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MONITORED NATURAL ATTENUATION INTERIM REPORT CNC CHARLESTON SC
3/17/1999
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**MONITORED NATURAL ATTENUATION
INTERIM REPORT**

**CHARLESTON NAVAL COMPLEX
NORTH CHARLESTON, SOUTH CAROLINA**

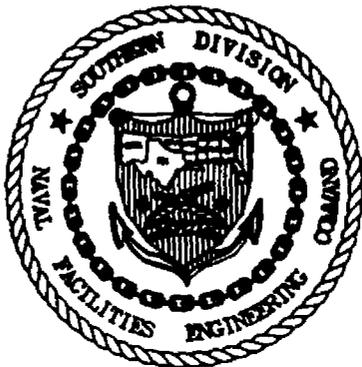


CTO-029

Contract Number: N62467-89-D-0318

Prepared for:

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



Prepared by:

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**March 17, 1999
Revision: 0**

Release of this document requires prior notification of the Commanding Officer of the Southern Division, Naval Facilities Engineering Command, North Charleston, South Carolina.



DEPARTMENT OF THE NAVY

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Mr. John Litton, P.E.
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Bureau of Land and Waste Management
South Carolina Department of Health and Environmental Control
2600 Bull Street
Columbia, SC 29201

Subj: SUBMITTAL OF THE MONITORED NATURAL ATTENUATION INTERIM
REPORT

Dear Mr. Litton:

The purpose of this letter is to submit the enclosed Monitored Natural Attenuation (MNA) Interim Report for Naval Base Charleston. The interim report is submitted to present a protocol for data collection and analysis to improve characterization of sites where MNA is being considered. The report contains all MNA data collected to date at SWMU 166 at the Charleston Naval Complex (CNC). Additional data will be collected at the completion of the Treatability Study for SWMU 166 and a revised report will be submitted.

The Navy requests that the Department and the USEPA review and provide comment on the document to provide the Navy with guidance on future MNA efforts at SWMU 166 and other sites at CNC. The need for submittal of interim reports for the remaining MNA sites will be determined after comments are received. If you should have any questions please contact me at (843) 820-5543 respectively.

Sincerely,

DAVID P. DODDS
Remedial Project Manager
Environmental Department

Encl:

(1) Monitored Natural Attenuation Interim Report, dated 17 March 1999

Copy to:

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CSO Naval Base Charleston (Billy Drawdy), SOUTHNAVFACENGCOM (Tony Hunt)
SPORTENVDETCNASN (Bobby Dearhart)

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INTERIM REPORT**

**CHARLESTON NAVAL COMPLEX
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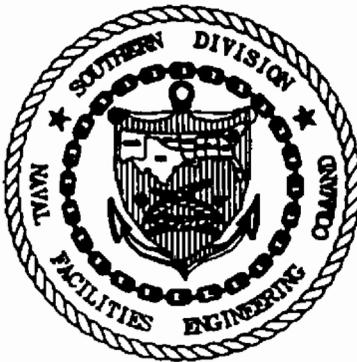


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1.0 INTRODUCTION

The Charleston Naval Complex (CNC) is currently undergoing a Corrective Measure Study (CMS) at several sites in accordance with Condition IV.E.2 and the Hazardous and Solid Waste Amendments (HSWA) portion of the Resource Conservation and Recovery Act (RCRA) Part B Permit (EPA SCD 170 022 560). The purpose of the CMS is to identify, screen, and evaluate/rank potential remedial options for a given site or group of sites. Viable remedial options will be evaluated and ranked primarily upon their ability to adequately protect human health and the environment, while complying with all applicable regulatory concerns and standards. One of these potential options is monitored natural attenuation (MNA) as described in EPA/600/R-98/128 *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater* (referred to herein as Technical Protocol, 1998). The document presents a protocol for data collection and analysis to improve characterization of sites at which a remedy involving MNA is being considered. The data collected using this protocol can be used to compare the effectiveness of MNA as well as other remedial options. For the MNA study at CNC, the protocol, along with input from the Charleston project team, was used as a guidance document in evaluating sites for MNA.

The United States Environmental Protection Agency (USEPA) defines monitored natural attenuation as (OSWER Directive 9200.4-17, 1997):

The term "monitored natural attenuation," as used in this Directive, refers to the reliance on natural attenuation processes (within the context of a carefully controlled and monitored clean-up approach) to achieve site-specific remedial objectives within a time frame that is reasonable compared to other methods. *The "natural attenuation processes" that are at work in such a remediation approach include a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity,*

mobility, volume, or concentration of contaminants in soil and groundwater. These in-situ processes include biodegradation, dispersion, dilution, sorption, volatilization, and chemical or biological stabilization, transformation, or destruction of contaminants. Monitored natural attenuation is appropriate as a remedial approach only when it can be demonstrated capable of achieving a site's remedial objectives within a time frame that is reasonable compared to that offered by other methods and where it meets the applicable remedy selection program for a particular OSWER program. EPA, therefore, expects that monitored natural attenuation typically will be used in conjunction with active remediation measures (e.g. source control), or as a follow-up to active remediation measures that have already been implemented.

RCRA Corrective Actions generally require that remedial actions prevent exposure to contaminated groundwater, minimize further migration of the plume, minimize further migration of contaminants from source materials and restore the plume to cleanup levels appropriate for current or future uses. In achieving these goals, MNA may be implemented along with other remedial measures. But before MNA can be selected as a remedial option for CNC, the fate in groundwater of chlorinated and fuel hydrocarbons in the selected sites must be evaluated.

1.1 Lines of Evidence

Before MNA can be designated as a remedial option, OSWER Directive 9200.4-17 identifies three lines of evidence that are to be used to scientifically document the occurrence of MNA and quantify the rates. The three lines of evidence are:

- Historical groundwater data that demonstrate a clear and meaningful trend of decreasing contaminant mass and/or concentration over time at appropriate monitoring points.

- Hydrogeologic and geochemical data that can be used to demonstrate indirectly the type(s) of natural attenuation processes active at the site, and the rate at which such processes will reduce contamination concentrations to required levels.
- Data from field or microcosm studies which demonstrate the occurrence of particular natural attenuation process at the site and its ability to degrade the contaminant of concern.

The historical data included at least four quarters of groundwater monitoring for volatile organic compounds (VOCs) at the sites, in addition to two rounds of groundwater sampling for MNA parameters collected in 1998. The first line of evidence is critical in determining if any exposure pathways exist for current or potential receptors. It should be noted, however, that the first line of evidence does not prove that the contaminants are being destroyed. Reduction in contaminant concentration may be caused by advection, dispersion, dilution, sorption, and volatilization.

Reductive dechlorination is the most important process for biodegradation of chlorinated solvents. During reductive dechlorination a chlorinated hydrocarbon is used as an electron acceptor, rather than an electron donor as in the biodegradation of fuel hydrocarbons and a chlorine atom is removed from the hydrocarbon and replaced with a hydrogen atom. Reductive dechlorination generally occurs in a sequence beginning with the most oxidized species, tetrachloroethene (PCE), to the least oxidized, vinyl chloride (VC). The full sequence of biologically mediated reductive dechlorination reactions for chlorinated aliphatic hydrocarbons is: PCE degrading to trichloroethene (TCE), then 1,2-dichloroethene (1,2-DCE), then to VC, and then to ethene.



DCE and VC may also be oxidized to carbon dioxide, water, and chloride ions.

Detectable concentrations of several mother-daughter compounds from the biodegradation sequence in the groundwater is an indicator that reductive dechlorination may be occurring, provided that the most oxidized chlorinated compound detected is the source of contamination.

To demonstrate that MNA is a viable remedial option, a reduction in contaminant mass must be shown. The second line of evidence uses chemical and physical data to show that contaminant mass is being destroyed and not just being diluted or sorbed to the aquifer. Mass balance calculations are made to show that decreases in contaminant and electron acceptor/donor concentrations can be directly correlated to increases in metabolic end products/daughter compounds. The third line of evidence should only be undertaken when it is the only means available for obtaining biodegradation rate estimates.

1.2 Protocol for Quantifying MNA

The Technical Protocol describes the quantification of contaminant migration and attenuation rates. Successful implementation of MNA remedial options requires addressing the following steps:

- Review analytical site data and develop a conceptual model.
- Screen the site and assess the potential for MNA.
- Collect additional site characterization data to support MNA.
- Refine the conceptual model and complete premodeling calculations.
- Simulate MNA using analytical or numerical solute fate and transport modeling that allows incorporation of a biodegradation term, as necessary.

- Identify current and future receptors and conduct an exposure pathway analysis. 1
- Prepare a long-term monitoring plan. 2
- Determine whether source treatment will be remediation, removal, containment, or a 3
monitoring plan. 4
- Present findings to regulatory agencies. 5

Figures 1.1 and 1.2 illustrate the steps for evaluating the typical MNA process. For CNC, the MNA evaluation process developed concurrently with the CMS. It should be noted that once it appears that MNA alone will not meet regulatory criteria, other remedial options are selected to meet regulatory requirements and the MNA evaluation process is temporarily discontinued. The option(s) that are selected are evaluated and an assessment is then made of the potential for MNA in conjunction with the remedial system installed.

1.3 Site Characterization

The characterization process, as stated in the Technical Protocol, for the proposed MNA sites at CNC included developing a conceptual site model, understanding the contaminant flow in the subsurface, and determining the extent and potential impacts on receptors. A conceptual site model explains what is known or suspected about contamination sources, release mechanisms, and the fate and transport of those contaminants. Site characterization should also include collecting data to define the nature and distribution of contamination sources.

Figure 1.1

Natural Attenuation of Chlorinated Solvents Flow Chart

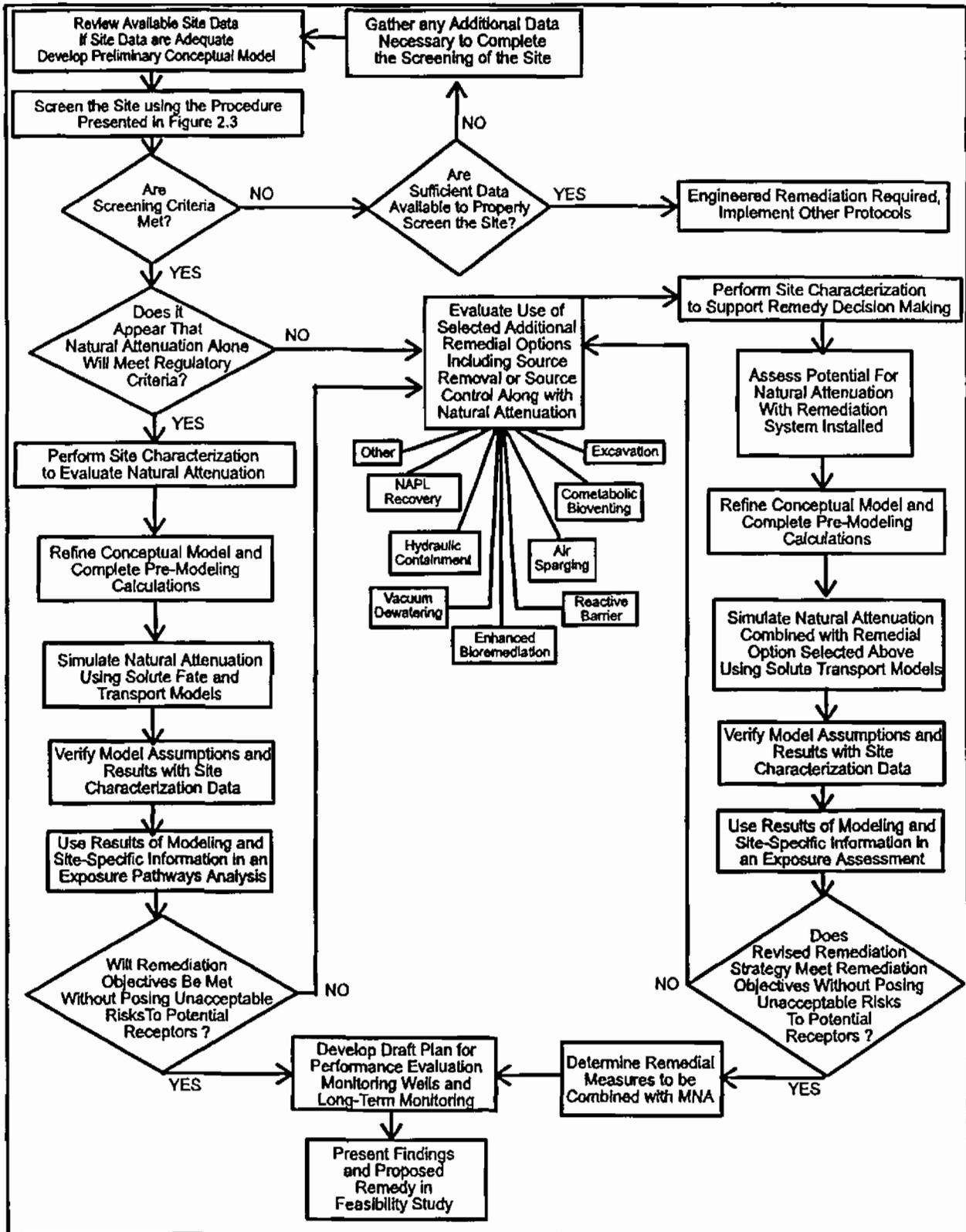
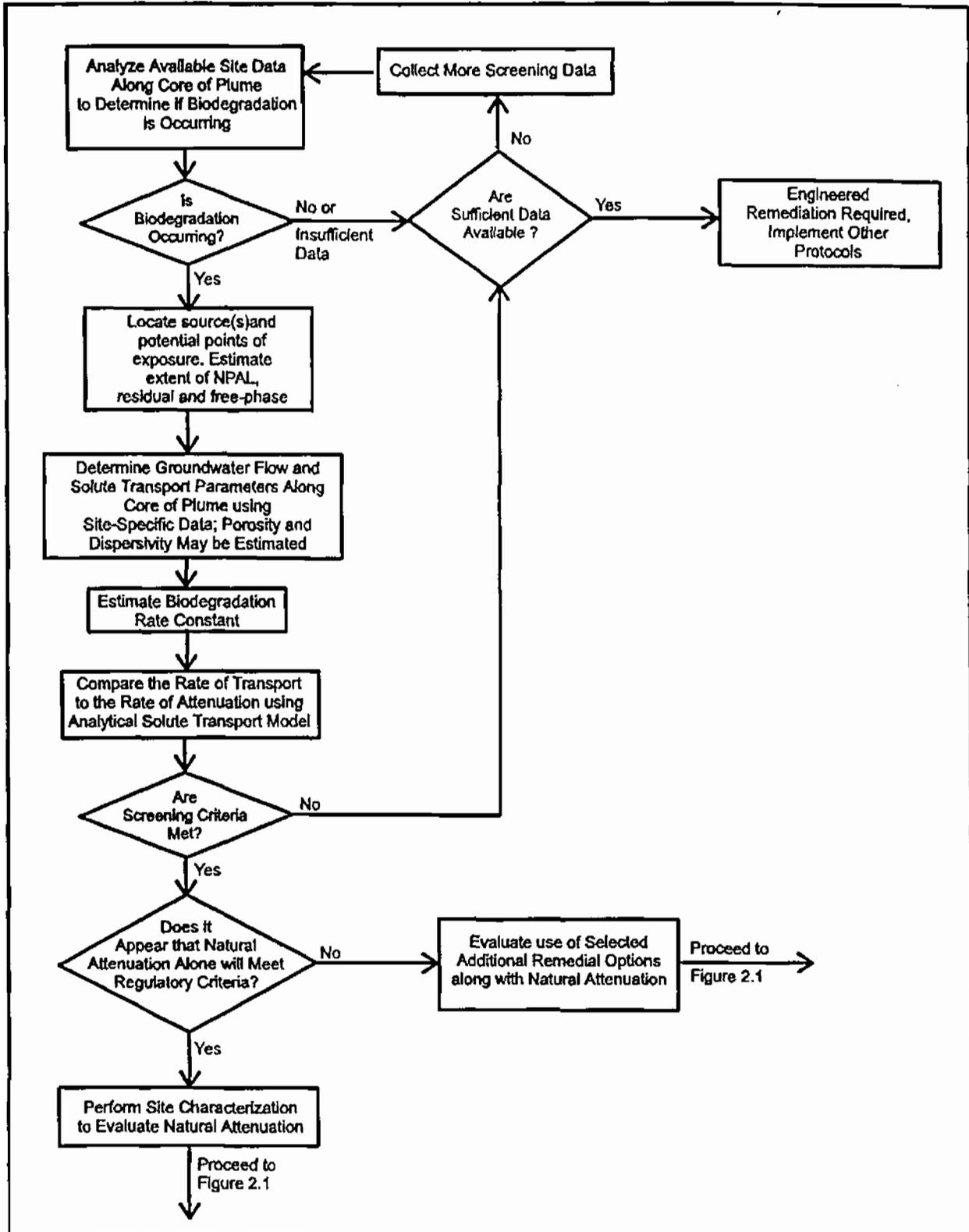


Figure 1.2

Initial Screening Process Flow Chart



Before the site characterization evaluation begins, the initial screening process should be completed to determine whether MNA is likely to be a viable remedial alternative. The following steps summarize the screening process:

- Determine whether biodegradation is occurring.
- Determine groundwater flow and solute transport parameters.
- Locate sources and receptor exposure points.
- Estimate the biodegradation rate constant.
- Compare the rate of transport to the rate of attenuation.
- Determine whether the screening criteria are met.

Quantifying groundwater flow and solute transport parameters is an important step after showing that biodegradation is occurring. Estimating the concentration, the rate of travel, and the direction of the plume are important processes affecting the fate and transport of chemical compounds. For modeling purposes, it is necessary to know the distance between the source of contamination, the leading edge of the plume, and any downgradient receptor exposure points.

Calculations of site specific biodegradation rates are the most important model input parameters. Whenever possible it is best to use field data to calculate the rates, but if it is demonstrated that biodegradation is occurring, literature values can be used instead. When refining the conceptual model, additional site information should be collected to determine biodegradation rates.

Comparison of transport and attenuation rates provides insight on the capability of attaining site-specific remediation objectives in a reasonable time period compared with other alternatives under present geochemical/analytical conditions. If modeling shows that MNA is a viable option and the screening criteria are met, then the MNA evaluation can proceed.

It should be noted that when reviewing site characterization data for MNA, a more detailed approach may be required to fully assess its appropriateness as a remedial option. In assessing the effects of sorption, dilution, and dispersion, a thorough knowledge of the site hydrology, recharge and discharge areas, and contaminant chemical properties is required. For biodegradation, characterization includes evaluation of electron acceptors/donors present in the groundwater, concentrations of by-products, and specific analyses to identify microbial populations.

Data collected for the site characterization can be used to show the fate and transport of contaminants in groundwater. Fate and transport models are used to predict the future extent and concentration of a plume. The MNA modeling effort has five objectives:

- To evaluate whether MNA is likely to attain site-specific remediation objectives in a time period that is reasonable compared to other alternatives.
- To predict the future extent and contamination of a dissolved contaminant plume by simulating the combined effects of contaminant loading, advection, dispersion, sorption, and biodegradation.
- To predict the most useful locations for groundwater monitoring.

- To assess the potential for downgradient receptors to be exposed to contaminant concentrations that exceed regulatory or risk-based levels intended to be protective of human health and the environment.
- To provide technical support for remedial options using MNA during screening and detailed evaluation of remedial alternatives in the RCRA Corrective Measures Study.

Once the fate and transport modeling efforts have been completed, predictions can be made as to whether MNA is a viable remedial option for a particular site.

1.4 Monitoring

Long-term groundwater monitoring is an essential element in a remedial option involving MNA. Due to the larger remediation time frames and the potential for contaminant migration, a greater emphasis is placed on continuing monitoring to ensure contamination remains below required cleanup levels. The monitoring program should specify the location, frequency, and type of samples and measurements needed to evaluate the remedial option performance. *The Monitoring Program OSWER Directive on Monitoring Natural Attenuation (9200.4-17)* describes the USEPA expectations for performance monitoring and emphasizes programs are designed to accomplish the following:

- Demonstrate that natural attenuation is occurring as expected.
- Identify any potentially toxic transformation products resulting from biodegradation.
- Determine if a plume is expanding (either downgradient, laterally or vertically).
- Ensure no impact to downgradient receptors.

- Detect new releases of contaminants to the environment that could impact the effectiveness of the natural attenuation remedy. 1
2
3
- Demonstrate changes in environmental conditions (e.g., hydrogeologic, geochemical, microbiological) that may reduce the efficacy of any natural attenuation processes. 4
5
6
- Verify attainment of cleanup objectives. 7
8

1.5 Scope of MNA at CNC 9

Once it became clear that MNA would be considered as a possible remedial option at several sites during the CMS at CNC, a preliminary list of wells was compiled whose analytical data showed the potential for MNA. The list originally included sites from Zones E, F, G, H & I. Wells at the sites were assigned a classification depending on the type and level of contamination found, primarily benzene, toluene, ethylbenzene, xylene (BTEX) or chlorinated compounds. A classification of "A" was assigned if VOCs were not detected in any of the quarterly sampling events, or if detections were isolated and the concentration levels did not pose a threat to human health and the environment. It was determined that MNA would unlikely play a role in deciding the future course of action for these wells. Classifications "B", "C", and "D" were used when numbers, frequencies and concentrations of VOCs increased in particular wells. 10
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A well classification of "B" indicated low contaminant levels and a reasonable assumption that little or no additional monitoring would be required. A well classification of "C" meant contaminant levels were at or below maximum contaminant levels (MCL), but insufficient data existed to determine if MNA was occurring. MNA sampling would be required to further evaluate the sites involved. A "D" classification meant that contaminant levels exceeded MCL levels or appropriate risk thresholds and long-term monitoring would be required. As a result of the classification procedure, the following sites were to be included in the MNA evaluation: solid waste 20
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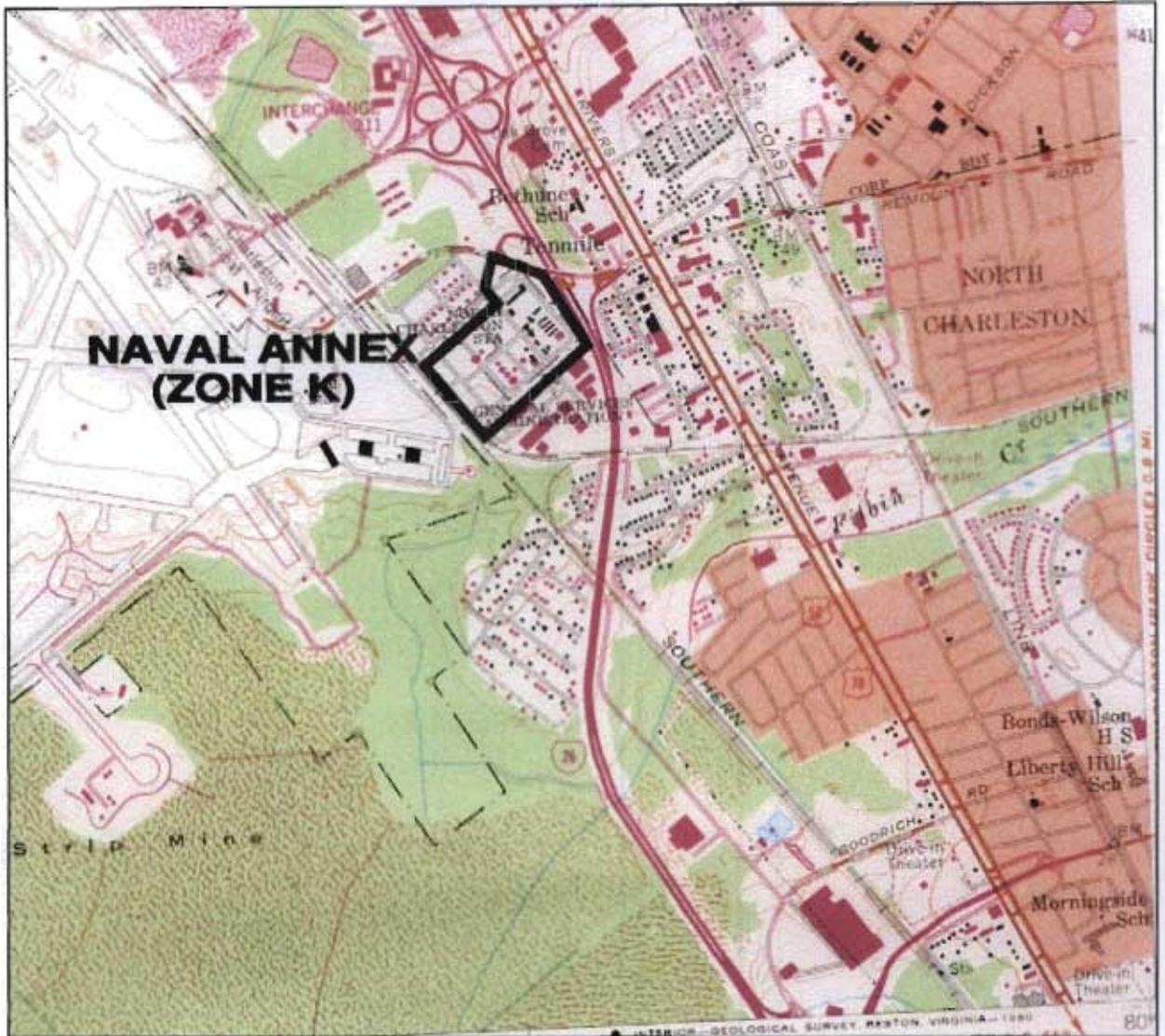
management units(SWMUs) 25, 65,70, and 172, area of concerns (AOCs) 549, 563, and 570 in Zone E and SWMUs 9 and 17 in Zone H.

It became the task of the Charleston project team to evaluate the significance of VOCs detected in the wells at the selected sites and the appropriateness of MNA. As part of that evaluation, the initial well selection list was expanded to include wells in SWMU 39 in Zone A, SWMU 166 in Zone K, and AOC 607 in Zone F. Figures 1.3 and 1.4 show the SWMUs/AOCs that were included in the MNA evaluation.

For the sites evaluated for MNA at CNC, two rounds of analytical and geochemical data were collected. To determine whether anaerobic biodegradation (reductive dechlorination) is occurring, the data were analyzed, tabulated and inputted into the USEPA scoring system. Results of the scores are provided in the site-specific evaluations. The scoring system was used as a simple screening tool to provide insight into the need for further MNA data acquisition.

1.5.1 Preliminary Screening for Anaerobic Biodegradation Processes

The preliminary screening for potential anaerobic biodegradation within the surficial aquifer at SWMU 166 used the screening process presented in the Technical Protocol. This process involves the collection of field parameters and analysis of groundwater for chemicals that are involved in the degradation of chlorinated organic compounds, primarily by the process of reductive dechlorination at each monitoring point. Each field parameter and analyte was ranked according to its value/concentration. Values or concentrations that are conducive to reductive dechlorination were ranked higher than those that are not. After each value or concentration was ranked, the values were totaled up at each monitoring point providing a qualitative measure of the local aquifer system's ability to biodegrade chlorinated organic compounds. The points awarded for each analysis are shown in Table 1.1. The interpretation of total points is summarized in Table 1.2.



ZONE K - SWMU 166
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FIGURE 1.4
 TOPOGRAPHY OF
 CHARLESTON NAVAL ANNEX
 AND
 SURROUNDING AREAS

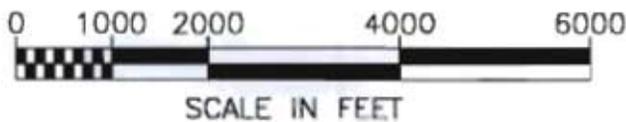


Table 1.1
Analytical Parameters and Weighting for Preliminary Screening
for Anaerobic Biodegradation Processes

Analysis	Concentration in Most Contaminated Zone	Value
Oxygen	<0.5 mg/L	3
	>5.0 mg/L	-3
Nitrate	<1.0 mg/L	2
Iron(II)	>1.0 mg/L	3
Sulfate	<20 mg/L	2
Sulfide	> 1.0 mg/L	3
Methane	< 0.5 mg/L	0
	> 0.5 mg/L	3
Oxidation Reduction Potential	< 50 millivolts (mv)	1
	< -100 mv	2
pH	5.0 < pH < 9.0	0
	5.0 > pH > 9.0	-2
Total Organic Carbon	> 20.0 mg/L	2
Temperature	> 20°C	1
Carbon Dioxide	> 2x background	1
Alkalinity	> 2x background	1
Chloride	> 2x background	2
Hydrogen	> 1.0 nanomole (nM)	3
	< 1.0 nM	0
BTEX	> 0.1 mg/L	2
PCE	Released material	0
TCE	Released material	0
	Daughter product	2
DCE	Released material	0
	Daughter product	2
VC	Released material	0
	Daughter product	2
1,1,1-Trichloethane (TCA)	Released material	0
Dichloroethane (DCA)	Daughter product of 1,1,1-TCA under reducing conditions.	2

**Table 1.1
 Analytical Parameters and Weighting for Preliminary Screening
 for Anaerobic Biodegradation Processes**

Analysis	Concentration in Most Contaminated Zone	Value
Carbon Tetrachloride	Released material	0
Chloroethane	Daughter product of DCA under reducing conditions.	2
Ethane/Ethene	>0.01 mg/L	2
	>0.1 mg/L	3
Chloroform	Released material	0
	Daughter product of carbon tetrachloride	2
Dichloromethane	Released material	0
	Daughter product of chloroform	2

**Table 1.2
 Interpretation of Total Points from Site Ranking**

Score	Interpretation
0	No evidence for biodegradation of chlorinated organics.
1 to 5	Inadequate evidence for biodegradation of chlorinated organics.
6 to 14	Limited evidence for biodegradation of chlorinated organics.
15 to 20	Adequate evidence for biodegradation of chlorinated organics.
>20	Strong evidence for biodegradation of chlorinated organics.

1.6 Goal of Interim Report

It is the goal of this interim report to provide information collected to date on the MNA evaluation process at SWMUs 9, 17, 39, 166 and AOC 607. Due to the fact that the Draft Zone E RFI has not been finalized and a CMS process has not yet been initiated, further analysis of the MNA data for the selected Zone E sites will be completed at a later date. As other CMS activities (i.e.

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treatability studies) are pending at SWMU 166, this site was chosen as the first to be submitted to the Charleston project team. The remaining sites will be submitted at a later date(s). Included in these reports will be tabulated and graphical presentation of geochemical and analytical data gathered during the RFI sampling events and the two MNA sampling events as well pertinent geologic and hydrogeologic data. Each site report will explain whether MNA is occurring and describe treatability studies for other remedial alternatives that will be evaluated concurrently with MNA.

1.6.1 SWMU 166 Treatability Study

An anaerobic-aerobic sequential groundwater treatment treatability study is designed to enhance in-situ bioremediation of the chlorinated solvent contamination at SWMU 166. This technology has been demonstrated as an Emerging Technology under the Superfund Innovative Technology Evaluation (SITE) Program by the USEPA. In theory, highly chlorinated compounds such as PCE and TCE readily biodegrade when aquifer redox conditions are anaerobic or reduced (absence of dissolved oxygen). The anaerobic zone is created by adding a carbon source (sucrose) and nutrients to groundwater pumped from downgradient extraction wells and reinjected into upgradient wells. Once the anaerobic zone is established, it is hoped that microorganisms will turn to sources other than oxygen, such as PCE and TCE, in order to complete respiration.

An aerobic zone will be created in the vicinity of the downgradient wells by injecting air into the aquifer via sparging wells connected to an aboveground blower. Under aerobic conditions, daughter products 1,2-DCE and VC are used by microbes as the primary growth substrates (electron donors). The aerobic degradation of VC results in the formation of benign end products such as ethene and ethane.

1.6.2 AOC 607 Treatability Study

A soil vapor extraction (SVE) system coupled with a dewatering system has been selected for a treatability study at AOC 607. The dewatering system will generate large quantities of water that will require treatment and disposal. This contaminated groundwater is treated with granulated activated carbon to adsorb dissolved VOCs and then pumped directly into the sanitary sewer system under permit from the Publicly Owned Treatment Works (POTW) in North Charleston. Once dewatering has reduced the degree of saturation so that the air movement through the vadose zone is less restrictive, the SVE system will apply negative pressure to the area of concern by passing a continuous flow of air through the porous media of the vadose zone. As a result of this process, dissolved chlorinated solvents are volatilized into the vapor phase.

At the time of this report, no other treatability studies have been approved for the remaining sites.

1.7 Final Report

The MNA final reports will assess data from the influence of the treatability studies at MNA sites and how it affects the geochemistry of the groundwater. The final report will quantify the physical, chemical and biological aspects involved in the MNA process largely through fate and transport modeling. The outcome of such a modeling effort would enable the calculation of biodegradation and attenuation rates and mass balance calculations. This option will be pursued at sites where MNA is being proposed as a remedial option.

2.0 FIELD INVESTIGATION

The following section lists the field investigation objectives for the MNA report and describes the technical sampling methods, procedures, and protocols implemented during first and second round data collection. Fieldwork was conducted in accordance with the *Final Comprehensive Sampling and Analysis Plan (CSAP)* (E/A&H, August 1994) and the U.S. Environmental Protection Agency USEPA Region IV Environmental Services Division, *Standard Operating Procedures and Quality Assurance Manual* (USEPA, February 1991) (ESDSOPQAM). Sampling and investigatory methods used in the MNA investigation are summarized in this section.

2.1 Investigation Objectives

The sampling strategy used at CNC for the MNA process as detailed in the Technical Protocol was designed to achieve two goals during site characterization. The first goal is to collect enough data to determine if natural attenuation is occurring at rates sufficient to attain CMS objectives in a feasible time period compared with other alternatives. The second goal is to develop a fate and transport model with sufficient site-specific data to predict of the future extent and concentrations of a contaminant plume. In order to reach these goals, adequate site characterization in support of MNA requires that the following site-specific parameters be determined:

- Location, nature, and extent of contaminant source area(s).
- Chemical properties (e.g., composition, solubility, volatility) of contaminant source materials.
- The possibility of a continuing source from sewers, leaking tanks, pipelines, or other site activities.
- Extent and types of soil and groundwater contamination.

•	Aquifer geochemical parameters.	1
		2
•	Regional hydrogeology.	3
		4
•	Local and site-specific hydrogeology, including:	5
	– Local drinking water aquifers	6
	– Location of industrial and domestic wells	7
	– Patterns of aquifer use	8
	– Lithology	9
	– Site stratigraphy	10
	– Potential pathways for solvent migration	11
	– Grain-size distribution	12
	– Aquifer hydraulic conductivity	13
	– Groundwater hydraulic information	14
	– Flow paths	15
	– Locations and types of surface water bodies	16
	– Areas of local groundwater recharge and discharge	17
		18
•	Identification of current and future potential exposure pathways, receptors, and exposure points.	19
		20
		21
2.2	Sample Identification	22
	All environmental samples collected during this investigation were identified using a 10-character alphanumeric system describing samples by site, sample matrix, location, and other pertinent information. This system is detailed in Section 11.4 of the (CSAP).	23
		24
		25
		26
		27

2.3 Monitoring Well Installation and Development

Section 5 of the CSAP details the methods used to install and develop monitoring wells. All monitoring wells were installed in accordance with South Carolina Well Standards and Regulations (R.61-71) after acquiring well permits from South Carolina Department of Health and Environmental Control (SCDHEC). The site-specific methods applied in the MNA investigation are described below.

2.3.1 Shallow Monitoring Well Installation

Eight shallow monitoring wells (four at SWMU 9 and four at SWMU 39) were installed after round one of the MNA investigation to facilitate groundwater sampling in the shallow water-bearing portion of the surficial aquifer. Section 3.2.3.1 of the Zone A Final RFI Report details the shallow monitoring well installation.

2.3.2 Intermediate Monitoring Well Installation

Four intermediate monitoring wells were installed at SWMU 39 after the first round of the MNA investigation to facilitate groundwater sampling between the shallow and deep monitoring wells. Section 3.2.3.2 of the Zone A Final RFI Report details the intermediate monitoring well installation.

2.3.3 Deep Monitoring Well Installation

Four deep monitoring wells were installed at SWMU 39 after the first round of the MNA investigation to facilitate groundwater sampling at the base of the shallow aquifer. Section 3.2.3.3 of the Zone A Final RFI Report details the deep monitoring well installation.

2.3.4 Monitoring Well Development

Section 3.2.3.5 of the Zone A RFI Report details MNA monitoring well development.

2.3.5 Monitoring Well Groundwater Sampling

Section 6 of the CSAP details the groundwater sampling process. The site-specific methods applied in the MNA investigation are described below. Groundwater samples were collected from new and existing monitoring wells based on review of existing site characteristic data.

2.4 Monitoring Well Groundwater Sample Collection for Onsite and Offsite Laboratory Parameter Analysis

The MNA investigation involved using both onsite and offsite laboratories which required separate sampling techniques for the analytical parameters. It was determined that the onsite laboratory contractor, Target Environmental Services, would be designated as the first crew to purge and sample the designated wells for the onsite parameters and dissolved gases, and EnSafe personnel would then sample the purged wells within 24 hours for the offsite parameters. The offsite parameters were sampled according to Section 3.2.4.2 of the Zone A RFI Report. The onsite sampling procedures for hydrogen, fixed gases, and anions and cations entailed:

- Recording well number, date, time, diameter, screen length, and total depth.
- Recording the depth to water using a resistive-type water level indicator.
- Inserting a new piece of Teflon tubing into the well until the inlet was directly at the center of the screened interval.
- Connecting the Teflon sampling tube to the silicon tube on the peristaltic pump.
- Cutting a one to two foot section of the Teflon tubing to connect the outlet of the peristaltic to the inlet of the flow-through cell and metering system. The flow-through cell and metering system was calibrated at the beginning of each day.

- Placing the outlet tube from the flow cell into a drum to catch the water. 1
2
- Turning on the pump and adjusting the flow rate to 300-600 ml/min. Flow rate was 3
determined by measuring the time required to collect a known volume of water. 4
5
- Using the water level indicator to monitor the water level within the well. Care was 6
taken to insure the groundwater level did not fall below the top of the well screen. 7
8
- Recording groundwater measurements once the flow rate had been established, including 9
temperature, pH, oxidation-reduction potential, conductivity, and ground water level for 10
every one to three liters of groundwater purged. Groundwater was be considered stable 11
and ready for sampling when three consecutive measurements of the above listed 12
parameters were within 10% of each other. 13
14
- Preparing appropriate sample containers and labels while purging was being conducted. 15
Preparing three syringes for dissolved gas sampling by purging each syringe three to 16
four times with laboratory grade helium. One syringe was used to inject the initial 17
bubble and the other two were used to collect the dissolved gas samples. 18
19
- Turning off the pump once groundwater had stabilized. The flow through cell and 20
metering system were then detached from the pump outlet tube. 21
- Connecting the outlet tube of the pump to the inlet of the dissolved gas sampling bulb. 22
The pump was turned on and the bulb was allowed to fill with water, making sure that 23
all air was removed from the bulb. 24
25
- Positioning the sampling bulb at a 45 degree angle, with the inlet side higher than the 26
outlet. 27

- Injecting 30 ml of laboratory grade helium into the bulb. 1
- 2
- Allowing the groundwater to flow through the sampling bulb for 30 minutes prior to sampling. 3
- 4
- 5
- Collecting the first sample after the appropriate amount of bubbling time, using a gas tight syringe with a stopcock. 6
- 7
- 8
- Purging the helium from the syringe into the atmosphere. 9
- 10
- Piercing the septum with the needle and extracting 1-2 ml of gas from the bubble. 11
- 12
- Removing the syringe and expelling the gas into the atmosphere. 13
- 14
- Reinserting the needle through the septum, and collecting a sample from the bubble. 15
- 16
- Labeling the syringe with the sample ID and time of collection 17
- 18
- Collecting a duplicate sample after five minutes using a second gas tight syringe with a stopcock, using the above procedure. 19
- 20
- Turning off the pump and detaching the sample bulb, then allowing the water contained inside to drain into the drum. 21
- 22
- 23
- Turning the pump on and filling the remaining sample containers (anions and cations) through the pump outlet; recording the sample ID and the time of collection. 24
- 25
- 26

- Transferring the samples to the mobile laboratory for analysis as quickly as possible to maintain sample integrity, and analyzing them quickly to provide accurate results.

2.5 Monitoring Well Groundwater Sample Preparation, Packaging, and Shipment

Section 3.2.4.3 of the Zone A RFI report details preparation, packaging, and shipment of groundwater samples collected at CNC and shipped to an offsite laboratory. This procedure was followed during the MNA investigation. The offsite samples (VOCs, sulfate, nitrate, chloride, and total organic carbon) were shipped priority overnight via FedEx to the Southwest Laboratory of Oklahoma in Tulsa. The heterotrophic plate count (HPC) samples were analyzed by General Engineering Laboratories in Charleston, SC and the BTEX and chlorobenzene degraders were analyzed by Retec in Seattle, WA. The HPC and degrader analyses were conducted only for the second round.

2.5.1 Monitoring Well Groundwater Sample Analysis

A total of 121 wells for the first round and 214 wells for the second round were sampled at various SWMUs and AOCs throughout the base for MNA. The offsite groundwater samples were analyzed per USEPA Method SW-846 at Data Quality Objectives (DQO) Level II as follows:

- VOCs USEPA Method 8260
- Sulfate USEPA Method 375.1
- Nitrate USEPA Method 352.1
- Chloride USEPA Method 325.1
- Total Organic Carbon USEPA Method 415.1
- Heterotrophic plate count
- BTEX and chlorobenzene degraders

The onsite groundwater samples were analyzed as follows:	1
	2
• Dissolved Oxygen	3
• Iron II and III	4
• Methane	5
• Ethane	6
• Ethene	7
• Alkalinity	8
• Oxidation-reduction potential	9
• pH	10
• Temperature	11
• Conductivity	12
• Hydrogen	13
	14
• Carbon dioxide	15
	16
• Manganese	17
	18
2.6 Vertical and Horizontal Surveying	19
Section 3.2.8 of the Zone A RFI report details vertical and horizontal surveying procedures for the MNA investigation.	20
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2.7 Decontamination Procedures	23
Section 3.2.10 of the Zone A RFI report details the decontamination procedures used during the MNA investigation.	24
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2.8 First Round Investigation

The first round of MNA sampling occurred between February and March 1998. Ten sites at CNC were designated as potential candidates for MNA evaluation due to histories of chlorinated VOC and/or petroleum hydrocarbon contamination. Five of these sites were SWMU 9 (Zone H), SWMU 17 (Zone H), SWMU 39 (Zone A), SWMU 166 (Zone F), and AOC 607 (Zone F). The remaining five sites were located in Zone E and were grouped into areas of VOC contamination due to the close proximity of SWMUs and AOCs within the zone. The five major sites in Zone E were SWMU 65, AOC 551 area, SWMU 172 and AOC 576 area, AOCs 569 and 570 area, and SWMUs 25 and 70 area.

The first round MNA sampling event and the data evaluation of existing soil and groundwater site history helped form a conceptual model for each site along with an assessment of MNA potential. On June 9, 1998, a report was provided to the CNC project team that included data plots of groundwater VOC results for each sampling event, preliminary MNA EPA ranking screening from the data collected, and groundwater flow maps for shallow, intermediate, and deep wells for each site where appropriate. Review of the first round data identified several items that needed to be addressed before the second round of MNA sampling could take place:

- The second round of sampling was to take place six months after the first round.
- Well locations were added or removed at several sites to better define VOC contamination.
- Methyl terbutyl ether (MTBE) was to be added to the VOC list to enhance BTEX plumes.

- Sulfide and iron III were to be added to the parameter list to better define oxidation reduction conditions in the aquifer. 1
2
3
- Well locations with only BTEX contamination would not be ranked for potential MNA screening. 4
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6
- Synoptic groundwater flow water level measurements were to be taken per site to allow for construction of groundwater potentiometric maps. 7
8
9
- Calculation of the aquifer capacity to degrade BTEX would be done for those sites with BTEX contamination. 10
11
12
- HPC and specific BTEX and chlorobenzene degrader analyses were to be added to ensure microbial populations are present. 13
14
15
- Total nitrogen in two to three locations were to be added within a plume to aid in microbial activity. 16
17
18

2.9 Second Round Investigation 19

The second round sampling event took place the last week of September and the first two weeks of October 1998 at all 10 sites. Due to the fact that the sampling effort had increased from the first round, additional sampling crews were utilized in order to achieve the necessary goals. All suggested items were addressed, with the only deviation being that total nitrogen results were provided at all well locations. 20
21
22
23
24

3.0 SWMU 166 DATA INTERPRETATION AND SITE EVALUATION

3.1 Site History

SWMU 166, located at the Naval Annex, includes areas west of Avenue B and south of Fifth Street to just east of Interstate 26. Prior to 1941, the Naval Annex area consisted of open spaces and forested areas. During World War II, Naval Annex was owned by the Air Force and was the location of a weather forecasting facility. In 1954 the Naval Annex was turned over to the 792nd Squadron of the Tactical Air Command. From 1954 to 1981 the facility was used as an operating radar system. In 1981, the radar station was dismantled and the Naval Annex was acquired by Naval Station Charleston. Mobile Mine Assembly Group 11 assumed operations at that time.

The Naval Annex is currently used by the U.S. Marine Corps as a reserve training center. The training center is comprised of administrative and classroom type buildings and a heavy vehicle storage and maintenance/small repair facility. SWMU 166 is the sanitary sewer system serving the Naval Annex and the former septic system, excluding the housing area. For the purposes of this report, areas previously investigated around SWMU 166 and 185 will be considered the same SWMU.

The area northwest of Building 2522 had been identified in the RFI as a proposed auto service rack (ASR). More recent research has concluded that this locale was the site of a former oil storage area (OSA). Throughout this report, this area will be referred to as the OSA.

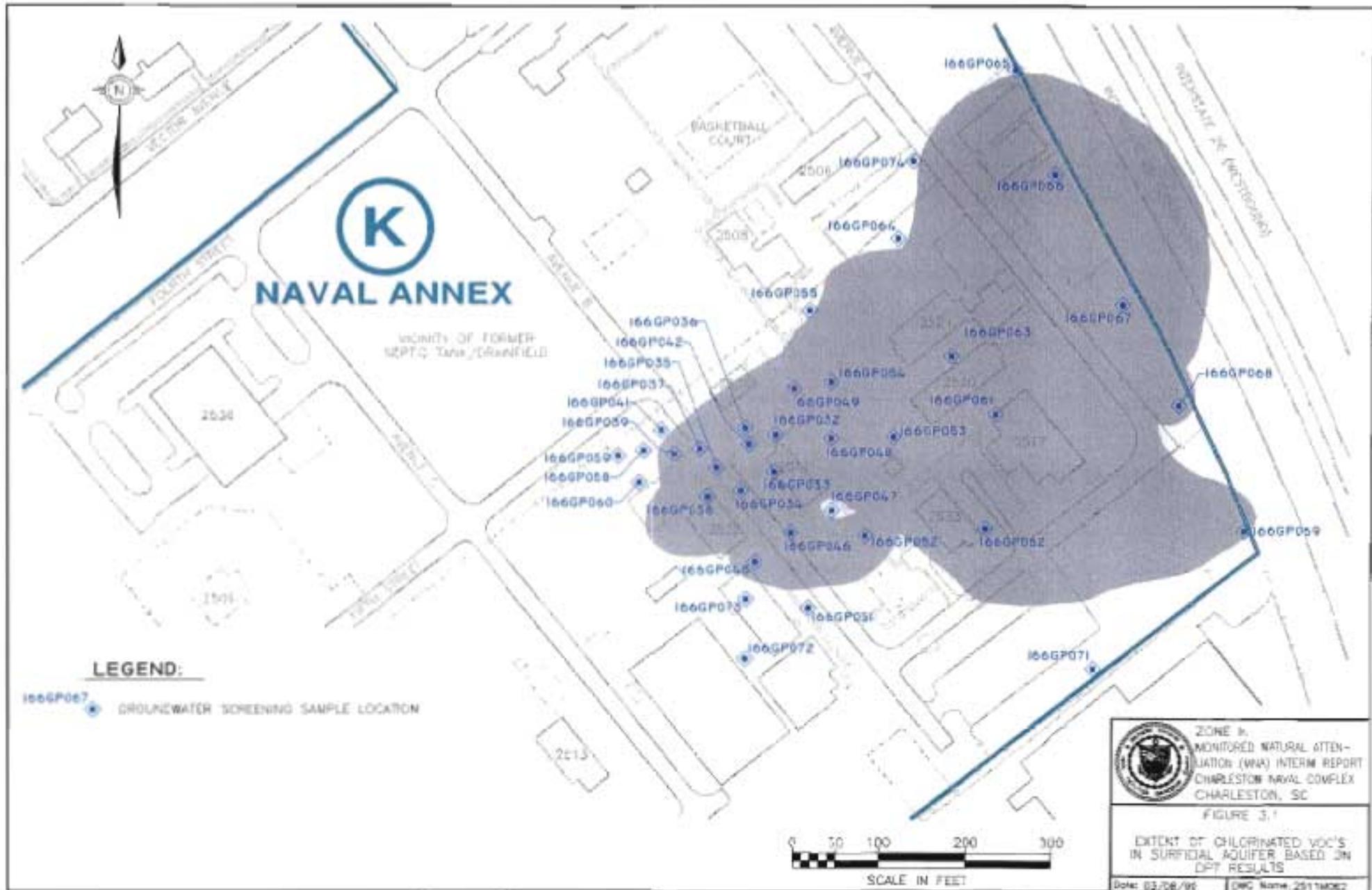
Previously, site investigations included sampling of soil and groundwater using several methods: conventional soil borings, Direct Push Technology (DPT) and groundwater monitoring. The DPT sampling was conducted in a multi-phased approach. DPT samples were collected along the sanitary sewer and septic tank area in November 1996. During this phase of DPT sampling, one sample was collected that contained TCE above the MCL of 5 $\mu\text{g}/\text{L}$. As a result of this detection, an additional five phased DPT investigation was implemented. Beginning in February 1997 and

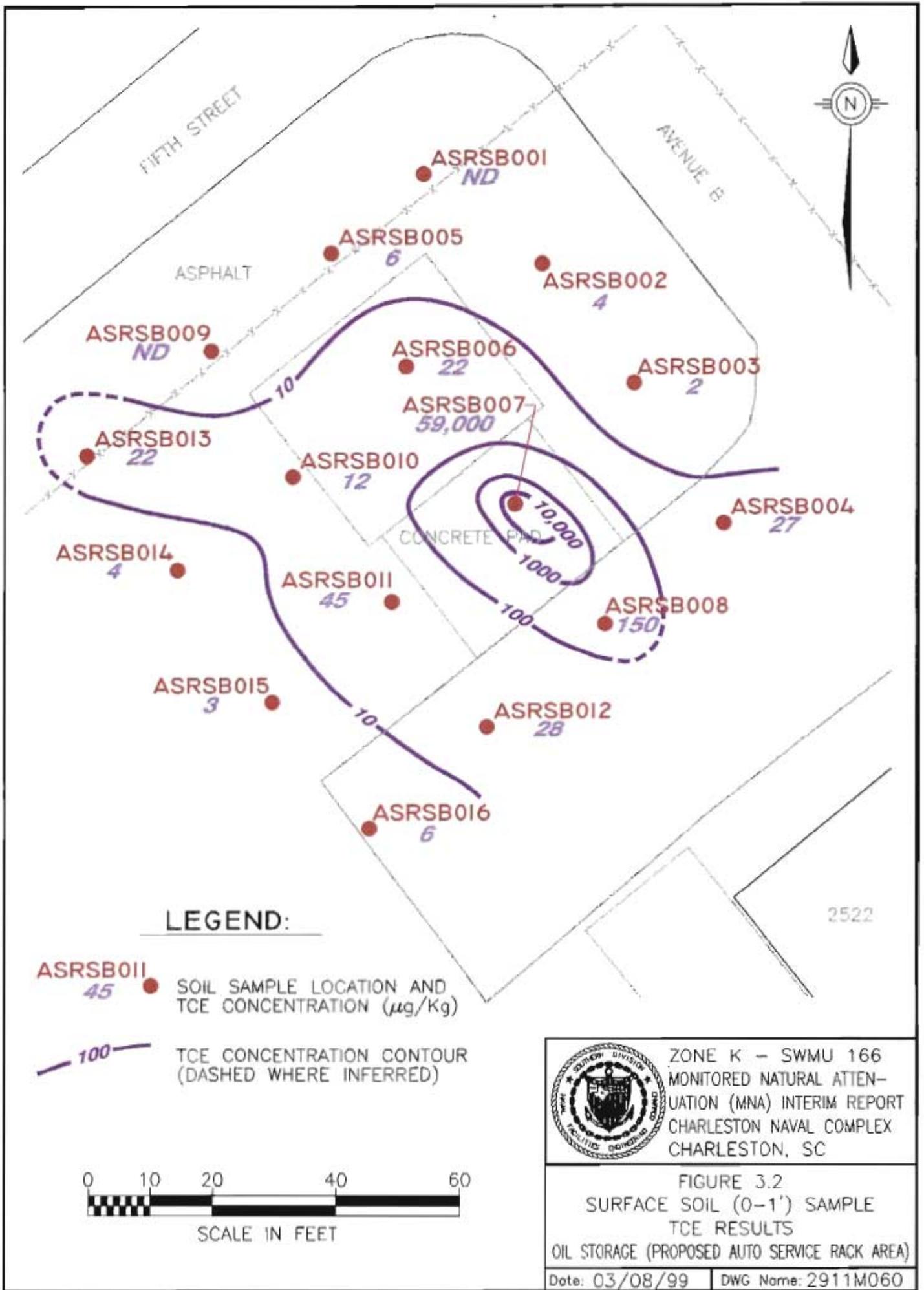
lasting until August 1997, 90 ground water DPT samples were collected for VOCs. Figure 3.1 illustrates the total contaminant groundwater DPT plume. The Zone K Draft RFI Report details the DPT sampling events and the results from laboratory analyses.

Thirty-two soil boring samples were collected and analyzed for VOCs in April 1997 at the OSA, which had been identified as a suspected source area during the DPT investigation. Soil boring sample ASRSB007 was identified in the Zone K RFI Report as having the highest TCE concentrations detected in the upper and lower intervals. Figures 3.2 and 3.3 illustrate surface and subsurface soil TCE concentration contours. The Zone K Draft RFI Report details the soil boring sampling event and the results from laboratory analyses.

Based on the TCE and DCE results during the groundwater DPT sampling events, shallow and deep monitoring wells were installed to confirm and monitor plume migration. The installations were performed in phases in an effort to facilitate data evaluation as follows:

- Phase I – May 1997 – Shallow/deep well pairs 16602/02D through 16608/08D and single deep wells 16609D through 16612D;
- Phase II – December 1997 – shallow/deep well pairs 166013/13D through 166021/21D;
- Phase III – July 1998 – deep wells 16622D and 16623D;
- Phase IV – October 1998 – shallow/deep well pairs 166024/24D through 166026/26D as part of CMS activities.





FIFTH STREET

AVENUE B



ASRSB001
ND

ASRSB005
6

ASRSB002
4

ASPHALT

ASRSB009
ND

ASRSB006
22

ASRSB003
2

ASRSB007
59,000

ASRSB013
22

ASRSB010
12

ASRSB004
27

ASRSB014
4

ASRSB011
45

CONCRETE PAD

ASRSB008
150

ASRSB015
3

ASRSB012
28

ASRSB016
6

2522

ASRSB011
45

100



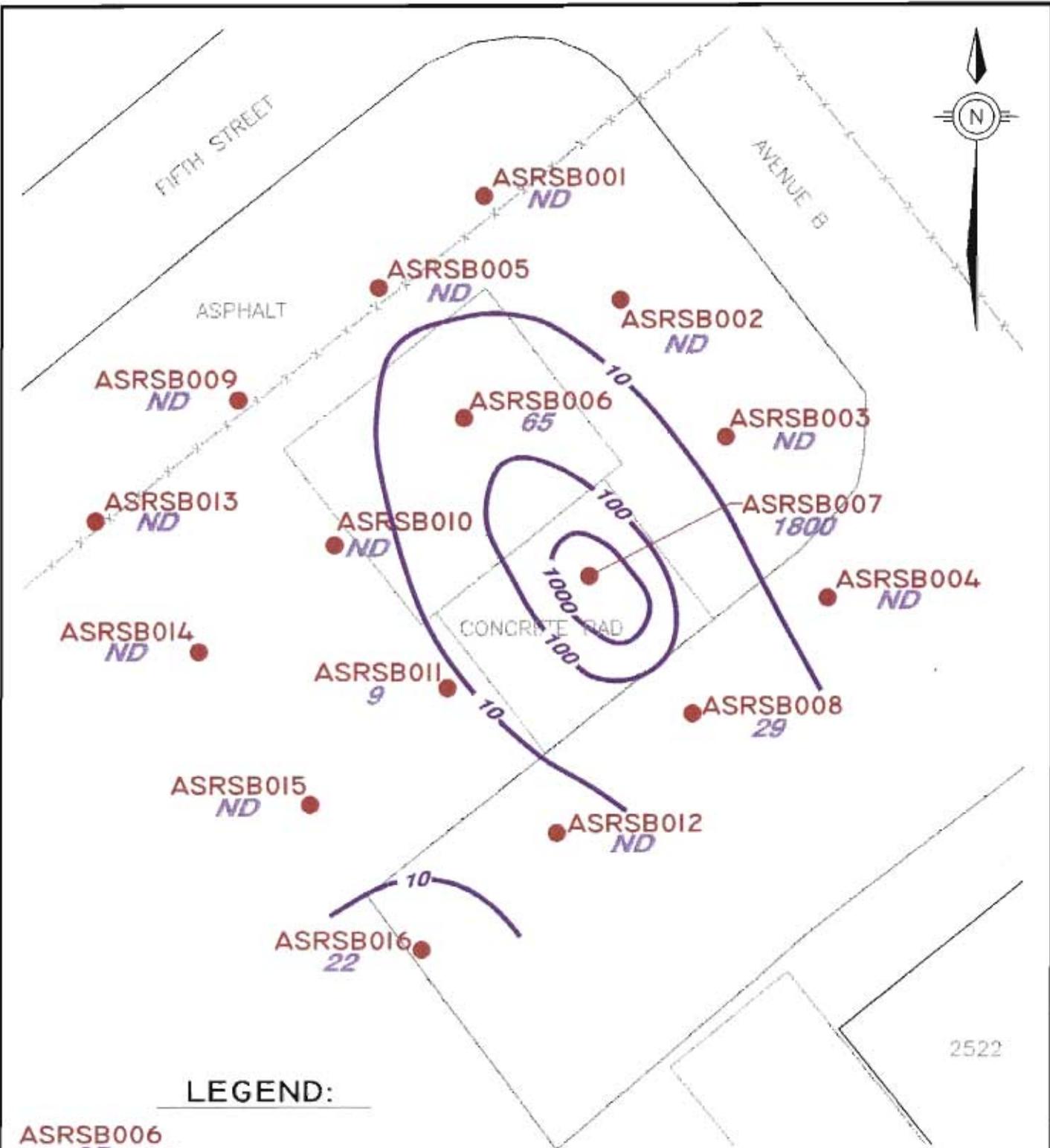
SCALE IN FEET



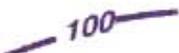
ZONE K - SWMU 166
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CHARLESTON, SC

FIGURE 3.2
SURFACE SOIL (0-1') SAMPLE
TCE RESULTS
OIL STORAGE (PROPOSED AUTO SERVICE RACK AREA)

Date: 03/08/99 | DWG Name: 2911M060



LEGEND:

- 
ASRSB006
65 SOIL SAMPLE LOCATION AND TCE CONCENTRATION ($\mu\text{g}/\text{Kg}$)
- 
100 TCE CONCENTRATION CONTOUR



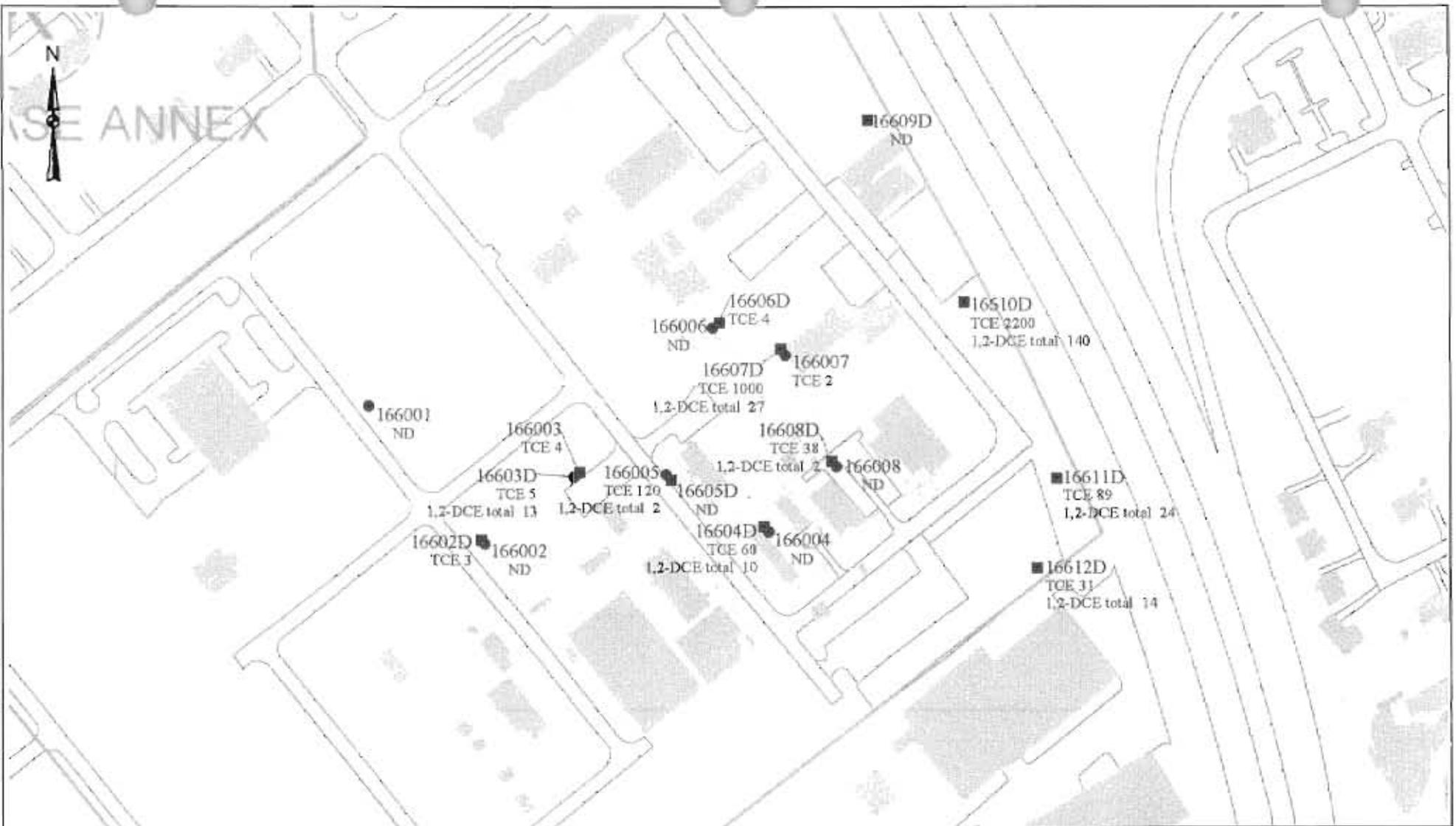
ZONE K - SWMU 166
 MONITORED NATURAL ATTENUATION (MNA) INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.3
 SUBSURFACE SOIL (3'-5') SAMPLE
 TCE RESULTS
 OIL STORAGE (PROPOSED AUTO SERVICE RACK AREA)

As part of the RFI, a monitoring well sampling program was implemented at SWMU 166. Figure 3.4 illustrates the monitoring well locations for SWMU 166. Figures 3.5 through 3.13 illustrate VOCs detections in both the shallow and deep monitoring wells.

