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# Final

# Study of Monitored Natural Attenuation at SWMU 15

## Naval Air Station, Oceana
## Virginia Beach, Virginia

Prepared for

## Department of the Navy
### Atlantic Division
### Naval Facilities Engineering Command

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Prepared by

**CH2MHILL**

**Baker**
Environmental, Inc.

**CDM**
Federal Programs Corp.

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## NAS Oceana
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Contract Task Order 0023

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Under the

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CH2MHILL

Herndon, Virginia

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# Acronyms and Abbreviations

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| BTEX | Benzene, Toluene, Ethylbenzene and Xylene |
| CERCLA | Comprehensive Environmental Response, Compensation, and Liability Act |
| CSL | Close Support Laboratory |
| DCE | Dichloroethylene |
| DPT | Direct Push Technology |
| EPA | Environmental Protection Agency |
| FID | Flame Ionizing Detector |
| IAS | Initial Assessment Study |
| LNAPL | Light Non-Aqueous Phase Liquid |
| MCL | Maximum Contaminant Level |
| Mg | Milligrams |
| MIP | Membrane Interface Probe |
| MNA | Monitored Natural Attenuation |
| NAPL | Non-Aqueous Phase Liquid |
| NAS | Naval Air Station |
| NRC | National Research Council |
| PAH | Polynuclear Aromatic Hydrocarbons |
| PID | Photo Ionizing Detector |
| PRG | Preliminary Remediation Goal |
| RCRA | Resource Conservation and Recovery Act |
| RFA | RCRA Facility Assessment |
| SVOC | Semivolatile Organic Compound |
| SWMU | Solid Waste Management Unit |
| TCL | Target Compound List |
| TPH | Total Petroleum Hydrocarbons |
| TPH | Total Petroleum Hydrocarbons |
| TPV | Total Petroleum Volatiles |
| TTCU | Time To Clean Up |
| VDEQ | Virginia Department of Environmental Quality |
| VOC | Volatile Organic Compound |
| VP | Vertical Profiling |

# Executive Summary

This report presents the results of the groundwater investigation of the Columbia Aquifer at SWMU 15, an abandoned fuel tank farm, at Naval Air Station, Oceana, Virginia Beach, Virginia. The purpose of the investigation was to determine the potential for natural attenuation of BTEX constituents, which had been released into the soil and shallow groundwater at the site. The main emphasis of this study was to evaluate the potential for naturally occurring degradation mechanisms to reduce dissolved-phase fuel-hydrocarbon concentrations in groundwater to levels that are protective of human health and the environment. Benzene and xylenes are the contaminants detected in the highest concentrations in groundwater samples, of which benzene is the primary contaminant of concern. Toluene and ethylbenzene apparently have, for the most part, biodegraded.

The horizontal and vertical distribution of BTEX contamination in groundwater and soil was characterized at SWMU 15. Groundwater quality analytical results indicate that elevated concentrations of BTEX exist in the lowermost sandy strata of the Columbia Aquifer and in the surrounding silt and clay confining units. The highest detections were located in the uppermost silt and clay layers of the lower confining unit beneath the aquifer. Some volatile hydrocarbon contamination was detected in the surficial confining unit as well. A residual NAPL, composed of BTEX and non-BTEX constituents of various degraded fuels, may be bound in the low-permeability silt and clay of the upper and lower confining units beneath the SWMU. The residual NAPL is not likely to migrate.

Two hypotheses were evaluated for SWMU 15: a hypothesis that NAPL is currently present at the site and is causing high concentrations of benzene to be maintained in the groundwater, and an alternative hypothesis that all of the NAPL was removed from the site through a soil excavation of the former tank farm area in 1996, and the high benzene concentrations are the result of no biodegradation taking place. The conclusions regarding the occurrence of natural attenuation at SWMU 15 are very different depending on which hypothesis is used.

Additional monitoring is recommended in order to verify the presence or absence of NAPL at the site and effectively characterize the natural attenuation process. Monitored natural attenuation alone might not be sufficient to remediate the petroleum release at this SWMU. Institutional controls and long-term monitoring may be appropriate if the contaminated groundwater plume is not expected to reach human or ecological receptors. Active remediation, such as installing a reactive ORC curtain in the contaminant plume downgradient of the source area or providing hydraulic containment of the plume through pumping, may be used to reduce the migration of contamination away from the site.

# 1. Introduction

This report documents the findings of an investigation of groundwater contamination at Solid Waste Management Unit #15 (SWMU 15) located at Naval Air Station (NAS) Oceana in Virginia Beach, Virginia. SWMU 15 is an abandoned tank farm that once served as the primary source of aircraft fuel for NAS Oceana from the mid-1950s to the mid-1970s. Fuel-related petroleum compounds were released into the subsurface, resulting in soil and groundwater contamination. The purpose of the investigation was to characterize the groundwater at the SWMU in order to support monitored natural attenuation (MNA) as a potential remedial alternative for site groundwater.

Petroleum hydrocarbons have relatively high mobility, solubility, and toxicity and are a common groundwater contaminant. The most important of these (benzene, toluene, ethylbenzene and xylene [BTEX] compounds), are the driving forces of regulatory concern. Extensive experience has been gained in the attempt to clean up BTEX contaminated sites, and has shown that these compounds are readily degraded by indigenous soil organisms. Monitored Natural Attenuation has recently been recognized by the EPA as a cost effective alternative for the cleanup of contaminated sites which do not pose an immediate threat to human health and the environment, and a protocol has been established in order to investigate the potential of applying this strategy. This report presents the results of a study for the potential of the remediation of petroleum hydrocarbon (BTEX) contaminated groundwater at SWMU 15 via the MNA protocol.

## 1.1 Natural Attenuation Processes

Natural attenuation processes include a variety of physical, chemical, and biological processes that, under favorable conditions, act to reduce the mass, toxicity, mobility, volume or concentration of a contaminant in soil and groundwater. These in situ processes include biodegradation, abiotic oxidation, hydrolysis, dispersion, dilution, sorption, and volatilization.

Of the above noted attenuation processes, biodegradation is typically the most significant. Biodegradation of hydrocarbons is the result of the metabolic activity of microorganisms. Metabolism is a term that embraces the diverse reactions by which a microorganism processes food materials to obtain energy and the compounds from which cell components are made. Biodegradation typically relies on heterotrophic microorganisms (that is, microorganisms that require carbon in the form of relatively complex, reduced organic compounds, such as petroleum hydrocarbons). These microbes rely on the oxidation of these reduced organics in exothermic degradation reaction sequences to yield energy and the "building blocks" of biosynthesis. Energy is produced through the oxidation of the reduced organic compound in a reaction involving the loss of hydrogen atoms that contain electrons. These electrons are then passed through an electron-transport system to a terminal electron acceptor. The electron-transport system is a series of electron carriers arranged so that the energy liberated in the oxidation of the organic is retained in a usable form by the microorganism.

Because oxygen is an efficient electron acceptor, organic contaminants such as BTEX are most readily biodegraded under aerobic conditions. To biodegrade a given quantity of organic contaminant, a corresponding quantity of oxygen is required. In soils, the presence of sufficient oxygen is often the factor that limits the rate of contaminant biodegradation. However, certain organic contaminants can be biodegraded by bacteria that use other electron acceptors under anaerobic conditions. When oxygen is not present in sufficient amounts, nitrate, sulfate, ferric iron, and carbon dioxide may be used as electron acceptors.

For thermodynamic reasons, microorganisms preferentially utilize those electron acceptors that provide the greatest amount of free energy during respiration. Once the available dissolved oxygen is depleted and anaerobic conditions dominate the interior regions of the contaminant plume, facultative or obligate anaerobic microorganisms can utilize other electron acceptors in the following order of preference: nitrate, manganese(IV), iron(III), sulfate, and finally carbon dioxide. As each electron acceptor being utilized for biodegradation becomes depleted, the next most preferable electron acceptor is utilized. Figure 1-1 is a list of terminal electron acceptors, their half-reactions, and their relative efficiency.

The biochemical reactions facilitated by these electron acceptors fall into two categories:

- Relatively fast transformations that involve the use of $O_2$ and $NO_3^-$.
- Relatively slow transformations that involve the reduction of Fe(III) and $SO_4^{2-}$, and methanogenesis using $H_2O$.

The first reactions to occur are nearly instantaneous. Once the $O_2$ and $NO_3^-$ are depleted and the environment turns more anaerobic, the slower reactions will begin. It is worth noting that even in a reducing environment, multiple reactions occur simultaneously, including the continuing reduction of $O_2$ owing to the replenishment of all electron acceptors by inflowing groundwater. Among all the electron acceptors, $O_2$ and $CO_2$ are the most readily available, due to natural recharge processes and aquifer geochemistry. Sulfate, iron, and manganese also occur naturally, but are generally dependent on site mineralogy. The predominant sources of nitrate are anthropogenic activities such as agriculture fertilization.

Estimation of the assimilative capacity of benzene in an intrinsic bioremediation system is given below for each type of electron acceptor.

### *Aerobic Oxidation*

The oxidation (mineralization) of benzene to carbon dioxide and water via aerobic respiration is given by:

$$7.5O_2 + C_6H_6 \rightarrow 6CO_2 + 3H_2O$$

Therefore, 7.5 moles of oxygen are required to metabolize 1 mole of benzene. On a mass basis, the ratio of oxygen to benzene is given by:

$$\text{Mass ratio of } O_2 \text{ to } C_6H_6 = 240:78 = 3.08:1$$

Therefore, 3.08 milligrams (mg) of oxygen are required to completely metabolize/degrade 1 mg of benzene. Similar calculations can be made for toluene, ethylbenzene, and the xylenes. Based on this, approximately 0.32 mg of BTEX is mineralized to carbon dioxide and water for every 1.0 mg of DO consumed.

### *Denitrification*

The mineralization of benzene to carbon dioxide and water via denitrification is given by:

$$6NO_3^- + 6H^+ + C_6H_6 \rightarrow 6CO_2 + 6H_2O + N_2$$

Therefore, 6 moles of nitrate are required to metabolize 1 mole of benzene. On a mass basis, the ratio of nitrate to benzene is given by:

$$\text{Mass ratio of } NO_3^- \text{ to } C_6H_6 = 372:78 = 4.77:1$$

Therefore, 4.77 mg of nitrate are required to completely metabolize/degrade 1 mg of benzene. Similar calculations can be made for toluene, ethylbenzene, and the xylenes. Based on this, approximately 0.21 mg of BTEX is mineralized for every 1.0 mg of nitrate consumed.

### *Manganese Reduction*

The mineralization of benzene to carbon dioxide and water via manganese reduction is given by:

$$15MnO_2 + 30H^+ + C_6H_6 \rightarrow 6CO_2 + 15Mn^{2+} + 18H_2O$$

Therefore, 15 moles of $MnO_2$ are required to metabolize 1 mole of benzene. On a mass basis, the ratio of $MnO_2$ to benzene is given by:

$$\text{Mass ratio of } MnO_2 \text{ to } C_6H_6 = 1{,}304:78 = 16.7:1$$

Therefore, 16.7 mg of $MnO_2$ are required to completely metabolize/degrade 1 mg of benzene. Alternatively, the mass ratio of manganese(II) produced during respiration to benzene degraded can be calculated and is given by:

$$\text{Mass ratio of } Mn^{2+} \text{ produced to } C_6H_6 \text{ degraded} = 824:78 = 10.6:1$$

Therefore, 10.6 mg of manganese(II) are produced during mineralization of 1 mg of benzene. Similar calculations can be made for toluene, ethylbenzene, and the xylenes. Based on this, approximately 1 mg of BTEX is mineralized for every 10.6 mg of manganese (II) produced.

Manganese reduction was not assessed in this study.

### *Iron Reduction*

The mineralization of benzene to carbon dioxide and water via iron reduction is given by:

$$60H^+ + 30Fe(OH)_3 + C_6H_6 \rightarrow 6CO_2 + 30Fe^{2+} + 78H_2O$$

Therefore, 30 moles of $Fe(OH)_3$ are required to metabolize 1 mole of benzene. On a mass basis, the ratio of $Fe(OH)_3$ to benzene is given by:

$$\text{Mass ratio of } Fe(OH)_3 \text{ to } C_6H_6 = 3{,}205.41:78 = 41.1:1$$

Therefore, 41.1 mg of $Fe(OH)_3$ are required to completely metabolize/degrade 1 mg of benzene. Alternatively, the mass ratio of iron(II) produced during respiration to benzene degraded can be calculated and is given by:

$$\text{Mass ratio of } Fe^{2+} \text{ produced to } C_6H_6 \text{ degraded} = 1{,}675.5:78 = 21.5:1$$

Therefore, 21.5 mg of iron(II) are produced during mineralization of 1 mg of benzene. Similar calculations can be made for toluene, ethylbenzene, and the xylenes. Based on this, approximately 1 mg of BTEX is mineralized for every 21.8 mg of iron(II) produced.

*Sulfate Reduction*

The mineralization of benzene to carbon dioxide and water via sulfate reduction is given by:

$$7.5H^+ + 3.75SO_4^{2-} + C_6H_6 \rightarrow 6CO_2 + 3.75H_2S + 3H_2O$$

Therefore, 3.75 moles of sulfate are required to metabolize 1 mole of benzene. On a mass basis, the ratio of sulfate to benzene is given by:

$$\text{Mass ratio of } SO_4^{2-} \text{ to } C_6H_6 = 360:78 = 4.6:1$$

Therefore, 4.6 mg of sulfate are required to completely metabolize/degrade 1 mg of benzene. Similar calculations can be made for toluene, ethylbenzene, and the xylenes. Based on this, approximately 0.21 mg of BTEX is mineralized for every 1.0 mg of sulfate consumed.

***Methanogenesis***

The mineralization of benzene to carbon dioxide and water via methanogenesis is given by:

$$4.5H_2O + C_6H_6 \rightarrow 2.25CO_2 + 3.75CH_4$$

The mass ratio of methane produced during respiration to benzene degraded can be calculated and is given by:

$$\text{Mass ratio of } CH_4 \text{ to } C_6H_6 = 60:78 = 0.77:1$$

Therefore, 0.77 mg of methane are produced during mineralization of 1 mg of benzene. Similar calculations can be made for toluene, ethylbenzene, and the xylenes. Based on this, approximately 1 mg of BTEX is mineralized for every 0.78 mg of methane produced. This reaction is accomplished in at least four steps. In each step hydrogen reacts with carbon. During the final step of methanogenesis, the methyl-coenzyme M methylreductase (CoM-$CH_3$) complex is formed and the carbon is reduced to methane.

## 1.2 Evaluation of Natural Attenuation

To demonstrate natural attenuation it is necessary to document at least two of the following three lines of evidence (NRC, 1994; ASTM, 1998):

1. Historical data showing plume stabilization and/or loss of contaminant over time.
2. Chemical and geochemical analytical data, including:
   - Depletion of terminal electron acceptors and donors.
   - Increasing metabolic by-product concentrations.
   - Decreasing parent compound concentrations.
   - Increasing daughter product concentrations.
3. Microbiological data that support the occurrence of degradation and gives estimates of biodegradation rates.

The first line of evidence should show that the plume is stabilized or is shrinking in size. This line of evidence does not prove that the contaminants are being destroyed. Reduction in contaminant concentration could be the result of advection, dispersion, dilution from recharge, sorption, and volatilization. However, this line of evidence is critical for determining if any exposure pathways exist for current or potential future receptors. Providing historical groundwater data at appropriate monitoring or sampling points that show a trend of decreasing contaminant mass and/or concentration over time is sufficient to support this first line of evidence.

The second line of evidence relies on chemical and physical data to show that contaminant mass is being destroyed, not just being diluted or sorbed to the aquifer matrix. This is accomplished by measuring the changes in groundwater chemistry that occur during biodegradation. Each type of terminal electron acceptor causes a unique change in the groundwater's chemistry.

- During aerobic respiration, oxygen is reduced to water, and dissolved oxygen concentrations decrease.
- In anaerobic systems where nitrate is the electron acceptor, the nitrate is reduced to $NO_2^-$, $N_2O$, NO, $NH^{4+}$, or $N_2$, and nitrate concentrations decrease.
- In anaerobic systems where iron(III) is the electron acceptor, iron(III) is reduced to iron(II), and iron(II) concentrations increase.
- In anaerobic systems where sulfate is the electron acceptor, sulfate is reduced to $H_2S$, and sulfate concentrations decrease.
- In anaerobic systems where carbon dioxide is used as an electron acceptor, carbon dioxide is reduced by methanogenic bacteria, and methane is produced.

Thus an active zone of biodegradation will have depleted dissolved oxygen, nitrate, and sulfate and/or elevated iron(II) and methane concentrations. This evidence can be used to show that electron acceptor/donor concentrations in groundwater are sufficient to facilitate degradation of dissolved contaminants.

The third line of evidence is directed toward proving that the soil has the microbial capacity to degrade the contaminant. This is most commonly done by performing microcosm studies. This is the least utilized line of evidence because while it indicates that the soil has the potential to degrade the contaminant, it does not show the actual rate at which degradation is naturally occurring.

The data collected during site characterization can be used to simulate the fate and transport of contaminants in the subsurface. The natural attenuation modeling effort has four primary objectives:

1. To evaluate whether MNA will be likely to attain site-specific remediation objectives in a time period that is reasonable compared to other alternatives;
2. To predict the future extent and concentration of a dissolved contaminant plume by simulating the combined effects of contaminant loading, advection, dispersion, sorption, and biodegradation;

3. To predict the most useful locations for groundwater monitoring;
4. 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.

Upon completion of the fate and transport modeling effort, model predictions can be used to evaluate whether MNA is a viable remedial alternative for a given site. This becomes an important tool in determining whether potential receptors will be impacted when there is little or no historical data available. Modeling is also the only method of estimating how long it will take for the plume to entirely degrade.

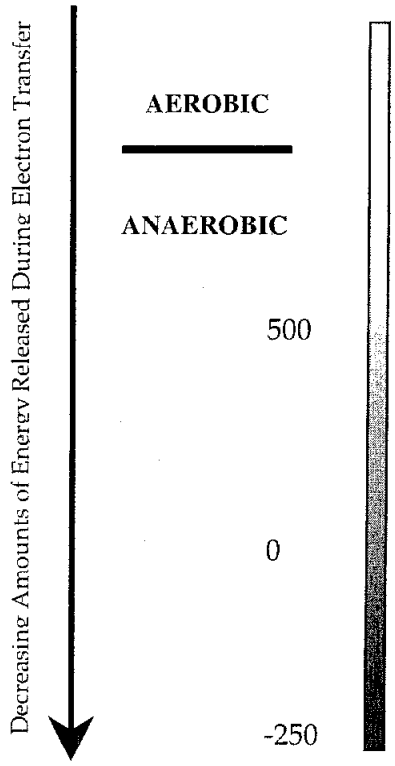
## 1.3 Objectives

The objectives of this study were to:

1. Define the nature and extent of groundwater contamination at this site.
2. Define the nature and extent of soil contamination near the source area.
3. Define the fate of contaminated groundwater.
4. Evaluate if natural attenuation is occurring and if so, determine the type, magnitude and rates of degradation.
5. Determine the viability of Monitored Natural Attenuation.
6. Assess the time required to attain groundwater cleanup to maximum contaminant levels.
7. Recommend a contaminant monitoring strategy.

## 1.4 Approach

An innovative approach was utilized at SWMU 15 to collect the data needed to support a monitored natural attenuation site characterization. This approach included setting up an on-site close support lab equipped with gas chromatograph/mass spec, ion chromatograph and sophisticated computer equipment; vertical profiling utilizing electrical conductivity measurements; membrane interface probe analysis for detection of volatiles in subsurface soil and groundwater; groundwater and soil sampling at discrete depth intervals and discrete depth hydraulic conductivity testing, in order to delineate the plume both vertically and horizontally. This comprehensive approach provided detailed information in real time, allowing decision makers to rapidly access data during the delineation process. The evaluation of natural attenuation processes was based on analyzing and modeling current site-specific data and historical data.




**Redox Potential in mV**

1000 at a pH of 7.0 and a temperature of 25 °C

$O_2 + 4H + 4e^- \rightarrow 2H_2O$ ($E_h = +820$)

$2NO_3 + 12H^+ + 10e^- \rightarrow N_2 + 6H_2O$ ($E_h = +740$)

$MnO_2 + HCO_3 + 3H^+ + 2e^- \rightarrow MnCO_3 + 2H_2O$ ($E_h = +520$)

Fe (III) + $e^-$ → Fe (II) ($E_h = -50$)

$SO_4 + 9H^+ + 8e^- \rightarrow HS^- + 4H_2O$ ($E_h = -220$)

$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$ ($E_h = -240$)

**FIGURE 1-1**
Terminal Electron Acceptors Utilized by Microorganisms
*(Adapted from Wiedemeier et al, 1999)*

# 2. Previous Investigations

SWMU 15 is an abandoned tank farm that once served as the primary source of aircraft fuel for the North Station area when it was active from the mid-1950s to the mid-1970s. The tank farm consisted of six above-ground tanks: a 414,000-gallon tank used to store JP-3 (tank G-9), two 50,000-gallon concrete tanks used for aviation gas (tanks G-5 and G-6), and three adjacent 12,000- to 18,000-gallon tanks believed to be used for automotive fuel, kerosene, or lube oil. Pipelines were used to transport fuel from the tanks to a distribution pump house. The tank locations are depicted on Figure 2-1.

The tanks were emptied of fuel and filled with water after they were abandoned. However, tank G-5 was later used to store waste oil. The tanks and their associated piping were dismantled and removed in the mid-1980s. Soil and groundwater contamination, associated with leakage and spillage from fuel storage and handling during the 20 years of tank farm activity, was discovered at the abandoned tank farm. This discovery triggered an interim action, initially regulated under RCRA and subsequently completed under CERCLA, to investigate and remediate the soil contamination.

## 2.1 1982 Initial Assessment Study

The first environmental investigation at the tank farm was conducted in 1982. Results are documented in the *Initial Assessment Study of Naval Air Station, Oceana, Virginia Beach, Virginia,* NEESA 13-067 December 1984. That report documented that R.E. Wright and Associates installed four monitoring wells and three test pits (BP-8 BP-09, and BP-10). The locations of the wells and test pits are illustrated on Figure 2-2. Free-phase product was discovered in all three test pits and in three of four well borings, indicating a large potential source area for petroleum contamination. The well boring that did not have product in it was MW-02. The 1984 Initial Assessment Study (IAS) identified the tank farm as a potential hazard. The 1988 RCRA Facility Assessment (RFA) identified the tank farm as SWMU 15 and documented recommendations for additional investigation.

## 2.2 RCRA Facility Investigations (1992 to 1995)

SWMU 15 was investigated during two phases of the RCRA Facility Investigation (RFI). Phase I was completed in 1993 and Phase II was completed in 1995. The purpose of the RFIs was to characterize the extent of soil and groundwater contamination. Results of the RFIs are documented in the *RCRA Facility Investigation Final Report – Phase I, Naval Air Station Oceana, Virginia Beach, Virginia,* December 1993 and the *RCRA Facility Investigation Report – Phase II, Naval Air Station Oceana, Virginia Beach, Virginia,* February 1985. A Corrective Measures Study (CMS) was initiated in 1995. Results are documented in the *Final Corrective Measures Study for SWMUs 2E, 15, and 24, Oceana Naval Air Station, Virginia Beach, Virginia,* March 1996. The purpose of the CMS was to define the extent of the groundwater contaminant plume, characterize surface soil contamination, obtain treatability data on contaminated soil and groundwater, and recommend remedial alternatives for soil and groundwater.

During the first phase of the RFI, conducted in November 1992, twelve direct push groundwater samples (GP-1 through GP-12) were collected. Aromatic volatiles were found in the groundwater in concentrations that exceeded federal maximum contaminant levels (MCLs) which indicated that some fuel releases occurred. Strong fuel odors were detected at most of the 12 sampling locations. The second phase of the RFI, conducted in 1994, involved collecting seventeen additional direct push groundwater samples (GP-13 through GP-30), installing and sampling eleven monitoring wells (MW-5 through MW-15), collecting 15 soil samples from seven locations, and assessing the extent of free-product contamination by excavating six test pits and installing six piezometers.

RFI Phase I and II direct push groundwater sample locations are depicted in Figure 2-3. Direct push groundwater samples collected from the top of the water table (7 to 9 ft bgs) indicated that concentrations of BTEX compounds were very high in the source area but undetectable in the outermost groundwater samples. The free product investigation revealed that the accumulation of free product on the water table was minimal. The wells, screened between 4 and 14 feet, indicated that the monitoring well groundwater was found to contain elevated concentrations of BTEX in wells MW-5, MW-7, MW-9, and MW-15. RFI Phase I and II monitoring well locations are depicted in Figure 2-4. The remaining well samples were below the detection limit for BTEX constituents. No measurable free product was observed in any of the monitoring wells.

RFI test pit locations are depicted in Figure 2-5. The test pits were excavated to depths of 8 to 10 ft bgs using a backhoe. No measurable free product was observed in any of the RFI test pits. However, a petroleum sheen was observed on the water surface in test pit TP-6 located approximately 120 ft directly west of tank G5. The test pit data supported the conclusion that the shallow soils are partially saturated with petroleum hydrocarbons, but little to no recoverable free product has accumulated and persisted at the water table surface.

Figure 2-6 illustrates the RFI Phase II soil sample collection locations and total BTEX concentrations at depths of 4-6 feet. The soil data indicated that petroleum contamination of unsaturated soil was widespread, with the highest of the concentrations found at locations in the center of the tank farm west of tank G-6. Total BTEX concentrations in eight of the samples were greater than 33,000 μg/Kg. The observation of a hydrocarbon sheen on the rods substantiate that these samples were collected from an area where soils were partially saturated with hydrocarbons.

## 2.3 Corrective Measures Study (1995)

During the 1995 CMS field investigation the Navy collected five direct push groundwater samples (GP-30 through GP-34) from the groundwater table to delineate the southwest edge of the groundwater plume. The DPT samples were analyzed for VOCs and TPV. Five surface soil samples were collected and analyzed for total BTEX, TPH, and PAHs to facilitate risk assessment. Three subsurface soil samples were collected and analyzed for TPH for treatability analysis. Two additional monitoring wells (MW-16 and MW-17) were installed and sampled to delineate the southwest edge of the plume. These wells were screened from 3 to 18 feet. The monitoring well samples were analyzed for total BTEX, TPH, and PAHs.

Results of the CMS DPT groundwater samples are depicted in Figure 2-7. Total BTEX constituents were detected at only one sample location: GP-30 in the southern part of the site at a concentration of 19 μg/L. The others were nondetects for total BTEX constituents. CMS surface soil sample locations are depicted in Figure 2-8. No BTEX-related constituents were detected in the surface soil samples. Groundwater sampling of MW-16 and MW-17 located at the extreme southern end of the SWMU indicated that the BTEX contaminant plume was not present at those locations.

A composite of groundwater samples from the April 1994 Phase II investigation and the March 1995 CMS investigation was used to determine the extent of benzene in groundwater to support the selection of remedial alternatives for the CMS. Figure 2-9 depicts the extent of benzene contamination in SWMU 15 groundwater detected in monitoring wells and direct push samples during the April 1994-March 1995 time frame. The shape of the plume indicates possible southwesterly-directed downgradient migration from the primary source area near tank G-6. Historical groundwater contamination data are tabulated in Appendix A.

Although the groundwater contaminants at SWMU 15 are primarily petroleum-related compounds, low concentrations of chlorinated VOCs were also detected. Vinyl chloride and/or isomers of 1,2-DCE were detected in four direct push groundwater samples (15-GP08, 15-GP27, 15-GP28, and 15-GP30).

In the CMS, the evaluation of remedial alternatives resulted in the recommendation of the following remedial actions:

**Soil:**

- Excavation of approximately 18,000 cubic yards of contaminated soil to be processed in an on-SWMU biopile with nutrient amendment and aeration
- Confirmatory sampling of biopile and excavation perimeter
- Replacement of treated soil into the excavation after remediation

**Groundwater:**

- MNA of groundwater

A preliminary remediation goal (PRG) of 26 μg/L was calculated for benzene in groundwater and a soil leaching model was completed to determine the appropriate contaminant level to use as a soil cleanup level. The PRGs were based on an adult industrial exposure risk for constituents that have been identified as chemicals of potential concern. Site soil contaminants that were found to present a risk or hazard above accepted limits, either through direct contact with the soil or leaching to groundwater, are TPH, benzene, and ethylbenzene.

## 2.4 Post CMS On-Site Remediation of SWMU 15 Soil (1996)

In May 1996 the Navy conducted soil sampling at SWMU 15 to further delineate the volume of contaminated soil to be removed and treated on site. A leaching model was developed to determine the concentration of benzene in the soil that would leach to groundwater with

levels that exceeded the PRG. Soil samples were collected to delineate the areal boundaries within which benzene in soil exceeded 91 μg/Kg, the leaching model preliminary remediation goal. Figure 2-10 depicts the soil sample locations used to delineate the 91 μg/Kg isoconcentration contour that was established as a boundary for soil excavation. The proposed excavation covered approximately 2 acres and was 7 feet deep. Some Phase I RFI and CMS data were used in the delineation of the excavation perimeter.

Beginning in August 1996, approximately 18,000 cubic yards of soil were excavated from the 2-acre plot and remediated on site in two biopiles. In October 1998, the Navy conducted confirmatory soil sampling of the biopile soil to check for compliance with Virginia Solid Waste Management Regulations. TPH exceeded the VDEQ limit for clean fill in soil at the base of the piles. The Navy also conducted a human health risk assessment of the soil that determined that all risks were below or within the USEPA's target levels for the residential user. In July 1999 the Navy deconstructed the biopiles. The soil from the base of the piles was spread out and tilled to aerate it. The soil was sampled twice in August 1999 for TPH. The second sampling event indicated that the TPH had dropped to levels that met the VDEQ requirement for clean fill. The soil was proposed for use in the tarmac restoration project adjacent to SWMU 15. However, the biopile soils needed an ecological risk assessment to insure that the habitat created by spreading the soil adjacent to runways would not be hazardous to the environment. In December 1999, the Navy collected a fourth round of samples of the biopile soil and the soil data passed an ecological screen. All of the soil was ultimately spread thinly within the tarmac restoration area. No further action is warranted for the SWMU 15 soil.

