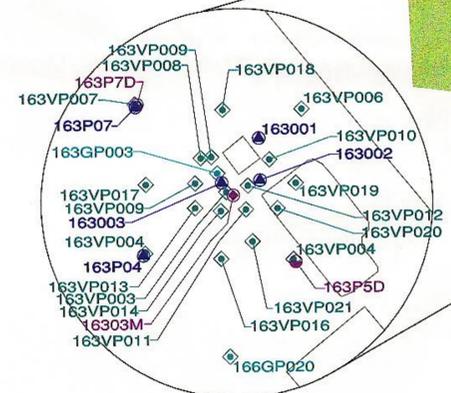


REVISIONS		
Rev Number:	Rev Date:	Rev By:
Rev Number:	Rev Date:	Rev By:
Rev Number:	Rev Date:	Rev By:
Rev Number:	Rev Date:	Rev By:
Rev Number:	Rev Date:	Rev By:

ZONE K - SWMU 166 A-A TREATABILITY STUDY REPORT CHARLESTON NAVAL COMPLEX (NAVAL ANNEX) CHARLESTON, SC		
FIGURE 3.2 SWMU 166 - TREATABILITY STUDY AREA SITE MAP		
Dr by: W. FAULK	Tr by: -	
Ck by: R. BRITTO	Appr by: T. HAVERKOST	Sheet 1
Date: 05/30/00	DWG Name: 2911C103	Of 1

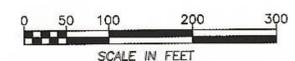


(K)
NAVAL ANNEX



SWMU 163 AREA
(MAGNIFIED 3X FOR CLARITY)

- LEGEND:**
- 166008 ● SHALLOW MONITORING WELL LOCATION
 - 16608D ● DEEP MONITORING WELL LOCATION
 - 16303M ● MULTI-LEVEL VERTICAL PROFILE MONITORING WELL LOCATION
 - 166GP003 ● GROUNDWATER DPT SAMPLE



REVISIONS		
Rev Number:	Rev Date:	Rev By:
Rev Number:	Rev Date:	Rev By:
Rev Number:	Rev Date:	Rev By:
Rev Number:	Rev Date:	Rev By:

 ZONE K - SWMU 166
A-A TREATABILITY
STUDY REPORT
CHARLESTON NAVAL COMPLEX (NAVAL ANNEX)
CHARLESTON, SC

FIGURE 3.1
GROUNDWATER MONITORING WELL LOCATION MAP
NAVAL ANNEX

Dr by: W. FAULK	Tr by: -	Sheet 1
Chk by: R. BRITTO	Appr by: T. HAVERKOST	Of 1
Date: 05/30/00	DWG Name: 2911C102	