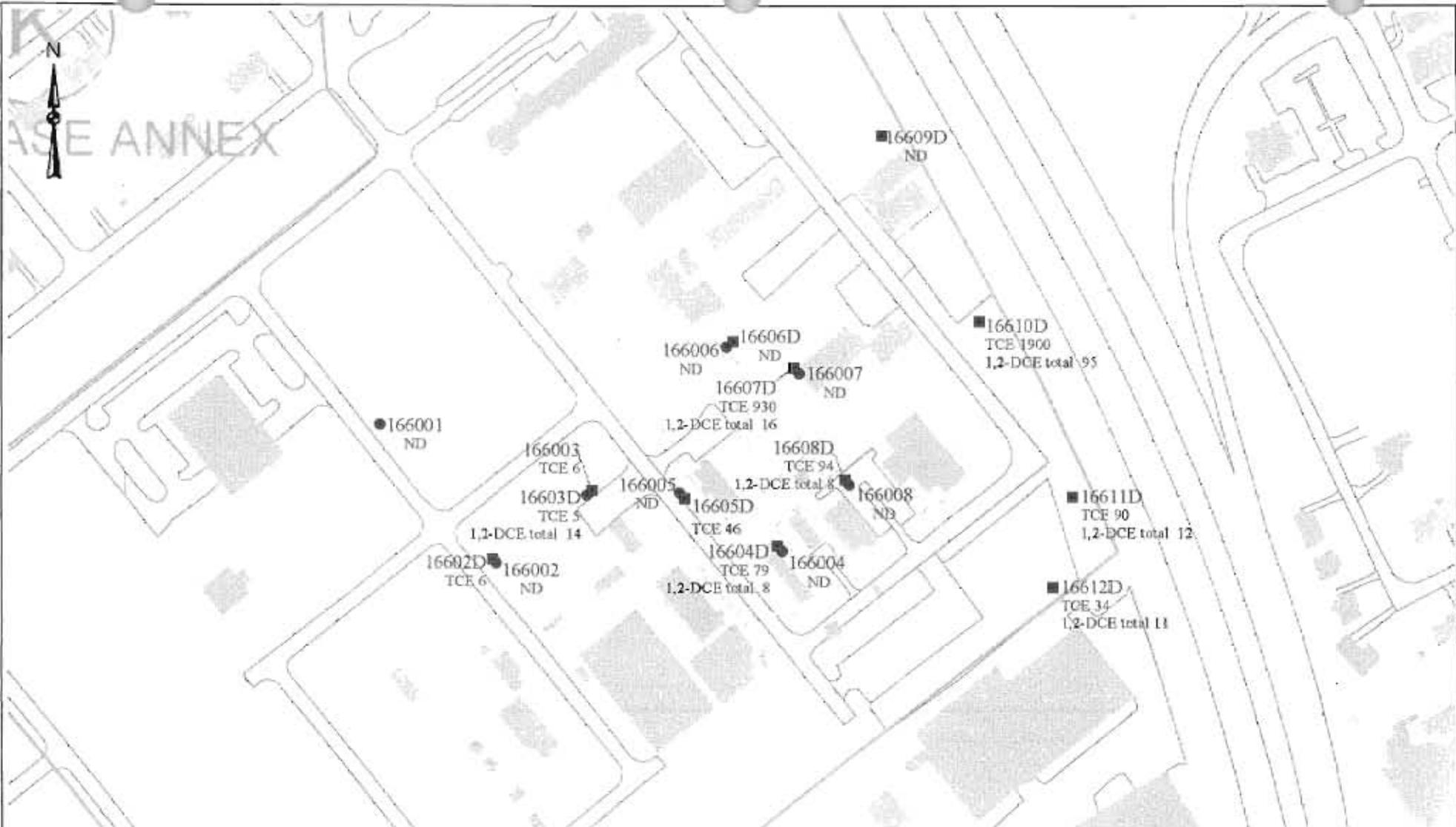
Nine groundwater sampling events were performed as follows:

- 1) May 1997 - Phase I wells sampled before well development for preliminary VOC delineation;
- 2) July 1997 - First primary sampling event for Phase I wells;
- 3) October 1997 - Second primary sampling event for Phase I wells;
- 4) January 1998 - Third primary sampling event for Phase I wells; first primary sampling event for Phase II wells;
- 5) March 1998- Round 1 MNA - Phase I wells sampled;
- 6) April 1998 - Fourth primary sampling event for Phase I wells; second primary sampling event for Phase II wells;
- 7) July 1998 - First primary sampling event for Phase III wells;
- 8) September 1998 - Round 2 MNA - Phase I, II and III wells sampled;
- 9) October 1998 - Round 1 CMS - First primary sampling event for Phase IV wells



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MNA INTERIM REPORT
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CHARLESTON, SC

FIGURE 3-5
MAY 1997
GROUNDWATER SAMPLING EVENT
GROUNDWATER VOC RESULTS (ug/L)



LEGEND

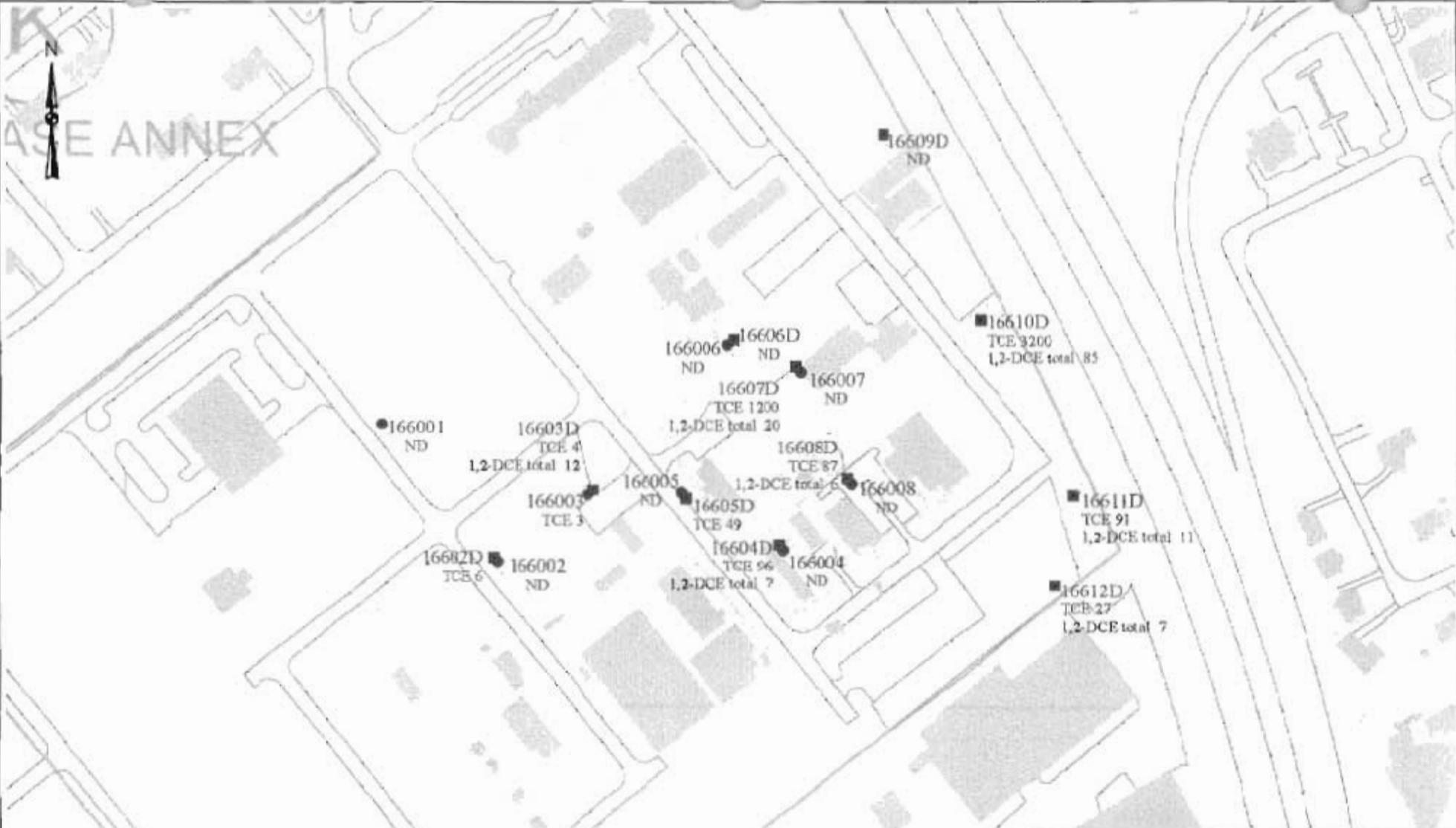
- SHALLOW MONITORING WELL LOCATION
- DEEP MONITORING WELL LOCATION
- ND NO VOCs DETECTED



ZONE K - SWMU 166
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 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3-6
 JULY 1997
 GROUNDWATER SAMPLING EVENT
 GROUNDWATER VOC RESULTS (ug/L)

BASE ANNEX



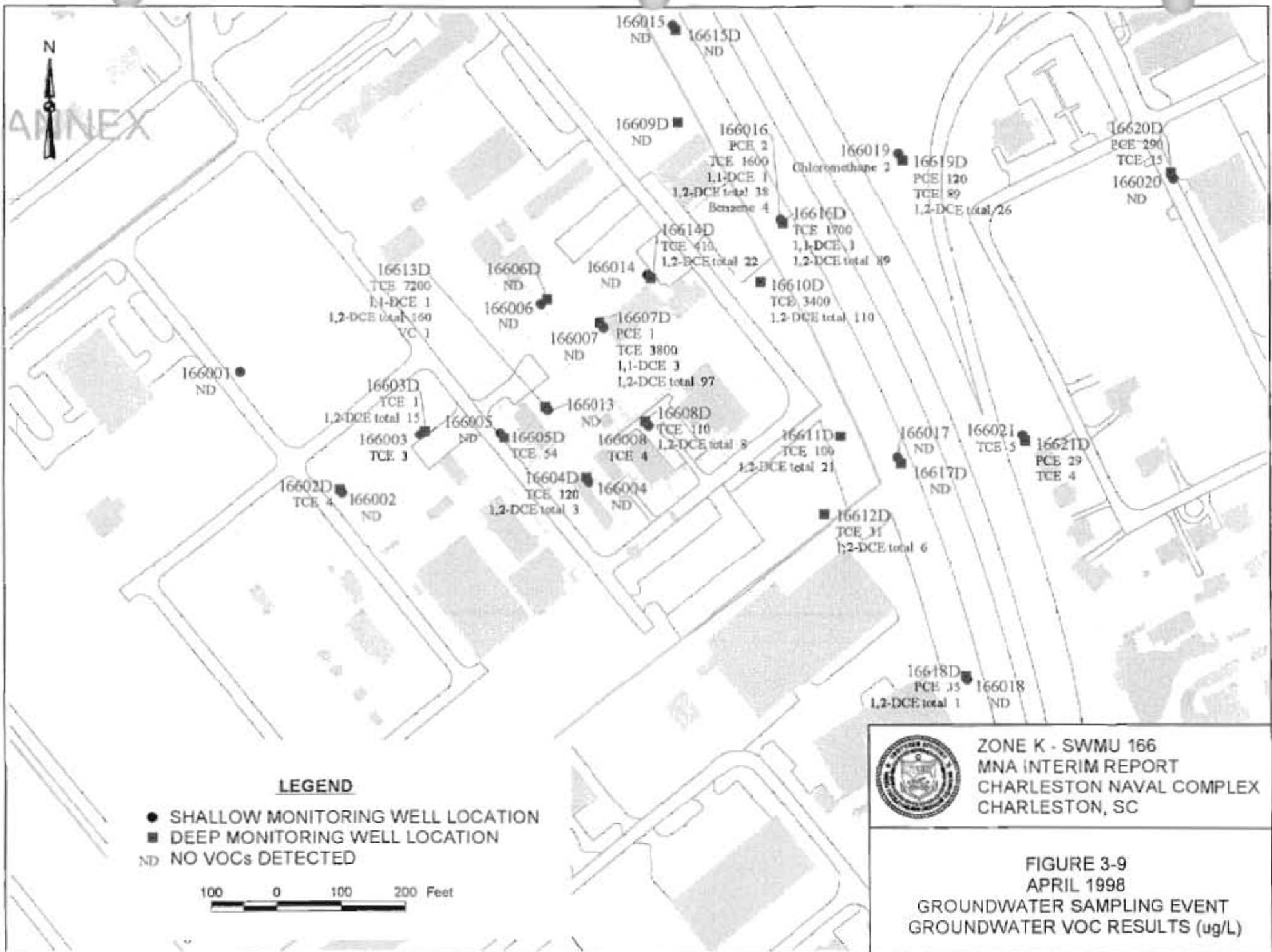
LEGEND

- SHALLOW MONITORING WELL LOCATION
- DEEP MONITORING WELL LOCATION
- ND NO VOCs DETECTED



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FIGURE 3-7
OCTOBER 1997
GROUNDWATER SAMPLING EVENT
GROUNDWATER VOC RESULTS (ug/L)



ANNEX

LEGEND

- SHALLOW MONITORING WELL LOCATION
- DEEP MONITORING WELL LOCATION
- ND NO VOCs DETECTED

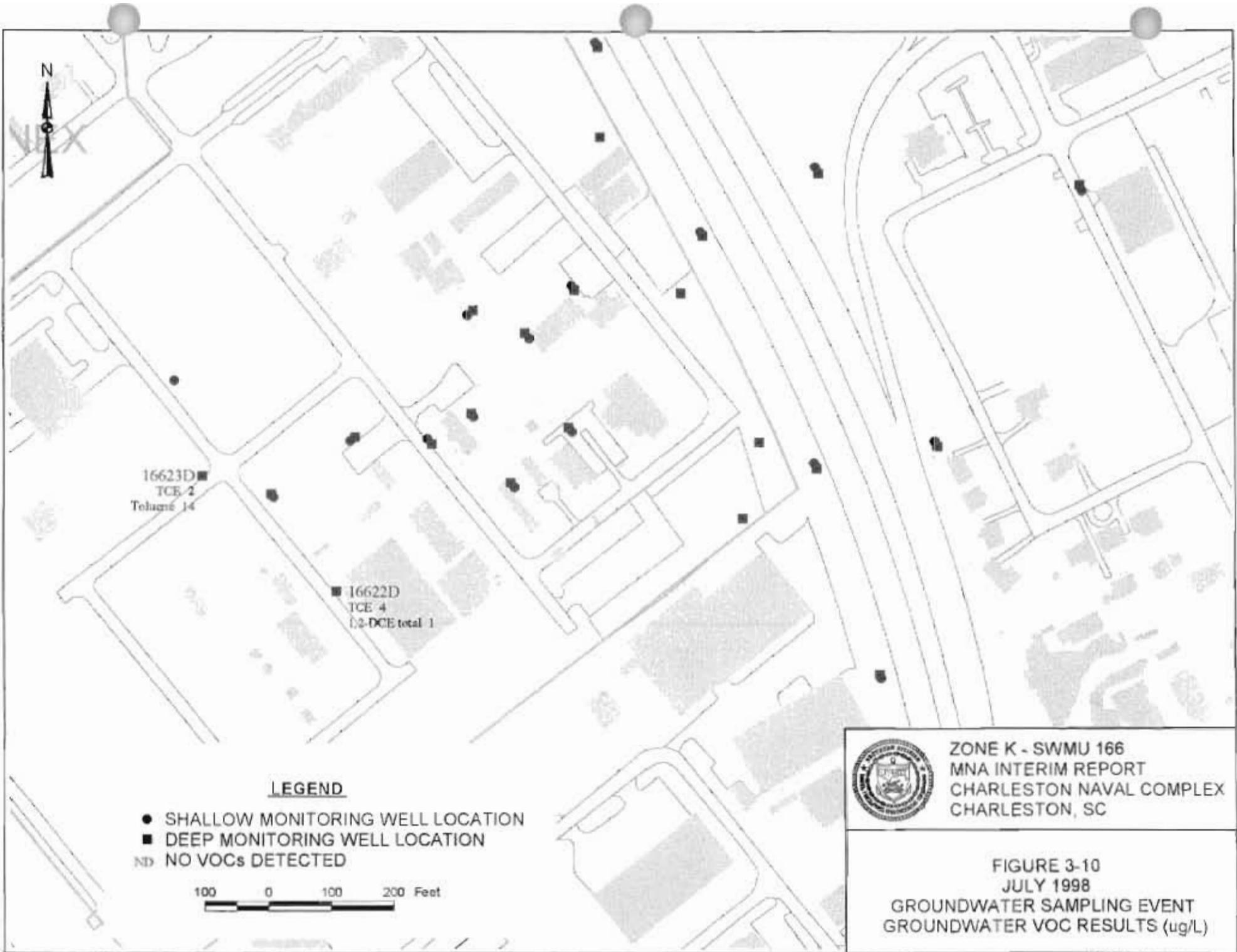
100 0 100 200 Feet



ZONE K - SWMU 166
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 CHARLESTON, SC

FIGURE 3-9
 APRIL 1998
 GROUNDWATER SAMPLING EVENT
 GROUNDWATER VOC RESULTS (ug/L)

Well ID	Well Type	VOC Results (ug/L)
166001	Shallow	ND
166002	Shallow	ND
166003	Shallow	TCE 3
166004	Shallow	TCE 120
166005	Shallow	ND
166006	Shallow	ND
166007	Shallow	ND
166008	Shallow	TCE 4
166009	Shallow	ND
166010	Deep	TCE 3400, 1,2-DCE total 110
166011	Deep	TCE 100, 1,2-DCE total 21
166012	Deep	TCE 31, 1,2-DCE total 6
166013	Shallow	ND
166014	Shallow	ND
166015	Shallow	ND
166016	Shallow	PCE 2, TCE 1600, 1,1-DCE 1, 1,2-DCE total 38, Benzene 4
166017	Shallow	ND
166018	Shallow	ND
166019	Shallow	Chloromethane 2
166020	Shallow	ND
166021	Shallow	TCE 5
166022	Shallow	TCE 4
166023	Shallow	PCE 29
166024	Shallow	TCE 25
166025	Shallow	PCE 290
166026	Shallow	TCE 89, 1,2-DCE total 26
166027	Shallow	PCE 120
166028	Shallow	TCE 1700, 1,1-DCE 1, 1,2-DCE total 89
166029	Shallow	TCE 410, 1,2-DCE total 22
166030	Shallow	TCE 7200, 1,1-DCE 1, 1,2-DCE total 160, VC 1
166031	Shallow	TCE 1, 1,2-DCE total 15
166032	Shallow	TCE 54
166033	Shallow	TCE 1
166034	Shallow	TCE 4
166035	Shallow	TCE 110, 1,2-DCE total 8
166036	Shallow	TCE 3800, 1,1-DCE 3, 1,2-DCE total 97
166037	Shallow	PCE 1
166038	Shallow	TCE 100
166039	Shallow	TCE 3
166040	Shallow	TCE 4
166041	Shallow	TCE 3
166042	Shallow	TCE 4
166043	Shallow	TCE 4
166044	Shallow	TCE 4
166045	Shallow	TCE 4
166046	Shallow	TCE 4
166047	Shallow	TCE 4
166048	Shallow	TCE 4
166049	Shallow	TCE 4
166050	Shallow	TCE 4
166051	Shallow	TCE 4
166052	Shallow	TCE 4
166053	Shallow	TCE 4
166054	Shallow	TCE 4
166055	Shallow	TCE 4
166056	Shallow	TCE 4
166057	Shallow	TCE 4
166058	Shallow	TCE 4
166059	Shallow	TCE 4
166060	Shallow	TCE 4
166061	Shallow	TCE 4
166062	Shallow	TCE 4
166063	Shallow	TCE 4
166064	Shallow	TCE 4
166065	Shallow	TCE 4
166066	Shallow	TCE 4
166067	Shallow	TCE 4
166068	Shallow	TCE 4
166069	Shallow	TCE 4
166070	Shallow	TCE 4
166071	Shallow	TCE 4
166072	Shallow	TCE 4
166073	Shallow	TCE 4
166074	Shallow	TCE 4
166075	Shallow	TCE 4
166076	Shallow	TCE 4
166077	Shallow	TCE 4
166078	Shallow	TCE 4
166079	Shallow	TCE 4
166080	Shallow	TCE 4
166081	Shallow	TCE 4
166082	Shallow	TCE 4
166083	Shallow	TCE 4
166084	Shallow	TCE 4
166085	Shallow	TCE 4
166086	Shallow	TCE 4
166087	Shallow	TCE 4
166088	Shallow	TCE 4
166089	Shallow	TCE 4
166090	Shallow	TCE 4
166091	Shallow	TCE 4
166092	Shallow	TCE 4
166093	Shallow	TCE 4
166094	Shallow	TCE 4
166095	Shallow	TCE 4
166096	Shallow	TCE 4
166097	Shallow	TCE 4
166098	Shallow	TCE 4
166099	Shallow	TCE 4
166100	Shallow	TCE 4
166101	Shallow	TCE 4
166102	Shallow	TCE 4
166103	Shallow	TCE 4
166104	Shallow	TCE 4
166105	Shallow	TCE 4
166106	Shallow	TCE 4
166107	Shallow	TCE 4
166108	Shallow	TCE 4
166109	Shallow	TCE 4
166110	Shallow	TCE 4
166111	Shallow	TCE 4
166112	Shallow	TCE 4
166113	Shallow	TCE 4
166114	Shallow	TCE 4
166115	Shallow	TCE 4
166116	Shallow	TCE 4
166117	Shallow	TCE 4
166118	Shallow	TCE 4
166119	Shallow	TCE 4
166120	Shallow	TCE 4
166121	Shallow	TCE 4
166122	Shallow	TCE 4
166123	Shallow	TCE 4
166124	Shallow	TCE 4
166125	Shallow	TCE 4
166126	Shallow	TCE 4
166127	Shallow	TCE 4
166128	Shallow	TCE 4
166129	Shallow	TCE 4
166130	Shallow	TCE 4
166131	Shallow	TCE 4
166132	Shallow	TCE 4
166133	Shallow	TCE 4
166134	Shallow	TCE 4
166135	Shallow	TCE 4
166136	Shallow	TCE 4
166137	Shallow	TCE 4
166138	Shallow	TCE 4
166139	Shallow	TCE 4
166140	Shallow	TCE 4
166141	Shallow	TCE 4
166142	Shallow	TCE 4
166143	Shallow	TCE 4
166144	Shallow	TCE 4
166145	Shallow	TCE 4
166146	Shallow	TCE 4
166147	Shallow	TCE 4
166148	Shallow	TCE 4
166149	Shallow	TCE 4
166150	Shallow	TCE 4
166151	Shallow	TCE 4
166152	Shallow	TCE 4
166153	Shallow	TCE 4
166154	Shallow	TCE 4
166155	Shallow	TCE 4
166156	Shallow	TCE 4
166157	Shallow	TCE 4
166158	Shallow	TCE 4
166159	Shallow	TCE 4
166160	Shallow	TCE 4
166161	Shallow	TCE 4
166162	Shallow	TCE 4
166163	Shallow	TCE 4
166164	Shallow	TCE 4
166165	Shallow	TCE 4
166166	Shallow	TCE 4
166167	Shallow	TCE 4
166168	Shallow	TCE 4
166169	Shallow	TCE 4
166170	Shallow	TCE 4
166171	Shallow	TCE 4
166172	Shallow	TCE 4
166173	Shallow	TCE 4
166174	Shallow	TCE 4
166175	Shallow	TCE 4
166176	Shallow	TCE 4
166177	Shallow	TCE 4
166178	Shallow	TCE 4
166179	Shallow	TCE 4
166180	Shallow	TCE 4
166181	Shallow	TCE 4
166182	Shallow	TCE 4
166183	Shallow	TCE 4
166184	Shallow	TCE 4
166185	Shallow	TCE 4
166186	Shallow	TCE 4
166187	Shallow	TCE 4
166188	Shallow	TCE 4
166189	Shallow	TCE 4
166190	Shallow	TCE 4
166191	Shallow	TCE 4
166192	Shallow	TCE 4
166193	Shallow	TCE 4
166194	Shallow	TCE 4
166195	Shallow	TCE 4
166196	Shallow	TCE 4
166197	Shallow	TCE 4
166198	Shallow	TCE 4
166199	Shallow	TCE 4
166200	Shallow	TCE 4
166201	Shallow	TCE 4
166202	Shallow	TCE 4
166203	Shallow	TCE 4
166204	Shallow	TCE 4
166205	Shallow	TCE 4
166206	Shallow	TCE 4
166207	Shallow	TCE 4
166208	Shallow	TCE 4
166209	Shallow	TCE 4
166210	Shallow	TCE 4
166211	Shallow	TCE 4
166212	Shallow	TCE 4
166213	Shallow	TCE 4
166214	Shallow	TCE 4
166215	Shallow	TCE 4
166216	Shallow	TCE 4
166217	Shallow	TCE 4
166218	Shallow	TCE 4
166219	Shallow	TCE 4
166220	Shallow	TCE 4
166221	Shallow	TCE 4
166222	Shallow	TCE 4
166223	Shallow	TCE 4
166224	Shallow	TCE 4
166225	Shallow	TCE 4
166226	Shallow	TCE 4
166227	Shallow	TCE 4
166228	Shallow	TCE 4
166229	Shallow	TCE 4
166230	Shallow	TCE 4
166231	Shallow	TCE 4
166232	Shallow	TCE 4
166233	Shallow	TCE 4
166234	Shallow	TCE 4
166235	Shallow	TCE 4
166236	Shallow	TCE 4
166237	Shallow	TCE 4
166238	Shallow	TCE 4
166239	Shallow	TCE 4
166240	Shallow	TCE 4
166241	Shallow	TCE 4
166242	Shallow	TCE 4
166243	Shallow	TCE 4
166244	Shallow	TCE 4
166245	Shallow	TCE 4
166246	Shallow	TCE 4
166247	Shallow	TCE 4
166248	Shallow	TCE 4
166249	Shallow	TCE 4
166250	Shallow	TCE 4



16623D
TCE 2
Toluene 14

16622D
TCE 4
1,2-DCE total 1

LEGEND

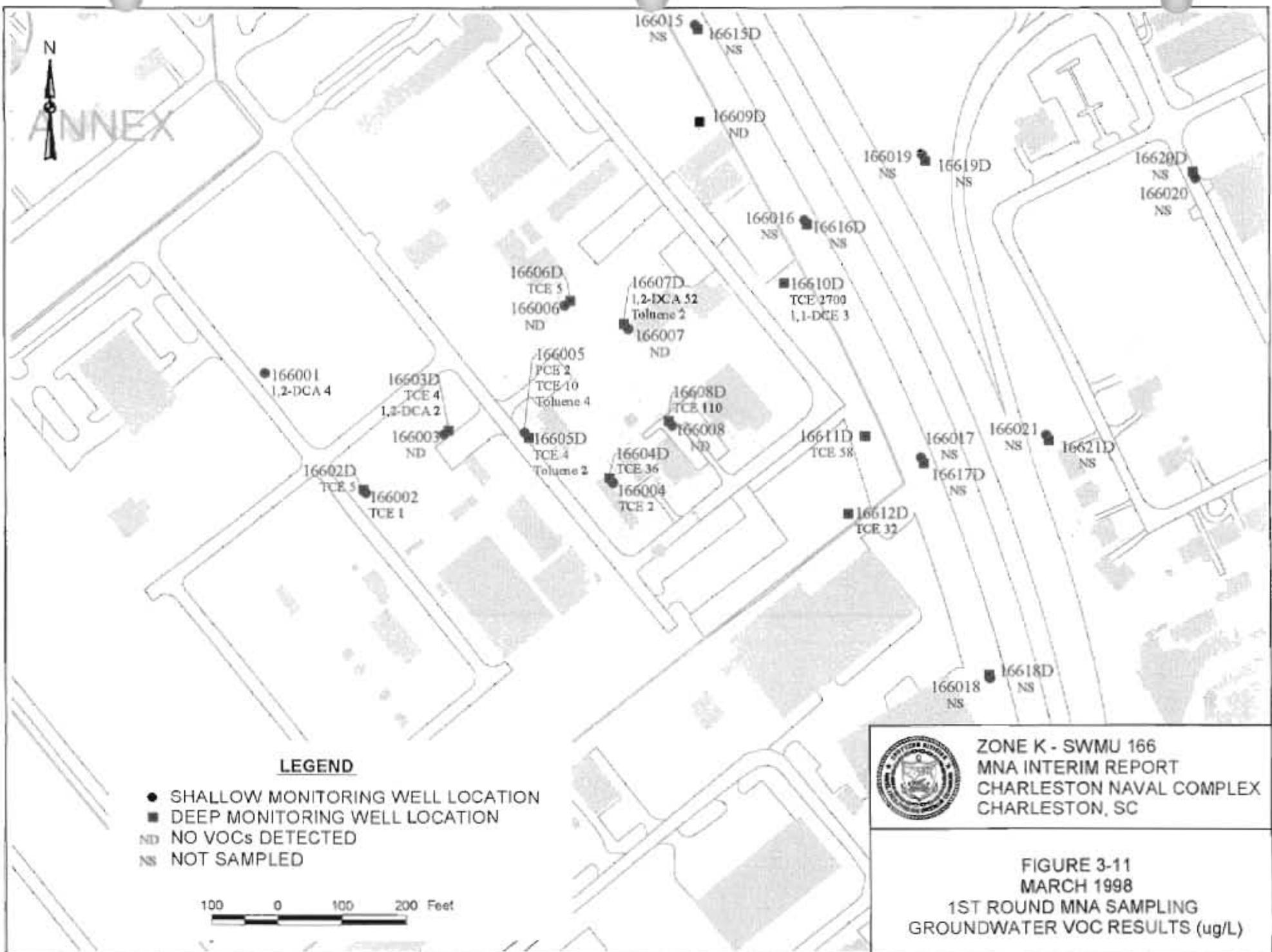
- SHALLOW MONITORING WELL LOCATION
- DEEP MONITORING WELL LOCATION
- ND NO VOCs DETECTED

100 0 100 200 Feet



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FIGURE 3-10
JULY 1998
GROUNDWATER SAMPLING EVENT
GROUNDWATER VOC RESULTS (ug/L)



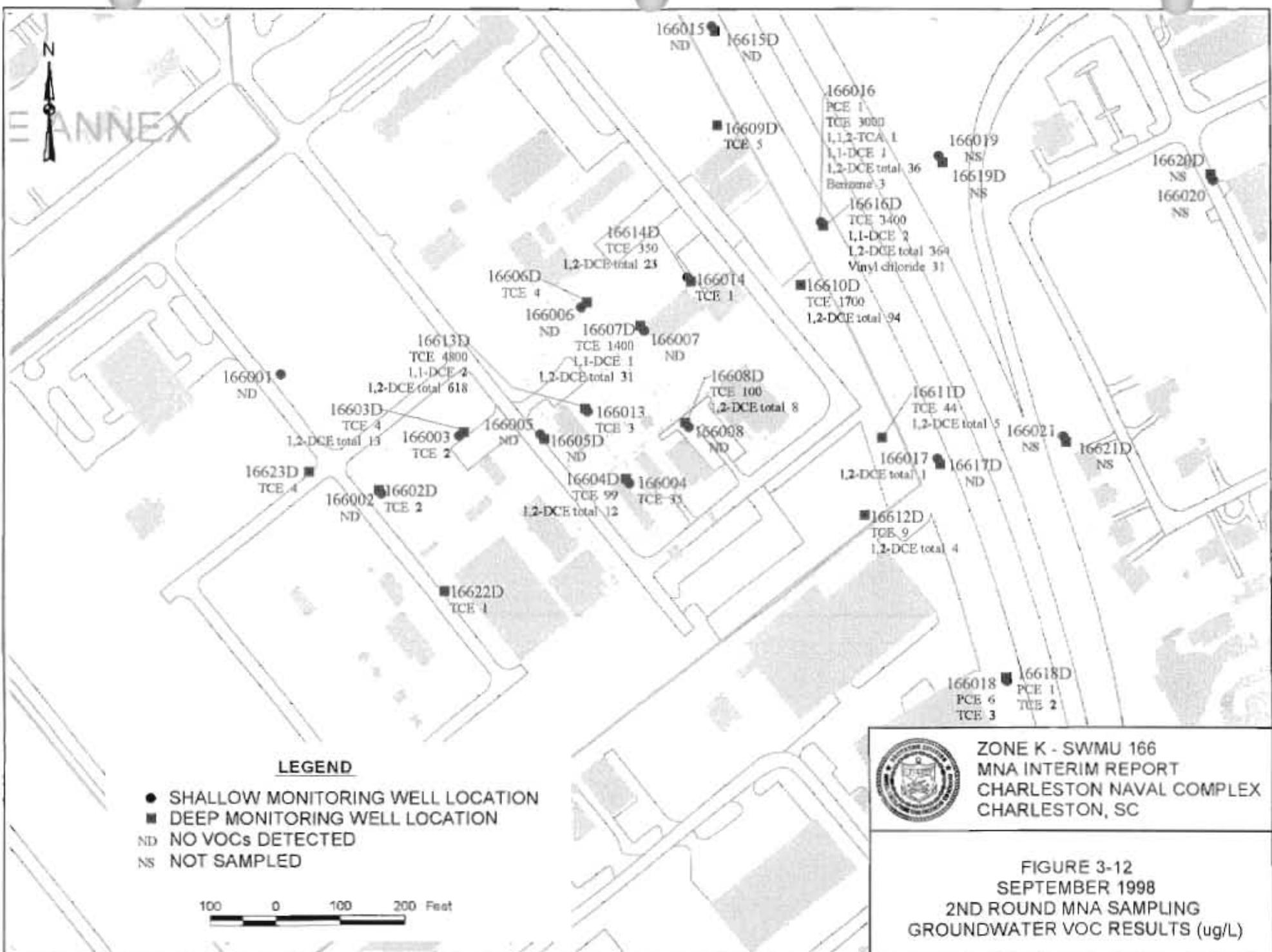
LEGEND

- SHALLOW MONITORING WELL LOCATION
- DEEP MONITORING WELL LOCATION
- ND NO VOCs DETECTED
- NS NOT SAMPLED



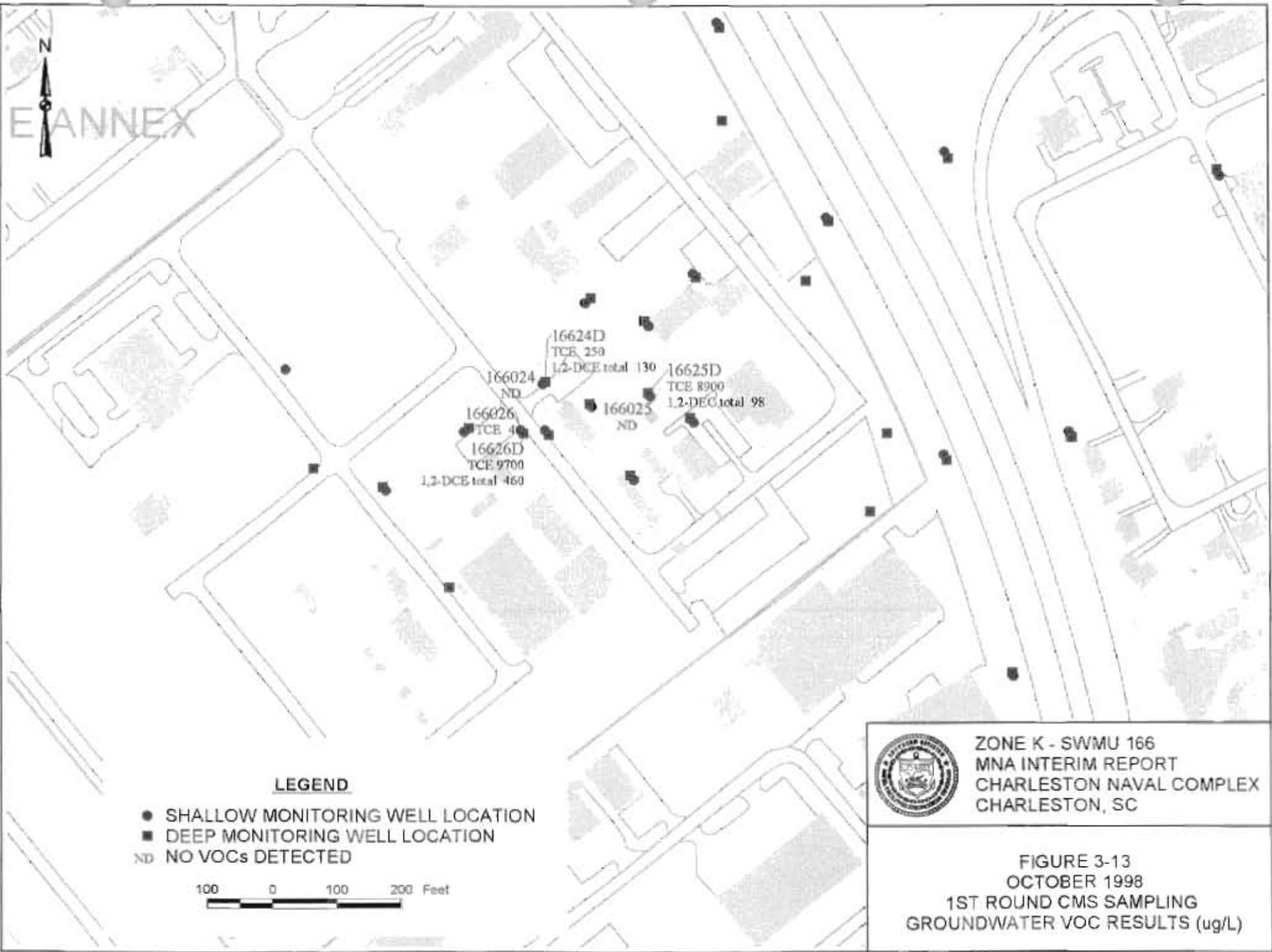
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FIGURE 3-11
MARCH 1998
1ST ROUND MNA SAMPLING
GROUNDWATER VOC RESULTS (ug/L)



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FIGURE 3-12
SEPTEMBER 1998
2ND ROUND MNA SAMPLING
GROUNDWATER VOC RESULTS (ug/L)



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FIGURE 3-13
 OCTOBER 1998
 1ST ROUND CMS SAMPLING
 GROUNDWATER VOC RESULTS (ug/L)

The Zone K Draft RFI Report (EnSafe, 1998) details the groundwater sampling events and the laboratory results that had been received at the time of its writing.

The first round of data collection for MNA at SWMU 166 occurred at well locations sampled in the October 1997 sampling event since data was not available from the January 1998 sampling event. Figure 3.11 illustrates the well locations and VOC detections for the first round of MNA sampling. The second round of MNA sampling included the wells installed in the second and third phase. Figure 3.12 illustrates the well locations and VOC detections for the second round of MNA sampling. Concentrations of TCE detected in the MNA samples were similar to the concentrations found in wells during the fourth round of quarterly sampling.

In an effort to better delineate a groundwater VOC source area, well pairs 166024/24D to 166026/26D were installed during the CMS investigation. The analytical results from those samples are illustrated in Figure 3.13.

3.2 Preliminary Conceptual Model: Geologic and Hydrogeologic Data

Construction of a conceptual model is a critical step in evaluating the contaminant history at any site. The conceptual model incorporates all the geologic, hydrogeologic, and chemical data so that the fate and transport of contaminants can be assessed. The wealth of data gathered during the RFI at Naval Annex comprises most of that needed to create a preliminary conceptual model. The model is continually updated and revised as additional data is collected and interpreted during various aspects of the CMS phase of the investigation.

The following is a summary of the pertinent geologic and hydrogeologic data from SWMU 166 taken from the Draft Zone K RFI Report. Modifications of the data presented in the Draft Zone K RFI Report have been necessary due to the additional field investigation (i.e., eight monitoring

wells) that has taken place since submittal of the report. The Draft Zone K RFI Report provides details regarding boring logs, geotechnical, and hydraulic conductivity data.

3.2.1 SWMU 166 Geology

Only Quaternary and Tertiary-age sediments were encountered during the Zone K RFI. The lowermost stratigraphic unit identified in Zone K is the Ashley Formation member of the Mid-Tertiary age Cooper Group. Overlying the Ashley are primarily younger Quaternary-age stratigraphic units; however, it is possible than some remnant of Upper Tertiary sediments may be present, but field identification of these deposits is extremely difficult.

3.2.1.1 Tertiary-Age Ashley Formation

The Ashley Formation is an olive-yellow to olive-brown, tight, slightly calcareous, clayey silt with varying amounts of very fine to fine grained sand that decreases rapidly with depth. It is firm to stiff, low in plasticity, and damp to moist. Deep well borings at the Naval Annex were advanced either to the Ashley or terminated just above the contact.

Elevations of the Ashley Formation range from 9.9 feet mean sea level (msl) at 16609D to 3.2 feet msl at 16605D. A trough in the Ashley Formation, identified in the vicinity of 16605D, trends slightly NW to SE across SWMU 166. Deep well data collected at five additional locations (16622D through 16626D), since the Draft Zone K RFI Report was submitted, indicate that this trough extends to the southwest.

3.2.1.2 Quaternary-Age Sediments

During Quaternary time, several marine transgression-regression sequences resulted in a jumbled network of terrace complexes composed of varied coastal depositional environments such as barrier islands, back barrier lagoons, tidal inlets, and shallow-ocean-marine shelf systems. This process of a erosion and redeposition may have produced a younger sequence of deposits on the

seaward side of and laterally adjacent to the previous (older) coastal deposit (Weems and Lemon, 1993). It can therefore be difficult to determine discrete formational units within the Quaternary system. Weems and Lemon identified and correlated several Quaternary-age formations, although field identification of these units is difficult since many characteristics may be evident only at the microscopic level.

Throughout the Naval Annex, Quaternary-age sediments extend from the top of the Ashley Formation to just below ground surface. Based on the 25 deep borings drilled at the Naval Annex, these sediments range from approximately 27 feet thick at 16617D to 37 feet thick at 16605D and 16608D. Due to the difficulty in positively identifying discrete formational units within the Quaternary, two Quaternary-age lithostratigraphic units have been correlated at the site and are described below.

Quaternary Clayey Sand and Clay (Qcs)

The Qcs unit typically unconformably overlies the Ashley Formation (Ta) at the Naval Annex. This unit generally consists of green to gray-green, fine to coarse clayey sand with varying amounts of silt. Phosphate nodules from pebble to cobble size and shell hash are often intermixed within the matrix or as distinct basal lenses. Clay lenses, when present, are often green, firm to stiff, and plastic. The deep wells installed at Naval Annex are primarily screened within this unit.

The only geotechnical data collected from the Qcs unit had a grain size composition of 90% sand, 6% silt, and 4% clay and a total porosity of 40.9 %.

Quaternary Sand (Qs)

The Qs unit overlies the Qcs unit and extends to ground surface, although smaller Qs lenses may be present at depth. The Qs is a gray, green, brown, and orange fine to medium sand with varying silt content and very distinctive mica content. The unit is marked by a lack of

cohesiveness due to limited fines content. Shallow wells installed at Naval Annex are screened within the Qs unit.

Based on geotechnical data from Shelby tube samples, the Qs deposits had an average grain size composition of 93.1% sand, 3.4% silt, and 3.5% clay. Total porosity estimates ranged from 43.0 to 46.9%.

Geologic cross-sections and groundwater flow paths for SWMU66 are presented on Figure 3.14. Figure 3.14 was taken from the Draft Zone K RFI Report and was not revised or updated with new geologic or hydrogeologic information. It was presented merely to demonstrate the relationships between the lithostratigraphic units encountered at the site.

3.2.2 Site Hydrogeology

The Naval Annex area is positioned on a surface water drainage divide and surface elevations at Naval Annex range from 40 feet and 45 feet msl. From this area, surface water would flow south toward Filbin Creek, or north toward Turkey Creek. Filbin Creek flows eastward and drains into the Cooper River. Turkey Creek flows toward the northeast and drains into Goose Creek, a tributary of the Cooper River.

3.2.2.1 Surficial Aquifer

The surficial aquifer is unconfined and extends from the water table to the top of the Ashley Formation which is the regional confining unit. Gross aquifer thicknesses vary across the site based on the surface topographic and Ashley Formation elevation.

Monitoring Well Network

Table 3.1 presents the current shallow and deep monitoring well network at Naval Annex with the exception of pumping and observation wells installed at SWMU 166 as part of the CMS. As

shown in Table 3.1, shallow and deep wells were installed with screened interval lengths of 1-foot, 5-foot, or 10-foot. Since all shallow monitoring wells are between 11.6 and 15.0 feet below ground surface (bgs) in depth, the screened interval either intersects the water table or monitors the sediments 5 to 10 feet below it. However, groundwater elevations in all shallow monitoring wells are considered representative of the hydraulic conditions in the shallow subsurface due to the predominance of the relatively homogeneous Qs deposits in the upper 20 to 25 feet bgs. Similarly, since the total depth of each deep well occurs at or near the top of the Ashley Formation, deep well groundwater elevations are considered representative of the hydraulic conditions at the base of the surficial aquifer. Throughout this report, chemical compounds detected in any shallow or deep well will be referred to as representing shallow groundwater and deep groundwater, respectively.

**Table 3.1
 Naval Annex Well Construction Data Summary**

Well ID	Installation Date	TOC elev. (feet msl)	Grnd elev. (feet msl)	Drilled Data (feet bgs)			DTW (feet)	GW Elev. (feet msl)
				TOS	BOS	BOW		
NBCK161001*	12/5/96	41.09	41.2	6.0	15.5	16.0	NA	-
NBCK162001*	12/4/96	38.51	38.5	5.0	14.5	15.0	1.10	37.41
NBCK162002*	12/4/96	42.24	39.8	5.0	14.5	15.0	4.00	38.24
NBCK163001*	12/3/96	42.13	39.6	5.0	14.5	15.0	4.56	37.57
NBCK166001*	12/5/96	41.02	40.8	5.0	14.5	15.0	0.05	40.97
NBCK166002**	5/8/97	42.24	41.0	7.0	11.7	12.0	4.52	37.72
NBCK16602D**	5/7/97	42.24	40.9	25.1	29.7	31.0	4.55	37.69
NBCK166003**	5/9/97	42.51	40.9	7.1	12.1	12.4	4.69	37.82
NBCK16603D**	5/8/97	42.51	40.9	28.1	32.7	33.0	4.78	37.73
NBCK166004**	5/8/97	42.25	40.5	8.0	12.7	13.0	4.19	38.06
NBCK16604D**	5/8/97	42.27	40.7	27.1	31.7	32.0	4.31	37.96
NBCK166005**	5/5/97	40.22	41.2	8.0	12.7	13.0	2.26	37.96
NBCK16605D**	5/6/97	39.99	41.2	25.0	29.7	30.0	2.13	37.86
NBCK166006**	5/12/97	43.21	41.7	7.1	11.7	12.0	5.84	37.37
NBCK16606D**	5/12/97	43.11	41.7	25.1	29.7	30.0	6.01	37.10
NBCK166007**	5/12/97	43.45	41.8	7.1	11.7	12.0	6.81	36.64

**Table 3.1
Naval Annex Well Construction Data Summary**

Well ID	Installation Date	TOC elev. (feet msl)	Grnd elev. (feet msl)	Drilled Data (feet bgs)			DTW (feet)	GW Elev. (feet msl)
				TOS	BOS	BOW		
NBCK16607D**	5/13/97	40.46	41.8	26.1	30.7	31.0	3.87	36.59
NBCK166008**	5/14/97	40.11	41.3	8.1	12.7	13.0	3.05	37.06
NBCK16608D**	5/13/97	40.34	41.5	29.1	33.7	34.0	3.31	37.03
NBCK16609D**	5/9/97	42.26	40.9	26.1	30.7	31.0	7.99	34.27
NBCK16610D**	5/14/97	43.01	41.4	26.1	30.7	31.0	8.17	34.84
NBCK16611D**	5/6/97	42.46	40.9	25.1	29.7	30.0	7.50	34.96
NBCK16612D**	5/7/97	42.63	40.5	25.1	29.7	30.0	7.27	35.36
NBCK166013***	12/17/97	39.41	39.7	9.8	11.2	11.6	2.09	37.32
NBCK16613D***	1/14/98	39.61	39.8	29.0	31.1	31.5	1.65	37.96
NBCK166014***	1/15/98	40.75	40.9	12.0	13.6	14.0	5.30	35.45
NBCK16614D***	12/18/97	40.34	40.9	29.8	31.3	31.7	4.79	35.55
NBCK166015***	12/18/97	33.23	33.5	10.0	11.2	11.6	1.72	31.51
NBCK16615D***	1/12/98	33.23	33.5	22.0	23.6	24.0	0.02	33.21
NBCK166016***	12/17/97	33.50	33.9	9.5	11.2	11.6	0.55	32.95
NBCK16616D***	1/12/98	33.73	34.0	23.3	24.7	25.1	0.02	33.71
NBCK166017***	1/6/98	33.95	34.3	9.5	11.2	11.6	0.44	33.51
NBCK16617D***	1/13/98	34.22	34.4	23.5	24.8	25.2	0.38	33.84
NBCK166018***	1/6/98	35.25	35.6	9.9	11.3	11.7	1.64	33.61
NBCK16618D***	1/13/98	35.23	35.5	23.5	25.0	25.4	1.44	33.79
NBCK166019***	1/6/98	39.52	40.0	9.9	11.2	11.6	NT	-
NBCK16619D***	1/14/98	39.70	40.0	19.9	21.1	21.5	NT	-
NBCK166020***	1/6/98	38.00	38.7	9.9	11.4	11.8	NT	-
NBCK16620D***	1/14/98	38.37	38.6	24.0	26.1	26.5	NT	-
NBCK166021***	1/5/98	39.99	40.4	9.9	11.2	11.6	NT	-
NBCK16621D***	1/5/98	40.15	40.4	29.4	30.9	31.3	NT	-
NBCK16622D***	6/3/98	42.04	39.8	25.0	29.4	30.0	4.99	37.05
NBCK16623D***	6/3/98	40.06	40.3	25.0	29.4	30.0	2.06	38.00
NBCK166024**	10/13/98	40.39	40.6	7.9	12.6	12.9	NI	-
NBCK16624D**	10/13/98	40.43	40.6	30.5	35.2	35.5	NI	-
NBCK166025**	10/13/98	39.95	40.1	7.9	12.6	12.9	NI	-
NBCK16625D**	10/13/98	39.97	40.2	27.5	32.2	32.5	NI	-
NBCK166026**	10/14/98	39.85	40.2	7.9	12.6	12.9	NI	-
NBCK16626D**	10/14/98	40.12	40.3	30.5	35.2	35.5	NI	-

**Table 3.1
 Naval Annex Well Construction Data Summary**

Well ID	Installation Date	TOC elev. (feet msl)	Grnd elev. (feet msl)	Drilled Data (feet bgs)			DTW (feet)	GW Elev. (feet msl)
				TOS	BOS	BOW		
NBCK698001*	12/6/96	43.72	40.9	5.0	14.5	15.0	9.81	33.91
NBCKGDK001*	12/5/96	43.41	40.9	5.0	14.5	15.0	9.00	34.41
NBCKGDK002*	12/3/96	41.66	39.2	5.0	14.5	15.0	7.91	33.75

Notes:

- * — 10-foot stainless steel screen
- ** — 5-foot stainless steel screen
- *** — 1-foot stainless steel screen
- msl = mean sea level
- bgs = below ground surface
- TOC = Top of well casing
- TOS = Top of screened interval including sand pack
- BOS = Bottom of screened interval
- BOW = Bottom of well (end cap)
- DTW = Depth to groundwater 9/22/98 from TOC. These depths should only be considered approximate since groundwater depths vary seasonally and diurnally.
- NA = Not accessible when measurements taken.
- NT = Not taken.
- NI = Not installed at time of 9/22/98 measurements
- = Not part of the GW elevation measurements of 9/22/98

3.2.2.2 Groundwater Flow Direction

The Interstate 26 road cut lies approximately 10 feet topographically lower than the Annex to the west and six feet lower than the land to the east, creating a discharge zone along its axis east of the Annex boundary. Groundwater originating east of the interstate flows west toward the interstate before migrating northwest along the interstate axis. Groundwater originating at the Annex flows northeast to east toward the interstate before flowing northwest along the interstate axis. The potentiometric low at the interstate is a result of the storm water sewer system installed during interstate construction. This may be seen more clearly in the flow net schematic shown in Figure 3.14. Groundwater elevation data in Figure 3.14 have not been updated for this report;

however, the flow net schematic remains a useful representation of the prevailing groundwater flow direction at Naval Annex.

Table 3.1 includes water level data taken within a two-hour period on September 22, 1998 as part of the second MNA sampling round at SWMU 166. Note that well pairs 166024/24D through 166026/26D were not installed at the time of these measurements, and well pairs 166019/19D through 166021/21D were not measured since they were not part of the MNA evaluation. Shallow and deep groundwater elevation contours are presented in Figure 3.15.

Previous water level measurements at Naval Annex have depicted radial flow away from a central recharge area. The majority of groundwater flow is east toward Interstate 26, with a less predominant southern component offsite eventually flowing toward Interstate 26 as stated in the Draft Zone K RFI Report. The September 22, 1998 data reveal subtle differences in recharge zone morphology, from previous events. During the second round MNA sampling shallow groundwater flowed predominantly west to east across the site, as evidenced by the two representative groundwater flowpaths labeled "A" and "B" on Figure 3.15. However, a localized high in shallow groundwater was observed at wells GDK002 and 166004, which confines the extent of the southern groundwater flow component. As a result, the water table surface throughout the south-central portion of the Naval Annex is relatively flat.

Deep groundwater flow has historically been primarily west to east toward Interstate 26. The September 22, 1998 data refined the upgradient portions of the site with additional groundwater elevation data at 16622D and 23D. Supplemental 0.1-foot contours reveal a small-scale high at 16613D and 04D, which suggests localized variations in recharge components of deep groundwater flow than had been evident in previous events. Groundwater flowpaths labeled "C" and "D" on Figure 3.15 represent the two dominant flow directions.

3.2.2.3 Horizontal Hydraulic Gradients

The horizontal hydraulic gradient (i) is a measure of the change in hydraulic head (Δh) (i.e., change in groundwater elevation) over the distance between two points (Δx). It is a dimensionless value generally used to determine the magnitude of groundwater flow in a given region.

Because well locations for the Naval Annex RFI were based solely on SWMU and AOC locations and historical land uses, few monitoring wells are actually located along the same groundwater flowpaths. As a result, horizontal hydraulic gradients were calculated along four representative flowpaths, presented in Figure 3.15 (labeled "A" through "D"). The results are presented in Table 3.2.

**Table 3.2
 Horizontal Hydraulic Gradients**

Flowpath	Δh (ft)	Δx (ft)	i
<i>Shallow Wells</i>			
A	7	675	0.0104
B	5	485	0.0103
<i>Deep Wells</i>			
C	3.9	410	0.0095
D	3.9	560	0.0070

3.2.2.4 Vertical Hydraulic Gradient

Vertical hydraulic gradients in the surficial aquifer were calculated from groundwater elevation data collected on September 22, 1998 for the 13 shallow/deep well pairs. Vertical hydraulic gradients were calculated by dividing the difference between groundwater elevations in shallow and deep well pairs by the vertical distance between the bottom of each corresponding well screen.

Positive values indicate downward vertical gradients whereas negative values indicate an upward vertical gradient. Table 3.3 lists the calculated vertical hydraulic gradients for each well.

All well pairs adjacent to Interstate 26 interstate showed an upward hydraulic gradient, as would be expected at a groundwater discharge zone. The magnitude of the upward vertical gradient increases northward along the interstate. The gradient along Interstate 26 is slight at the 018/18D well pair, and increases at the 017/17D and 016/16D well pair; reaching its highest magnitude at well pair 015/15D. Seven of nine well pairs on Naval Annex property were slightly downward

**Table 3.3
Vertical Hydraulic Gradients at Naval Annex
September 22, 1998**

Well Pair	Shallow Well GW Elev. (ft msl)	Deep Well GW Elev. (ft msl)	GW Elev. Diff (ft msl)	Vertical Dist. (ft)	Vertical Hyd. Gradient
166002 and 02D	37.72	37.69	0.03	19.0	0.0016
166003 and 03D	37.82	37.73	0.09	20.6	0.0044
166004 and 04D	38.06	37.96	0.10	19.0	0.0053
166005 and 05D	37.96	37.86	0.10	17.0	0.0059
166006 and 06D	37.37	37.10	0.27	18.0	0.0150
166007 and 07D	36.64	36.59	0.05	19.0	0.0026
166008 and 08D	37.06	37.03	0.03	21.0	0.0014
166013 and 13D	37.32	37.96	-0.64	19.9	-0.0322
166014 and 14D	35.45	35.55	-0.10	17.7	-0.0056
166015 and 15D	31.51	33.21	-1.70	12.4	-0.1371
166016 and 16D	32.95	33.71	-0.76	13.5	-0.0563
166017 and 17D	33.51	33.84	-0.33	13.6	-0.0243
166018 and 18D	33.61	33.79	-0.18	13.7	-0.0171

Note:

A positive number for the vertical hydraulic gradient indicates potential for downward flow; negative number indicates potential for upward flow.

and of small magnitude, indicating a predominantly horizontal groundwater flow in these areas. 1
 The two exception are well pairs 013/13D and 014/14D. Well pair 014/14D is the closest well 2
 pair on the Naval Annex to Interstate 26 and indicates that the lateral extent of the discharge zone 3
 extends west of Interstate 26 into the Naval Annex. The upward gradient at well pair 013/13D 4
 is unusual since it is in site interior and is separated from well pair 014/14D by well pairs 006/06D 5
 and 007/07D. No Qcs deposits occur over the Ashley Formation at location 16613D such that 6
 both the shallow and deep wells monitor shallow and deep Qs deposits. This geologic anomaly 7
 may account for the upward gradient at 166013/13D. 8

3.2.2.5 Horizontal Hydraulic Conductivity 9

The following section summarizes the horizontal hydraulic conductivity data collected at Naval 10
 Annex and presented in the Draft Zone K RFI Report. Three methods were used to estimate 11
 hydraulic conductivity: slug tests, specific conductivity tests, and grain-size evaluation of Shelby 12
 tube samples. Table 3.4 presents the geometric mean of each method by testing location. Refer 13
 to the Draft Zone K RFI Report for details regarding each of these methods. 14

**Table 3.4
 Horizontal Hydraulic Conductivity Results in feet/day**

Well	Lith Type	Slug Test Geometric Mean ^a	Specific Capacity Geometric Mean ^b
NBCK162002	Qs	31.03	NC
NBCK166002	Qs	6.39	NC
NBCK166003	Qs	9.13	NC
NBCK166004	Qs	6.05	NC
NBCK166007	Qs	16.28	NC
NBCKGDK001	Qs	6.10	NC
NBCKGDK002	Qs	7.77	NC
NBCK16602D	Qcs	1.39	1.61
NBCK16603D	Qcs	0.39	0.44

Table 3.4
Horizontal Hydraulic Conductivity Results in feet/day

Well	Lith Type	Slug Test Geometric Mean ^a	Specific Capacity Geometric Mean ^b
NBCK16604D	Qcs	0.45	NC
NBCK16605D	Qs/Qcs	NC	1.37
NBCK16606D	Qs	2.78	2.86
NBCK16607D	Qs/Qcs	3.72	3.16
NBCK16609D	Qcs	3.72	2.11
NBCK16610D	Qs	4.41	4.27
NBCK16611D	Qcs	3.17	3.25
NBCK16612D	Qs/Qcs	NC	5.32
NBCK16613D	Qcs	NC	1.17
NBCK16614D	Qcs	NC	5.38

GRAIN-SIZE EVALUATION

Location	Lith. Type	Sample Depth (feet bgs)	Grain-Size Evaluation Geometric Mean ^c
NBCK161001	Qs	10-12	35.70
NBCK162001	Qs	6-8	37.23
NBCK163001	Qs	8-10	0.23
NBCKGDK001	Qs	8-10	30.10

Note:

- ^a = Geometric mean of falling head and rising head test results.
- ^b = Geometric mean of specific capacity results based on hypothetical specific yields of 0.01 and 0.3.
- ^c = Geometric mean of Beyer, Hazen, and Terzaghi empirical formulas.
- NC = Not conducted

Horizontal hydraulic conductivity results from slug tests, specific capacity tests, and grain-size 1
 evaluations were averaged (geometric mean) to produce a representative effective conductivity 2
 value ($K_{h(eff)}$) for the Qs and Qcs lithologic units (Table 3.5). Only the specific capacity K_h values 3
 generated using $S_y = 0.01$ were included in the averaged K_h since they were higher than the other 4
 specific capacity K_h values. Equal weight was given to each method since each revealed value 5
 ranges of the same order of magnitude as the ranges between the three methods. No grain-size 6

evaluation was conducted on Qcs samples. A vertical permeability (K_v) mean was calculated from
 Shelby tube sample results, presented in Table 2.3 of the Draft Zone K RFI Report.

Table 3.5
Hydraulic Conductivity Summary for Quaternary-age Units
in Zone K

Lithologic Unit	K_v (feet/day)	$K_{h(eff)}$ (feet/day)
Quaternary Sand (Qs)	3.59	5.9
Quaternary clayey sand and clay (Qcs)	0.77	2.2

3.2.2.6 Groundwater Velocity

It is possible to estimate the rate at which site groundwater travels using the following formula:

$$V = \frac{K_h * i}{n_e}$$

Where:

- V = horizontal groundwater velocity K_h = hydraulic conductivity
 i = horizontal hydraulic gradient n_e = effective porosity

Groundwater velocities were computed using the shallow and deep groundwater flowpaths along
 which horizontal hydraulic gradients had been calculated, as described in Section 3.2.2.3. Shallow
 groundwater flows primarily through Qs deposits whereas deep groundwater flows through Qcs
 deposits. As such, data pertinent to each lithologic unit were used in the above calculation. Total
 porosity values from geotechnical data were taken from the Draft Zone K RFI Report and
 substituted for n_e values since no site-specific effective porosity estimates were available.
 However, it is understood that a site-specific n_e would be lower than that applied and thus produce

higher groundwater flow velocities. As a result, the lowest and highest total porosity values for each lithology were used for n_c to provide a range of groundwater flow velocities.

The estimated minimum and maximum groundwater velocities are presented in Table 3.6. Since the horizontal hydraulic gradient was equal for shallow groundwater flowpaths "A" and "B," they are combined in the table.

**Table 3.6
 Groundwater Velocity Results**

Flowpath*	Porosity		$K_{h(eff)}$ (ft/day)	i	GW velocity (ft/day)	
	Min	Max			Min	Max
<i>Shallow Groundwater</i>						
A and B	0.430	0.469	5.9	0.0104	0.1308	0.1427
<i>Deep Groundwater</i>						
C	0.409	0.409	2.2	0.0095	0.0511	0.0511
D	0.409	0.409	2.2	0.0070	0.0377	0.0377

Note:

* = Flowpaths shown on Figure 3.15.

3.2.2.7 Preliminary Conceptual Model Summary

SWMU 166 consists of two lithostratigraphic units (Qs and Qcs) that comprise a surficial unconfined aquifer overlying a third impermeable unit that is the regional confining unit. Shallow wells monitor the homogeneous Qs unit whereas deep wells monitor the Qcs unit, which immediately overlies the confining unit. The Qs and Qcs units differ primarily by clay content in the soil matrix although not enough geotechnical data has been collected to fully quantify the differences in clay content between the two units. However, hydraulic conductivity data and groundwater velocity calculations indicate that the Qs is about twice as permeable as the Qcs.

Aquifer recharge occurs at the center of the site. Shallow and deep groundwater flows primarily west to east toward Interstate 26, the localized discharge zone. A secondary flow direction component is evident in the deep groundwater that may move contaminants toward the southeastern portion of the site.

The chemical component of the conceptual model will be addressed at the end of the following section.

3.3 Site Geochemistry

3.3.1 SWMU 166 Ranking

Nineteen monitoring wells (8 shallow and 11 deep) were sampled during the first round in March 1998. During the second round in September 1998, an additional six shallow monitoring wells and eight deep monitoring wells were added to the evaluation. The analytical data used in the ranking, the screening values for individual parameters, and the final ranking for each monitoring well for each MNA sampling round (when applicable) are found in Table 3.7.

Table 3.8 summarizes both MNA sampling rounds by presenting the change in ranking from round one to round two for each monitoring well (when applicable). Seven of the eight shallow monitoring wells sampled in both rounds increased in rank (conditions became more conducive to reductive dechlorination) and one decreased (conditions became less conducive to reductive dechlorination). Of the 11 deep monitoring wells sampled in both rounds, eight increased in rank, two decreased in rank, and one was unchanged. Overall, the ranking of the groundwater increased in anaerobic biodegradation potential.