## 2.5 Post-CMS Groundwater Remediation (1999)

No investigation activities had been taken at SWMU 15 with respect to groundwater from the time when the CMS was publicized, until July 1999. A meeting was convened between the Navy and the EPA in June 1999 in which the EPA's office of research and development representative, Dr. John Wilson, reviewed the groundwater contamination at SWMU 15. The EPA and the Navy jointly scoped an approach to characterize groundwater contamination in a manner which would best support an assessment of monitored natural attenuation as a viable remedial alternative.

In July 1999 the Navy installed four monitoring wells near the ponded excavation at SWMU 15 to replace wells destroyed during the soil remediation process (wells MW-18, MW-20, and MW-21) and to place a monitoring well directly downgradient of the excavated source area (MW-19). In February 2000 the Navy began an investigation of SWMU 15 groundwater to support an assessment of MNA. The results of this assessment are documented later in this report.

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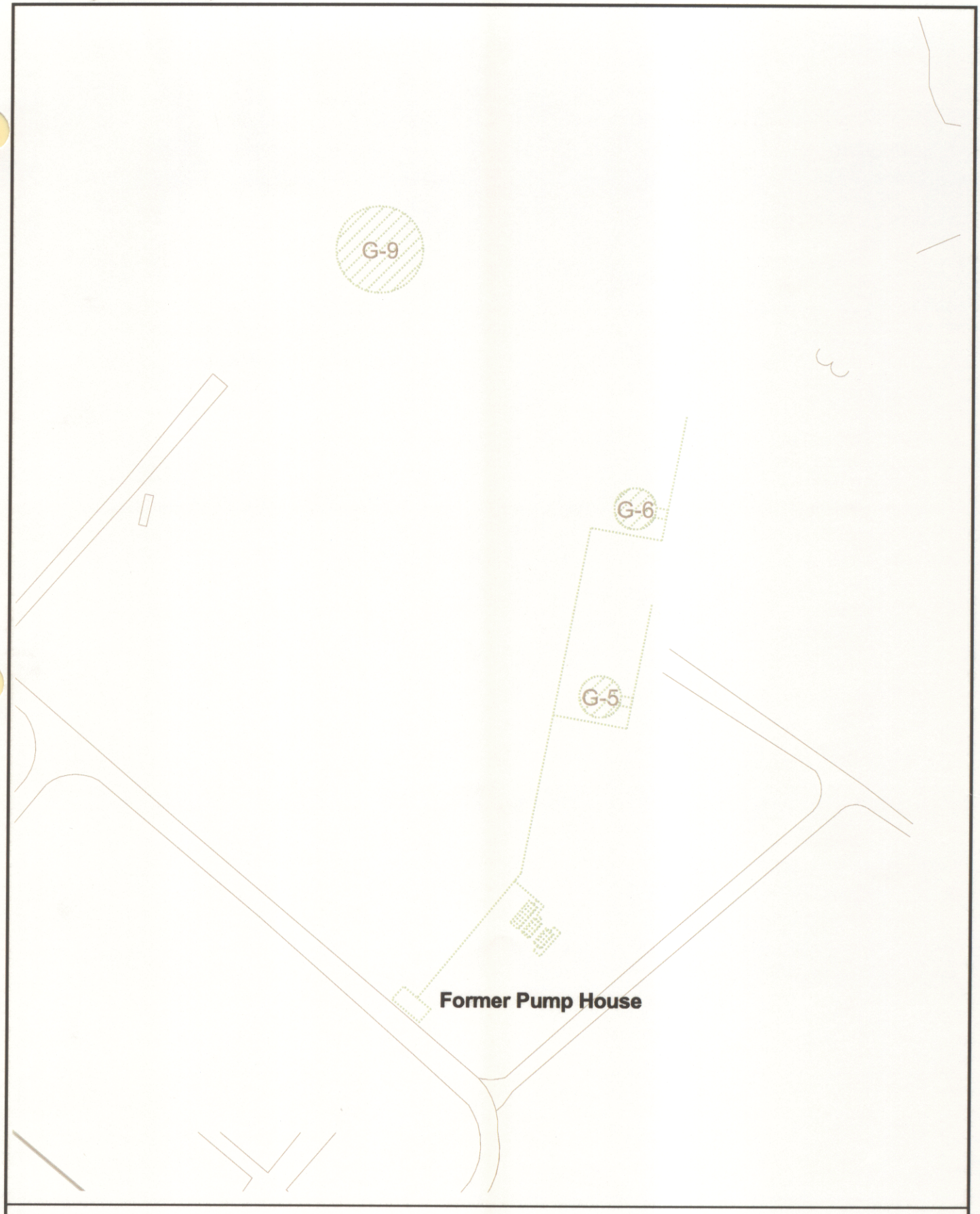


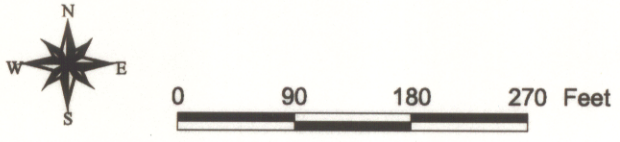


Figure 2-1
Former Tank and Pipeline Locations - SWMU 15
NAS Oceana, Virginia Beach, Virginia

**CH2M HILL**

00526 E B14

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0 70 140 210 Feet

Figure 2-2
Monitoring Well and Test Pit Locations - 1982
NAS Oceana, Virginia Beach, Virginia

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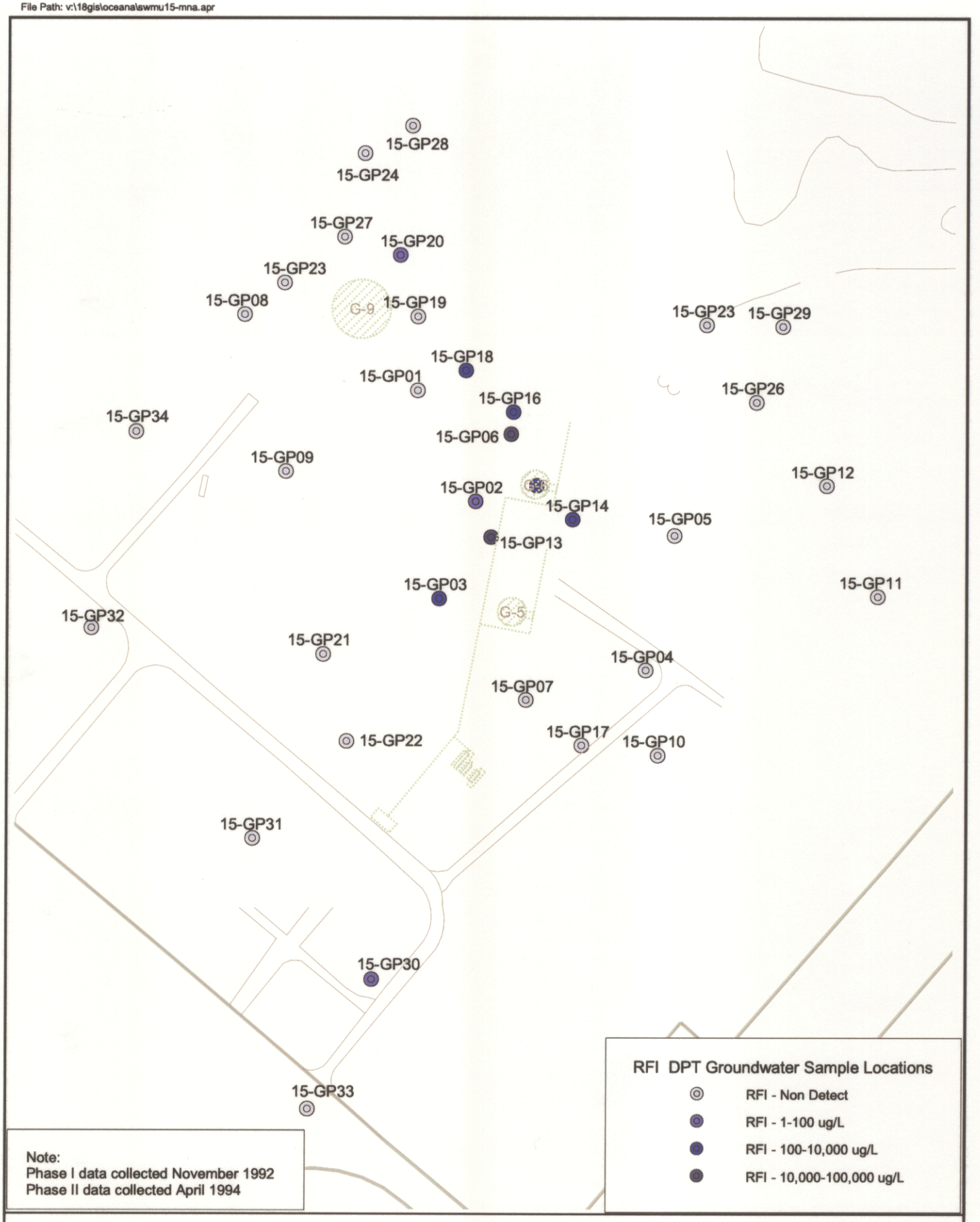


Figure 2-3
Phase I & II RFI DPT Groundwater Sample Locations
NAS Oceana, Virginia Beach, Virginia

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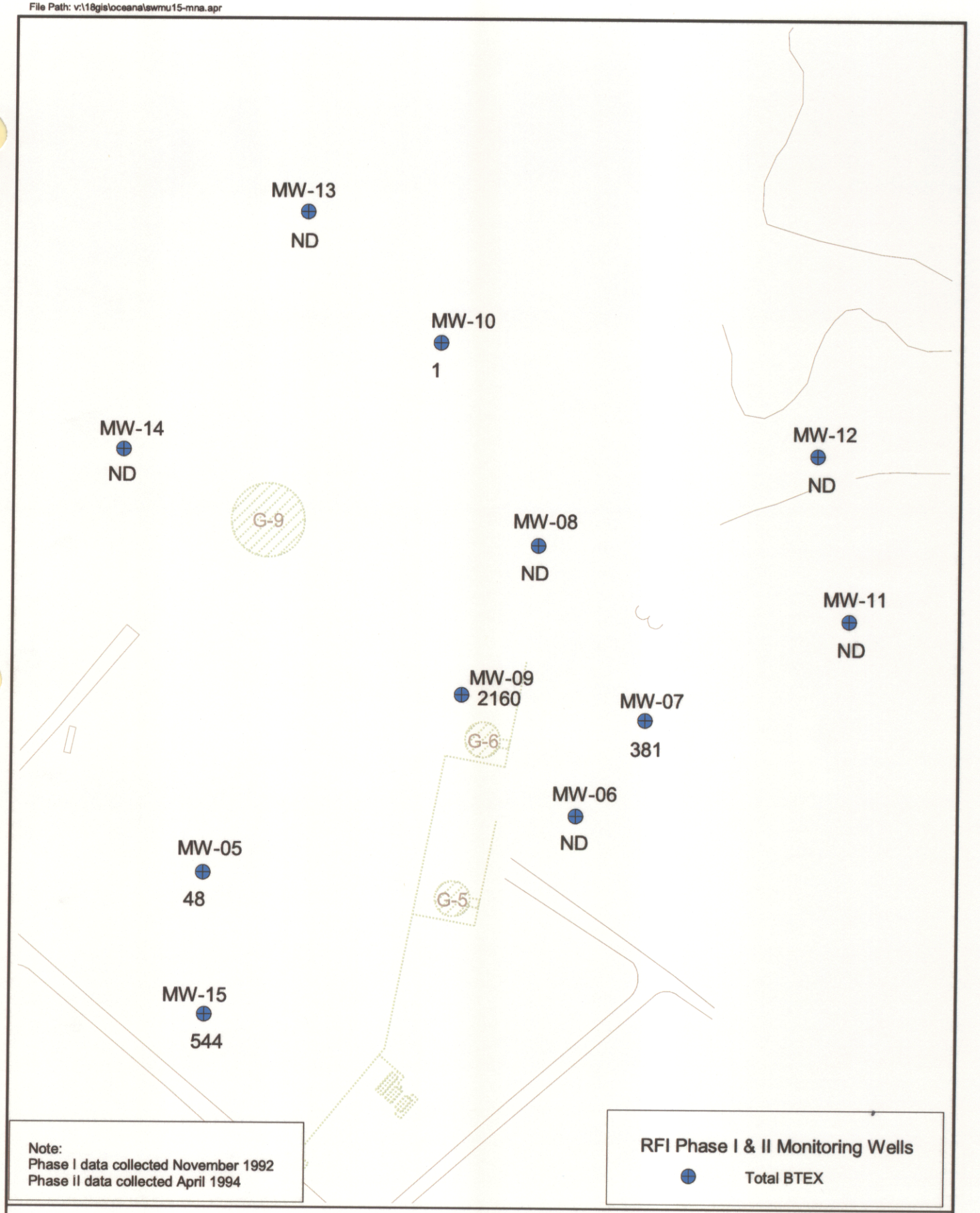


N
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0 80 160 240 Feet

Figure 2-4
Phase I & II RFI Monitoring Well Locations
NAS Oceana, Virginia Beach, Virginia

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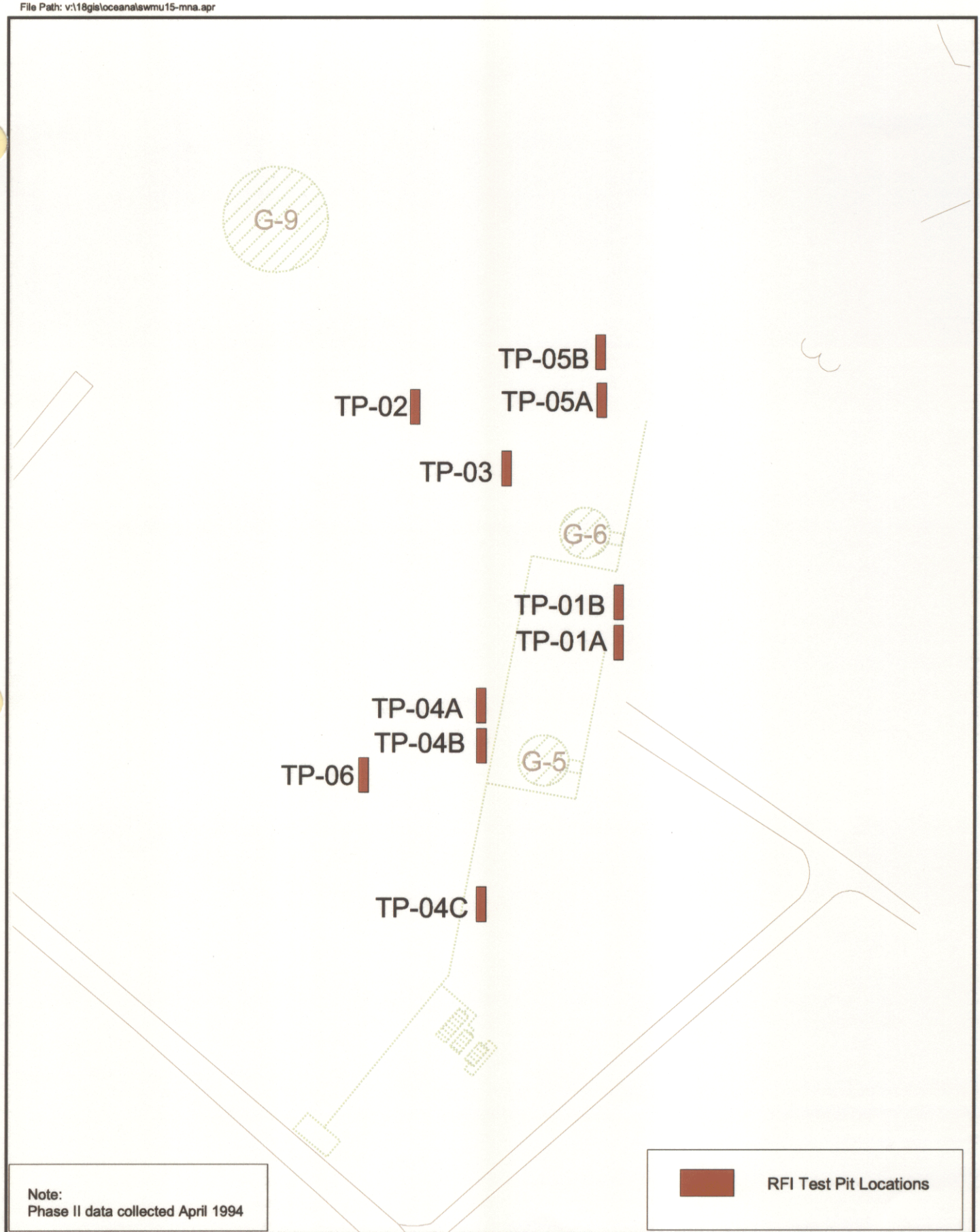

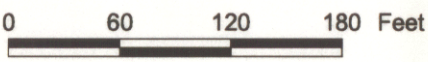


Figure 2-5
Phase II RFI Test Pit Locations
NAS Oceana, Virginia Beach, Virginia

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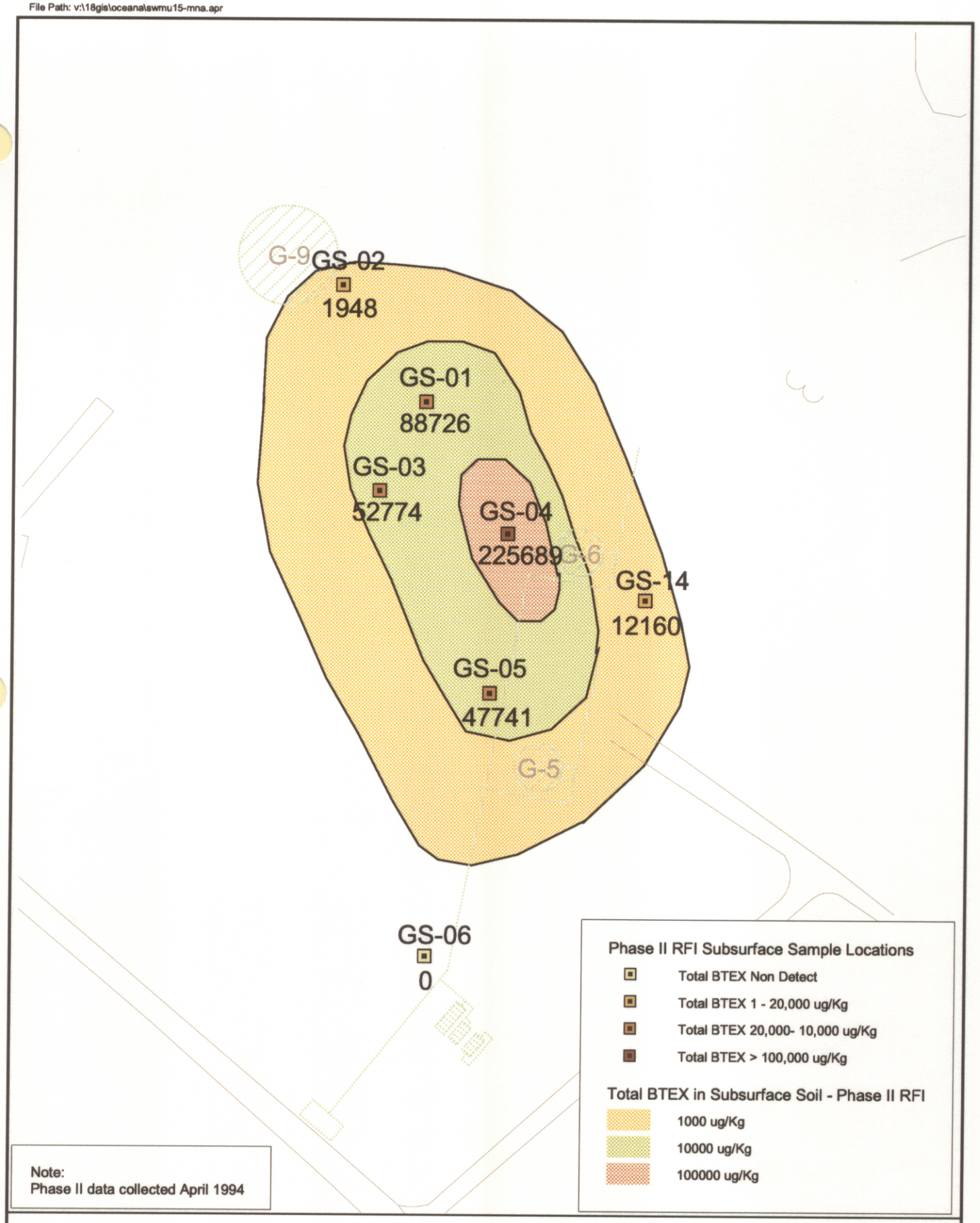


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0 60 120 180 Feet

Figure 2-6
Phase II RFI Total BTEX in Subsurface Soil
NAS Oceana, Virginia Beach, Virginia

**CH2M HILL**

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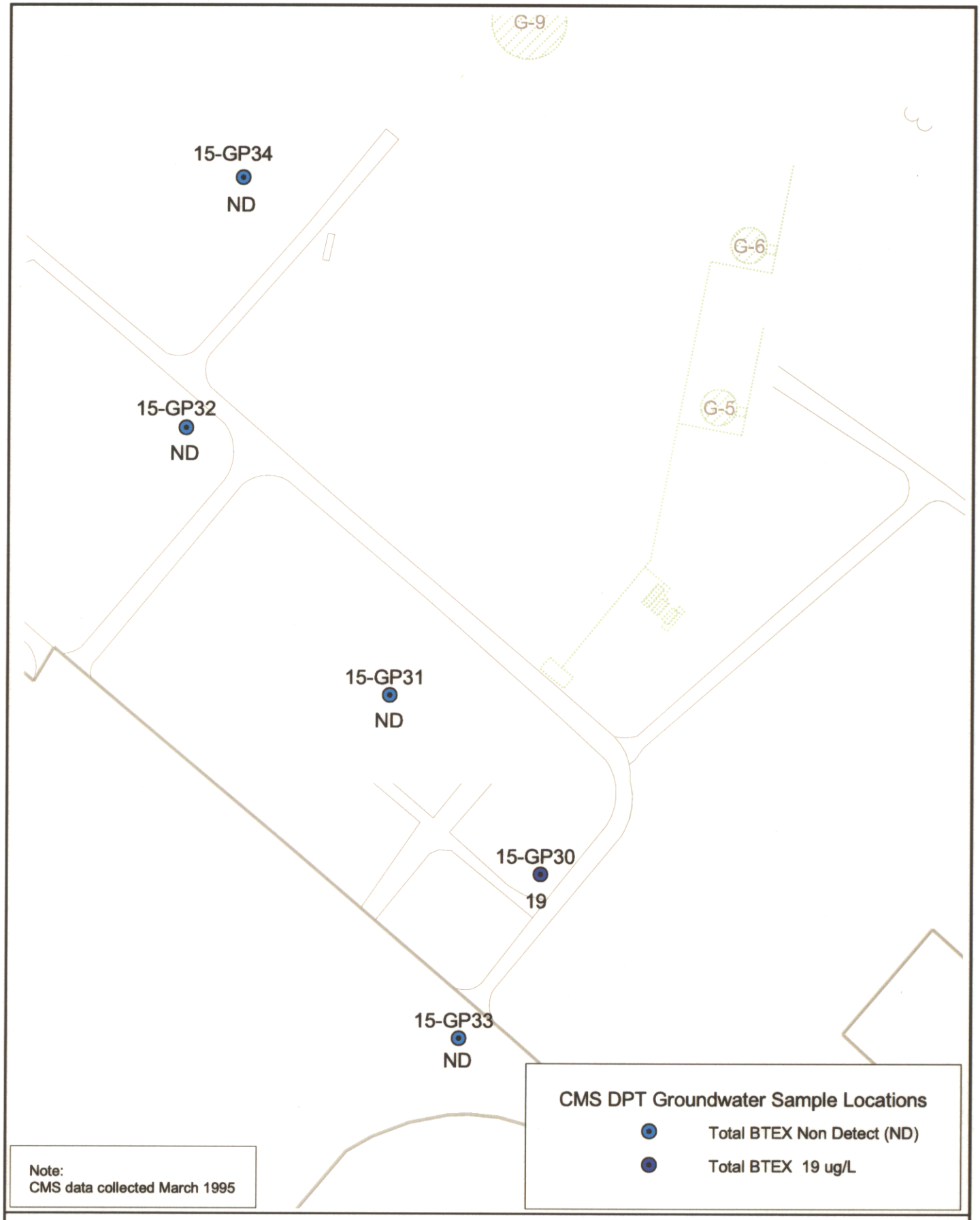


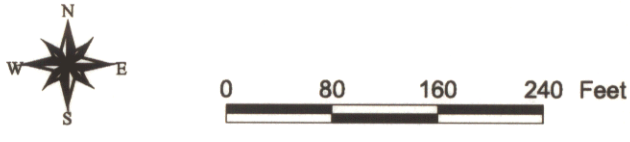


Figure 2-7
CMS DPT Groundwater Sample Locations
NAS Oceana, Virginia Beach, Virginia

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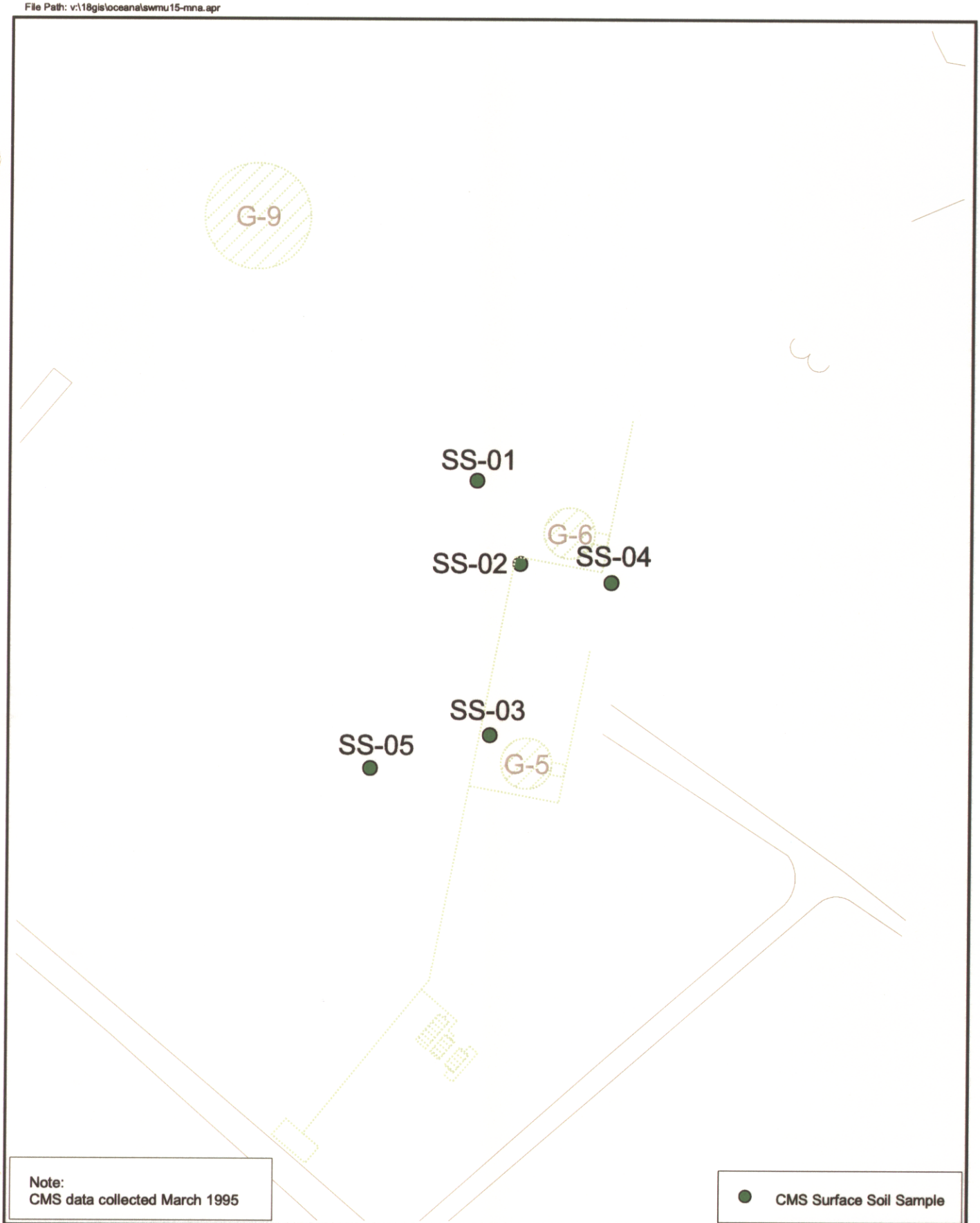


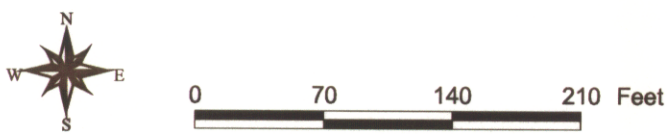


Figure 2-8
CMS Surface Soil Sample Locations
NAS Oceana, Virginia Beach, Virginia