The geographic distribution of the second round rankings is presented in Figures 3.16 and 3.17 for the shallow and deep rankings respectively. The first round is not presented due to limited site coverage. Shallow groundwater generally ranked lower at the center and the western edge of the

Table 3.7

SWMU 166 Monitoring Natural Attenuation Preliminary Ranking for Round 1 and Round 2 Monitoring Locations

		166001		166002		166003		166004		166005		
Analyte	units	Rd 1	Rd 2	Rd 1	Rd 2	Rd 1	Rd 2	Rd 1	Rd 2	Rd 1	Rd 2	
VOCs	Benzene	ug/l										
	Toluene	ug/l								4		
	Ethylbenzene	ug/l										
	Xylene	ug/l										
	PCE	ug/l								2		
	TCE	ug/l			1			2	2	35	10	
	cis-1,2-DCE	ug/l										
	trans-1,2-DCE	ug/l										
	1,2-DCE total	ug/l										
	1,1-DCE	ug/l										
	VC	ug/l										
	1,1,2-TCA	ug/l										
1,2-DCA	ug/l	4										
Dissolved Gases	Carbon Dioxide	mg/l	39.50	48.90	29.00	54.90	60.90	55.25	26.00	34.30	34.70	46.95
	log Carbon Dioxide		1.60	1.69	1.46	1.74	1.78	1.74	1.41	1.54	1.54	1.67
	Dissolved Oxygen	mg/l	0.90	1.30	0.97	0.60	2.57	1.70	1.09	1.60	1.72	3.35
	Hydrogen	nmol/l	0.08	0.77	0.19	0.67	0.25	1.07	0.44	1.15	0.19	1.13
	Nitrogen	mg/l	3.73	4.40	2.67	7.70	6.26	4.90	3.14	4.45	5.76	15.3
	Methane	ug/l	1.0 U	1.0 U	5.21	4.13	1.0 U	1.0 U	1.0 U	2.18	1.0 U	1.0 U
	log Methane				0.717	0.616				0.339		
	Ethane	ng/l	3.0 U	5.0 U	3.0 U	8	3.0 U	5.0 U	3	5.0 U	6	30
	Ethene	ng/l	3.0 U	10	6	115	7	15	11	17	10	32
	Geochemical Parameters	pH	std. Units	5.96	6.09	7.20	6.26	NA	6.54	5.96	5.70	5.31
Redox Potential		mV	204	309	-73	-51	55	276	199	268	168	187
Alkalinity		ppm	11	11	28	20	23	40	12	10 U	10	10 U
Nitrate		mg/l	0.14	0.10 U	0.10 U	0.10 U	0.10 U	0.41	0.20	0.10	1.0	5.4
Manganese(II)		mg/l	NA	0.500 U	NA	0.500 U	NA	0.500 U	NA	0.500 U	NA	0.500 U
Iron (II)		mg/l	0.500 U	0.500 U	0.500 U	0.902	0.500 U					
Iron (III)		mg/l	NA	0.500 U	NA	0.500 U	NA	0.500 U	NA	0.500 U	NA	0.500 U
Sulfate		mg/l	10.6	28	12.8	17	8.4	4.8	18.7	17	15.3	7.9
log Sulfate			1.03	1.45	1.11	1.23	0.92	0.68	1.27	1.23	1.18	0.90
Sulfide		mg/l	NA	1.00 U	NA	1.00 U	NA	1.00 U	NA	1.00 U	NA	1.00 U
Total Organic Carbon		mg/l	2.00 U	3.80	5.90	6.90	3.30	3.00	2.00 U	2.00 U	2.00 U	1.20
Nitrogen (TKN)		mg/l	NA	1.70	NA	1.00 U	NA	1.70	NA	1.00 U	NA	1.40
Total Phosphorus		mg/l	NA	0.100 U	NA	0.120	NA	0.100 U	NA	0.100 U	NA	0.100 U
Chloride		mg/l	1.8	NA	1.5	NA	1.0	NA	1.8	NA	1.8	NA
Specific Conductivity		nmho/cm	0.020	0.780	0.200	0.196	0.201	0.131	0.026	0.053	0.110	0.101
Temperature	°C	18.4	25.2	17.6	25.0	17.9	25.5	18.5	26.8	19.2	27.2	
Preliminary Screening Ranking	Dissolved Oxygen	POINTS	0	0	0	0	0	0	0	0	0	0
	Nitrate		2	2	2	2	2	2	2	2	0	0
	Iron (II)		0	0	0	0	0	0	0	0	0	0
	Sulfate		2	0	2	2	2	2	2	2	2	2
	Methane		0	0	0	0	0	0	0	0	0	0
	Redox Potential		0	0	1	1	0	0	0	0	0	0
	pH		0	0	0	0	0	0	0	0	0	0
	Total Organic Carbon		0	0	0	0	0	0	0	0	0	0
	Temperature		0	1	0	1	0	1	0	1	0	1
	Carbon Dioxide		0	0	0	0	0	0	0	0	0	0
	Alkalinity		0	0	0	0	0	1	0	0	0	0
	Hydrogen		0	0	0	0	0	3	0	3	0	3
	BTEX		0	0	0	0	0	0	0	0	0	0
	TCE		0	0	0	0	0	0	0	0	0	0
	DCE		0	0	0	0	0	0	0	0	0	0
	VC		0	0	0	0	0	0	0	0	0	0
	Ethene		0	0	0	0	0	0	0	0	0	0
Ethane	0	0	0	0	0	0	0	0	0	0		
Total Points		4	3	5	6	4	9	4	8	2	6	
NA evidence?		I	I	I	L	I	L	I	L	I	L	

Table 3.7

SWMU 166 Monitoring Natural Attenuation Preliminary Ranking for Round 1 and Round 2 Monitoring Locations

	Analyte	units	166006		166007		166008		166013	166014	166015	166016
			Rd 1	Rd 2	Rd 1	Rd 2	Rd 1	Rd 2				
VOCs	Benzene	ug/l										3
	Toluene	ug/l										
	Ethylbenzene	ug/l										
	Xylene	ug/l										
	PCE	ug/l										1
	TCE	ug/l							3	1		3000
	cis-1,2-DCE	ug/l										36
	trans-1,2-DCE	ug/l										
	1,2-DCE total	ug/l										36
	1,1-DCE	ug/l										1
	VC	ug/l										
	1,1,2-TCA	ug/l										1
1,2-DCA	ug/l											
Dissolved Gases	Carbon Dioxide	mg/l	18.10	28.40	35.00	40.80	18.10	34.25	23.05	58.30	46.30	57.90
	log Carbon Dioxide		1.26	1.45	1.54	1.61	1.26	1.53	1.36	1.77	1.67	1.76
	Dissolved Oxygen	mg/l	5.06	3.00	1.97	1.65	3.34	3.65	2.90	0.75	0.80	1.15
	Hydrogen	nmol/l	0.35	0.94	0.22	0.60	0.29	1.30	1.66	1.73	0.88	1.40
	Nitrogen	mg/l	9.15	6.60	5.46	13.2	9.62	14.4	6.35	6.65	14.0	13.1
	Methane	ug/l	1.0 U	1.0 U	1.0 U	1.74	1.0 U	1.0 U	1.0 U	60.70	2.34	26.30
	log Methane				0.240					1.783	0.369	1.420
	Ethane	ng/l	3.0 U	5.0 U	3.0 U	5.0 U	3.0 U	5.0 U	4	5.0 U	5.0 U	45
	Ethene	ng/l	6	5	5	6	7	11	32	5.0 U	9	98
Geochemical Parameters	pH	std. Units	6.52	5.91	4.35	4.47	NA	5.84	4.84	5.39	5.14	5.49
	Redox Potential	mV	121	137	250	275	97	168	380	94	104	96
	Alkalinity	ppm	12	10 U	10	10 U	14	13	10 U	10 U	10 U	10 U
	Nitrate	mg/l	0.10 U	0.16	0.10 U	0.10 U	3.0	1.8	0.12	0.10 U	0.10 U	0.10 U
	Manganese(II)	mg/l	NA	0.500 U	NA	0.500 U	NA	0.500 U				
	Iron (II)	mg/l	0.500 U	2.90	2.29							
	Iron (III)	mg/l	NA	0.500 U	NA	0.500 U	NA	0.500 U				
	Sulfate	mg/l	9.3	8.1	22.1	9.6	9.1	11	6.5	20	17	11
	log Sulfate		0.97	0.91	1.34	0.98	0.96	1.04	0.81	1.30	1.23	1.04
	Sulfide	mg/l	NA	1.00 U	NA	1.00 U	NA	1.00 U				
	Total Organic Carbon	mg/l	5.30	3.60	2.00 U	2.00 U	2.00 U	4.20	1.70	1.10	2.00 U	2.00 U
	Nitrogen (TKN)	mg/l	NA	2.20	NA	1.70	NA	1.00 U	3.90	2.20	1.00 U	1.00 U
	Total Phosphorus	mg/l	NA	0.100 U	NA	0.100 U	NA	0.100 U				
	Chloride	mg/l	1.7	NA	5.6	NA	2.0	NA	NA	NA	NA	NA
	Specific Conductivity	mmho/cm	0.063	0.058	0.067	0.036	0.085	0.097	0.033	0.065	0.055	0.055
Temperature	°C	17.6	27.0	17.1	23.7	18.3	25.7	25.0	24.6	24.5	25.4	
Preliminary Screening Ranking	Dissolved Oxygen	POINTS	-3	0	0	0	0	0	0	0	0	0
	Nitrate		2	2	2	2	0	0	2	2	2	2
	Iron (II)		0	0	0	0	0	0	0	0	3	3
	Sulfate		2	2	0	2	2	2	2	0	2	2
	Methane		0	0	0	0	0	0	0	0	0	0
	Redox Potential		0	0	0	0	0	0	0	0	0	0
	pH		0	0	-2	-2	0	0	-2	0	0	0
	Total Organic Carbon		0	0	0	0	0	0	0	0	0	0
	Temperature		0	1	0	1	0	1	1	1	1	1
	Carbon Dioxide		0	0	0	0	0	0	0	0	0	0
	Alkalinity		0	0	0	0	0	0	0	0	0	0
	Hydrogen		0	0	0	0	0	3	3	3	0	3
	BTEX		0	0	0	0	0	0	0	0	0	0
	TCE		0	0	0	0	0	0	0	0	0	0
	DCE		0	0	0	0	0	0	0	0	0	2
	VC		0	0	0	0	0	0	0	0	0	0
	Ethene		0	0	0	0	0	0	0	0	0	0
	Ethane		0	0	0	0	0	0	0	0	0	0
Total Points		1	5	0	3	2	6	6	6	8	13	
NA evidence?		I	I	N	I	I	L	L	L	L	L	

Table 3.7

SWMU 166 Monitoring Natural Attenuation Preliminary Ranking for Round 1 and Round 2 Monitoring Locations

	Analyte	units	166017	166018	16602D		16603D		16604D		16605D	
			Rd 2	Rd 2	Rd 1	Rd 2						
VOCs	Benzene	ug/l										
	Toluene	ug/l									2	
	Ethylbenzene	ug/l										
	Xylene	ug/l										
	PCE	ug/l		6								
	TCE	ug/l		3	5	2	4	4	36	99	4	
	cis-1,2-DCE	ug/l	1									11
	trans-1,2-DCE	ug/l										2
	1,2-DCE total	ug/l	1									13
	1,1-DCE	ug/l										
	VC	ug/l										
	1,1,2-TCA	ug/l										
1,2-DCA	ug/l						2					
Dissolved Gases	Carbon Dioxide	mg/l	47.10	27.95	33.30	36.15	33.20	24.15	25.50	23.60	28.20	35.05
	log Carbon Dioxide		1.67	1.45	1.52	1.56	1.52	1.38	1.41	1.37	1.45	1.54
	Dissolved Oxygen	mg/l	0.90	0.75	0.60	0.45	0.84	0.95	0.43	1.60	0.56	0.90
	Hydrogen	nmol/l	1.21	0.58	0.16	1.65	0.24	1.18	0.21	2.09	0.29	1.15
	Nitrogen	mg/l	14.0	14.3	3.04	3.45	8.26	11.3	2.99	6.85	15.2	15.8
	Methane	ug/l	58.30	34.55	6.31	7.83	67.80	78.10	16.28	21.15	12.56	9.12
	log Methane		1.766	1.538	0.800	0.893	1.831	1.893	1.212	1.325	1.099	0.960
	Ethane	ng/l	18	5.0 U	14	22	53	71	105	61	34	94
	Ethene	ng/l	25	12	5	15	20	44	154	149	19	45
Geochemical Parameters	pH	std. Units	4.68	5.06	6.62	6.31	NA	6.48	6.77	6.33	5.94	5.84
	Redox Potential	mV	129	94	-41	17	-39	-111	-51	-38	-22	-43
	Alkalinity	ppm	10 U	10 U	16	22	22	33	20	33	12	13
	Nitrate	mg/l	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U	0.10 U
	Manganese(II)	mg/l	0.500 U	0.500 U	NA	0.500 U						
	Iron (II)	mg/l	1.16	1.24	1.89	1.82	1.60	1.04	1.42	1.34	10.8	18.4
	Iron (III)	mg/l	0.500 U	0.500 U	NA	0.500 U						
	Sulfate	mg/l	22	18	10.8	18	9.8	8.1	25.8	17	108	78
	log Sulfate		1.34	1.26	1.03	1.26	0.99	0.91	1.41	1.23	2.03	1.89
	Sulfide	mg/l	1.00 U	1.00 U	NA	1.00 U						
	Total Organic Carbon	mg/l	2.00 U	2.00 U	2.00 U	1.60	2.00 U	1.10	2.00 U	2.00 U	2.00 U	2.00 U
	Nitrogen (TKN)	mg/l	1.00 U	1.00 U	NA	1.00 U	NA	4.20	NA	1.00 U	NA	1.40
	Total Phosphorus	mg/l	0.100 U	0.100 U	NA	0.370	NA	1.200	NA	1.100	NA	0.110
	Chloride	mg/l	NA	NA	3.2	NA	4.7	NA	4.0	NA	3.0	NA
Specific Conductivity	mmho/cm	0.075	0.049	0.044	0.045	0.173	0.235	0.040	0.127	0.208	0.127	
Temperature	°C	27.6	25.1	20.4	22.5	21.1	23.3	21.6	23.0	22.2	24.4	
Preliminary Screening Ranking	Dissolved Oxygen	POINTS	0	0	0	3	0	0	3	0	0	0
	Nitrate		2	2	2	2	2	2	2	2	2	2
	Iron (II)		3	3	3	3	3	3	3	3	3	3
	Sulfate		0	2	2	2	2	2	2	0	2	0
	Methane		0	0	0	0	0	0	0	0	0	0
	Redox Potential		0	0	1	1	1	2	1	1	1	1
	pH		-2	0	0	0	0	0	0	0	0	0
	Total Organic Carbon		0	0	0	0	0	0	0	0	0	0
	Temperature		1	1	1	1	1	1	1	1	1	1
	Carbon Dioxide		0	0	0	0	0	0	0	0	0	0
	Alkalinity		0	0	0	0	0	0	0	0	0	0
	Hydrogen		3	0	0	3	0	3	0	3	0	3
	BTEX		0	0	0	0	0	0	0	0	0	0
	TCE		0	0	0	0	0	0	0	0	0	0
	DCE		0	0	0	0	0	2	0	2	0	0
	VC		0	0	0	0	0	0	0	0	0	0
	Ethene		0	0	0	0	0	0	0	0	0	0
	Ethane		0	0	0	0	0	0	0	0	0	0
	Total Points			7	8	9	15	9	15	10	14	7
NA evidence?		L	L	L	A	L	A	L	L	L	L	

Table 3.8
Summary of Monitored Natural Attenuation Ranking of SWMU 166

Well ID	Round 1		Round 2		Change in Total Points (2)
	Total Pts	NA evidence (1)	Total Pts	NA evidence	
166GW001	4	I	3	I	-1
166GW002	5	I	6	L	1
166GW003	4	I	9	L	5
166GW004	4	I	8	L	4
166GW005	2	I	6	L	4
166GW006	1	I	5	I	4
166GW007	0	N	3	I	3
166GW008	2	I	6	L	4
166GW013	NS	NS	6	L	NS
166GW014	NS	NS	6	L	NS
166GW015	NS	NS	8	L	NS
166GW016	NS	NS	13	L	NS
166GW017	NS	NS	7	L	NS
166GW018	NS	NS	8	L	NS
166GW02D	9	L	15	A	6
166GW03D	9	L	15	A	6
166GW04D	10	L	14	L	4
166GW05D	7	L	10	L	3
166GW06D	8	L	11	L	3
166GW07D	11	L	9	L	-2
166GW08D	9	L	14	L	5
166GW09D	9	L	9	L	0
166GW10D	9	L	11	L	2
166GW11D	11	L	10	L	-1
166GW12D	12	L	13	L	1
166GW13D	NS	NS	10	L	NS
166GW14D	NS	NS	14	L	NS
166GW15D	NS	NS	9	L	NS
166GW16D	NS	NS	13	L	NS
166GW17D	NS	NS	12	L	NS
166GW18D	NS	NS	12	L	NS
166GW22D	NS	NS	12	L	NS
166GW23D	NS	NS	12	L	NS

Notes:

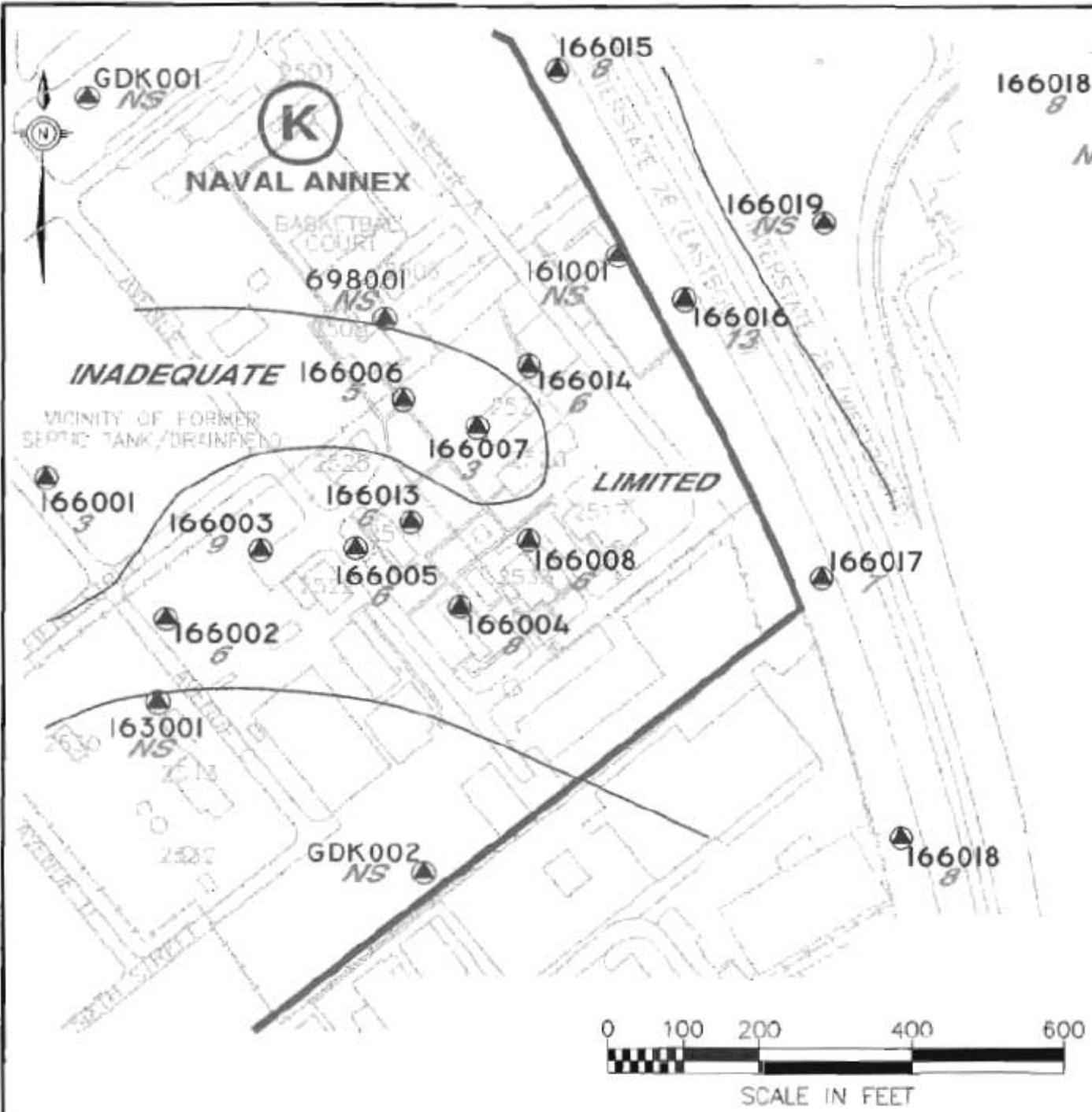
1 - Ranking results

- N= No evidence
- I= Inadequate evidence
- L= Limited evidence
- A= Adequate evidence
- S= Strong evidence
- NS= Not Sampled

2 - The change in total point was calculated by subtracting the second round data from the first round data.

- change = decrease in MNA ranking

+ change = increase in MNA ranking



LEGEND:

- 166018  SHALLOW MONITORING WELL W/ ID NUMBER AND RANKING
- NS* = NOT SAMPLED



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FIGURE 3.16

GEOGRAPHICAL DISTRIBUTION OF
 SHALLOW WELL RANKINGS

site and progressively increased in ranking towards the eastern and southern edges. The distribution of deep monitoring well rankings indicated a nucleus of higher ranked monitoring wells near the southwestern edge of the site.

For both sampling rounds the shallow wells ranked lower in anaerobic biodegradation potential than the deep monitoring wells. Based upon the ranking parameters, this trend reflects higher concentrations of iron (II), and chlorinated compounds; lower dissolved oxygen at the center of the site, lower oxidation-reduction potential, and a pH closer to 7 in deep groundwater as compared to shallow groundwater. An exception to the preceding observation appeared during the second round involving well 166016. The groundwater from this monitoring well, located along the eastern boundary of the site, had a ranking and geochemical properties more similar to those found in the deep monitoring wells from Round 2. This exception is most likely due to the discharge nature of the aquifer in the vicinity of this monitoring well. The groundwater from the more heavily contaminated deeper portions of the surficial aquifer flows towards the surface on the east side of the site.

Based upon the rankings, the deep groundwater on the southwestern edge of the site has the highest potential to support intrinsic biodegradation. Shallow groundwater on the northern and eastern edge of the site and deep groundwater across the site has some potential for intrinsic biodegradation.

3.3.2 Spatial Distribution of Analytical Parameters

The spatial distribution of compounds (contaminants, metabolic by-products, field parameters, etc.) is important for assessing the natural attenuation potential of a contaminated aquifer. Identifying such features as contaminant plumes and oxidation-reduction zones is best done visually as isopleth (contour) maps. Superimposing of analyte distributions may also enhance understanding of the geochemical and microbial processes occurring in an aquifer.

The larger well population sampled in Round 2 allowed for better data coverage than Round 1. Isopleths were constructed only for those parameters with an important role in defining the geochemical system as pertaining to MNA. Isopleths were not constructed for compounds with only one or two detections.

3.3.2.1 Chlorinated Compounds

PCE

Shallow Groundwater

PCE was detected in only one first round shallow groundwater sample at 2.0 $\mu\text{g/L}$ and twice in second round samples at 1.0 $\mu\text{g/L}$ and 6.0 $\mu\text{g/L}$ (Figure 3.18).

PCE was located during Round 2 at isolated sample points on the extreme edges of SWMU 166, offsite to the extreme southeast at 166018 and northeast at 166016. Because the MCL for PCE is 5 $\mu\text{g/L}$, these detections are minor.

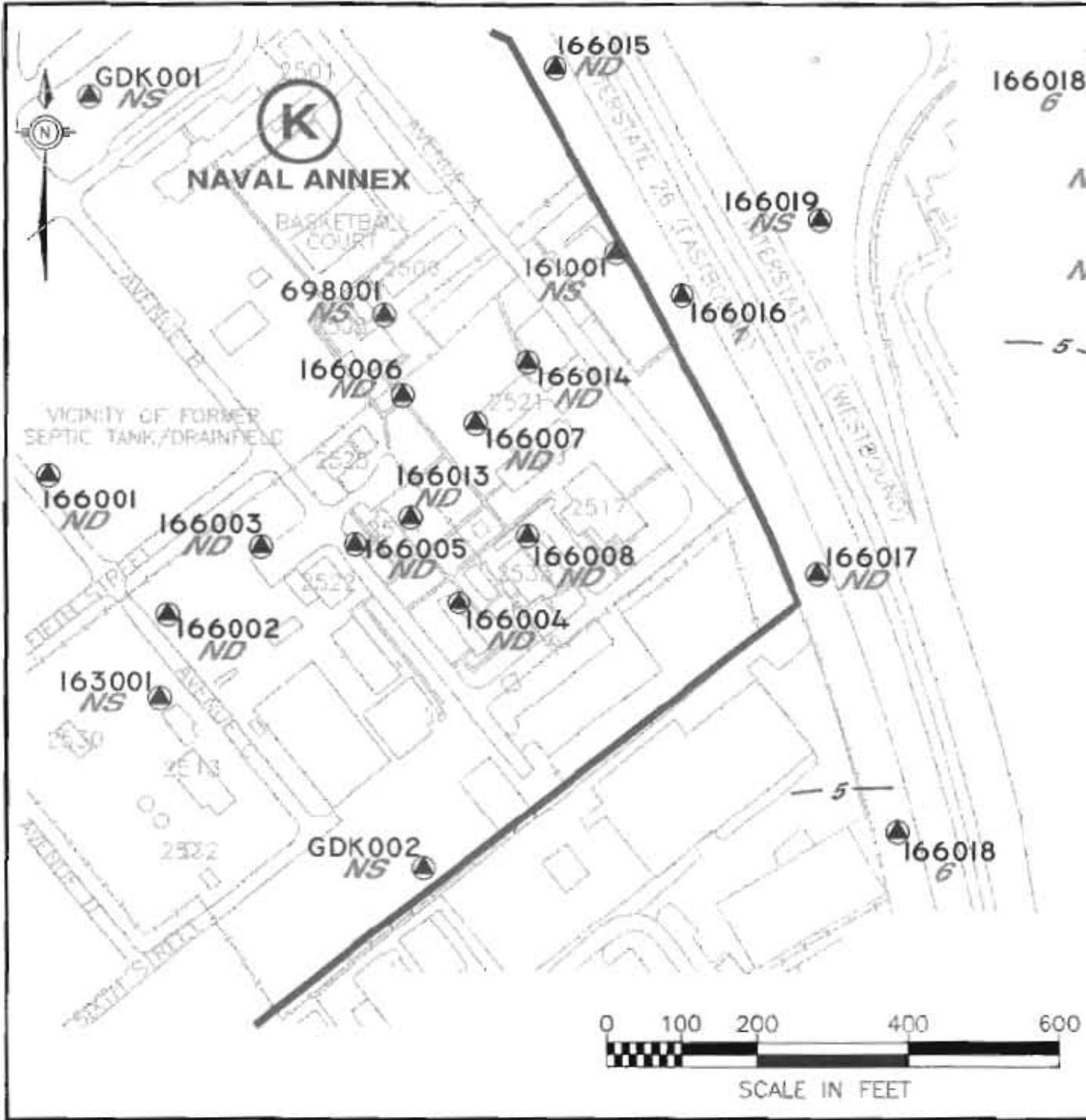
Deep Groundwater

PCE was not detected in the deep groundwater during Round 1 and only once in Round 2 at 1.0 $\mu\text{g/L}$ at 16618D.

TCE

Shallow Groundwater

TCE was detected in three of eight Round 1 shallow monitoring wells and six of 14 Round 2 shallow monitoring wells. First and second round detections ranged between 1.0 to 10.0 $\mu\text{g/L}$ and 1.0 to 3000 $\mu\text{g/L}$ (Figures 3.19 and 3.20).



LEGEND:

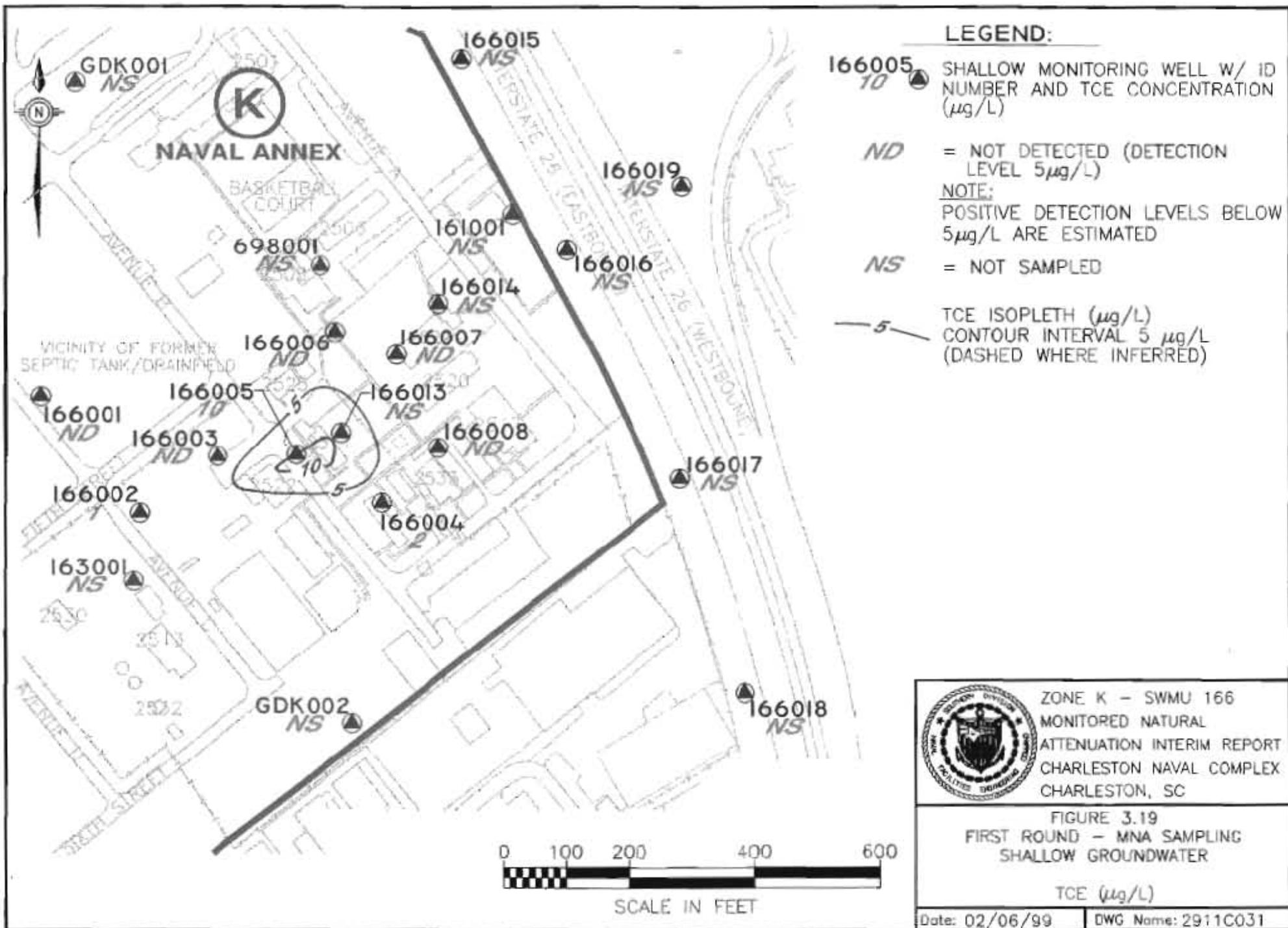
- 166018  SHALLOW MONITORING WELL W/ ID NUMBER AND PCE CONCENTRATION ($\mu\text{g/L}$)
- ND* = NOT DETECTED (DETECTION LEVEL 5 $\mu\text{g/L}$)
- NS* = NOT SAMPLED
- 5 - PCE ISOPLETH ($\mu\text{g/L}$)
CONTOUR INTERVAL 5 $\mu\text{g/L}$
(DASHED WHERE INFERRED)

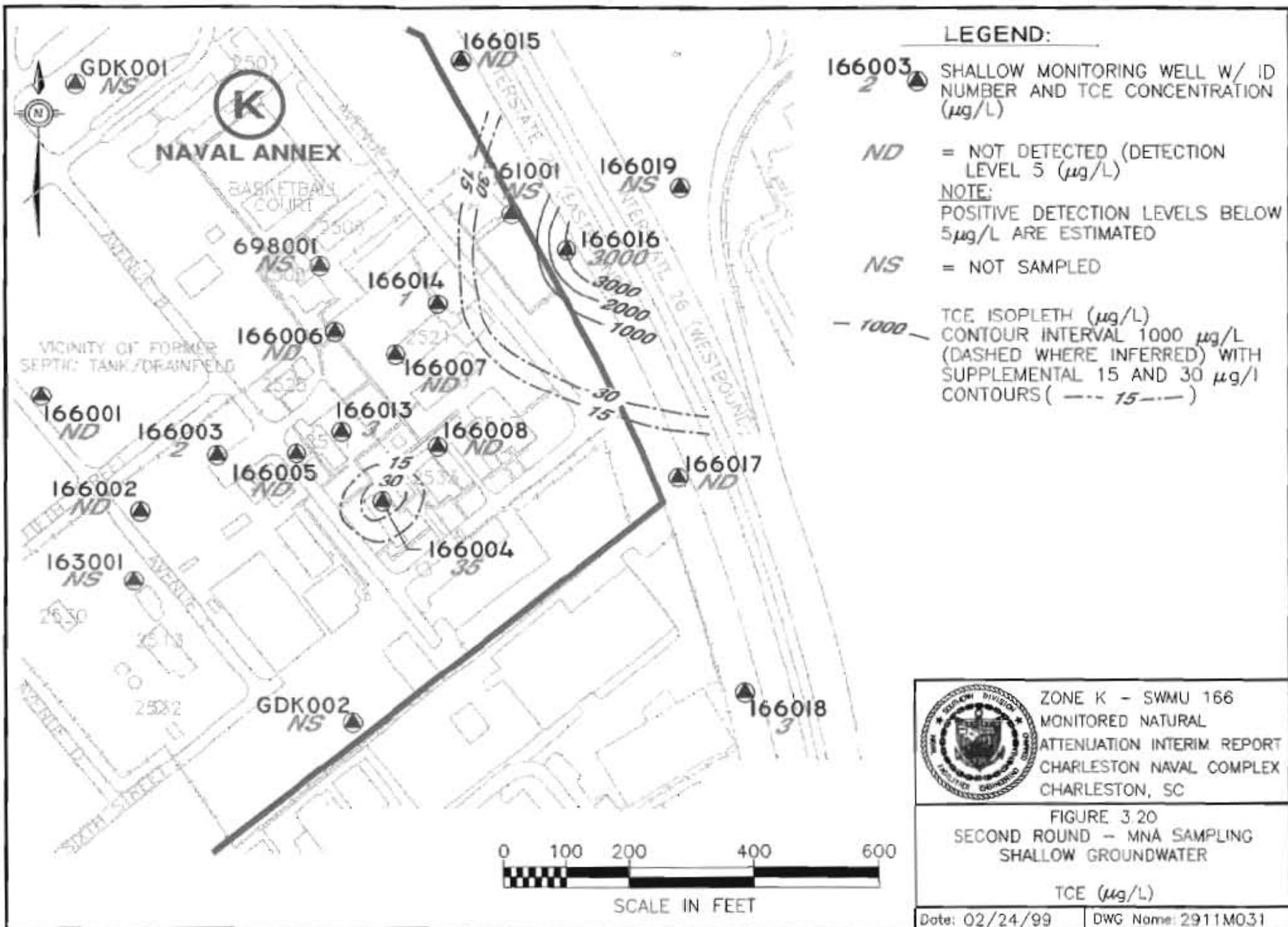


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FIGURE 3.18
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

PCE ($\mu\text{g/L}$)





GDK001
NS

K

NAVAL ANNEX

BASKETBALL COURT

698001
NS

166014
1

166006
ND

166007
ND

VICINITY OF FORMER SEPTIC TANK/DRAINFIELD

166001
ND

166003
2

166005
ND

166013
3

166008
ND

166002
ND

163001
NS

GDK002
NS

166004
35

166015
ND

61001
NS

166019
NS

166016
3000

3000

2000

1000

30

15

166017
ND

166018
3



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FIGURE 3.20
SECOND ROUND - MNA SAMPLING
SHALLOW GROUNDWATER

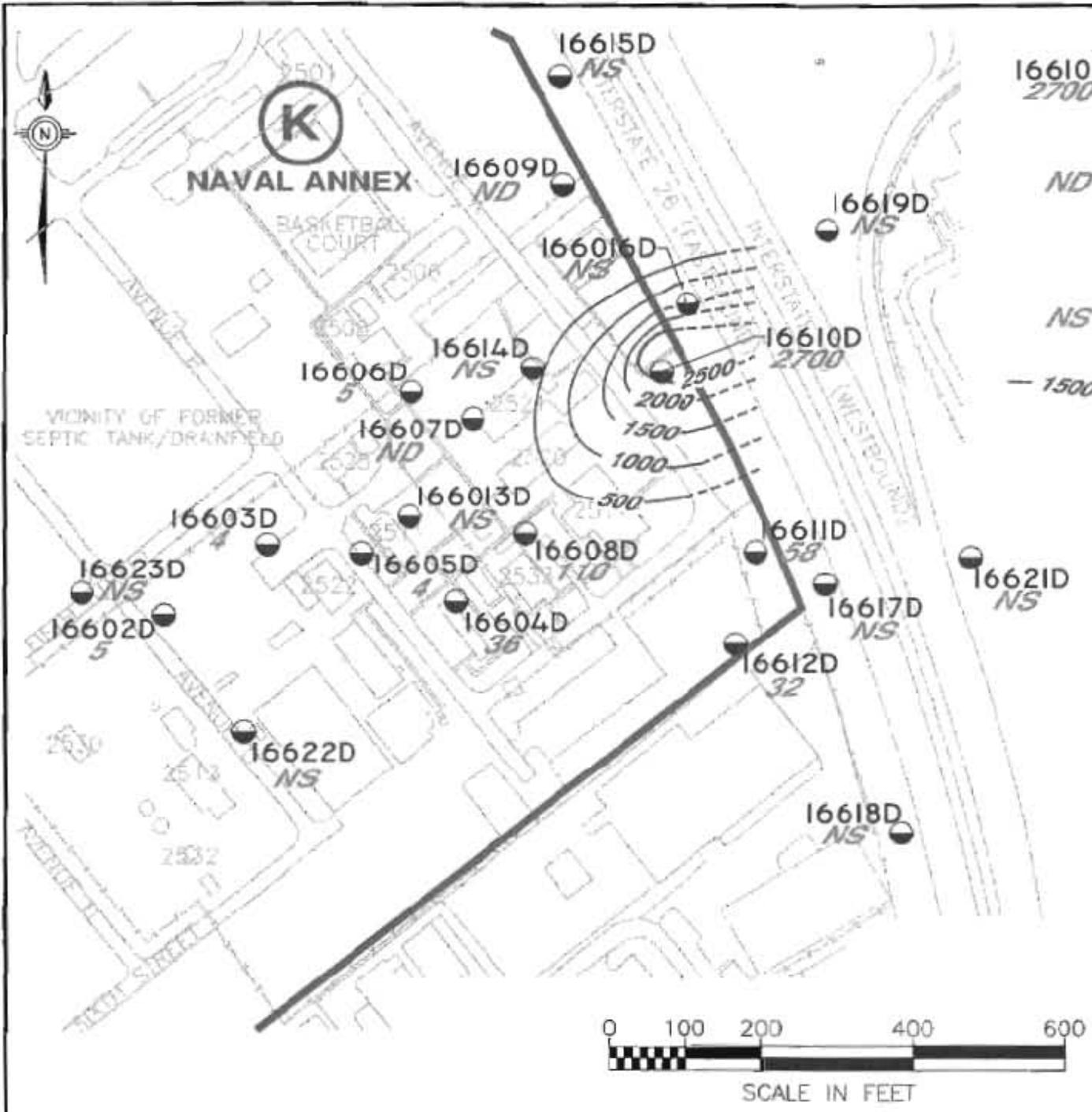
TCE ($\mu\text{g/L}$)

Well 166005 was the location of the only significant shallow groundwater TCE detection at 10 $\mu\text{g/L}$ (the other two are estimated values below the MCL limit of 5.0 $\mu\text{g/L}$). The two detections above the MCL occurred at wells 166004 (35.0 $\mu\text{g/L}$) and 166016 (3,000 $\mu\text{g/L}$). The difference in plume morphology evident in Figure 3.20 is largely the result of the expanded Round 2 well network. It is important to note that closer to the source area, higher concentrations occurred at 166004 in Round 2 than at 166005 in Round 1.

Deep Groundwater

TCE was detected in nine of 11 first round deep wells, ranging in concentrations from 4.0 to 2,700 $\mu\text{g/L}$ (Figure 3.21). Sixteen of 19 second round deep wells revealed TCE detections, between 1.0 to 4800 $\mu\text{g/L}$ (Figure 3.22).

The first round TCE concentrations were unusual since they did not mimic the quarterly results. TCE in deep groundwater during Round 1 appeared as an isolated high near 16610D, surrounded by relatively minor detections upgradient to the west and crossgradient to the south-southwest. TCE in groundwater during Round 2 appeared as a massive plume moving northeast across the site, originating at 16613D and flowing toward and moving offsite at 16616D. The unusual spatial distribution of TCE in the Round 1 results can be attributed to two factors. First, Round 1 data encompassed a smaller area due to the smaller population of SWMU 166 wells sampled. Deep well 16613D was not sampled in Round 1, and as indicated by Round 2 data, this well is close to the TCE source area. Second, the order of magnitude decreases in TCE concentrations for Round 1 are most likely due to the large amounts of rainfall recorded for March 1998 (this point is further discussed in Section 3.3.3). For example well 16607D, which is hydraulically downgradient of 16613D, had nondetectable concentrations of TCE during Round 1 and 1400 $\mu\text{g/L}$ of TCE in Round 2. The Round 2 concentration at 16607D correlated closely with its quarterly TCE concentration which ranged from 900 to 2,000 $\mu\text{g/L}$.



LEGEND:

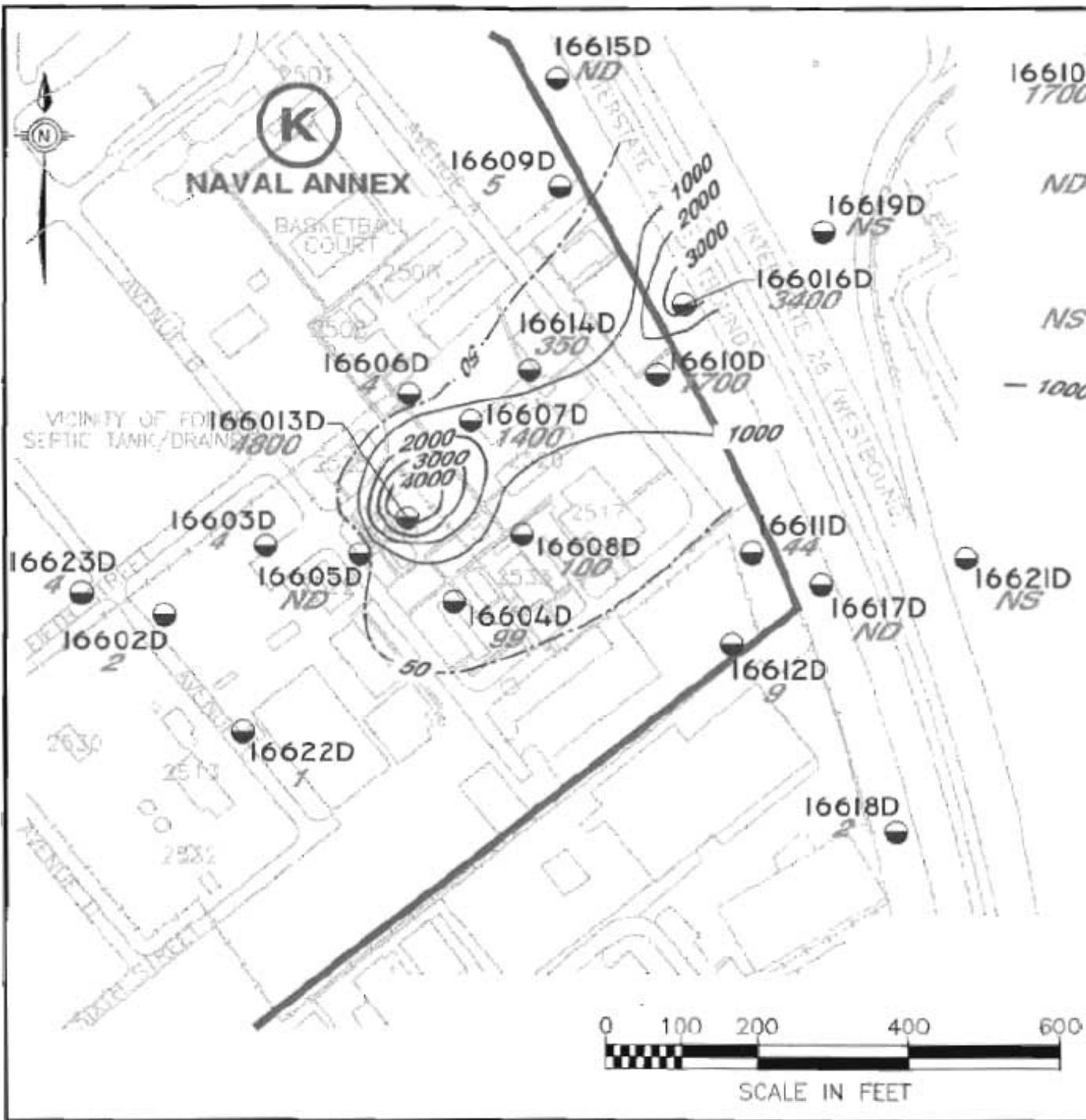
- 16610D**
2700 ● DEEP MONITORING WELL W/ ID NUMBER AND TCE CONCENTRATION ($\mu\text{g/L}$)
- ND** = NOT DETECTED (DETECTION LEVEL $5\mu\text{g/L}$)
- NOTE:**
POSITIVE DETECTION LEVELS BELOW $5\mu\text{g/L}$ ARE ESTIMATED
- NS** = NOT SAMPLED
- 1500 —**
TCE ISOPLETH ($\mu\text{g/L}$)
CONTOUR INTERVAL $500\mu\text{g/L}$
(DASHED WHERE INFERRED)



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FIGURE 3.21
 FIRST ROUND - MNA SAMPLING
 DEEP GROUNDWATER

TCE ($\mu\text{g/L}$)



LEGEND:

- 16610D 1700 ● DEEP MONITORING WELL W/ ID NUMBER AND TCE CONCENTRATION ($\mu\text{g/L}$)
- ND = NOT DETECTED (DETECTION LEVEL $5\mu\text{g/L}$)
- NOTE: POSITIVE DETECTION LEVELS BELOW $5\mu\text{g/L}$ ARE ESTIMATED
- NS = NOT SAMPLED
- 1000 - TCE ISOPLETH ($\mu\text{g/L}$)
CONTOUR INTERVAL $1000\mu\text{g/L}$ (DASHED WHERE INFERRED) WITH SUPPLEMENTAL $50\mu\text{g/L}$ CONTOUR (--- 50 ---)



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FIGURE 3.22
SECOND ROUND - MNA SAMPLING
DEEP GROUNDWATER

TCE ($\mu\text{g/L}$)

1,2-DCE (total)

1,2-DCE (total) is the sum of concentrations of the isomers cis-1,2-DCE and trans-1,2-DCE.

Shallow Groundwater

1,2-DCE (total) was not detected in shallow groundwater during Round 1, but was detected in two second round shallow wells at concentrations of 1.0 $\mu\text{g/L}$ (166017) and 36.0 $\mu\text{g/L}$ (166016) (Figure 3.23).

Deep Groundwater

1,2-DCE (total) was not detected in any Round 1 deep groundwater samples, but was detected in seven deep wells in Round 2 between 12.0 and 618 $\mu\text{g/L}$ (Figure 3.24).

The lack of 1,2-DCE (total) in shallow groundwater near the source area as well as the high concentrations evident at 16613D, indicate that solvent contamination favors vertical over lateral migration. However, lateral migration is favored once contamination reaches deeper portions of the aquifer, as evidenced by the high concentrations extending along the flowpath from 16613D toward 16616D. The appearance of 1,2-DCE (total) at 166016 reflects the hydraulic role of the interstate as a discharge zone where fluxes are predominantly upward.

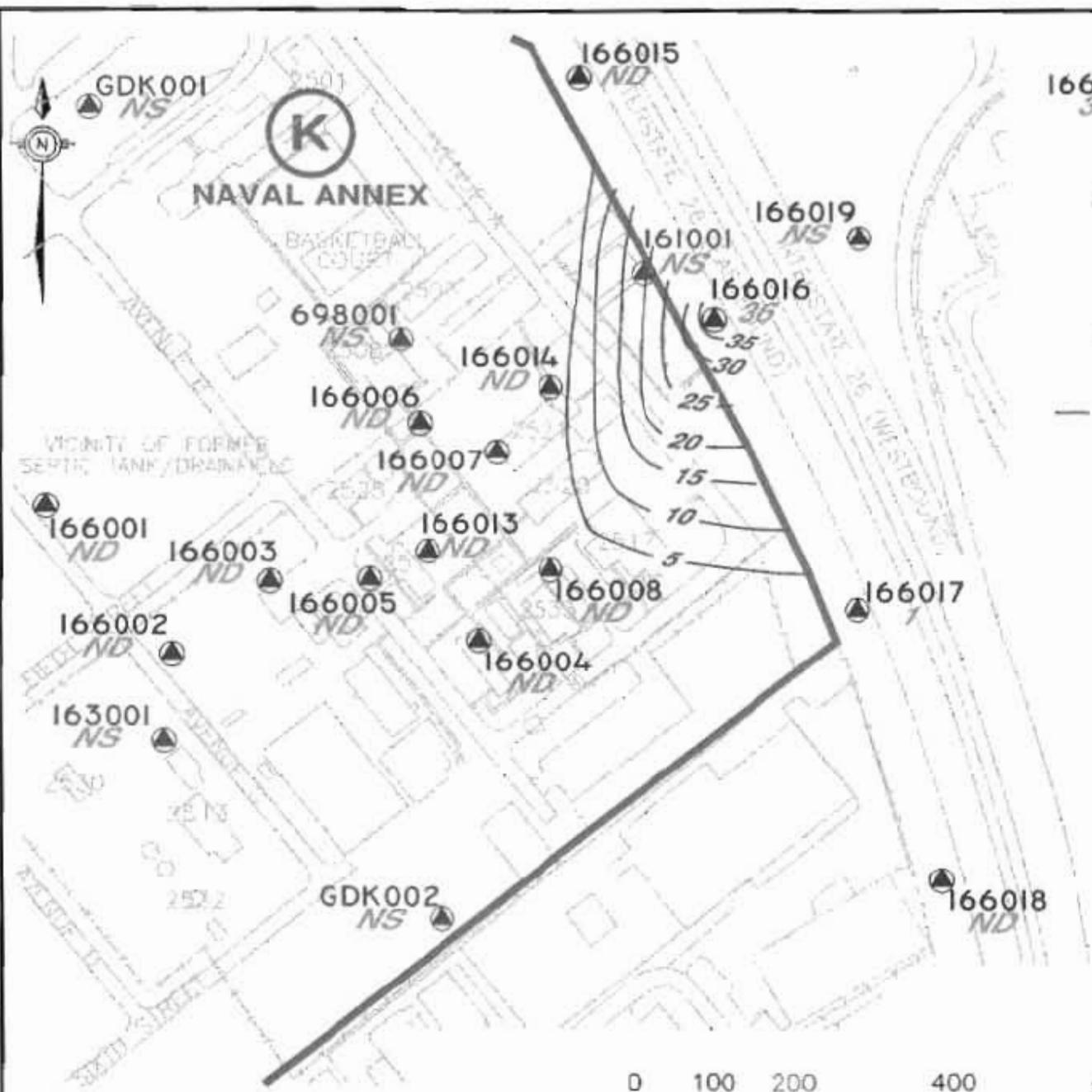
VC

Shallow Groundwater

VC was not detected in shallow groundwater samples from either Round 1 or Round 2 samples.

Deep Groundwater

VC was not detected in Round 1 deep groundwater samples, and only once in Round 2 (31.0 $\mu\text{g/L}$ at 16616D) (Figure 3.25). This well is the easternmost well before the discharge zone coinciding with Interstate 26.



LEGEND:

166016 ³⁶ ● SHALLOW MONITORING WELL W/ ID NUMBER AND 1,2-DCE (TOTAL) CONCENTRATION (µg/L)

ND = NOT DETECTED (DETECTION LEVEL 5 (µg/L))

NOTE:
POSITIVE DETECTION LEVELS BELOW 5µg/L ARE ESTIMATED

NS = NOT SAMPLED

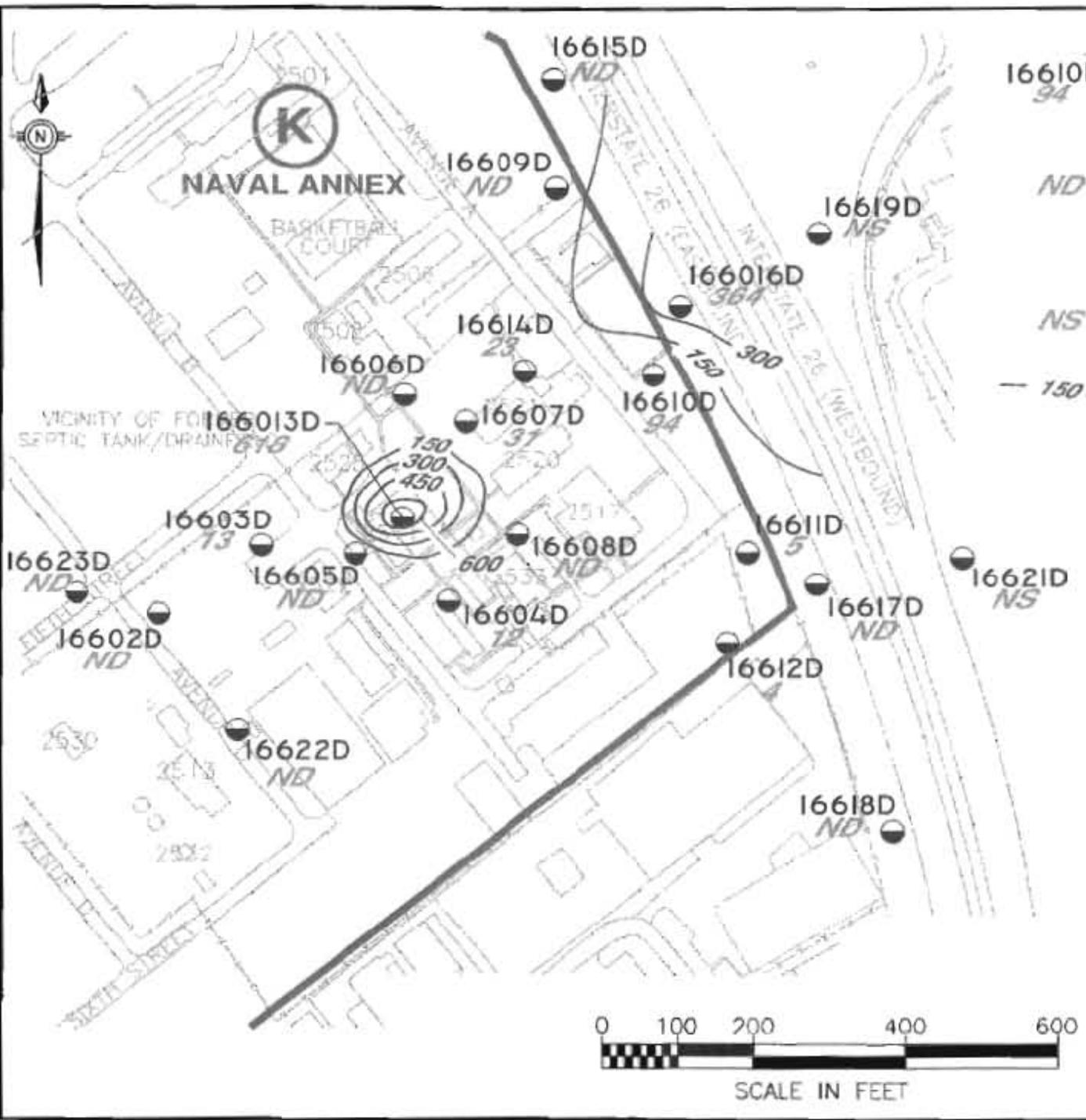
— 20 — 1,2-DCE (TOTAL) ISOPLETH (µg/L)
CONTOUR INTERVAL 5 µg/L
(DASHED WHERE INFERRED)



ZONE K - SWMU 166
MONITORED NATURAL
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FIGURE 3.23
SECOND ROUND - MNA SAMPLING
SHALLOW GROUNDWATER

1,2-DCE (TOTAL) (µg/L)



LEGEND:

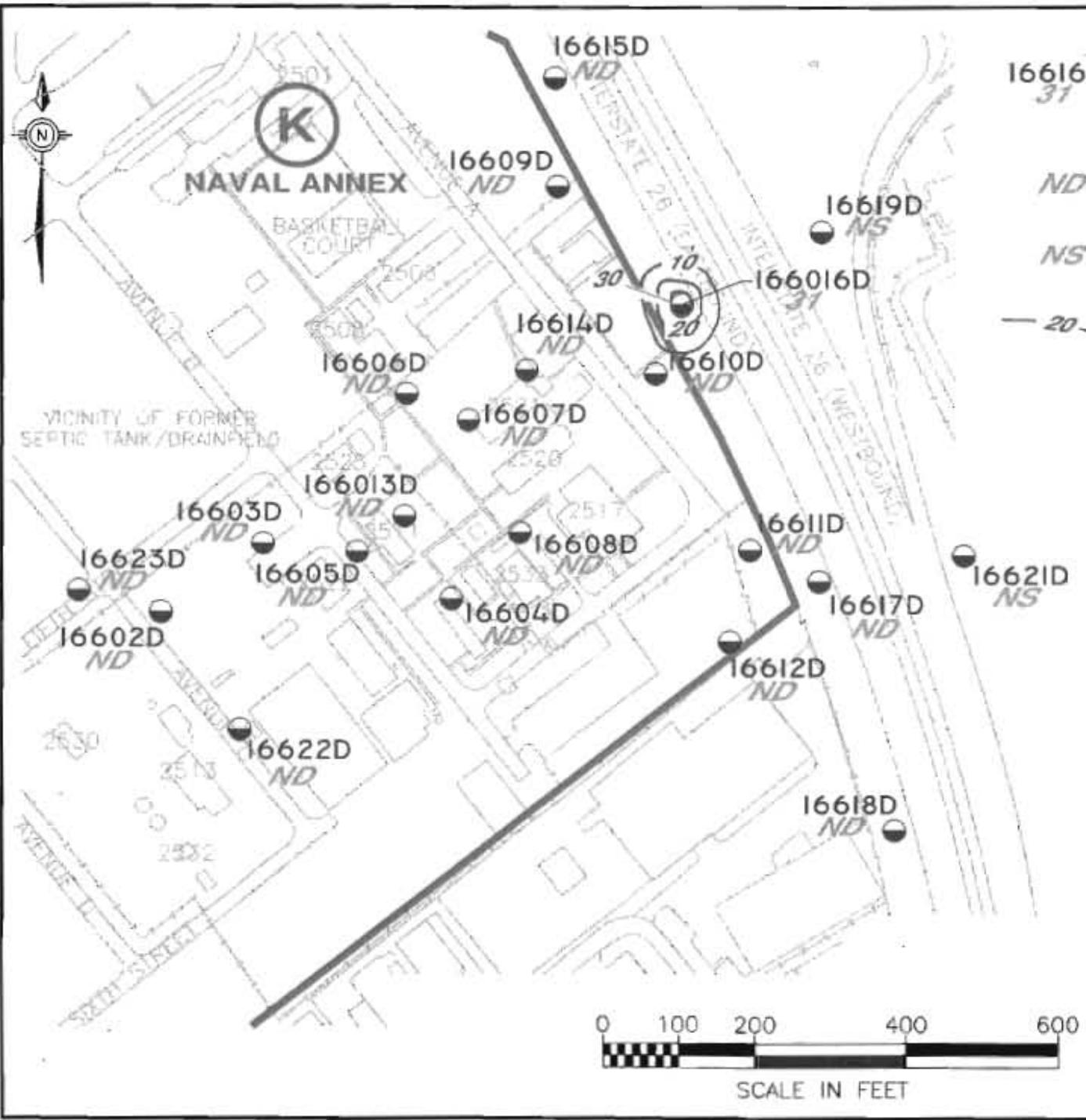
- 16610D₉₄ ● DEEP MONITORING WELL W/ ID NUMBER AND 1,2-DCE (TOTAL) CONCENTRATION ($\mu\text{g/L}$)
- ND = NOT DETECTED (DETECTION LEVEL $5\mu\text{g/L}$)
- NOTE: POSITIVE DETECTION LEVELS BELOW $5\mu\text{g/L}$ ARE ESTIMATED
- NS = NOT SAMPLED
- 150 - 1,2-DCE (TOTAL) ISOPLETH ($\mu\text{g/L}$) CONTOUR INTERVAL $150\mu\text{g/L}$ (DASHED WHERE INFERRED)



ZONE K - SWMU 166
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FIGURE 3.24
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER

1,2-DCE (TOTAL) ($\mu\text{g/L}$)



LEGEND:

- 16616D
31 ● DEEP MONITORING WELL W/ ID NUMBER AND VC CONCENTRATION ($\mu\text{g/L}$)
- ND = NOT DETECTED (DETECTION LEVEL $5\mu\text{g/L}$)
- NS = NOT SAMPLED
- 20 — VC ISOPLETH ($\mu\text{g/L}$)
CONTOUR INTERVAL $10\mu\text{g/L}$
(DASHED WHERE INFERRED)



ZONE K - SWMU 166
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FIGURE 3.25
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER

VC ($\mu\text{g/L}$)

Date: 03/02/99

DWG Name: 2911M051



Ethene

Shallow Groundwater

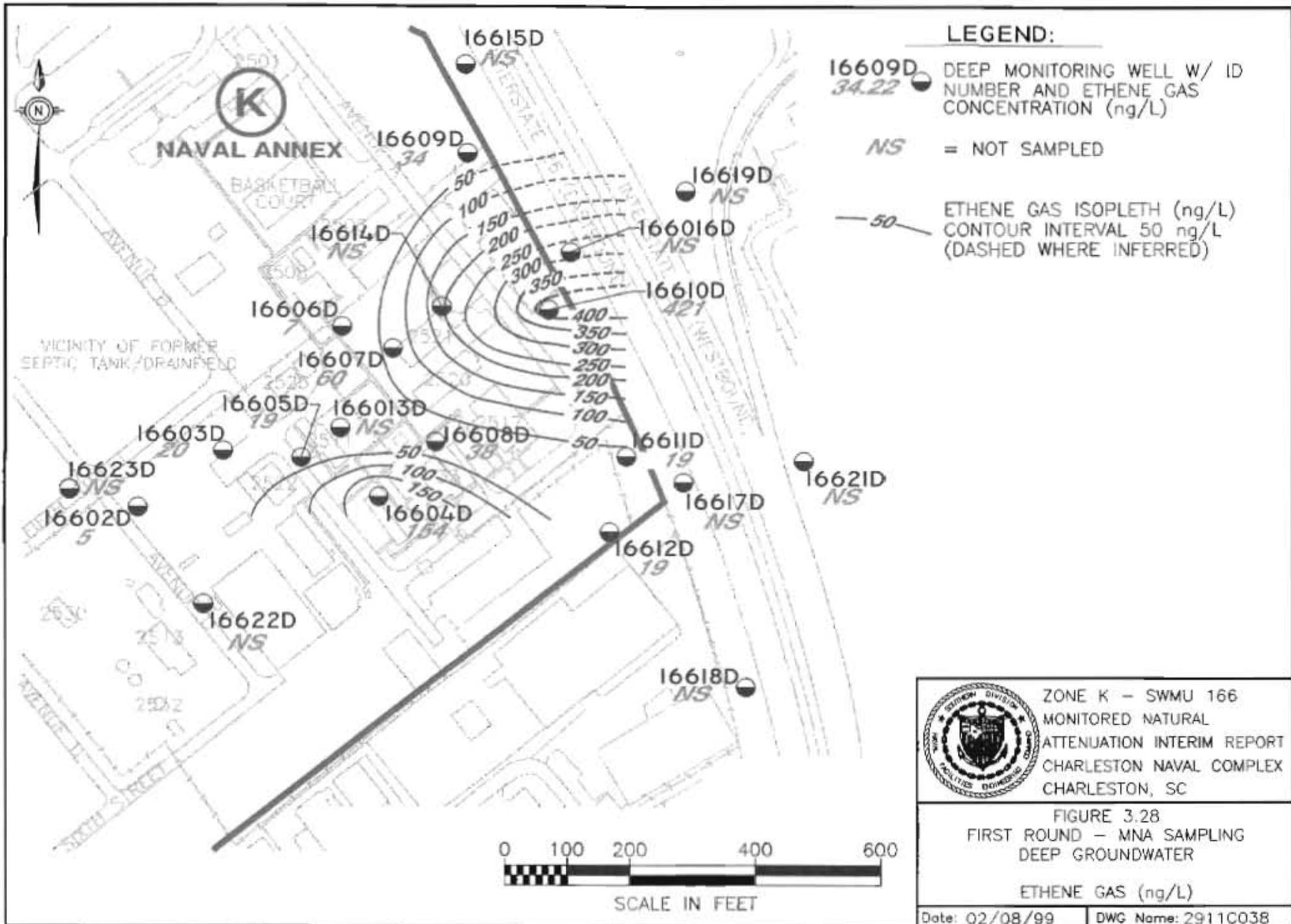
Ethene was detected in all eight first round shallow wells, ranging in concentration from 5 to 11 ng/L (Figure 3.26). Ethene was detected in all but one second round shallow well (166014) between 5 to 115 ng/L (Figure 3.27).

Ethene concentrations in shallow groundwater during Round 1 were clustered around 166004 and decreased in all directions except south (no data to infer southern trend). Round 2 ethene concentrations were highest at 166002 (115 ng/L) on the southwest side of the site and at 166016 (98 ng/L) on the northeast side. As a result, a region of low ethene concentration bisects SWMU 166 from northwest to southeast (Figure 3.27).

Deep Groundwater

Ethene was detected in all 11 first round deep wells and all 19 second round deep wells (Figures 3.28 and 3.29). First round ethene concentrations ranged between 5 and 421 ng/L, whereas second round concentrations ranged from 5 to 5,735 ng/L.

Ethene in Round 1 was found as isolated concentration highs around wells 16610D and 16604D. Concentrations distributed along the eastern site boundary were further refined in Round 2 with the expanded sampled well network. The Round 2 data also showed a localized ethene concentration high at 16613D. Ethene distributions in Round 2 reflect the distribution of TCE in that Round which delineated a plume originating at 16613D and flowing northeast across the site to 16616D at the interstate.



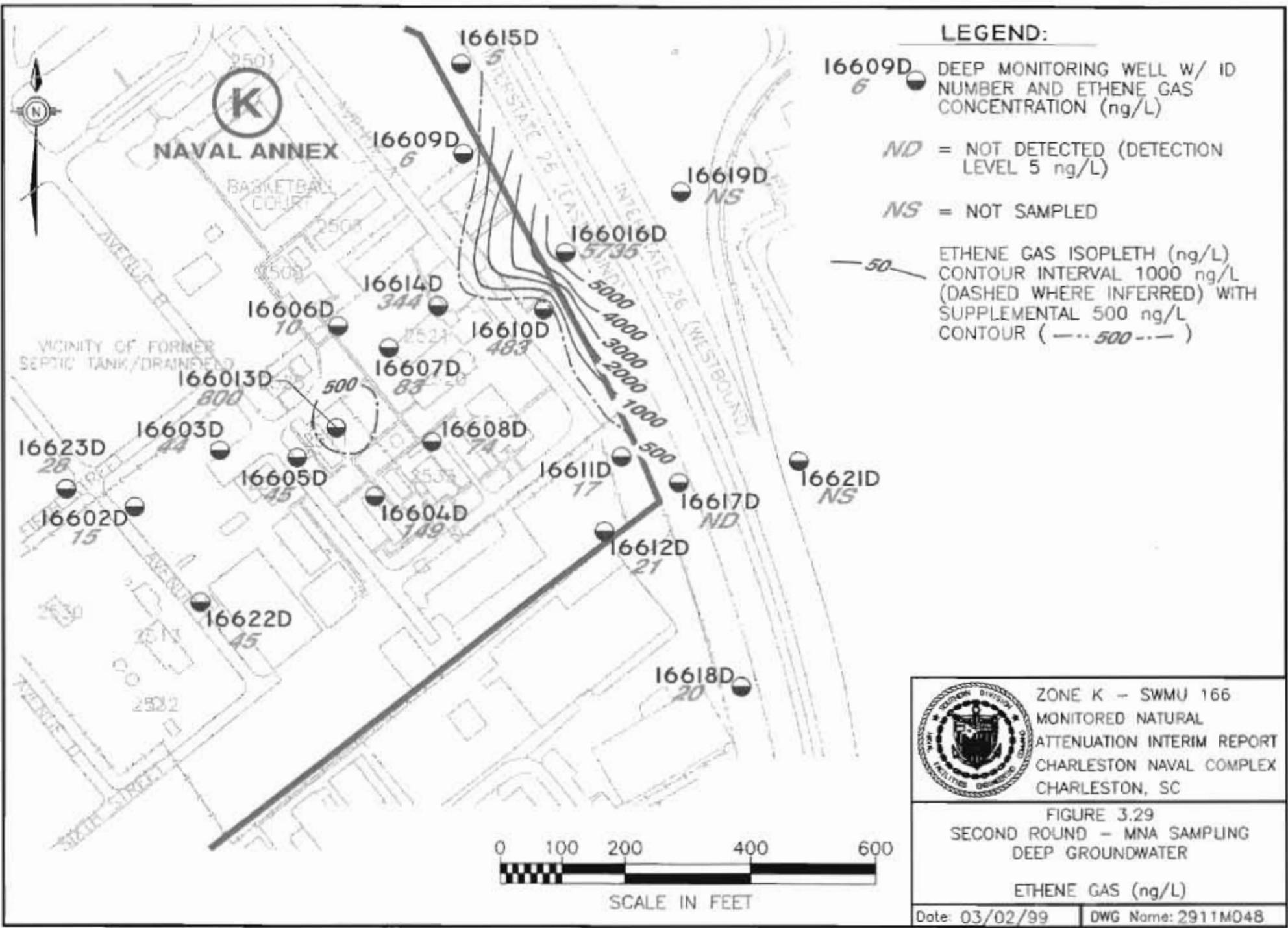
LEGEND:

- 16609D 34.22 ● DEEP MONITORING WELL W/ ID NUMBER AND ETHENE GAS CONCENTRATION (ng/L)
- NS ● = NOT SAMPLED
- 50 — ETHENE GAS ISOPLETH (ng/L) CONTOUR INTERVAL 50 ng/L (DASHED WHERE INFERRED)


 ZONE K - SWMU 166
 MONITORED NATURAL
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FIGURE 3.28
 FIRST ROUND - MNA SAMPLING
 DEEP GROUNDWATER

ETHENE GAS (ng/L)




 ZONE K - SWMU 166
 MONITORED NATURAL
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FIGURE 3.29
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER
 ETHENE GAS (ng/L)
 Date: 03/02/99 | DWG Name: 2911M048

3.3.2.2 Metabolic By-products and Field Parameters

Oxidation-Reduction Potential

Natural attenuation of hydrocarbons via oxidation-reduction (redox) reactions is mediated by microorganisms. The redox potential of groundwater is a measure of the tendency for chemicals in groundwater to transfer their electrons. Microorganisms foster these reactions by utilizing electron transfer to do work.

Many biodegradation processes are carried out in the presence of oxygen. Oxygen is the most thermodynamically favorable electron acceptor since it produces the most energy. In an environment without oxygen, microorganisms must seek out new electron acceptors. The next most favorable electron acceptors in decreasing order are nitrate, manganese (IV), iron (III), sulfate, and carbon dioxide. When these chemicals accept electrons from microorganisms, they become new compounds with different chemistries and reactivities. These new compounds can then be detected in groundwater and attributed to a specific redox process.

Redox reactions involving organic compounds are also sensitive to the redox state of an aquifer, that is, they only occur under specific redox conditions. Reductive dechlorination is one of these reactions. Reductive dechlorination is carried out only in an anaerobic, oxygen-deficient environment. Reductive dechlorination can operate under a wide range of redox conditions, typically +700 millivolts (mV) to -250 mV. However, the optimal range for reductive dechlorination is approximately -100 mV to -250 mV, which is associated with sulfate and carbon dioxide reduction. Unfortunately, the exact redox state of an aquifer is difficult to measure. Unique redox potentials in groundwater do not exist. Redox reactions typically occur simultaneously among several different redox couples in any given groundwater. The measure of redox potential, at best, gives a broad view of the oxidation-reduction state of an aquifer.

Shallow Groundwater

Oxidation-reduction potential (ORP) was measured during Rounds 1 and 2 using a silver/silver chloride electrode. ORP measurements from Round 1 shallow wells ranged from -73 to 250 mV and from -51 to 380 mV in Round 2 (Figures 3.30 and 3.31). All Round 1 and Round 2 shallow wells had a positive ORP, with a lone exception at 166002 during both rounds (ORP of -73 and -51 mV, respectively). The distribution of ORP appears to create a ridge of oxidizing (ORP > 0) conditions trending northwest to southeast. Conditions in the northeast and southeast regions of SWMU 166 are less oxidizing.

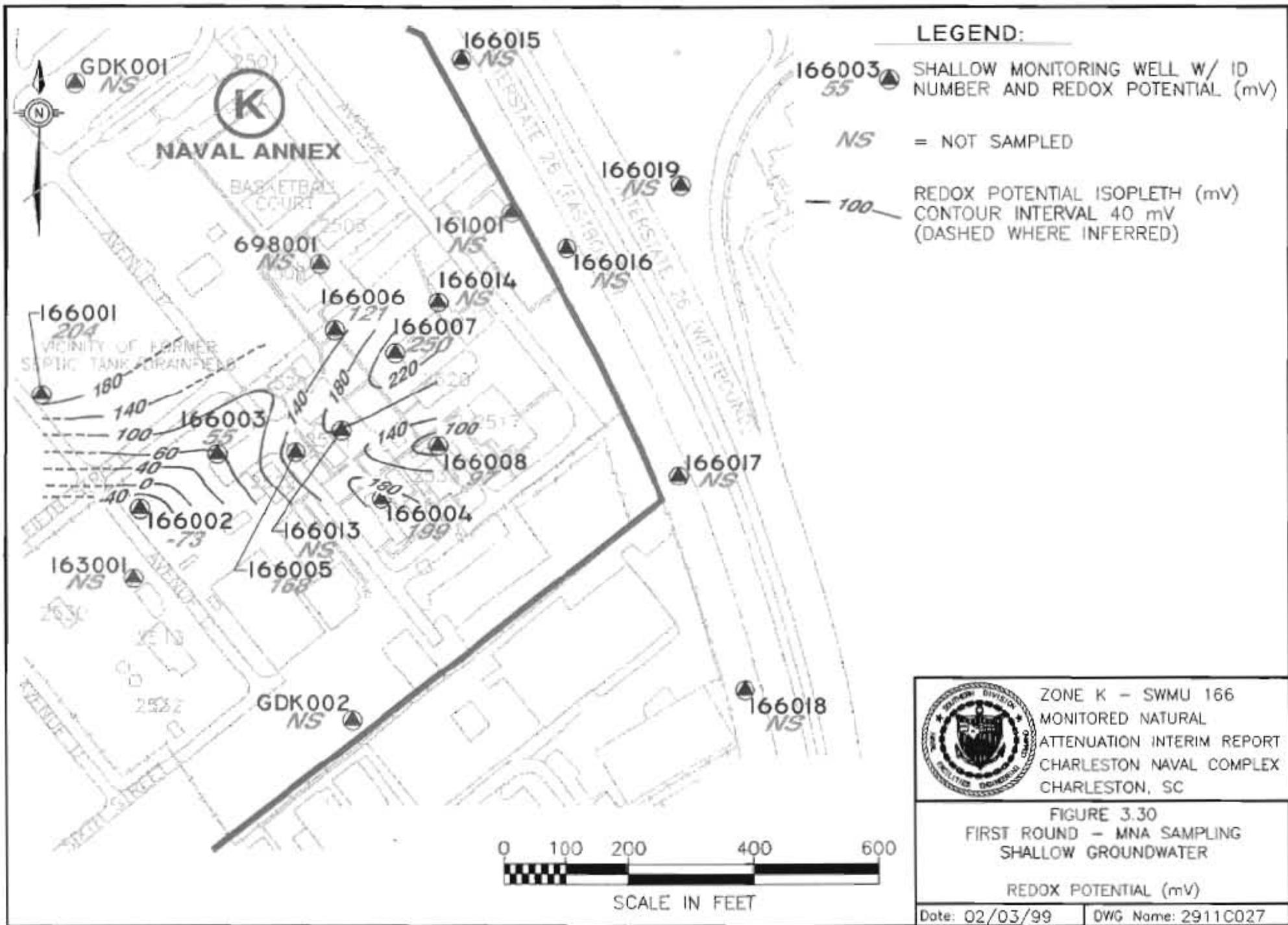
Deep Groundwater

Lower ORP measurements were evident in deep groundwater during Rounds 1 and 2. The Round 1 range for deep wells was -86 to 163 mV, whereas the Round 2 range was -111 to 125 mV (Figures 3.32 and 3.33).

First round results indicated a trend of oxidizing conditions northwest to southeast across the site, with more reducing conditions (ORP < 0) existing northeast and southwest of the trend. During the second round a ridge of oxidizing conditions was found in the center of the site, trending roughly west to east. Conditions became more reducing north and south of the ridge. Most important was the appearance of reducing conditions at the eastern extent of the site.

Hydrogen gas

Hydrogen gas concentrations have been linked to oxidation-reduction conditions in an aquifer because hydrogen gas is constantly produced during the an aerobic decomposition of organic matter. After hydrogen gas has been produced by fermentative microorganisms respiratory microorganisms consume it. These respiratory microorganisms, as stated earlier, may use iron (III), sulfate, or carbon dioxide as terminal electron acceptors. The microorganisms that use iron (III) have been found to utilize the free hydrogen gas more efficiently than microorganisms



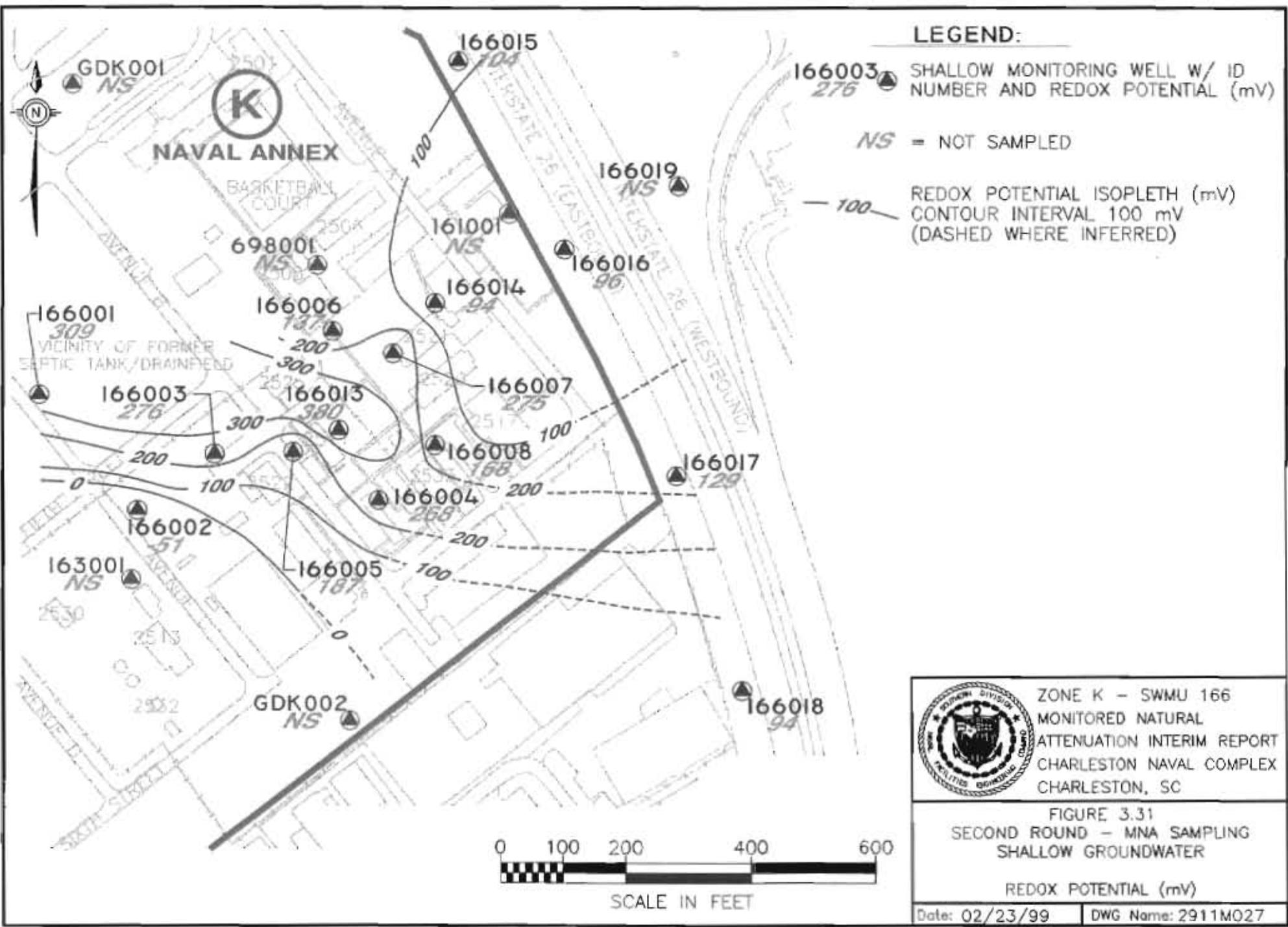
LEGEND:

- 166003/55 ● SHALLOW MONITORING WELL W/ ID NUMBER AND REDOX POTENTIAL (mV)
- NS = NOT SAMPLED
- 100 --- REDOX POTENTIAL ISOPLETH (mV) CONTOUR INTERVAL 40 mV (DASHED WHERE INFERRED)


 ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.30
 FIRST ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

REDOX POTENTIAL (mV)



LEGEND:

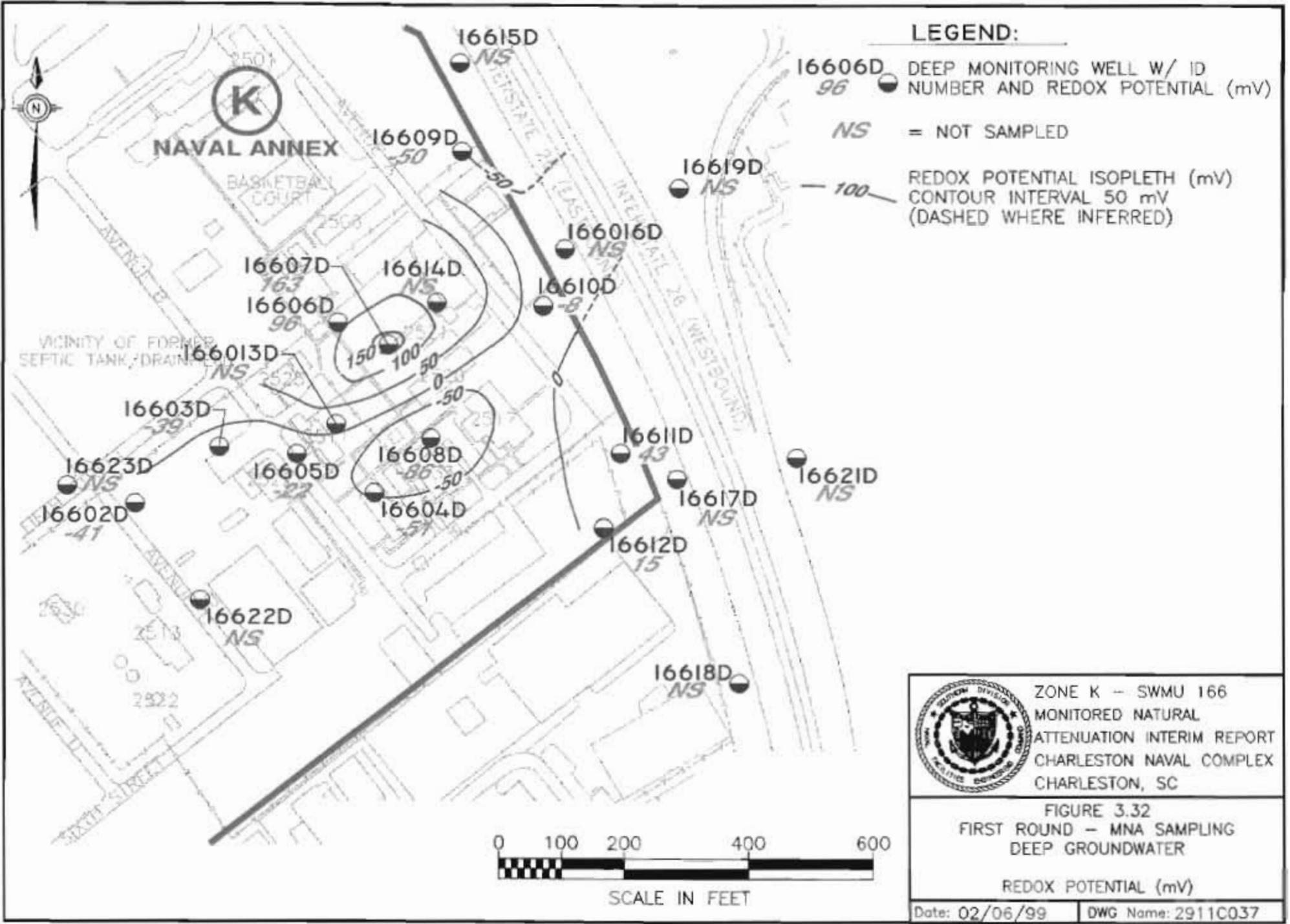
- 166003/276 SHALLOW MONITORING WELL W/ ID NUMBER AND REDOX POTENTIAL (mV)
- NS = NOT SAMPLED
- 100 REDOX POTENTIAL ISOPLETH (mV) CONTOUR INTERVAL 100 mV (DASHED WHERE INFERRED)



ZONE K - SWMU 166
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FIGURE 3.31
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

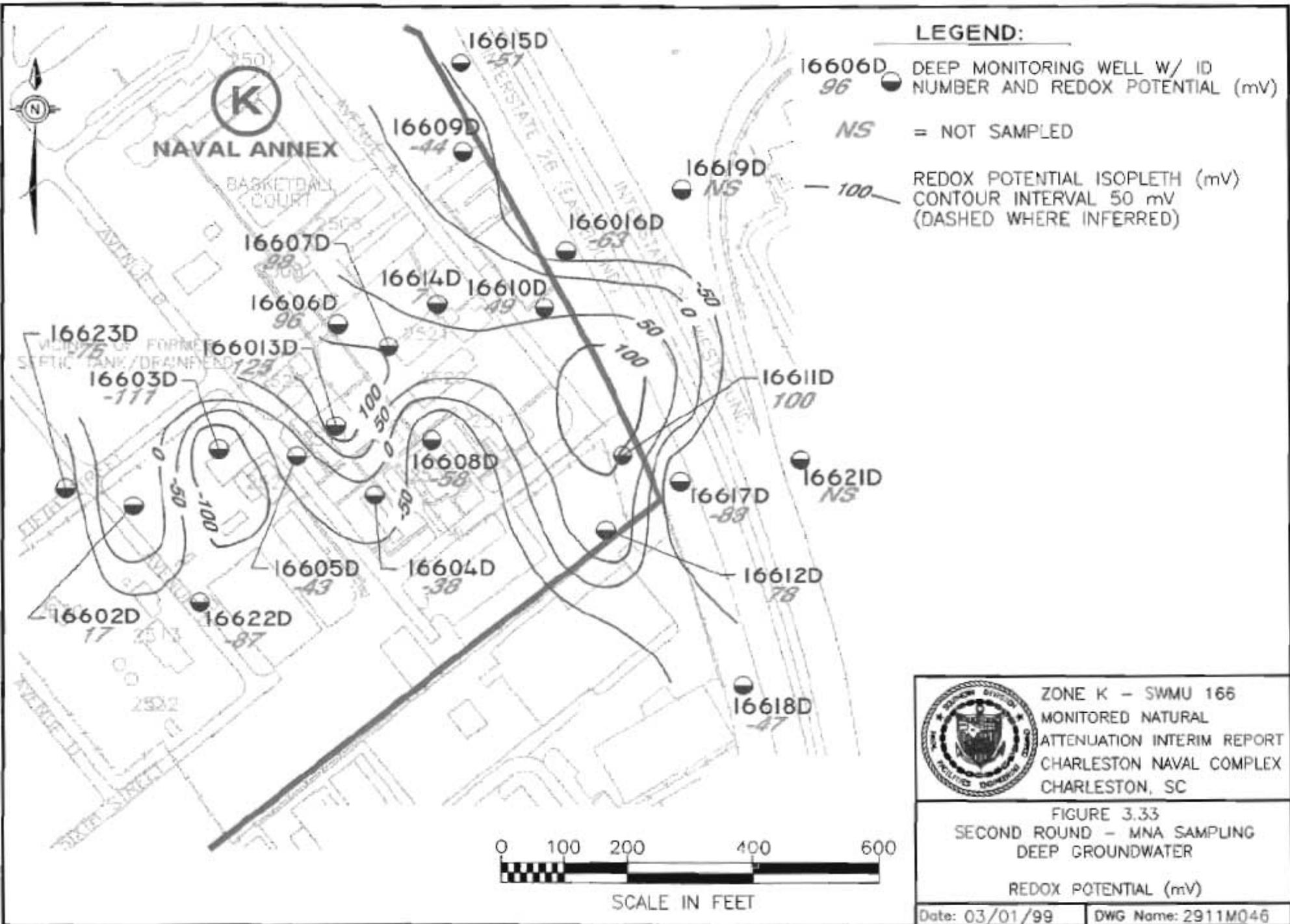
REDOX POTENTIAL (mV)




 ZONE K -- SWMU 166
 MONITORED NATURAL
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FIGURE 3.32
 FIRST ROUND - MNA SAMPLING
 DEEP GROUNDWATER

REDOX POTENTIAL (mV)




ZONE K - SWMU 166
 MONITORED NATURAL
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FIGURE 3.33
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER
 REDOX POTENTIAL (mV)
 Date: 03/01/99 | DWG Name: 2911M046

that use sulfate, and even more so than those that use carbon dioxide. This efficiency for using hydrogen gas maintains different equilibrium concentrations in solution and can be linked to a specific redox process in the following manner (Chappelle et al., 1995):

- hydrogen gas concentration < 0.1 nm/L is indicative of denitrification
- hydrogen gas concentration between 0.2 to 0.8 nm/L is indicative of iron (III) reduction
- hydrogen gas concentration between 1 to 4 nm/L is indicative of sulfate reduction
- hydrogen gas concentration between 5 to 20 nm/L is indicative of methanogenesis

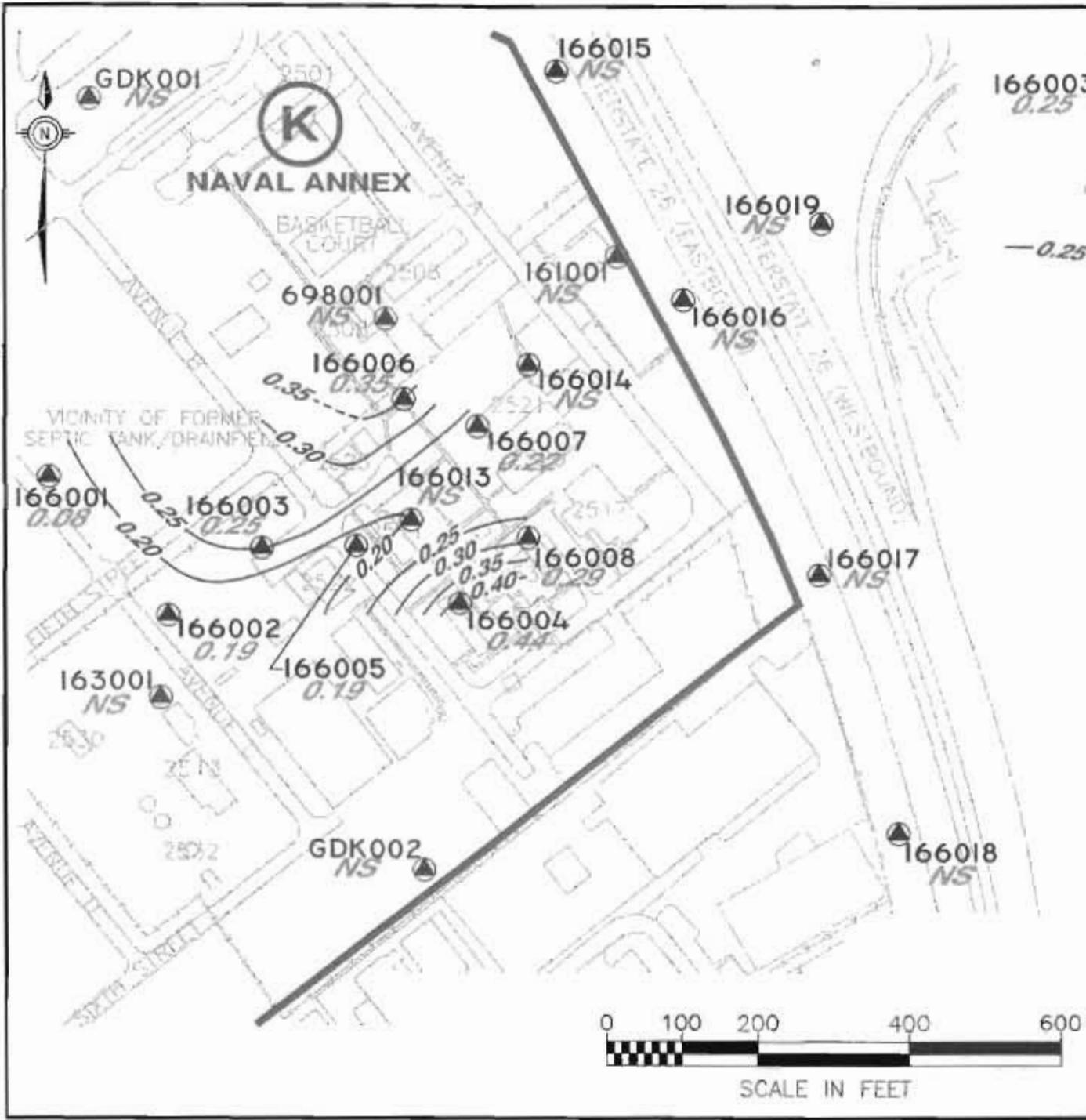
The optimal hydrogen gas concentration range for reductive dechlorination, is greater than 1.0 nm/L (Technical Protocol, 1998).

Shallow Groundwater

Shallow groundwater hydrogen gas concentrations ranged from 0.08 to 0.44 nm/L in Round 1 samples, (Figure 3.34), which corresponds to the range for denitrification and iron (III) reduction. Second round hydrogen gas concentrations ranged from 0.58 nm/L to 1.73 nm/L, (Figure 3.35), indicating iron(III) and sulfate reduction may be occurring. Little spatial variation in hydrogen gas concentrations occurred in the shallow groundwater during Round 1 with only one well (166001), having concentrations within the denitrification range. During Round 2 a large region with hydrogen gas concentrations greater than 1.0 nm/L (sulfate reduction) dominates the central and eastern portions of the site. Within this region, hydrogen concentrations were highest at 166014 and 166013 with 1.66 nm/L and 1.73 nm/L, respectively. Northwest of this area, concentrations decreased, indicative of the iron (III) reduction range.

Deep Groundwater

Deep groundwater hydrogen gas concentrations ranged from nondetect (<0.08 nm/L) to 1.16 nm/L, (Figure 3.36), indicating possible denitrification, iron (III) reduction, and sulfate



LEGEND:

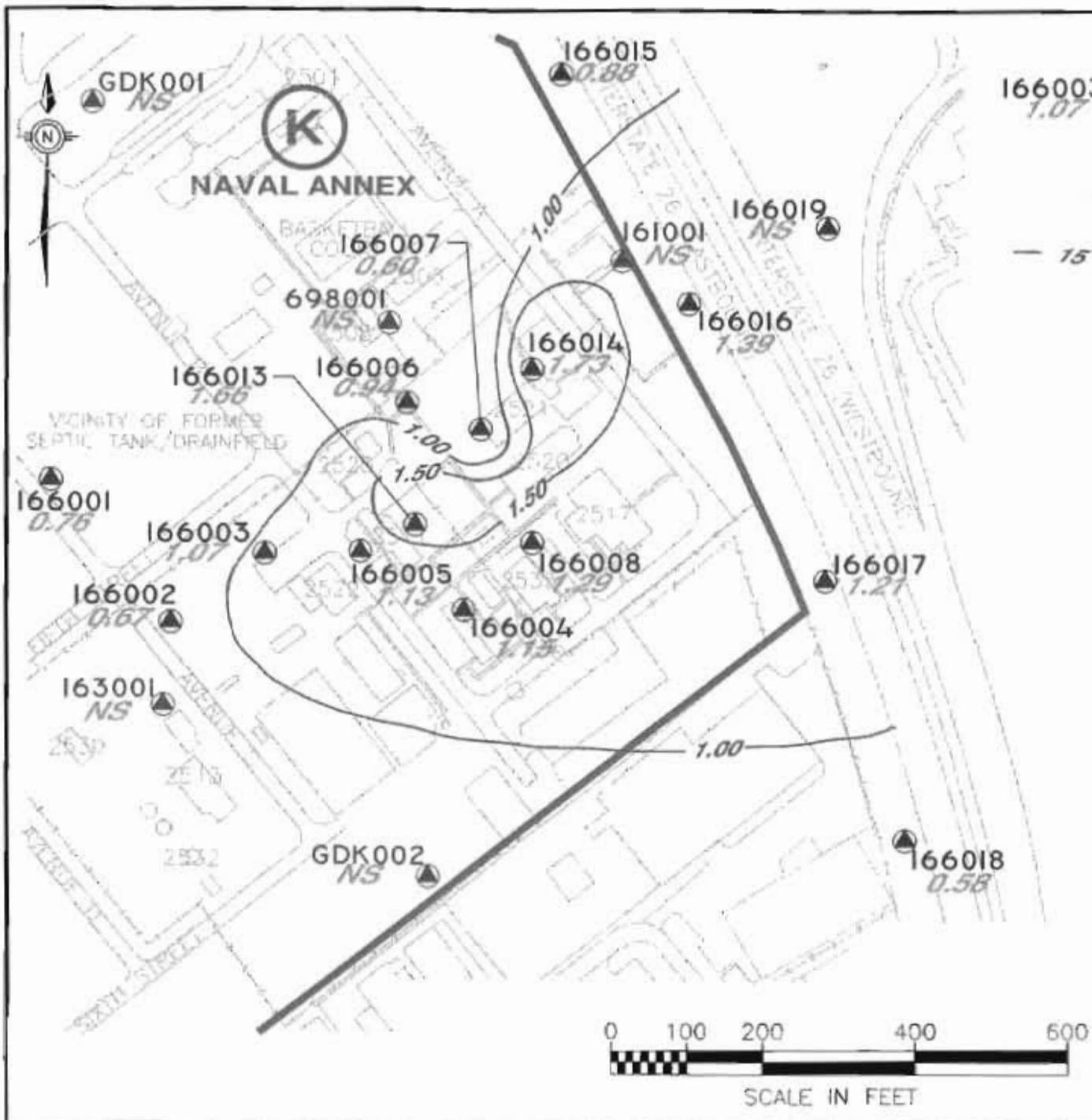
- 166003
0.25 SHALLOW MONITORING WELL W/ ID NUMBER AND HYDROGEN GAS CONCENTRATION (nmol/L)
- NS = NOT SAMPLED
- 0.25- HYDROGEN GAS ISOPLETH (nmol/L) CONTOUR INTERVAL 0.05 nmol/L (DASHED WHERE INFERRED)



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FIGURE 3.34
 FIRST ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

HYDROGEN GAS (nmol/L)



LEGEND:

166003
1.07 SHALLOW MONITORING WELL W/ ID NUMBER AND HYDROGEN GAS CONCENTRATION (nmol/L)

NS = NOT SAMPLED

— 15 — HYDROGEN GAS ISOPLETH (nmol/L) CONTOUR INTERVAL 0.5 nmol/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
MONITORED NATURAL
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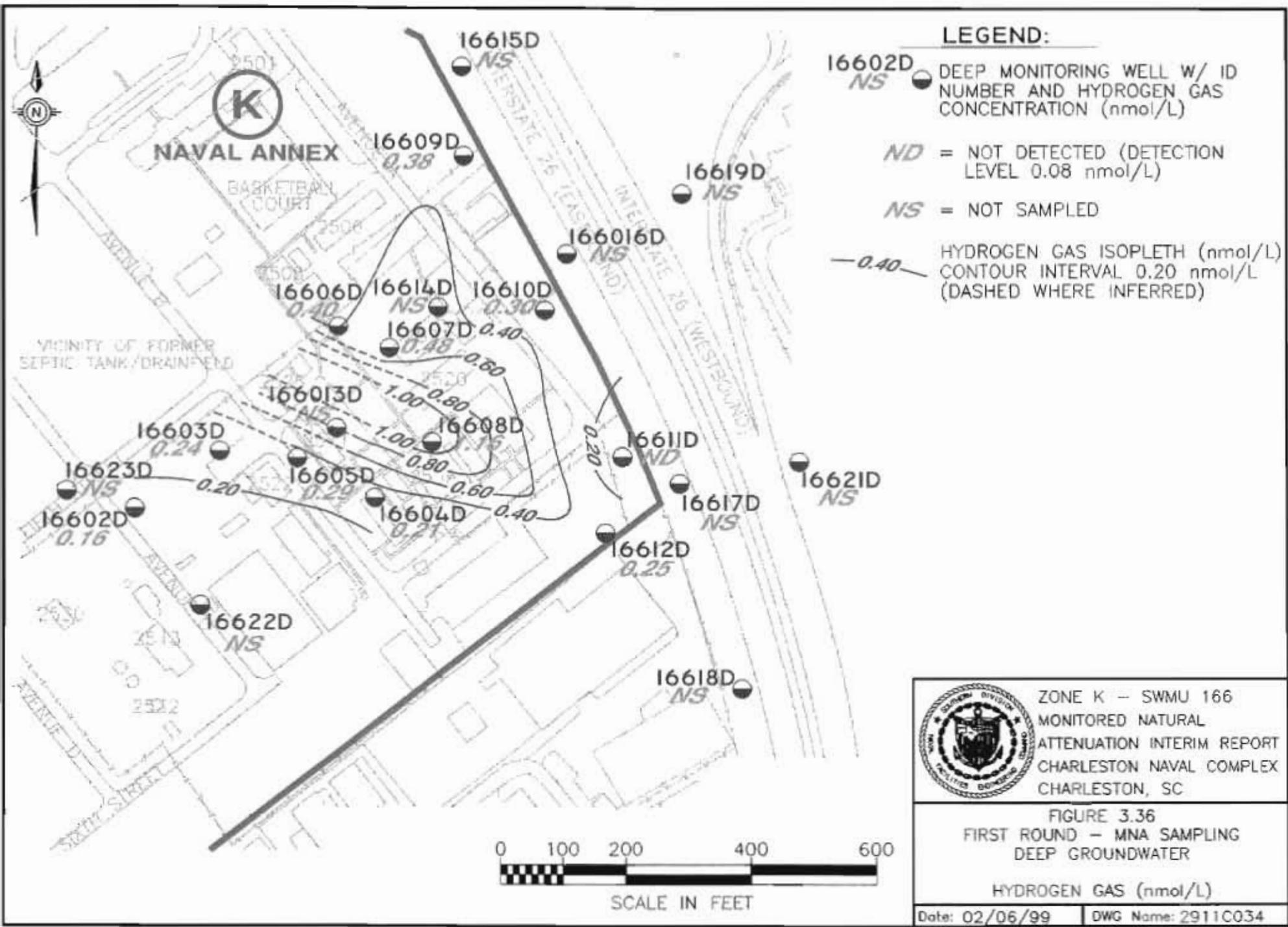
FIGURE 3.35
SECOND ROUND - MNA SAMPLING
SHALLOW GROUNDWATER

HYDROGEN GAS (nmol/L)

Date: 02/23/99

DWG Name: 2911M024

SCALE IN FEET




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FIGURE 3.36
 FIRST ROUND - MNA SAMPLING
 DEEP GROUNDWATER
 HYDROGEN GAS (nmol/L)
 Date: 02/06/99 | DWG Name: 2911C034

reduction conditions. Second round hydrogen gas concentrations ranged from 0.79 to 2.38 nm/L, (Figure 3.37), spanning the ranges for iron (III) and sulfate reduction

Hydrogen gas results from Round 1 indicated an isolated region of concentrations greater than 1.0 nm/L in the center of the site near 16608D. Concentrations quickly decline away from this well to levels more typical of iron (III) reduction and possibly denitrification. Second round hydrogen gas concentrations were predominantly above 1.0 nm/L. The highest concentrations occurred at wells 16613D (2.38 nm/L) and 16604D (2.09 nm/L) which may indicate sulfate reduction. Isolated highs also occurred at 16614D at 1.83 nm/L and 16602D (1.65 nm/L) which also suggest sulfate reduction. Equally important is a region of hydrogen gas concentration less than 1.0 nm/L trending northwest to southeast, between the two aforementioned high concentration regions. This zone of lower hydrogen concentration is suggested by detections at 16607D and 16611D.

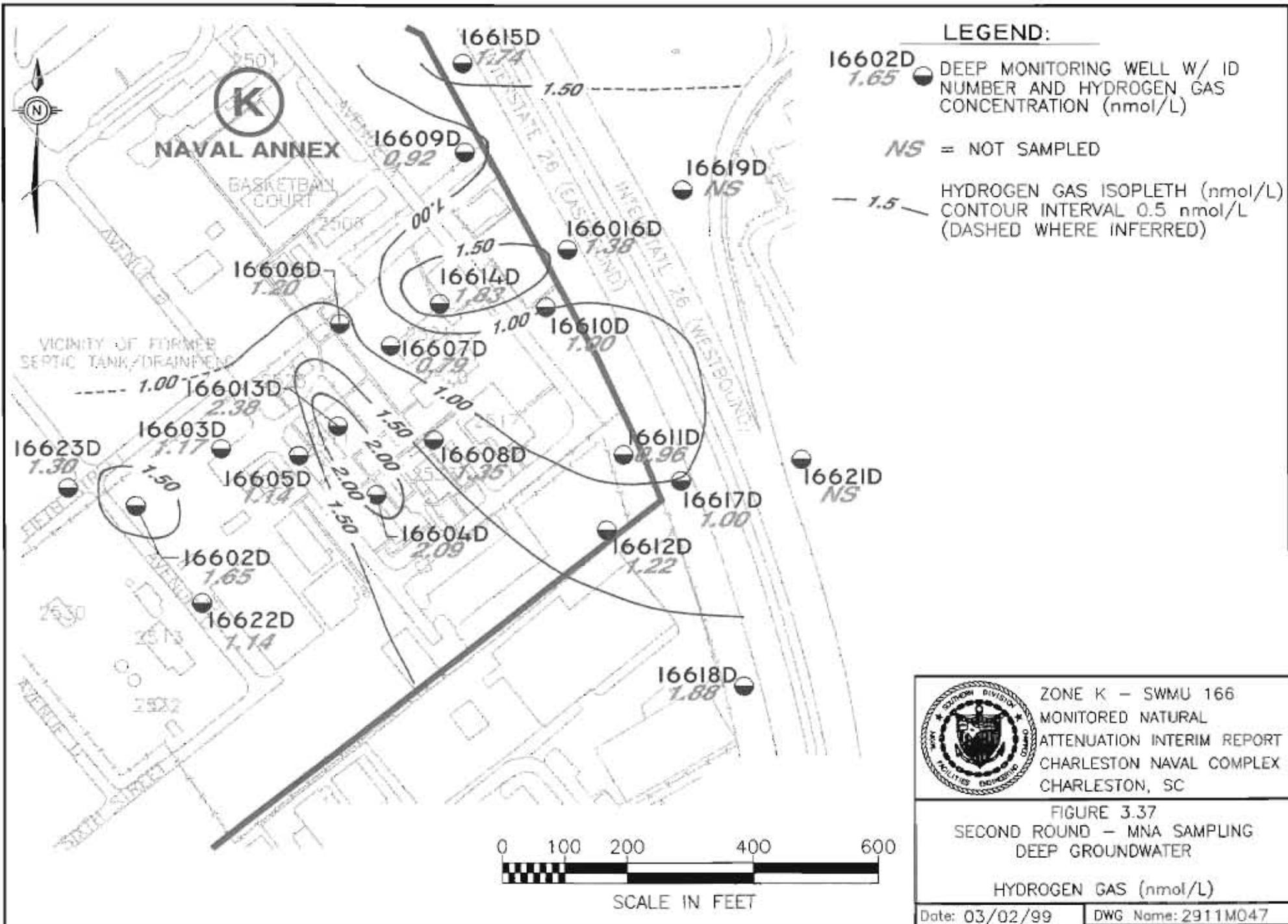
Aerobic respiration

Dissolved Oxygen

Dissolved oxygen (DO) is the most thermodynamically favored electron acceptor for microorganisms to use in the aerobic biodegradation of organic materials. However, anaerobic biodegradation processes like reductive dechlorination cannot occur in environments with more than approximately 0.5 mg/L of dissolved oxygen (Technical Protocol, 1998).

Shallow Groundwater

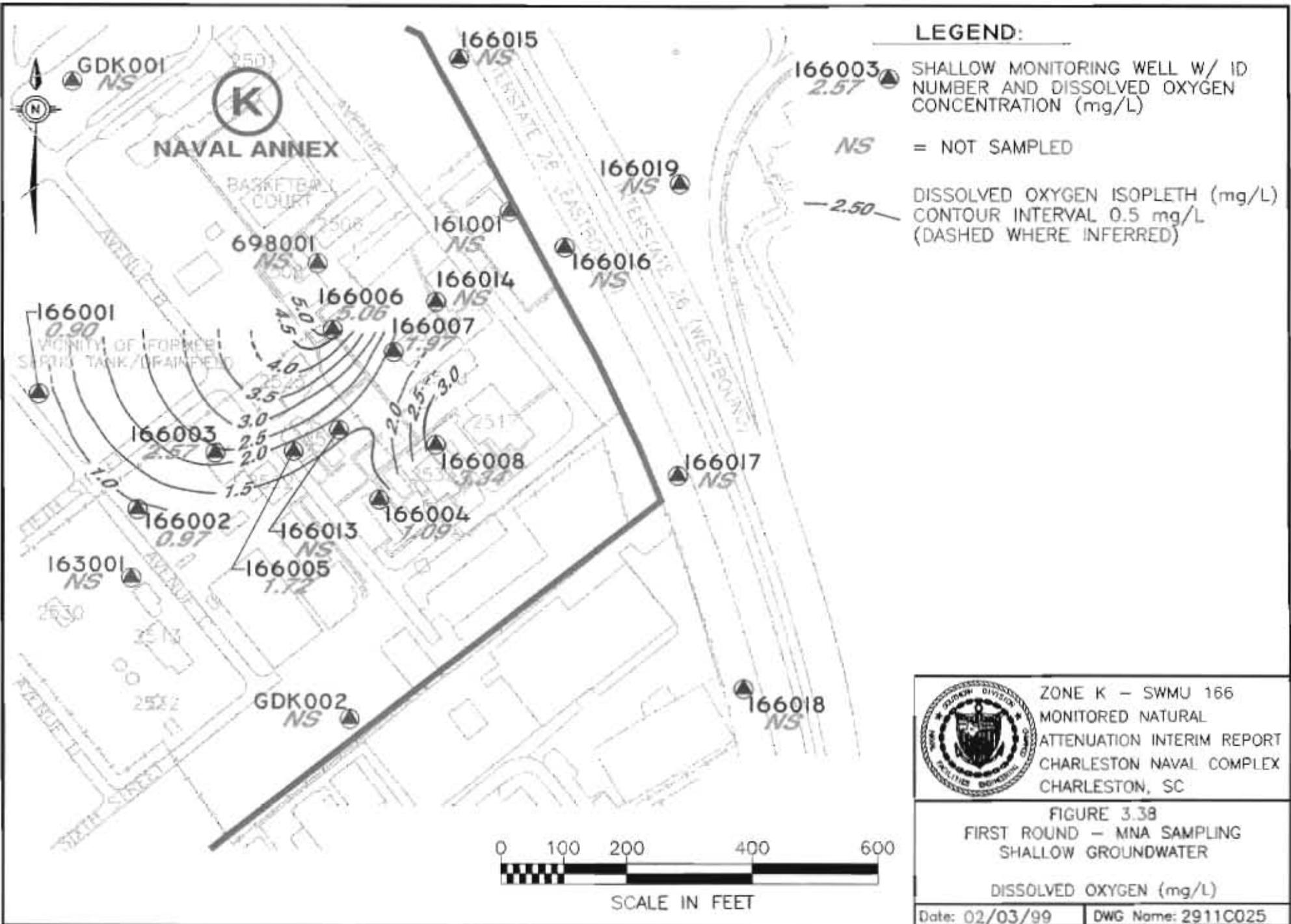
DO was detected in all shallow monitoring wells during Rounds 1 and 2. First round DO concentrations ranged from 0.90 to 5.06 mg/L, and second round concentrations ranged from 0.60 mg/L to 3.65 mg/L (Figures 3.38 and 3.39). DO was highest in the first round at 166006, with a second high at 166008, the farthest shallow well to the southeast. DO decreased south and west of these locations. Concentrations at 166006 and 166008 remained high during the second



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FIGURE 3.37
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER

HYDROGEN GAS (nmol/L)



LEGEND:

- 
 166003
2.57
SHALLOW MONITORING WELL W/ ID NUMBER AND DISSOLVED OXYGEN CONCENTRATION (mg/L)
- NS = NOT SAMPLED
- 
 2.50
DISSOLVED OXYGEN ISOPLETH (mg/L) CONTOUR INTERVAL 0.5 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
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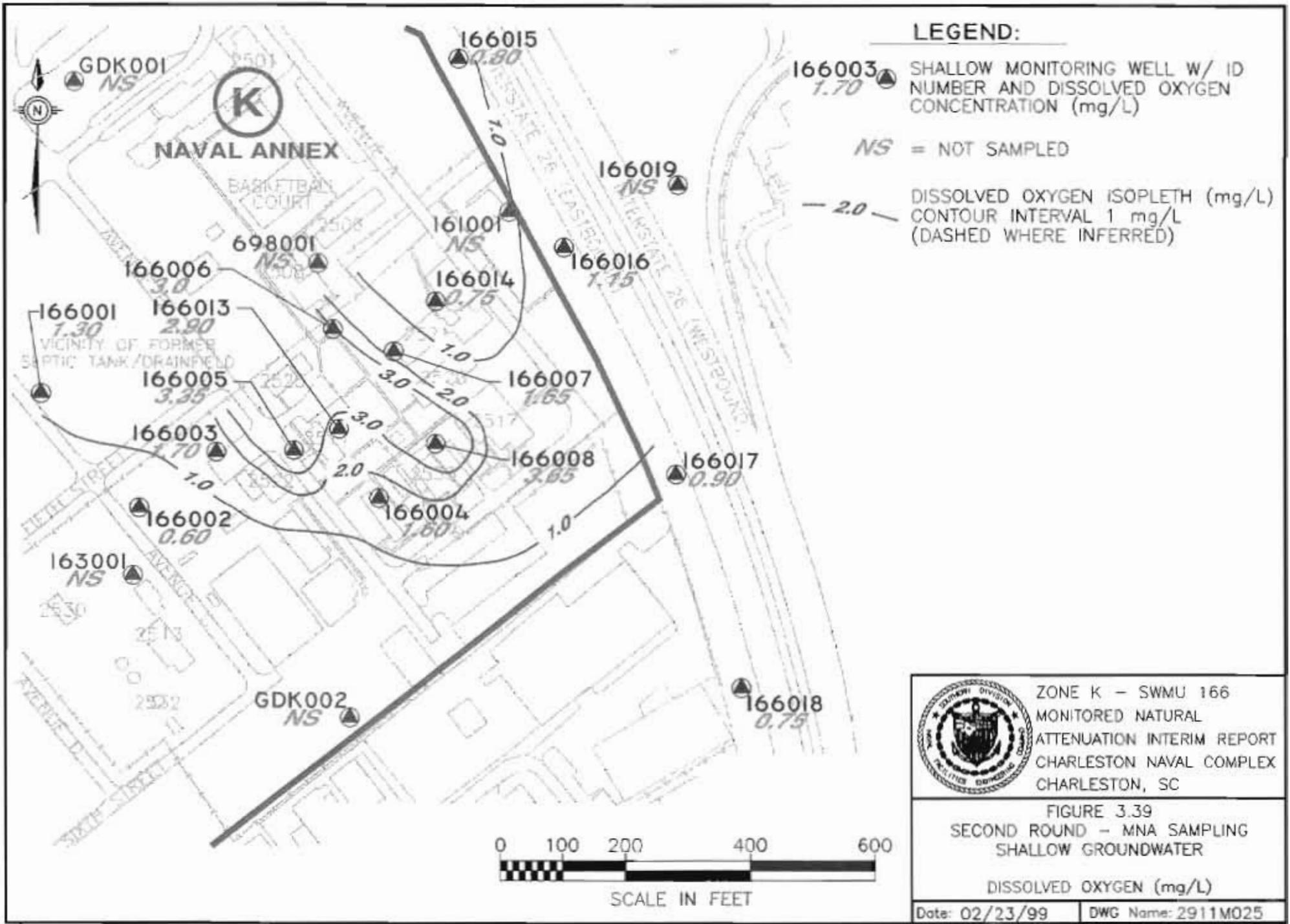
FIGURE 3.38
 FIRST ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

DISSOLVED OXYGEN (mg/L)

Date: 02/03/99

DWG Name: 2911C025





LEGEND:

- 166003 1.70 SHALLOW MONITORING WELL W/ ID NUMBER AND DISSOLVED OXYGEN CONCENTRATION (mg/L)
- NS = NOT SAMPLED
- 2.0 - DISSOLVED OXYGEN ISOPLETH (mg/L) CONTOUR INTERVAL 1 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
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FIGURE 3.39
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

DISSOLVED OXYGEN (mg/L)

round, and coupled with new data from 166013 and an increase in DO at 166005, form a zone of highly oxygenated groundwater trending northwest to southeast across the center of the site.

Deep Groundwater

First round deep groundwater DO concentrations ranged from 0.35 to 0.87 mg/L, from 0.45 to 1.60 mg/L in the second round (Figures 3.40 and 3.41).

The highest DO concentrations in the first round occurred at 16608D and 16603D, with lower concentrations throughout the remainder of the site. DO in Round 2 was considerably higher across the site as compared to Round 1. For example, DO was nearly four times as high at 16604D and more than twice as high at 16606D in Round 2. In general, a narrow, well-defined ridge of more oxygenated water transects the site northwest to southeast, roughly perpendicular to predominant deep groundwater flow direction. DO concentrations decreased southwest and northeast of the high DO ridge, contributing to it's well-defined shape.

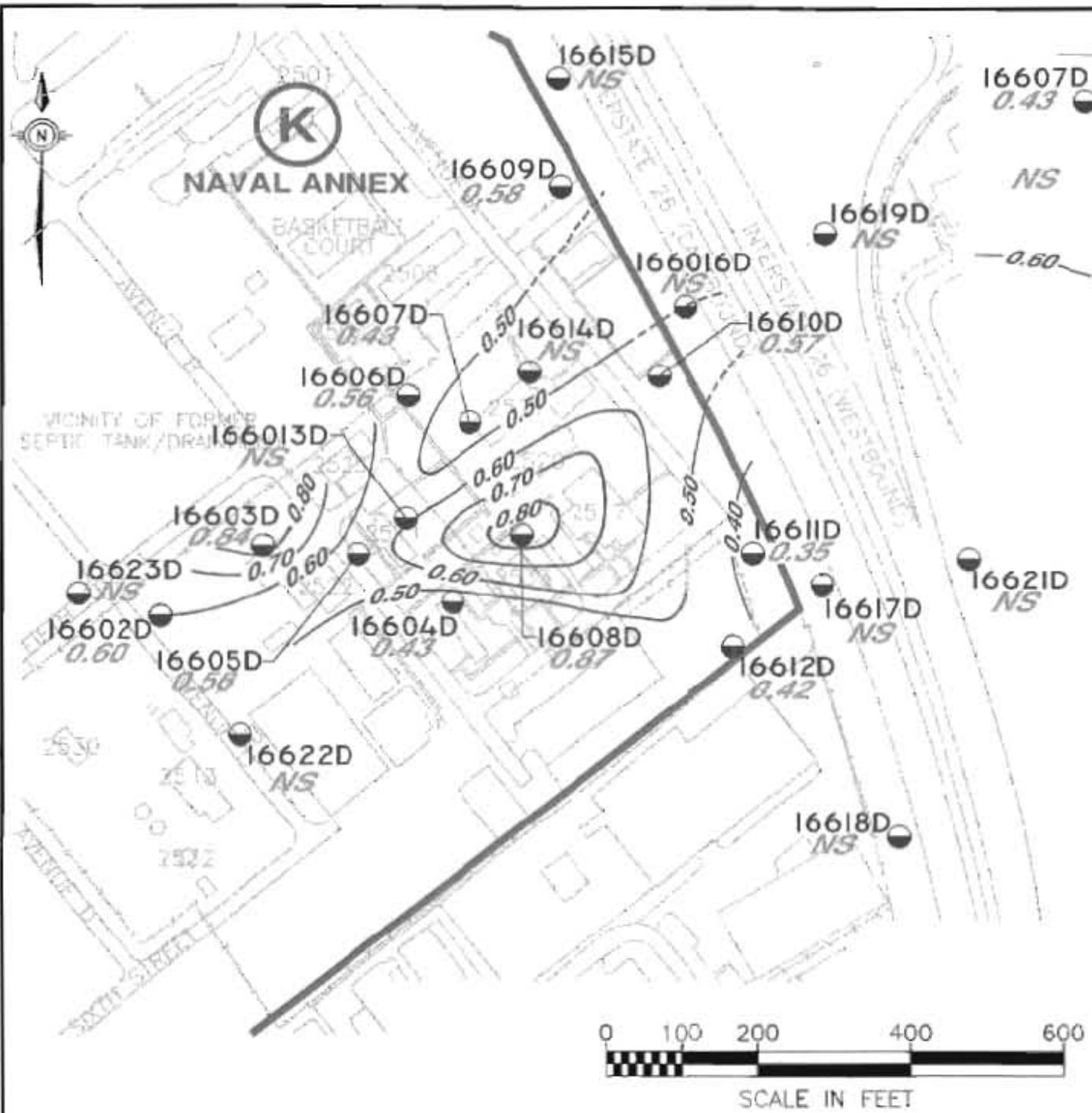
Denitrification

After all the dissolved oxygen is utilized, nitrate is the next electron acceptor. This biologically mediated process is called denitrification by which nitrate is ultimately reduced to nitrogen gas. Nitrate concentrations greater than 1.0 mg/L inhibit reductive dechlorination. Thus, for reductive dechlorination to occur, the concentration of groundwater nitrate must be less than 1.0 mg/L (or 0.23 mg/L nitrate-nitrogen).

Nitrate

Shallow Groundwater

Nitrate was detected in only four of eight first round shallow wells, at concentrations between 0.14 and 3.0 mg/L (Figure 3.42). Nitrate-nitrogen was detected in six of 14 second round shallow wells and at concentrations between 0.10 to 5.4 mg/L (Figure 3.43). Nitrate concentrations were



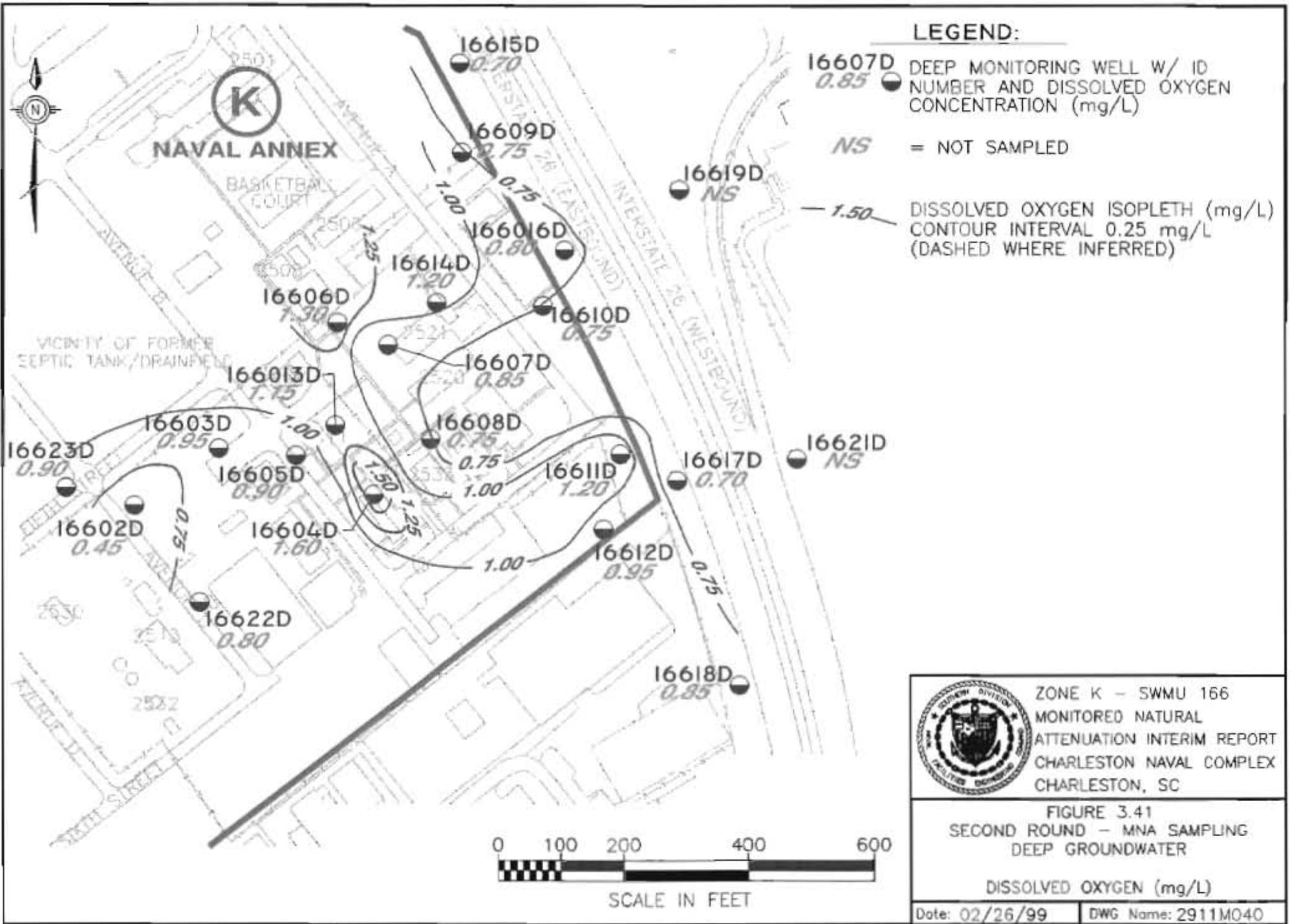
LEGEND:

16607D
0.43 ● DEEP MONITORING WELL W/ ID NUMBER AND DISSOLVED OXYGEN CONCENTRATION (mg/L)

NS = NOT SAMPLED

— 0.60 — DISSOLVED OXYGEN ISOPLETH (mg/L) CONTOUR INTERVAL 0.1 mg/L (DASHED WHERE INFERRERD)

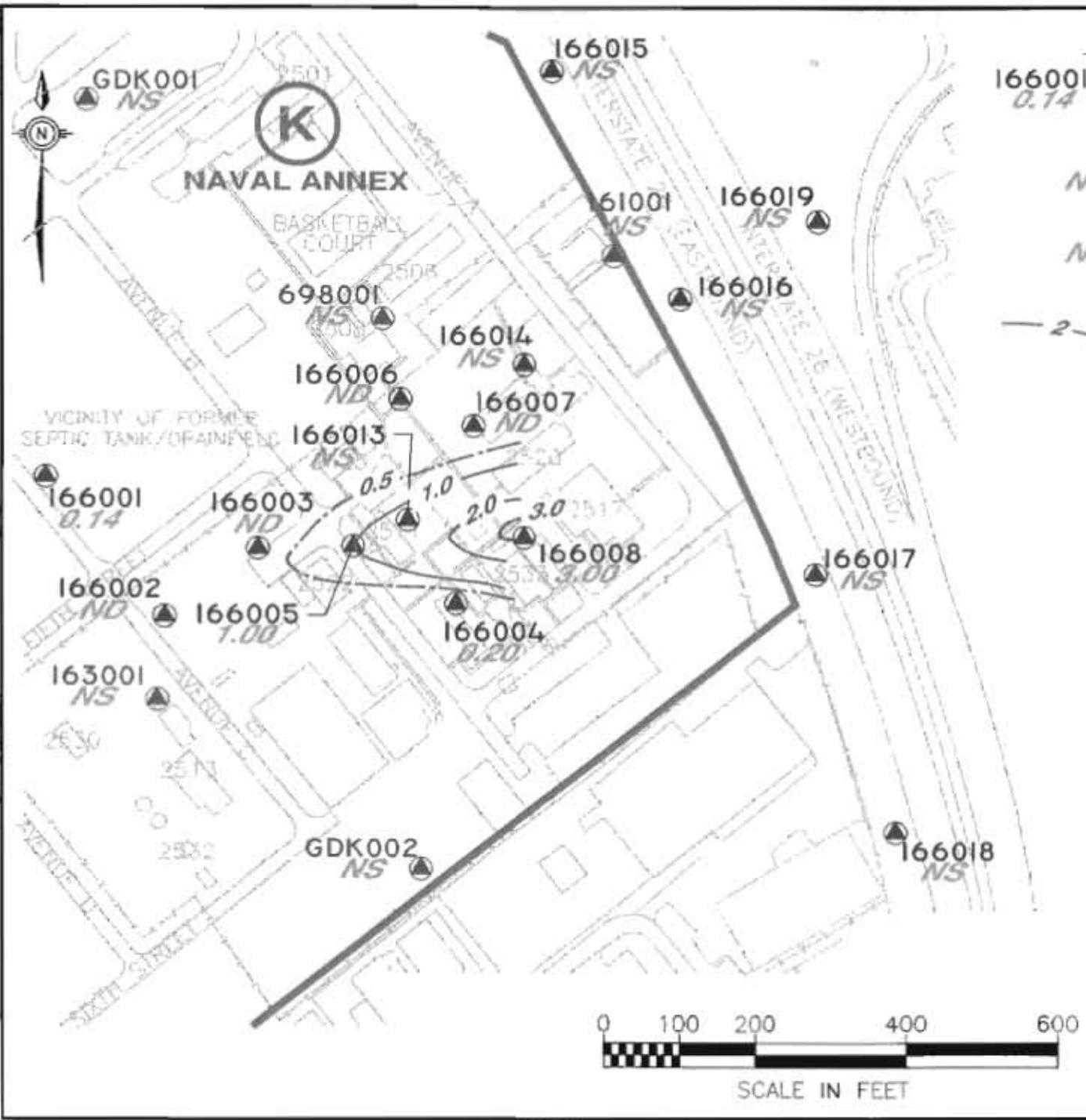
	ZONE K - SWMU 166 MONITORED NATURAL ATTENUATION INTERIM REPORT CHARLESTON NAVAL COMPLEX CHARLESTON, SC
	FIGURE 3.40 FIRST ROUND - MNA SAMPLING DEEP GROUNDWATER DISSOLVED OXYGEN (mg/L)
Date: 02/06/99	DWG Name: 2911C035




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FIGURE 3.41
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER

DISSOLVED OXYGEN (mg/L)



LEGEND:

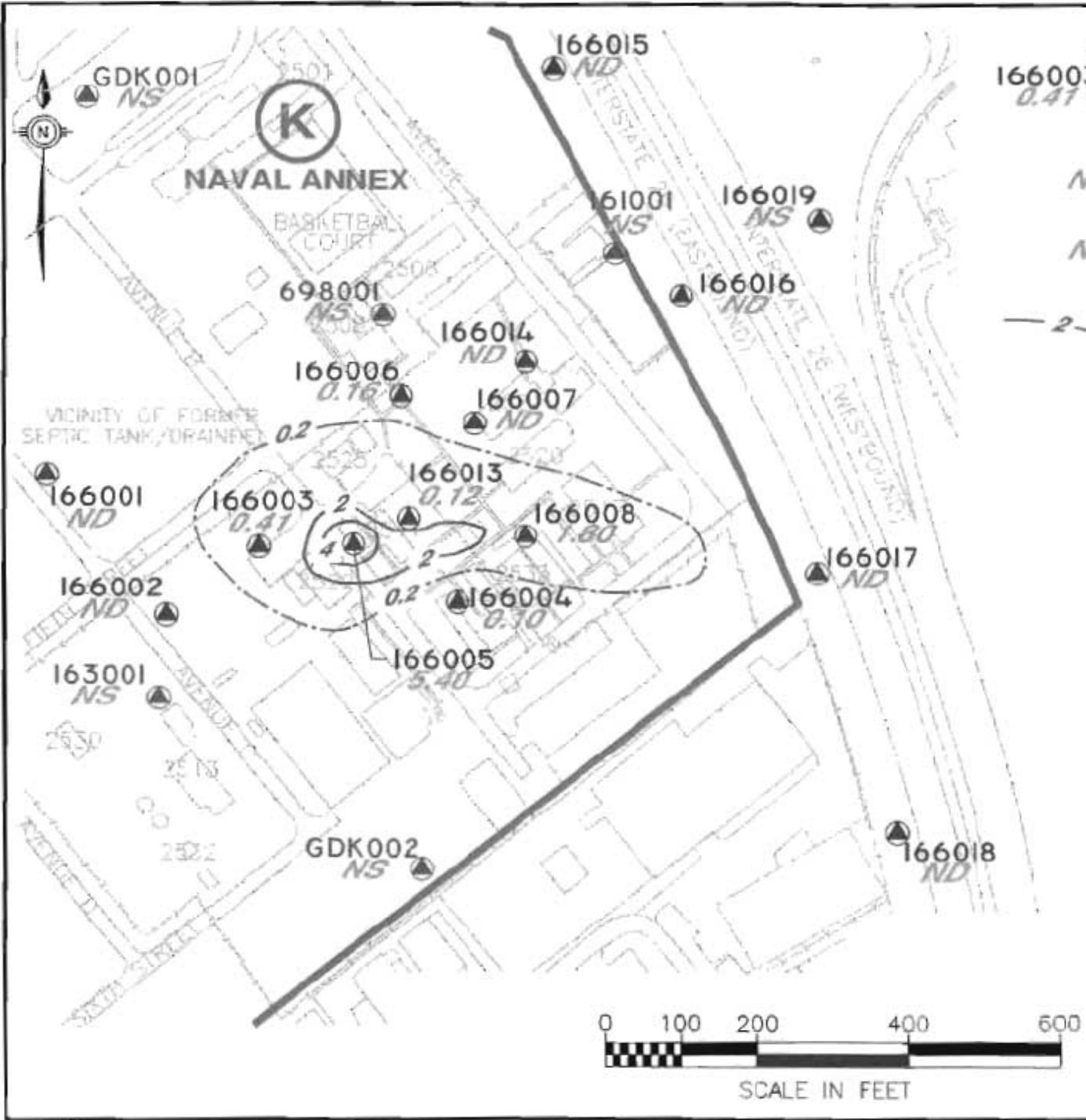
- 166001
0.14 SHALLOW MONITORING WELL W/ ID NUMBER AND NITRATE CONCENTRATION (mg/L)
- ND = NOT DETECTED (DETECTION LEVEL 0.10 mg/L)
- NS = NOT SAMPLED
- 2 - NITRATE ISOPLETH (mg/L) CONTOUR INTERVAL 1 mg/L (DASHED WHERE INFERRED) WITH SUPPLEMENTAL 0.5 mg/l CONTOUR (--- 0.5 ---)



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FIGURE 3.42
 FIRST ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

NITRATE (mg/L)



LEGEND:

- 166003
0.41 SHALLOW MONITORING WELL W/ ID NUMBER AND NITRATE CONCENTRATION (mg/L)
- ND = NOT DETECTED (DETECTION LEVEL 0.10 mg/L)
- NS = NOT SAMPLED
- 2 - NITRATE ISOPLETH (mg/L) CONTOUR INTERVAL 2 mg/L (DASHED WHERE INFERRED) WITH SUPPLEMENTAL 0.2 mg/l CONTOUR (---0.2---)


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FIGURE 3.43
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

NITRATE (mg/L)

highest at 166008 during Round 1, creating a localized region of elevated nitrate in the south-central portion of SWMU 166. Although this isolated high may continue to the east along the groundwater flowpath, the limited set of shallow wells sampled during Round 1 does not provide the data necessary to characterize the eastern section of the site. The expanded well population sampled during Round 2 indicated that nitrate concentrations were isolated in the center of the site, near 166005. Nitrate concentrations decreased rapidly to the east, parallel to the direction of local groundwater flow.

Deep Groundwater

Nitrate was not detected in any deep groundwater samples during Rounds 1 or 2.

Nitrogen (gas)

Shallow Groundwater

Nitrogen gas was detected in all first round shallow well samples at concentrations ranging from 2.7 to 9.2 mg/L, and in all second round shallow wells ranging between 4.4 and 15.3 mg/L (Table 3.1). Due to the limited dissolved nitrate found in first and second round groundwater, nitrogen isopleths were not constructed. Although the isolated high nitrate concentrations in second round groundwater samples were accompanied by equally high nitrogen gas concentrations, high nitrogen gas concentrations exist along the eastern perimeter of the site (Interstate 26) where no nitrate was detected.

Deep Groundwater

Nitrogen gas was detected in all first round deep well samples at concentrations between 3.0 and 15.2 mg/L, and all second round samples at concentrations ranging from 3.45 to 15.8 mg/L (Table 3.1). Since no nitrate was detected in any deep groundwater samples in either round, nitrogen gas isopleths were not constructed. In general, however, nitrogen gas was highest in the deep wells adjacent to Interstate 26 and wells in the northwestern portion of the site.

Manganese (IV) Reduction

Manganese (II), the by-product of manganese (IV) reduction, was analyzed in only second round groundwater samples with the hope of providing additional aquifer redox data. However, no manganese (II) was detected in any shallow or deep wells (Table 3.1).

Iron (III) Reduction

Iron (II), or ferrous iron, is the by-product of reduction of iron (III) (ferric iron) by microorganisms during anaerobic biodegradation. If microorganisms are utilizing iron (III) as an electron acceptor, the concentration of iron (II) will increase in the surrounding groundwater. Microorganism will typically use iron (III) as an electron acceptor only after they have consumed all available DO and nitrate.

Iron (III)

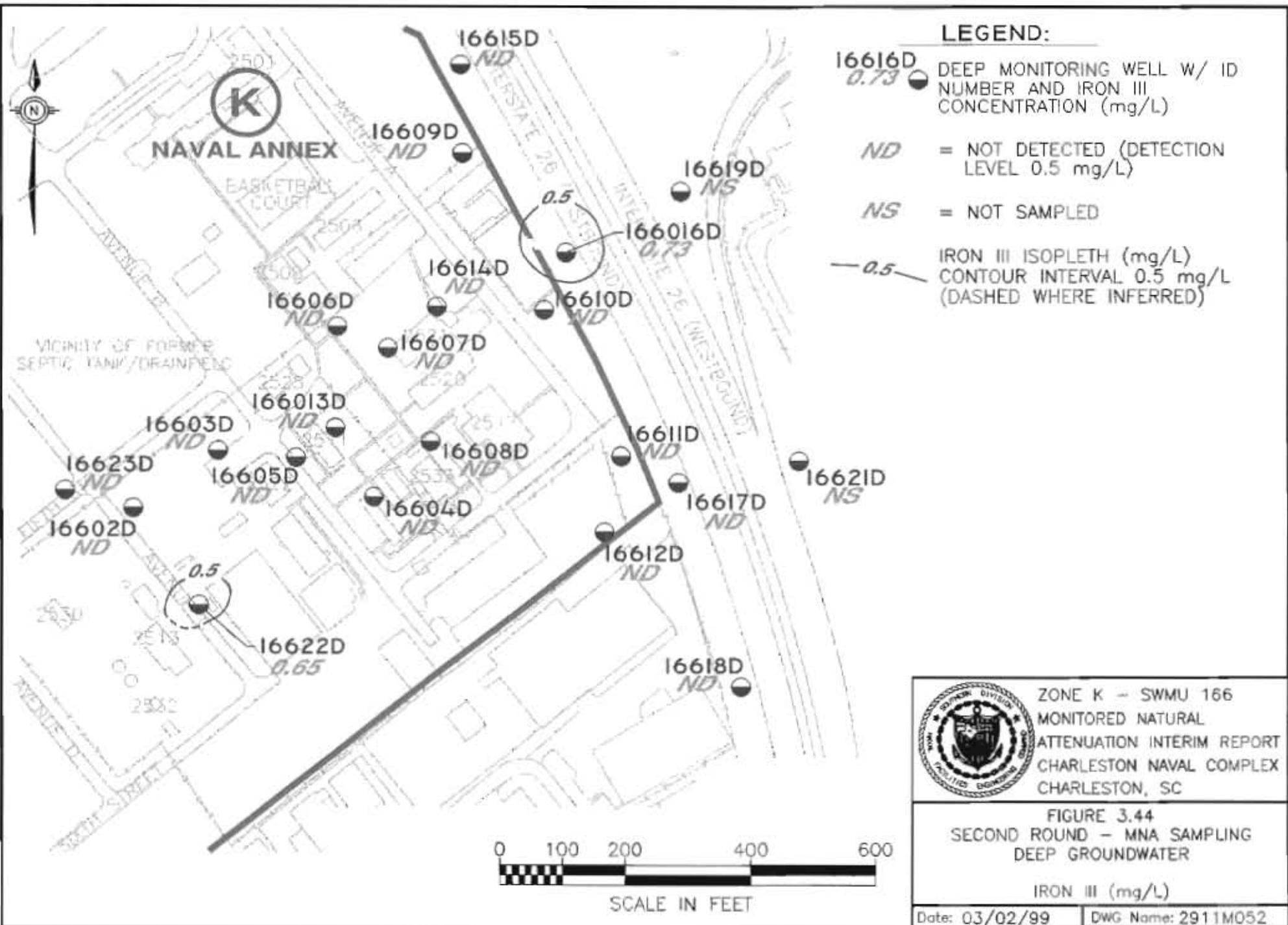
Dissolved iron (III), or ferric iron, was analyzed in only the second round of groundwater samples. The presence of any iron (III) indicates that iron (II) reduction may take place if all other redox conditions (i.e., available nutrients and substrates) are still met.

Shallow Groundwater

No iron (III) was detected above the 0.5 mg/L detection level in any second round shallow wells.

Deep Groundwater

Only two deep well locations, 16616D and 16622D, revealed detectable iron (III) concentrations during the second round (Figure 3.44). These localized iron (III) concentrations were at the extreme southwestern and northeastern portions of the site.



LEGEND:

- 16616D
0.73 ● DEEP MONITORING WELL W/ ID NUMBER AND IRON III CONCENTRATION (mg/L)
- ND = NOT DETECTED (DETECTION LEVEL 0.5 mg/L)
- NS = NOT SAMPLED
- 0.5 — IRON III ISOPLETH (mg/L) CONTOUR INTERVAL 0.5 mg/L (DASHED WHERE INFERRED)



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FIGURE 3.44
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER

IRON III (mg/L)

Iron (II)

Shallow Groundwater

Iron (II) was not detected in any shallow groundwater samples during Round 1. Iron (II) was detected in five shallow wells during Round 2 at concentrations between 0.90 and 2.90 mg/L (Figure 3.45).

Iron (II) was distributed in Round 2 shallow groundwater along the eastern edge of the site at the wells adjacent Interstate 26. The central portion of SWMU 166 was entirely devoid of iron (II) with the single exception of an isolated high at 166002 to the southwest.