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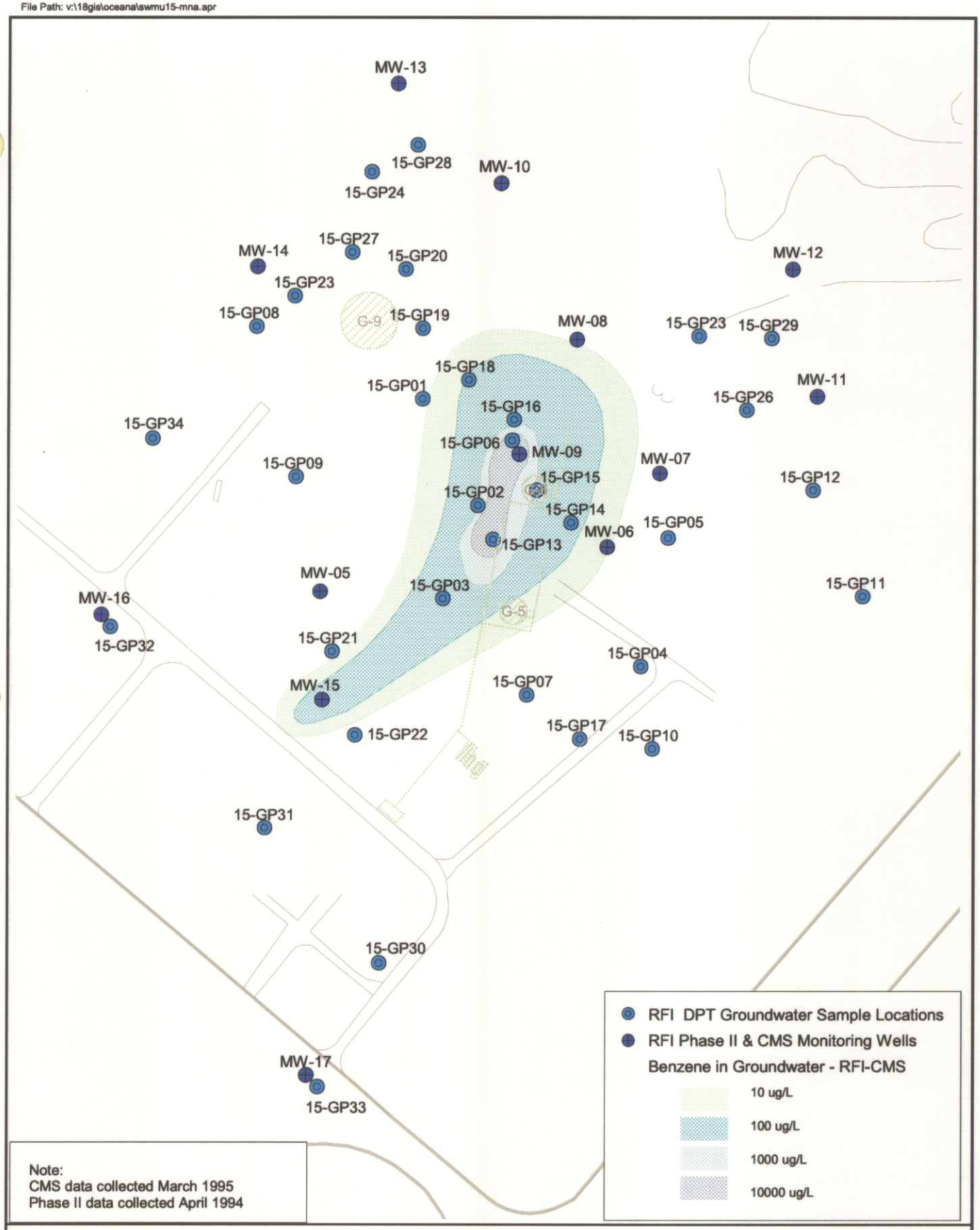


Figure 2-9
Benzene in Groundwater - RFI and CMS
NAS Oceana, Virginia Beach, Virginia

**CH2M HILL**

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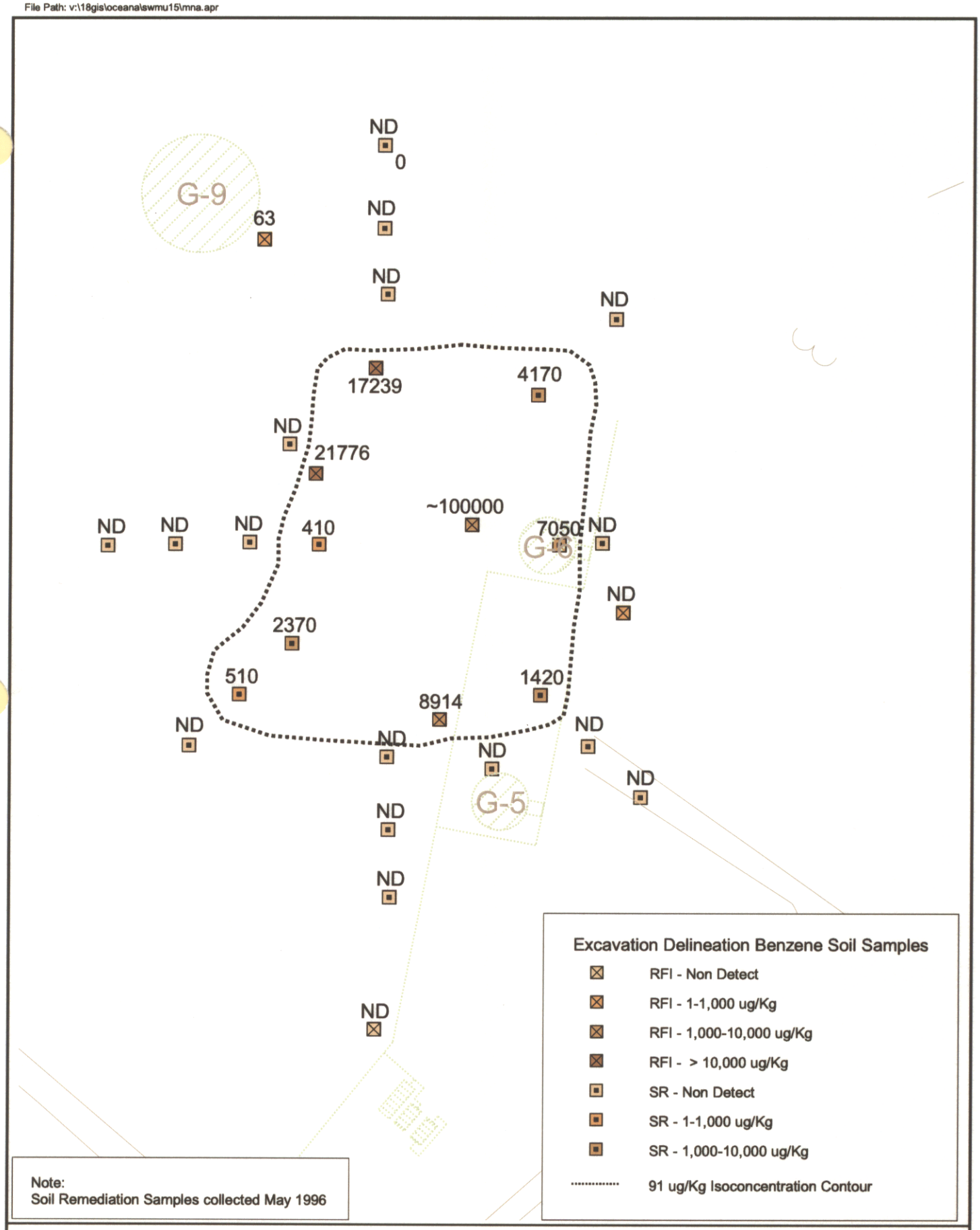


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0 60 120 180 Feet

Figure 2-10
Soil Remediation Subsurface Soil Sample Locations
NAS Oceana, Virginia Beach, Virginia

**CH2M HILL**

# 3. SWMU 15 Hydrogeology

The hydrogeology of SWMU 15 is documented below. Included are stratigraphy, lithology, and hydraulic characteristics.

## 3.1 Stratigraphy and Lithology

NAS Oceana is located in the outer Atlantic Coastal Plain Physiographic Province, which is characterized by low elevations and gently sloping relief. The Station is underlain by more than 2,000 feet of gently dipping sandy sediment, ranging in age from Recent to Lower Cretaceous. Table 3-1 tabulates stratigraphic and hydrogeologic units of southeast Virginia.

The uppermost geologic unit is the Columbia Group, composed of the Sand Bridge Formation and the underlying Norfolk Formation. The Columbia Group is approximately 60 feet thick. The upper 20 to 40 feet consist of unconsolidated fine sands and silts of low to moderate permeability. The lower 20 to 40 feet consist of relatively impermeable silt, clay, and sandy clay. The Yorktown Formation underlies the Columbia Group. The Yorktown Formation is approximately 90 to 100 feet thick in the vicinity of the Station. It consists of moderately consolidated coarse sand and gravel with abundant shell fragments.

Two significant aquifer systems in the area are the water-table aquifer in the upper 20 to 40 feet of the Columbia Group and the underlying Yorktown Aquifer. The water-table aquifer reportedly is thin and consists of discontinuous heterogeneous sand and shell lenses. The depth to the water table is usually between 3 and 7 feet below ground surface. The Yorktown Aquifer is semi-confined beneath a clay layer in the upper Yorktown Formation. Water-bearing zones in the Yorktown Aquifer consist of fine to coarse sand, gravel, and shells.

The lithology at SWMU 15 has been determined by soil logging during the installation of monitoring wells, and by electrical conductivity variations logged during the membrane interface probe (MIP) survey. A map view of SWMU 15 with DPT sampling locations, MIP logging locations, and a registration line for a stratigraphic cross section, is depicted in Figure 3-1. A generalized cross sectional lithologic profile of SWMU 15 is depicted in Figure 3-2. The SWMU 15 MNA investigation was conducted within the Columbia Group. According to monitoring well logs the uppermost 5-6 feet of the Columbia Group is composed of clay-rich silt interbedded with discontinuous lenses of fine-grained sand. At approximately 5-6 feet below ground surface the silt grades into a fine to medium-grained sand. The sandy section is generally medium-grained at the top and grades downward into a fine-grained sand, interbedded with discontinuous thin stringers of silt. The bottom of the sandy section, between depths of 18 and 23 feet, is generally medium grained. At a depth of approximately 23 feet the medium-grained sand grades abruptly into a silt and clay with interbedded fine sand. The silt and clay unit continues to depths greater than 30 feet.

The central portion of the tank farm area was covered with soil spread out for additional biological treatment. This soil temporarily added from 1 to 2.5 feet of additional thickness to the soil profile.

### 3.1.1 Hydrogeology

In general the Columbia Aquifer at SWMU 15 is composed of the fine to medium grained sand at depths from approximately 6 to 23 feet below ground surface. The aquifer is semi confined between clay rich silt in the uppermost 6 feet and at depths below approximately 23 feet. The lower confining unit is known to extend to depths of approximately 60 feet and separates the Columbia Aquifer from the underlying Yorktown Aquifer. At SWMU 15 the 7-foot deep excavation of BTEX-contaminated soil has breached the upper confining unit and creates a pond that has a direct hydraulic link to the Columbia Aquifer.

Historically, the water table at SWMU 15 is known to vary between 1 and 7 feet below ground surface depending upon precipitation. This is a factor in determining the potential "smear zone" within which floating product can be distributed and the appearance or disappearance of product detected in site monitoring wells.

Hydraulic conductivity values were collected from various depths at the four MIP survey locations surrounding the excavated source area. The four MIP locations are shown in Figure 3-1 and the hydraulic conductivity test locations and depths, the hydraulic conductivity values, the calculated groundwater velocities, and the lithology are listed in Table 3-1.

Hydraulic conductivity measurements were collected to identify and quantify zones of varying permeability in the Columbia Aquifer to determine contaminant fate and transport characteristics. The flow tests were conducted over a 2-foot discrete interval at two or more depths. A Waterloo Water Profiler was used to conduct these tests. This tool was pushed to a target depth and water was pumped from the discrete horizon while the water level was monitored. The hydraulic conductivity estimates, depths of measurement, and lithology are summarized in Table 3-2. Hydraulic conductivity values estimated from these tests ranged from $4.1 \times 10^{-3}$ to $3.9 \times 10^{-4}$ cm/second indicating the lithology at sampling depths possesses hydraulic conductivity of a silty sand to medium-grained sand. These values are consistent with the lithology as logged during soil sampling and monitoring well construction. Using an effective porosity of 25 percent and an average gradient of 0.0015 ft/foot the groundwater velocity in the Columbia Aquifer ranges from 2.2 feet per year in the silty sand to 24 feet per year in the medium grained sand with an average velocity in the aquifer of 9.9 feet per year.

The water levels collected during monitoring well sampling in February of 2000 are unreliable due to the extremely wet conditions and are not usable to determine groundwater flow direction. Abundant precipitation raised the water table to an elevation close to, and in some places, above ground surface. There was standing water in various portions of the site and the water level in some well casings was observed to be higher than the ground surface.

A second round of water levels was collected in May 2000. These are presented in a water table elevation map as Figure 3-3. The May water table shows southwesterly directed groundwater flow south of the pond and a northeasterly flow north of the pond, indicating

that the pond was still creating a mound in the water table which affects groundwater flow directions. Historic data showed groundwater flow to vary from southwesterly to north-westerly, depending upon the season. However, the prevailing groundwater flow direction at the SWMU and at the Station is south to southwesterly.

A third round of water levels was collected in February 2001. These are presented in a water table elevation map as Figure 3-4. The February 2001 water table shows south-southwesterly directed groundwater flow across the SWMU. The water table gradient flattens in the northern portion of the SWMU indicating a possible groundwater divide located north of the SWMU.

Historic data showed groundwater flow to vary in direction from southwesterly to northwesterly, depending upon the season. However, the prevailing groundwater flow direction at the SWMU and at the Station is south to southwesterly.

## 3.2 Potential Receptors

Groundwater flow directions at NAS Oceana are generally southerly directed, with local perturbations, as evidenced by historical water table elevation maps and plume migration directions across the Station. At SWMU 15 the gradient is generally south-southwest as evidenced by the migration of the fuel-related compounds in groundwater from the excavated source area. However, as documented above, the hydraulic gradient sometimes shifts to westerly and northwesterly directions for short periods of time. The southerly flow regime which dominates at SWMU 15 directs groundwater from SWMU 15 under the runways and eventually to the flight line (Figure 3-5). The approximate distance from SWMU 15 to the flight line area of the Station, the nearest area of human activity in a hydraulically downgradient direction, is 5,000 feet. Given the range of hydraulic conductivity of the Columbia Aquifer, groundwater would require between 200 and 2,000 years to travel beneath the runways to the flight line area of the base. The nearest potential receptor identified in a northerly direction from the SWMU is the residential area located approximately 1,000 feet north of the SWMU 15 soil excavation. Given the range of hydraulic conductivity of the Columbia Aquifer groundwater would require between 42 and 450 years to reach the residential area. These travel time derivations do not account for any attenuating factors such as dilution, adsorption, dispersion, and biodegradation.

Potential groundwater receptors at NAS Oceana are documented in Appendix I of the Final Corrective Measures Study for SWMUs 1, 2B, and 2C, dated November 1995. According to this document there are seven wells on the base that extract groundwater from the subsurface. The locations of these wells are illustrated on Figure 3-5. Two of the seven wells (designated WS-5 and WS-7) extract groundwater from the Columbia Aquifer. The others extract water from the underlying Yorktown Aquifer. Of the two wells in the Columbia Aquifer one supplies water to a maintenance sink. This well is located 9,000 feet from SWMU 15. The other well supplies a guard house bathroom. This well is located 16,000 from SWMU 15.

Surface water runoff from the station is facilitated by a system of drainage ditches and surface canals that direct flow south and west into West Neck Creek, north to London Bridge and Great Neck Creeks, and east to Owls Creek and Lake Rudee. In some areas of

the station the ditches are deeper than the water table so the ditches receive groundwater discharge from the Columbia Aquifer and hold standing or convey slowly flowing water during dry periods. The nearest stormwater drainage ditch to SWMU 15 in a south-southwest direction that is known to be deep enough to intercept the water table during periods of normal precipitation is located approximately 4,000 feet from SWMU 15. Given the range of hydraulic conductivity of the Columbia Aquifer, groundwater would require between 160 and 1,800 years to travel beneath the runways to the flight line area of the base. The nearest deep stormwater drainage ditch in a northerly direction is unknown.

Table 3-1
Stratigraphic and Hydrogeologic Units
of Southeast Virginia
(From Harsh and Laczniak, 1990)

| Geologic Age | | Group | Stratigraphic Formation | Hydrogeologic Unit |
|---|---|---|---|---|
| Period | Epoch | | | |
| Quaternary | Holocene | Columbia | Holocene Deposits | Columbia Aquifer |
| | Pleistocene | | Undifferentiated Deposits | |
| Tertiary | Pliocene | Chesapeake | Yorktown Formation | Yorktown Confining Unit |
| | Miocene | | Eastover Formation | Yorktown- Eastover Aquifer |
| | | | St. Mary's Formation | St. Mary's Confining Unit |
| | | | Choptank Formation | St. Mary's-Choptank Aquifer |
| | | | Calvert Formation | Calvert Confining Unit |
| | Oligocene | Pamunkey | Old Church Formation | Chickahominy-Piney Point Aquifer |
| | Eocene | | Chickahominy Formation | |
| | | | Piney Point Formation | |
| | | | Nanjemoy Formation | Nanjemoy-Marlboro Clay Confining Unit |
| | | | Marlboro Clay | |
| | Paleocene | | Aquia Formation | Aquia Aquifer |
| | | | Brightseat Formation | Brightseat-Upper Potomac Confining Unit |
| Cretaceous | Late Cretaceous | | Potomac Formation | Brightseat-Upper Potomac Aquifer |
| | | | | Middle Potomac Confining Unit |
| | Early Cretaceous | | | Middle Potomac Aquifer |
| | | | | Lower Potomac Confining Unit |
| | | | | Lower Potomac Aquifer |

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**Table 3-2**
**Hydraulic Conductivity Estimates**
**SWMU 15 - NAS Oceana**

| Sample Location | Depth (ft) | K (cm/s) | K (ft/s) | K (ft/d) | Gradient | E-Porosity | V (ft/d) | V (ft/y) | Electrical Conductivity (ms/M) | Lithology |
|---|---|---|---|---|---|---|---|---|---|---|
| OW15-MIP04-07 | 7 | 3.3E-03 | 1.0E-04 | 8.6 | 0.0015 | 0.25 | 5.2E-02 | 18.9 | 13 | Tan-gray fine to medium-grained |
| OW15-MIP01-07 | 7 | 2.2E-03 | 6.8E-05 | 5.9 | 0.0015 | 0.25 | 3.5E-02 | 13.0 | 7 | Tan-gray fine to medium-grained sand with silt |
| | | | | | | | | | | |
| OW15-MIP02-11 | 11 | 5.3E-04 | 1.6E-05 | 1.4 | 0.0015 | 0.25 | 8.3E-03 | 3.0 | 8 | Gray fine-grained, poorly sorted, loose |
| OW15-MIP03-11 | 11 | 6.7E-04 | 2.1E-05 | 1.8 | 0.0015 | 0.25 | 1.1E-02 | 3.9 | 12 | Gray medium-grained, poorly sorted, loose |
| | | | | | | | | | | |
| OW15-MIP01-14 | 14 | 2.2E-03 | 6.8E-05 | 5.9 | 0.0015 | 0.25 | 3.5E-02 | 12.9 | 14 | Gray medium-grained, poorly sorted, loose |
| | | | | | | | | | | |
| OW15-MIP02-17 | 17 | 1.1E-03 | 3.4E-05 | 3.0 | 0.0015 | 0.25 | 1.8E-02 | 6.5 | 10 | Gray fine-grained, poorly sorted, loose |
| OW15-MIP03-17 | 17 | 8.5E-04 | 2.6E-05 | 2.2 | 0.0015 | 0.25 | 1.3E-02 | 4.9 | 15 | Gray fine-grained, poorly sorted, loose |
| | | | | | | | | | | |
| OW15-MIP01-23 | 23 | 3.9E-04 | 1.2E-05 | 1.0 | 0.0015 | 0.25 | 6.1E-03 | 2.2 | 10 | Silt with sand |
| OW15-MIP03-23 | 23 | 4.2E-03 | 1.3E-04 | 11.0 | 0.0015 | 0.25 | 6.6E-02 | 24.0 | 18 | Medium-grained, poorly sorted, loose |
| | | | | | | | | | | |
| Averages | | 1.7E-03 | 5.2E-05 | 4.5 | | | 2.7E-02 | 9.9 | | |

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1

MIP-02
G-9
DW20
DW19
A'
MIP-01
DW18
G-6
MIP-04
DW16
DW26
MIP-03
DW15
G-5
DW21
DW17
DW14
DW13
DW25
DW08
DW02
DW05
DW06
DW09
DW01
DW07
DW04
DW22
DW03
DW10
DW12
DW23
DW28
DW11
A
DW27
DW24
DW29
DW30

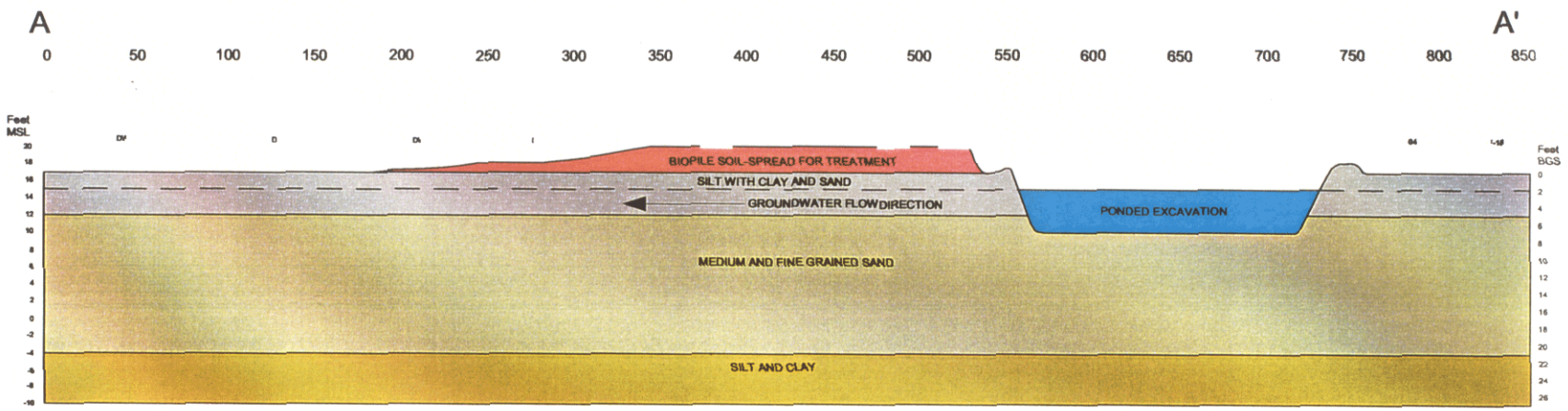
Direct Push Locations
MIP/VP Locations
Ponded Excavation

N
W
E
S
0 80 160 240 Feet

Figure 3-1
Registration Line for Stratigraphic Cross Section
NAS Oceana, Virginia Beach, Virginia

CH2M HILL

00526 E B24




LITHOLOGY

- BIOPILE SOIL-SPREAD
- SILT W/CLAY AND SAND
- POND EXCAVATION
- MEDIUM-FINE GRAINED SAND
- SILT AND CLAY

Figure 3-2
Lithologic Cross Section A-A'
NAS Oceana, Virginia Beach, Virginia

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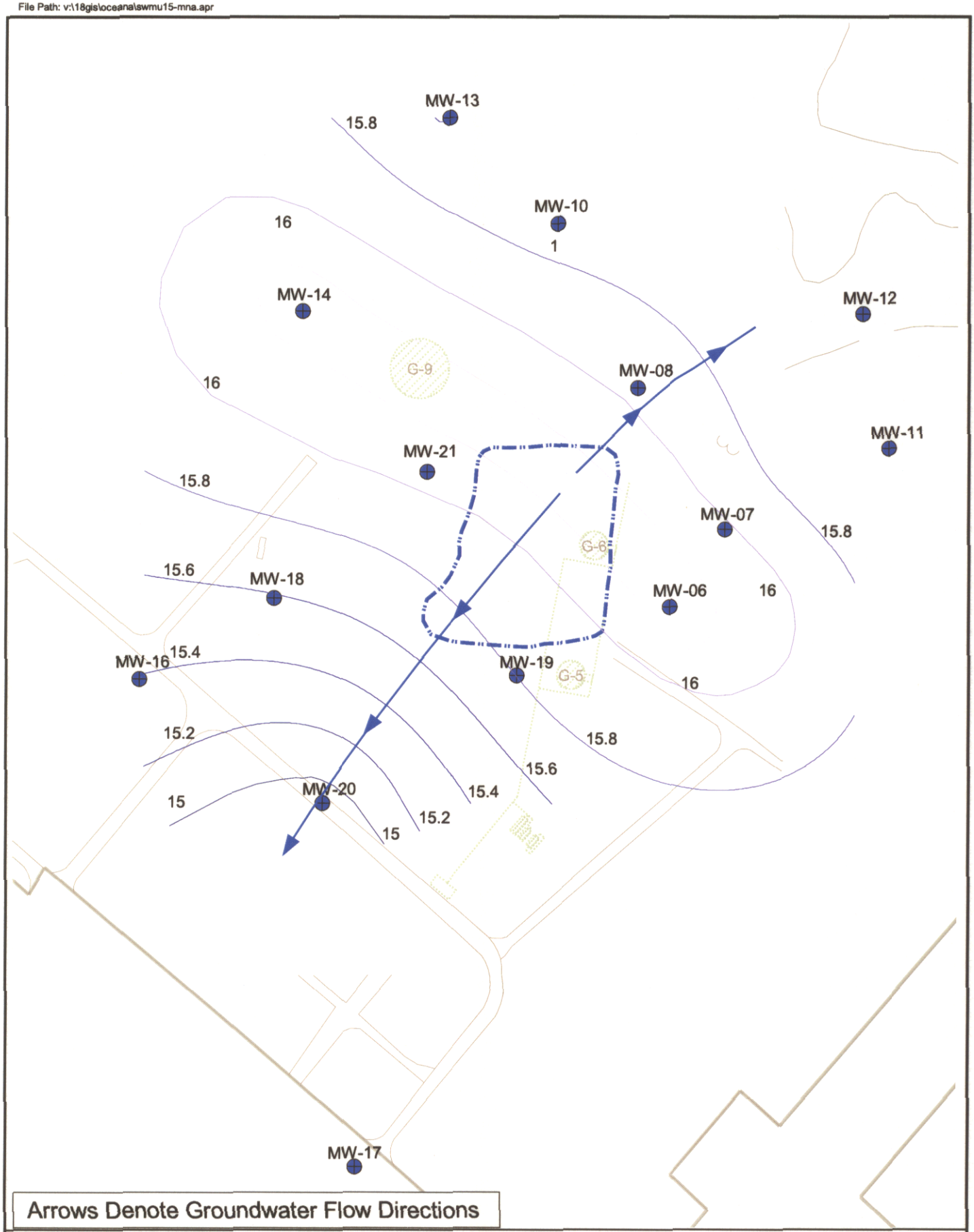


N
W E
S

0 90 180 270 Feet

Figure 3-3
Water Table Elevation Map - May 2000
NAS Oceana, Virginia Beach, Virginia

CH2M HILL

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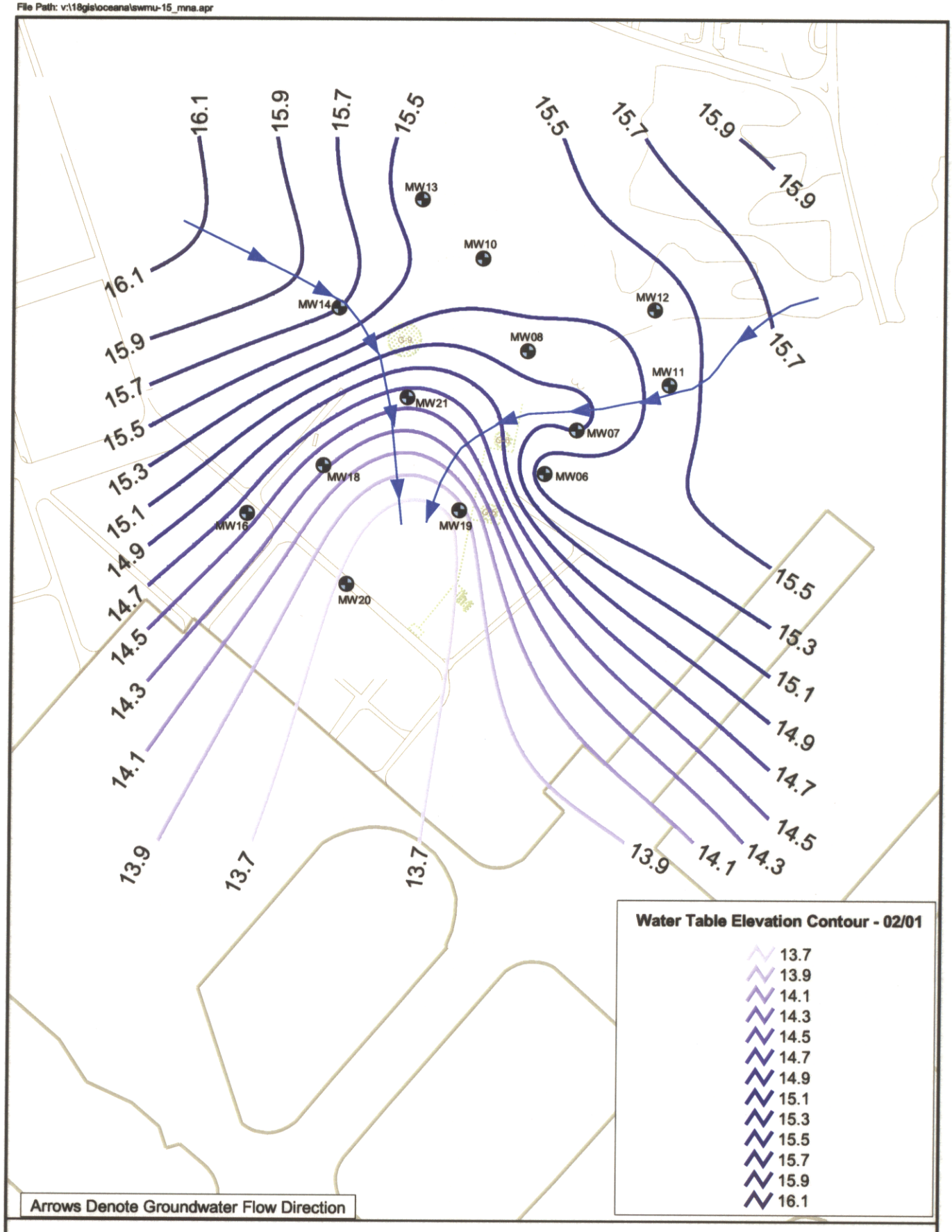