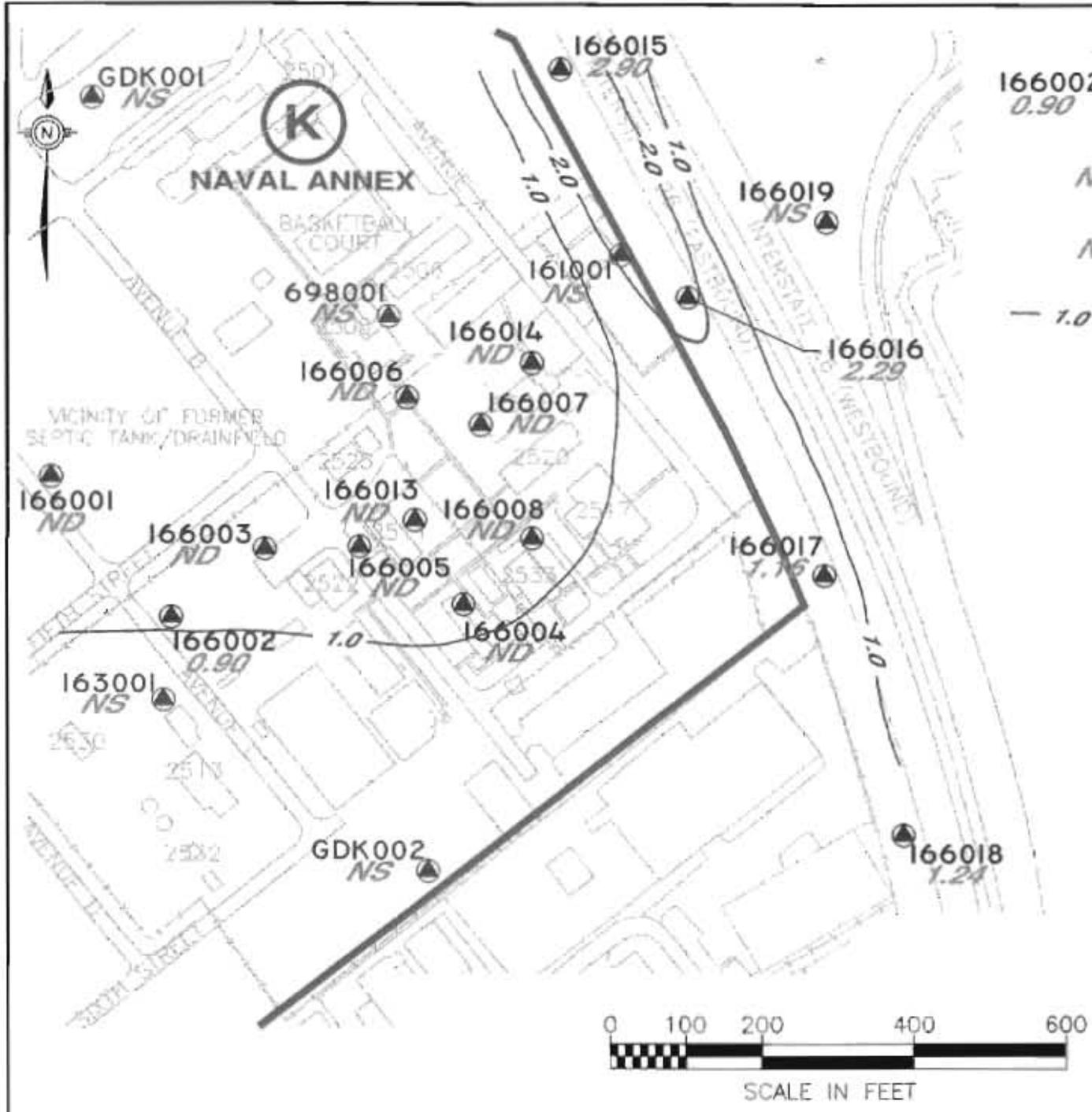
Deep Groundwater

Iron (II) was detected in all 11 first round deep well samples, ranging from 0.72 to 10.8 mg/L (Figure 3.46). Sixteen of 19 deep wells had detectable iron (II) concentrations during Round 2, which ranged from 1.04 to 18.4 mg/L (Figure 3.47).

First round iron (II) concentrations decreased radially from a high of 10.8 mg/L at 16605D. Iron (II) concentrations slightly increased in the deep wells at the eastern boundary of SWMU 166. These trends were reproduced during Round 2 as the highest iron (II) concentration at 16605D increased to 18.4 mg/L.

Sulfate Reduction

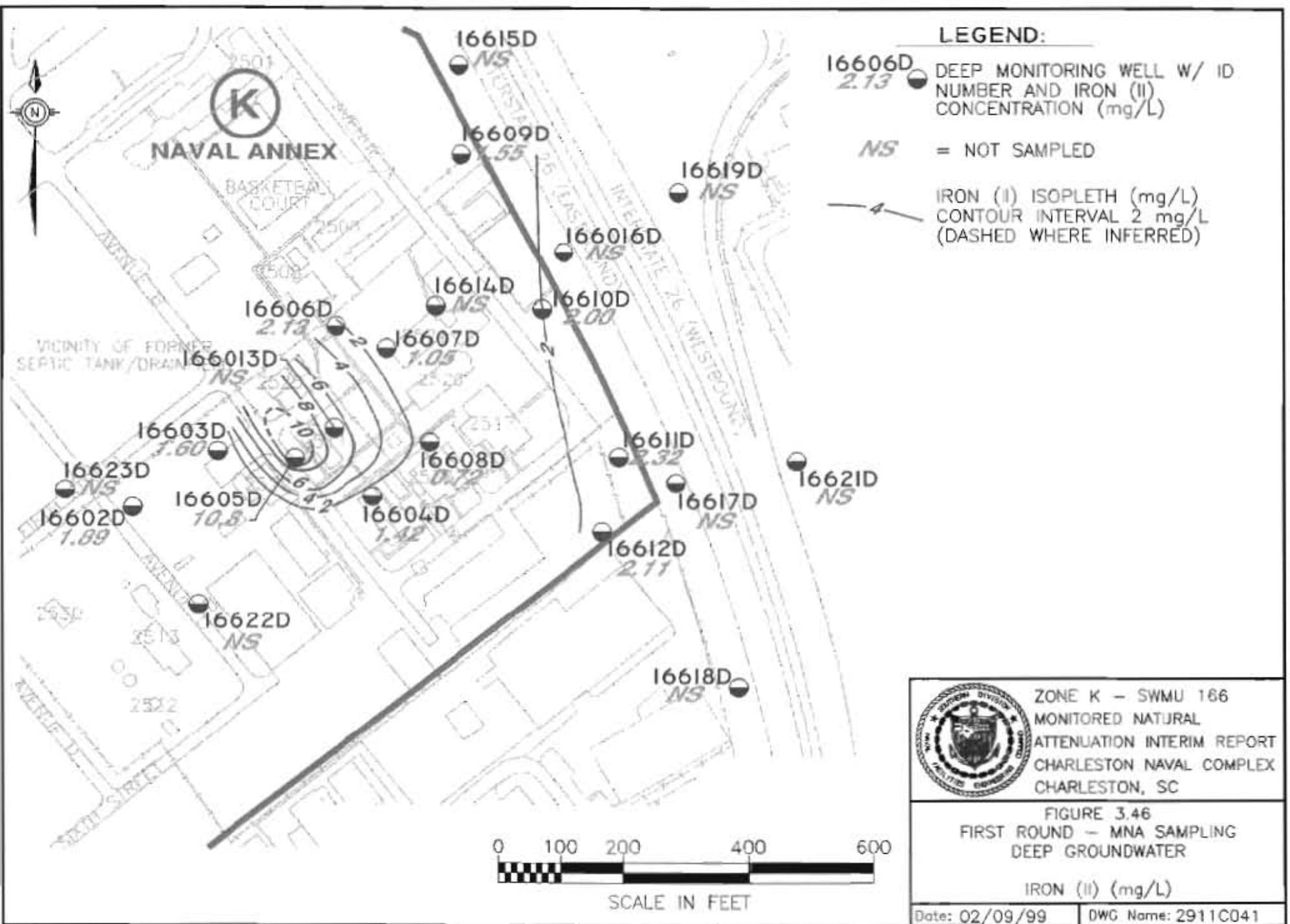
Anaerobic microorganisms may begin to use sulfate as an electron acceptor after the DO, nitrate, and iron (III) supplies have been exhausted. Sulfate is reduced to sulfide during the reduction process, although excessive concentrations of sulfate (>20 mg/L) may cause competitive exclusion of dechlorination, thus preventing any potential for biodegradation of chlorinated compounds.



LEGEND:

- 166002** **0.90** SHALLOW MONITORING WELL W/ ID NUMBER AND IRON (II) CONCENTRATION (mg/L)
- ND** = NOT DETECTED (DETECTION LEVEL 0.5 mg/L)
- NS** = NOT SAMPLED
- 1.0** — IRON (II) ISOPLETH (mg/L) CONTOUR INTERVAL 1 mg/L (DASHED WHERE INFERRED)

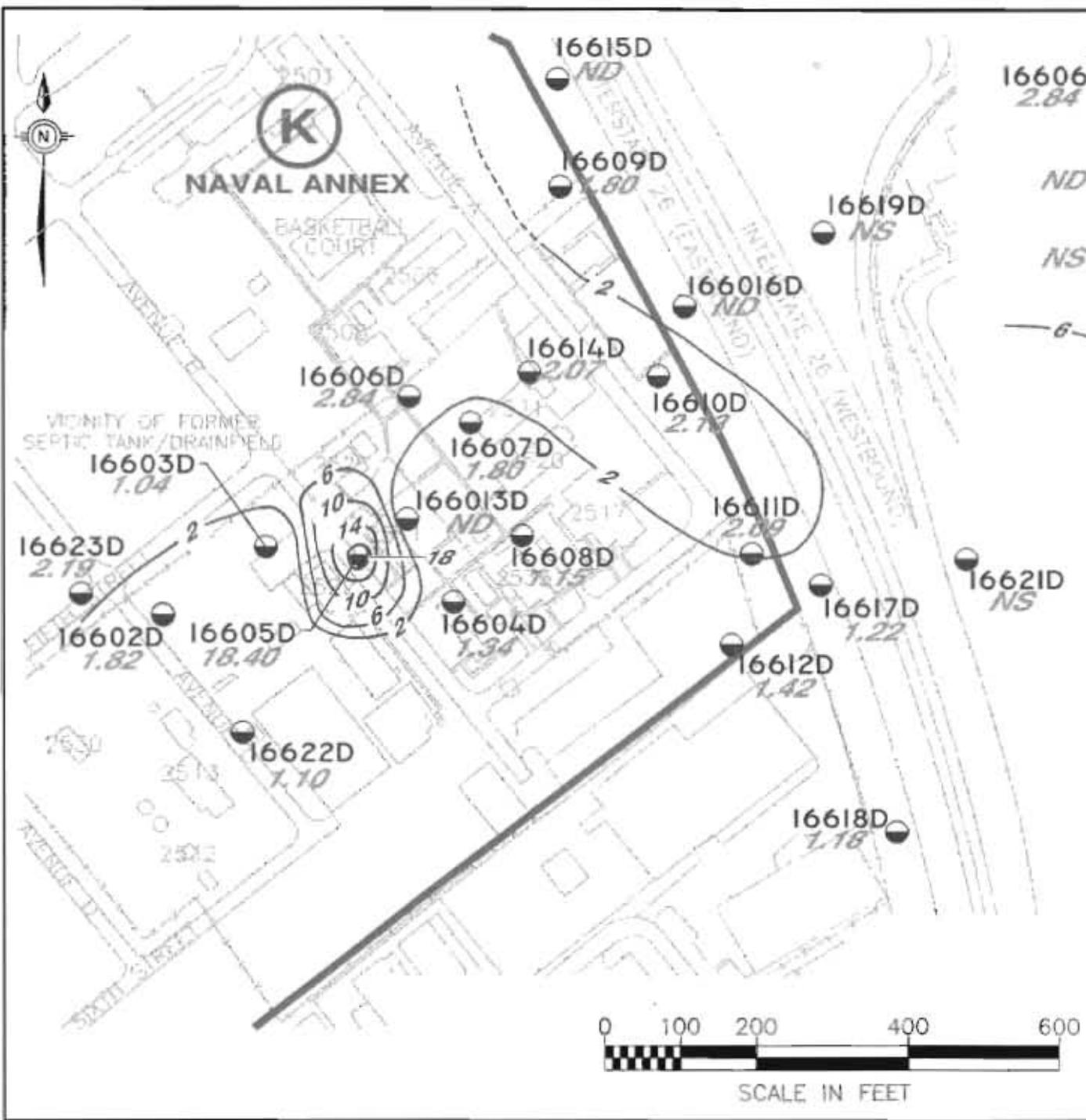
	<p>ZONE K - SWMU 166 MONITORED NATURAL ATTENUATION INTERIM REPORT CHARLESTON NAVAL COMPLEX CHARLESTON, SC</p>
	<p>FIGURE 3.45 SECOND ROUND - MNA SAMPLING SHALLOW GROUNDWATER</p>
<p>IRON (II) (mg/L)</p>	
<p>Date: 02/24/99 DWG Name: 2911M034</p>	



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FIGURE 3.46
 FIRST ROUND - MNA SAMPLING
 DEEP GROUNDWATER

IRON (II) (mg/L)



LEGEND:

- 16606D
2.84 ● DEEP MONITORING WELL W/ ID NUMBER AND IRON (II) CONCENTRATION (mg/L)
- ND = NOT DETECTED (DETECTION LEVEL 0.5 mg/L)
- NS = NOT SAMPLED
- 6 — IRON (II) ISOPLETH (mg/L) CONTOUR INTERVAL 4 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
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FIGURE 3.47
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER

IRON (II) (mg/L)

Date: 03/01/99

DWG Name: 2911MC044



Sulfate

Shallow Groundwater

Sulfate was detected in all eight Round 1 shallow wells and all 14 Round 2 shallow wells. Concentrations ranged from 8.4 to 22.1 mg/L in Round 1 and 4.8 to 28 mg/L in Round 2 (Figures 3.48 and 3.49).

A trough of low groundwater sulfate concentrations occurred west to east across SWMU 166 between high concentrations at 166004 and 166007 during the first round. Further definition of this trough was evident during the second round, as high concentrations at 166002 and 166017 bound its southern extent.

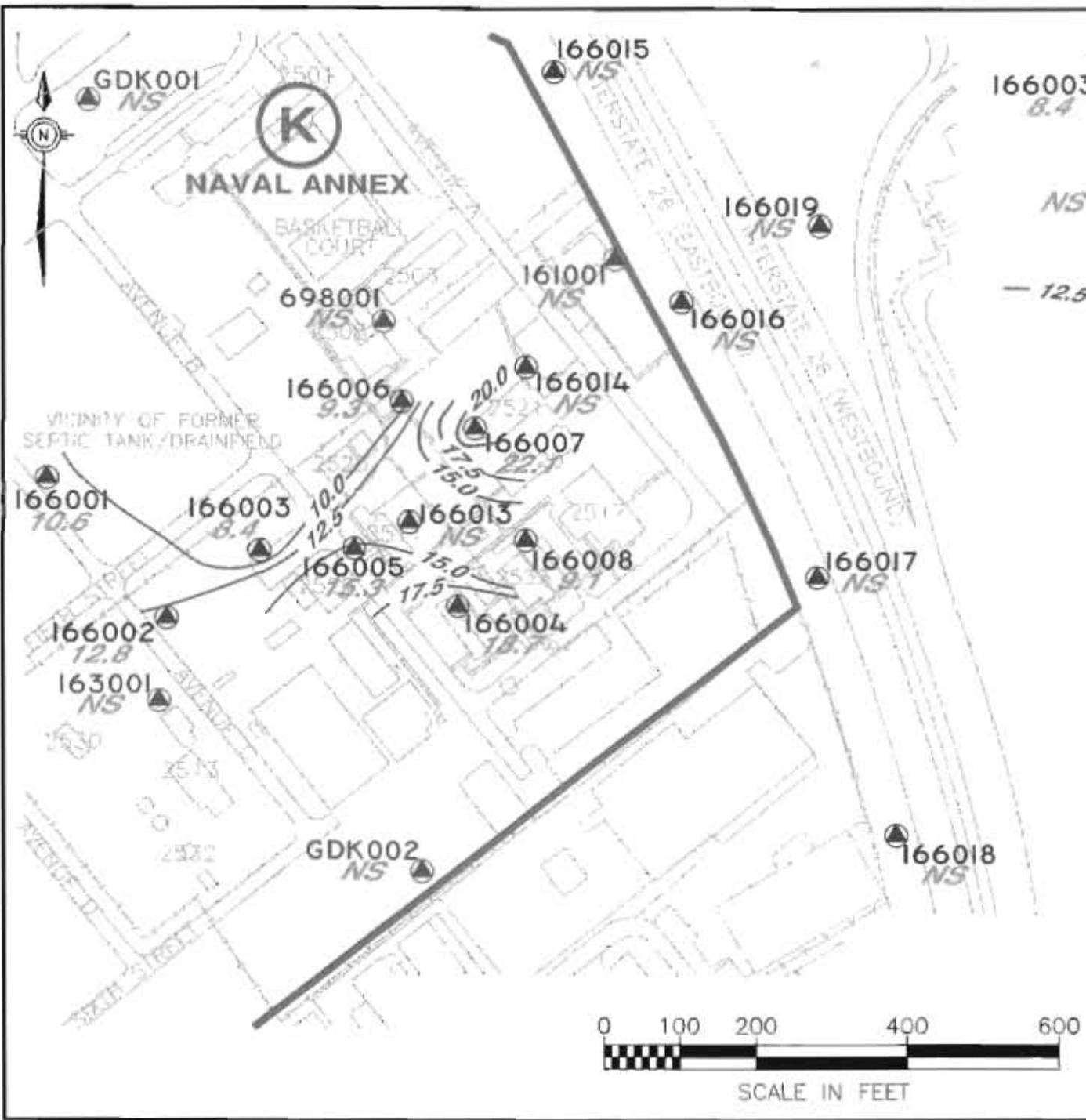
Deep Groundwater

Sulfate was detected in all 11 Round 1 and all 19 Round 2 deep wells. Sulfate concentrations ranged from 4.0 to 108 mg/L during the first round, and 3.2 to 78.0 mg/L during the second round (Figures 3.50 and 3.51).

First round sulfate concentrations decreased radially away from a high centered at 16605D. This well was again the highest of all sampled in Round 2, although its concentration had decreased by nearly a third. However, a small region of lower sulfate concentrations was found at 16613D and 16608D before concentrations again increased at 16607D.

Sulfide

Sulfide was analyzed only on second round groundwater samples. Sulfide is the end member of sulfate reduction and thus would indicate the presence and magnitude of sulfate reduction occurring at the site.



LEGEND:

- 166003
8.4 SHALLOW MONITORING WELL W/ ID NUMBER AND SULFATE CONCENTRATION (mg/L)
- NS = NOT SAMPLED
- 12.5 - SULFATE ISOPLETH (mg/L) CONTOUR INTERVAL 2.5 mg/L (DASHED WHERE INFERRED)

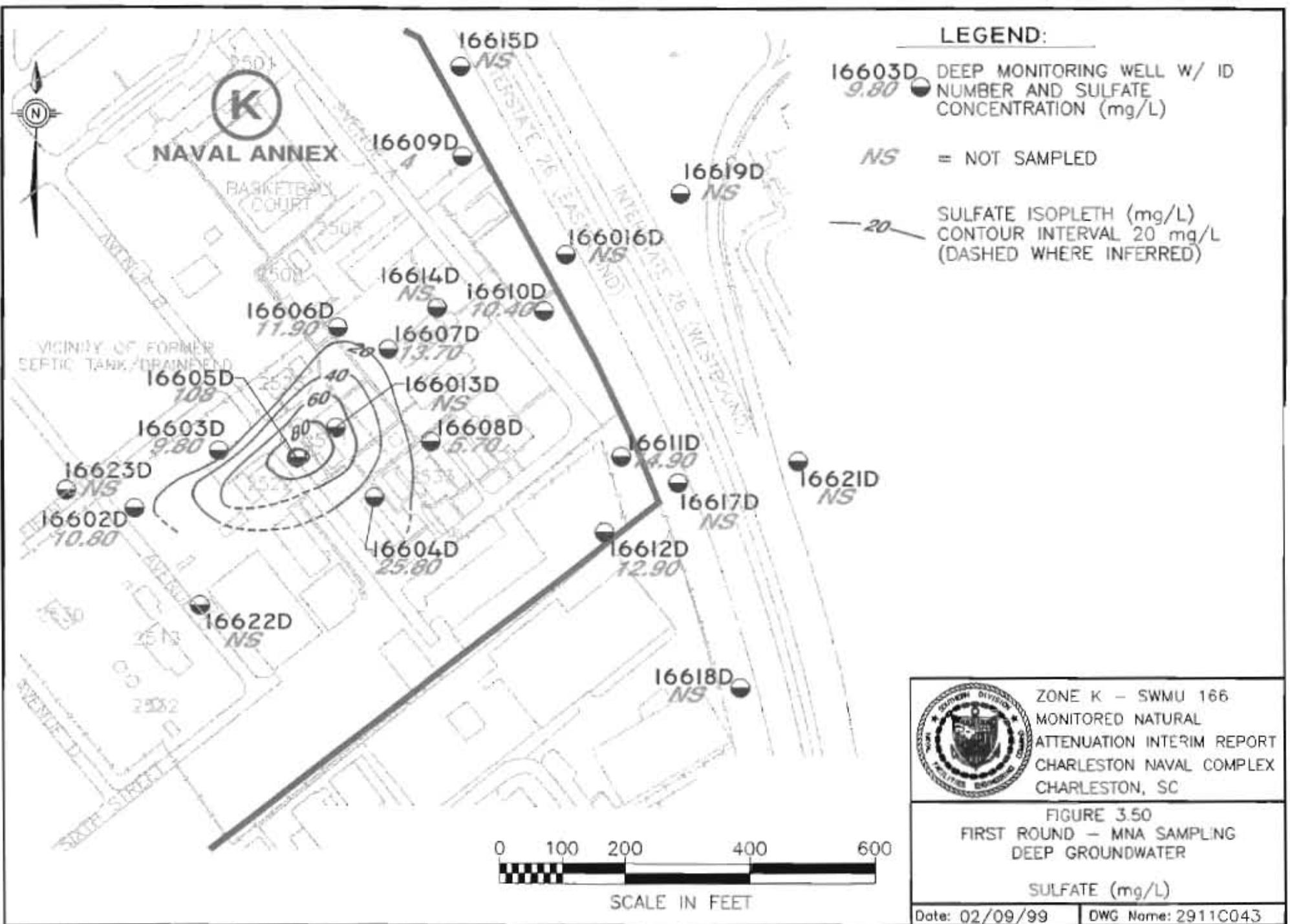


ZONE K - SWMU 166
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FIGURE 3.48
 FIRST ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

SULFATE (mg/L)





LEGEND:

16603D 9.80 ● DEEP MONITORING WELL W/ ID NUMBER AND SULFATE CONCENTRATION (mg/L)

NS = NOT SAMPLED

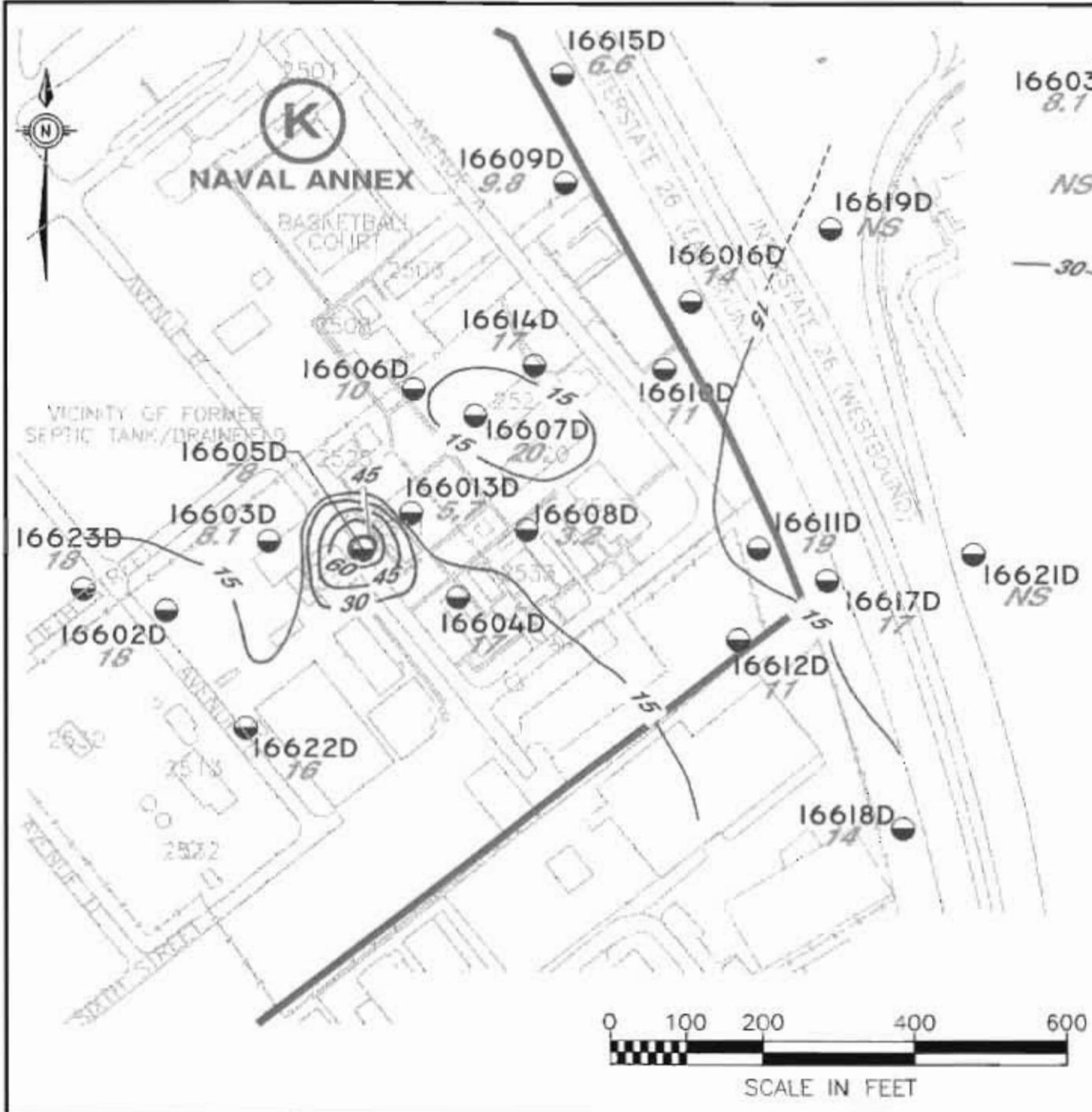
—20— SULFATE ISOPLETH (mg/L) CONTOUR INTERVAL 20 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
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FIGURE 3.50
 FIRST ROUND - MNA SAMPLING
 DEEP GROUNDWATER

SULFATE (mg/L)



LEGEND:

- 16603D 8.1 ● DEEP MONITORING WELL W/ ID NUMBER AND SULFATE CONCENTRATION (mg/L)
- NS = NOT SAMPLED
- 30 — SULFATE ISOPLETH (mg/L) CONTOUR INTERVAL 15 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
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FIGURE 3.51
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER

SULFATE (mg/L)

Sulfide was not detected above its 1.0 mg/L detection level in any shallow groundwater samples. 1
Only one deep groundwater sample, 16623D, had a detectable sulfide concentration of 1.2 mg/L 2
(Table 3.1). 3

Methanogenesis 4

Carbon dioxide may be used as an electron acceptor once all of the DO, nitrate, iron (III), and 5
sulfate have been used by microorganisms. During this electron transfer, carbon dioxide is 6
reduced to methane gas via methanogenesis. If carbon dioxide is being utilized as an electron 7
acceptor at the site, increases in methane concentrations would indicate sustained biodegradation 8
of chlorinated solvents. 9

Carbon Dioxide 10

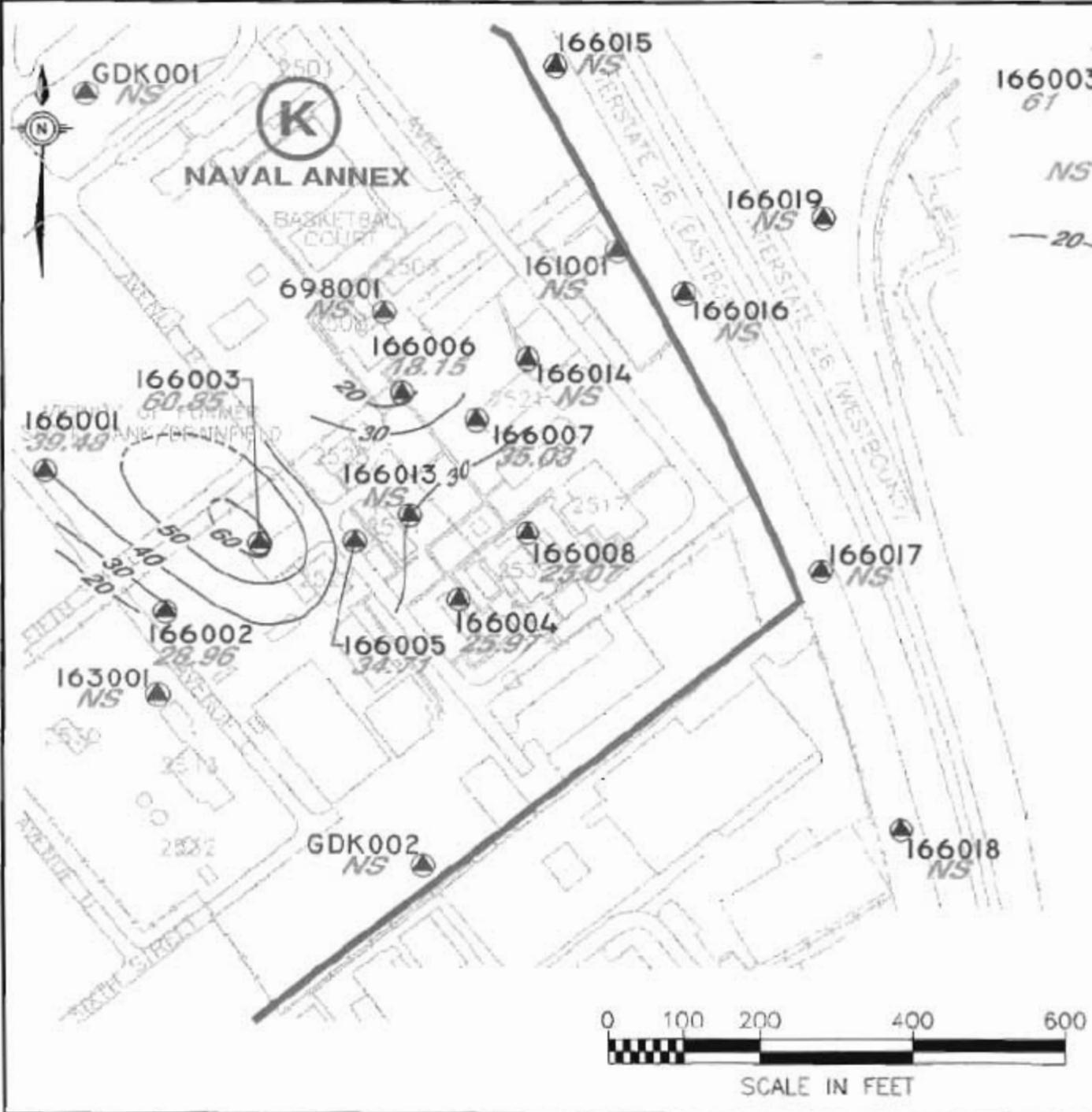
Shallow Groundwater 11

Carbon dioxide was detected in all eight first round shallow wells and all 14 second round shallow 12
wells. First and second round carbon dioxide concentration ranges were 18.15 to 60.85 mg/L and 13
23.05 to 58.30 mg/L, respectively (Figures 3.52 and 3.53). 14

The highest carbon dioxide concentrations in first round shallow groundwater were centered near 15
166003. The second round carbon dioxide results indicated a high concentration region to the 16
southwest (vicinity of 166003), separated from another high concentration region to the northeast 17
(vicinity of 166014) by a northwest-southeast trending trough. 18

Deep Groundwater 19

Carbon dioxide was detected in all 11 first round deep wells and all 19 second round deep wells. 20
First and second round carbon dioxide concentration ranges were 13.89 to 65.25 mg/L and 1.65 21
to 63.95 mg/L, respectively(Figures 3.54 and 3.55). 22



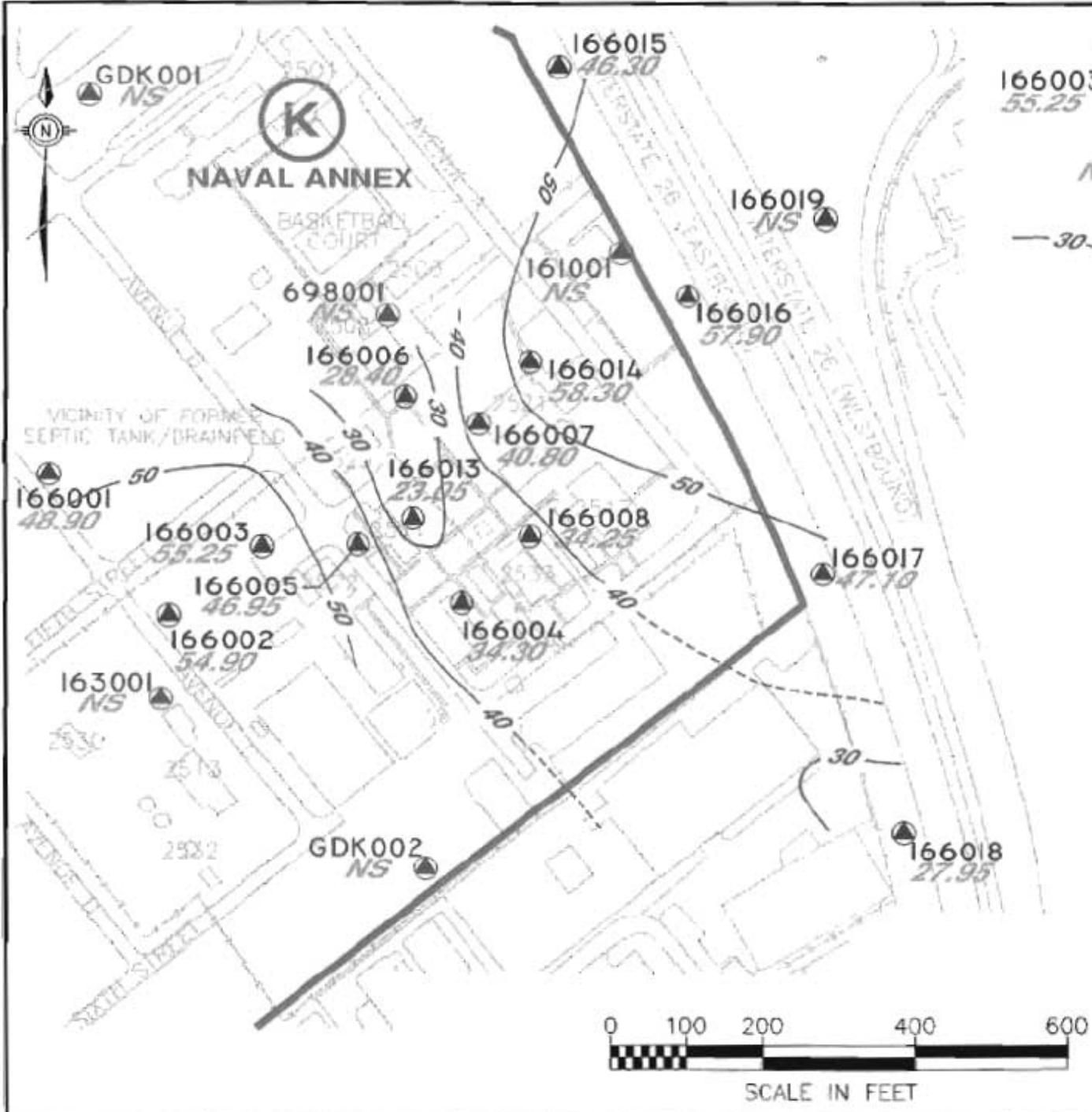
LEGEND:

- 166003
61 SHALLOW MONITORING WELL W/ ID NUMBER AND CARBON DIOXIDE CONCENTRATION (mg/L)
- NS = NOT SAMPLED
- 20- CARBON DIOXIDE ISOPLETH (mg/L)
CONTOUR INTERVAL 10 mg/L
(DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.52
 FIRST ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER
 CARBON DIOXIDE (mg/L)



LEGEND:

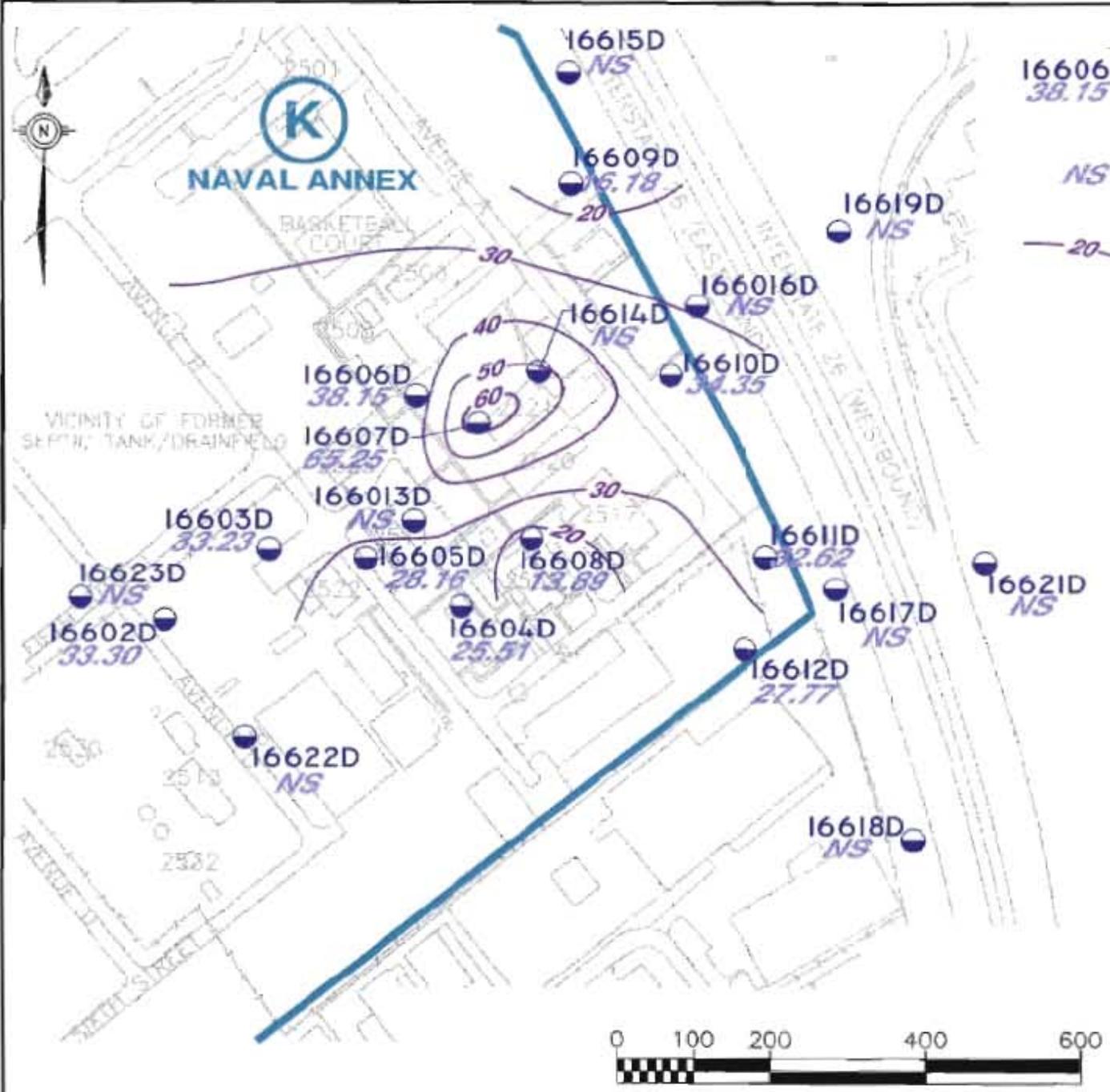
- 166003
55.25 SHALLOW MONITORING WELL W/ ID NUMBER AND CARBON DIOXIDE CONCENTRATION (mg/L)
- NS = NOT SAMPLED
- 30 CARBON DIOXIDE ISOPLETH (mg/L) CONTOUR INTERVAL 10 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
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 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.53
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

CARBON DIOXIDE (mg/L)



LEGEND:

- 16606D
38.15 ● DEEP MONITORING WELL W/ ID NUMBER AND CARBON DIOXIDE CONCENTRATION (mg/L)
- NS = NOT SAMPLED
- 20 — CARBON DIOXIDE ISOPLETH (mg/L) CONTOUR INTERVAL 10 mg/L (DASHED WHERE INFERRED)



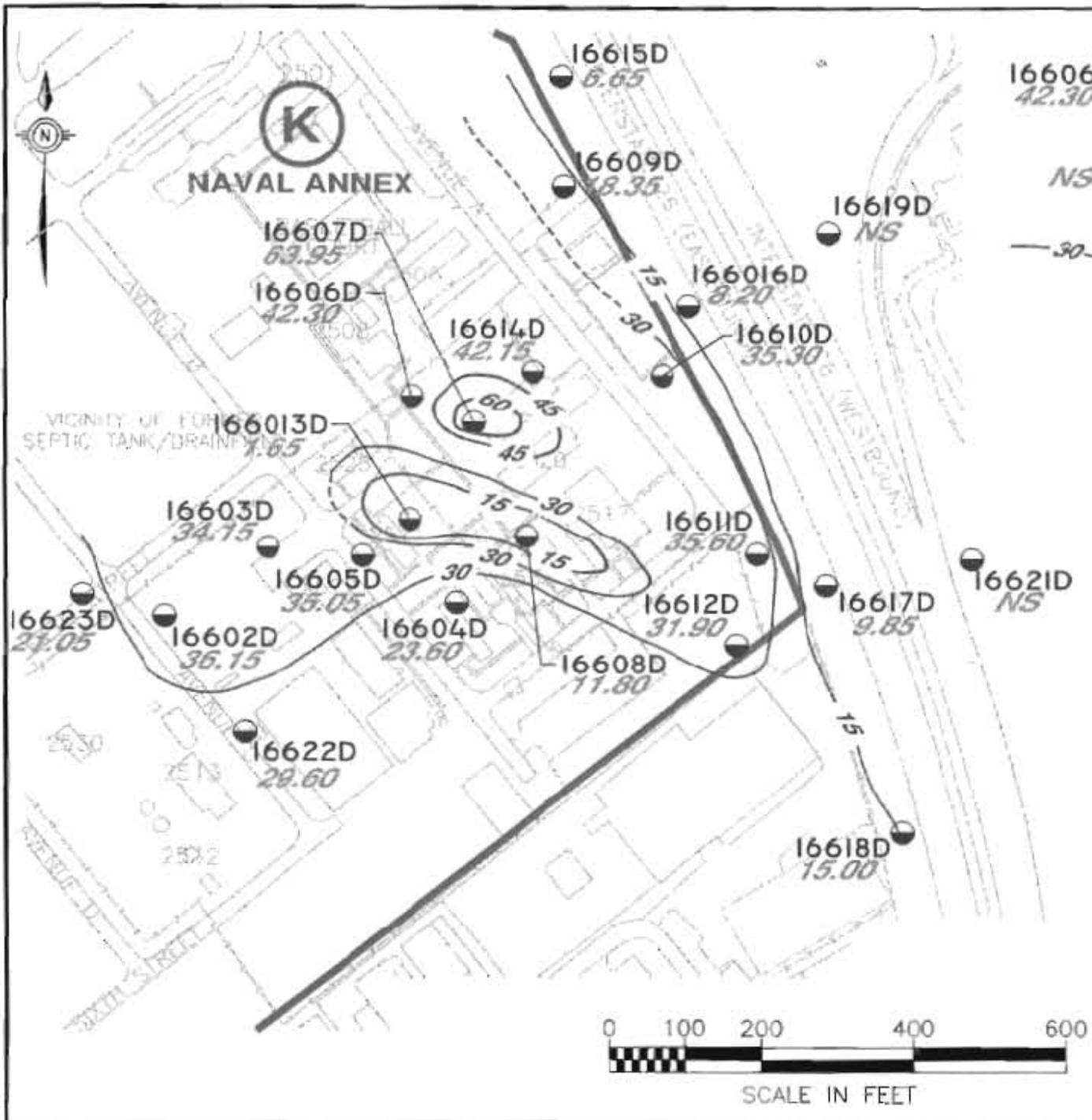
ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.54
 FIRST ROUND - MNA SAMPLING
 DEEP GROUNDWATER

CARBON DIOXIDE (mg/L)



SCALE IN FEET



LEGEND:

- 16606D 42.30 ● DEEP MONITORING WELL W/ ID NUMBER AND CARBON DIOXIDE CONCENTRATION (mg/L)
- NS = NOT SAMPLED
- 30 — CARBON DIOXIDE ISOPLETH (mg/L) CONTOUR INTERVAL 15 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.55
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER

CARBON DIOXIDE (mg/L)

A localized carbon dioxide concentration high was centered near 16607D during the first round. Carbon dioxide concentrations gradually decreased radially away from this high. Second round carbon dioxide results reproduced the high at 16607D, although immediately to the south was an anomalous low corresponding to wells 16613D and 16608D.

Methane

Shallow Groundwater

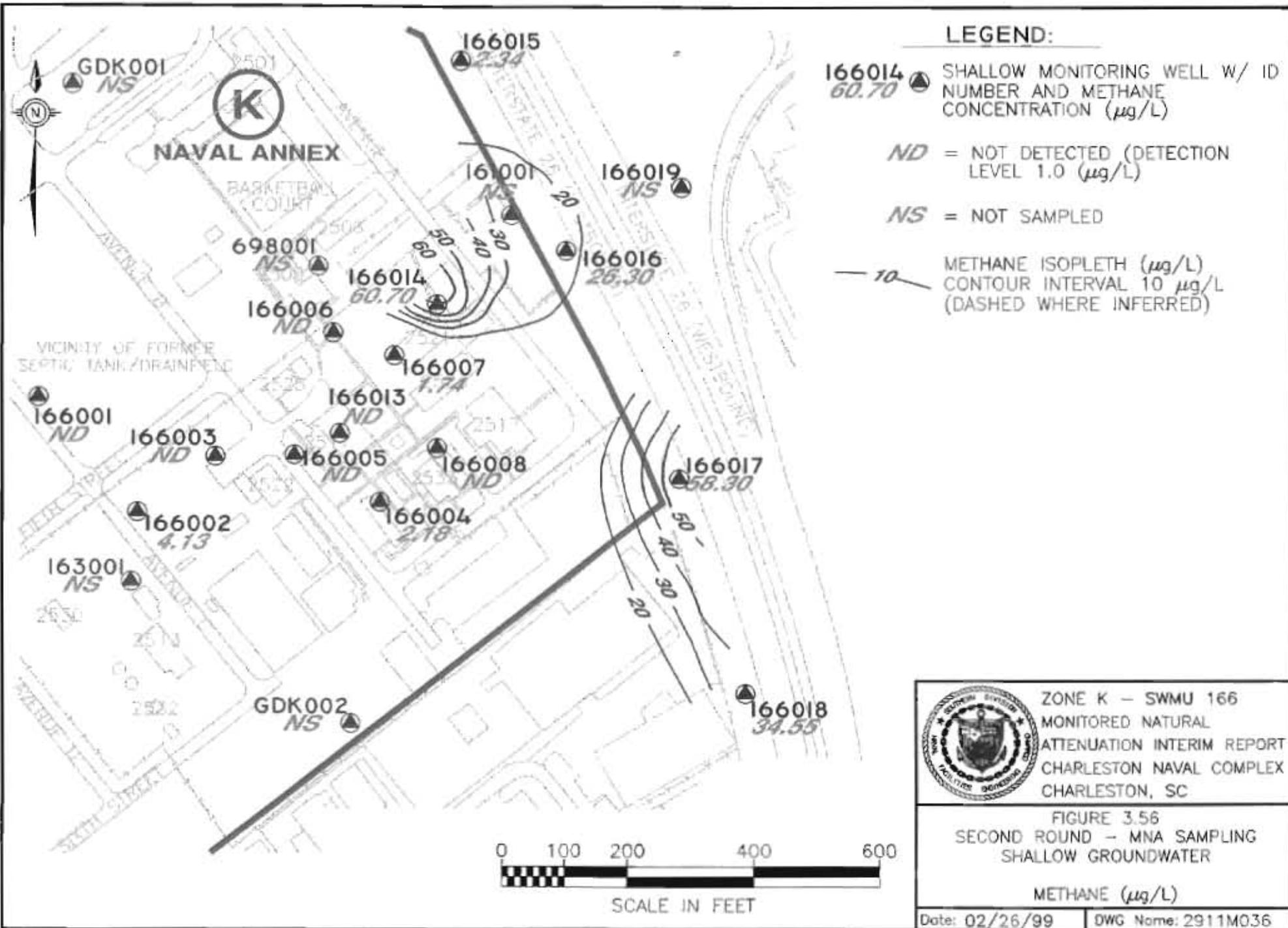
Methane was not detected in any first round shallow groundwater samples (ND = 1.0 $\mu\text{g/L}$). Methane was detected in eight of 14 second round shallow groundwater samples, ranging in concentration between 1.74 and 60.70 $\mu\text{g/L}$ (Figure 3.56).

Methane concentrations were highest at two isolated points, 166014 and 166017, on the east side of the site during Round 2. Concentrations of methane appeared to increase offsite to the east, parallel with the predominant groundwater flow direction.

Deep Groundwater

Methane was detected in all 11 first round deep wells and all 19 second round deep wells. First and second round methane concentrations ranged from 6.31 to 67.80 $\mu\text{g/L}$ and 1.51 to 531 $\mu\text{g/L}$, respectively (Figures 3.57 and 3.58).

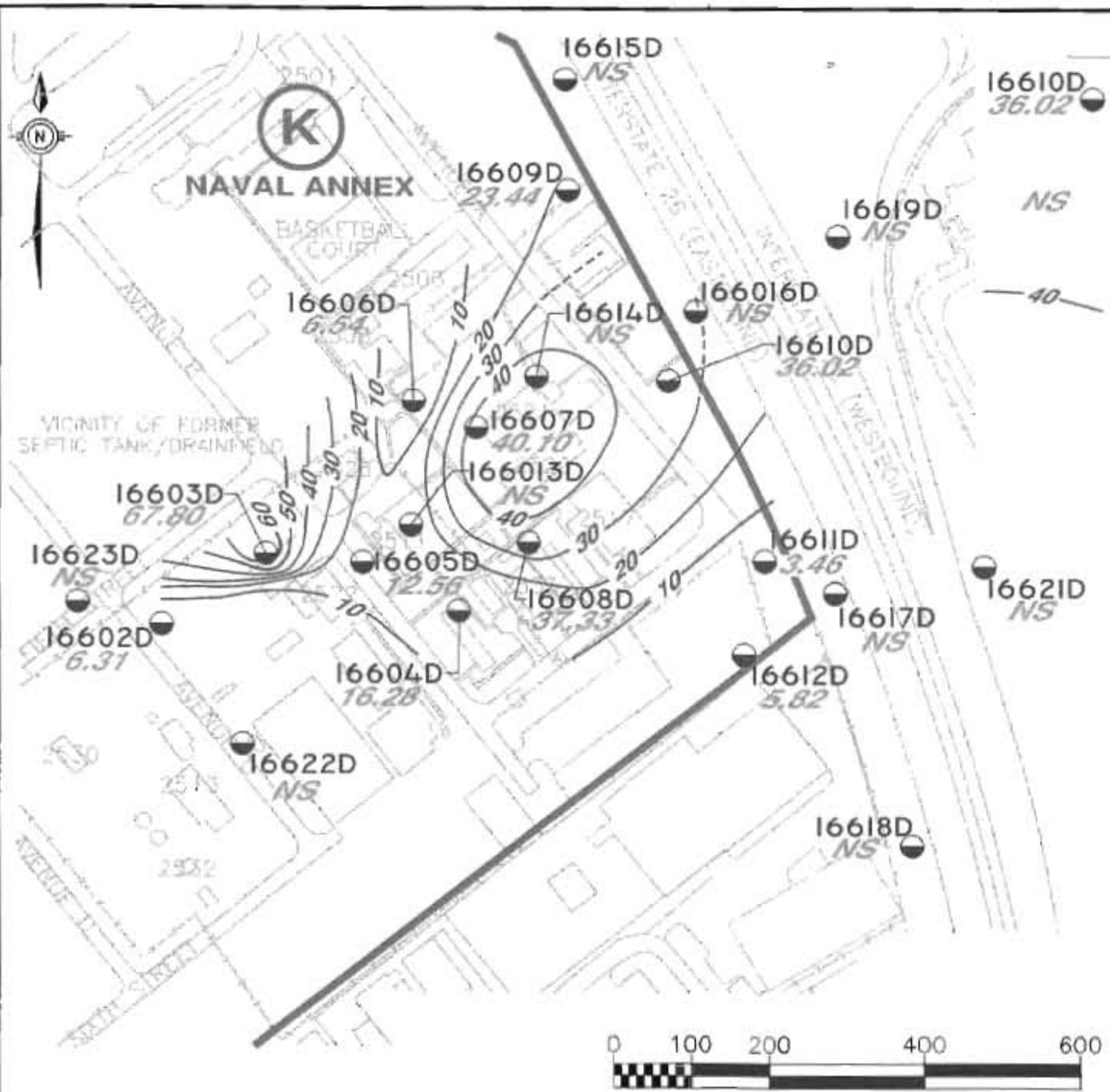
Two high methane concentrations were evident in Round 1 data at 16603D and 16607D. Methane concentrations were low in a trough trending roughly north to south between these two wells. The high centered at 16607D was much broader and appeared to be deformed along the groundwater flow direction, creating a plume of methane-rich groundwater migrating eastward. During the second round, the high methane concentrations were reproduced at 16603D with a more southerly component encompassing 16622D. The first round high methane concentration at 16607D moved eastward along the flowpath to 16614D. The highest methane concentrations at the site were



ZONE K - SWMU 166
 MONITORED NATURAL
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 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.56
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

METHANE (µg/L)



LEGEND:

- 16610D 36.02 ● DEEP MONITORING WELL W/ ID NUMBER AND METHANE CONCENTRATION ($\mu\text{g/L}$)
- NS = NOT SAMPLED
- 40 — METHANE ISOPLETH ($\mu\text{g/L}$) CONTOUR INTERVAL 10 $\mu\text{g/L}$ (DASHED WHERE INFERRED)

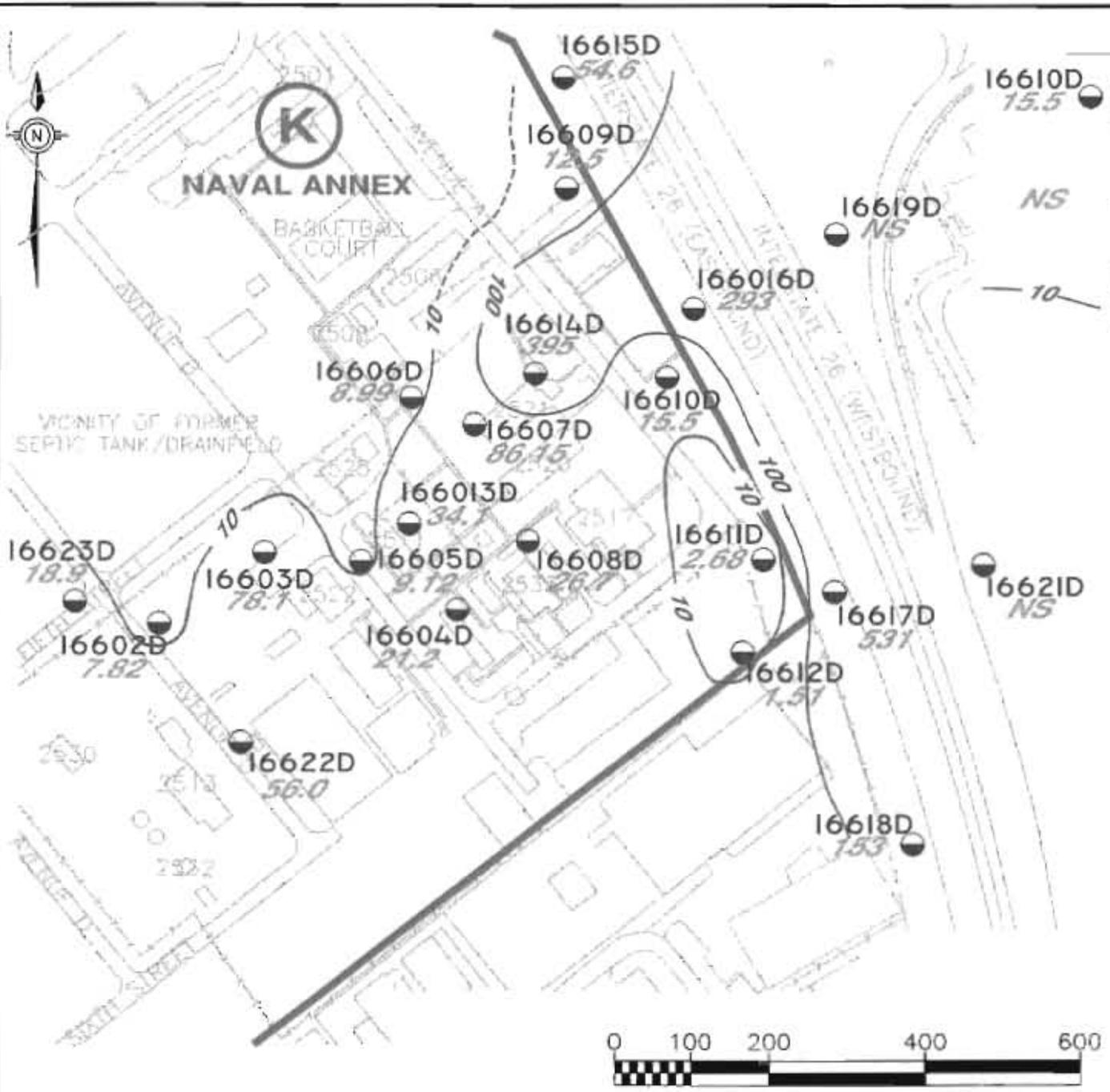


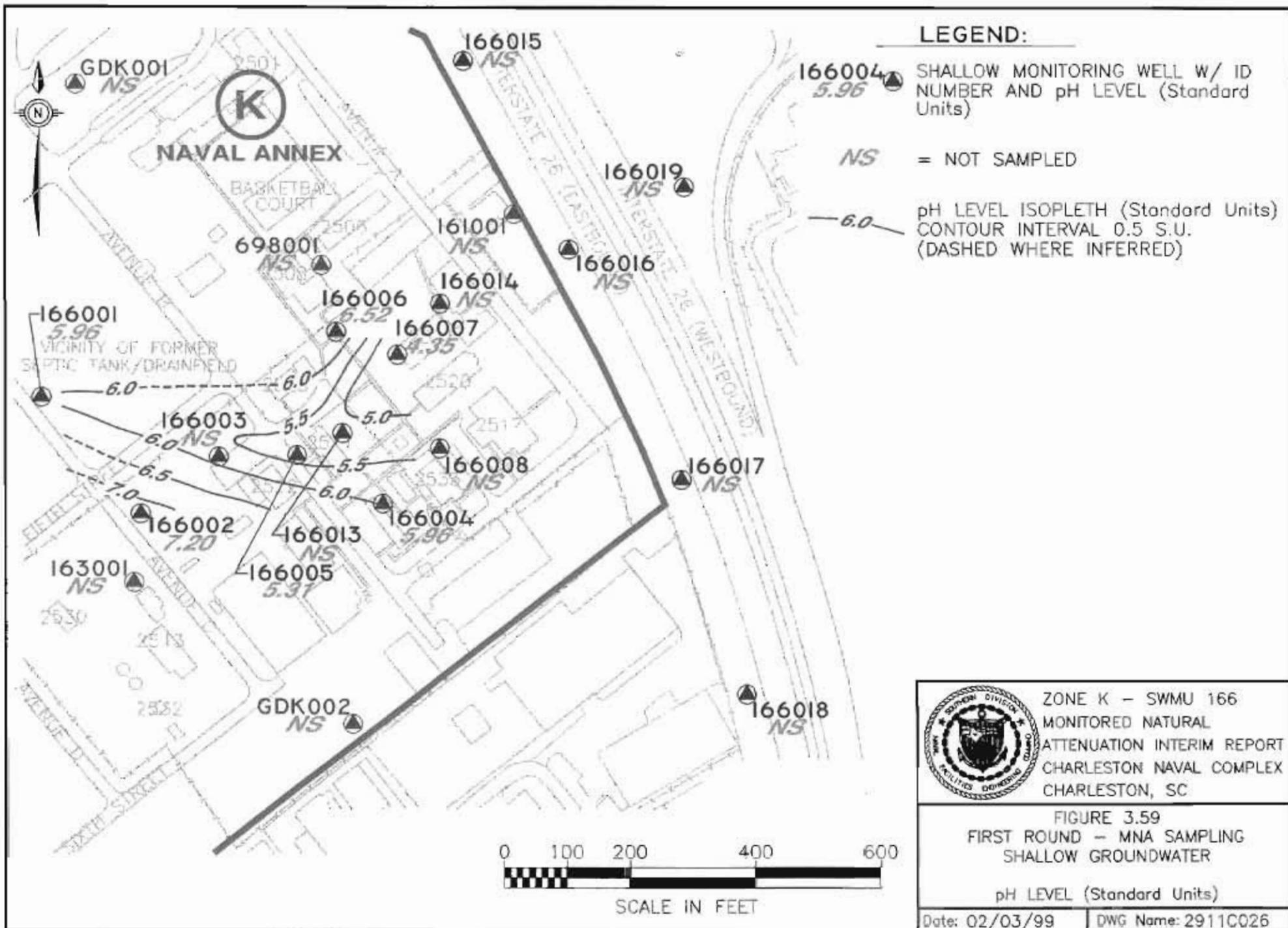
ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.57
 FIRST ROUND - MNA SAMPLING
 DEEP GROUNDWATER

METHANE ($\mu\text{g/L}$)



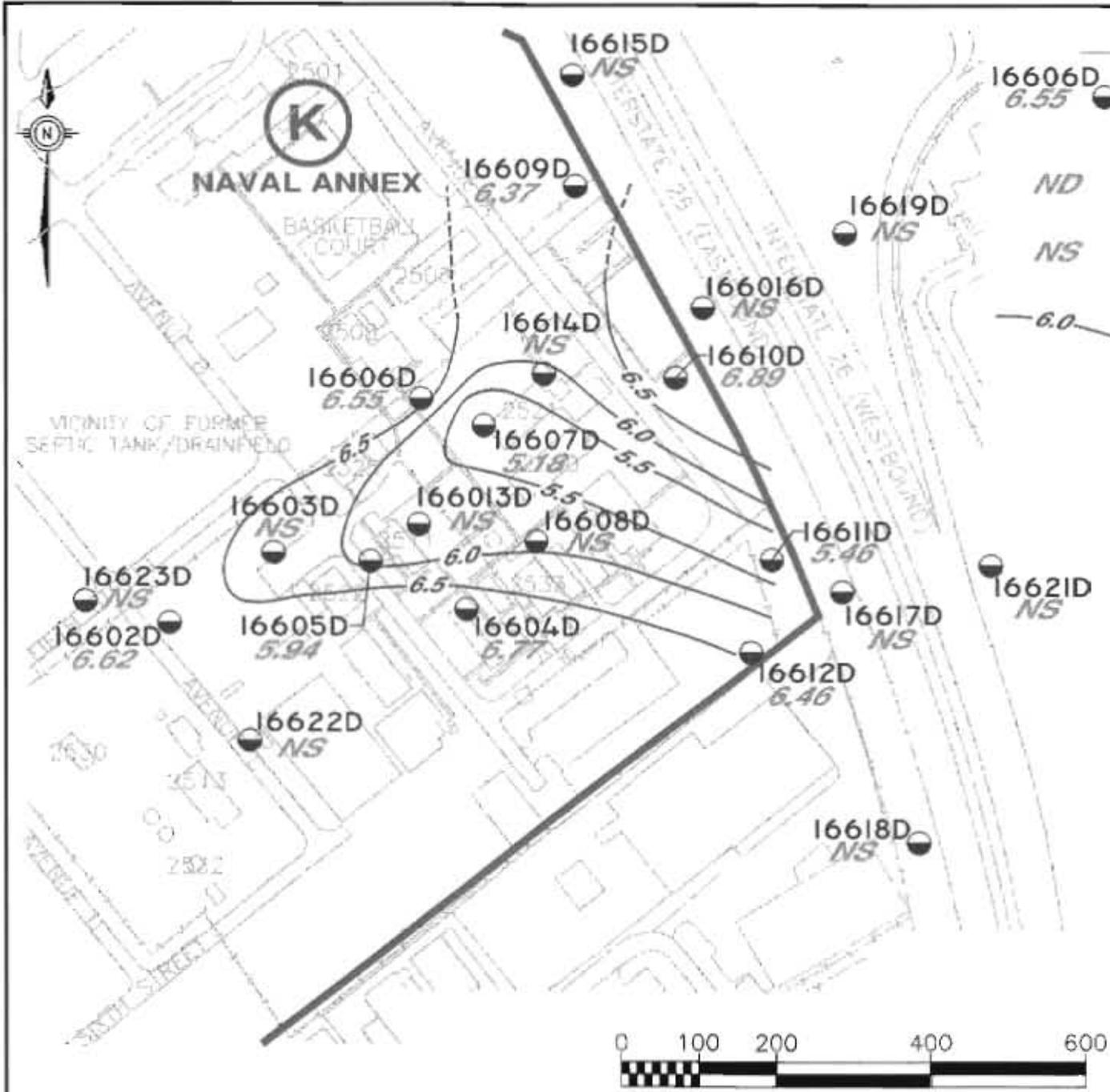







 ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.60
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER
 pH LEVEL (Standard Units)
 Date: 02/23/99 DWG Name: 2911M026



LEGEND:

- DEEP MONITORING WELL W/ ID NUMBER AND pH LEVEL (Standard Units)
- ND = NOT DETECTED (DETECTION LEVEL 0.5 S.U.)
- NS = NOT SAMPLED
- pH LEVEL ISOPLETH (Standard Units) CONTOUR INTERVAL 0.5 S.U. (DASHED WHERE INFERRED)

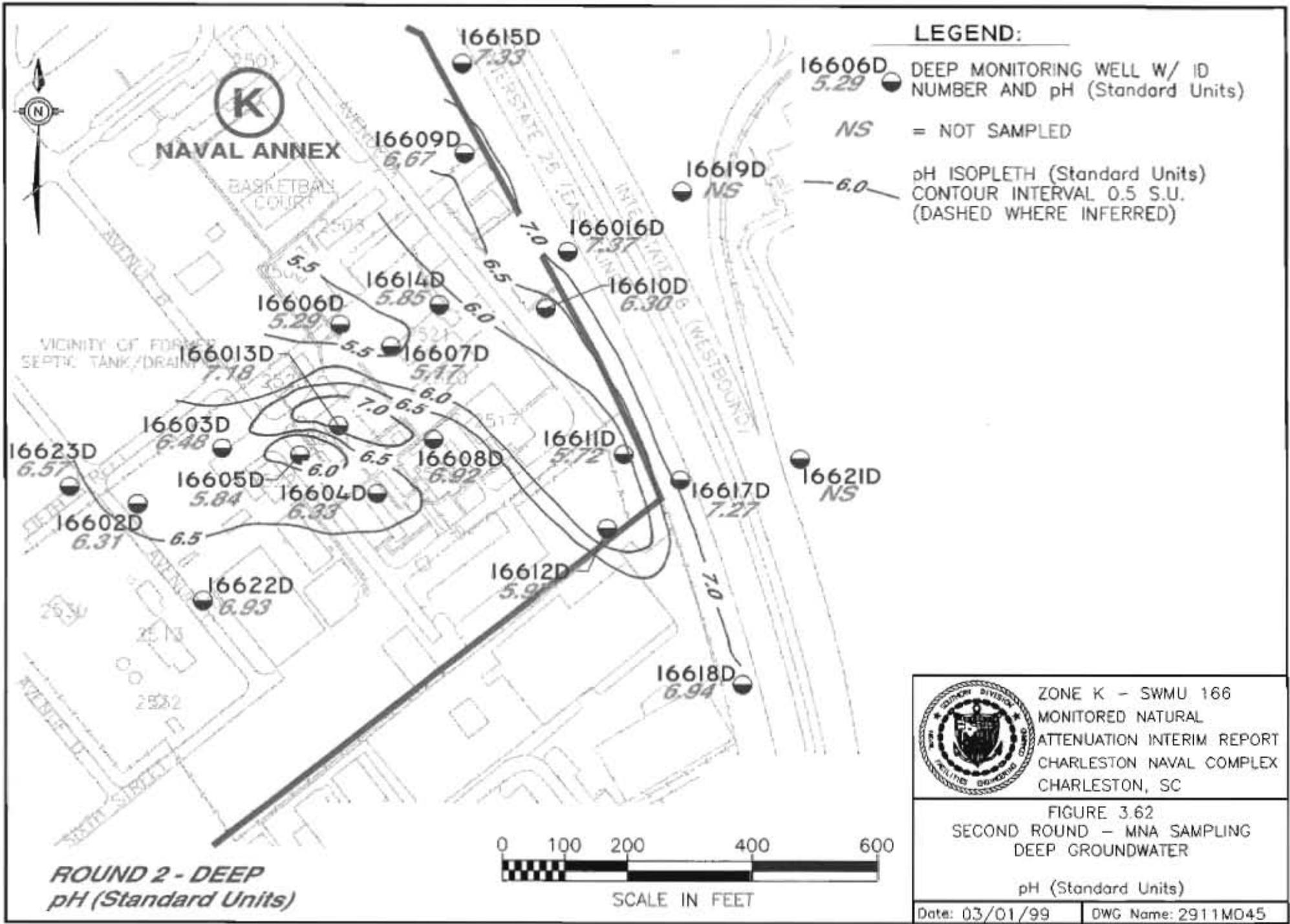


ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.61
 FIRST ROUND - MNA SAMPLING
 DEEP GROUNDWATER

pH LEVEL (Standard Units)





LEGEND:

16606D 5.29 ● DEEP MONITORING WELL W/ ID NUMBER AND pH (Standard Units)

NS = NOT SAMPLED

6.0 - pH ISOPLETH (Standard Units) CONTOUR INTERVAL 0.5 S.U. (DASHED WHERE INFERRED)

**ROUND 2 - DEEP
pH (Standard Units)**



 ZONE K - SWMU 166
MONITORED NATURAL
ATTENUATION INTERIM REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC

FIGURE 3.62
SECOND ROUND - MNA SAMPLING
DEEP GROUNDWATER
pH (Standard Units)
Date: 03/01/99 DWG Name: 2911M045

southwest of this low. More neutral pH was found in the wells along Interstate 26 and wells 16613D and 16608D which demarcate the southern extent of the low pH zone.