N
W E
S

200 0 200 400 Feet

Figure 3-4
Water Table Elevation Map - February 2001
NAS Oceana, Virginia Beach, Virginia

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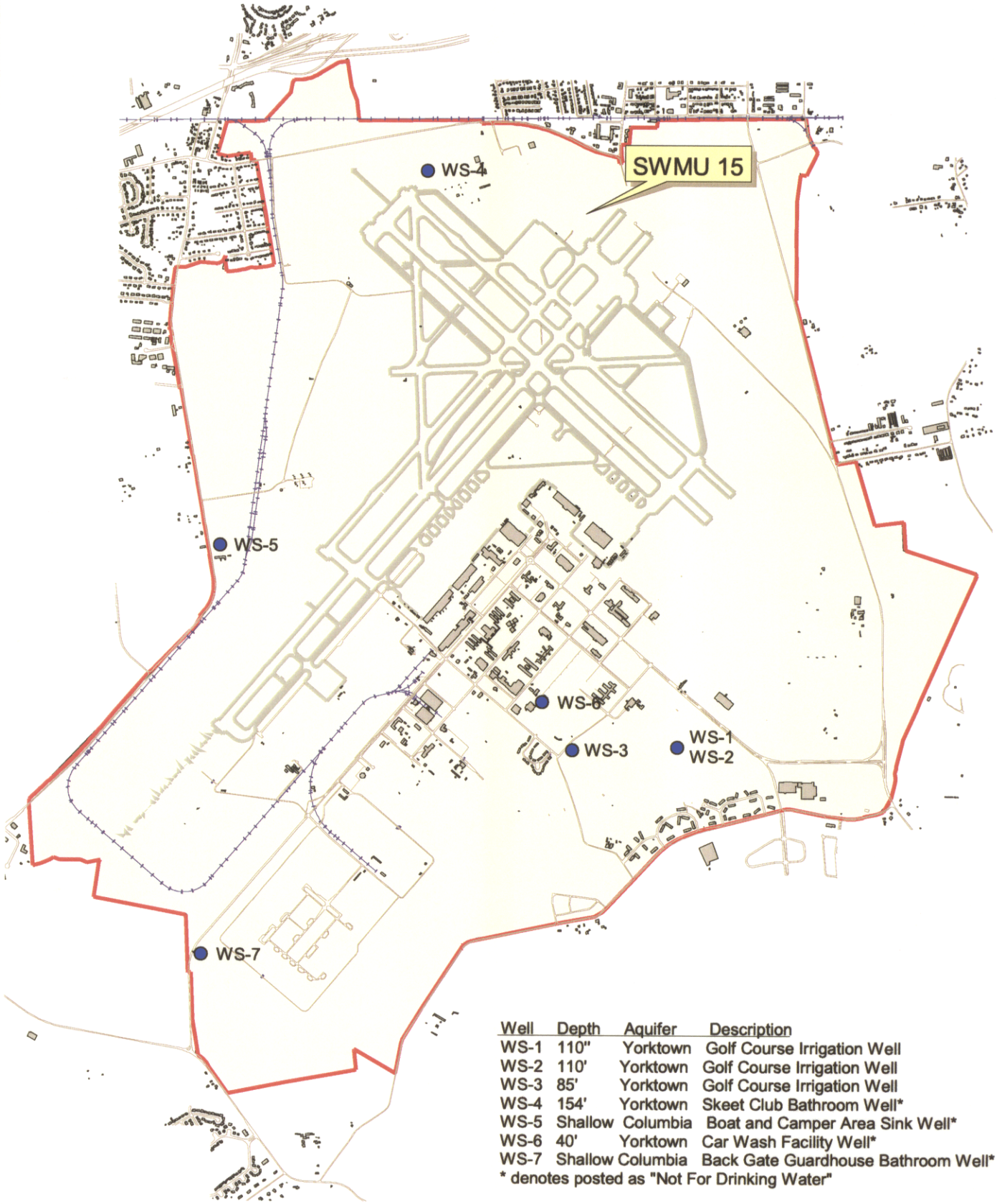
File Path: v:\18gis\oceana\swmu15-mna.apr




| Well | Depth | Aquifer | Description |
|---|---|---|---|
| WS-1 | 110" | Yorktown | Golf Course Irrigation Well |
| WS-2 | 110' | Yorktown | Golf Course Irrigation Well |
| WS-3 | 85' | Yorktown | Golf Course Irrigation Well |
| WS-4 | 154' | Yorktown | Skeet Club Bathroom Well* |
| WS-5 | Shallow | Columbia | Boat and Camper Area Sink Well* |
| WS-6 | 40' | Yorktown | Car Wash Facility Well* |
| WS-7 | Shallow | Columbia | Back Gate Guardhouse Bathroom Well* |

* denotes posted as "Not For Drinking Water"

N W E S

0 2000 4000 6000 Feet

Figure 3-5
Active Water Supply Wells (as of 1995)
NAS Oceana, Virginia Beach, Virginia

CH2M HILL

# 4. MNA Investigation Strategy

The Navy conducted groundwater and soil sampling at SWMU 15 during the months of February and March 2000. The scope of work is documented in the *Draft Work Plan Addendum- Sediment, Surface Water, and Surface Soil Sampling at Multiple SWMUs to Support Ecological Risk Assessment, Direct Push Technology Investigation to Support MNA at SWMU 15, and Monitored Natural Attenuation Study at SWMU 15* dated November 1999. The Navy's consultant, CH2M HILL was supported in the SWMU 15 investigation by Columbia Technologies of Columbia, Maryland. Columbia mobilized a close support laboratory (CSL), two truck-mounted direct-push technology (DPT) rigs, and one Membrane Interface Probe (MIP) rig to NAS Oceana.

Monitoring well sampling was conducted to determine the overall distribution of the BTEX contaminant plume. Once the highest levels of contamination were located, DPT groundwater sampling was initiated at multiple depths to determine the depth at which the maximum levels of contamination resided. Then DPT groundwater sampling was conducted on a grid array, at the depth of the highest detected contamination, to horizontally delineate the BTEX groundwater contaminant plume. At the same time, the MIP rig was used to characterize the contamination surrounding and hydraulically upgradient of the former source area, currently a ponded excavation. Discrete-depth DPT groundwater and soil sampling and hydraulic conductivity determinations were conducted at the four MIP locations to verify the results obtained during the MIP survey and vertically profile the contaminant plume.

The project was planned in a manner to conduct the MIP survey and discrete depth groundwater sampling for vertical profiling (VP) at the MIP locations prior to doing DPT plume-delineation sampling and using the MIP/VP results as a guide. Unfortunately, the MIP rig was held up at another job so the sampling team proceeded with multiple-depth DPT groundwater sampling adjacent to the monitoring well with the highest contamination, to determine the most appropriate depth for further plume-delineation sampling. Methods employed in MIP subsurface characterization, monitoring well sampling, DPT groundwater sampling, and DPT soil sampling are documented below.

## 4.1 Monitoring Well Sampling Procedures

Fourteen monitoring wells were sampled at SWMU 15 and analyzed in the CSL for TCL volatiles, including BTEX, using EPA Method 8260. The samples were also analyzed for the MNA parameters chloride, methane, ethene, ethane, ferric iron, ferrous iron, nitrate, sulfate, and sulfide. The purpose of the monitoring well sampling was to determine the site-wide distribution of groundwater contaminants in the shallow aquifer and to provide contaminant-distribution information to direct the subsequent DPT groundwater sampling for detailed plume delineation. All the site monitoring wells are screened from 3 to 18 feet below ground surface and the samples were drawn from the middle of the screen at a depth of approximately 12 feet.

The monitoring well groundwater sampling was done under low-flow conditions using a flow-through cell to monitor the groundwater parameters dissolved oxygen, Eh, pH, temperature, and conductivity. Groundwater parameters were collected from each well using the flow-through cell once those properties had stabilized after purging. Then groundwater samples were collected from the flow-through cell. The groundwater samples were analyzed by an on-site CSL. The monitoring well locations are depicted in Figure 4-1.

Monitoring well MW-17, a flush mount well located hydraulically down-gradient, near the runways south of SWMU 15, was covered with clean fill as part of the tarmac restoration project and could not be located. Monitoring well MW-21 was damaged by heavy equipment during the biopile soil remediation project and could not be sampled. Therefore, temporary DPT piezometers screened from 3 to 18 were installed and sampled at the same locations.

## 4.2 Direct Push Sampling Procedures

Direct push technology was used to collect groundwater samples in order to characterize the areal distribution of the groundwater contaminant plume and the MNA parameters. Additional direct push vertical profile sampling and hydraulic conductivity estimates were also conducted around the original source area, now the ponded excavation, at the locations where MIP profiling was conducted. DPT soil sampling was also conducted at specific depths at the MIP locations. The DPT and vertical profile sampling results are documented below and the MIP results are documented in the next subsection of this report.

### 4.2.1 Direct Push Groundwater Sampling for Areal Plume Delineation

A total of 45 DPT groundwater samples were collected from 30 sampling locations and analyzed in the CSL for TCL volatiles including BTEX using EPA Method 8260 and MNA parameters, including chloride, methane, ethene, ethane, ferric iron, ferrous iron, nitrate, sulfate, and sulfide. The purpose of the DPT sampling was to further define the horizontal and vertical extent of the BTEX contaminant plume and MNA parameters. The DPT groundwater sampling was done under low-flow conditions using a flow-through cell to monitor groundwater parameters of dissolved oxygen, Eh, pH, temperature, and conductivity. Groundwater parameters were collected from each DPT location using the flow-through cell once those properties had stabilized after purging. Then groundwater samples were collected from the flow-through cell. The DPT locations were subsequently located using a global positioning satellite surveying device. Figure 4-2 depicts the DPT sample locations.

The initial DPT sampling locations began in the vicinity of elevated benzene concentrations detected at MW-20. At the first five DPT locations (DW01-DW05) groundwater samples were collected from multiple depths of 5, 10, and 17 feet below ground surface to determine the region of the Columbia Aquifer where the highest contaminant levels resided. The sample intervals of 5 to 10 feet and 10 to 15 feet below ground surface yielded total benzene detections less than 2 μg/L. Whereas, the deepest depths of 17 to 22 feet were elevated (maximum detected concentration of 3,410 μg/L). Therefore, this depth below ground surface was selected as the top of the 5-foot sampling interval for further sampling. For the remaining 25 DPT locations, sample depth adjustments were made according to site

topography to keep the sampling interval at the same relative elevation. Therefore, most samples were collected from the 17-22 foot lithologic interval, some samples were collected from the 15-20 foot interval, and others from the 20-25 foot interval, depending upon topography.

The MIP work was conducted during the process of collecting the DPT groundwater samples. The results of the MIP work indicated that the depth of the DPT samples was sufficient to characterize the elevated total benzene concentrations detected at the base of the aquifer plume, so no depth adjustments were made as DPT sampling proceeded.

### 4.2.2 Discrete Interval Groundwater Sampling for Vertical Profiling

Discrete interval groundwater samples were collected at specific intervals at the four MIP locations, after the MIP survey was completed, to profile the vertical distribution of groundwater contaminants and MNA parameters. The sampling was conducted utilizing a probe with a 1-foot retractable screen. Between 7 and 9 samples were collected at each vertical profiling location. Some depths sampled within the tight silty clay did not yield enough groundwater to collect a sample.

The discrete interval groundwater sampling was done under low-flow conditions using a flow-through cell to monitor groundwater parameters of dissolved oxygen, Eh, pH, temperature, and conductivity. Groundwater parameters were collected from each interval using the flow-through cell once those properties had stabilized after purging. Then groundwater samples were collected from the flow-through cell. The discrete interval groundwater samples were analyzed by an on-site CSL. The analytical protocol for the groundwater samples included TCL volatiles using EPA Method 8260, TPH using Method 8015, and MNA parameters of methane, ethane ethene, nitrate, sulfate, sulfide, ferric iron, and ferrous iron. The discrete depths at which the samples were collected are tabulated in Table 4-1.

### 4.2.3 Discrete Interval Soil Sampling for Vertical Profiling

The EPA/ORD requested that the Navy collect discrete interval soil at specific intervals at the four MIP locations. The selected sampling intervals were located at the interface between the upper confining unit and the Columbia Aquifer, the interface between the aquifer and the lower confining unit, and at locations of highest contaminant concentrations. The samples were collected using a probe with a 2-foot spoon. The 2-foot cores were collected in transparent acetate sleeves which were cut into 1-foot sections, capped, and taped. The EPA agreed to perform TPH and BTEX analysis at their own contracted laboratory using a methanol extraction technique. The discrete depth intervals at which the samples were collected are tabulated in Table 4-1.

### 4.2.4 Hydraulic Conductivity Estimates

Hydraulic Conductivity measurements were collected from discrete depths at the four MIP/ Vertical Profiling locations to confirm the findings of the electrical conductivity and to identify and quantify zones of varying permeability to determine contaminant fate and transport. The results are tabulated in Table 3-2 in the previous section of the report.

## 4.3 MIP Vertical Soil Profiling

A truck equipped with a MIP was used at SWMU 15 to characterize the vertical distribution of volatile organic compounds and soil characteristics at four locations adjacent to the ponded excavation, which was the former source area for BTEX groundwater contamination. Three locations situated on the west, south, and east, sides of the excavation were selected to profile the soil and groundwater for the presence of volatile organic compounds and to log the variation in electrical conductivity with depth. A fourth location, north of the pond, was used as a background location. Access to other locations north of the pond was limited. The four MIP survey and sampling locations are depicted in Figure 4-3.

The Membrane Interface Probe facilitated the continuous detection of VOCs with depth. Photo Ionizing Detector (PID) and Flame Ionizing Detector (FID) data were collected as the rods were advanced into the subsurface. VOCs in the soils and groundwater were heated and migrated across a membrane into a closed loop that brought them to the surface for analysis by the PID and FID detectors. Results were reported as relative values of total volatiles, sensitive to minimum detection levels in the range of 100ppb of benzene. The PID and FID responses were plotted to graphically illustrate the subsurface depth intervals with elevated volatiles. The MIP locations were subsequently located using a global positioning satellite surveying device.

The electrical conductivity logging tool was employed simultaneously with the MIP to collect information on the soil types encountered at the four survey locations at SWMU 15. Electrical conductivity data were collected as the rods were advanced into the ground. The relative conductivity/resistance of the soils were plotted to graphically illustrate differences in clay content with depth. Zones of clay and silty clay (high conductivity) were readily differentiated from zones of medium to course sand (low conductivity). The graphical vertical profiles were used to determine locations that have relatively higher permeability.

**Table 4-1**
**Discrete Interval Groundwater and Soil Sampling Depth Summary**
**SWMU 15 - NAS Oceana**

| Sample | Depth of Groundwater Sample | Depth of Soil Sample |
|---|---|---|
| OW-15-MIP01 | 6 ft | 6 - 8 ft |
| | 10 ft | --- |
| | 14 ft | --- |
| | 17 ft | --- |
| | 20 ft | --- |
| | 22 ft | 22 - 24 ft |
| | 23 ft | |
| | --- | 24 - 26 ft |
| | 25 ft | --- |
| | 26 ft | --- |
| OW-15-MIP02 | --- | 6 - 8 ft |
| | 11 ft | --- |
| | 14 ft | --- |
| | 17 ft | --- |
| | 20 ft | --- |
| | 22 ft | 22 - 24 ft |
| | 23 ft | --- |
| | 29 ft | --- |
| OW-15-MIP03 | --- | 5 - 7 ft |
| | 11 ft | --- |
| | 14 ft | --- |
| | 17 ft | --- |
| | 20 ft | 20 - 22 ft |
| | 22 ft | 22 - 24 ft |
| | 23 ft | --- |
| | --- | 24 - 26 ft |
| | 25 ft | --- |
| | 26 ft | --- |
| OW-15-MIP04 | 7 ft | --- |
| | --- | 6 - 8 ft |
| | 11 ft | --- |
| | 14 ft | --- |
| | 17 ft | 17 - 19 ft |
| | --- | 19 - 21 ft |
| | 20 ft | --- |
| | --- | 21 - 23 ft |
| | 22 ft | --- |
| | 23 ft | --- |

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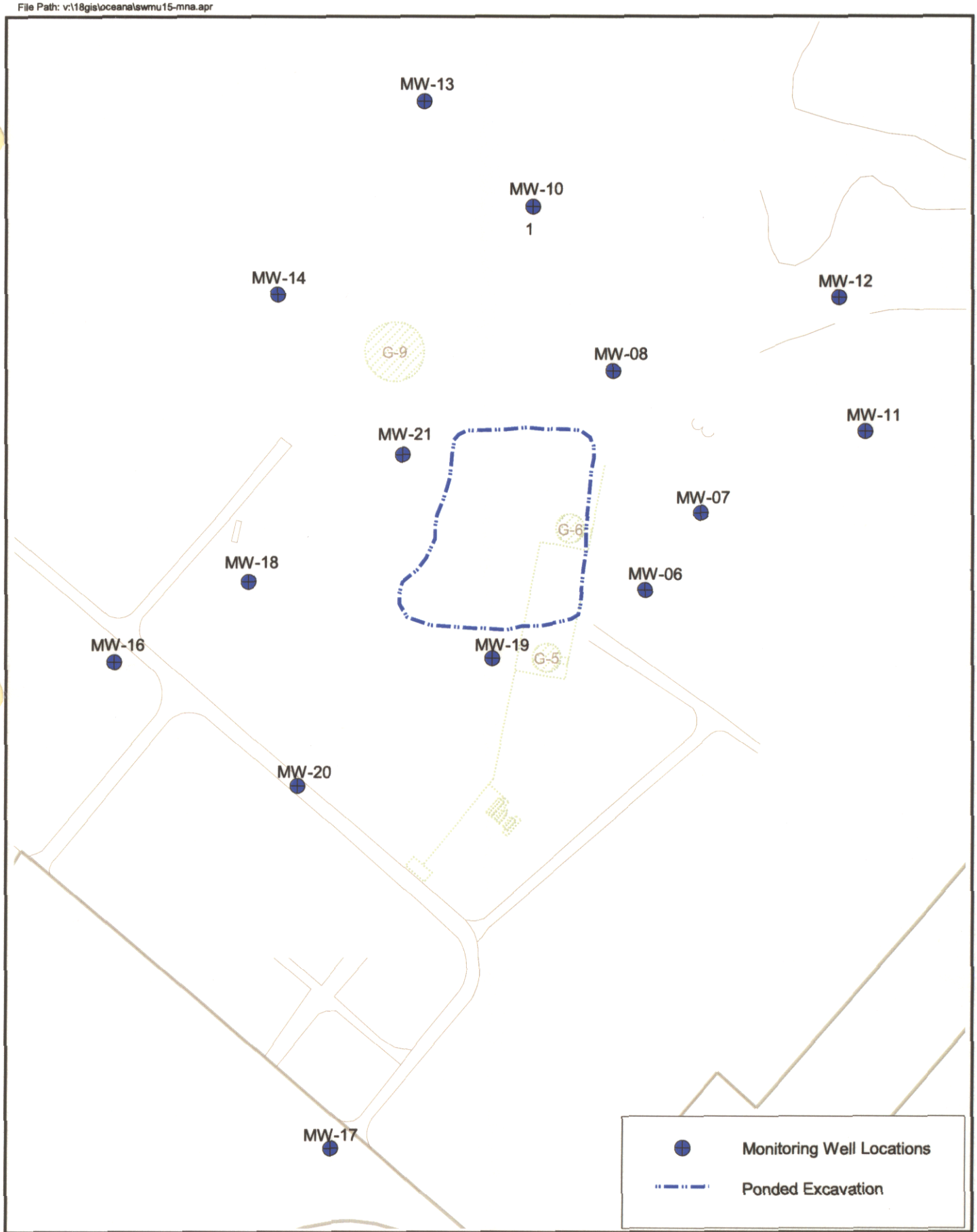

0 100 200 300 Feet

Figure 4-1
Monitoring Well Locations - SWMU 15
NAS Oceana, Virginia Beach, Virginia

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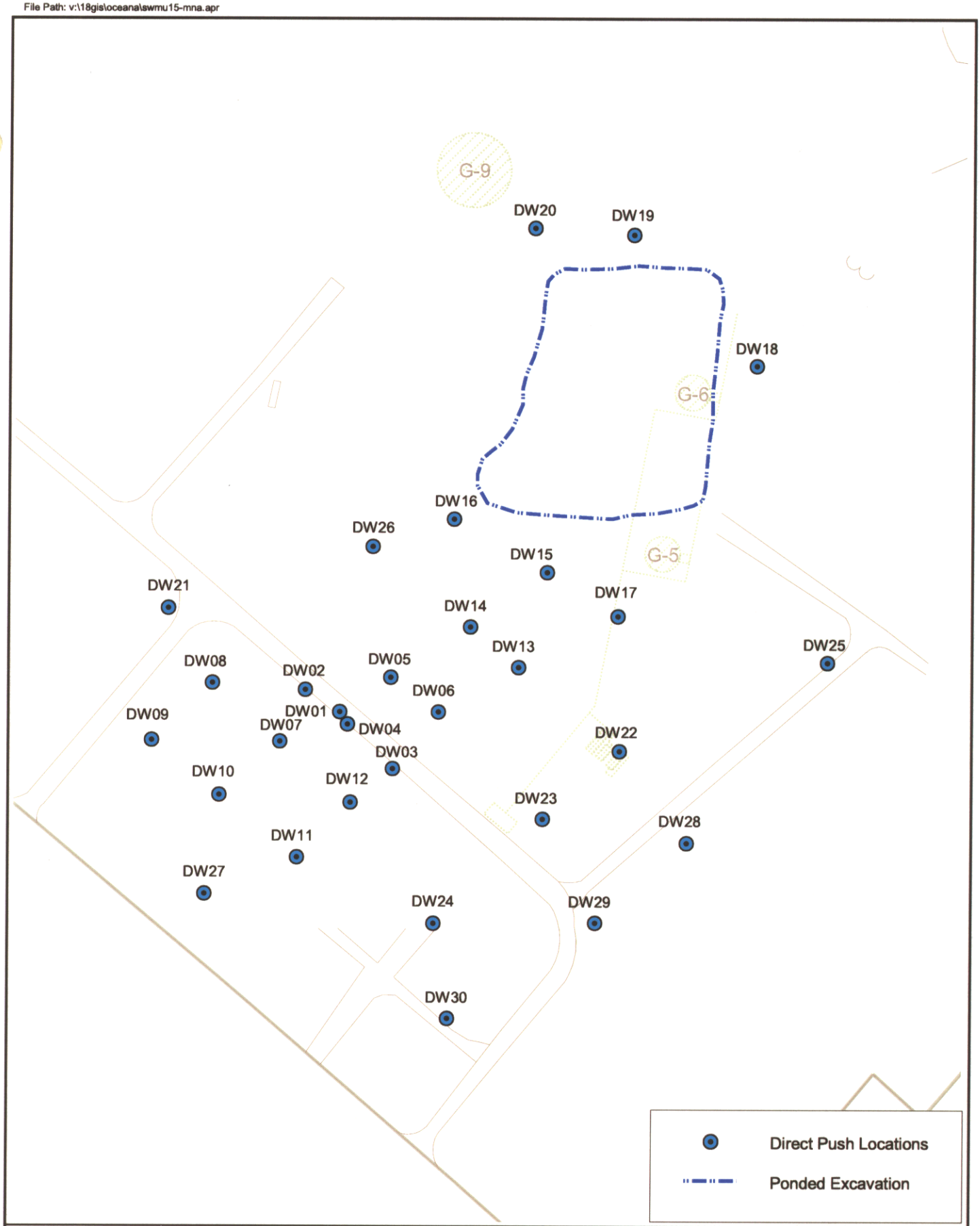


N
W
E
S

0 70 140 210 Feet

Figure 4-2
DPT Groundwater Sampling Locations - SWMU 15
NAS Oceana, Virginia Beach, Virginia

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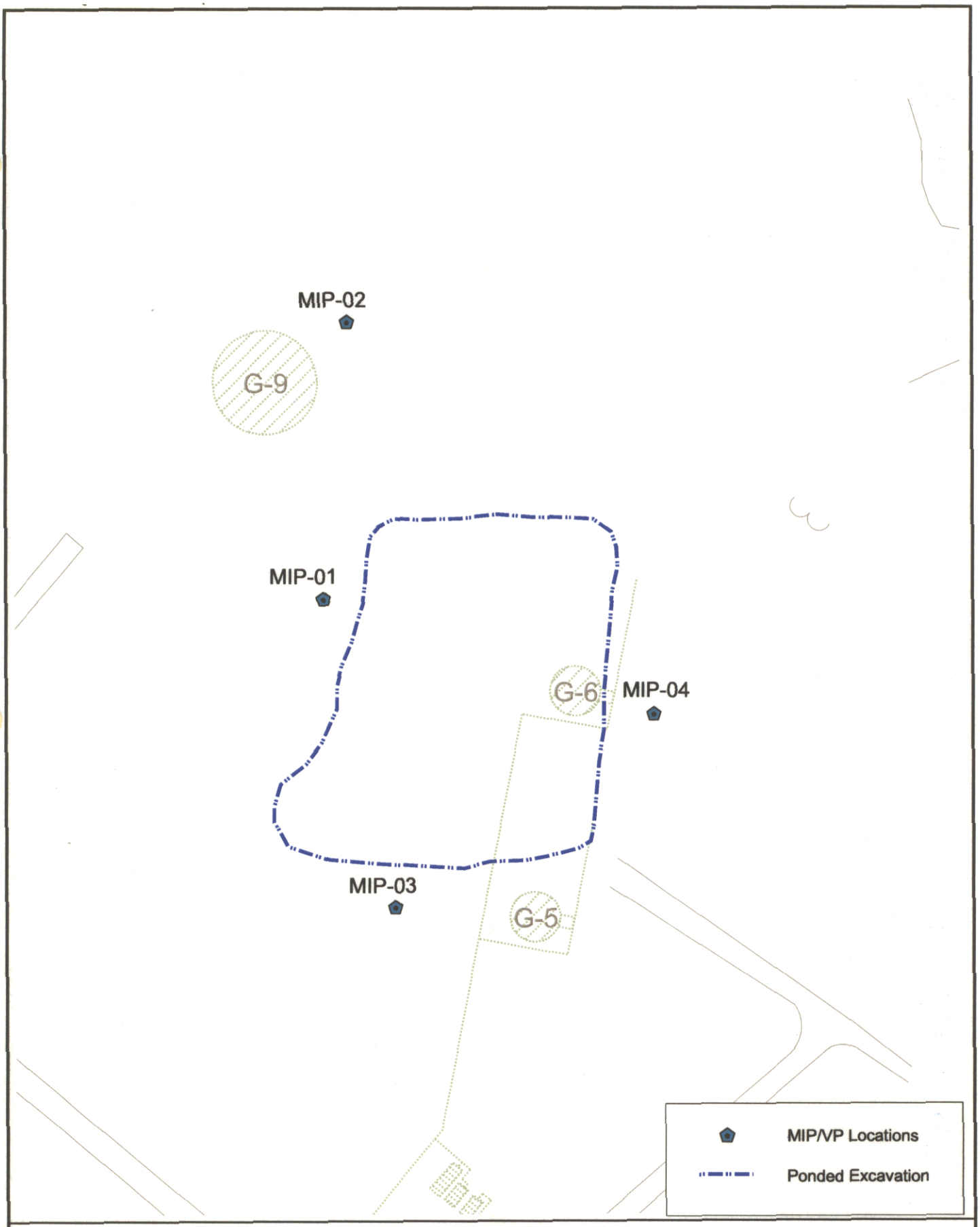


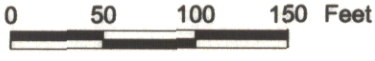



Figure 4-3
MIP Survey and VP Sampling Locations
NAS Oceana, Virginia Beach, Virginia

CH2M HILL

# 5. MNA Investigation Results

Samples collected during monitoring well, DPT, and discrete depth sampling were analyzed in the close support laboratory, located on site. The laboratory personnel reported the analytical results in an electronic deliverable format to facilitate database storage, data evaluation, GIS presentation, and reporting. The results of monitoring well sampling, DPT groundwater sampling, and subsurface MIP characterization with groundwater and soil sampling are documented below. Also documented below is a description of statistical evaluations conducted on the analytical data.

## 5.1 Monitoring Well Sampling Results

Groundwater samples from the fourteen monitoring wells were analyzed for TCL volatiles, including BTEX, using EPA Method 8260. The samples were also analyzed for MNA parameters including chloride, methane, ethene, ethane, ferric iron, ferrous iron, nitrate, sulfate, and sulfide. The monitoring well data were subjected to full data validation. The validated data are contained in Appendix B.

The distribution of total BTEX as detected in monitoring well groundwater indicates that that the highest concentration of BTEX (4,476 μg/L) was detected in MW-20, located approximately 450 feet southwest of the center of the original source area, now the ponded excavation. The remaining monitoring wells were non-detects for BTEX constituents. Well MW-20 was installed in 1999 to replace well MW-15 which was destroyed during excavation and on-site treatment of the soil in the source area. MW-20 is screened from 3 to 18 feet. The last time MW-15 was sampled, in October of 1994 , the benzene concentration was 270 μg/L. The February 1999 sampling of MW-20 yielded a benzene concentration of 3,010 μg/L. The increase in benzene concentration indicates that contaminated groundwater has migrated to the vicinity of MW-20 from the former source area at the ponded excavation, or that a secondary source area may be located east of MW-20.

The monitoring well sampling results were used to determine where to focus the subsequent DPT investigation to delineate the groundwater plume. Based on the sample results, the DPT investigation was initiated at MW-20, the well that had the only detected concentration of BTEX constituents.

A statistical summary of the monitoring well data that includes the analyte name, frequency of detection, maximum detected concentration, sample identification of maximum detected value, mean concentration value for the parameter, and the standard deviation of the mean value is tabulated in Table 5-1. Current total BTEX concentrations in monitoring well groundwater at SWMU 15 are compared to historical concentrations in Table 5-2. The highest detected value of total BTEX (4,476 μg/L) was in MW-20, sampled in February 2000 as part of this investigation. The second highest detected value of total BTEX (2,160 μg/L) was found in MW-9 sampled in April 1994. This monitoring well was located at the center of the former source area adjacent to tank G-6, now the ponded excavation, and no longer exists.

A discussion of how monitoring well groundwater sampling results support the evaluation of monitored natural attenuation at SWMU 15 is documented in the subsequent section of this report. Monitoring well construction information is contained in Table 5-3.

## 5.2 Direct Push Sampling Results

Results of the DPT groundwater sampling, vertical profile groundwater sampling, and DPT soil sampling are documented below. A discussion of how these results support the evaluation of monitored natural attenuation at SWMU 15 is documented in the subsequent section of this report.

### 5.2.1 Direct Push Groundwater Sampling for Areal Plume Delineation

Direct push groundwater data were analyzed for TCL volatiles including BTEX using EPA Method 8260 and MNA parameters, including chloride, methane, ethene, ethane, ferric iron, ferrous iron, nitrate, sulfate, and sulfide. The raw data and detected parameters are tabulated in Appendix C. A statistical summary of the DPT groundwater data that includes the analyte name, frequency of detection, maximum detected concentration, sample identification of maximum detected value, mean concentration value for the parameter, and the standard deviation of the mean value is tabulated in Table 5-4. The maximum detected values for total BTEX constituents detected in DPT groundwater at SWMU 15 are tabulated in Table 5-5.

The initial DPT sampling began at locations in the vicinity of MW-20 where elevated benzene concentrations were detected. At the first four DPT locations (DW01-DW04) groundwater samples were collected from multiple depth intervals of 5 to 10, 10 to 15, and 17 to 22 feet below ground surface to determine the region of the Columbia Aquifer where the highest contaminant levels resided. DW05 was sampled from depth intervals of 7 to 12, 12 to 17, and 18 to 23. The highest levels of BTEX contamination were found in the lowermost sampling depth interval at these five sampling locations.

At SWMU 15 the Columbia Aquifer is located within the depth intervals of 6 and 22 feet below ground surface, between two semi-confining silty clay units. Below 22 feet the sand grades into a silty clay. The depth comparison indicates that elevated concentrations of hydrocarbons reside at the base of the sandy unit of the Columbia aquifer where the medium-grained sand grades into a silt with clay. The lowermost 1 foot of the DPT screens penetrated the silty clay. However, the highest concentrations of hydrocarbon contamination outside of the known source area (i.e., the ponded excavation) reside within the uppermost interval of the silty confining unit between 22 and 25 feet below ground surface.

The results of the groundwater samples collected from 45 DPT locations were used to further define the horizontal extent of the BTEX contaminant plume and MNA parameters. The distribution of BTEX is documented below. A discussion of MNA parameters is documented in a subsequent section.

The areal distribution of total BTEX in groundwater as detected from the DPT survey is depicted in Figure 5-1. Detections from the discrete depth groundwater sampling locations (documented below) from depths that correlate with the DPT sample depths, are also contoured in this figure to provide groundwater quality data around the former ponded

excavation area. This figure shows where the highest concentration of total BTEX (11,234 µg/L) was detected in the Columbia Aquifer, at DPT groundwater sample location DW13, located approximately 325 feet south-southwest of the ponded excavation area. This sample was collected from 20 to 25 feet below ground surface. Based upon total BTEX detections at the three discrete interval sampling locations adjacent to the ponded excavation, a similar zone of elevated BTEX might be expected beneath the pond. Unfortunately, no samples could be collected from the base of the aquifer beneath the pond.

The axis of the total BTEX groundwater contaminant plume arcs from beneath the ponded excavation, southerly through DW13 and then southwesterly through DW06 and DW07. A finger of the plume also extends southerly through DW30. The nature of the plume is likely to be more sinuous and fingered than appears on the contoured map, which is smoothed by the contouring algorithm and the number of data points evaluated.

The highest concentrations of BTEX contamination centered near DW13 appear to be potentially disassociated from a similar elevated area expected to occur beneath the pond. The disassociation might be caused by a secondary contaminant source area located in the vicinity of sample locations DW13 and 22. Three small tanks and the associated piping were located near the DW13 and DW22 sample locations and the area was not sampled in any of the previous investigations (see Figure 2-9 from a previous section). Another possibility is that the high BTEX concentrations detected around sample locations DW13 and 22 are the result of southerly directed contaminant plume migration from beneath the excavated source area. In that case, perhaps the plumes do connect but the sampling locations DW15, DW17, and MW-19 missed the elevated concentrations which would connect the two areas.

Another potential source area is around DPT sampling location DW07, where total BTEX was detected at 5,740 µg/L. This area was not sampled during previous investigations and total BTEX concentrations decrease somewhat in the upgradient direction. The area around DW30 might represent another potential source area. Shallow groundwater at this approximate location was sampled in 1995 in conjunction with the CMS investigation (GP-30). Results indicate the presence of xylenes, DCE, and vinyl chloride; whereas, groundwater sampled further upgradient toward the known source area had no detects of BTEX constituents.

During direct push sampling at locations DW01 through DW07 and at locations DW13 and DW22, the samplers noted a petroleum sheen on groundwater samples and could smell petroleum hydrocarbons during sampling. This may indicate the presence of a residual non-aqueous phase liquid (NAPL) or product in the subsurface. Based upon this observation, residual NAPL could exist in areas where total BTEX concentrations exceed 2,000 to 3,000 µg/L. This area is well defined in regions south of the known source area (i.e., the ponded excavation). But around the ponded excavation there are not enough data points to adequately define the distribution of total BTEX.

The overall shape of the plume is consistent with a predominantly south-southwesterly groundwater flow direction which intermittently shifts to a westerly to northwesterly direction during periods of heavy precipitation. The relatively flat hydraulic gradient and fluctuating groundwater flow direction might have kept the plume from migrating as far as it might have under a regime of a consistent groundwater flow direction.

### 5.2.2 Discrete Interval Groundwater Sampling for Vertical Profiling

Discrete interval vertical profile (VP) groundwater samples were collected at specific intervals at the four MIP locations, after the MIP survey was completed, to profile the vertical distribution of groundwater contaminants and MNA parameters. Raw data and detected parameters are tabulated in Appendix D. A statistical summary of the VP groundwater data that includes the analyte name, frequency of detection, maximum detected concentration, sample identification of maximum detected value, mean concentration value for the parameter, and the standard deviation of the mean value is tabulated in Table 5-6. Total BTEX constituents in VP groundwater at SWMU 15 are tabulated in Table 5-7 to show the vertical distribution of BTEX concentrations. The results of the discrete depth VP groundwater sampling will be discussed later in this section.

### 5.2.3 Discrete Interval Soil Sampling for Vertical Profiling

The EPA/ORD requested that the Navy collect discrete interval VP soil samples at specific intervals at the four MIP locations where the photoionization detector/flame ionization detector (PID/FID) response was the greatest and where discrete depth groundwater sampling yielded the highest detections. The EPA performed TPH analysis as JP-4 (jet fuel) for the VP soil samples, at their contracted laboratory using a methanol extraction technique. The results of the soil sampling are tabulated in Table 5-8. Only one TPH detection of TPH as JP-4 at a concentration of 401 μg/g was found, at a shallow depth of 7 to 7.5 feet in the background location MIP-02.

The soil samples were analyzed by the EPA for TPH as JP-4 using a methanol extraction technique. Appendix E contains the laboratory results and summary sheet. This extraction technique was calibrated for JP-4 and the concentrations of JP-4 were reported in the analytical results. Unfortunately, the method used to determine TPH will not yield results which indicate the presence or absence of total BTEX. According to the laboratory used to analyze other samples associated with this investigation, TPH calibrated to total BTEX uses a different method that does not involve extraction. The primary source area is adjacent to tank G-6 which contained aviation gas. In the 1950s and 1960s much of the fuel used at the Base was used to propel aircraft that did not have jet engines. This aviation gas had a composition similar to gasoline, containing BTEX constituents, and not jet fuel which is more similar to kerosene. Therefore, these analytical results are not reliable as an indicator of the presence or absence of total BTEX as a residual NAPL in subsurface soil.

## 5.3 MIP Soil Profiling

The MIP was used to characterize the vertical distribution of volatile organic compounds and soil characteristics at the four survey locations adjacent to the ponded excavation. Figures 5-2 through 5-5 contain the graphical representations of soil conductivity, PID and FID response at the four MIP survey locations. Added to these figures are graphs of concentrations of total BTEX which were obtained through VP groundwater sampling at the same location. Total BTEX is plotted in milligrams per liter in these figures.

The conductivity signals were recorded in millisiemens per meter. Higher signal strength correlates with greater conductivity and this correlates with higher content of clay minerals in the soil. The PID and FID signals were recorded in millivolts. Higher signal strength

correlates with higher concentrations of volatile organic compounds. The FID is sensitive to methane whereas the PID is not. Therefore, a comparison of these signals is useful for detecting depth intervals where the predominant volatile detected is methane rather than petroleum hydrocarbons.

### MIP-01

Survey location MIP-01 is located on the west side of the ponded excavation. The electrical conductivity shows that the upper 7 feet are composed of interbedded sand and silty clay (Figure 5-2). Silty sand and some medium to coarse sand predominate from 7 to 23 feet and silty clay predominates below 23 feet. The PID and FID show that volatile organic compounds are present in soil or groundwater at a depth interval of 21 to 28 feet below ground surface. The highest detection of VOCs is located in silty sand at the base of the aquifer at a depth of 22 feet below ground surface. Discrete depth groundwater sampling shows that the sample collected at 22 feet has a total BTEX concentration of 5.96 mg/L, the sample collected at 23 feet has a total BTEX concentration of 4.05 mg/L, and the concentration of total BTEX at 25 feet is 0.23 mg/L. Therefore, the discrete depth groundwater sampling correlates well with the MIP results. The methane concentrations from the discrete depth groundwater samples show that some of the response detected by the FID at 22 feet can be attributed to methane.

### MIP-02

Survey location MIP-02 is located on the north side of the ponded excavation. This location served as a background location for the survey (Figure 5-3). Although some fuel farm activity did occur at this location. The electrical conductivity shows that the upper 7 feet is composed of interbedded silt and clay. Sand and silty sand predominate from 7 to 23 feet and silt predominates below 23 feet. The PID and FID show that volatile organic compounds are present at the groundwater table at a depth interval of 3 to 5 feet below ground surface. This detection is substantiated by the detection of TPH as JP-5 in a soil sample collected at this depth and location. Discrete depth groundwater samples collected from depths of 11, 14, 17, 20, 22, and 23 feet showed no detectable total BTEX concentrations. In addition, attempts were made to collect groundwater samples at 7, 8, 9, and 10 feet below ground surface. However, the lithology was too tight to provide an adequate yield of groundwater to sample.

### MIP-03

Survey location MIP-03 is located on the south side of the ponded excavation. The electrical conductivity shows that the upper 9 feet is composed of interbedded sand, silt, and clay (Figure 5-4). Sand and silty sand predominate from 9 to 26 feet and silty clay predominates below 26 feet. This location is on top of approximately 2 feet of treated biopile soil that was spread on the ground surface south of the pond. The presence of this soil means that greater depths at this location correspond to shallower depths at locations MIP-01 and MIP-02. The PID and FID show that volatile organic compounds are present in soil or groundwater at depth intervals of 3 to 8 feet in the surficial silty clay and from 20 to 31 feet below ground surface in silty sand at the base of the aquifer unit and within the basal silt and clay confining unit. Discrete depth groundwater sampling shows that total BTEX concentrations range from 0.35 mg/L to 4.73 mg/L between 20 and 26 feet below ground surface. The

highest total BTEX concentration of 4.73 mg/L occurs at a depth of 25 feet. Therefore, the discrete depth groundwater sampling correlates well with the MIP PID results. The surficial silt and clay was too tight to extract a groundwater sample. The methane concentrations from the discrete depth groundwater samples show that some of the response detected by the FID between 20 and 25 feet can be attributed to methane.

#### MIP-04

Survey location MIP-04 is located on the east side of the ponded excavation (Figure 5-5). The response indicates that the upper 7 feet are composed of interbedded sand and silty clay. Silty sand and sand predominate from 7 to 23 feet and silty clay predominates below 23 feet, similar to the other locations. The PID and FID show that volatile organic compounds are present in soil or groundwater at depth intervals 6 to 8 feet and from 16 to 27 feet below ground surface. The highest PID response occurs at about 25 feet in the uppermost silts and the highest FID response occurs at the base of the sandy unit at a depth of 22 feet, indicating the presence of both BTEX constituents and methane.

Discrete depth groundwater sampling shows that the sample collected at 17 feet has a total BTEX concentration of 2.75 mg/L, the sample collected at 22 feet has a total BTEX concentration of 5.16 mg/L, and the concentration of total BTEX at 23 feet is 3.38 mg/L. Water could not be extracted from the clay-rich silts below 23 feet. The highest value was detected at a depth of 22 feet. Therefore, the discrete depth groundwater sampling correlates well with the MIP results. The surficial silt and clay was too tight to extract a groundwater sample. The methane concentrations from the discrete depth groundwater samples show that some of the response detected by the FID between 17 and 22 feet can be attributed to methane.

In summary, it is important to note that the MIP PID and FID data did show high levels of contamination at the groundwater table in MIP-02, -03, and –04, but the tight soils did not permit collecting confirmational groundwater samples.

## 5.4 Depth and Concentration Correlation

Five hydro-lithologic cross sections were prepared to illustrate the vertical distribution of BTEX in the aquifer. Figure 5-6 is a site map delineated with the locations of the five lines of cross section. Figures 5-7 through 5-11 contain hydro-lithologic cross sections depicting the site topography, lithology, the water table elevation, sampling locations with screened intervals, and concentrations of total BTEX detected in direct push groundwater samples.

Cross sections A-A′ and B-B′ are oriented approximately parallel to the prevailing groundwater flow direction at the SWMU, whereas cross sections C-C′ through E-E′ are oriented approximately perpendicular to the prevailing groundwater flow direction. The cross sections illustrate at what depth the highest contamination was detected and whether the sampling locations were adequate to fully characterize the plume.

### 5.4.1 Cross Section A-A'

Cross section A-A′ (Figure 5-7) is oriented parallel to the prevailing hydraulic gradient. In this cross section the terminus of the dissolved phase total BTEX contaminant plume likely

occurs in proximity to and hydraulically downgradient of sample location DW10. The total BTEX concentration at this sample location is 15 µg/L. In a hydraulically upgradient direction from DW10 the total BTEX concentrations increase markedly up to 5,740 µg/L at sampling location DW07. There is the possibility of residual NAPL at this location, based upon a petroleum sheen observed on purge water. Therefore, somewhere between DW07 and DW10 is possibly the downgradient extent of the residual NAPL and the transition zone to a dissolved-phase contaminant plume only.

Locations DW01 and DW05 were sampled at multiple depths during the initial effort to calibrate the direct push sampling to the depths with the highest total BTEX contamination. As depicted on the cross section, the highest total BTEX concentrations are located at the base of the Columbia Aquifer in the basal sand or silty sand material at depths of 0 to –5 feet below mean sea level (MSL) which corresponds to 20 to 25 feet below ground surface at this location. Groundwater samples collected at intermediate depths of the Columbia Aquifer in medium grained sand resulted in non-detects for total BTEX. Groundwater samples were generally not collected at the groundwater table due to the low permeability silty soils and the shallow results of the first five DPT sampling locations, which did not indicate shallow contamination.

Locations MIP-03 and MIP-04, located on the south and east sides of the excavated source area produced contaminant profiles which indicate that the highest levels of contamination are located within the silt and clay with significant but somewhat lower concentrations located in the basal sand or silty sand material. The PID and FID readouts for these two locations indicate that the contaminant concentrations drop off rapidly beyond approximately 4 feet into the silt. However, the MIP PID/FID results indicate there are contaminant levels as high or higher at the water table than at the bottom of the aquifer around the known source area (i.e., the ponded excavation).

### 5.4.2 Cross Section B-B'

Cross section B-B' (Figure 5-8) also is oriented parallel to the prevailing hydraulic gradient. In this cross section the terminus of the dissolved phase total BTEX contaminant plume likely occurs in close proximity to and hydraulically downgradient of sample location DW27. The total BTEX concentration is 5.9 µg/L at this location. In a hydraulically upgradient direction total BTEX concentrations increase. At sample location DW11 the concentration is 107 µg/L, which is indicative of a dissolved-phase plume and the absence of NAPL. At sample location DW12 the concentration is 2,316 µg/L which could be at or near the edge of the extent of residual NAPL. Sample location DW03 is somewhat lower in concentration, perhaps due to the expected fingering nature of the contaminant plume. However, hydraulically upgradient through sample location DW06 to DW13 the concentrations of total BTEX rise dramatically from 3,336 µg/L to 11,234 µg/L. These concentrations are indicative of the presence of residual NAPL in addition to dissolved phase contaminants. There is expected to be residual NAPL at these locations, based upon a petroleum sheen observed on purge water and a strong odor of gasoline noted on the rods during sampling. Total BTEX concentrations drop off considerably to 4,976 µg/L in a hydraulically upgradient direction from DW13, indicating that the former fuel tank and pipeline area around DW13 might be another contaminant source area.

### 5.4.3 Cross Section C-C'

Cross section C-C' (Figure 5-9) is oriented perpendicular to the prevailing hydraulic gradient and just downgradient of the former source. At sample location DW26 the total BTEX concentration is 7 μg/L. Notably, this sample was collected a few feet above the bottom of the sand section. Therefore, the detected concentrations might be biased low relative to samples collected in the basal section of the aquifer. However, this concentration is considerably less than some detections at similar depth intervals in the middle of the contaminant plume and likely represents the northwestern edge of the plume. Total BTEX increases in concentration through the center of the plume at sample locations DW14, DW13, and DW22 and decreases markedly at the southeasterly edge of the plume at sample location DW28.

### 5.4.4 Cross Section D-D'

Cross section D-D' (Figure 5-10) is oriented perpendicular to the prevailing hydraulic gradient. At sample location DW21 the total BTEX concentration is 8.3 μg/L. This sample was also collected a few feet above the bottom of the sand section and, as at location DW26 in Figure 5-9, the detected concentrations might be biased low relative to samples collected in the basal section of the aquifer. However, this concentration is considerably less than some detections as similar depth intervals in the middle of the contaminant plume and likely represents the northwestern edge of the plume. Total BTEX increases in concentration into and through the center of the plume at sample locations DW08, DW07, and DW12 and decreases markedly at the southeasterly edge of the plume at sample location DW24. Again, this sample was collected a few feet above the bottom of the sand section but likely indicates a close proximity to the southeastern edge of the plume due to it's relatively low total BTEX concentration.

### 5.4.5 Cross Section E-E'

Cross section E-E' (Figure 5-11) is oriented perpendicular to the prevailing hydraulic gradient across the southern part of the contaminant plume. At sample location DW09 the total BTEX concentration is 8.2 μg/L, which indicates that this sample location is in close proximity to the northwestern edge of the plume. Total BTEX increases slightly in concentration across the downgradient edge of the plume at sample locations DW10 and DW11. Concentrations then increase markedly at DW30. This sample might be located in a finger of contamination or might represent a minor source area separate from the main body of the plume. Soil samples collected near this location during the RFI had detectable concentrations of total BTEX and total petroleum volatiles.

Analysis of these cross sections leads to the conclusion that the BTEX contamination in the sand is sufficiently characterized both vertically and horizontally throughout most of the plume with the exception of sample location DW30 where the plume boundary is not well delineated. In future sampling efforts, plume delineation downgradient of the known source area (i.e., the ponded excavation) would be improved if most groundwater samples were collected from the lowermost sand/silt interface, and some samples collected at the uppermost sand/silt interface in order to monitor the water table contamination. Additional samples should also be collected in the vicinity of DW30.

### 5.4.6 Sample Depth and Screen Length Comparison

Table 5-9 provides a comparison of total BTEX detected in groundwater collected from MW19 (which is screened from 3 to 18 feet), DW15 (screened from 20 to 25 feet) and the discrete groundwater sample collected in MIP-03 from 25 feet below ground surface. These three sample locations are located within 35 feet of each other at the hydraulically down-gradient edge of the ponded excavation (Figure 5-1 shows the locations of DW15 and MIP-03). A comparison of total BTEX detections in the aquifer indicates a dramatic difference in groundwater quality with varying depths and screen interval lengths. Concentrations of BTEX are highest at the base of the aquifer where the sand transitions into silty clay. Groundwater residing in the top to lower middle of the aquifer (MW-19) is generally uncontaminated relative to the base of the aquifer (DW15 and MIP-03). Also, the smallest screen size set at the sampling interval with the highest anticipated contaminant concentration (MIP-03) yields the highest detected contaminant concentrations. Greater screen lengths facilitate dilution of contaminants when they are concentrated within small lithologic intervals.

## 5.5 Contaminant Fate and Transport

Groundwater quality analytical results indicate that elevated concentrations of benzene and xylenes, and lesser concentrations of toluene, and ethylbenzene exist within the Columbia Aquifer at SWMU 15. Benzene and xylenes are the primary constituents detected in the volatile fraction. The other BTEX constituents apparently have, for the most part, biodegraded.

The Columbia Aquifer, comprising fine-to medium-grained sand, is semi-confined between surficial and basal layers of silt and clay. Discrete-depth groundwater sampling and MIP survey results indicated that elevated BTEX constituents exist at the groundwater table and in the lowermost sand of the aquifer and in the uppermost silty layers of the basal confining unit adjacent to the known source area (i.e., the ponded excavation). Hydraulically down-gradient of the known source area, there is an apparent lack of BTEX contamination in the upper two thirds of the sand section comprising the Columbia Aquifer, even at locations where high BTEX concentrations are detected in the lowermost sand of the aquifer and the uppermost silts of the lower confining unit. Based upon hydraulic conductivity measurements the basal sand has moderate permeability and the silt and clay have low permeability.

Free product that leaks from storage tanks and pipelines will migrate downward through the vadose zone soils until it encounters the capillary fringe of saturated soils above the water table. Because petroleum product has a specific gravity that is less than water, it will accumulate within the capillary fringe due to its buoyancy. When a large enough quantity of free product accumulates within the capillary fringe, it will depress the water table and develop pressure gradients that will spread the product laterally across the water table. In steady multiphase (air, water, NAPL) flow, the different fluids flow practically independent of each other. Thus, depending on the quantity of fuel that was released and the resulting pressure head on the NAPL lens, the NAPL may spread at a much higher rate than the local groundwater velocity. The NAPL will continue to spread across the water table until it comes into equilibrium with gravity, buoyancy, capillary, and pressure head forces. It will

also spread vertically within a "smear zone" as groundwater levels fluctuate. As the NAPL migrates through the subsurface soils, a portion will remain trapped within the soil matrix in the form of globules or ganglia that are not capable of flow. This remaining NAPL is called "residual NAPL." The highest concentrations of fuel hydrocarbons in groundwater are normally found in the smear zone and near the water table surface due to dissolution of LNAPL.

The previous investigations of SWMU 15 focused on the characterization of the surficial soil, the smear zone, and the water table where BTEX contamination would be expected. However, this investigation has also determined that high concentrations of BTEX are present in the lower most strata of the Columbia Aquifer and the uppermost strata of the silt-clay confining unit. The fate and transport mechanisms that caused high concentrations of BTEX or NAPL to reach the lower portions of the aquifer are unknown. The following causes may have contributed to the observed contaminant distribution:

- Permeable sands at the lower depths of the Columbia Aquifer may have created a preferential pathway for NAPL to migrate vertically downward from the source area
- Downward flow gradients in the Columbia Aquifer may have drawn high levels of dissolved-phase contamination from the groundwater table into the lower portions of the aquifer
- Differential flow patterns may have caused the more permeable sandy soil matrix at intermediate depths of the aquifer to be flushed out faster than the less permeable silty soils at the base of the aquifer
- Differential biodegradation zones (such as aerobic versus anaerobic zones) may have caused contaminants to biodegrade faster at shallower depths than at the base of the aquifer

These mechanisms will be evaluated as part of the groundwater modeling presented in a later section of this report.

**Table 5-1**
**Statistical Summary of Monitoring Well Groundwater Data (January 2000)**
**SWMU 15 - NAS Oceana**

| AnalyteName | Detection Frequency | Maximum Detected Concentration | SampleID of Maximum Detected Value | Mean Value | Standard Deviation |
|---|---|---|---|---|---|
| **Volatile Organic Compounds (UG/L)** | | | | | |
| BENZENE | 4 - 15 | 3,010 | OW15-MW20-R02 | 202.08 | 776.79 |
| ETHYLBENZENE | 1 - 15 | 9.8 | OW15-MW19-R02 | 2.85 | 5.26 |
| M- AND P-XYLENE | 2 - 15 | 1,430 | OW15-MW20-R02 | 96.55 | 368.89 |
| O-XYLENE | 2 - 15 | 1.6 | OW15-MW08-R02 | 2.31 | 4.90 |
| TOLUENE | 1 - 15 | 16 | OW15-MW20-R02 | 2.47 | 3.74 |
| TRICHLOROETHENE | 1 - 15 | 2 | OW15-MW06-R02 | 2.33 | 4.89 |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | |
| ALKALINITY | 6 - 14 | 90 | OW15-MW20-R02 | 23.71 | 27.97 |
| CHLORIDE | 15 - 15 | 63.5 | OW15-MW06-R02 | 17.15 | 14.91 |
| COND (MS/CM) | 14 - 14 | 626 | OW15-MW21-R02 | 233.96 | 159.67 |
| DO | 14 - 14 | 4.43 | OW15-MW18-R02 | 0.90 | 1.19 |
| ETHANE (NG/L) | 14 - 15 | 19,726 | OW15-MW20-R02 | 1,622.30 | 5,038.81 |
| ETHENE (NG/L) | 11 - 15 | 559 | OW15-MW17-R02 | 70.93 | 144.20 |
| IRON II | 5 - 15 | 11 | OW15-MW21-R02 | 2.60 | 3.84 |
| IRON III | 4 - 15 | 1.2 | OW15-MW19-R02 | 0.45 | 0.35 |
| MANGANESE | 1 - 15 | 0.5 | OW15-MW21-R02 | 0.27 | 0.06 |
| METHANE (UG/L) | 15 - 15 | 7,060 | OW15-MW20-R02 | 516.13 | 1,813.32 |
| NITRATE | 2 - 15 | 2.35 | OW15-MW10-R02 | 0.43 | 0.56 |
| pH (unitless) | 14 - 14 | 6.15 | OW15-MW19-R02 | 5.31 | 0.62 |
| REDOX (mV) | 13 - 13 | 269.1 | OW15-MW11-R02 | 83.57 | 178.15 |
| SULFATE | 15 - 15 | 166 | OW15-MW21-R02 | 31.93 | 46.37 |
| SULFIDE | 14 - 14 | 0.22 | OW15-MW20-R02 | 0.11 | 0.04 |
| TEMP (Celsius) | 14 - 14 | 15.83 | OW15-MW19-R02 | 12.32 | 2.64 |
| TOTAL ORGANIC CARBON (TOC) | 13 - 15 | 14 | OW15-MW20-R02 | 5.25 | 3.80 |
| TURB (NTU) | 13 - 13 | 1,831 | OW15-MW19-R02 | 777.97 | 627.58 |

**Table 5-2**
**Comparison of Current and Historic Monitoring Well Total BTEX Concentrations**
**SWMU 15 - NAS Oceana**

| Sample ID | 15-MW5 | 15-MW6 | | 15-MW7 | | 15-MW8 | | 15-MW9 | 15-MW10 | | 15-MW11 | | 15-MW12 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sampling Date | Apr-94 | Apr-94 | Feb-00 | Apr-94 | Feb-00 | Apr-94 | Feb-00 | Apr-94 | Apr-94 | Feb-00 | Oct-94 | Feb-00 | Oct-94 | Feb-00 |
| Benzene | 22 | 5 U | 1.1 J | 300 D | 2 U | 5 U | 2.4 | 740 D | 5 U | 2 U | 5 U | 2 U | 5 U | 2 U |
| Toluene | 5 U | 5 U | 3 U | 2 J | 3 U | 5 U | 3 U | 140 D | 5 U | 3 U | 5 U | 3 U | 5 U | 3 U |
| Ethylbenzene | 26 | 5 U | 2 U | 5 U | 2 U | 5 U | 2 U | 300 D | 5 U | 2 U | 5 U | 2 U | 5 U | 2 U |
| Xylene | 5 U | 5 U | 1.1 J | 80 | 2 U | 5 U | 1.6 J | 980 D | 1 J | 2 U | 5 U | 2 U | 5 U | 2 U |
| **Total BTEX** | **48** | **ND** | **2.2** | **382** | **ND** | **0** | **4** | **2,160** | **1** | **ND** | **ND** | **ND** | **ND** | **ND** |

| Sample ID | 15-MW13 | | 15-MW14 | | 15-MW15 | 15-MW16 | | 15-MW17 | | 15-MW18 | 15-MW19 | 15-MW20 | 15-MW21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sampling Date | Oct-94 | Feb-00 | Oct-94 | Feb-00 | Oct-94 | Mar-95 | Feb-00 | Mar-95 | Feb-00 | Feb-00 | Feb-00 | Feb-00 | Feb-00 |
| Benzene | 5 U | 2 U | 5 U | 2 U | 270 D | 1 U | 2 U | 1 U | 2 U | 2 U | 6.7 | 3,010 | 2 U |
| Toluene | 5 U | 3 U | 5 U | 3 U | 1 J | 1 U | 3 U | 1 J | 3 U | 3 U | 3 U | 16 J | 3 U |
| Ethylbenzene | 5 U | 2 U | 5 U | 2 U | 3 J | 1 U | 2 U | 1 U | 2 U | 2 U | 9.8 | 40 U | 2 U |
| Xylene | 5 U | 2 U | 5 U | 2 U | 270 | 1 U | 2 U | 1 U | 2 U | 2 U | 5.3 | 1,430 | 2 U |
| **Total BTEX** | **ND** | **ND** | **ND** | **ND** | **544** | **ND** | **ND** | **1** | **ND** | **ND** | **21.8** | **4,456** | **ND** |

Highest Total BTEX Concentration observed at a Monitoring Well

Monitoring wells MW-5, MW-9, and MW-15 were not sampled in Feb 2000 because the wells were destroyed.
Monitoring well MW-15 was replaced by MW-20.