Alkalinity

Alkalinity is increased in regions of an aquifer that sustain large microbial populations. Acids formed during aerobic and anaerobic reactions dissolve the surrounding aquifer materials. The dissolved aquifer materials tend to increase groundwater alkalinity and thus buffer the pH. This buffering is important in sustaining a groundwater pH that supports resident microbial populations.

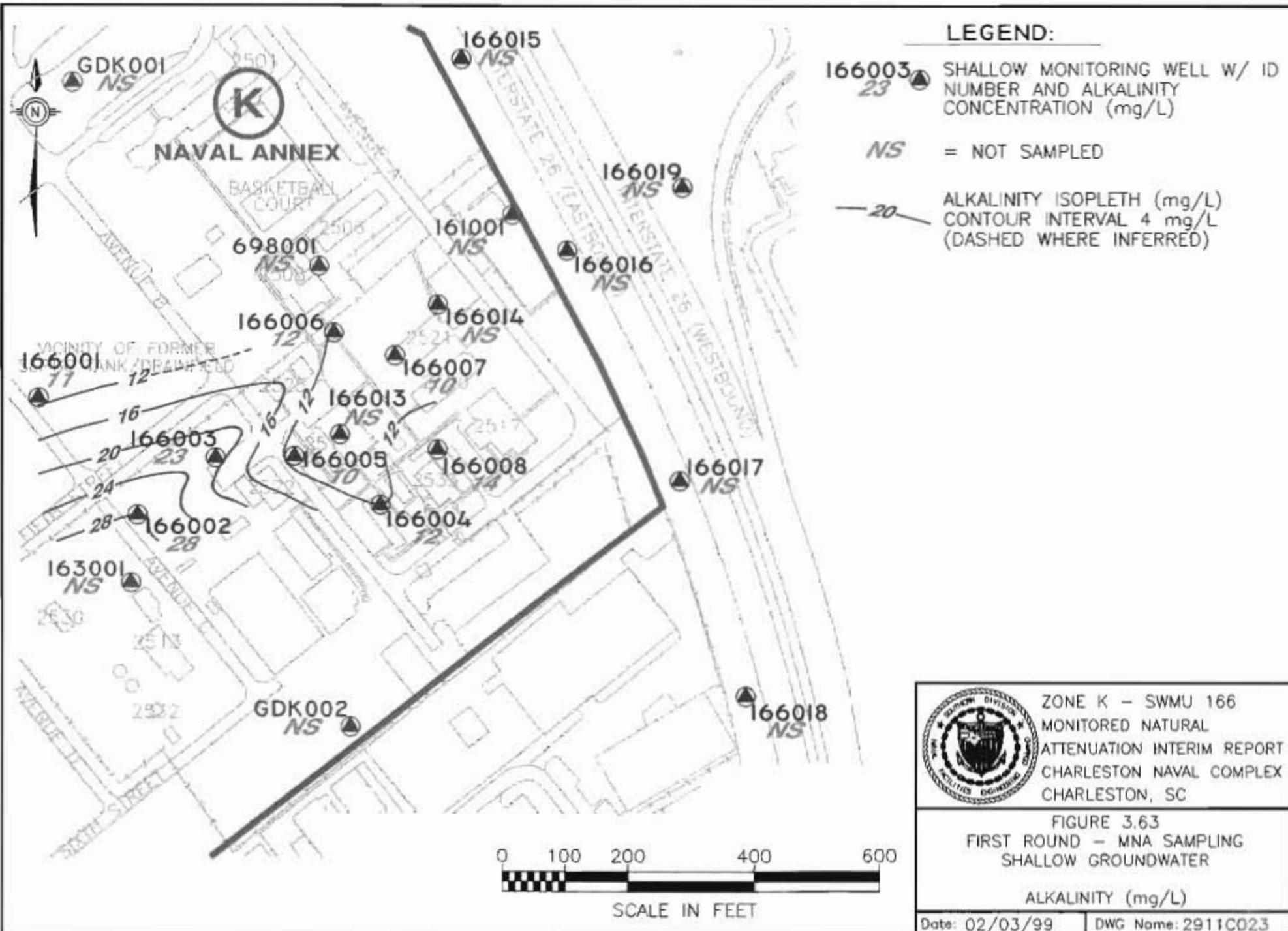
Shallow Groundwater

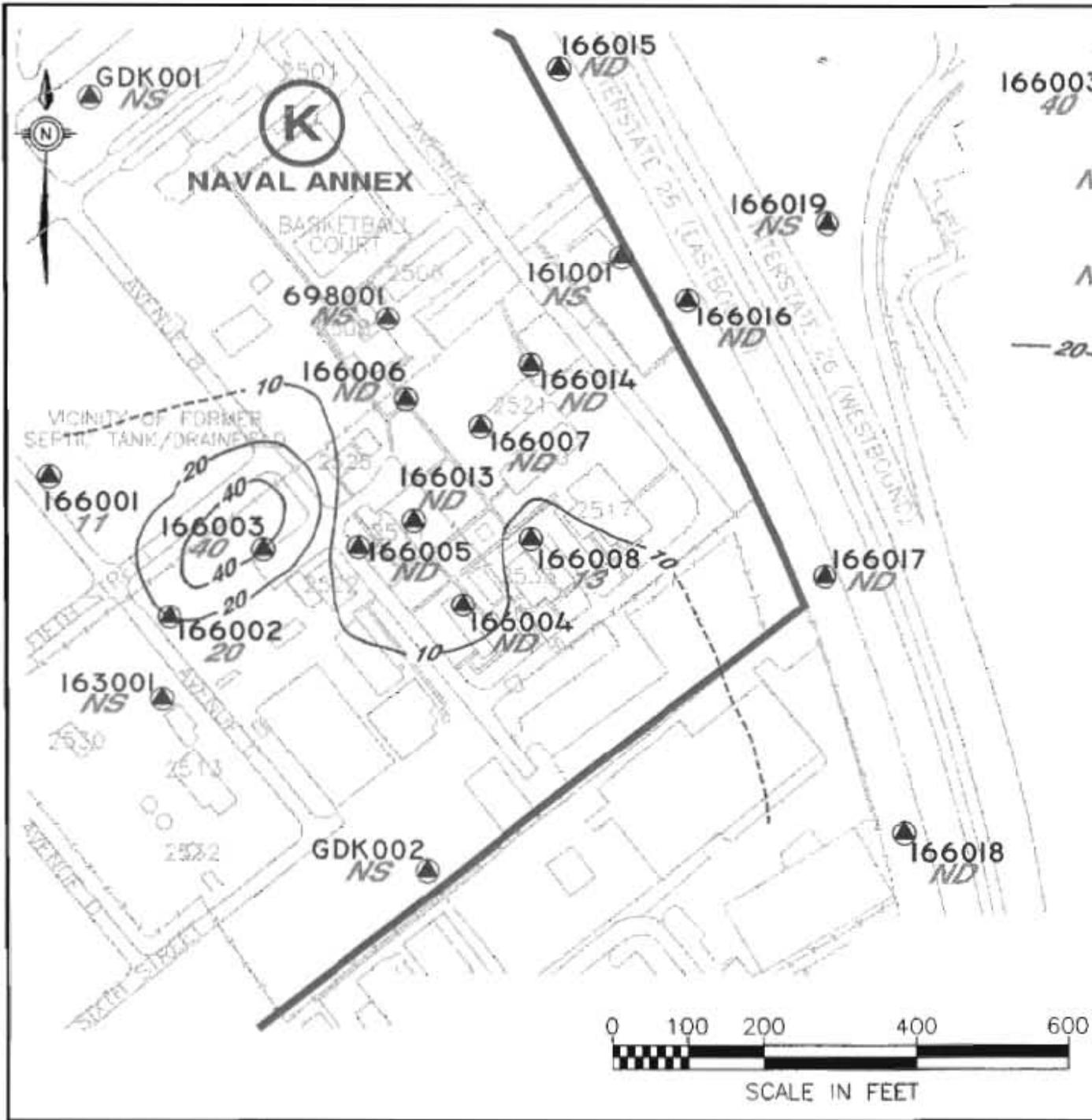
First round alkalinity ranged from 10.0 to 28.0 mg/L in Round 1 samples (Figure 3.63). During the second round, alkalinity was detected above its detection limit (10.0 mg/L) in only four wells with a range of 11 to 40 mg/L (Figure 3.64). Variations in alkalinity during Rounds 1 and 2 were minimal, although in Round 2, the non-detections were found throughout comprise the eastern half of the site.

Deep Groundwater

First round alkalinity in deep groundwater ranged from 10.0 to 22.0 mg/L (Figure 3.65). Second round alkalinity when detected ranged from 13.0 to 50.0 mg/L (Figure 3.66).

First round alkalinity data indicated lower concentrations in the center of the site than at the fringes. This lower alkalinity zone appears oriented toward the southeast, which may be due to the smaller Round 1 well population. Second round alkalinity data revealed several anomalies. Alkalinity was elevated (greater than 30.0 mg/L) in a kidney-bean shaped ridge of deep groundwater, extending east from 16603D to 16604D and 16608D. Immediately north-northwest (wells 16606D and 16607D) and southeast (wells 16611D and 16612D) of this higher alkalinity





LEGEND:

166003/40 SHALLOW MONITORING WELL W/ ID NUMBER AND ALKALINITY CONCENTRATION (mg/L)

ND = NOT DETECTED (DETECTION LEVEL 10 mg/L)

NS = NOT SAMPLED

20 ALKALINITY ISOPLETH (mg/L) CONTOUR INTERVAL 10 mg/L (DASHED WHERE INFERRED)



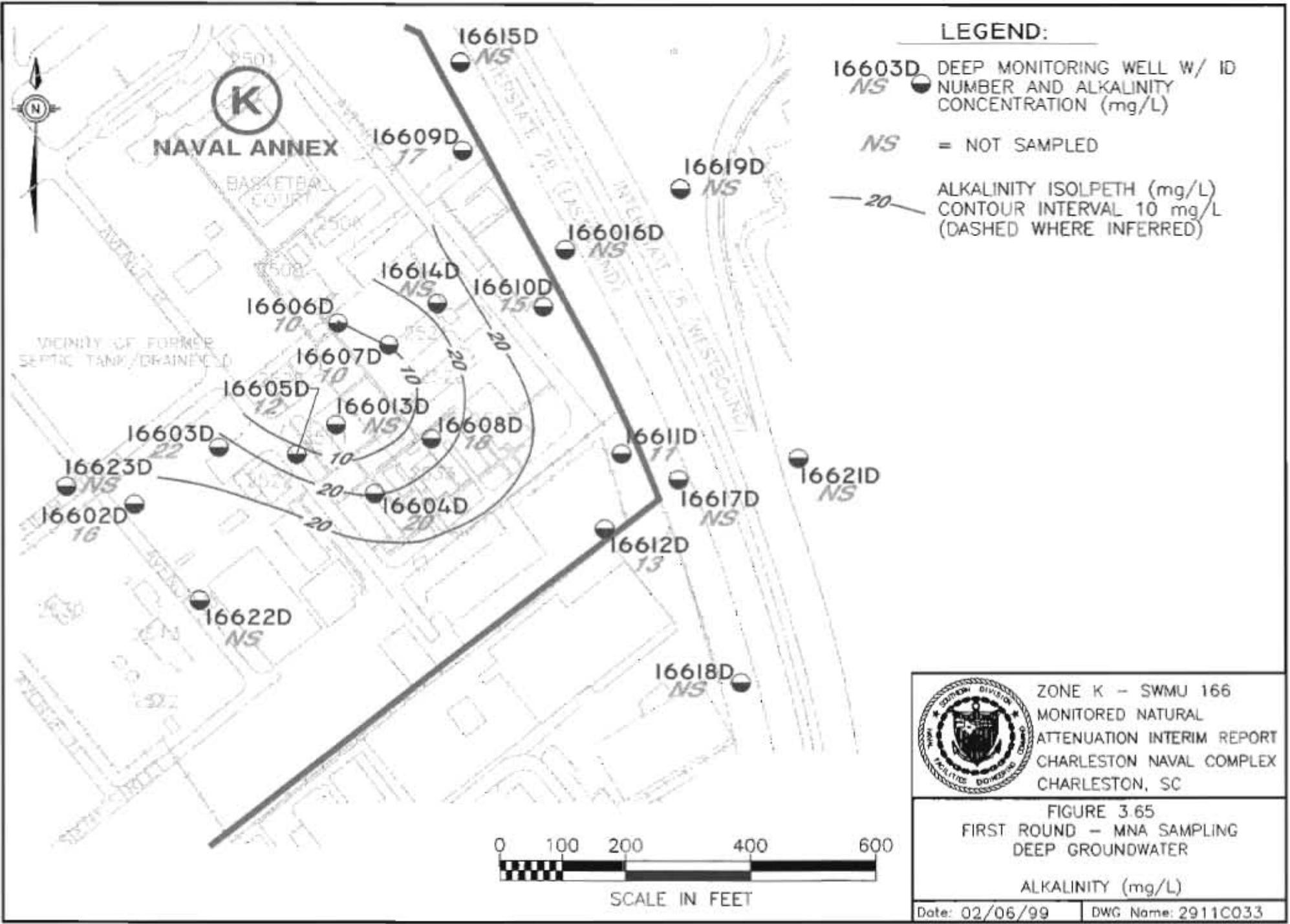
ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

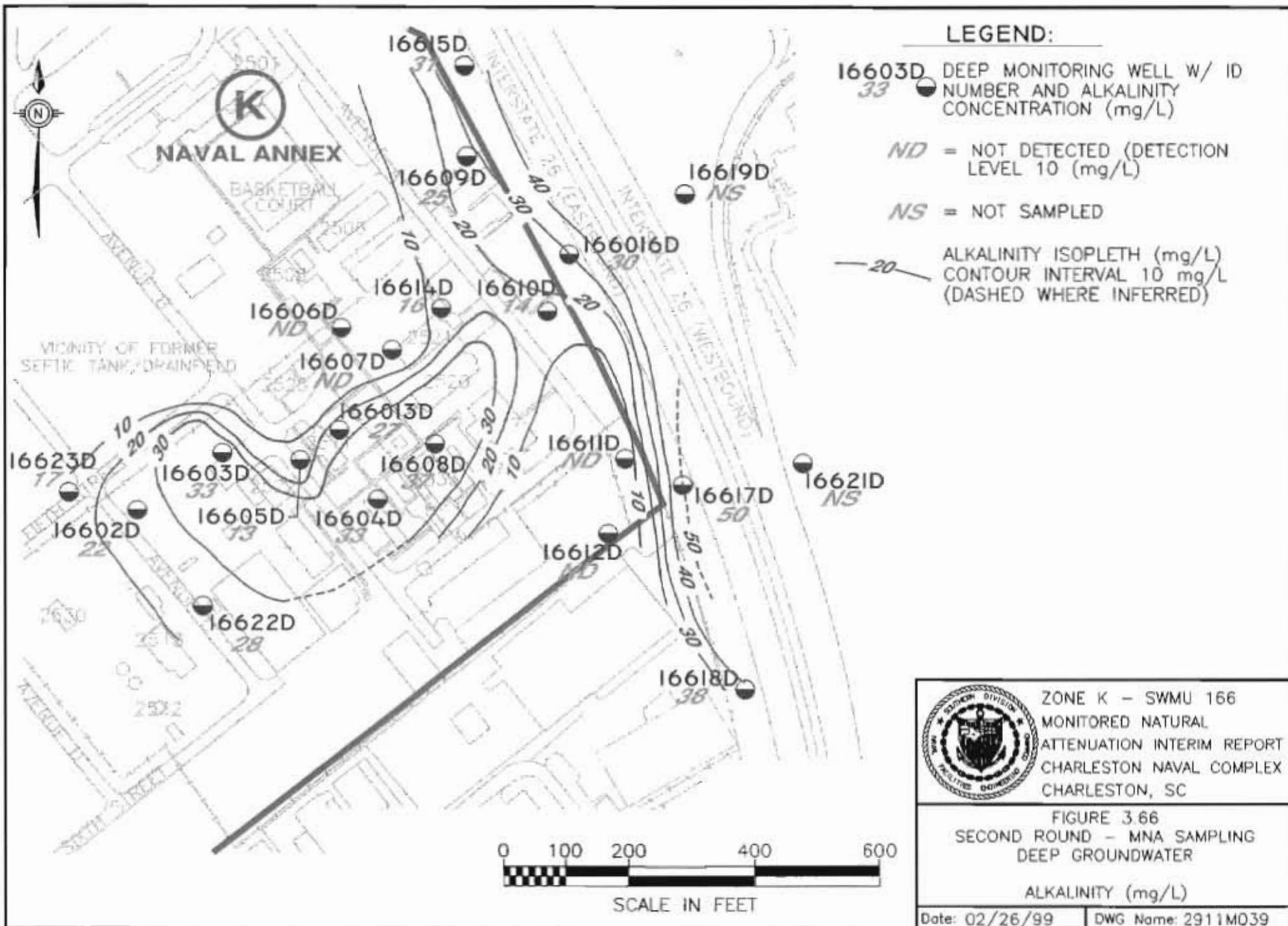
FIGURE 3.64
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

ALKALINITY (mg/L)

Date: 02/22/99 | DWG Name: 2911M023







zone were zones with no detectable alkalinity. Alkalinity increased along the eastern edge of the site in the wells along Interstate 26.

Chloride

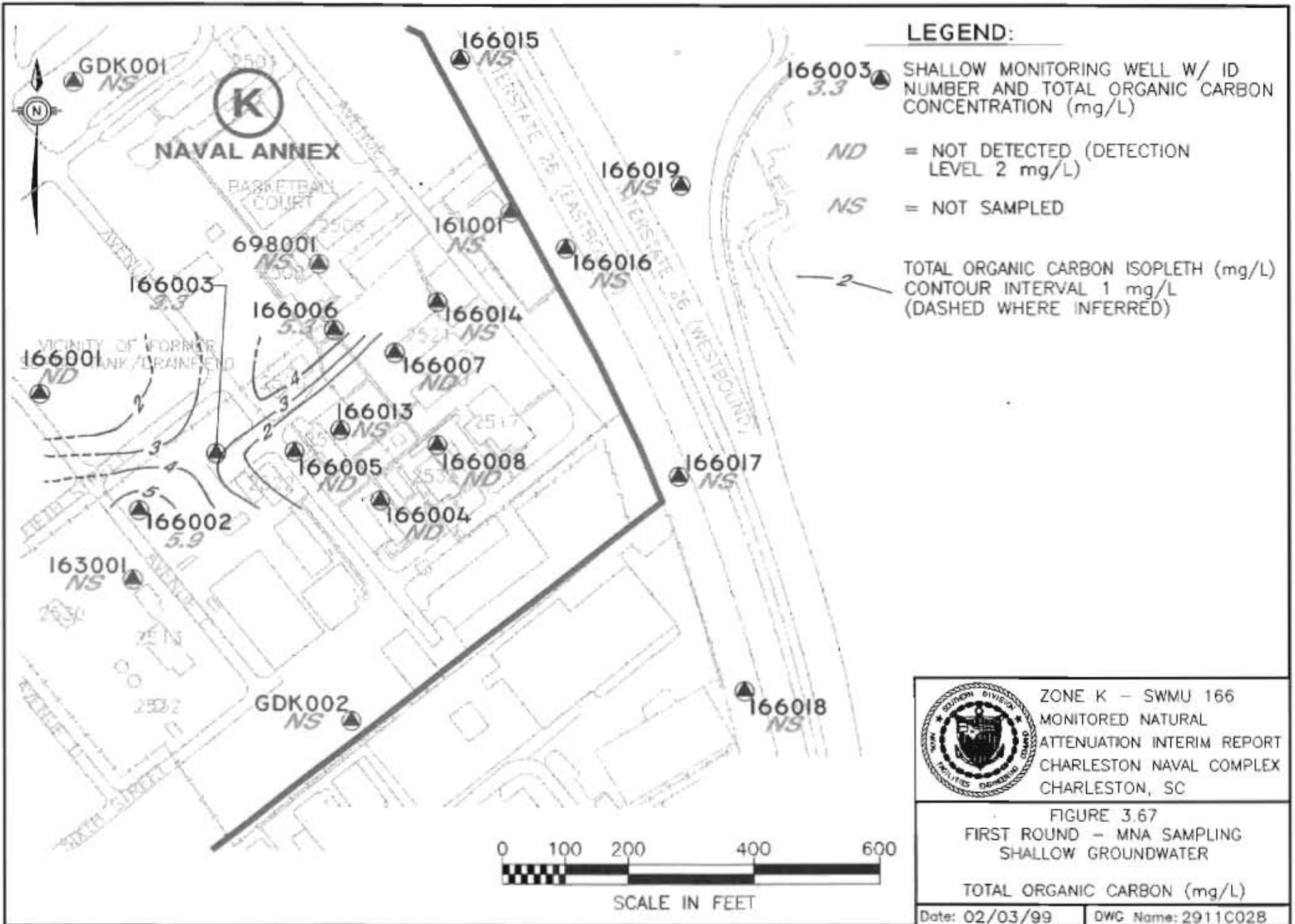
The chloride ion is the most common form of chlorine in natural groundwater and may be used as a conservative groundwater tracer due to its physical and chemical stability and high solubility (Hem, 1985). Chloride ions are liberated from chlorinated hydrocarbons during the reductive dechlorination process, resulting in groundwater chloride concentrations higher than background. However, chloride concentrations are difficult to interpret in coastal settings, such as that of CNC and the Naval Annex, since briny porewater is common within sediments. As a result, chloride was only analyzed in first round samples and was omitted from the preliminary screening ranking (Table 3.1).

Total Organic Carbon

Total organic carbon (TOC) is the total concentration of organic materials, both natural and anthropogenic, in groundwater. Because microorganisms use organic carbon for energy and as a substrate, a high TOC concentration in an aquifer encourages the growth of microbial communities and thus maintains the aquifer's capacity to degrade other organic chemical compounds.

Shallow Groundwater

TOC was detected only in three shallow wells above its detection limit of 2.0 mg/L in Round 1; these detections ranged from 3.3 to 5.9 mg/L (Figure 3.67). TOC was detected in eight of 14 Round 2 shallow wells and between 1.1 to 6.9 mg/L (Figure 3.68).



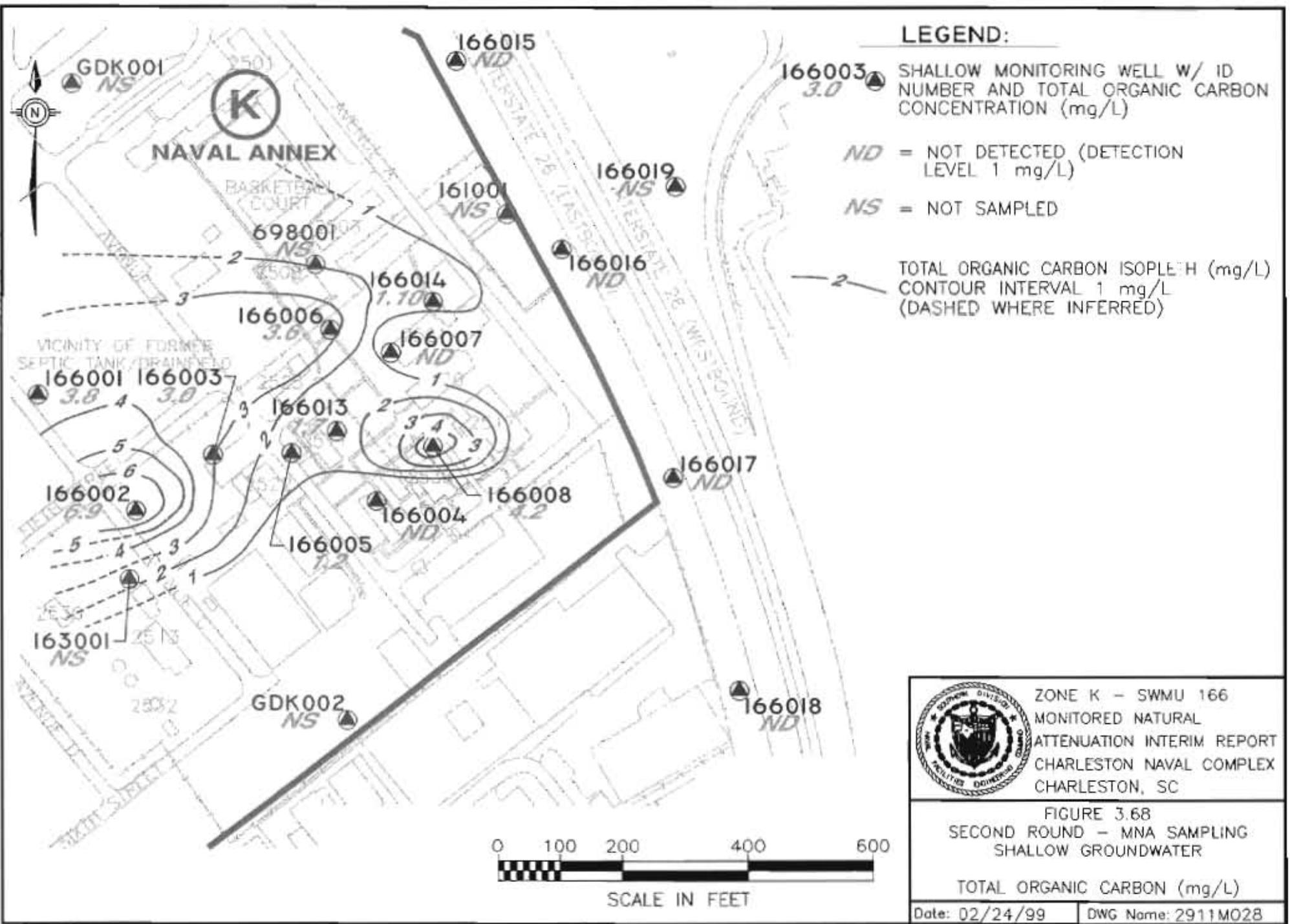
ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.67
 FIRST ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

TOTAL ORGANIC CARBON (mg/L)

Date: 02/03/99

DWG Name: 2911C028



LEGEND:

166003 3.0 SHALLOW MONITORING WELL W/ ID NUMBER AND TOTAL ORGANIC CARBON CONCENTRATION (mg/L)

ND = NOT DETECTED (DETECTION LEVEL 1 mg/L)

NS = NOT SAMPLED

TOTAL ORGANIC CARBON ISOPLETH (mg/L) CONTOUR INTERVAL 1 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.68
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

TOTAL ORGANIC CARBON (mg/L)

Date: 02/24/99

DWG Name: 2911M028



Due to limited first round data, no definitive pattern in TOC concentrations was seen. During Round 2, TOC was highest along the west-northwest portion of the site and decreased to nondetectable concentrations to the east. The two highest TOC concentrations occurred at 166002 and 166008, which form isolated zones of elevated TOC in shallow groundwater.

Deep Groundwater

TOC was not detected in first round deep groundwater samples. In Round 2, TOC was detected in eight of 19 deep wells above its second round detection limit of 1.0 mg/l ranging in from 1.1 to 2.2 mg/L (Figure 3.69).

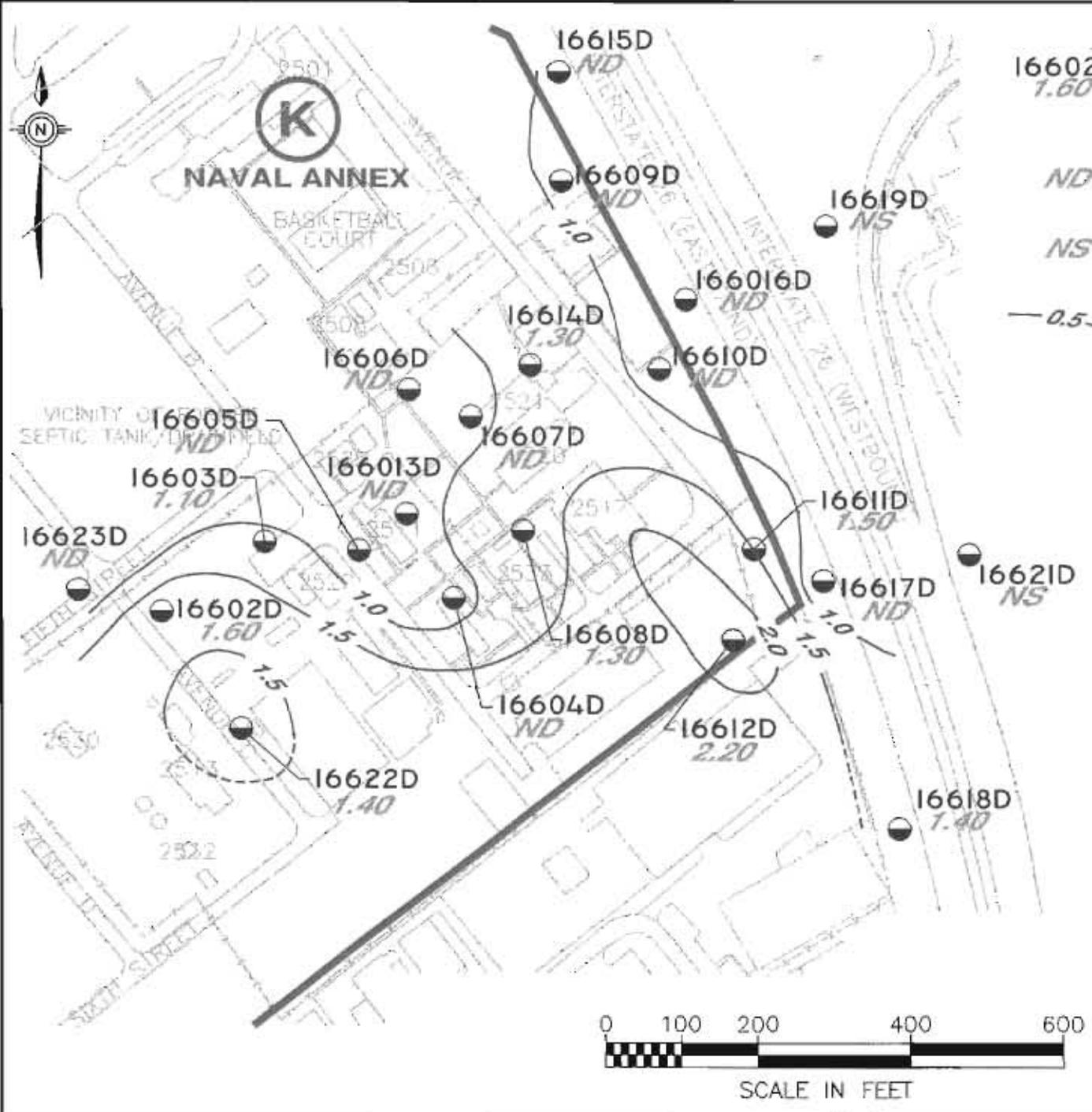
TOC was not detected in deep groundwater in the northwest portion of the site. Although TOC may be found in detectable concentrations in the center and southern portions of the site, these concentrations are very low.

Heterotrophic Plate Counts

Heterotrophic plate counts (HPCs) were used to gauge the size of microbial populations in groundwater. Larger populations of microorganisms may result in greater the potential to biodegrade VOCs.

Shallow Groundwater

HPCs were collected only during Round 2 and from a select subset of wells (four total). Shallow wells 166002, 166013, 166006, and 166016 were chosen because of their proximity to the primary shallow groundwater flowpath. The counts ranged from 908 CFU/ml at 166002 to 8,010 CFU/ml at 166013 (Figure 3.70). Based on the limited data, HPCs appeared to decrease north and west of 166013.



LEGEND:

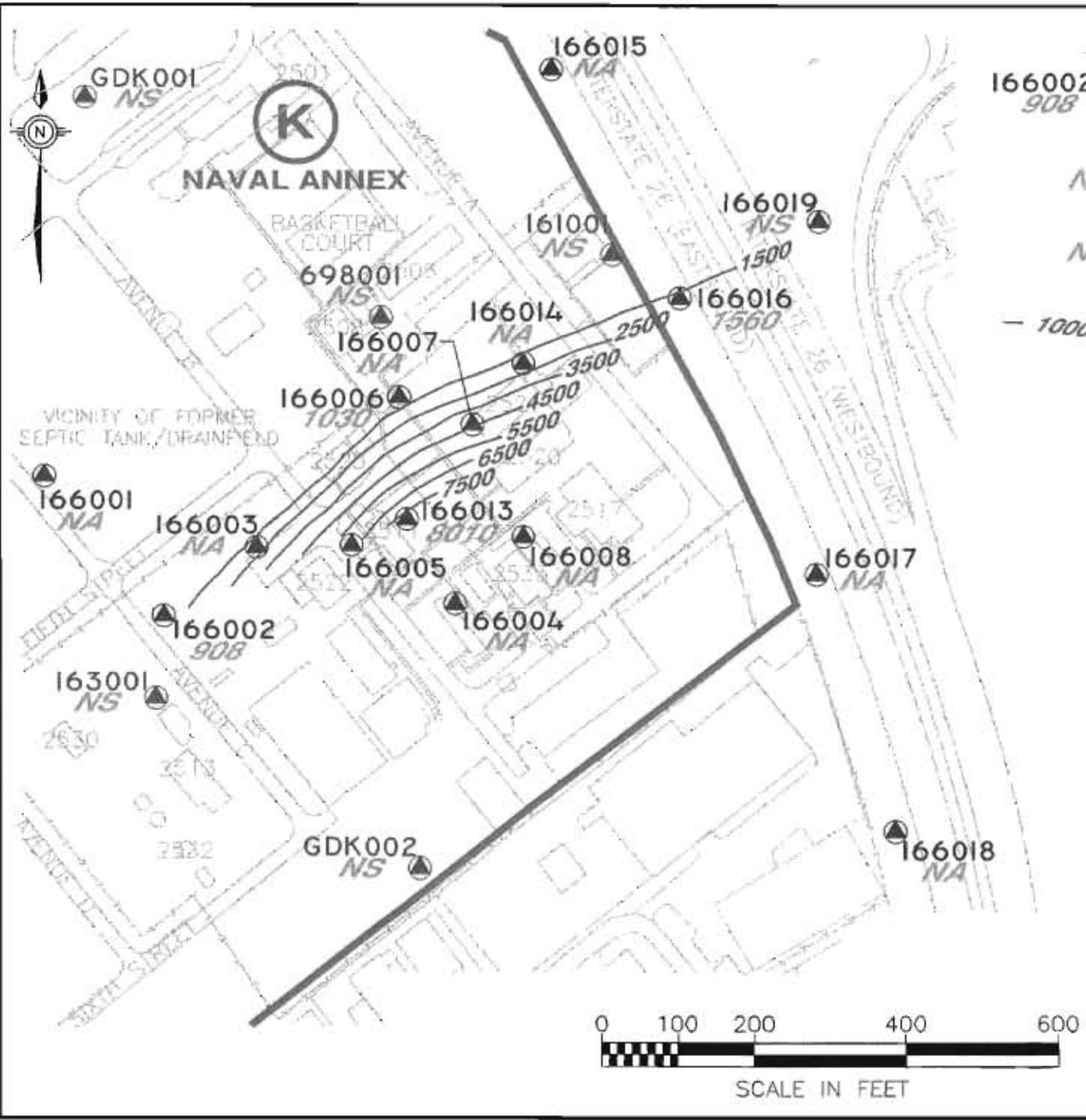
- 16602D
1.60 ● DEEP MONITORING WELL W/ ID NUMBER AND TOTAL ORGANIC CARBON CONCENTRATION (mg/L)
- ND = NOT DETECTED (DETECTION LEVEL 1 mg/L)
- NS = NOT SAMPLED
- 0.5 — TOTAL ORGANIC CARBON ISOPLETH (mg/L) CONTOUR INTERVAL 0.5 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.69
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER

TOTAL ORGANIC CARBON (mg/L)



LEGEND:

- 166002
908 SHALLOW MONITORING WELL W/ ID NUMBER AND HETEROTROPHIC PLATE COUNTS (C.F.U./mL)
- NA = NOT ANALYZED
- NS = NOT SAMPLED
- 1000 - HETEROTROPHIC PLATE COUNTS ISOPLETH (C.F.U./mL) CONTOUR INTERVAL 1000 C.F.U./mL (DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.70
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

HETEROTROPHIC PLATE COUNTS(C.F.U./mL)

Date: 02/26/99 | DWG Name: 2911M037

Deep Groundwater

Groundwater from four selected deep wells (16602D, 16613D, 16606D, 16616D) was analyzed for HPC in Round 2 based on the primary deep groundwater flowpath at the site. A fifth well, 16611D, was chosen as a sampling point to best represent background microbial populations. The counts ranged from 234 CFU/ml at 16611D to 34,200 CFU/ml at 16616D (Figure 3.71). Deep groundwater HPC results suggest increasing microbial populations parallel with the predominant northeastern deep groundwater flow direction from 16613D to 16616D.

Nutrients and Miscellaneous Parameters

Total Kjeldahl Nitrogen (TKN)

TKN was only analyzed in second round groundwater samples to determine what nutrient concentrations were available in the aquifer. These nutrients are critical to sustaining microbial populations and help indicate the potential for microbial population growth.

Shallow Groundwater

TKN was detected above its 1.0 mg/L detection level in only seven of 14 shallow wells, ranging in concentration from 1.4 to 3.9 mg/L (Figure 3.72). TKN was detected only in the northwestern portion of the site around an isolated high concentration at 166013 (3.9 mg/L).

Deep Groundwater

TKN was detected in only nine of 19 second round deep wells between 1.1 and 9.0 mg/L (Figure 3.73). Similar to the pattern seen in shallow groundwater, the southern and eastern portions of the site had no detectable deep groundwater TKN concentrations. TKN concentrations form a southeast-northwest ridge across the highest concentration at 16614D (9.0 mg/L).

Total Phosphorus

Total phosphorus is an additional nutrient indicator for the sustainability of microbial populations. Total phosphorus was only analyzed in Round 2 samples.



LEGEND:

16602D
234 ● DEEP MONITORING WELL W/ ID NUMBER AND HETEROTROPHIC PLATE COUNTS CONCENTRATION (C.F.U./mL)

NA = NOT ANALYZED

NS = NOT SAMPLED

— 5000 — HETEROTROPHIC PLATE COUNTS ISOPLETH (C.F.U./mL)
CONTOUR INTERVAL 5000 C.F.U./mL (DASHED WHERE INFERRED)



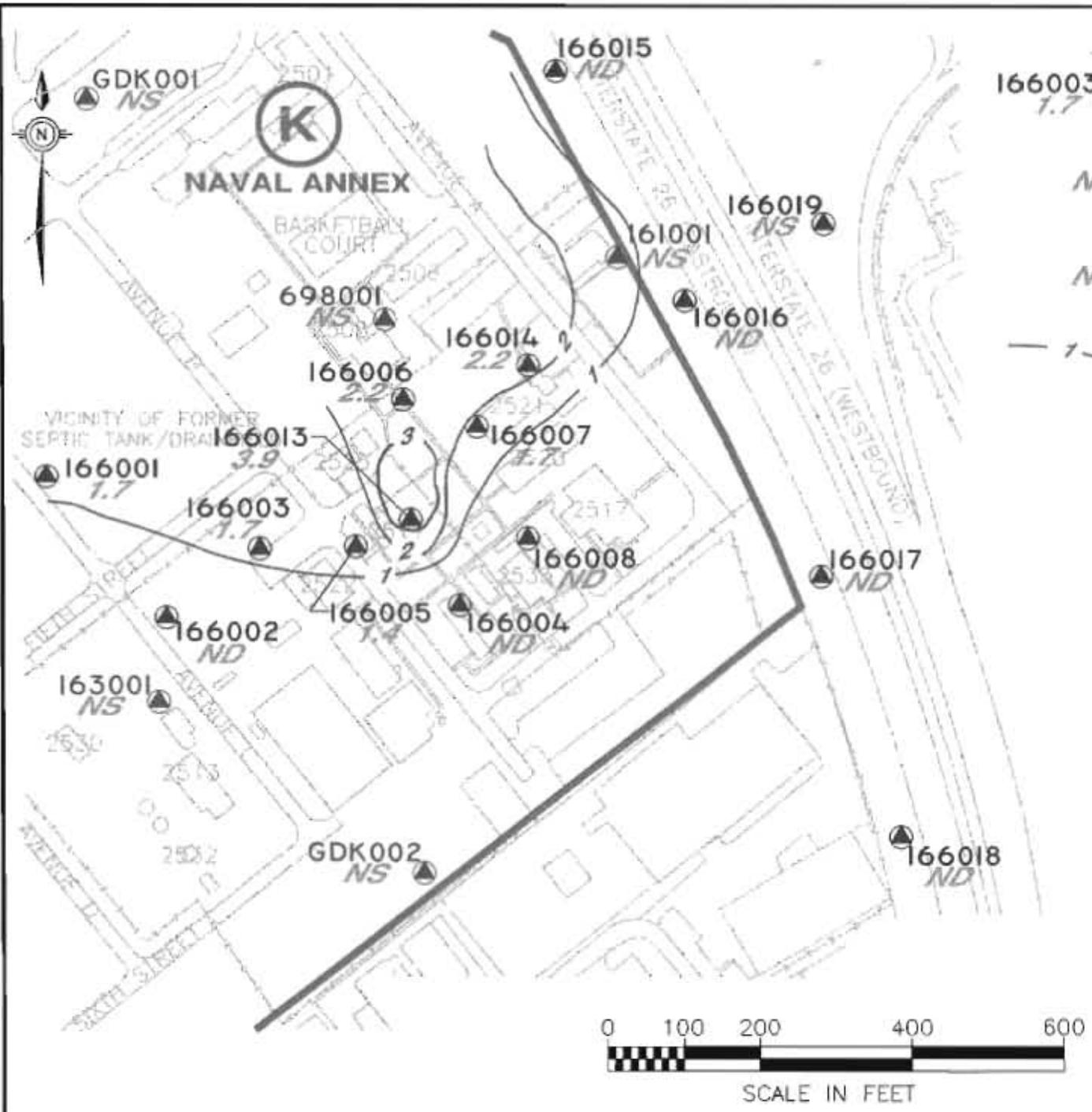
ZONE K - SWMU 166
MONITORED NATURAL
ATTENUATION INTERIM REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC

FIGURE 3.71
SECOND ROUND - MNA SAMPLING
DEEP GROUNDWATER

HETEROTROPHIC PLATE COUNTS(C.F.U./mL)

Date: 03/02/99

DWG Name: 2911M054



LEGEND:

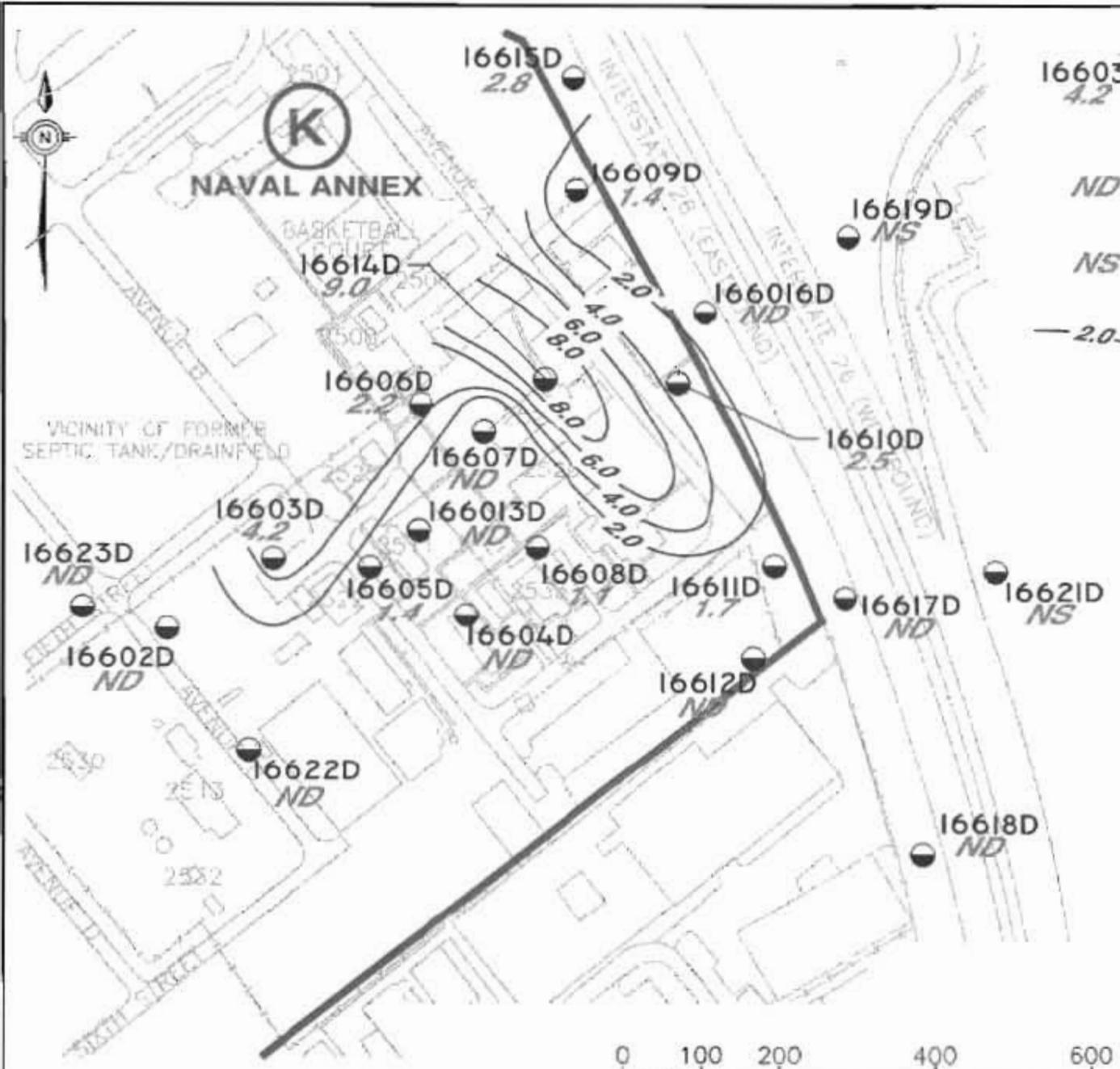
- 166003
1.7 ● SHALLOW MONITORING WELL W/ ID NUMBER AND TOTAL KJELDAHL NITROGEN CONCENTRATION (mg/L)
- ND = NOT DETECTED (DETECTION LEVEL 1.0 mg/L)
- NS = NOT SAMPLED
- 1 — TOTAL KJELDAHL NITROGEN ISOPLETH (mg/L) CONTOUR INTERVAL 1 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.72
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

TOTAL KJELDAHL NITROGEN (mg/L)



LEGEND:

- 16603D
4.2 ● DEEP MONITORING WELL W/ ID NUMBER AND TOTAL KJELDAHL NITROGEN CONCENTRATION (mg/L)
- ND = NOT DETECTED (DETECTION LEVEL 1.0 mg/L)
- NS = NOT SAMPLED
- 2.0- TOTAL KJELDAHL NITROGEN ISOPLETH (mg/L)
CONTOUR INTERVAL 2.0 mg/L
(DASHED WHERE INFERRED)



ZONE K - SWMU 166
MONITORED NATURAL
ATTENUATION INTERIM REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC

FIGURE 3.73
SECOND ROUND - MNA SAMPLING
DEEP GROUNDWATER

TOTAL KJELDAHL NITROGEN (mg/L)

Shallow Groundwater

Total phosphorus was detected above its 0.10 mg/L detection level in only two of 14 second round shallow well samples. These detections were 0.12 mg/L at 166002 and 1.2 mg/L at 166004 as illustrated in Figure 3.74.

Deep Groundwater

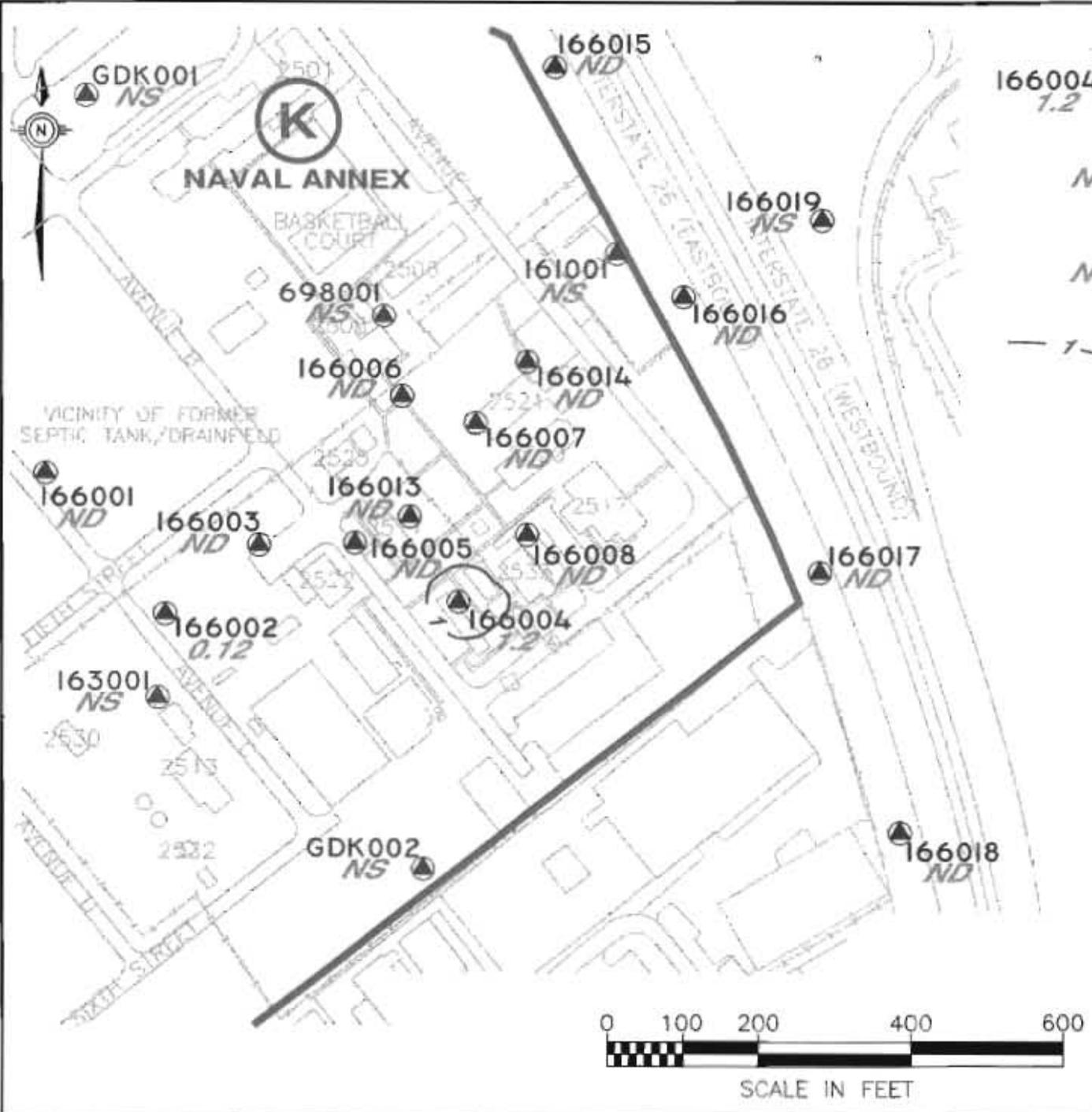
Total phosphorus was detected in all 19 second round deep well samples between 0.11 and 1.4 mg/L (Figure 3.75). In general, total phosphorus was lower throughout the center of the site, forming a slight trough in deep groundwater between isolated highs in the north (1.4 mg/L at 16609D) and south (1.2 mg/L at 16603D and 1.1 mg/L at 16604D).

Groundwater Temperature

Groundwater temperature data were collected during both MNA sampling rounds due to its importance in determining aquifer stability during well purging. Groundwater temperature was considered in the preliminary screening ranking since higher temperatures influence dissolved gas solubilities and microbial activity (Technical Protocol, 1998). These data are presented in Table 3.1.

Specific Conductivity

Specific conductivity, the measure of the ability of a liquid to conduct electricity, is primarily influenced by the concentration of dissolved ions in solution (Technical Protocol, 1998). Specific conductivity data were collected during both MNA sampling rounds due to its importance in determining aquifer stability during well purging. These data are presented in Table 3.1.



LEGEND:

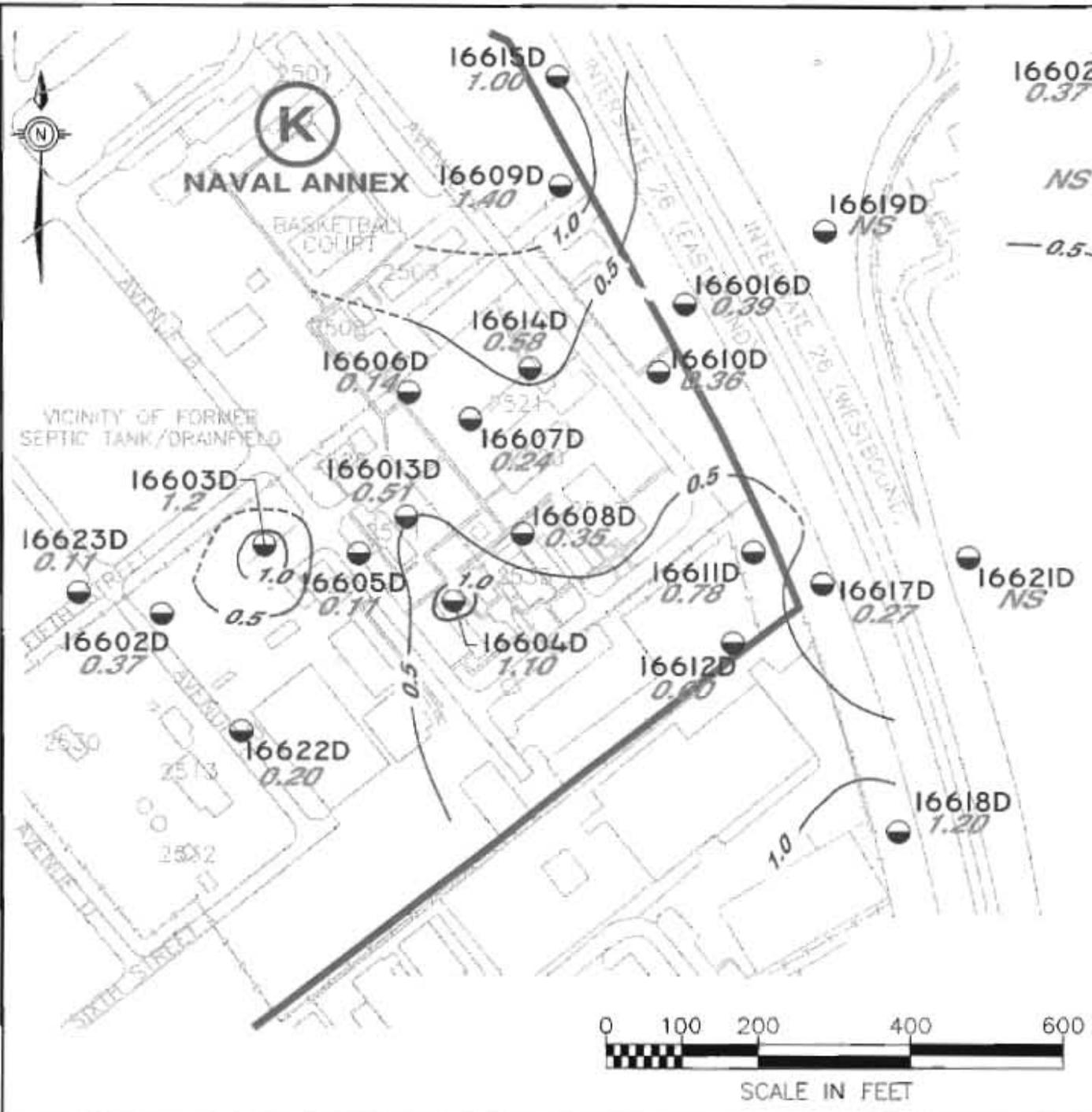
- 166004
1.2 SHALLOW MONITORING WELL W/ ID NUMBER AND TOTAL PHOSPHORUS CONCENTRATION (mg/L)
- ND = NOT DETECTED (DETECTION LEVEL 0.10 mg/L)
- NS = NOT SAMPLED
- TOTAL PHOSPHORUS ISOPLETH (mg/L) CONTOUR INTERVAL 1 mg/L (DASHED WHERE INFERRED)



ZONE K -- SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.74
 SECOND ROUND - MNA SAMPLING
 SHALLOW GROUNDWATER

TOTAL PHOSPHORUS (mg/L)



LEGEND:

- 16602D
0.37 ● DEEP MONITORING WELL W/ ID NUMBER AND TOTAL PHOSPHORUS CONCENTRATION (mg/L)
- NS = NOT SAMPLED
- 0.5- TOTAL PHOSPHORUS ISOPLETH (mg/L) CONTOUR INTERVAL 0.5 mg/L (DASHED WHERE INFERRED)



ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.75
 SECOND ROUND - MNA SAMPLING
 DEEP GROUNDWATER

TOTAL PHOSPHORUS (mg/L)

3.3.3 Temporal Trends of Volatile Organic Compounds

Temporal changes in VOC concentrations can be attributed to dilution, a nondestructive process which occurs when an increase in aquifer recharge results in a decrease in contaminant concentration. If little or no precipitation occurs over a period of time, groundwater elevations will generally decrease due to evaporation and transpiration, resulting in apparent increases in groundwater contaminant concentrations. Before dilution may be discussed in detail, a trend between precipitation and groundwater elevation must be established.

3.3.3.1 Precipitation Trends at SWMU 166 (1997 - 1998)

Precipitation data for SWMU 166 were obtained as weekly composites from the South Carolina Department of Natural Resources as recorded at Charleston International Airport (Table 3.9). Brief, heavy precipitation events are typically tempered by infiltration into the underlying aquifer, evaporation at the ground surface or deflection by overland flow. Removing short-term trends in any precipitation data set exposes long-term trends that can be used to examine any relationships between precipitation and groundwater elevation. Computing a weighted precipitation average over a four-week interval is a more appropriate means of comparing groundwater elevations with precipitation (Davis, 1986). This calculation averages each weekly composite of precipitation data with the previous three weeks of data. The weekly composited precipitation data and weighted average data are presented in Figure 3.76.

Based on the weighted precipitation average, three large-scale precipitation events occurred at SWMU 166 between January 1997 and October 1998 (Figure 3.76). The first four months of 1997 were drier than normal when approximately 9.8 inches of rain fell compared with the 14-inch average during the same time previous years (SCDNR). The first major rainfall event occurred during May, June, and part of July 1997 (herein referred to as the Summer 1997 event), with 24.6 inches recorded compared with an average of 10 inches for the same time interval in previous years. As a result, the composited weighted average weekly rainfall remained elevated until

Table 3.9 Weekly Composite Precipitation Data
Charleston International Airport, North Charleston, SC

Year	Week	Weekly Precipitation Composite (inches)	4 wk weighted average (inches)
1997	Dec 30-Jan 05	0.16	*
	Jan 06 - 12	2.10	*
	Jan 13 - 19	0.05	*
	Jan 20 - 26	0.09	0.6000
	Jan 27-Feb 02	0.09	0.5825
	Feb 03 - 09	0.03	0.0650
	Feb 10 - 16	2.11	0.5800
	Feb 17 - 23	0.56	0.6975
	Feb 24-Mar 02	0.12	0.7050
	Mar 03 - 09	0.00	0.6975
	Mar 10 - 16	1.04	0.4300
	Mar 17 - 23	0.30	0.3650
	Mar 24 - 30	0.48	0.4550
	Mar 31-Apr 06	0.00	0.4550
	Apr 07 - 13	1.84	0.6550
	Apr 14 - 20	0.00	0.5800
	Apr 21 - 27	0.80	0.6600
	Apr 28-May 04	5.00	1.9100
	May 05 - 11	0.20	1.5000
	May 12 - 18	0.59	1.6475
	May 19 - 25	0.00	1.4475
	May 26 -Jun 01	0.37	0.2900
	Jun 02 - 08	5.73	1.6725
	Jun 09 - 15	0.79	1.7225
	Jun 16 - 22	1.89	2.1950
	Jun 23 - 29	5.08	3.3725
	Jun 30-July 06	1.08	2.2100
	July 07 - 13	2.33	2.5950
	July 14 - 20	1.56	2.5125
	July 21- 27	0.97	1.4850
	Jul 28 -Aug 03	0.70	1.3900
	Aug 04 -10	0.65	0.9700
	Aug 11 - 17	0.58	0.7250
	Aug 18 - 24	0.05	0.4950
	Aug 25 - 31	0.84	0.5300
	Sep 01 - 07	0.16	0.4075
	Sep 08 -14	3.57	1.1550
	Sep 15 - 21	0.59	1.2900
	Sep 22 - 28	5.26	2.3950
	Sep 29-Oct 05	0.00	2.3550
	Oct 06 - 12	0.00	1.4625
	Oct 13 - 19	no data	1.3150
	Oct 20 - 26	1.66	0.4150
	Oct 27-Nov 02	2.25	0.9775
	Nov 03 - 09	0.02	0.9825
	Nov 10 - 16	1.35	1.3200
	Nov 17 - 23	0.28	0.9750
	Nov 24 - 30	0.45	0.5250
	Dec 01 - 07	0.04	0.5300
	Dec 08 - 14	0.96	0.4325

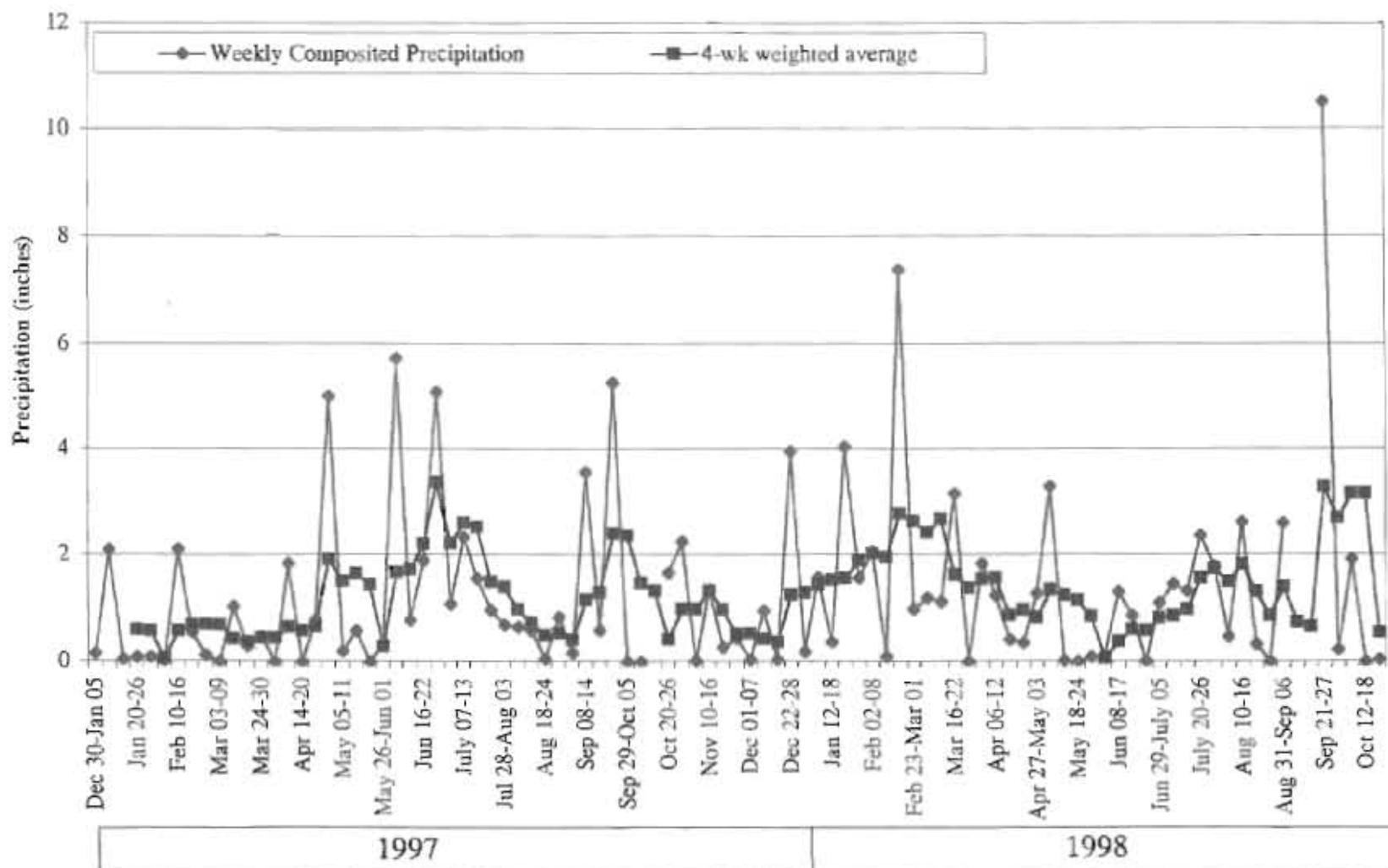
Table 3.9 Weekly Composite Precipitation Data
Charleston International Airport, North Charleston, SC

Year	Week	Weekly Precipitation Composite (inches)	4 wk weighted average (inches)
1998	Dec 15 - 21	0.04	0.3725
	Dec 22 - 28	3.96	1.2500
	Dec 29 -Jan 04	0.19	1.2875
	Jan 05 - 11	1.58	1.4425
	Jan 12 - 18	0.38	1.5275
	Jan 19 - 25	4.05	1.5500
	Jan 26-Feb 01	1.57	1.8950
	Feb 02 - 08	2.06	2.0150
	Feb 09 - 15	0.09	1.9425
	Feb 16 - 22	7.38	2.7750
	Feb 23 -Mar 01	0.98	2.6275
	Mar 02 - 08	1.20	2.4125
	Mar 09 - 15	1.13	2.6725
	Mar 16 - 22	3.16	1.6175
	Mar 23 - 29	0.00	1.3725
	Mar 30-Apr 05	1.83	1.5300
	Apr 06 - 12	1.24	1.5575
	Apr 13 - 19	0.42	0.8725
	Apr 20 - 26	0.36	0.9625
	Apr 27-May 03	1.28	0.8250
	May 04 - 10	3.30	1.3400
	May 11 - 17	0.02	1.2400
	May 18 - 24	0.00	1.1500
	May 25 - 31	0.09	0.8525
	Jun 01 - 07	0.13	0.0600
	Jun 08 - 14	1.31	0.3825
	Jun 15 - 21	0.87	0.6000
	Jun 22 - 28	0.01	0.5800
	Jun 29-July 05	1.10	0.8225
	July 106 - 12	1.45	0.8575
	July 13 - 19	1.32	0.9700
	July 20 - 26	2.36	1.5575
	July 27-Aug 02	1.78	1.7275
	Aug 03 - 09	0.47	1.4825
Aug 10 -16	2.62	1.8075	
Aug 17 - 23	0.33	1.3000	
Aug 24 - 30	0.00	0.8550	
Aug 31-Sep 06	2.60	1.3875	
Sep 7 - 13	no data	0.7325	
Sep 14 - 20	no data	0.6500	
Sep 21 - 27	10.52	3.2800	
Sep 28-Oct 04	0.23	2.6875	
Oct 05 -11	1.91	3.1650	
Oct 12 - 18	0.00	3.1650	
Oct 19 - 25	0.04	0.5450	

Notes:

* = The moving average using the previous 4 weeks of data cannot be calculated for these weeks because 3 weeks of previous data, last three weeks of 1996, has not been included.