**Table 5-3**
**Monitoring Well Construction Summary**
**SWMU 15 - NAS Oceana**

| Well | Date Installed | Measuring Point Elevation (ft above MSL) | Ground Surface Elevation (ft above MSL) | Total Depth (ft) | Screened Interval (ft BGS) | Water-Table Elevation (ft) | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | May-94 | Oct-94 | Mar-95 | May-00 | |
| 15-MW1 | 11/1/82 | ND | 18.4 | 16 | 0.5 - 10.5 | - | - | - | - | Abandoned |
| 15-MW2 | 11/1/82 | ND | 17.6 | 20 | 0.5 - 10.5 | - | - | - | - | Abandoned |
| 15-MW3 | 11/1/82 | ND | 18.8 | 20 | 0.5 - 10.5 | - | - | - | - | Abandoned |
| 15-MW4 | 11/1/82 | ND | ND | ND | ND | - | - | - | - | Abandoned |
| 15-MW5 | 3/9/94 | 20.13 | 18.4 | 18 | 3 - 18 | 13.61 | 11.01 | 15.43 | - | Removed during soil removal action |
| 15-MW6 | 4/13/94 | 21.11 | 17.9 | 20 | 3 - 18 | 13.63 | 10.93 | 15.83 | 16.26 | - |
| 15-MW7 | 4/12/94 | 19.02 | 16.6 | 18 | 3 - 18 | 13.42 | 10.82 | 15.6 | 15.88 | - |
| 15-MW8 | 4/12/94 | 19.94 | 17.8 | 18 | 3 - 18 | 13.39 | 10.65 | 15.84 | 15.91 | - |
| 15-MW9 | 3/11/94 | 20.23 | 18.3 | 20 | 3 - 18 | 13.58 | 10.9 | 15.75 | - | Removed during soil removal action |
| 15-MW10 | 4/13/94 | 20.38 | 17.8 | 20 | 3 - 18 | 13.25 | 10.49 | 15.77 | 15.75 | - |
| 15-MW11 | 9/28/94 | 19.16 | 17.3 | 20 | 5 - 20 | - | 10.87 | 15.63 | 15.71 | - |
| 15-MW12 | 9/27/94 | 19.16 | 17.6 | 20 | 5 - 20 | - | 10.76 | 15.74 | 15.68 | - |
| 15-MW13 | 9/28/94 | 18.6 | 16.1 | 20 | 5 - 20 | - | 10.28 | 15.57 | 15.59 | - |
| 15-MW14 | 9/27/94 | 19.37 | 17.7 | 20 | 5 - 20 | - | 10.41 | 15.65 | 16.25 | - |
| 15-MW15 | 9/27/94 | 18.8 | 17.3 | 20 | 5 - 20 | - | 11.16 | 15.16 | - | Removed during soil removal action |
| 15-MW16 | 3/6/95 | 20.39 | 17.7 | 19.5 | 4.5 - 19.5 | - | - | 15.05 | 15.39 | - |
| 15-MW17 | 3/6/95 | 18.04 | 17.9 | 20 | 5 - 20 | - | - | 14.73 | - | Covered, installed piezometer next to it. |
| 15-MW18 | 7/1/99 | 21.58 | 19.99 | 18 | 3 - 18 | - | - | - | 14.36 | |
| 15-MW19 | 7/1/99 | 21.13 | 19.64 | 18 | 3 - 18 | - | - | - | 14.73 | |
| 15-MW20 | 7/1/99 | 17.52 | 17.6 | 18 | 3 - 18 | - | - | - | 14.9 | |
| 15-MW21 | 7/1/99 | 20.32 | 18.53 | 18 | 3 - 18 | - | - | - | - | Backed into, installed piezometer next to it. |

**Table 5-4**
**Statistical Summary of DPT Groundwater Data (February 2000)**
**SWMU 15 - NAS Oceana**

| AnalyteName | Detection Frequency | Maximum Detected Concentration | SampleID of Maximum Detected Value | Mean Value | Standard Deviation |
|---|---|---|---|---|---|
| **Volatile Organic Compounds (UG/L)** | | | | | |
| 1,1-DICHLOROETHANE | 5 - 41 | 4.3 | OW15-DW04-10 | 12.56 | 29.46 |
| BENZENE | 29 - 41 | 8,090 | OW15-DW22-20 | 1,140.14 | 1,879.69 |
| ETHYLBENZENE | 11 - 41 | 47 | OW15-DW13-20 | 17.46 | 29.84 |
| M- AND P-XYLENE | 30 - 41 | 4,230 | OW15-DW13-20 | 401.07 | 800.13 |
| O-XYLENE | 5 - 41 | 6.1 | OW15-DW13-20 | 12.68 | 29.43 |
| TOLUENE | 11 - 41 | 41 | OW15-DW13-20 | 21.44 | 43.82 |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | |
| ALKALINITY | 41 - 41 | 135 | OW15-DW12-17 | 74.73 | 36.15 |
| CHLORIDE | 41 - 41 | 18 | OW15-DW08-17 | 12.97 | 2.97 |
| COND (MS/CM) | 38 - 38 | 891 | OW15-DW02-05 | 342.21 | 188.35 |
| DO | 38 - 38 | 1.87 | OW15-DW02-17 | 0.33 | 0.32 |
| ETHANE (NG/L) | 41 - 41 | 47,174 | OW15-DW30-20 | 11,791.46 | 12,824.23 |
| ETHENE (NG/L) | 41 - 41 | 1,057 | OW15-DW15-20 | 282.93 | 203.28 |
| IRON II | 35 - 41 | 28 | OW15-DW03-10 | 11.02 | 6.52 |
| IRON III | 27 - 41 | 7 | OW15-DW02-17 | 0.83 | 1.06 |
| MANGANESE | 6 - 41 | 1.2 | OW15-DW06-18 | 0.32 | 0.19 |
| METHANE (UG/L) | 41 - 41 | 20,130 | OW15-DW03-05 | 4,084.81 | 4,846.22 |
| NITRATE | 1 - 41 | 57 | OW15-DW02-05 | 1.63 | 8.86 |
| pH (unitless) | 39 - 39 | 6.91 | OW15-DW04-05 | 6.01 | 0.32 |
| REDOX (mV) | 39 - 39 | 11.7 | OW15-DW02-05 | -322.30 | 181.53 |
| SULFATE | 33 - 41 | 400 | OW15-DW06-18 | 49.81 | 87.41 |
| SULFIDE | 41 - 41 | 0.39 | OW15-DW15-20 | 0.17 | 0.07 |
| TEMP (Celsius) | 39 - 39 | 16.75 | OW15-DW19-15 | 14.62 | 1.71 |
| TOTAL ORGANIC CARBON (TOC) | 41 - 41 | 33 | OW15-DW13-20 | 10.61 | 7.19 |
| TURB (NTU) | 37 - 37 | 1,836 | OW15-DW16-18 | 731.51 | 695.39 |

**Table 5-5**
**Total BTEX in February 2000 Direct Push Groundwater Samples**
**SWMU 15 - NAS Oceana**

| Sample ID | OW15-DW01 | OW15-DW02 | OW15-DW03 | OW15-DW04 | OW15-DW05 | OW15-DW06 | OW15-DW07 | OW15-DW08 | OW15-DW09 | OW15-DW10 | OW15-DW11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth | 17 ft | 17 ft | 17 ft | 17 ft | 18 ft | 18 ft | 17 ft | 17 ft | | 17 ft | 17 ft |
| Benzene | 1,800 | 1,520 | 261 | 1,920 | 3,410 | 2,500 | 3,840 | 332 | 3.2 | 5.9 | 73 |
| Toluene | 12 | 60 U | 30 U | 60 U | 17 U | 300 U | 300 U | 1.7 J | 3 U | 3 U | 3 U |
| Ethylbenzene | 21 | 40 U | 20 U | 40 U | 13 | 200 U | 200 U | 2 U | 2 U | 2 U | 2 U |
| m&p-Xylene | 1,050 | 1,710 | 138 | 840 | 1,330 | 486 | 1,550 | 224 | 1.5 J | 5.3 | 30 |
| o-Xylene | 3.8 | 40 U | 20 U | 40 U | 3.3 | 200 U | 200 U | 2 U | 2 U | 2 U | 2 U |
| **Total BTEX** | **2,887** | **3,230** | **399** | **2,760** | **4,756** | **2,986** | **5,390** | **557.7** | **4.7** | **11.2** | **103** |

| Sample ID | OW15-DW12 | OW15-DW13 | OW15-DW14 | OW15-DW15 | OW15-DW16 | OW15-DW17 | OW15-DW18 | OW15-DW19 | OW15-DW20 | OW15-DW21 | OW15-DW22 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth | 17 ft | 20 ft | 20 ft | 20 ft | 18 ft | 20 ft | 15 ft | 15 ft | 18 ft | 15 ft | 20 ft |
| Benzene | 2,118 | 6,910 | 2,870 | 1,120 | 9 | 3,350 | 416 | 192 | 29 | 3.8 | 8,090 |
| Toluene | 26 | 41 E | 10 | 300 U | 3 U | 16 | 6 | 1.2 J | 3 U | 3 U | 10.1 |
| Ethylbenzene | 41 E | 47 E | 19 | 200 U | 8.2 | 28 | 5.4 | 0.7 J | 2 U | 2 U | 35 E |
| m&p-Xylene | 130 E | 4,230 | 784 | 210 | 35 | 1,578 | 6.3 | 12 | 8.7 | 1 J | 10 |
| o-Xylene | 2 U | 6.1 | 2.9 | 200 U | 2 U | 3.8 | 2 U | 2 U | 2 U | 2 U | 2 U |
| **Total BTEX** | **2,315** | **11,234** | **3,686** | **1,330** | **52.2** | **4,976** | **433.7** | **205.9** | **37.7** | **4.8** | **8,145** |

| Sample ID | OW15-DW23 | OW15-DW24 | OW15-DW25 | OW15-DW26 | OW15-DW27 | OW15-DW28 | OW15-DW29 | OW15-DW30 |
|---|---|---|---|---|---|---|---|---|
| Depth | 20 ft | 15 ft | 15 ft | 15 ft | 15 ft | 20 ft | 20 ft | 20 ft |
| Benzene | 1,380 | 97 | 2 J | 1.1 J | 2 U | 8 U | 150 | 1,008 |
| Toluene | 2 J | 3 U | 3 U | 3 U | 3 U | 12 U | 30 U | 30 U |
| Ethylbenzene | 3.5 | 2 U | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| m&p-Xylene | 112 E | 59 | 2 U | 2 J | 1.4 J | 42 | 79 | 468 |
| o-Xylene | 2 U | 2 U | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| **Total BTEX** | **1,498** | **156** | **1.5** | **3** | **1.4** | **42** | **229** | **1,476** |

Highest Total BTEX Concentration observed at a Direct Push Groundwater Sample in 2000

**Table 5-6**
**Statistical Summary of VP Groundwater Data (February 2000)**
**SWMU 15 - NAS Oceana**

| AnalyteName | Detection Frequency | Maximum Detected Concentration | SampleID of Maximum Detected Value | Mean Value | Standard Deviation |
|---|---|---|---|---|---|
| **Volatile Organic Compounds (UG/L)** | | | | | |
| BENZENE | 18 - 34 | 5,920 | OW15-MIP01-22 | 949.54 | 1,707.83 |
| ETHYLBENZENE | 14 - 34 | 35 | OW15-MIP01-23 | 6.33 | 8.99 |
| M- AND P-XYLENE | 15 - 34 | 364 | OW15-MIP03-25 | 37.05 | 80.38 |
| O-XYLENE | 5 - 34 | 4.2 | OW15-MIP03-25 | 1.27 | 0.75 |
| TOLUENE | 11 - 34 | 12 | OW15-MIP04-22 | 2.85 | 2.77 |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | |
| ALKALINITY | 29 - 34 | 140 | OW15-MIP04-20 | 60.59 | 44.79 |
| CHLORIDE | 34 - 34 | 18 | OW15-MIP04-07 | 10.82 | 3.06 |
| COND (MS/CM) | 27 - 27 | 460 | OW15-MIP01-14 | 281.22 | 85.09 |
| DO | 26 - 26 | 7.46 | OW15-MIP03-22 | 1.07 | 1.95 |
| ETHANE (NG/L) | 34 - 34 | 89,723 | OW15-MIP04-22 | 16,847.12 | 27,585.53 |
| ETHENE (NG/L) | 33 - 34 | 5,992 | OW15-MIP04-23 | 518.13 | 1,210.67 |
| IRON II | 32 - 34 | 38 | OW15-MIP04-07 | 11.70 | 8.91 |
| IRON III | 21 - 34 | 1.3 | OW15-MIP04-07 | 0.56 | 0.31 |
| MANGANESE | 8 - 34 | 1 | OW15-MIP03-26 | 0.37 | 0.24 |
| METHANE (UG/L) | 34 - 34 | 16,650 | OW15-MIP01-23 | 3,049.34 | 4,701.54 |
| NITRATE | 1 - 34 | 7.2 | OW15-MIP01-06 | 0.45 | 1.19 |
| pH (unitless) | 27 - 27 | 6.55 | OW15-MIP01-20 | 5.98 | 0.34 |
| REDOX (mV) | 27 - 27 | 74.5 | OW15-MIP02-11 | -94.13 | 76.35 |
| SULFATE | 29 - 34 | 234 | OW15-MIP01-14 | 61.56 | 70.40 |
| SULFIDE | 34 - 34 | 0.33 | OW15-MIP02-17 | 0.15 | 0.05 |
| TEMP (Celsius) | 27 - 27 | 18.88 | OW15-MIP02-17 | 15.71 | 1.39 |
| TOTAL ORGANIC CARBON (TOC) | 32 - 33 | 31 | OW15-MIP04-07 | 9.89 | 7.82 |
| TURB (NTU) | 27 - 27 | 1,838 | OW15-MIP03-26 | 502.09 | 602.05 |

**Table 5-7**
**Vertical Distribution of Total BTEX in MIP Groundwater Samples (February 2000)**
**SWMU 15 - NAS Oceana**

| Sample | Depth | Total BTEX | Benzene | Toluene | Ethylbenzene | m&p-Xylenes | o-Xylenes |
|---|---|---|---|---|---|---|---|
| OW-15-MIP01 | 6 ft | **0.9** | 0.9 J | 3 U | 2 U | 2 U | 2 U |
| | 10 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 14 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 17 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 20 ft | **81** | 81 | 3 U | 2 U | 2 U | 2 U |
| | 22 ft | **5,961** | 5,920 | 7.8 | 16 | 14 | 2.9 |
| | 23 ft | **4,053** | 3,980 | 7.4 | 35 E | 28 | 2.6 |
| | 25 ft | **232.3** | 227 | 1.1 J | 2.6 | 1.6 J | 2 U |
| | 26 ft | **40.3** | 39 | 1.3 J | 2 U | 2 U | 2 U |
| OW-15-MIP02 | 11 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 14 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 17 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 20 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 22 ft | **12.9** | 2 U | 3 U | 4.5 | 8.4 | 2 U |
| | 23 ft | **13.3** | 4.3 | 3 U | 2.1 | 6.9 | 2 U |
| | 29 ft | **2.9** | 2 U | 3 U | 2 U | 2.9 J | 2 U |
| OW-15-MIP03 | 11 ft | **2.2** | 2.2 | 3 U | 2 U | 2 U | 2 U |
| | 14 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 17 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 20 ft | **1,427** | 1,230 | 3.1 | 24 | 170 J | 2 U |
| | 22 ft | **410.2** | 328 | 3 U | 6.2 | 76 | 2 U |
| | 23 ft | **2,083** | 1,820 | 3.3 | 15 | 243 | 1.3 J |
| | 25 ft | **4,743** | 4,340 | 7.8 | 27 | 364 | 4.2 |
| | 26 ft | **346.8** | 304 | 3 U | 4.8 | 38 | 2 U |
| OW-15-MIP04 | 7 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 11 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 14 ft | **ND** | 2 U | 3 U | 2 U | 2 U | 2 U |
| | 17 ft | **2,753** | 2,700 | 3.5 | 14 | 35 | 2 U |
| | 20 ft | **3,071** | 3,030 | 5.5 | 21 | 11 | 3.1 |
| | 22 ft | **5,161** | 5,000 | 12 | 13 | 136 E | 2 U |
| | 23 ft | **3,386** | 3,260 | 9.5 | 10 | 106 E | 2 U |

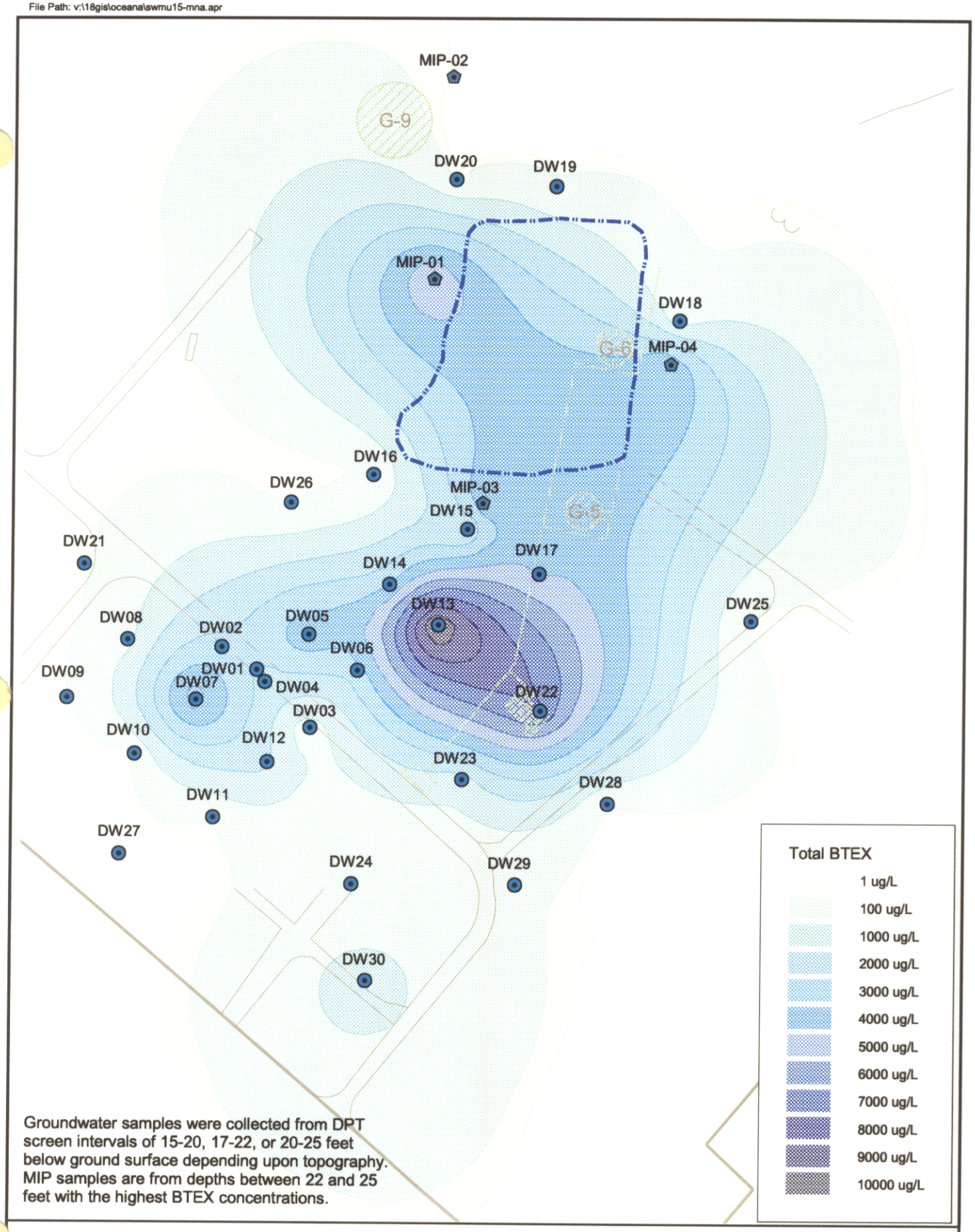
**Table 5-8**
**TPH (as JP-5) Detected in VP Soil Samples (April 2000)**
**SWMU 15 - NAS Oceana**

| LOCATION | DEPTH | TPH (ng/ul) | TPH/Soil (ug/g) |
|---|---|---|---|
| MIP01 | 6.5 - 7.0 | ND | ND |
| | 7.5 - 8.0 | ND | ND |
| | 22.0 - 22.5 | ND | ND |
| | 23.0 - 23.5 | ND | ND |
| | 24.5 - 25.0 | ND | ND |
| | 25.5 - 26.0 | ND | ND |
| MIP02 | 6.0 - 6.5 | BLQ | BLQ |
| | 7.0 - 7.5 | 1,560 | 401 |
| | 22.5 - 23.0 | ND | ND |
| | 23.5 - 24.0 | ND | ND |
| MIP03 | 5.0 - 5.5 | ND | ND |
| | 6.0 - 6.5 | ND | ND |
| | 21.5 - 22.0 | ND | ND |
| | 22.5 - 23.0 | ND | ND |
| | 23.0 - 23.5 | ND | ND |
| | 24.0 - 24.5 | ND | ND |
| | 25.5 - 26.0 | ND | ND |
| | 26.0 - 26.5 | ND | ND |
| | 27.0 - 27.5 | ND | ND |
| MIP04 | 6.5 - 7.0 | ND | ND |
| | 7.5 - 8.0 | ND | ND |
| | 17.0 - 17.5 | ND | ND |
| | 18.5 - 19.0 | ND | ND |
| | 19.5 - 20.0 | ND | ND |
| | 21.0 - 21.5 | ND | ND |
| | 22.0 - 22.5 | ND | ND |

**Table 5-9**
**Depth and Concentration Correlation Between MW, DPT, and VP Groundwater Sample Results**
**SWMU 15 - NAS Oceana**

| Sample Location | Screened Interval (Feet) | Depth to Center of Screen (Feet) | Length of Screen (Feet) | Date Sampled | Total BTEX in Groundwater (ug/L) |
|---|---|---|---|---|---|
| MW-19 | 3 to 18 | 10 | 15 | 01/28/2000 | 23.3 |
| DW-15 | 20 to 25 | 22.5 | 5 | 02/09/2000 | 2030 |
| MIP-3 | 24.5 to 25.5 | 25 | 1 | 02/22/2000 | 4538 |

File Path: v:\18gis\oceana\swmu15-mna.apr




N
W E
S

0 80 160 240 Feet

Figure 5-1
Total BTEX in Groundwater - SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2M HILL

00526 G B44

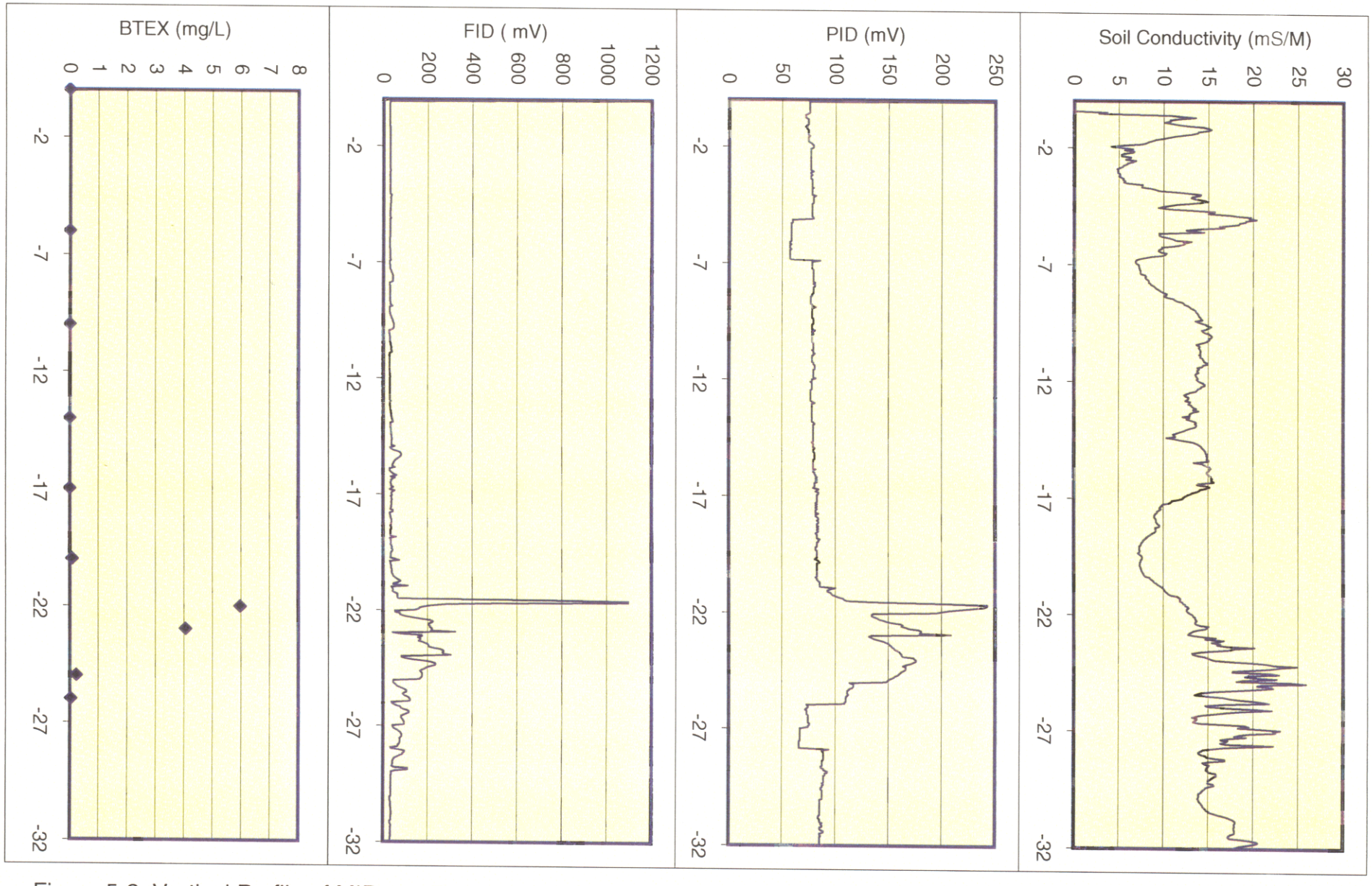



Figure 5-2: Vertical Profile of MIP-01. This location is west of the excavated source region, and shows a maximum concentration of BTEX of 5,957 ug/L at 22 feet below surface.

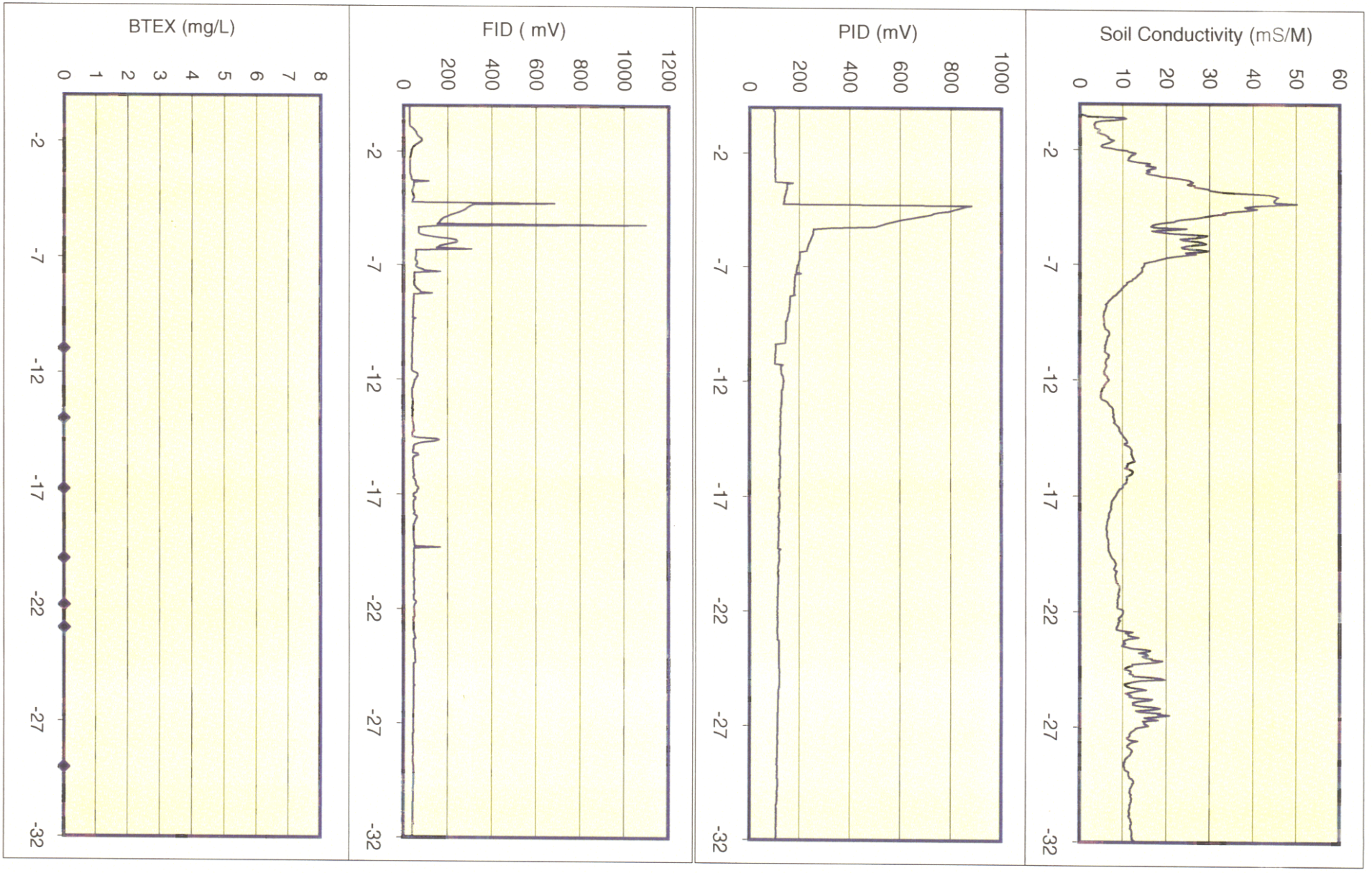



Figure 5-3: Vertical Profile of MIP-02. This location had very low contamintion levels (10 ug/L). The soil stratification is similar to VP-01.

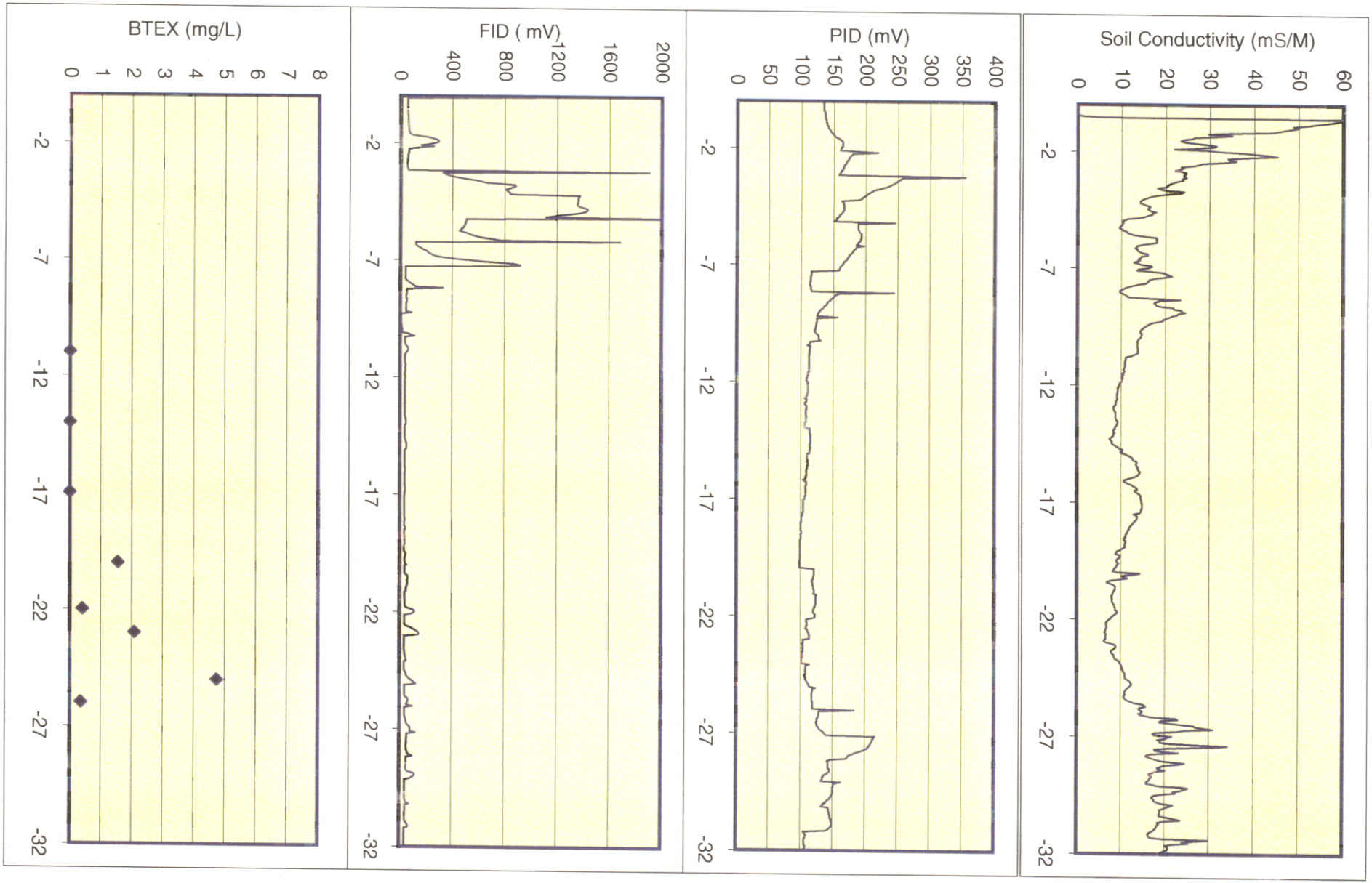



Figure 5-4: Vertical Profile of MIP-03 located south and downgradient of the excavated source region. This location shows a high of 4,738 ug/L at 25' below the surface.

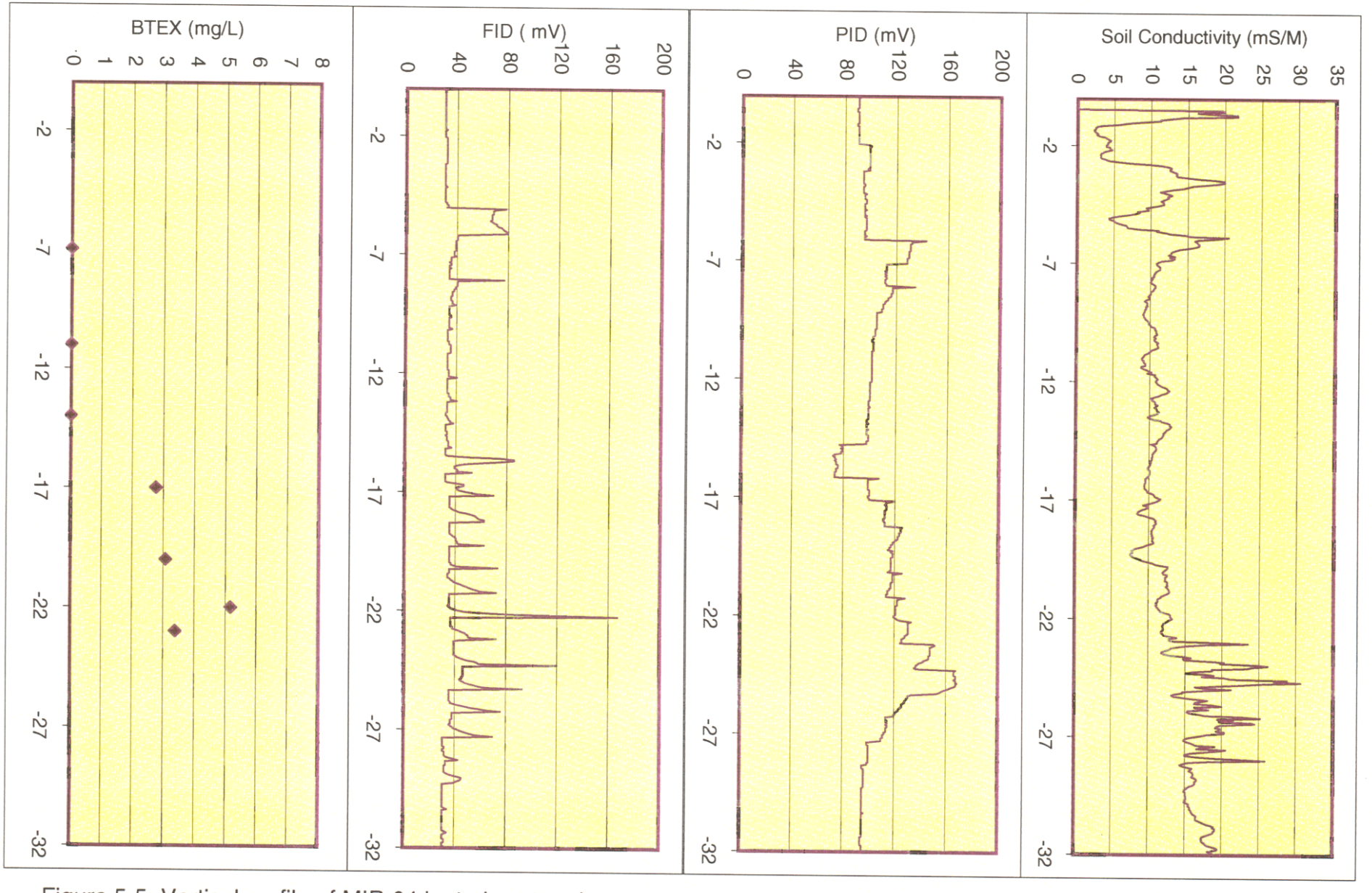
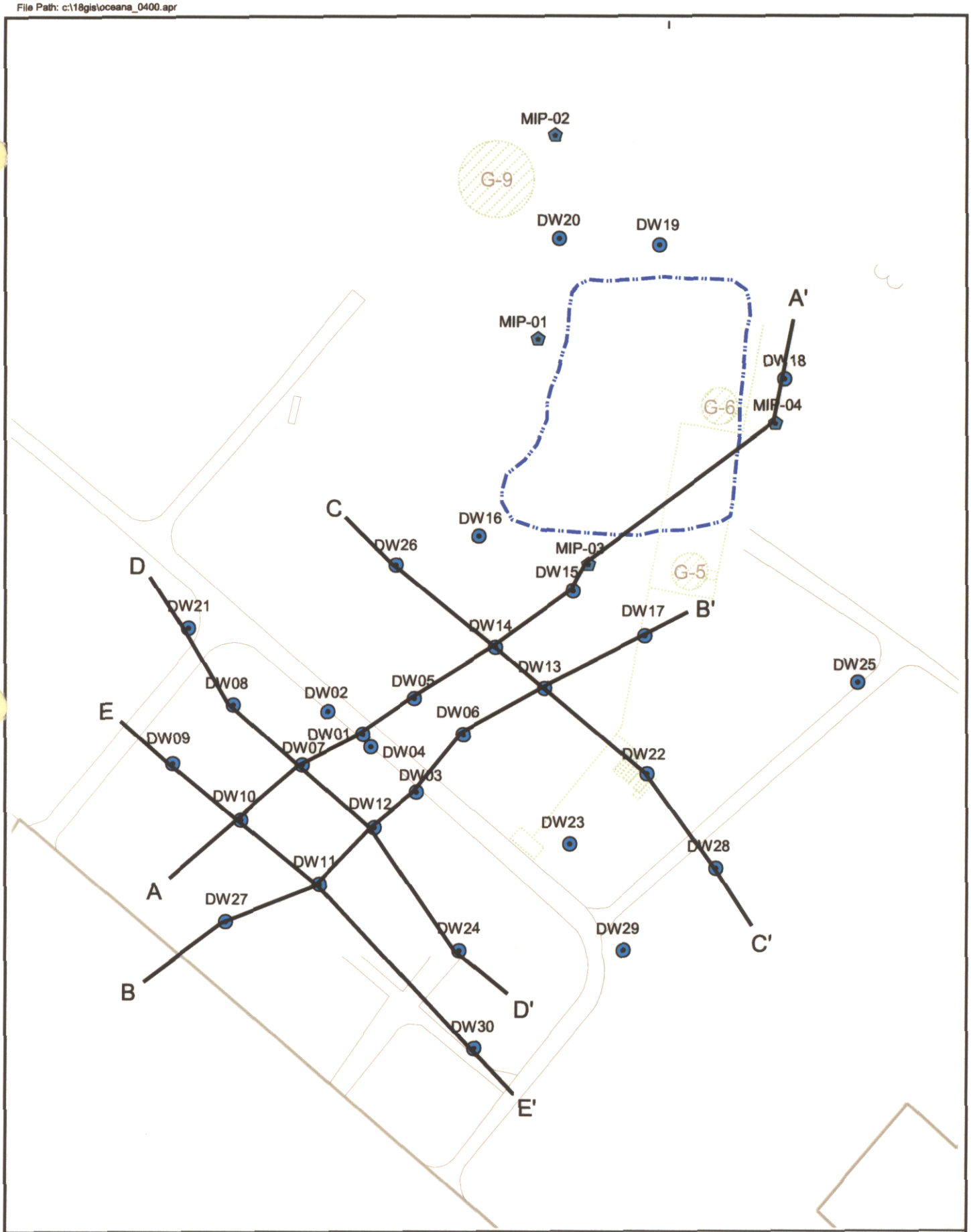



Figure 5-5: Vertical profile of MIP-04 loated east and upgradient of the excavated source region. This location has a high of 5,161 ug/L at 22' below the surface.

File Path: c:\18gis\oceana_0400.apr

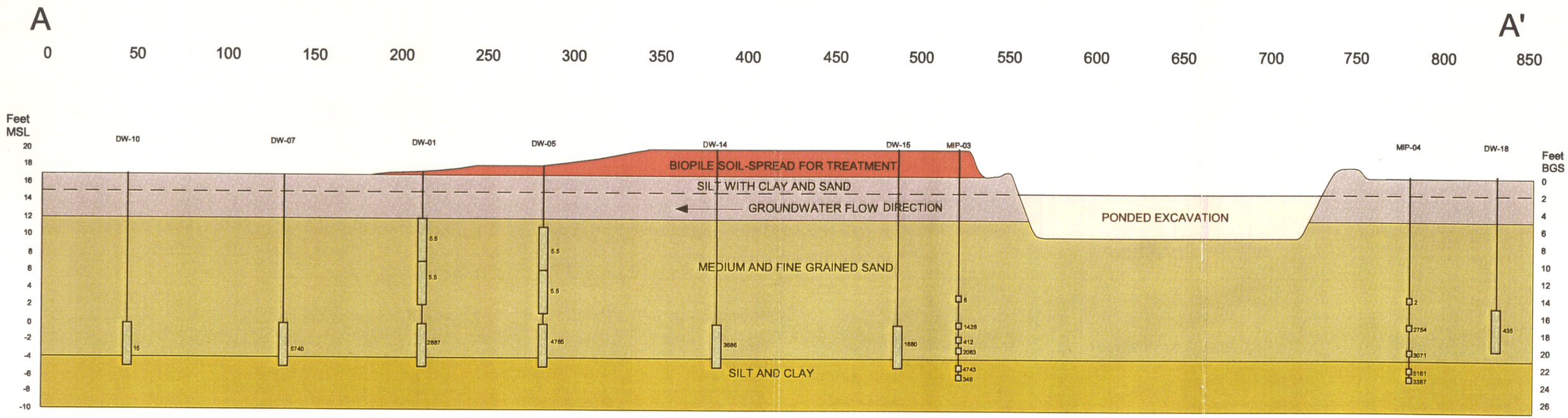



N
W E
S

0 80 160 240 Feet

Figure 5-6
Hydro-Lithologic Cross Section Registration Lines
NAS Oceana, Virginia Beach, Virginia

CH2M HILL




LITHOLOGY

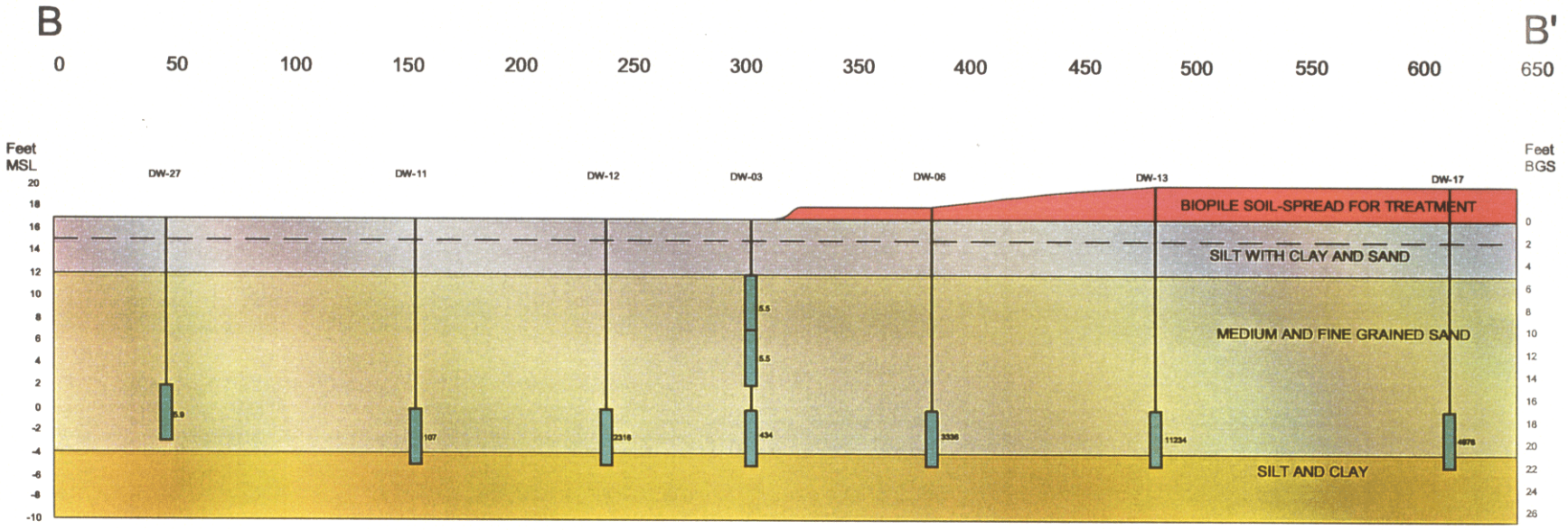
- BIOPILE SOIL-SPREAD
- SILT W/CLAY AND SAND
- POND EXCAVATION
- MEDIUM-FINE GRAINED SAND
- SILT AND CLAY

DPT SCREEN INTERVALS

- TOTAL BTEX

Figure 5-7
Cross Section A-A' SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2M HILL




LITHOLOGY

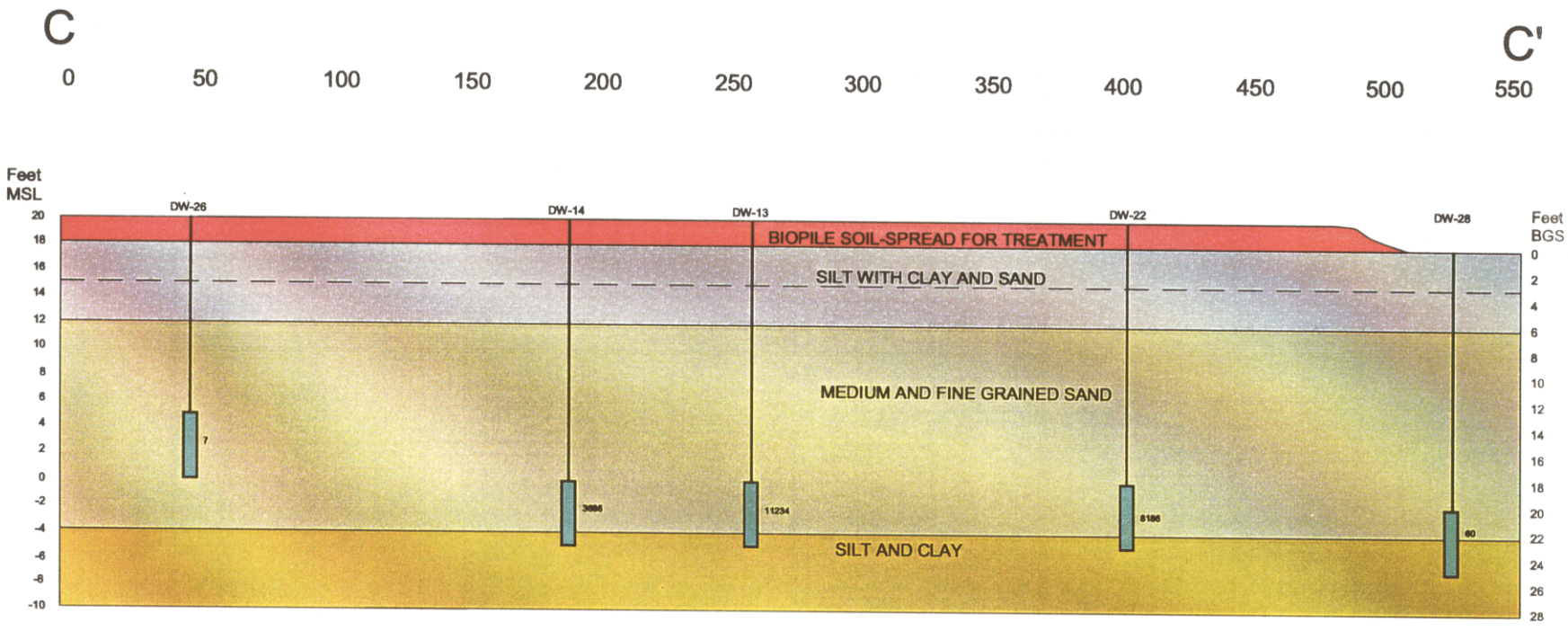
- BIOPILE SOIL
- SILT WITH CLAY AND SAND
- FINE-MEDIUM GRAINED SAND
- SILT AND CLAY

DPT SCREENED INTERVALS

- TOTAL BTEX

Figure 5-8
Cross Section B-B' SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2M HILL




LITHOLOGY

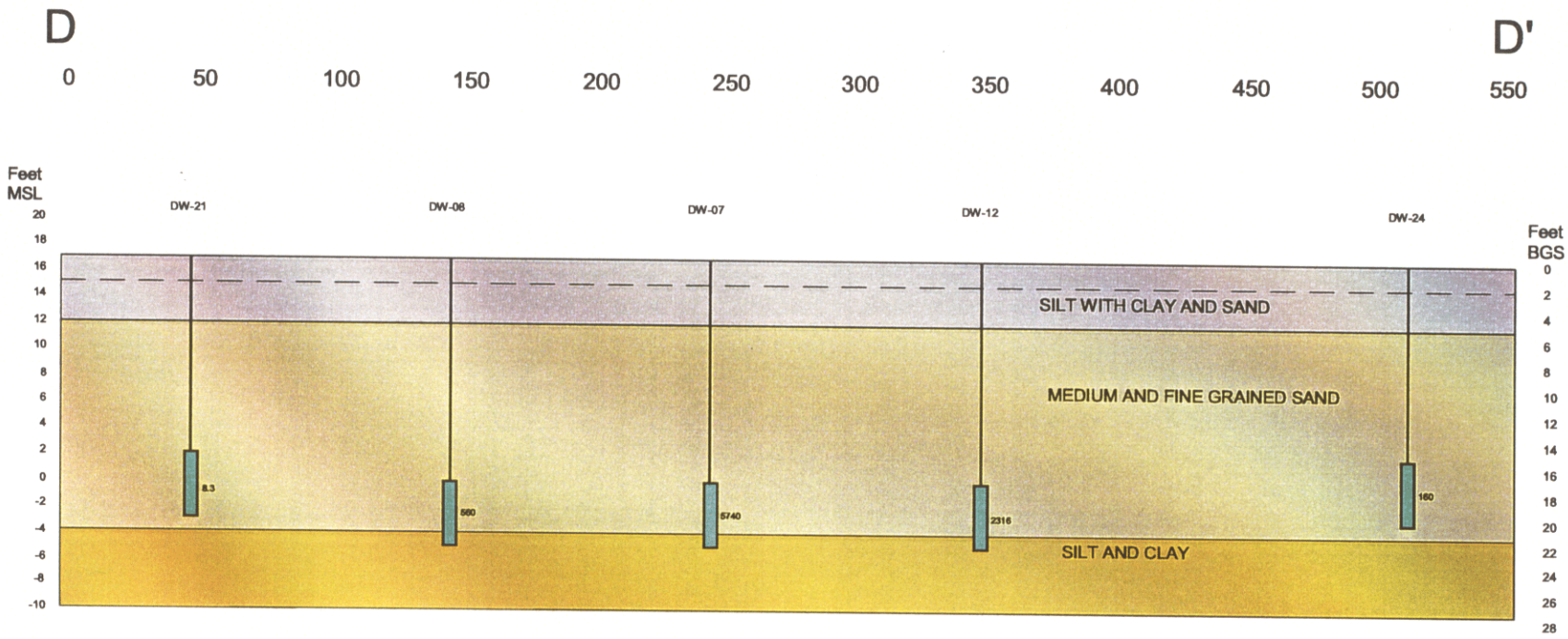
- BIOPILE SOIL-SPREAD
- SILT WITH CLAY AND SAND
- FINE-MEDIUM GRAINED SAND
- SILT AND CLAY

DPT SCREEN INTERVALS

- TOTAL BTEX

Figure 5-9
Cross Section C-C' SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2M HILL



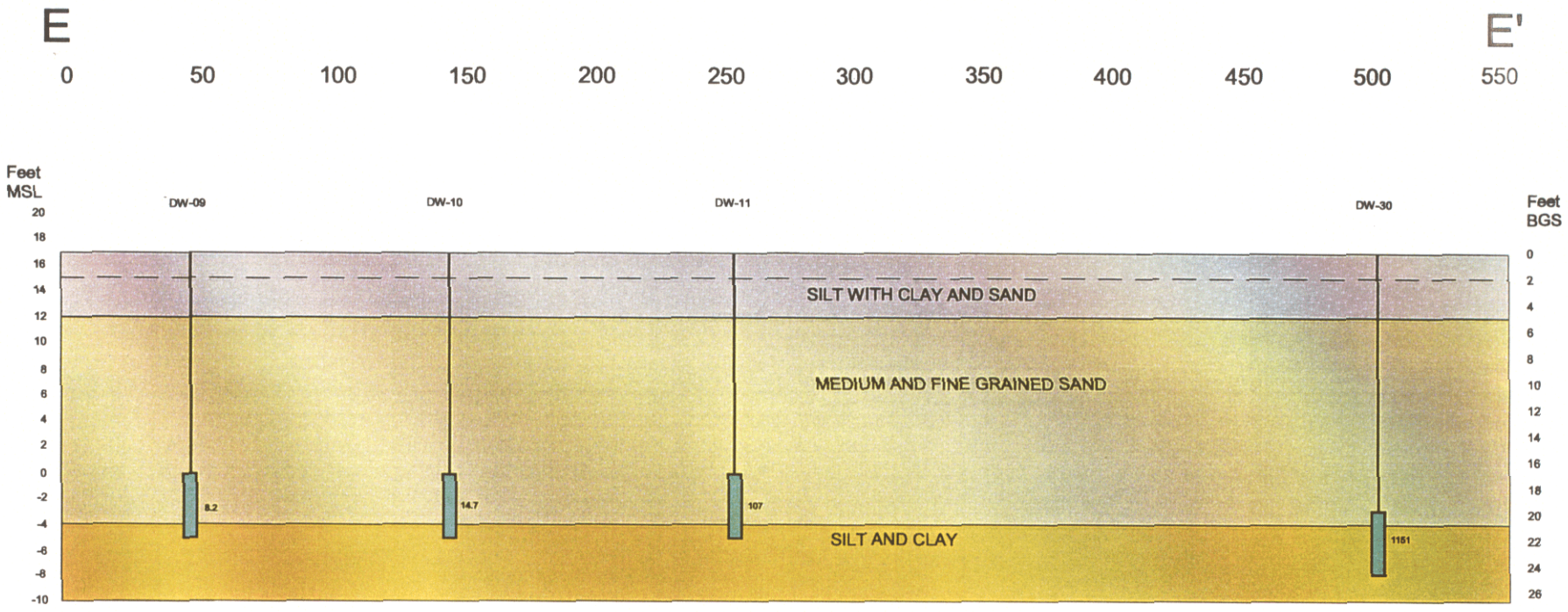

LITHOLOGY

- SILT W/CLAY AND SAND
- FINE TO MEDIUM-GRAINED SAND
- SILT AND CLAY

TOTAL BTEX

Figure 5-10
Cross Section D-D' SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2M HILL




LITHOLOGY

- SILT WITH CLAY AND SAND
- FINE-MEDIUM GRAINED SAND
- SILT AND CLAY

DPT SCREENED INTERVALS

- TOTAL BTEX

Figure 5-11
Cross Section E-E' SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2M HILL

# 6. Lines of Evidence to Support Natural Attenuation

This section summarizes information that supports the hypothesis that natural attenuation is occurring at SWMU 15. The lines of evidence include a reduction in contaminant concentrations over time and patterns of geochemical data that are indications of biodegradation. Evidence to support natural attenuation is also derived from degradation rates estimated from modeling the plume.