Figure 3.76 Weekly Composited Raw and 4-Week Weighted Average Precipitation Data



mid-July. Below average precipitation was recorded from mid-July to late December 1997 at 1
19.4 inches, compared with the 27-inch average for the same time span in previous years. 2
Precipitation increased briefly, however, from late September through early October 1997, in 3
which a total of 4.8 inches of rain fell during a two-week period. The second major event 4
occurred from late December 1997 through mid-March 1998 (herein referred to as the Winter 5
1998 event). This event is important due to its occurrence just before the first round of MNA 6
sampling. During this period, 25.6 inches of rain was recorded, which far exceeded the average 7
of 14 inches during the same time in previous years. From mid-March 1998 through 8
September 1998, below average precipitation was recorded (a total of 28 inches) as compared with 9
the average of 36 inches. The third major event began in late September 1998 and persisted 10
through October 1998 (herein referred to as the Fall 1998 event) and the end of the data set, when 11
12 inches of rainfall was recorded. The typical amount of rainfall during this time period is a little 12
over three inches. 13

3.3.3.2 Precipitation Effects on Groundwater Elevation 14

Groundwater elevation data from 14 monitoring well locations were used to assess the effects of 15
precipitation on groundwater elevation. Well hydrographs using groundwater elevation data from 16
each sampling event were plotted against the weighted average rainfall in Figure 3.77. Although 17
there are significantly fewer groundwater elevation data points than precipitation data points, it 18
is possible to qualitatively discuss the responsiveness of the aquifer at SWMU 166 to precipitation 19
events. 20

As indicated in Figure 3.77, the first sampling event (May 1997) began approximately 3 weeks 21
after the Summer 1997 event started and the last sampling event in September 1998 occurred just 22
as the Fall 1998 event was beginning. As a result, only the Winter 1998 event was entirely 23
bracketed within the monitoring period (May 1997 to September 1998) at SWMU 166. General 24

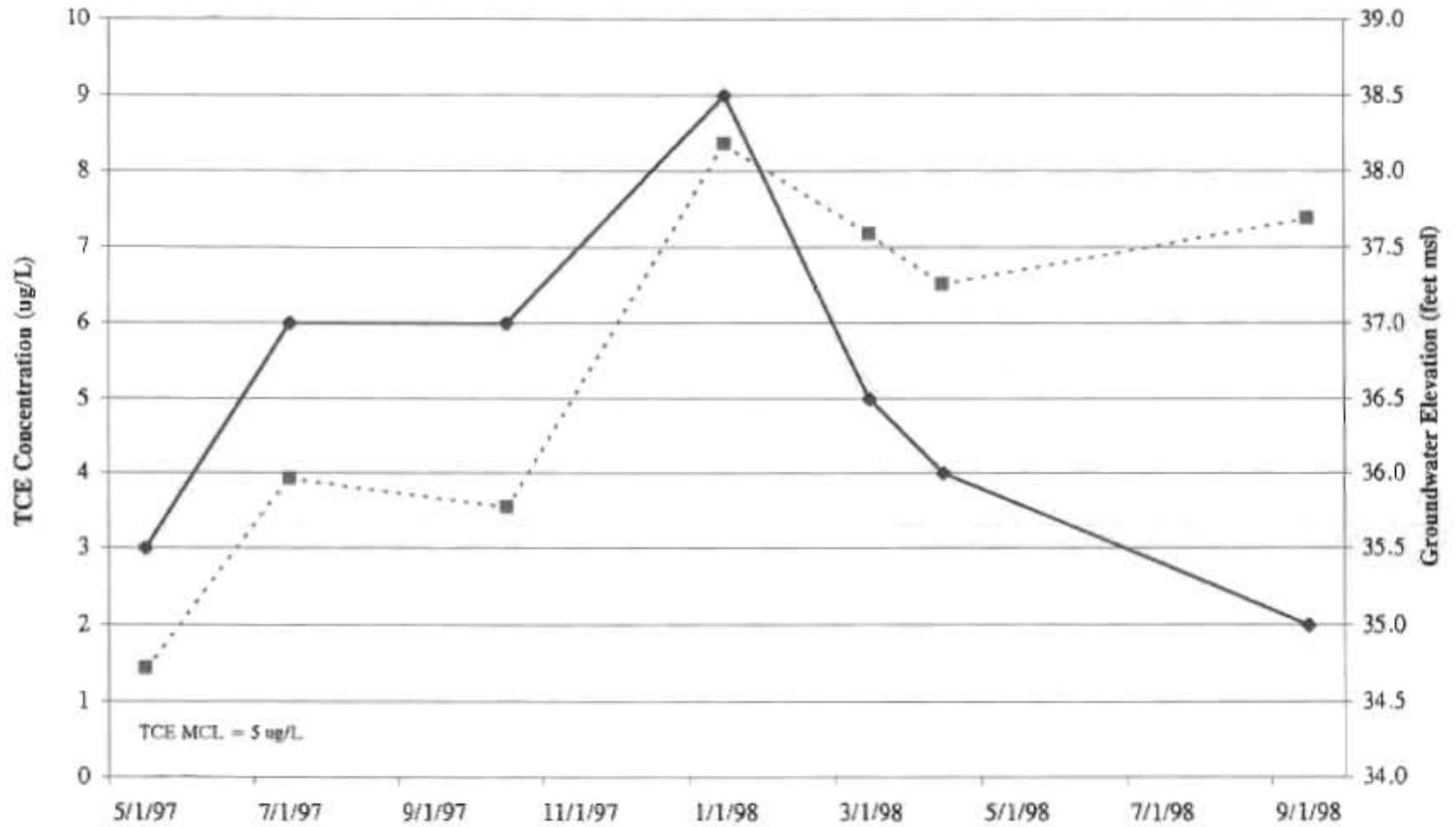
trends in groundwater elevation are evident despite the shortcomings of the monitoring period length.

Groundwater elevations in each of the 14 wells were higher in July 1997 than in May 1997 in response to the Summer 1997 event. Groundwater elevations remained relatively static over the next sampling event in October 1997. The onset of the Winter 1998 precipitation event in late December 1997 resulted in slight increases in groundwater elevations in all wells during the January 1998 sampling event. Note that groundwater elevation at 16602D was much more sensitive to the onset of the Winter 1998 event. This response may be a function of ground cover or the hydraulic properties of the near-surface sediments in the near vicinity of 16602D. The precipitation peak in February-March 1998 during the Winter 1998 event was seen clearly in all 14 wells during the first-round MNA sampling event in March 1998. The decreasing trend evident for groundwater elevation at 16616D is deceiving since this well was not sampled in March 1998. The majority of the wells revealed decreasing groundwater elevations in April 1998 as recharge to the aquifer declined after the Winter 1998 event. Groundwater elevations were higher in all 14 wells in September 1998 than April 1998, though it is worth noting that this five-month gap between sampling events coincided with fairly dry conditions at the site. The lack of data after September 1998 does not allow for the effects of the Fall 1998 event to be fully evaluated.

3.3.3.3 Groundwater Elevation Influence on Dissolved VOC Concentrations

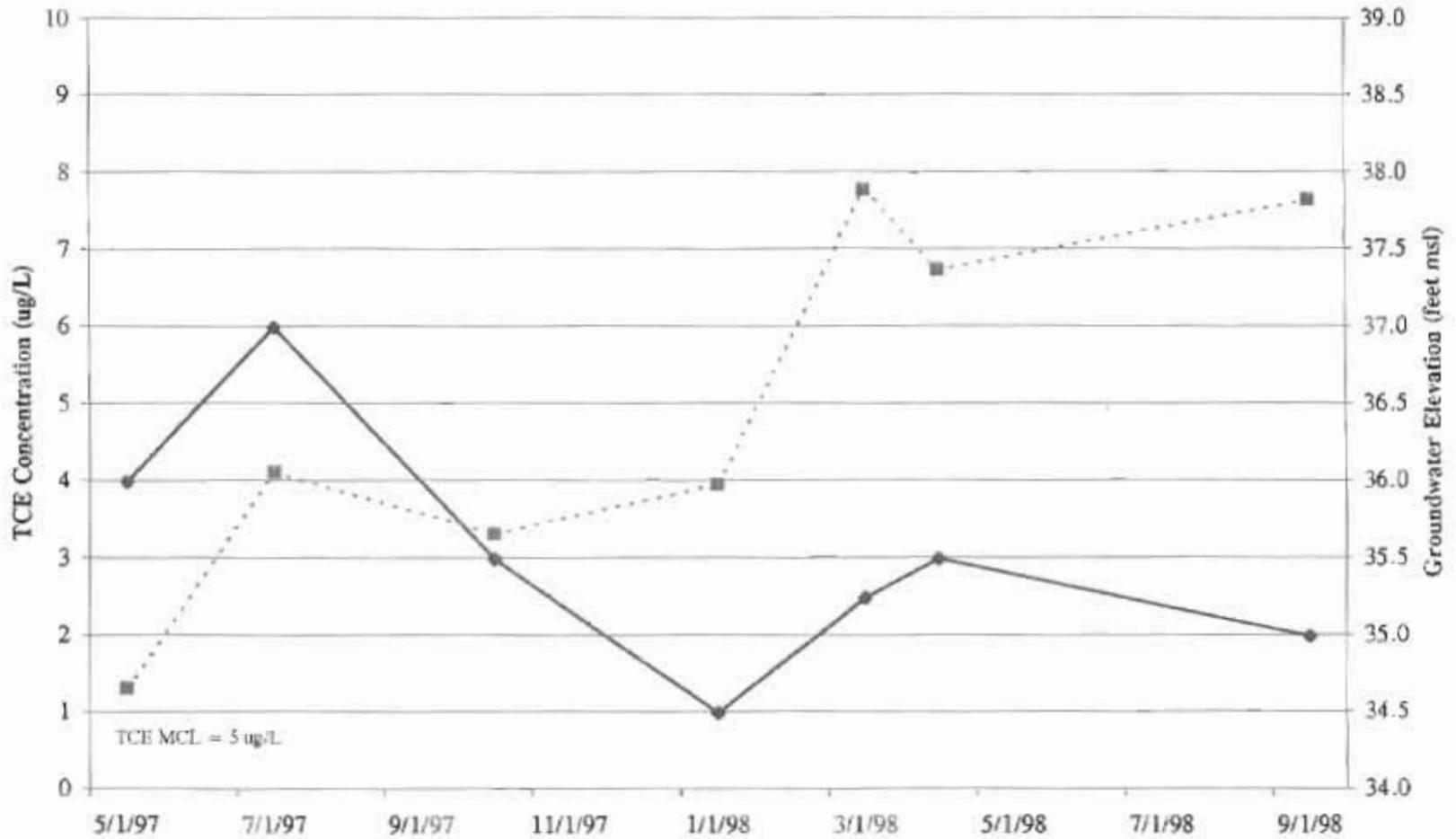
The groundwater sampling history at SWMU 166 to date includes a maximum of nine sampling events listed previously in Section 3.1. However, the sampling frequency at each well varied due to the phased-approach of well installations. Dissolved VOC concentrations from each sampling event were plotted against time for 15 wells with a history of VOC contamination (Figures 3.78 to 3.92). Non-detects were given a concentration equal to one-half the detection level or 2.5 µg/L instead of 0. Groundwater elevation was included in these plots for reference and also to provide insight into the role of dilution at the site.

Figure 3.78 Changes in TCE Concentration and Groundwater Elevation at 16602D



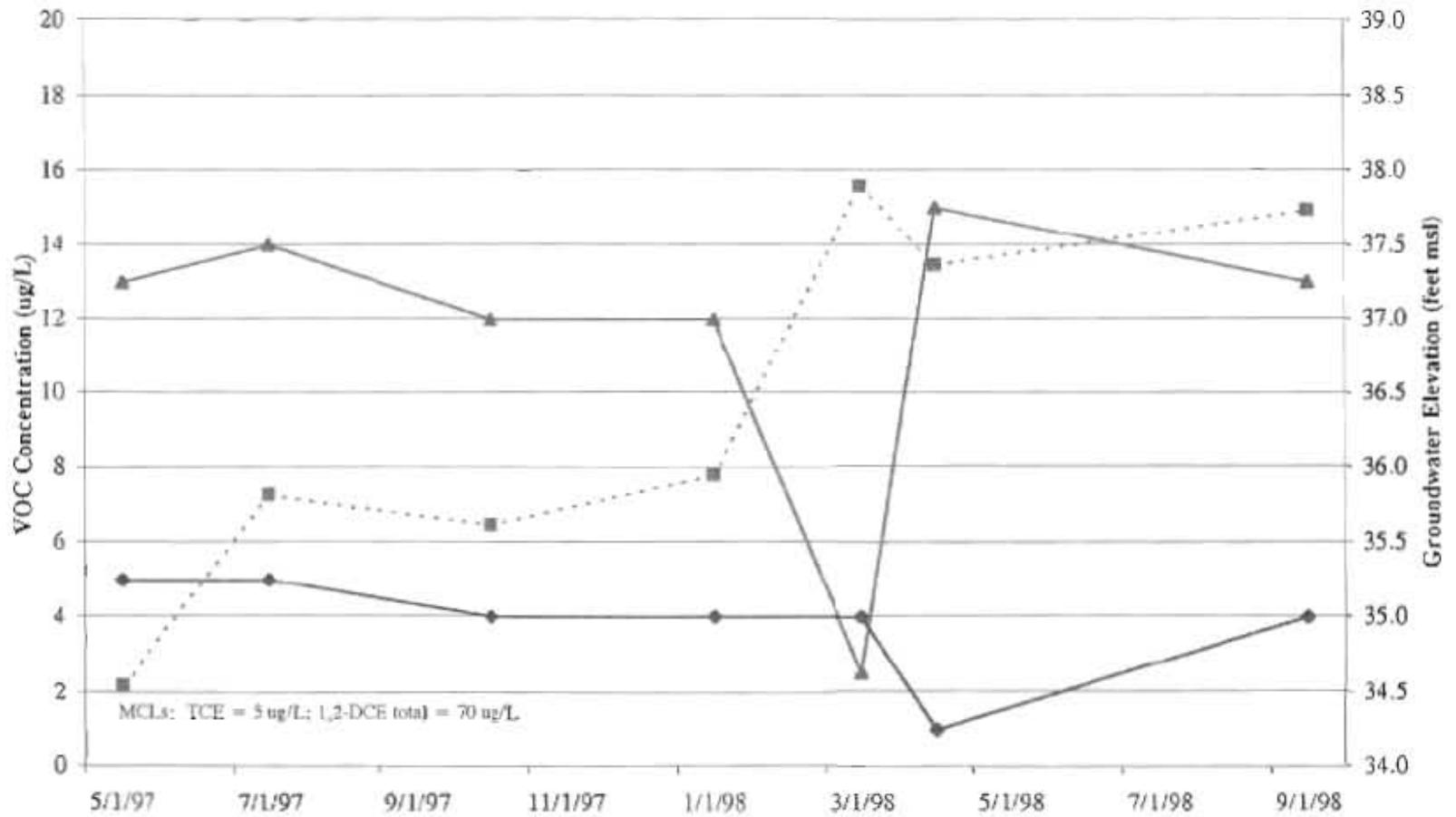
	5/23/97	7/30/97	10/14/97	1/23/98	3/12/98	4/7/98	9/24/98
●—● TCE	3	6	6	9	5	4	2
■····· GW ELEV	34.72	35.96	35.77	38.18	37.59	37.26	37.69

Figure 3.79 Changes in TCE Concentration and Groundwater Elevation at 166003



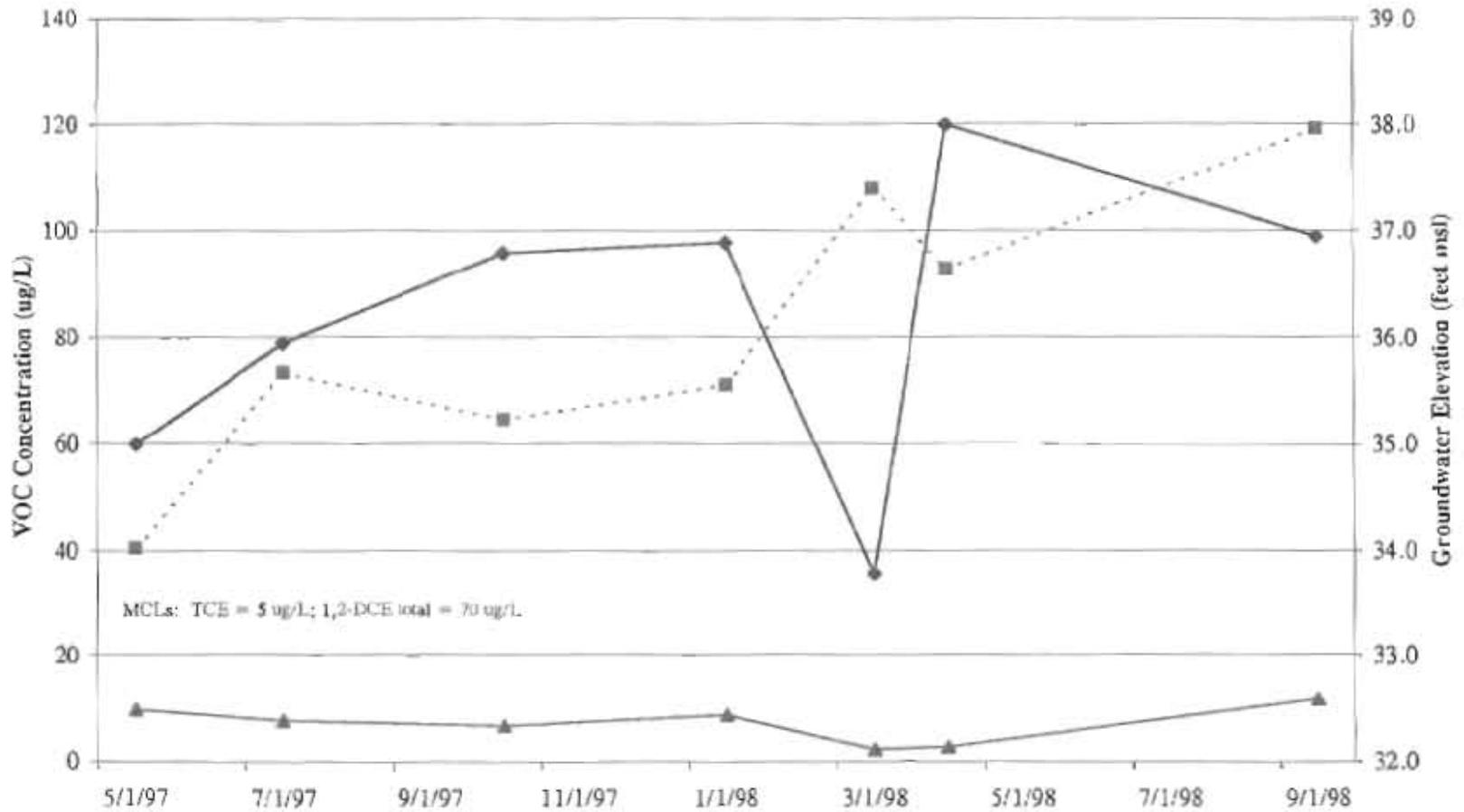
	5/23/97	7/24/97	10/14/97	1/14/98	3/12/98	4/7/98	9/25/98
—●— TCE	4	6	3	1	2.5	3	2
- - ■ - - GW ELEV	34.66	36.06	35.66	35.98	37.89	37.37	37.82

Figure 3.80 Changes in VOC Concentration and Groundwater Elevation at 16603D



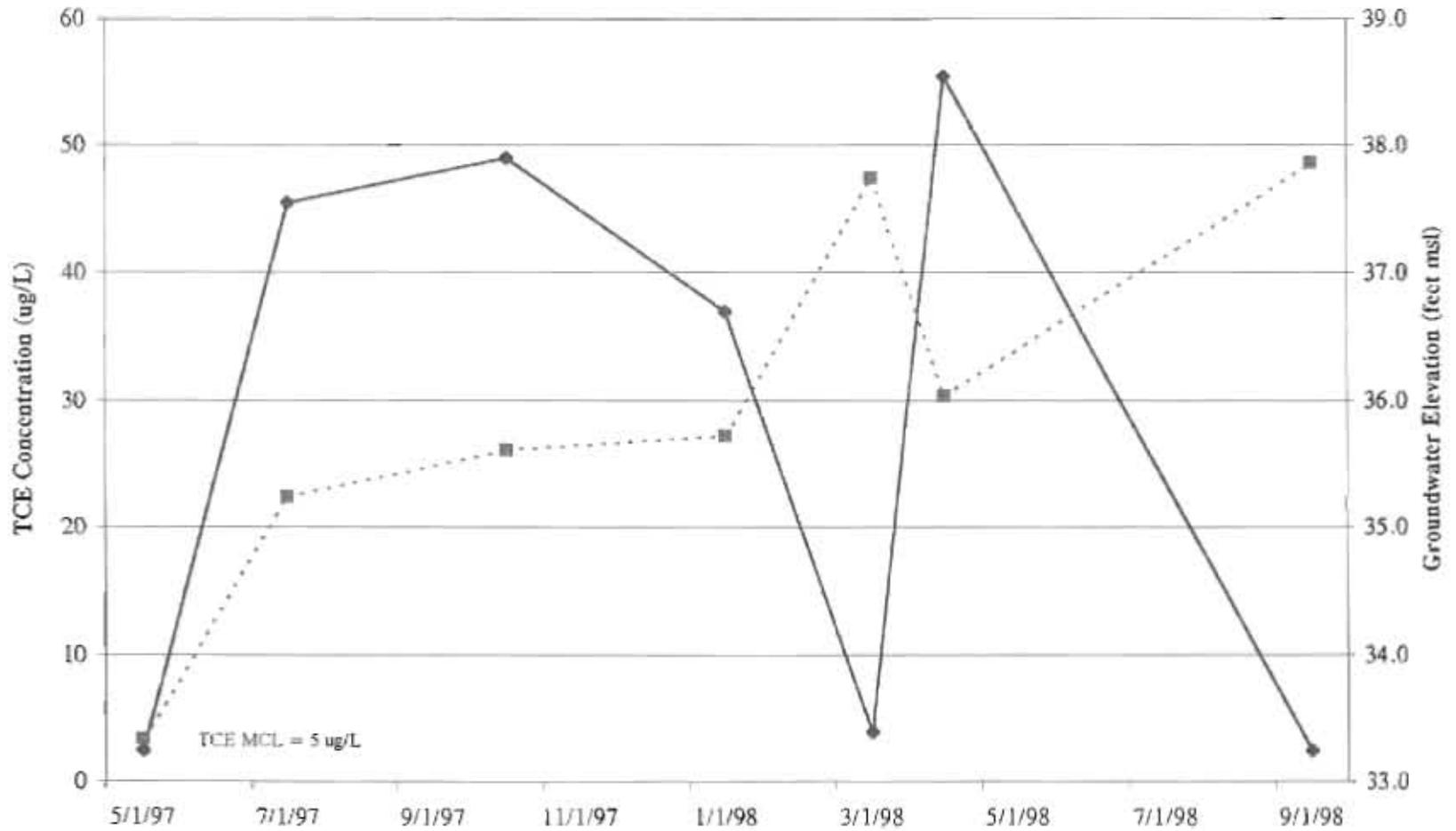
	5/23/97	7/24/97	10/14/97	1/14/98	3/12/98	4/7/98	9/25/98
●—● TCE	5	5	4	4	4	1	4
▲—▲ 1,2-DCE tot	13	14	12	12	2.5	15	13
■ - - - GW ELEV	34.55	35.81	35.61	35.94	37.89	37.36	37.73

Figure 3.81 Changes in VOC Concentration and Groundwater Elevation at 16604D



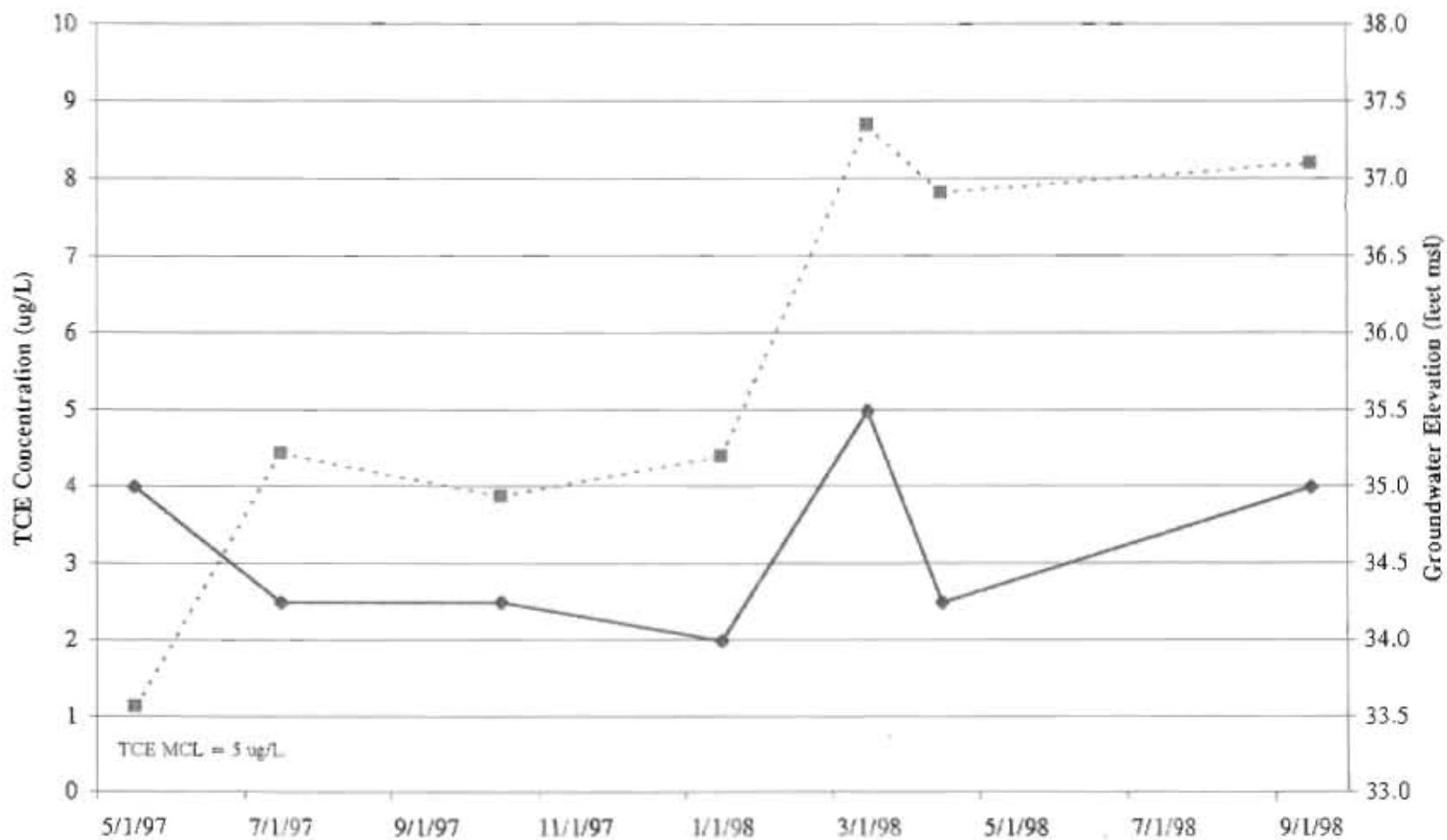
	5/22/97	7/24/97	10/15/97	1/15/98	3/12/98	4/8/98	9/26/98
●—● TCE	60	79	95	98	36	120	99
▲—▲ 1,2-DCE tot	10	8	7	9	2.5	3	12
■····· GW ELEV	34.03	35.67	35.24	35.56	37.40	36.65	37.96

Figure 3.82 Changes in TCE Concentration and Groundwater Elevation at 16605D



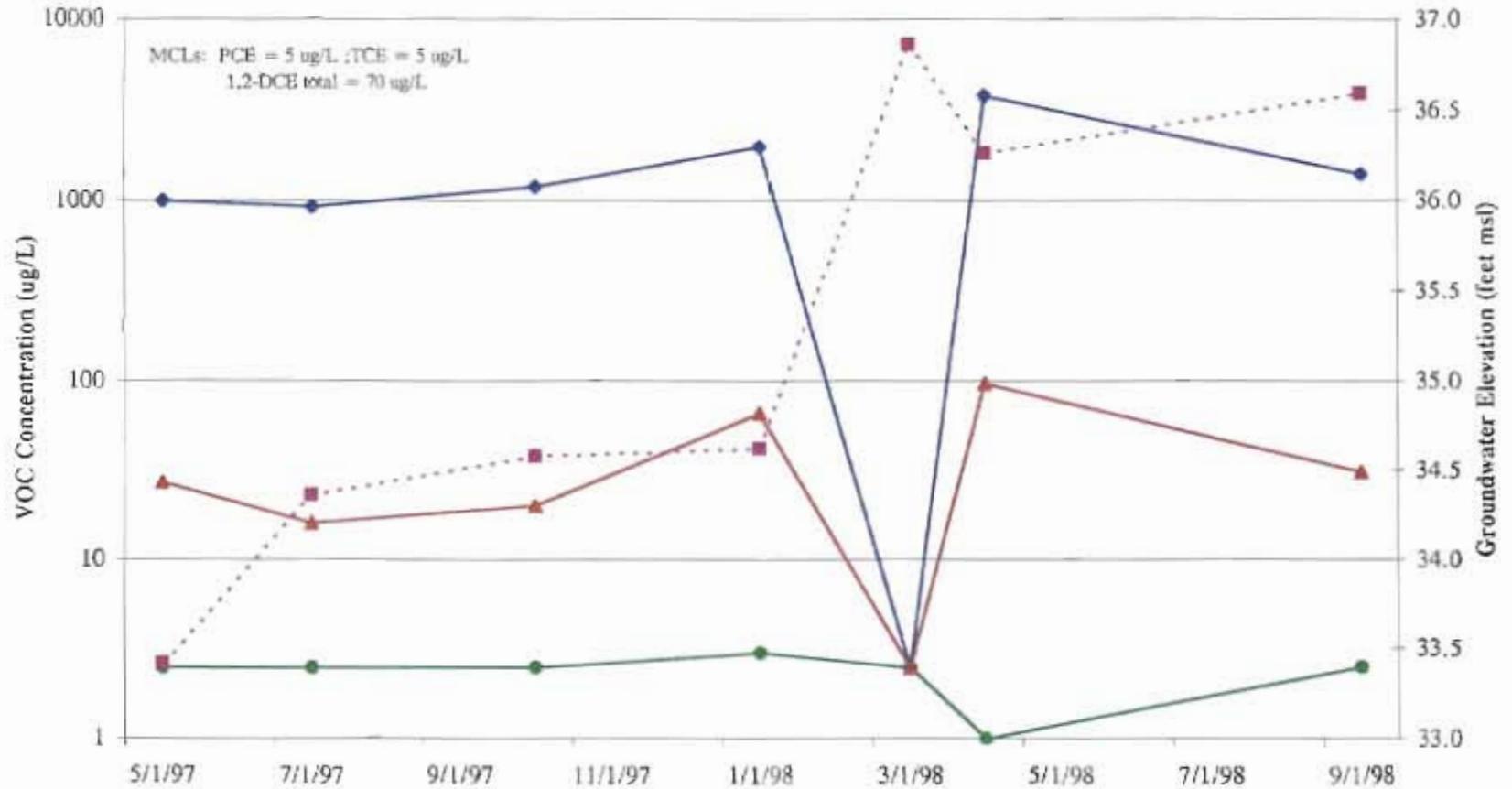
	5/22/97	7/29/97	10/15/97	1/16/98	3/12/98	4/7/98	9/25/98
—◆— TCE	2.5	45.5	49	37	4	55.5	2.5
- - ■ - - GW ELEV	33.34	35.24	35.61	35.72	37.74	36.04	37.86

Figure 3.83 Changes in TCE Concentration and Groundwater Elevation at 16606D



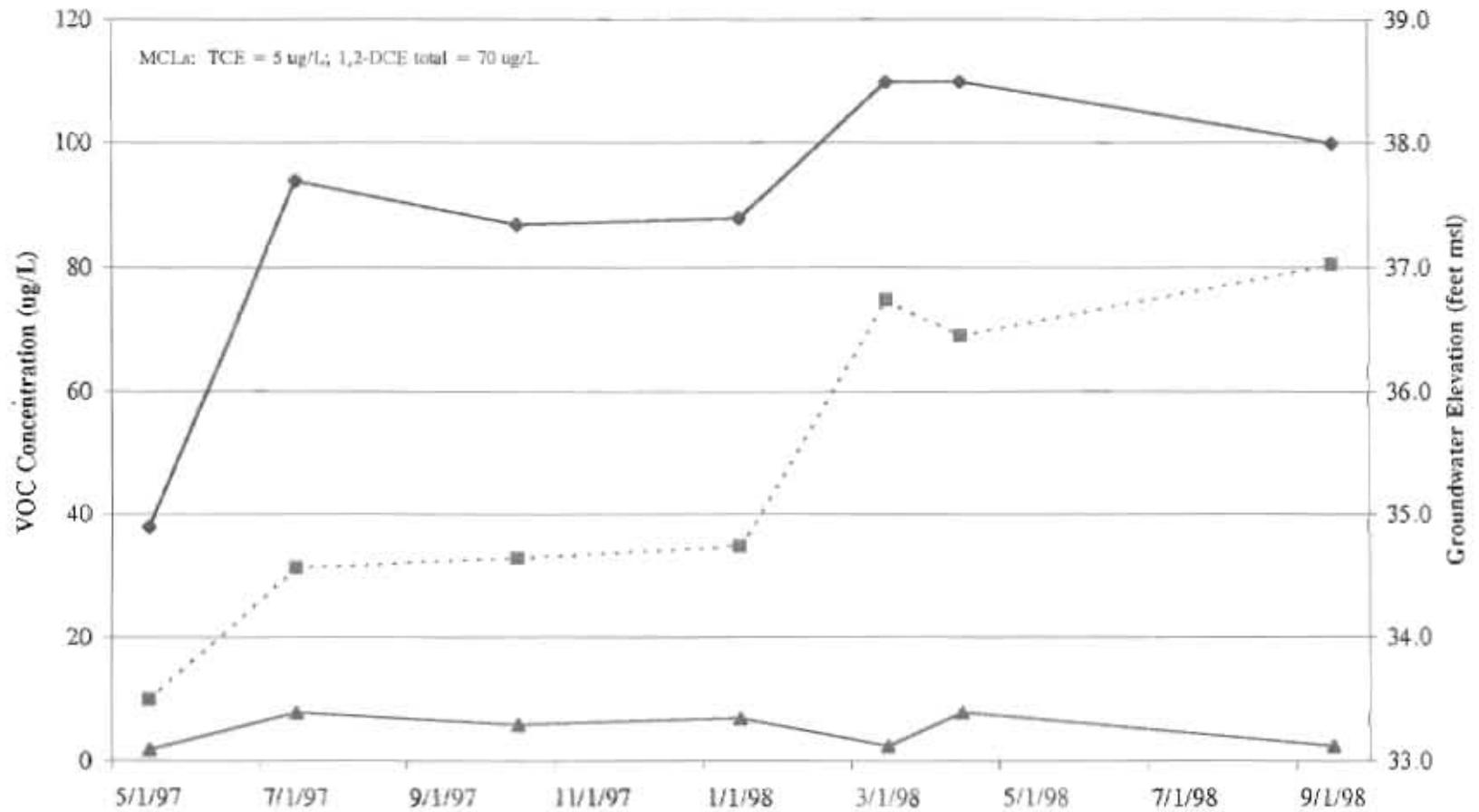
	5/22/97	7/25/97	10/16/97	1/15/98	3/12/98	4/9/98	9/25/98
—◆— TCE	4	2.5	2.5	2	5	2.5	4
- - ■ - - GW ELEV	33.57	35.22	34.94	35.20	37.35	36.91	37.10

Figure 3.84 Changes in VOC Concentration and Groundwater Elevation at 16607D



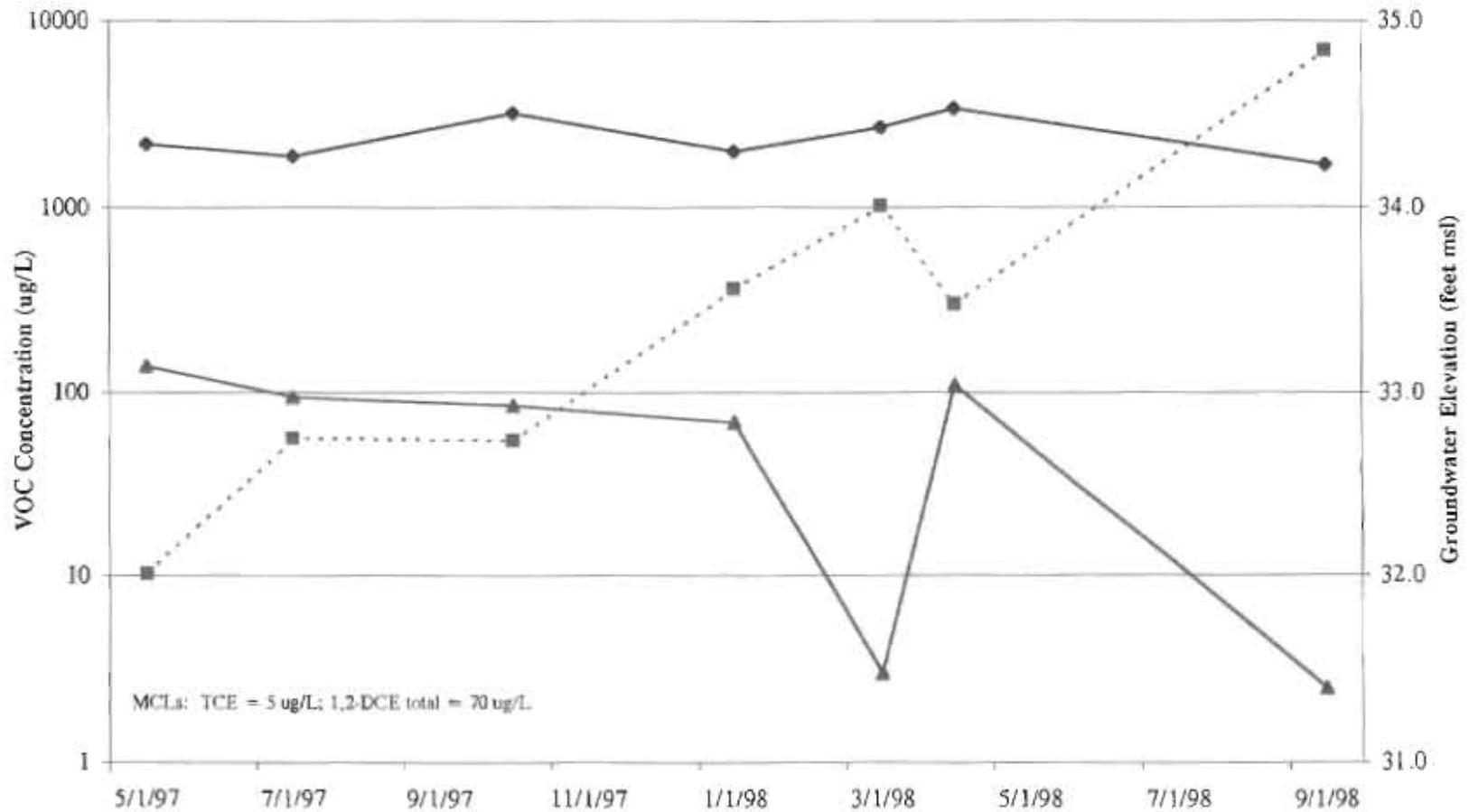
	5/22/97	7/25/97	10/16/97	1/22/98	3/12/98	4/9/98	9/25/98
● PCE	2.5	2.5	2.5	3	2.5	1	2.5
● TCE	1000	930	1200	2000	2.5	3800	1400
▲ 1,2-DCE tot	27	16	20	66	2.5	97	31
■ GW ELEV	33.42	34.36	34.58	34.62	36.86	36.26	36.59

Figure 3.85 Changes in VOC Concentration and Groundwater Elevation at 16608D



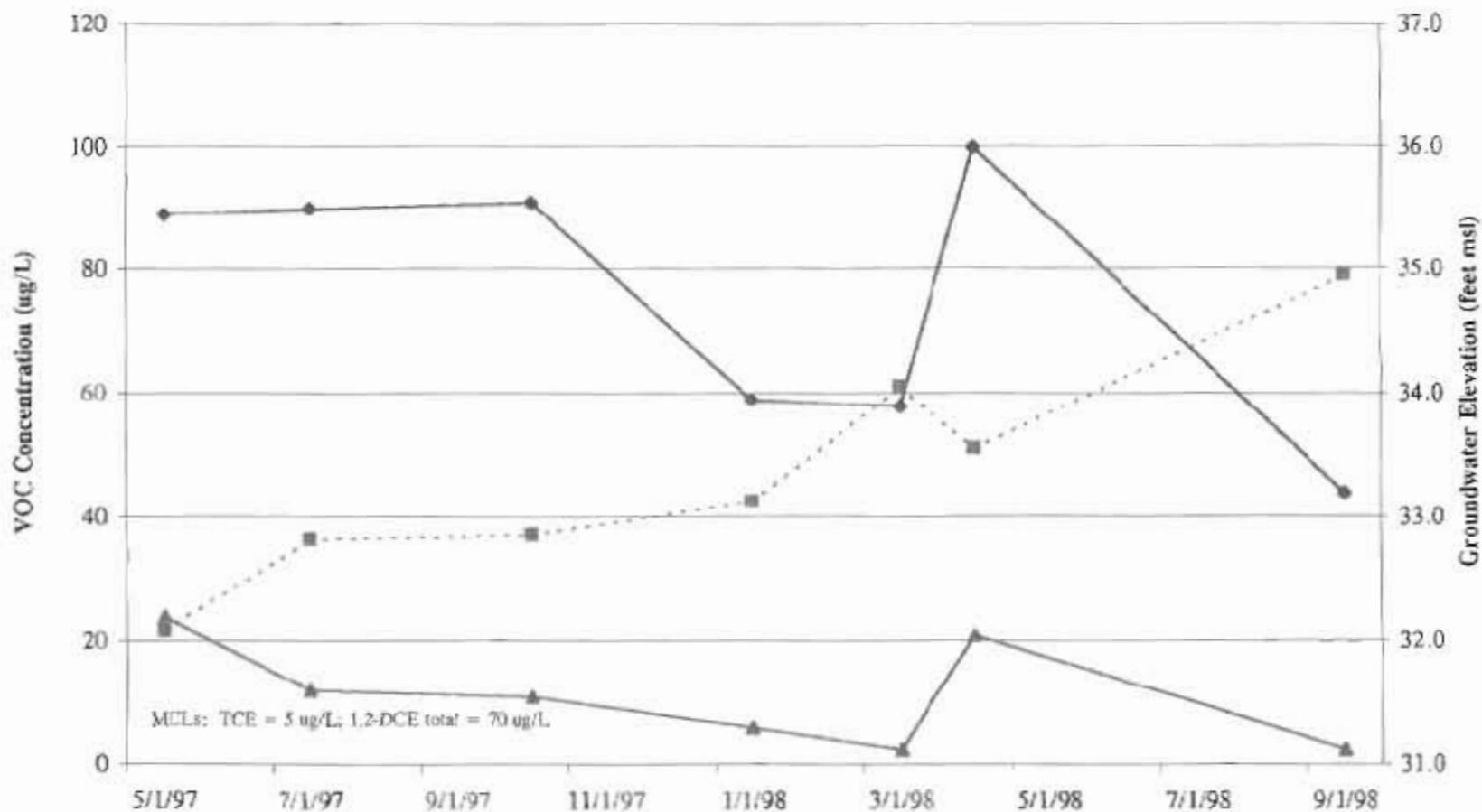
	5/22/97	7/28/97	10/17/97	1/22/98	3/12/98	4/10/98	9/24/98
—◆— TCE	38	94	87	88	110	110	100
—▲— 1,2-DCE tot	2	8	6	7	2.5	8	2.5
- - ■ - - GW ELEV	33.50	34.56	34.64	34.74	36.75	36.46	37.03

Figure 3.86 Changes in VOC Concentration and Groundwater Elevation at 16610D



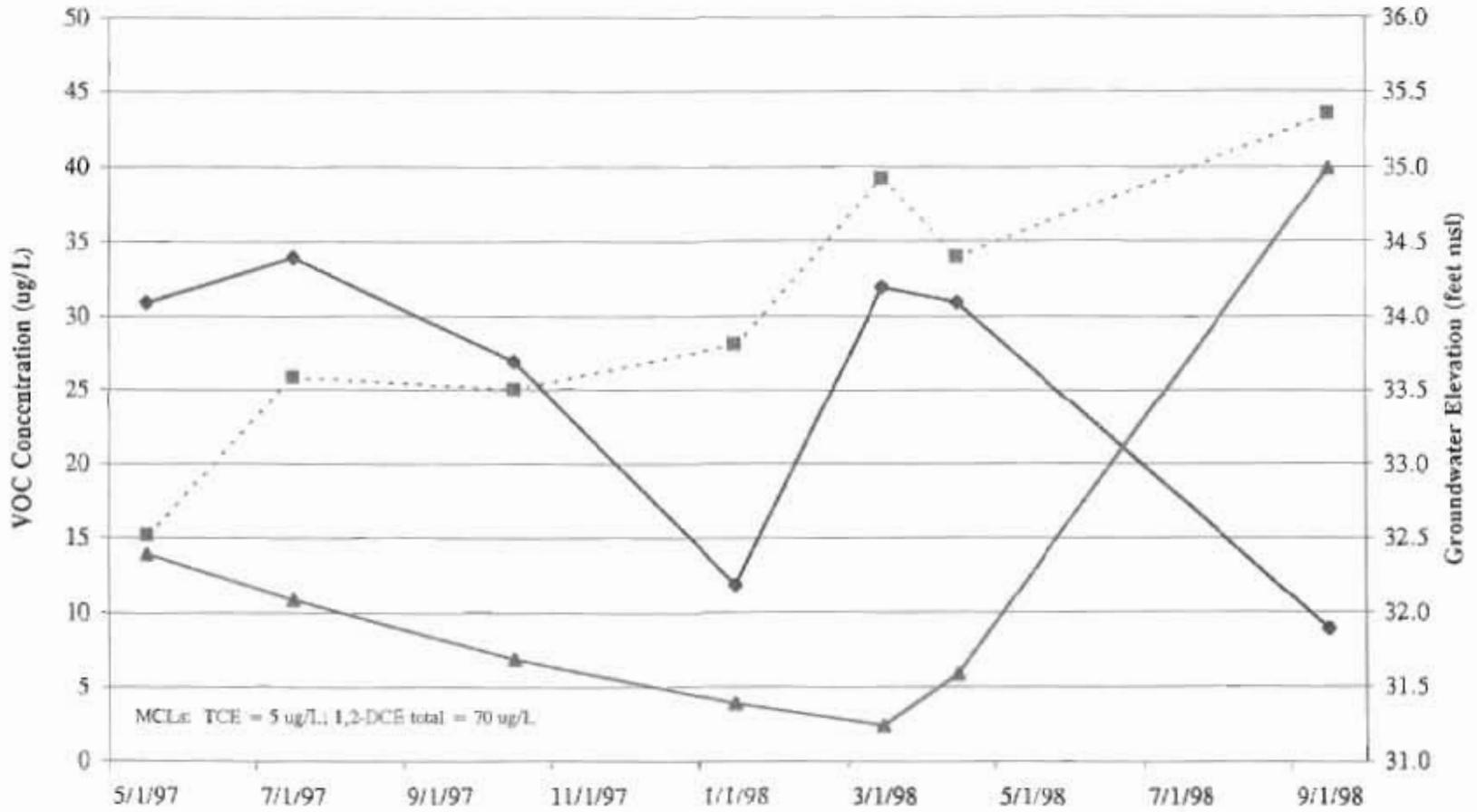
	5/22/97	7/30/97	10/17/97	1/23/98	3/12/98	4/14/98	9/25/98
◆ TCE	2200	1900	3200	2000	2700	3400	1700
▲ 1,2-DCE tot	140	95	85	69	3	110	2.5
■ GW ELEV	32.01	32.75	32.74	33.56	34.01	33.48	34.84

Figure 3.87 Changes in VOC Concentration and Groundwater Elevation at 16611D



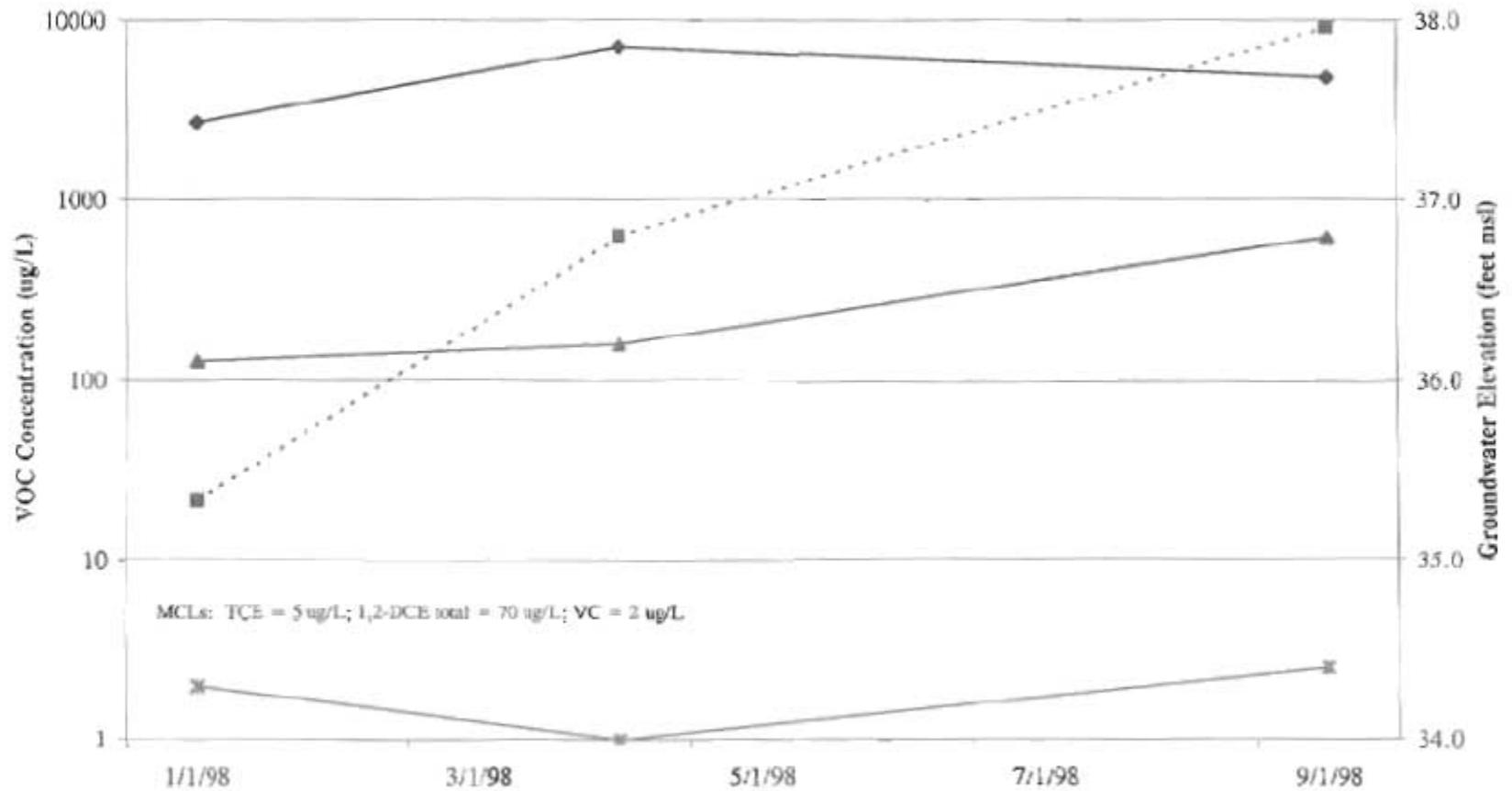
	5/22/97	7/30/97	10/17/97	1/22/98	3/12/98	4/8/98	9/24/98
● TCE	89	90	91	59	58	100	44
▲ 1,2-DCE tot	24	12	11	6	2.5	21	2.5
■ -GW ELEV	32.09	32.82	32.86	33.13	34.06	33.56	34.96

Figure 3.88 Changes in VOC Concentration and Groundwater Elevation at 16612D



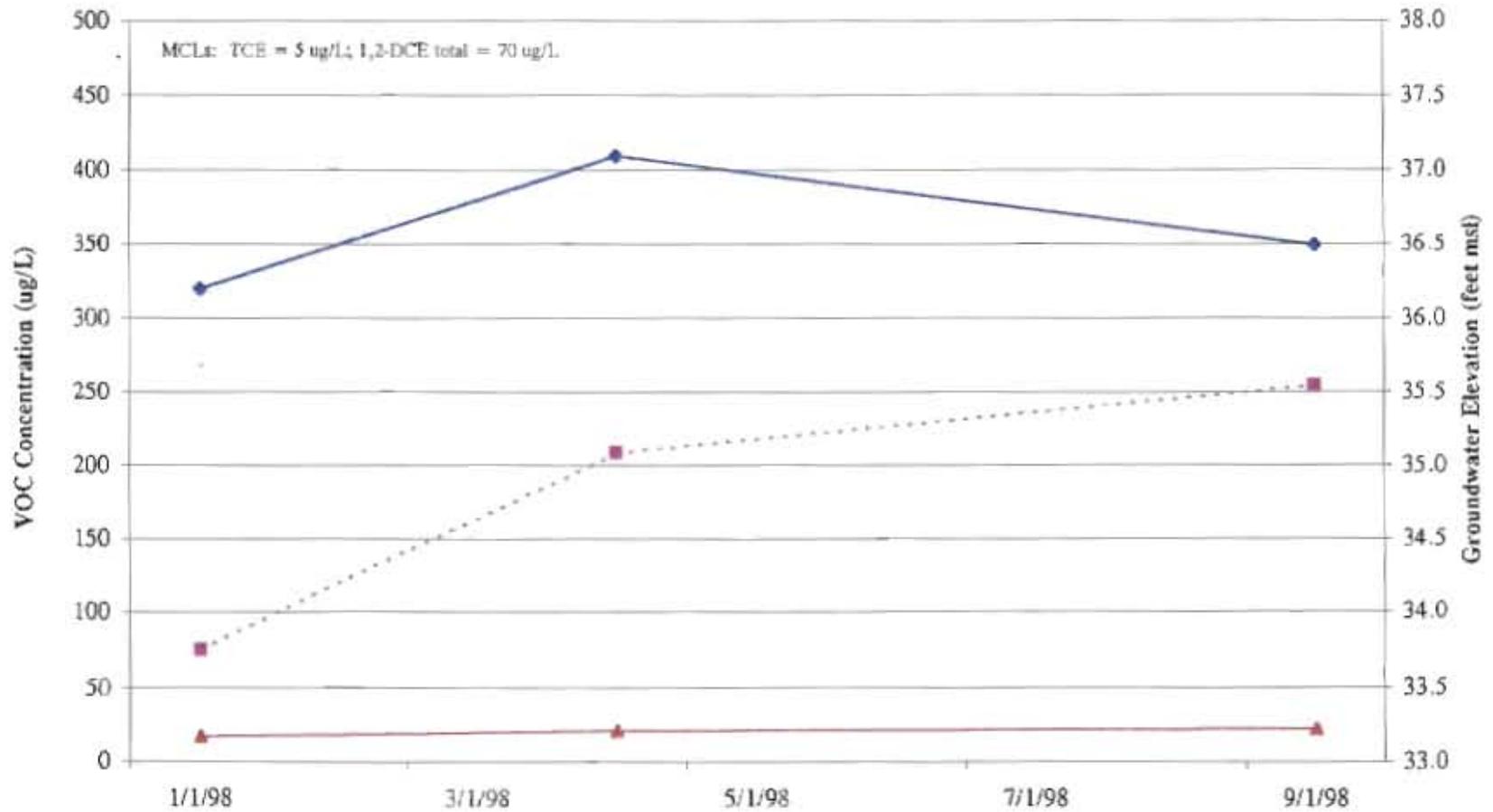
	5/22/97	7/29/97	10/17/97	1/22/98	3/12/98	4/8/98	9/24/98
● TCE	31	34	27	12	32	31	9
▲ 1,2-DCE tot	14	11	7	4	2.5	6	40
■ GW ELEV	32.53	33.59	33.51	33.82	34.93	34.40	35.36

Figure 3.89 Changes in VOC Concentration and Groundwater Elevation at 16613D



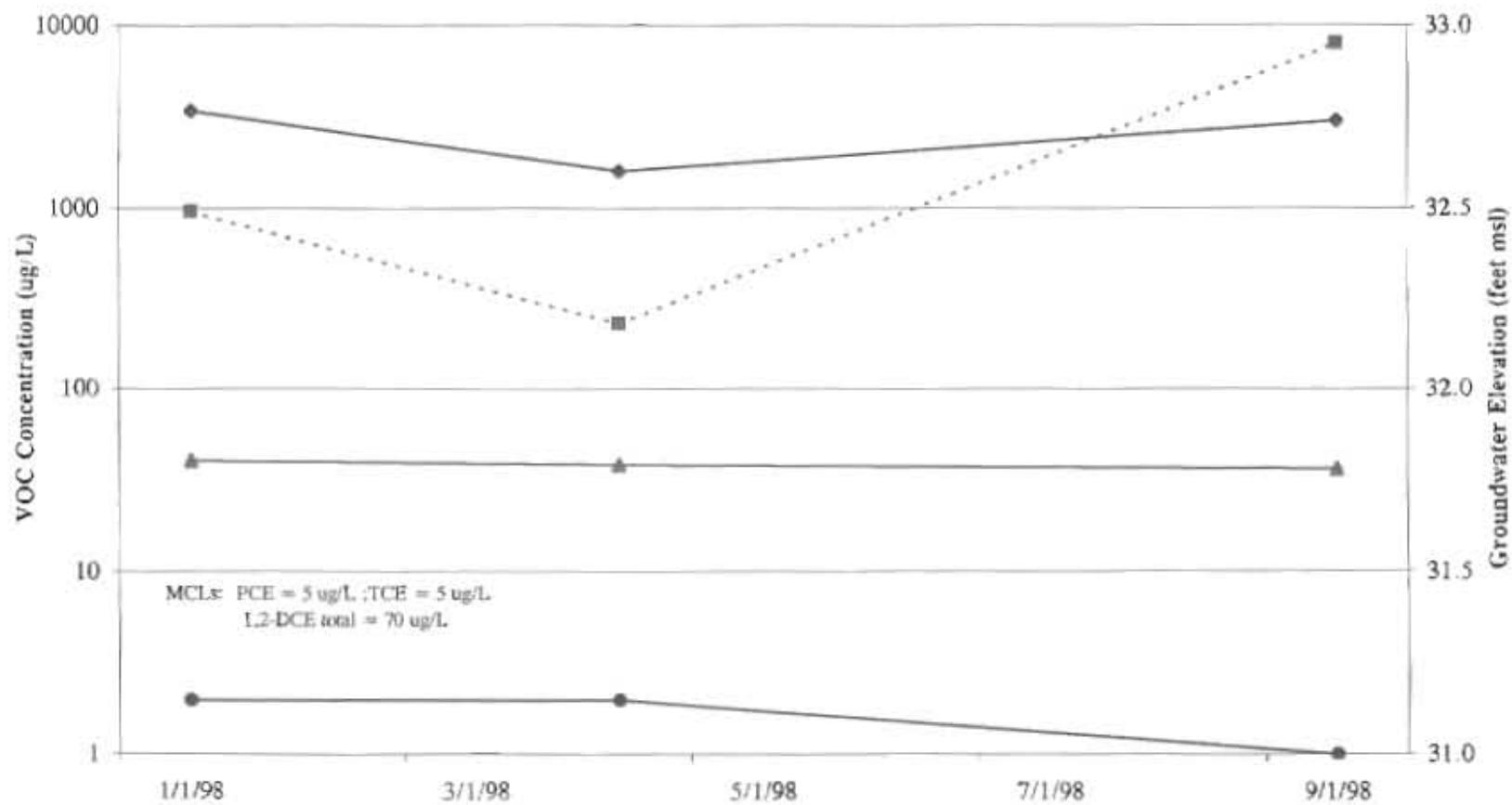
	1/22/98	4/14/98	9/25/98
◆ TCE	2700	7200	4800
▲ 1,2-DCE tot	130	160	618
✕ VC	2	1	2.5
■ GW ELEV	35.34	36.80	37.96

Figure 3.90 Changes in VOC Concentration and Groundwater Elevation at 16614D



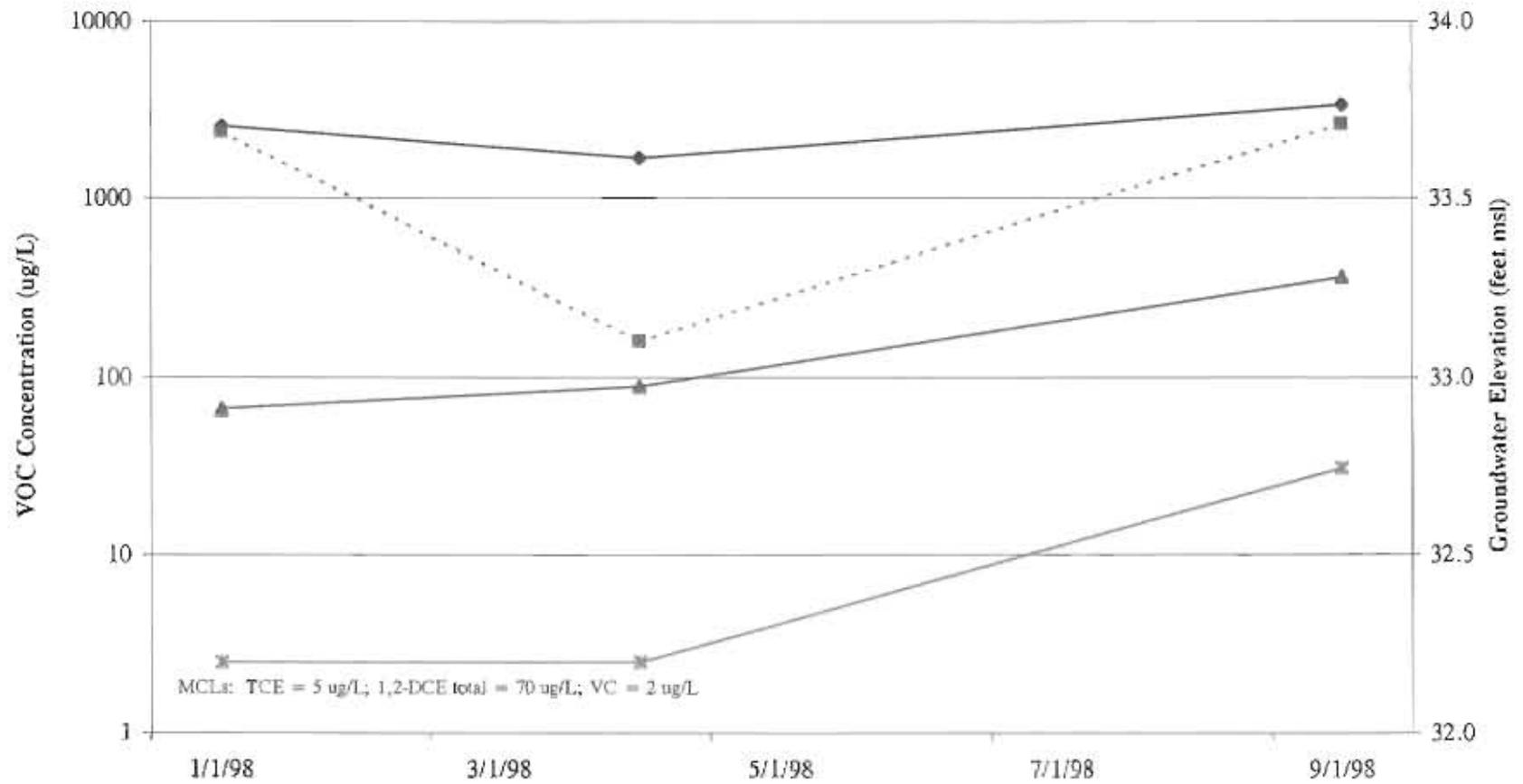
	1/22/98	4/15/98	9/25/98
—◆— TCE	320	410	350
—▲— 1,2-DCE tot	18	22	23
- - ■ - - GW ELEV	33.76	35.09	35.55

Figure 3.91 Changes in VOC Concentration and Groundwater Elevation at 166016



	1/28/98	4/17/98	9/26/98
● PCE	2	2	1
◆ TCE	3400	1600	3000
▲ 1,2-DCE tot	40	38	36
■ GW ELEV	32.49	32.18	32.95

Figure 3.92 Changes in VOC Concentration and Groundwater Elevation at 16616D



	1/28/98	4/17/98	9/26/98
—◆— TCE	2600	1700	3400
—▲— 1,2-DCE tot	67	89	364
—*— VC	2.5	2.5	31
- - ■ - - GW ELEV	33.69	33.10	33.71

VOC concentrations varied significantly at each well during their sampling history. By correlating VOC concentrations and groundwater elevation, some insight into the role of dilution at the site may be made. Given the three major recharge events that occurred during the monitoring period, the Winter 1998 event is most critical since it was entirely bracketed within the May 1997 to September 1998 groundwater monitoring period. Figures 3.78 to 3.92 show that the greatest changes in VOC concentrations occurred between January and April 1998, which directly coincides with the Winter 1998 event. The temporal plots show that significant decreases in total VOC concentrations occurred at one of the three sampling events (January 1998, March 1998, and April 1998) within this time period at 12 of 15 well locations. The greatest decrease usually occurred in the March 1998 sampling event, which closely coincided with the peak in recharge. The three exceptions were 08D, 13D, and 14D where total VOC concentrations were higher in April 1998 when recharge was dissipating than in January 1998 prior to the recharge peak.

The most significant decrease in total VOC concentrations occurred at 07D in which concentrations declined from 2,069 $\mu\text{g}/\text{L}$ in January 1998 to non-detect in March 1998. VOC concentrations returned to their original levels in April 1998 after recharge had dissipated at 07D. Well pair 166016/16D showed the next greatest decline between January and April 1998 although the diluted TCE concentrations at each well and 1,2-DCE concentration at 16D remained well above the their respective MCLs. These concentrations returned to similar levels in the next sampling event in September 1998.

3.4 Data Interpretation

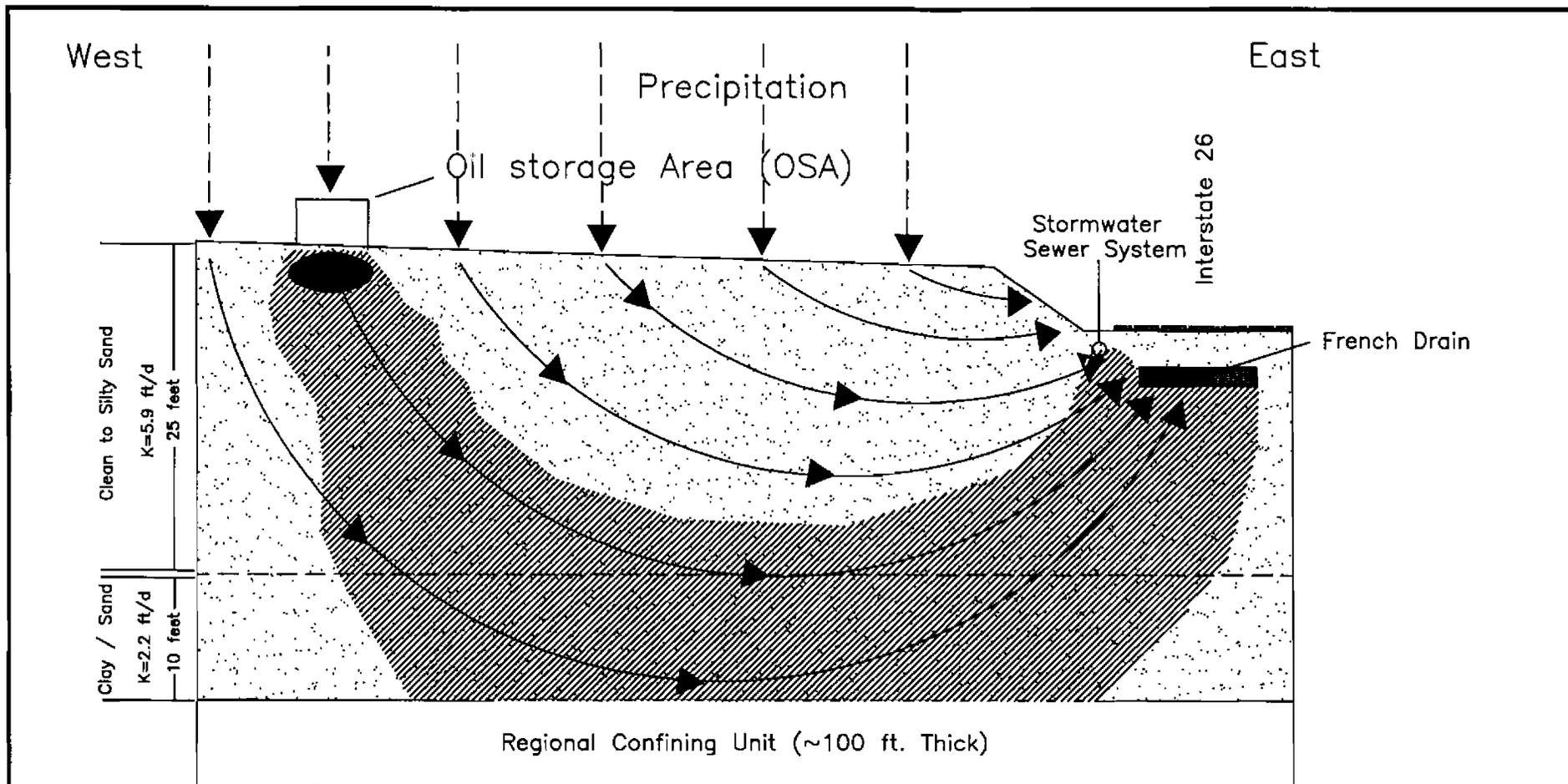
Determining if natural attenuation is occurring within a contaminated aquifer is a difficult and lengthy process. There is a complex interrelationship among the many parameters that must be considered, along with the physical distribution of the parameters, both spatially and temporally. Additionally, complete understanding of the site geology, hydrogeology, VOC composition, and geochemistry makes assessing natural attenuation an involved process.

3.4.1 SWMU 166 VOC Plume Morphology

The source of VOC contamination is at the OSA, which is located just southeast of the local recharge area within the center of Naval Annex. The VOC plume at SWMU 166 at the end of Round 2 appeared to begin at well pair 166013/13D (Figure 3.12). Additional data, collected in October 1998 during the CMS, indicates that the plume originates at well pair 166026/26D (Figure 3.13). As groundwater infiltrates the aquifer, desorbing of remnant

VOC NAPL in soil occurs, enriching the dissolved VOC concentrations which eventually migrate deep into the surficial aquifer (Figure 3.93). Ultimately, vertical migration of the plume is limited by the regional confining unit (Ashley Formation) such that VOCs migrate primarily within the Qcs unit immediately overlying the Ashley Formation. The plume, based upon VOC concentrations, appears to move along a major deep groundwater flow path starting in the vicinity of deep well pairs 16626D and including 16624D, 25D, 13D, 7D, 14D, and 10D at which point it moves off-site. The last monitoring point occurs at well pair 166016/16D, adjacent to Interstate 26, the local discharge zone. As such, upward vertical gradients move contaminants back into shallow groundwater and eventually into the french drain and storm water sewer systems associated with Interstate 26. Along this major deep groundwater flowpath, VOC concentrations decreased until reaching well pair 166016/16D where VOC concentrations are of the same magnitude as those in the source area.

The bulk of the plume appears to be narrow, no more than 100 to 150 feet wide. It is broader on its south side due to dispersion as groundwater flow diverges from the recharge zone near 16601. Groundwater flow lines are more parallel on the north side of the plume and the plume is less modified by dispersion.



LEGEND

-  Dissolved Phase Contamination
-  Source Area in Soil
-  Groundwater Flow Vector
-  Precipitation (Rainfall)

NOTE: Drawing is not to scale.



ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.93
 PLUME MORPHOLOGY OF SWMU 166

Date: 03/16/99

DWG Name: 2911M078

The flowpath from 166026D to 16616D showed concentrations of 1,2-DCE, VC, and ethene indicative of limited reductive dechlorination taking place, but at a rate not sufficient to reach MCLs.

A minor deep groundwater flowpath also originates from the OSA and moves south/southeast passing near wells 16604D, and 12D, and eventually toward well pair 018/18D. Though VOC concentrations in these wells are significantly lower compared to those along the major flowpath MCL exceedences still occurred for some VOCs. The primary VOC of concern, TCE, decreased below its MCL of 5 $\mu\text{g/L}$ along the minor flowpath by the time it reached well pair 018/18D, the last wells before the discharge zone. However, PCE had a detection of 6 $\mu\text{g/L}$ at 166018 which exceeded its MCL of 5 $\mu\text{g/L}$.

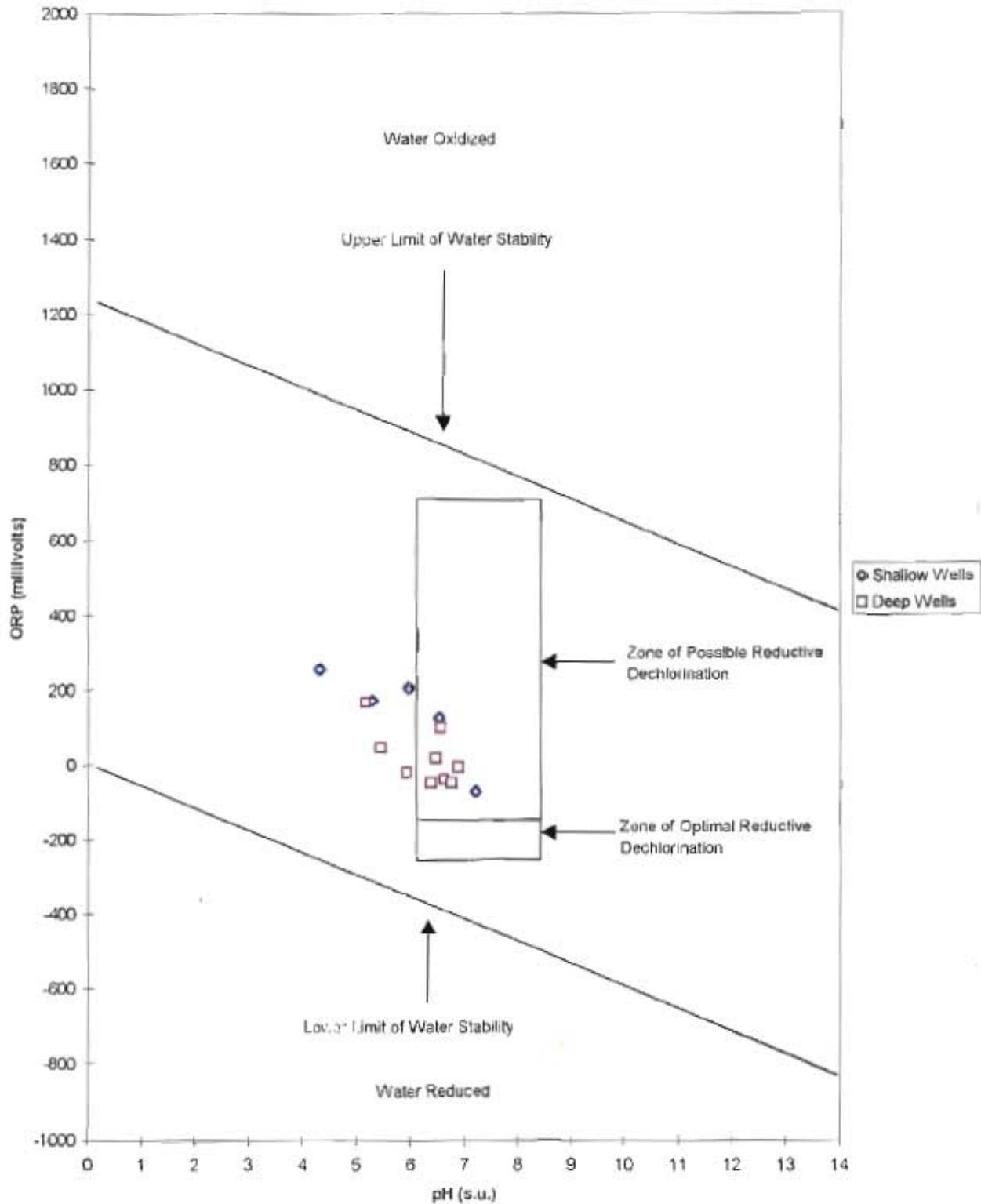
3.4.2 ORP - pH DIAGRAMS

Biologically mediated redox reactions are the driving force behind natural attenuation. The effectiveness of reductive dechlorination can be linked to specific redox conditions. Plotting ORP (redox potential) and pH is useful in identifying which samples have the greatest potential for natural attenuation. ORP-pH diagrams are based upon and assist in visualizing acid-base and redox equilibrium relationships between dissolved species. One of the limits associated with ORP-Eh diagrams is the potential deviation from equilibrium conditions in groundwater. This is not uncommon and thus must be kept in mind when interpreting ORP-pH plots. Figures 3.94, 3.95, and 3.96 illustrate the associations between ORP, pH, alkalinity, and primary parameters such as VOCs.

Round 1

The groundwater from the shallow and deep groundwater at SWMU 166 clustered closely together (Figure 3.98) and fell into the ORP-pH region typical of groundwater becoming isolated from the atmosphere (Brownlow, 1979) . Except for 166002, the samples from shallow groundwater had

Figure 3.98
SWMU 166 First Round MNA ORP-pH Diagram



higher ORP and lower pH values. These higher ORP values may indicate some contact with the atmosphere through gaseous exchange through the unsaturated zone. Low partial pressures of the carbon dioxide in the root zone lead to production of carbonic acid lowering the groundwater pH. Low alkalinity in groundwater is not enough to buffer the pH.

The groundwater samples from deep groundwater had slightly lower ORP values and similar pH values compared to shallow groundwater. The slightly lower ORP values probably arise from further isolation from the atmosphere as groundwater penetrates deeper into the aquifer.

Plotted on Figure 3.98 are the zones of possible and optimal reductive dechlorination based upon ORP and pH values (Technical Document, 1998). No groundwater samples from Round 1 fell within the zone of optimal reductive dechlorination. Only three wells in shallow groundwater (166002, 166004, and 166006) had pH values at or above 6, which is considered an optimal value for the growth of microorganisms that degrade chlorinated aliphatic hydrocarbons. ORP values were in the possible range for reductive dechlorination. In deep groundwater three wells (16605D, 16607D and 16611D) had pH values below 6 and all three wells had ORP values that are considered possible for reductive dechlorination. Overall, based on ORP/pH values, conditions in the deep groundwater are somewhat more favorable to reductive dechlorination than conditions in the shallow groundwater.

From the well population where samples were taken, only one well along the major flowpath (16610D) had a pH value above 6. The minor flowpath had pH values above 6 at 16604D and 16612D.

Round 2

The larger population of wells sampled provided additional data to better understand the relationship between the ORP and pH values measured. The shallow and deep groundwater at

SWMU 166 are clustered together (Figure 3.99) and ranged from ORP-pH values typical of groundwater exposed to the atmosphere to those transitioning to atmospheric isolation. The zones of possible and optimal reductive dechlorination are also shown in Figure 3.99. The shallow groundwater ORP and pH values were higher and lower, respectively, compared to deep groundwater. The pH of the shallow groundwater from was moderately acidic to slightly acidic (4.47 to 6.54). This again may be due to contact with atmospheric or root zone carbon dioxide reservoirs and low to non-detectable alkalinity. All of the shallow wells had a ORP value within the possible range of reductive dechlorination but only three of the wells (16601, 16603, and 166002) had pH values above 6.

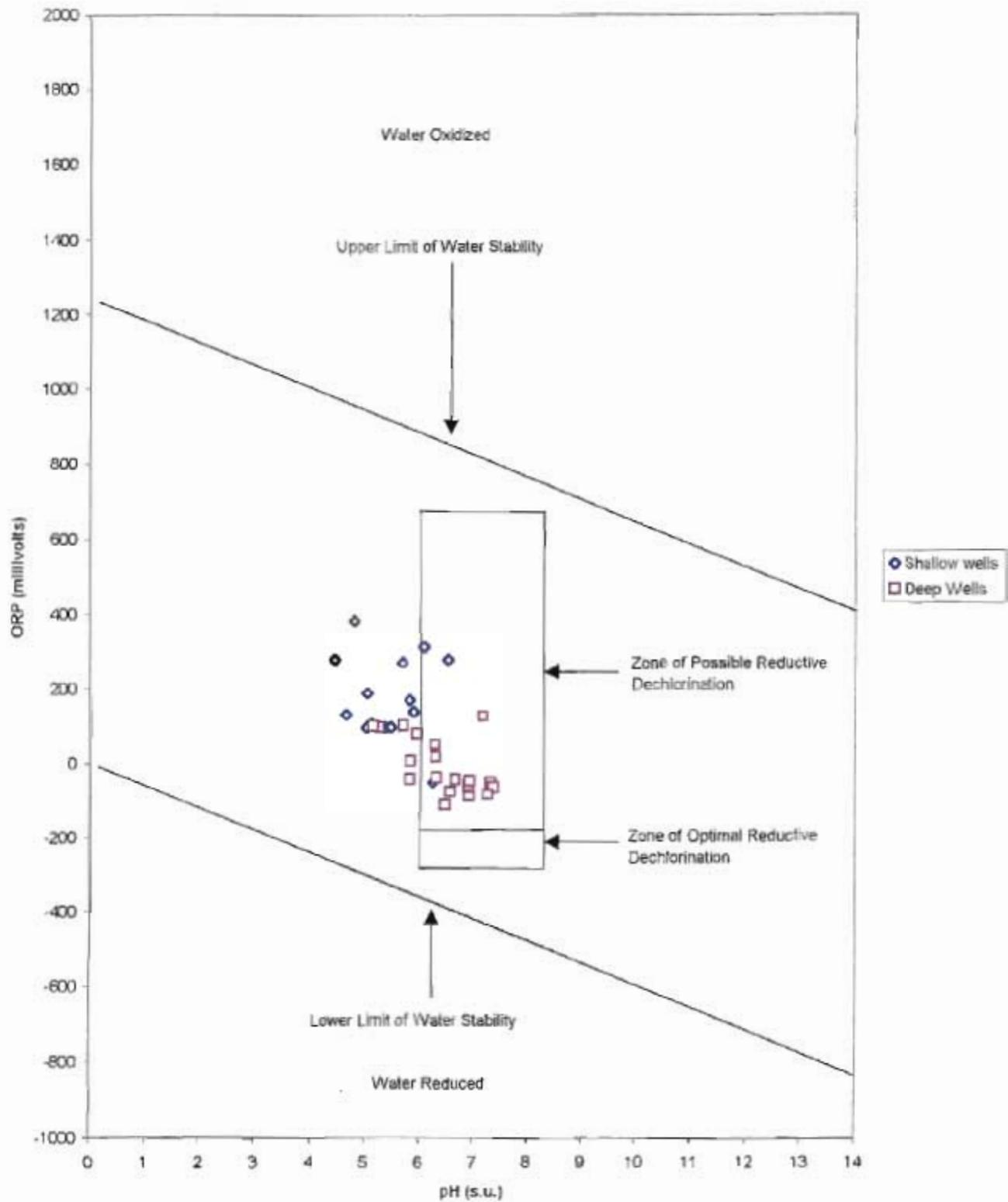
All deep wells had ORP values within the possible range of reductive dechlorination. Six out of the 19 wells (16605D, 16606D, 16607D,16611D, 16612D, and 16614D) had pH values below 6. This may be due to increased isolation from high carbon dioxide in the root zone and an increase in buffering capacity with depth (i.e., higher alkalinity).

Overall, groundwater conditions in deep groundwater were more favorable to reductive dechlorination than in the shallow flow zone. ORP values for wells along the major flowpath show a definite decrease (125 at 166013D to -63 at 166016D) which relates to an improving scenario for possible reductive dechlorination but, nonetheless, not reaching the optimal range needed for reductive dechlorination. ORP values were generally lower for the minor flowpath wells with values between a high of 78 (16612D) to a low of -58 (16608D).

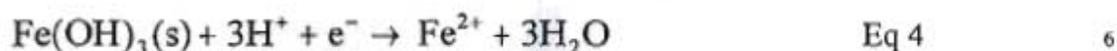
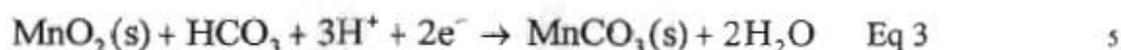
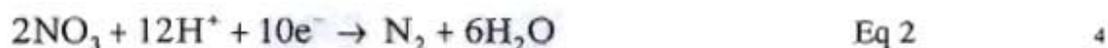
3.4.3 Spatial Trends - Oxidation-Reduction Zones

Redox zonation is the result of microorganisms using sequentially pairs of redox couples such as O_2/H_2O , NO_3/N_2 , $Mn(IV)/Mn(II)$, $Fe(III)/Fe(II)$, SO_4/HS^- , and CO_2/CH_4 as electron acceptors. The difference between each species in the redox pair is that the first species is oxidized and the

Figure 3.99
SWMU 166 Second Round MNA ORP-pH Diagram



second is reduced. The reduction occurs as a result of accepting an electron from a microorganism
illustrated in the following series of equations:



Microorganisms obtain electrons from organic materials in the aquifer, i.e., contaminants or
naturally occurring organic material. Microorganisms ingest the organic material and utilize it
as a carbon source for anabolic processes such as building/repairing cell structures, or catabolic
processes by supplying electrons for energy.

How effective an aquifer environment will be at biodegrading contaminants can be gauged by
which redox pair is predominant. In the case of fuel hydrocarbons, an oxygenated environment
is always desired. Fuel hydrocarbons are invariably electron donors and favor aerobic conditions.
However, chlorinated aliphatic compounds can be electron donors, acceptors and cometabolites.
Highly chlorinated organics, such as PCE and TCE can degrade at ORP values indicative of
denitrification and Fe(III) reduction. Lightly chlorinated compounds such as 1,2-DCE and VC
require more extreme reducing conditions though oxidizing conditions may also lead to the
degradation of 1,2-DCE and VC. By identifying which redox pair is predominant will give an
indication as to the biodegradation potential of each portion of the aquifer.

Redox zonation occurs as a result of the depletion of successive electron acceptors by microbial communities as the groundwater moves along a flowpath. The aquifer directly around the contaminant source tends to be the first area depleted with respect to all redox couples. As the groundwater flows through and downgradient of the contaminant source, the groundwater becomes less reducing with ORP values decreasing, thus supporting different microorganisms utilizing different redox couples. The sequence of redox couples is geographically reversed, compared to the sequence of favorable reactions. The shape of redox zones can be effected by groundwater velocity. As groundwater moves faster the zones will be larger, at slower groundwater velocities, redox zones will occur closer together and may be less distinct.

3.4.3.1 Methods for Delineating Redox Zones

Three techniques for redox zone delineation were used at SWMU 166: 1) ORP measurement in groundwater samples with a Ag/AgCl electrode, 2) Analytical determination of dissolved hydrogen gas concentration in groundwater samples and 3) Analytical determination of redox couple concentrations in groundwater, i.e., electron acceptor availability and the presence of metabolic by-products.

ORP

Oxidation-reduction measurements using a Ag/AgCl electrode are the simplest means in which to gauge the redox conditions of an aquifer (see Sections 2.4 and 2.5 for procedure). The drawback of this method is that ORP meters are geared for measuring only one of several possible redox couples and requires the assumption that redox in the aquifer is at equilibrium, which is hardly the case. If the ORP electrode is not sensitive to the dominant redox reaction (if there is one) occurring within the aquifer, then redox measurements will be erroneous. The advantage to this method is that data may be collected quickly and provide a gross indication of overall groundwater redox conditions.

Hydrogen Gas

Although more labor intensive, the use of dissolved hydrogen gas for redox measurements is more reliable under most conditions than use of an ORP electrode. Sample acquisition was discussed in Section 2.4. The methodology to using hydrogen gas is discussed at length by Chapelle et al (1995). Hydrogen gas maintains different equilibrium concentrations in solution and can be linked to a specific redox process in the following manner (Chappelle et al., 1995):

- hydrogen gas concentration < 0.1 nm/L is indicative of denitrification
- hydrogen gas concentration between 0.2 to 0.8 nm/L is indicative of iron(III) reduction
- hydrogen gas concentration between 1 to 4 nm/L is indicative of sulfate reduction
- hydrogen gas concentration between 5 to 20 nm/L is indicative of methanogenesis

The optimal hydrogen gas concentration range for reductive dechlorination is greater than 1.0 nm/L (Technical Protocol, 1998).

This method is prone to errors in the case of small-scale redox zonation, when large variations in redox conditions occur over short distances within the aquifer. For example, Fe(II) reduction may dominate a portion of aquifer immediately adjacent to another portion of aquifer in which methanogenesis dominates. If equal amounts of groundwater are drawn from each zone and mixed during purging, the resultant hydrogen gas concentration will be an average of the two zones, or sulfate reduction (Chappelle, et. al., 1996).

Analytical Determination of Redox Couples

The most comprehensive method of determining redox zonation is through geochemical analysis of groundwater samples for each suspected redox couple. The redox state of the groundwater system at each well is determined by which redox pair is found in the groundwater. Depletion of each redox couple is evidenced by non detection of the oxidized member and high concentrations

of the reduced member. The next successive redox couple is then analyzed to determine if it is dominant. This procedure continues until an oxidized member of redox couple is detected and the reduced member is not detected, indicating that microbes have not yet reached that redox state. As a result, this can become a very time consuming process.

During this project, several redox couples were decided upon for analysis prior to sampling in hopes of collecting additional data to reinforce either ORP electrode measurements or hydrogen gas measurements. This decision was fortuitous since ORP and hydrogen gas measurements did contradict one another.

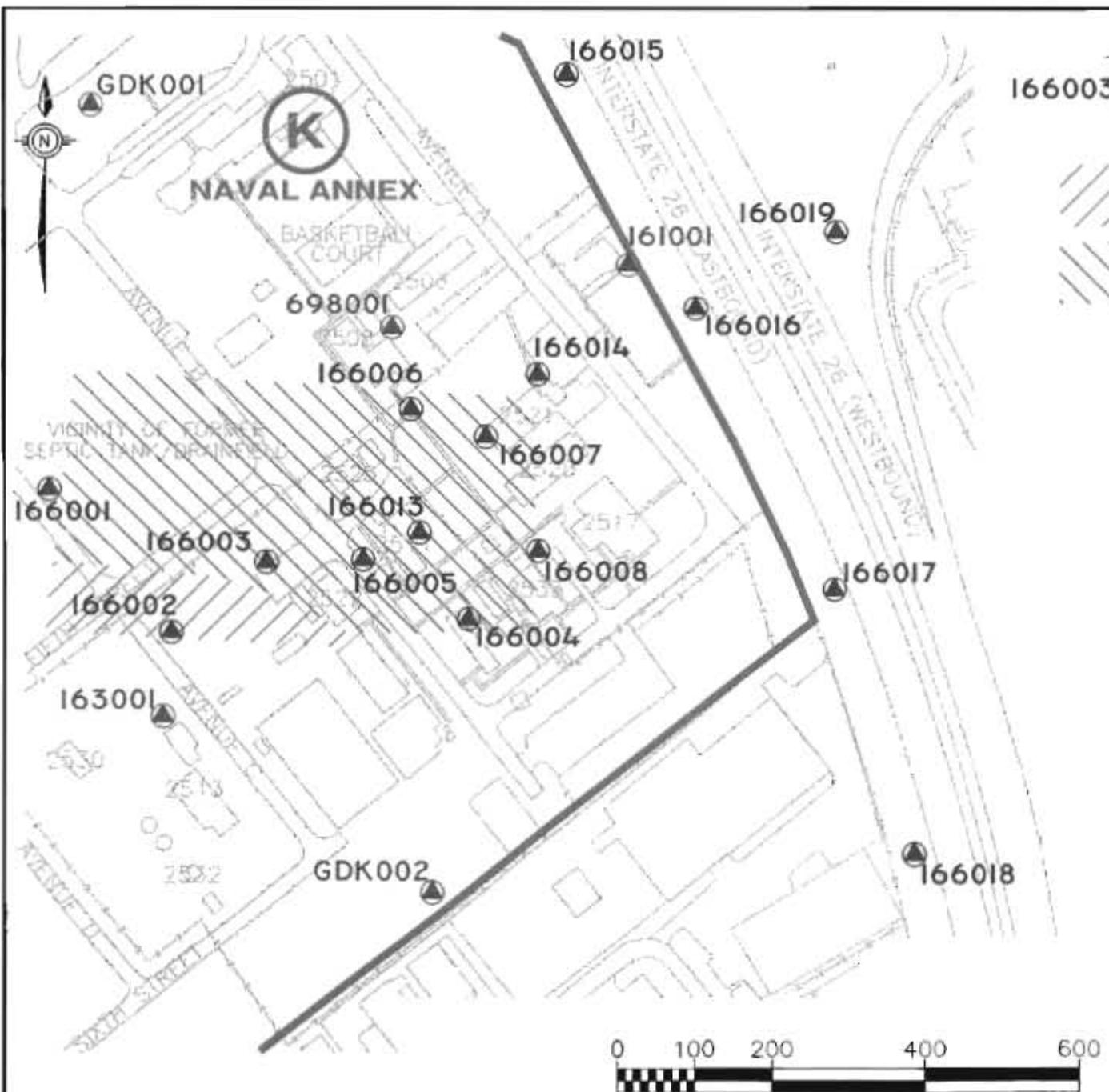
3.4.3.2 Redox Zonation by ORP

Shallow

A small zone of Fe(III) reduction was located in shallow groundwater surrounding 166002 during both Rounds 1 and 2. The ORP values for the major and minor flowpath indicate denitrification as the principle electron accepting process (Figure 3.100 and 3.101).

Deep

In deep groundwater for Round 1, zones of Fe(III) reduction were found in the northeast near 166015D and in the south near 16604D and 16608D (Figure 3.102). The rest of the area, including the major flowpath, indicates a zone of denitrification. The second round showed a iron reduction zone along I-26, and an increased iron reduction zone in the south end which included 16603D, 16608D, and 16622D. A denitrification zone transected the iron reduction zones and is the main redox zone for the major flowpath until groundwater reaches 16616D (Figure3.103). The minor flowpath begins in a denitrification zone and as groundwater moves towards 16618D, the redox zones alternate between denitrification and iron reduction.



LEGEND:

166003 SHALLOW MONITORING WELL
W/ ID NUMBER

IRON REDUCTION

DENITRIFICATION

 ZONE K - SWMU 166
MONITORED NATURAL
ATTENUATION INTERIM REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC

FIGURE 3.100

ROUND 1 - SHALLOW
REDOX ZONES BY O.R.P.





LEGEND:

166003 SHALLOW MONITORING WELL W/ ID NUMBER

IRON REDUCTION

DENITRIFICATION



ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.101

ROUND 2 - SHALLOW
 REDOX ZONES BY O.R.P.





LEGEND:

16602D ● DEEP MONITORING WELL
W/ ID NUMBER

▨ IRON REDUCTION

▩ DENITRIFICATION



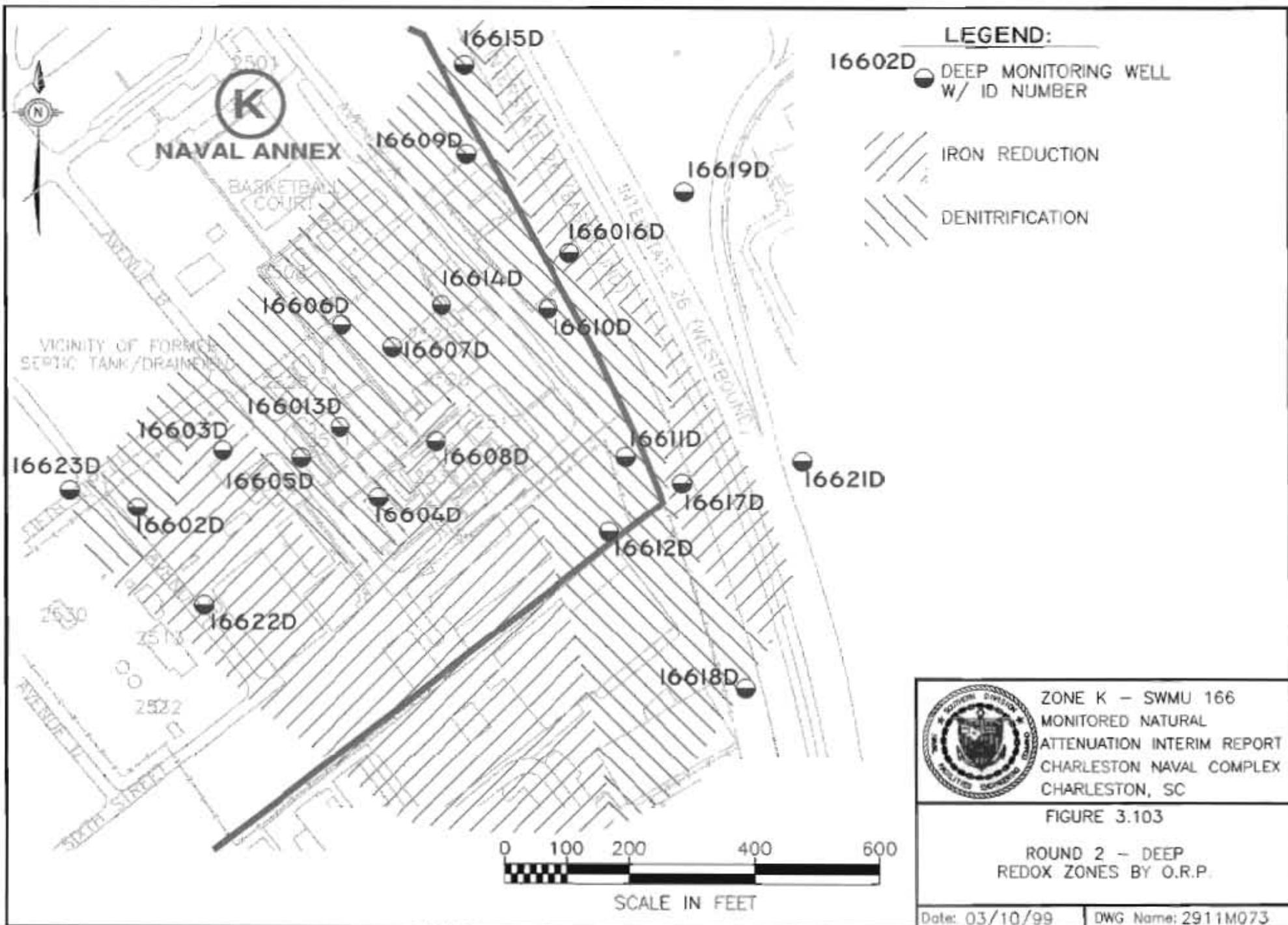
ZONE K - SWMU 166
MONITORED NATURAL
ATTENUATION INTERIM REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC

FIGURE 3.102

ROUND 1 - DEEP
REDOX ZONES BY O.R.P.

Date: 03/10/99

DWG Name: 2911M072



LEGEND:

16602D ● DEEP MONITORING WELL
W/ ID NUMBER

▨ IRON REDUCTION

▨ DENITRIFICATION



ZONE K - SWMU 166
MONITORED NATURAL
ATTENUATION INTERIM REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC

FIGURE 3.103

ROUND 2 - DEEP
REDOX ZONES BY O.R.P.

3.4.3.3 Redox Zonation by Hydrogen Gas Concentrations

Shallow and deep groundwater hydrogen gas concentrations in the first and second MNA sampling rounds are presented in Figure 3.94 with TCE, 1,2-DCE total, DO, and ORP.

Shallow

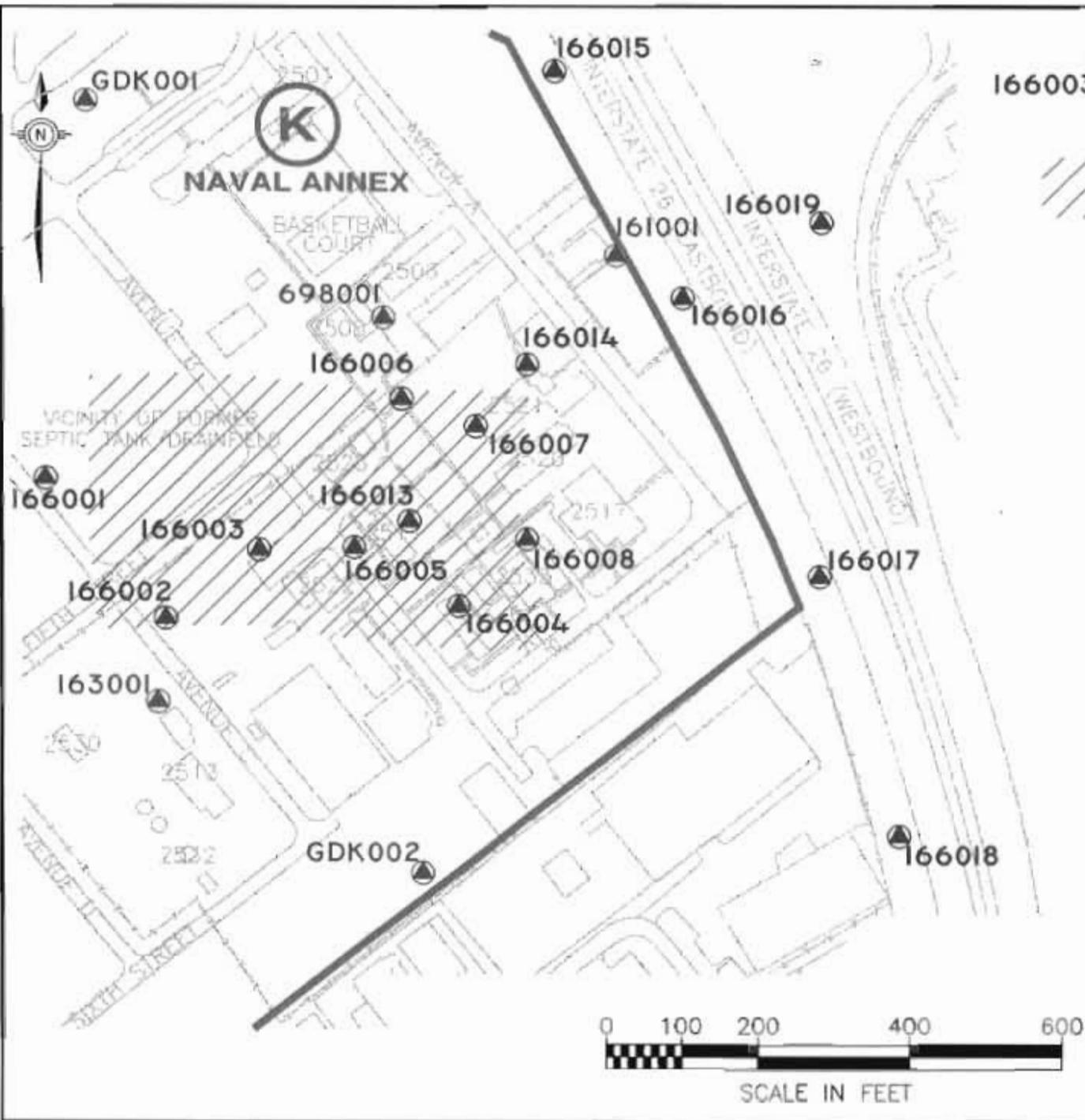
Round 1 hydrogen gas concentrations were less than 1.0 nm/L indicating iron (III) reduction (0.2-0.8 nm/L) (Figure 3.104). Due to a hydrogen gas concentration at the detection level (0.08 nm/L) at 166001, a very limited zone of denitrification (<0.1 nm/L) may exist at the western edge of SWMU 166. During the second round, hydrogen gas concentrations were significantly greater and correspond to the higher end of the iron (III) reduction range (0.2-0.8 nm/L) and the lower end of the sulfate reduction range (1-4 nm/L) (Figure 3.105).

Sulfate reduction extends east from 166003 and 166004 to the shallow wells adjacent to Interstate 26. The iron (III) reduction zone lies along the southern and western perimeter of the sulfate reduction zone and extends into it in the north at 166007.

Deep

Round 1 hydrogen gas concentrations corresponded with the low end of the iron (III) reduction range (0.2-0.8 nm/L) except for a small region of aquifer near 16608D where sulfate reduction exists (Figure 3.106). Round 2 results fell within the sulfate reduction range (1-4 nm/L) in the southern portion of the site and the northeastern at wells 16615D, 16616D, and 16614D (Figure 3.107). Between these two sulfate reduction zones and to the northwest lies the iron (III) reduction zone (0.2-0.8 nm/L)

Along the major deep groundwater flowpath, groundwater at the source area between wells 16603D and 16613D coincides with sulfate reduction. A small portion of aquifer within the flowpath reverts back to iron (III) reduction in the vicinity of 16606D and 16607D before



LEGEND:

166003 SHALLOW MONITORING WELL
W/ ID NUMBER

IRON REDUCTION



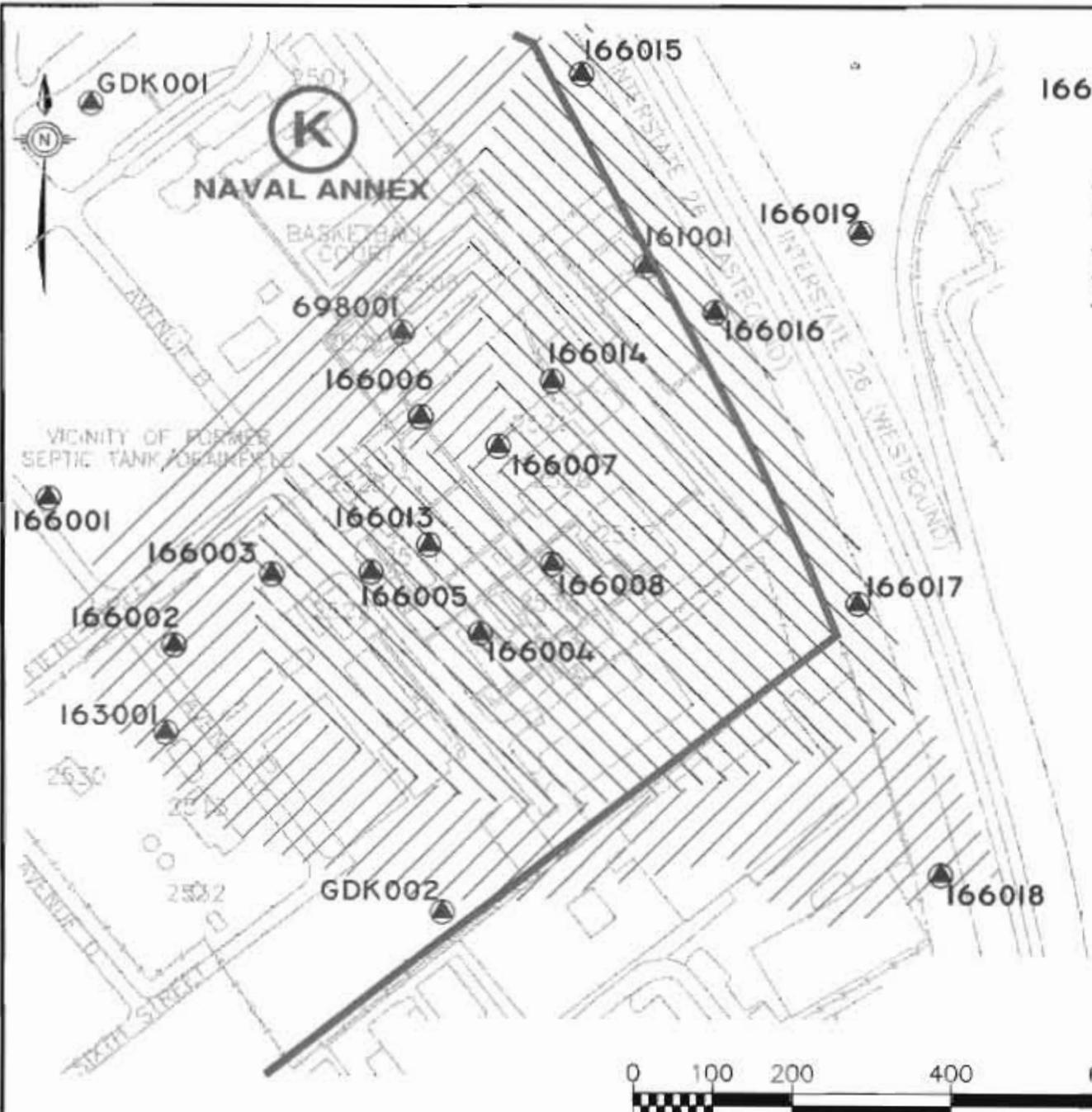
ZONE K - SWMU 166
MONITORED NATURAL
ATTENUATION INTERIM REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC

FIGURE 3.104

ROUND 1 - SHALLOW
REDOX ZONES BY HYDROGEN GAS

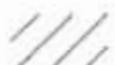
Date: 03/10/99

DWG Name: 2911M074



LEGEND:

166003  SHALLOW MONITORING WELL
W/ ID NUMBER

 IRON REDUCTION

 SULFATE REDUCTION



ZONE K - SWMU 166
MONITORED NATURAL
ATTENUATION INTERIM REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC

FIGURE 3.105

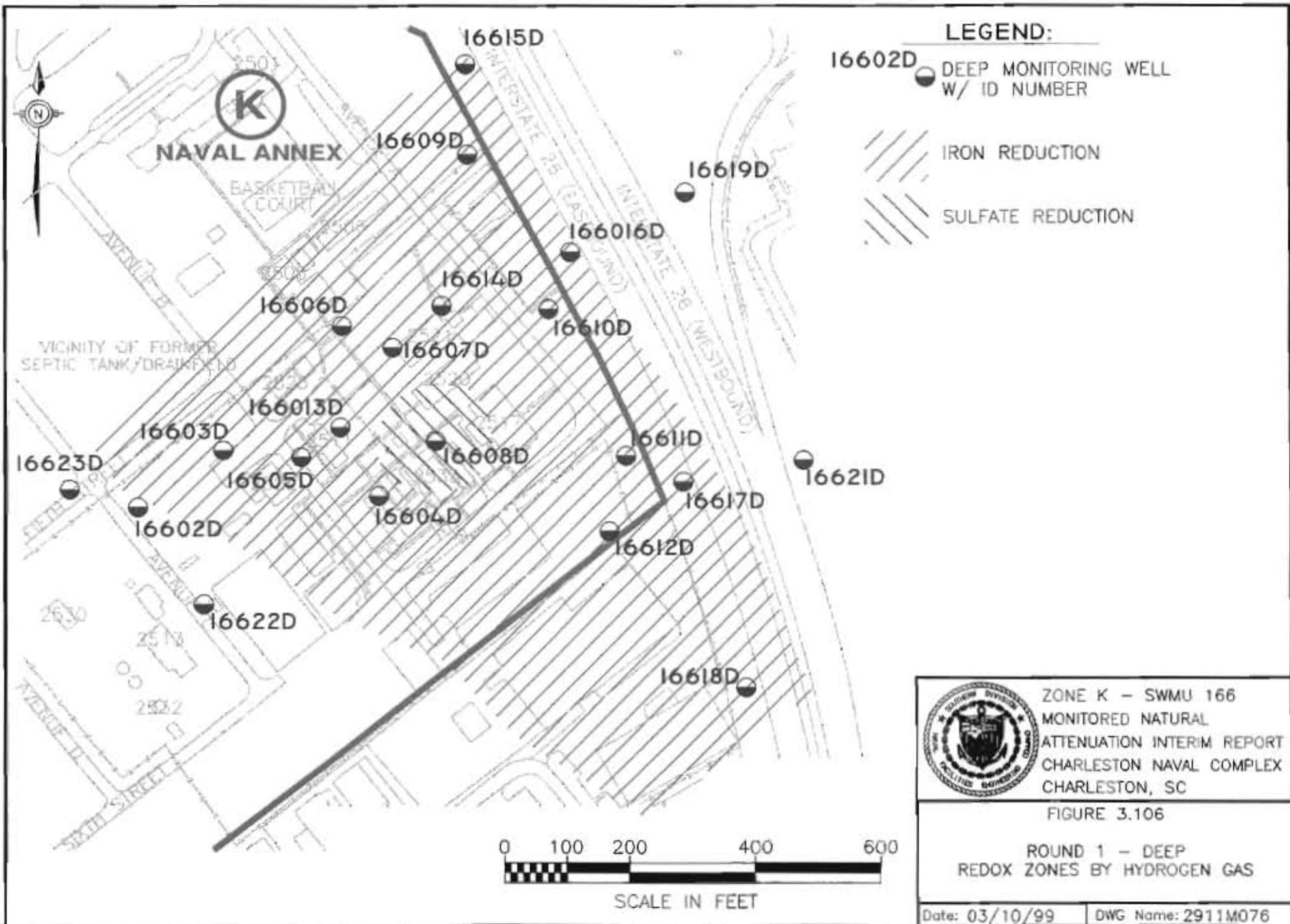
ROUND 2 - SHALLOW
REDOX ZONES BY HYDROGEN GAS



SCALE IN FEET

Date: 03/10/99

DWG Name: 2911M075



LEGEND:

- 16602D ● DEEP MONITORING WELL W/ ID NUMBER
-  IRON REDUCTION
-  SULFATE REDUCTION

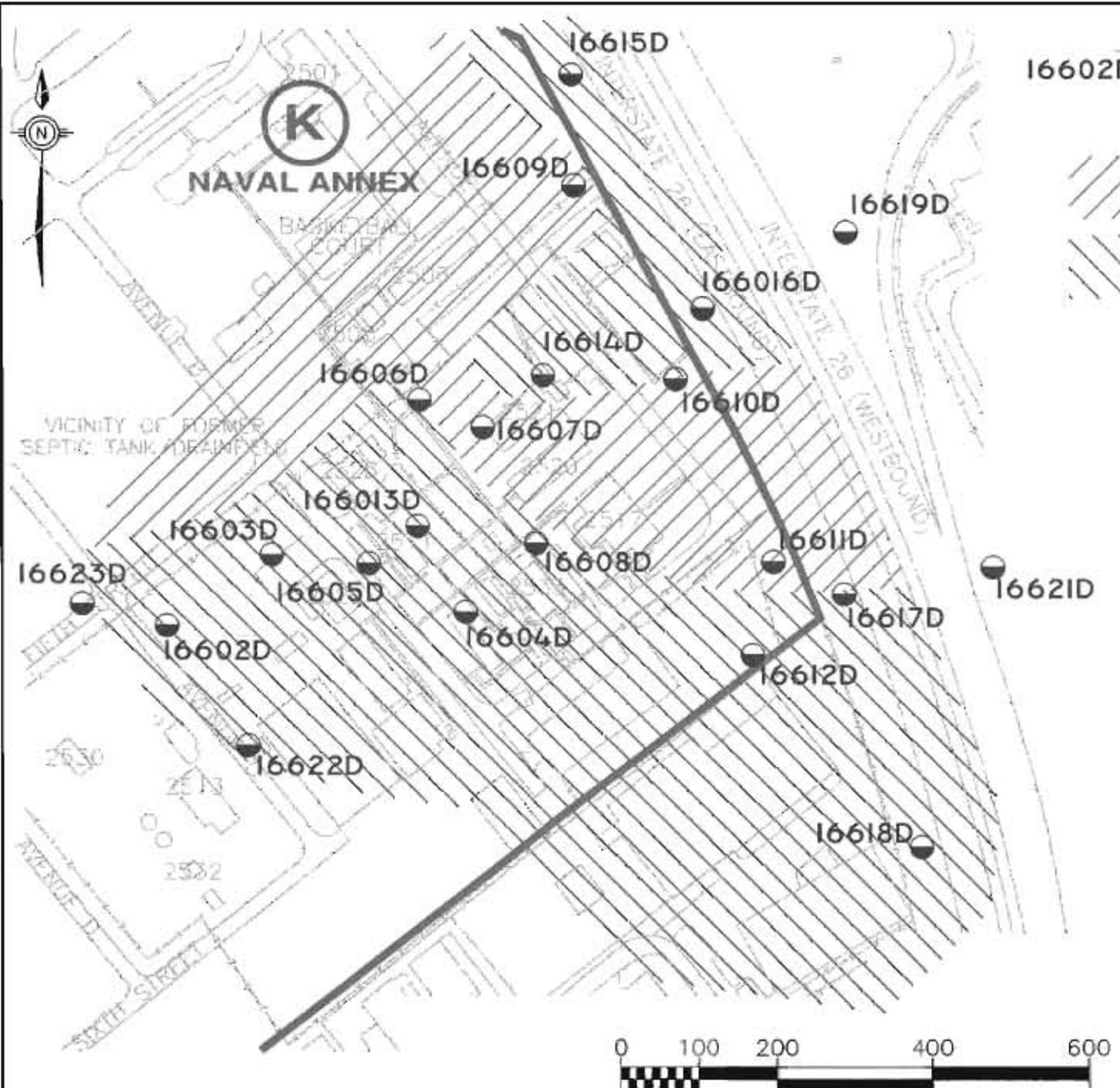


ZONE K - SWMU 166
 MONITORED NATURAL
 ATTENUATION INTERIM REPORT
 CHARLESTON NAVAL COMPLEX
 CHARLESTON, SC

FIGURE 3.106

ROUND 1 - DEEP
 REDOX ZONES BY HYDROGEN GAS





LEGEND:

16602D ● DEEP MONITORING WELL
W/ ID NUMBER

▨ IRON REDUCTION

▨ SULFATE REDUCTION



ZONE K - SWMU 166
MONITORED NATURAL
ATTENUATION INTERIM REPORT
CHARLESTON NAVAL COMPLEX
CHARLESTON, SC

FIGURE 3.107

ROUND 2 - DEEP
REDOX ZONES BY HYDROGEN GAS



SCALE IN FEET

Date: 03/10/99

DWG Name: 2911M077

transitioning to the second sulfate reduction zone from 16614D to 16616D and the discharge zone. Groundwater migrating from the source area to the southeast coincides entirely with the southern sulfate reduction zone. It is important to note that well locations with the highest VOC concentrations (16613D, 16614D, 16610D, and 16616D) lie within sulfate reduction zone.

3.4.3.4 Redox Zonation Through Metabolic By-products

In order to sustain metabolic processes, microorganisms progress through a series of redox couples as outlined in Section 3.4.3. The second species in each redox couple is formed by accepting an electron from a microorganism, thus being reduced. This reduced species is also known as a metabolic by-product. Because microorganisms progress through a series of redox couples sequentially, it may be possible to assess the redox state, and the biodegradation potential of a region of aquifer, by tracing metabolic by-products and/or oxidized parents. The presence of oxidized parents such as nitrate, sulfate, manganese(IV), etc, and the absence of metabolic by-products, such as nitrogen gas, hydrogen sulfide, or manganese(II) indicate microbial communities have not depleted previous redox pairs further up the sequence. The presence of oxidized parents and metabolic by-products in the groundwater simultaneously indicate active reduction by microbial communities. If only metabolic by-products are present, microbial communities have already utilized all of the oxidized parent and moved further down the sequence of redox couples. This process is spatially variable giving rise to redox zonation in an aquifer.

DO- Aerobic Respiration

DO concentrations were typically greater than 1 mg/L in Rounds 1 and 2 shallow groundwater (Figure 3.94) indicating that the shallow portions of the surficial aquifer exhibit aerobic zones. Two areas with DO less than 1 mg/L exist: one northeast of well 166007 and the other across the southern half of the site as depicted by the second Round 1.0 mg/L contour in Figure 3.94. Deep groundwater was anaerobic in Round 1 but revealed more aerobic zones in Round 2 (Figure 3.94). Along the major deep groundwater flowpath, groundwater DO was greater than 1.0 mg/L at

16613D but becomes progressively anaerobic (< 1.0 mg/L) as it flows northeast toward Interstate 26 and well pair 166016/16D. Groundwater flowing along the minor deep groundwater flowpath also begins in an aerobic zone at 16604D but quickly decreases to less than 1.0 mg/L throughout the remainder of its flowpath toward Interstate 26 (well pair 166018/18D). Data indicated microorganisms depleted the available DO before both groundwater flowpaths reached the discharge zone at Interstate 26.

Denitrification

Nitrate, the oxidized species in denitrification, was only detected in shallow groundwater during Rounds 1 and 2. High nitrate in Round 2 (Figure 3.43) coincides with high DO (Figure 3.49); however, this area has no dissolved VOCs with the exception of TCE at 166004 where nitrate is at the detection level (Figure 3.94). Since aerobic conditions still exist in this portion of the aquifer, nitrate has not been utilized by microbes yet and may not since no VOCs are present for electron exchange.

When comparing the distribution of the reduced nitrogen species, nitrogen gas, the picture is not much clearer. In general, wells west of 166007 and 166008 had nitrogen gas results less than 10 mg/L. An exception occurred at 166005 where high nitrate and high nitrogen gas (15.25 mg/L) were found, indicating that denitrification has occurred to some extent at that location. The remaining wells within the high nitrate region (Figure 3.43) have low nitrogen gas results except for 166008. Wells east of 166007 and 166008 had nitrogen gas concentrations greater than 10 mg/L and no detectable nitrate such that denitrification will not occur.

No nitrate was detected in deep groundwater in either MNA round. Nitrogen gas results were highest adjacent to Interstate 26 and within the northern portion of the site at wells 16606D, 16614D, 16605D, 16603D, and 16623D (Table 3.7). The absence of deep groundwater nitrate

indicates conditions along both the major and minor deep groundwater flowpaths have proceeded beyond denitrification.

Manganese (IV) Reduction

No manganese (II) was detected in either shallow or deep groundwater in Round 2 (Table 3.7). This indicates that either not enough manganese (IV) was available for this redox reaction to occur or that microbes skipped this reaction and proceeded to iron (III) reduction.

Iron (III) Reduction

Although iron (III) was not detected in any round two shallow groundwater samples, iron (II) was detected in the four wells adjacent to Interstate 26 and one background, upgradient well, 166002 (Table 3.7). Iron (III) reduction must have been a more prominent process in shallow groundwater closest to the interstate at some time in the past. However, the utility of iron (III) as an electron acceptor has been exhausted in shallow groundwater.

Iron (III) was only detected in two deep groundwater samples in Round 2: at 16622D, an upgradient background location and 16616D, the last well in the major deep groundwater flowpath (Table 3.7). Iron (III) concentrations in the past must have been higher, however, to produce the high iron (II) results measured at 16605D in both MNA rounds. Other than this isolated high, iron (II) concentrations range between non-detect and approximately 2 mg/L.

Along the major deep groundwater flowpath from 16613D toward 16616D, groundwater is depleted of enough iron (III) for its reduction to continue, resulting in the low iron (II) concentrations at 16613D, 16610D, and 16614D (Figure 3.96). However, the absence of iron (II) at 16616D at the end of the major flowpath indicates that iron (III) reduction has not occurred, even though iron (III) is available. Along the minor groundwater flowpath from 16604D toward

16618D, iron (III) reduction has occurred to some extent, but will no longer continue due to the depletion of iron (III).

Sulfate Reduction

Oxidized sulfur, in the form of sulfate, was detected at high concentrations in shallow and deep groundwater during both MNA rounds. The reduced form of sulfur, hydrogen sulfide, was detected only once in deep groundwater during Round 2. Since large supplies of sulfate are available for microbial utilization, it appears that aquifer redox has not yet reached sulfate reduction.

High concentrations of sulfate are encountered immediately upgradient of the major deep groundwater flowpath at 16605D (108 and 78 mg/L in Rounds 1 and 2, respectively). These concentrations may be the result of this well screening a slightly shallower portion of deep groundwater. It is worth noting that sulfate concentrations greater than 20 mg/L may result in competitive exclusion of reductive dechlorination (Technical Document, 1998) allowing for greater masses of dissolved VOCs at the upgradient end of the flowpath. However, throughout the remainder of the major flowpath, sulfate concentrations remain at or less than 20 mg/L. As a result, plenty of sulfate is available for additional reductive dechlorination via sulfate reduction should the microbes progress to that step. Along the minor deep groundwater flowpath from 16604D to 16618D, sulfate concentrations are less than 20 mg/L.

Methanogenesis

Shallow groundwater carbon dioxide concentrations were uniformly high in shallow and deep groundwater during both MNA rounds, indicating that carbon dioxide should not be the limiting species in methanogenesis should aquifer redox conditions ever progress to this step. Methane, the reduced species in methanogenesis, was detected at significant concentrations in shallow and deep groundwater, especially Round 2 deep groundwater (Figure 3.97). Methane data is difficult

to interpret. Based on an second round average methane concentration from upgradient and background well locations (16602D, 16622D, and 16623D) of 27.6 µg/L, methane at several downgradient well locations is far greater (16614D and 15516D). This production of methane suggests that methanogenesis is active within the aquifer, even though other sulfate reduction has not yet taken place. Significant ambiguity does exists with methane due to the coastal setting of Naval Annex. Organic muds and other organics in the subsurface undergoing organic decay would produce methane regardless of aquifer redox conditions, and thus mask methane solely via redox.

3.4.3.5 Oxidation-Reduction Zonation Summary

ORP Results

Redox zonation based upon ORP measurements indicates that the shallow groundwater is dominated by denitrification and that deep groundwater is dominated by denitrification in the center of the site and iron (III) reduction along the eastern and southern edges.

Hydrogen Gas Results

Hydrogen gas concentrations revealed variably shaped redox zones. Shallow groundwater was exclusively undergoing iron (III) reduction in Round 1 whereas in Round 2, only the southern and western portions of the site were undergoing iron (III) reduction and the central and eastern portion of the site (including the source area) were undergoing sulfate reduction. Deep groundwater moving with the major flowpath transitions from sulfate reduction to iron (III) reduction and back to sulfate reduction in Round 2. The entire minor groundwater flowpath lies within the sulfate reduction zone.

Metabolic By-product Results

The presence of inorganic parental compounds and their corresponding metabolic by-products indicate that the gross surficial aquifer has low DO, depleted nitrate and iron (III) parental

compounds, and significant metabolic by-products of nitrogen gas and iron (II). Both shallow and deep groundwater have substantial concentrations of sulfate and virtually no hydrogen sulfide, indicating that sulfate reduction has begun but not progressed far enough to deplete the aquifer of sulfate or concentrate hydrogen sulfide. High concentrations of carbon dioxide and methane are probably indicative of natural conditions in the aquifer and not related to the VOC plume.

Based upon the inherent limitations of measuring ORP in groundwater for such a broad range of redox couples, the ORP results are probably not sensitive enough to gauge the redox state of the aquifer for natural attenuation purposes since these results contradict those based on hydrogen gas and redox couples. It can be concluded that most of the aquifer is transitioning from iron reduction to sulfate reduction. The regions closer to the source area (OSA) are further along this transition than are other regions. It is important to note that redox zones are temporally variable since high recharge events would introduce more oxygenated water into the aquifer. The likely consequence of this would be the transitioning back to the more thermodynamically favored DO as an electron acceptor by microbial populations, re-precipitating metabolic by-products such as iron (II). The proximity of the recharge zone to the source area complicates redox zonation as it pertains to the dissolved VOC plume.

3.5 Biological Parameters and Redox-VOC Distribution

3.5.1 TOC

TOC was analyzed to determine if there was an energy source in substantial quantities for the microbial population to actively engage in reductive dechlorination. The Technical Document mentions that the optimal level of TOC in which an aquifer is conducive to reductive dechlorination is 20 mg/L and geared towards highly contaminated sites. This number may not be realistic for SWMU 166, which has relatively low levels of contamination i.e., in the 0.5 mg/L to 5.0 mg/L range. According to Wiedemeier (1996), 10.5 mg TCE requires 1.0 mg/L of TOC. Theoretically this could be enough TOC in the aquifer to dechlorinate TCE to VC but along the

major flowpath only 16614D has a detectable TOC concentration. Since the detection limit for TOC is at 1.0 mg/L, there may be smaller quantities of TOC that are contributing to reductive dechlorination but on a limited scale.

3.5.2 HPC

HPCs were used to gauge the overall microbial activity at SWMU 166. HPCs decreased along the major shallow groundwater flowpath from 166013 to 166016. Conversely, HPCs increased along the major deep groundwater flowpath from 16613D to 16616D. At 16613D, high VOC concentrations correlate with low TOC and low HPC. However, at the downgradient well 16616D, high VOC concentrations coincide with non-detectable TOC (less than 1.0 mg/L) but high HPC (34,200 CFU/mL). This contradiction at 16616D may be the consequence of rapid microbial utilization of available TOC as it is released from the aquifer matrix such that a low equilibrium TOC concentration is maintained in groundwater. Another possibility is that microbial population at 16616D is still not large enough to consume the high concentrations of VOCs in that locale.

In general, high HPCs correlate with high alkalinity, the result of increased in carbon dioxide via microbial respiration. In shallow groundwater, alkalinity was not detected above its 10 mg/L detection level in the four shallow wells with HPC data. Alkalinity was detected at three of the four deep wells in the major deep groundwater flowpath with HPC results and was highest at the end of the flowpath (16616D) where HPC was the greatest.

3.6 Preliminary Sorption and Retardation Calculations

To provide a reasonable estimate of the rate of contaminant mass transport, preliminary sorption and retardation calculations have been made using available site-specific data. These calculations were made for four chemicals of concern (COCs) at the site: TCE, cis-1,2-DCE, trans-1,2-DCE, and VC. Although cis-1,2-DCE and trans-1,2-DCE have been combined into 1,2-DCE total

previously in this report, sorption calculations are not possible for 1,2-DCE total since each isomer has its own chemical characteristics.

The distribution coefficient (K_d) was calculated for each COC using the following expression:

$$K_d = (K_{oc})(f_{oc})$$

Since no aquifer matrix data for total organic carbon is available at the site, the lowest and thus most conservative fraction of organic carbon (f_{oc}) value of 0.0002 was taken for fine to medium sand (Technical Protocol, 1998). Literature data was used for the organic carbon partitioning coefficient (K_{oc}) for each COC (Technical Protocol, 1998). COC-specific K_{oc} and K_d values are shown in Table 3.10.

Retardation (R) was calculated for each COC using the formula:

$$R = 1 + \frac{\rho_b K_d}{n}$$

Geotechnical data from the single Qcs sample was used to determine values for the bulk density (ρ_b) and total porosity (n), which were 1.96 g/cm³ and 0.409, respectively. The COC-specific R results are shown in Table 3.10.

The contaminant velocity (v_c) may be estimated by the following relationship:

$$v_c = \frac{v_x}{R}$$

where v_x is the maximum average linear groundwater velocity calculated for the major and minor deep groundwater flowpaths in Table 3.6, converted to units of m/day. Contaminant velocities for each flowpath are shown in Table 3.10.

Table 3.10
Preliminary Sorption and Retardation Calculations

COC	K_{oc} (L/kg)	K_d (L/kg)	R (unitless)	Major flowpath		Minor flowpath	
				v_x (m/day)	v_c (m/day)	v_x (m/day)	v_c (m/day)
TCE	87	0.0174	1.083384	0.0156	0.01438	0.0115	0.0106
cis-1,2-DCE	49	0.0098	1.046963	0.0156	0.01488	0.0115	0.0110
trans-1,2-DCE	36	0.0072	1.034504	0.0156	0.01506	0.0115	0.0111
VC	2.5	0.0005	1.002396	0.0156	0.01554	0.0115	0.0115

These results reflect the typical behavior of chlorinated solvents in groundwater. They are mobile as their retardation factors are slightly greater than 1, which would be the retardation of a conservative tracer that migrates solely by advection. As expected, TCE is more retarded than the less chlorinated COCs like the 1,2-DCE isomers and VC. Contaminant velocities are slightly lower for the minor flowpath compared to the major flowpath due to the lower average linear velocity of the minor flowpath.

3.7 Conceptual Model Refinement

A preliminary conceptual model was developed in Section 3.2 prior to discussion of the geochemical and VOC analytical data. Incorporation of these data is a necessary step in the continual refinement of the conceptual model.

Dissolved chlorinated solvent concentrations in groundwater increase with depth in the aquifer. This is largely due to two factors: 1) the relative geologic homogeneity in the subsurface that results in no aquitards restricting vertical contaminant migration; and 2) the low pH values in

shallow groundwater, due in part to the close proximity of the root zone carbon dioxide reservoir and a low buffering capacity, creating a hostile environment to microbial growth (pH < 6.0). The highest TCE concentrations were measured in wells 16626D (9,700 µg/L) and 16625D (8,900 µg/L) in October 1998. Well 16626D is the first downgradient well from the OSA source area. Deep groundwater and the slightly retarded dissolved VOCs migrate away the source area along a major flowpath as follows (based on September 1998 MNA data): 16613D (4,800 µg/L) to 16607D (1,400 µg/L) to 16610D (1,700 µg/L), and finally to 16616D (3,400 µg/L) immediately adjacent to the discharge zone.

Along the major deep groundwater flowpath, microbial populations increase toward the discharge zone in the northeast. These populations utilize natural carbon as an energy source while undergoing the process of reductive dechlorination. Redox analysis of deep groundwater indicates that dissolved oxygen, nitrate, and ferric iron have been utilized and depleted such that the aquifer has reached sulfate reduction, albeit the early stages. Some associated reductive dechlorination of chlorinated VOCs is seen as daughter products 1,2-DCE total and VC increase along the flowpath. However, not enough reductive dechlorination is occurring since solvent concentrations at the 166016/16D well pair at the end of the flowpath increase instead of decrease. This may be due in part to the relatively short length of the flowpath (approximately 800 feet from recharge to discharge) and the relatively high permeability within the aquifer. As a result, highly contaminated groundwater reaches the discharge zone at Interstate 26 and flows upward into the french drain system beneath the interstate. This water then moves into the storm water sewer system parallel to the eastern boundary of the Naval Annex and flows north parallel to Interstate 26.

3.8 Conclusions and Recommendations

After two rounds of MNA sampling and data interpretation at SWMU 166, several assumptions can be made concerning the feasibility of MNA occurring at this stage of the CMS process:

- A low to moderate microbial population exists. 1

- pH values are on the low end of the optimal range to sustain a suitable environment for microbial growth. 2
3

- Low TOC concentrations in the major flowpath inhibit the microbial population from attaining an adequate energy source needed to fully degrade the VOCs present. 4
5

- At 16616D, the endpoint of the major deep groundwater flowpath, VOC concentrations have increased above MCLs for several VOCs. 6
7

- Along the minor deep groundwater flowpath, VOC concentrations are nearing MCL limits. 8
At 16618D PCE (6 $\mu\text{g/L}$) was the only VOC exceeding its MCL of 5 $\mu\text{g/L}$. 9

Overall, the present geochemical conditions in the groundwater are not optimal for reductive dechlorination to effectively degrade the high concentrations of VOCs. 10
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Following the completion of the anaerobic-aerobic sequential groundwater treatability study, the following recommendations will be proposed to further evaluate MNA in conjunction with an engineering remedial option: 12
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- Evaluate the influence of the treatability study on groundwater and how it effects the MNA process. 15
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- Review analytical and geochemical data collected during implementation of treatability study. 17
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- Collect an additional round of MNA data from selected wells to re-establish a geochemical baseline after the aquifer stabilizes (approximately, two months from completion of the treatability study). 1
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- Proceed with fate and transport modeling using the newly-acquired baseline dataset. The model will focus on the portion of aquifer affected by the treatability study to determine if MNA will further reduce the remaining contaminant mass. 4
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- Modeling results will determine if MNA is a viable option in attaining regulatory limits after an active remedial phase. A long-term monitoring plan will be included in the CMS report should MNA successfully reduce contaminant mass. 7
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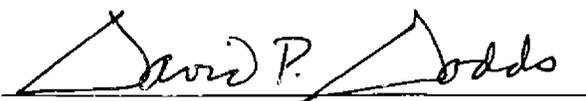
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5.0 SIGNATORY REQUIREMENT

Condition I.E. of the Hazardous and Solid Waste Amendments (HSWA) portion of RCRA Part B Permit (EPA SCO 170 022 560) states: *All applications, reports, or information submitted to the Regional Administrator shall be signed and certified in accordance with 40 CFR §270.11.* The certification reads as follows:

I certify under penalty of law that this document and all attachments were prepared under by direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.



DAVID P. DODDS
SOUTHERN DIVISION
NAVAL FACILITIES ENGINEERING COMMAND

3/23/99

Date