## 6.1 Conceptual Site Model for a Large NAPL Source Area and Dissolved-Phase Plume Distribution

The interpretation as to whether or not natural attenuation is occurring at SWMU 15 depends on the conceptual site model for NAPL distribution. In areas where NAPL is present, the contaminant concentrations in groundwater that is in contact with the NAPL will be recharged by the NAPL, as determined by the effective solubility of the contaminant. Dissolved-phase plume concentrations will only decrease in regions of the plume that are not in contact with NAPL. For this reason, natural attenuation mechanisms as described in current protocols (AFCEE, ASTM, EPA, etc.) are applicable to only the dissolved-phase portion of the contaminant plume, which resides downgradient of the NAPL area. The delineation of the edge of the NAPL zone and beginning of the dissolved-phase plume zone in therefore a critical step in evaluating whether natural attenuation is occurring at a site.

Some evidence of NAPL at SWMU 15 is provided through observations of free product during various soil and groundwater sampling events. Figure 6-1 summarizes the sampling locations where free product has been observed. Free product was discovered during the first environmental investigation at the site by R. E. Wright in 1982. Free product was observed in all three test pits (BP-08, BP-09, and BP–10) and in three of the four well borings (MW-01, MW-03, and MW-04). During the RFI field investigation in 1994, a petroleum sheen was observed on the water surface in test pit TP-06 located approximately 120 feet west of former tank G-5. Soil samples collected at depths of 4 to 6 feet at GS-01, GS-03, GS-04, and GS-05, and 1.3 feet of free product measured in 15-PZ4, indicated that petroleum contamination of unsaturated soil was widespread in the tank farm area west of former tank G-6. These observations indicate that NAPL was present in shallow soils within the former tank farm area that was excavated in 1996 and at several locations south of the excavation area. Test pit BP-08 and well MW-01 are approximately 150 feet south of the excavation area and BP-09 is approximately 250 feet southeast of the excavation area.

During the 2000 sampling event, petroleum sheens and gasoline odors were encountered at nine DPT locations (DW-01 through DW-07, plus DW-13 and DW-22) in water samples collected from 17 to 25 feet bgs, located up to 360 feet southwest of the excavation area. The presence of petroleum sheens on samples from near the bottom of the Columbia Aquifer suggests that NAPL may be bound up in the basal silty soils. The high BTEX concentrations

that were detected in DW-13 and DW-22 suggests that there may be a second source area for groundwater contamination, such as the three former tanks and pipelines near DW-22 that stored automotive fuel, kerosene, or lube oil.

Another indication of NAPL at SWMU 15 is the relatively high and stable concentrations of benzene that have been detected in groundwater samples. As NAPL dissolves in groundwater, the aqueous concentrations of benzene and other compounds are approximately related to their solubility and mole fraction in the NAPL phase. This relationship, which is similar to Raoult's law for gases, is known as the effective solubility and can be written as

$$C_L \cong XS$$

where $C_L$ = concentration of contaminant in soil leachate (mg/L)
$X$ = mole fraction of contaminant in NAPL (unitless)
$S$ = aqueous solubility of contaminant (mg/L)

This relationship is considered approximate because errors are introduced due to the complex solubility relationships between the numerous compounds in fuel; however, the level of accuracy is considered appropriate for environmental studies where there are often may other uncertainties (Pankow and Cherry, 1996; Wiedemeier et al., 1999). The effective solubility relationship explains why dissolved concentrations in NAPL zones generally do not approach the solubility concentration of pure phase compounds, and why most of the hydrocarbons in the dissolved-phase plume of a gasoline spill are BTEX compounds due to their relatively high solubility, even though BTEX represents a small fraction of the NAPL mass (Wiedemeier, 1999). The approximate effective solubilities for benzene in groundwater plumes resulting from contact with fresh and weathered fuels are summarized in Table 6-1. Since there is considerable variability in the composition of fresh and weathered fuels, the effective solubilities for benzene presented below should only be used as a general indicator for what might be expected at SWMU-15.

Benzene concentrations detected during the February 2000 groundwater sampling at several wells were greater than 1 mg/L and as high as 8 mg/L. These levels indicate that the benzene concentrations are near or within the effective solubility range, which would indicate that NAPL is present at SWMU 15.

## 6.2 Documented Contaminant Changes at the Site

### 6.2.1 Changes at Specific Groundwater Monitoring Locations Over Time

At SWMU 15, there are not many wells where temporal data are available to evaluate changes in groundwater contaminant levels. This is either because (1) groundwater sampling was performed using temporary probes that were removed after sampling, (2) monitoring wells were located in areas that were not contaminated, or (3) monitoring wells were destroyed or abandoned during the excavation of contaminated soils and construction of the biopile. Table 5-2 summarizes historical and current results for BTEX in monitoring wells. Three wells (MW-05, MW-09, and MW-15), which had benzene concentrations above the MCL in 1994, were located in the excavation or biopile area and destroyed prior to the 2000 sampling event. Several wells that did not have BTEX

contamination in 2000 were also uncontaminated when they were first sampled in 1994 and 1995.

Well MW-07, located east of former tank G-6, was sampled in both 1994 and 2000. The 1994 results indicated benzene and xylenes at 300 and 80 μg/L, respectively. In 2000, these compounds were not detected in MW-07. This suggests that the BTEX detected at MW-07 in 1994 had completely attenuated to below detection limits by the time the well was resampled in 2000.

### 6.2.2 Changes Along Groundwater Flowpaths

Groundwater monitoring probes installed during the 2000 DPT investigation were grouped into five flowpaths along the direction of groundwater flow. The flowpaths are shown in Figure 6-2. Flowpaths A, B, and G originate within the assumed NAPL zone at the base of the Columbia Aquifer, which generally falls within the 3,000 μg/L BTEX contour line. Flowpaths F and H are located on either side of the assumed NAPL source area. Figure 6-3 shows benzene concentrations along the flowpaths.

Flowpath A wells had consistently high benzene concentrations (from 1,120 to 5,000 μg/L) between MIP4 and DW07. If NAPL is present, benzene would be maintained at high concentrations along the flowpath due to dissolution from the NAPL into the groundwater. Approximately 110 feet downgradient of DW07, the benzene concentration is 5.9 μg/L at DW10. If the edge of the NAPL source area is located just downgradient of DW07, then the reduction in benzene concentration at DW10 would be due to natural attenuation processes.

Flowpath B wells also had high benzene concentrations (from 2,118 to 6,910 μg/L) at wells DW06, DW12, DW13, and DW17. A drop in concentration between DW06 and DW12 may be due to fingering of the NAPL or discontinuous source areas, such as another source area in the vicinity of DW07. Downgradient of DW12, the benzene concentrations drop to 73 μg/L at DW11 and below detection limits at DW27, over a distance of approximately 200 feet. If DW12 is located near the edge of the NAPL source area, the changes in benzene concentrations would again likely be due to natural attenuation processes.

Flowpath G wells also show a decrease in benzene from 8,090 μg/L at DW22 to 97 μg/L at DW24, although the rate of decrease is slower than what was observed in the downgradient plumes along Flowpaths A and B. Flowpaths F and H show a rise in benzene concentrations at wells nearest to the hotspots, but it appears that these wells are generally not within the suspected NAPL source area.

BTEX attenuation within the dissolved-phase plume appears to occur within 200 feet along Flowpaths A and B. This agrees with other numerous other studies where dissolved-phase petroleum hydrocarbon plumes have generally been observed to be less than 250 feet in length. For example, an extensive analysis of 271 leaking underground fuel tank sites in California showed that plume concentrations greater than 10 μg/L of benzene extended no more than 250 feet in 90 percent of the cases (Rice, 1995).

## 6.3 Geochemical Indicators of Biodegradation

The following is a discussion of the analytical parameters used to assess intrinsic bioremediation. Table 6-2 shows the concentrations of the geochemical indicators at the six most contaminated wells in comparison to the concentrations at the background wells. Appendix F contains a summary of the geochemistry data from the February 2000 sampling event.

### 6.3.1 Biodegradation Mechanisms

*Aerobic Respiration:* Oxygen is the highest energy-yielding electron acceptor for biodegradation of organic constituents. Throughout the site dissolved oxygen levels are generally low. The low background oxygen concentrations observed at the site suggest that aerobic biodegradation of the BTEX compounds is not a significant removal mechanism.

*Denitrification*: When the oxygen in a contaminated site has been depleted the next efficient terminal electron acceptor to be consumed is nitrate. The concentrations of nitrate and nitrite are extremely low throughout the site. The background concentrations of nitrate and nitrite were below detection limits and for this reason it is assumed that nitrate reduction is not a significant factor in the degradation of BTEX at this site.

*Iron Reduction*: The background concentrations of iron(III) are very low, which is to be expected because in the Iron (III) state the iron precipitates as an oxide, and thus will not be detected in the dissolved phase. Background concentrations of iron(II) averaged 0.09 mg/L, while at the most contaminated wells the average concentration was 16.7 mg/L. Figure 6-2 shows graphically that areas with elevated total BTEX concentrations correlate with the areas having elevated iron(II) concentrations. This is a strong indication that anaerobic biodegradation of the BTEX compounds by iron reduction has occurred at the site.

*Sulfate Reduction*: Background concentrations of sulfate ranged between 8.6 and 23.3 mg/L. The sulfate concentration in contaminated wells MW-16 and MW-20 was within the range of the background concentrations and does not appear to indicate that biodegradation by sulfate reduction is occurring. The lower sulfate concentration at MW-18 follows the expected pattern for sulfate-reducing biodegradation. The high sulfate concentration reported in MW-19 (121 mg/L) appears to be an outlier.

*Methanogenesis:* This appears to be the largest contributor to BTEX degradation at this site. The background concentration of methane averaged 0.04 mg/L while at the contaminated wells the average concentration was 10.8 mg/L. Figure 6-3 shows graphically that areas with elevated total BTEX concentrations correlate with the areas having elevated methane concentrations. This is a strong indication that anaerobic biodegradation of the BTEX compounds by methanogenesis has occurred at the site.

### 6.3.2 Expressed Assimilative Capacity

Geochemical data can also be used with stoichiometric relationships to estimate the mass of BTEX degraded by biodegradation processes. The term "expressed assimilative capacity" (EAC) refers to the amount of intrinsic hydrocarbon mineralization resulting from aerobic and anaerobic biodegradation that can be accounted for by observed changes in concentrations of electron acceptors and metabolic byproducts. The stoichiometric relationships

were presented in Section 1. Table 6-3 summarizes the mass balance equations for calculating the EAC for BTEX compounds.

Applying these calculations to the 2000 sampling results, the EAC for natural attenuation processes to biodegrade BTEX contamination is calculated. Table 6-4 summarizes the results. These results indicate that there are adequate levels of electron acceptors in the plume for biodegradation and that BTEX is being biodegradated by several anaerobic pathways. Iron reduction and methanogenesis appear to be the predominant biodegradation pathways.

### 6.3.3 Other Geochemical Indicators

*Ethane/Ethene*: These compounds are the ultimate metabolic byproducts of reductive dehalogenation of chlorinated compounds. The concentrations of ethane and ethene averaged 102 and 29 ng/L, respectively, in the background wells north of SWMU 15, while the concentration of ethane and ethene in the most contaminated wells averaged 43,852 and 1,294 ng/L respectively. The maximum ethane concentration of 89,723 ng/L and the maximum ethene concentration of 5,992 ng/L were both found at OW15-MIP04. Figure 6-6 depicts the concentrations of these daughter products, and indicates that the highest levels of degradation to ethane and ethene occurred around the soil excavation area. These elevated concentrations suggest that chlorinated compounds existed under the soil excavation area at one time and were subsequently degraded to undetectable levels. During the 2000 sampling event trichloroethene was detected in only one well (15-MW06) that was located just to the east of the excavated area. Another ethane hotspot is located around the 15-DW07 groundwater sample. In this same vicinity 1,1-dichloroethane was detected in four direct-push groundwater samples (15-DW01, 15-DW04, 15-DW08, and 15-DW-12) in 2000.

Historically, chlorinated compounds have only been detected four times:

- in November 1992, trans-1,2-dichloroethane was detected in a direct-push groundwater sample (15-GP08) that was located to the west of Tank G-9,
- in February 1994, 1,1,1-trichloroethane was detected in a direct-push soil sample (15-GS14) that was located just to the east of the excavated area,
- in September 1994, cis-1,2-dichloroethane was detected in two direct-push groundwater samples (15-GP27 and 15-GP28) that were located just north of Tank G-9, and
- in February 1995, trans-1,2-dichloroethane and vinyl chloride were detected in a direct-push groundwater sample (15-GP30) that was located south of the site.

All the chlorinated compound detections from the historical data and the 2000 sampling event were significantly below maximum contaminant levels (MCLs) and risk based concentrations (RBCs), except the 1995 vinyl chloride concentration that exceeded both the MCL and RBC.

*Alkalinity*: This parameter is a measure of a groundwater's ability to buffer changes in pH caused by the addition of biologically generated acids. It is also an indication of the amount of carbon dioxide dissolved in the groundwater. Carbon dioxide is an ultimate metabolic byproduct of aerobic respiration, denitrification, iron reduction, and sulfate reduction. The average alkalinity concentration in the most contaminated wells at SWMU 15 was 25 times

greater than the average concentration in the background wells. This is a strong indication that biodegradation of the BTEX compounds has occurred at the site.

*Conductivity*: The more ions a solution contains, the higher the conductivity. At SWMU 15, the average conductivity value in the most contaminated wells is double the average value in the background wells. This is probably due to the increase in iron(II) and alkalinity in the contaminated wells and suggests that degradation is occurring.

*Oxidation-Reduction Potential (ORP)*: The redox potential of a groundwater system depends on which electron acceptor is being reduced by microbes during BTEX oxidation. ORP ranges from +500 mV for aerobic conditions to –300 mV or less for methanogenic conditions. At SWMU 15, the average background ORP value was 173 mV while the average ORP value in the most contaminated wells was –351 mV. Wells with low redox potentials coincide with the wells having high BTEX contamination, elevated iron(II) concentrations, and elevated methane concentrations. This gives evidence that biodegradation by iron reduction and methanogenesis has occurred.

*pH*: The pH of a solution is the negative logarithm of the hydrogen ion concentration [$H^+$]. Microbial activity tends to be reduced outside of a pH range of 5 to 9. Many anaerobic bacteria are particularly sensitive to pH extremes. The pH will increase as the alkalinity of the solution increases; this is seen at SWMU 15. The pH ranged from 4.8 to 5.8 in the background wells that had little/no alkalinity and in the most contaminated wells that had high alkalinity the pH ranged from 5.9 to 6.3. This increase in pH is further proof that there has been an increase in the $CO_2$ released as a result of biodegradation.

*Temperature*: Temperature affects the types and growth rates of bacteria that can be supported in the groundwater environment, with higher temperatures generally resulting in higher growth rates. Elevated temperatures can also occur as a result of the exothermic biodegradation reactions. This is seen at SWMU 15. The background temperature at SWMU 15 averages 12.0 °C while the temperature of the most contaminated wells averages 15.7 °C. This increase in temperature may indicate that exothermic biodegradation reactions have occurred.

*Total Organic Carbon*: This is a measure of the total concentration of organic material in groundwater that may be available for biological degradation. TOC detects decomposing plant and animal organic matter, volatile and semivolatile organic contaminants, and microorganisms. At SWMU 15, the average background TOC concentration was 5.2 mg/L while the contaminated wells had an average TOC concentration of 21 mg/L. Only 6.7 mg/L of this average TOC concentration was from the BTEX. Although the presence of soluble, non-BTEX components of fuel were not analyzed for (which could contribute to TOC), the difference between the TOC and BTEX concentrations could be also be due to the presence of a large microbial population, which would indicate that microorganisms are present and thriving in the BTEX contaminated regions.

### 6.3.4 Summary of Geochemical Indicators

The data presented above suggest that mineralization of BTEX compounds is occurring through the microbially mediated processes of iron reduction and methanogenesis. A horizontal correlation between BTEX, iron(II), and methane was interpreted from the plume maps in Figures 6-4 and 6-5. A vertical correlation can also be interpreted from the vertical

cross section of segment A-A′ in Figure 6-7 where iron(II) and methane concentrations increase with depth as BTEX concentrations increase.

## 6.4 Groundwater Modeling With Biodegradation

### 6.4.1 Modeling Overview

A three-dimensional, screening-level, groundwater model was developed to test different hypotheses of NAPL distribution and the fate and transport of groundwater contaminants, and predict the effectiveness of various remedial actions including natural attenuation. A description of groundwater model is presented in Appendix J. Some of the questions evaluated with the model are:

- Can the benzene distribution reported in the 2000 sampling results be replicated assuming various configurations of a residual NAPL source area at the groundwater table?
- Does the size of the benzene plume indicate that biodegradation is occurring?
- How long will the benzene persist until natural attenuation brings concentrations below cleanup goals (5 μg/L)?

It is important to acknowledge that modeling is an approximation. The complexity of site hydrogeology and chemical deposition is rarely determined even during comprehensive site investigations. Modeling results are sensitive to input parameters such as source character, size, and concentration, aquifer properties, and monitoring locations (relative to the source area and dissolved-phase plume boundaries). Therefore, simplifying assumptions regarding site parameters and remediation processes are used. The following general assumptions were used in setting up the models:

- The prevailing groundwater flow direction on the south side of the excavation pit is assumed to be towards the southwest, as shown by groundwater elevation measurements taken during May 2000 and February 2001.
- The contaminant source area (i.e., area with residual or free-phase NAPL in soil) is assumed to be where free product (sheen or greater thickness) has been observed during the groundwater sampling events. This generally corresponds to locations where benzene concentrations greater than 3,000 μg/L have been reported.
- The anaerobic biodegradation of benzene is assumed to follow a first-order decay process.
- Benzene biodegradation rates are assumed to be similar in the source area and the dissolved-phase plume.
- All simulations were run at steady-state. Therefore, the modeling does not take into account any transient effects such as spatial variations in groundwater velocity and flow direction.
- The aquifer system was assumed to be clean at the beginning of each simulation.

A primary objective of this screening assessment is to provide data that improves the understanding of site conditions and processes that are expected to most greatly affect the remediation rate.

### 6.4.2 Modeling Overview

To further evaluate the hypothesis that natural attenuation may be occurring at the site, three sets of model simulations were performed using the three-dimensional numerical model described in Appendix J. These simulations assume either a shallow NAPL source located within the upper two feet of the Columbia Aquifer, a deep LNAPL source located near the bottom of the Columbia Aquifer within the upper two feet of the silt/clay aquitard, or a combination of the two. For simulations containing a shallow source, it was assumed that the source was present at the site for 30 years (1965-1995) and that the portion of the source located within the pond excavation was excavated in 1996. Later portions of the simulations assume a modified source extent with the excavated portion of the source removed. All of the simulations described below assume a benzene biodegradation half-life of 300 days. These simulations are described below.

1. A simulation assuming a shallow NAPL source term located in the uppermost two feet of the Columbia Aquifer. The extent of the source term is defined by the extent of observed BTEX concentrations in groundwater above 3,000 μg/L (Figure 6-1). The data used to define this distribution of contamination were collected from the deeper portion of the Columbia Aquifer. However, due to the lack of shallow groundwater quality data over much of this area, it was assumed that this extent was also a reasonable representation for a shallow benzene source. The source concentration declines over time according to the three-phase TTCU tool described in Appendix J.

2. A simulation that assumes an NAPL source near the base of the Columbia Aquifer within the upper two feet of the silt/clay aquitard that is identical in extent to the shallow source (Figure 6-1). The source concentration declines over time according to the three-phase TTCU tool described in Appendix J.

3. A simulation that combines the shallow and deep sources described for the first two simulations. The concentration in both sources declines over time according to the three-phase TTCU tool described in Appendix J.

### 6.4.3 Modeling Results

The first simulation assumes an NAPL source area with declining concentrations over time based on the assumptions contained in the TTCU model, and an extent defined by BTEX concentrations in groundwater greater than 3,000 μg/L. The configuration of the source reactors used in the TTCU tool is shown in Figure 6-8. The decline in source concentrations for reactors 1, 5, and 10 are shown in Figure 6-9. With a 300-day benzene half-life, the benzene concentrations in the source area will decline to the MCL in approximately 260 years. The simulated distribution of benzene in the shallow and deep portions of the Columbia Aquifer is shown on Figure 6-10. The simulation predicts a benzene plume with an extent that is similar to that observed in the field. The influence of the pond excavation is evident with lower benzene concentrations simulated at that location. Due to the assumption of a shallow source zone however, this simulation also predicts higher benzene

concentrations in the shallow portion of the aquifer than in the deeper portions. Water quality data collected at the site suggest that benzene concentrations are actually higher in the deeper portions of the Columbia Aquifer. However, it should be noted that only a few shallow groundwater samples have been collected at the site, and the actual distribution of benzene in the shallow groundwater is poorly defined.

The second simulation assumes a NAPL source near the bottom of the aquifer in the upper two feet of the silt/clay aquitard. This source area exhibits declining concentrations over time based on the assumptions contained in the TTCU model, and an extent defined by the area with BTEX concentrations greater than 3,000 µg/L in groundwater. The configuration of the source reactors and transient variability in source concentrations is identical to the shallow source described above. The model forecast distribution of benzene concentrations in year 2000 for both the shallow and deep portion of the aquifer are shown on Figure 6-11. These simulation results agree reasonably well with the plume extent observed in the field. Due to the assumption of a deep source, the model results predict higher benzene concentrations in the deeper portion of the aquifer, which is consistent with water quality data collected at the site.

The final simulation assumes both a shallow and a deep source area as were defined in the two simulations described above. The forecasted benzene plumes in the year 2000, both for the shallow and deep portions of the Columbia Aquifer, are shown on Figure 6-12. The extent of the benzene plume predicted by this simulation is similar to the previous runs, however the benzene concentrations in the shallow portion of the alluvial aquifer exceed those simulated in the deeper portion of the aquifer. Similar to Run 1 with a shallow source only, the influence of the pond excavation on benzene concentrations is evident in Figure 6-12.

In summary, the simulations performed here all produce plumes that reasonably match the observed plume extent in the field. However, the simulations that include a shallow source area suffer from over-prediction of benzene concentrations in the shallow portion of the Columbia Aquifer. This distribution cannot be confirmed with the limited groundwater data that is available for the benzene distribution in shallow groundwater at the site.

## 6.5 Conclusions and Recommendations for Scenario Supporting Natural Attenuation

### 6.5.1 Conclusions

Several evaluations were performed as part of this study to determine if the "weight of evidence" indicates that natural attenuation is occurring at SWMU 15. The following conclusions support the hypothesis that natural attenuation is remediating contaminated groundwater at the site:

- Elevated levels of benzene in groundwater appear to be caused by residual NAPL at the water table and at the base of the Columbia Aquifer, up to several hundred feet south of the former tank farm area that was excavated in 1996. The evidence for NAPL includes field observations of free product sheen on groundwater samples from wells and test

pits, and benzene concentrations that are near the theoretical effective solubility for dissolved-phase benzene in contact with NAPL.

- BTEX compounds attenuate from greater than 1,000 μg/L near the edges of the apparent NAPL source area to less than 10 μg/L within 200 feet along groundwater flowpaths.
- Temporal data at well MW-07, located east of former tank G-6, indicates that benzene and xylenes decreased from 300 and 80 μg/L in 1994 to non-detect in 2000
- Changes in electron acceptor and metabolic byproduct concentrations between the contaminated plume and reference background locations suggests that biodegradation of BTEX compounds is occurring, with iron reduction and methanogenesis being the likely dominant processes.
- The calculated first-order biodegradation rate constant for benzene ranges from 0.0006 to 0.0036 $day^{-1}$ (half-lives of 192 to 1136 days). The average biodegradation rate is approximately 0.0023 $day^{-1}$ (half-life of 300 days).
- Groundwater modeling simulations assuming a relatively large NAPL area and a benzene biodegradation half-life of 300 days produce simulated plumes that reasonably match the observed plume extent in the field.

### 6.5.2 Recommendations

The evidence for natural attenuation at SWMU 15 is related to the apparent distribution of NAPL up to several hundred feet south of the former tank farm area that was excavated in 1996. If monitored natural attenuation is selected as a remedial action for SWMU 15, verification of the NAPL is recommended for the DPT sampling locations DW01 through DW01, DW13, DW17 and DW22 (shown in Figure 6-1). Confirmational soil and groundwater sampling should be performed at both shallow (water table) and deeper depths near the bottom of the Columbia Aquifer. If the presence of NAPL is verified, additional samples may be required to determine the downgradient edges of the NAPL source zone. Monitoring wells for monitoring natural attenuation would then be installed along groundwater flowpaths as follows:

- One well at an uncontaminated upgradient location
- One well at the downgradient edge of the NAPL source zone, and
- Two or three wells within the downgradient dissolved-phase plume.

Additional "sentinel" wells may be useful in uncontaminated groundwater locations further downgradient of the dissolved-phase plume to verify that the contamination is not spreading.

**TABLE 6-1**
Effective Solubilities for Benzene Resulting from Dissolution of Fresh and Weathered Fuels

| NAPL Type | Mass Fraction | Mole Fraction | Pure-Phase Solubility (mg/L) | Effective Solubility (mg/L) |
|---|---|---|---|---|
| Fresh Gasoline | 0.0076 | 0.0093 | 1780 | 17 |
| Weathered Gasoline 1 | 0.01 | 0.0137 | 1780 | 24 |
| Weathered Gasoline 2 | 0.0021 | 0.003 | 1780 | 5 |
| Virgin JP-4 | 0.005 | 0.023 | 1780 | 42 |

Reference: Newell et al. (1997)

## Table 6-2
## Comparison of the Concentrations of MNA Parameters in Background Wells and Contaminated Wells
## SWMU 15 - NAS Oceana

*Concentrations of Geochemical Indicators in Background Wells (mg/L)*

| | | Average | MW-10 (3-18ft) | MW-11 (5-20ft) | MW-12 (5-20ft) | MW-13 (5-20ft) | MW-14 (5-20ft) | MW-18 (3-18ft) |
|---|---|---|---|---|---|---|---|---|
| | Total BTEX | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Electron Acceptors used in Biodegradation | Dissolved Oxygen | 1.5 | 0.41 | 2.26 | 0.72 | 0.69 | 0.32 | 4.43 |
| | Nitrate | 0.5 | 2.35 | 0.9 | 0 | 0 | 0 | 0 |
| | Iron III | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Sulfate | 10.6 | 12.7 | 9.7 | 9.2 | 16.4 | 8.58 | 7.3 |
| Biodegradation Products | Chloride | 11.1 | 10.2 | 15 | 8.7 | 12.2 | 10 | 10.5 |
| | Ethane (ng/L) | 101.7 | 363 | 21 | 29 | 15 | 0 | 182 |
| | Ethene (ng/L) | 29.2 | 38 | 17 | 38 | 0 | 39 | 43 |
| | Iron II | 0.09 | 0 | 0 | 0 | 0 | 0 | 0.55 |
| | Methane | 0.04 | 0.007 | 0.017 | 0.006 | 0.003 | 0.0002 | 0.18 |
| | Sulfide | 0.1 | 0.1 | 0.09 | - | 0.1 | 0.1 | 0.09 |
| Other Geochemical Indicators | Alkalinity | 5 | 0 | 0 | - | 0 | 0 | 25 |
| | Conductivity (ms/cm) | 147.5 | 174 | 157 | 125 | 157 | 99 | 173 |
| | ORP (mV) | 173 | 261.1 | 269.1 | 153.9 | 138.5 | 147 | 67.7 |
| | pH (unitless) | 5.2 | 4.76 | 4.81 | 5.22 | 5.63 | 5.21 | 5.77 |
| | Temperature (°C) | 12.0 | 11 | 10.04 | 11.7 | 12.58 | 11.72 | 14.88 |
| | Total Organic Carbon | 5.2 | 4.9 | 2.2 | 4.6 | 2.6 | 13 | 4 |

*Concentrations of Geochemical Indicators in Most Contaminated Wells (mg/L)*

| | | Average | DW13-20 | DW22-20 | MIP01-22 | MIP04-22 | DW17-20 | DW05-18 |
|---|---|---|---|---|---|---|---|---|
| | Total BTEX | 6.7 | 11.2 | 8.1 | 6.0 | 5.2 | 6.0 | 4.8 |
| Electron Acceptors used in Biodegradation | Dissolved Oxygen | 0.5 | 0.07 | 0.32 | 0.26 | 1.57 | 0.4 | 0.33 |
| | Nitrate | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Iron III | 1.0 | 1.3 | 1.7 | 0.8 | 0.5 | 1 | 0.9 |
| | Sulfate | 9.2 | 0.5 | 0 | 52 | 0 | 0.5 | 2 |
| Biodegradation Products | Chloride | 14 | 16 | 15 | 11 | 13 | 14 | 15 |
| | Ethane (ng/L) | 43,852 | 28,372 | 29,424 | 79,212 | 89,723 | 17,997 | 18,966 |
| | Ethene (ng/L) | 1294.2 | 436 | 277 | 155 | 5,992 | 154 | 301 |
| | Iron II | 16.7 | 21 | 20 | 13 | 15 | 10 | 16 |
| | Methane | 10.8 | 10.6 | 16.35 | 14.65 | 12.49 | 11 | 7.3 |
| | Sulfide | 0.1 | 0.15 | 0.09 | 0.14 | 0.12 | 0.16 | 0.19 |
| Other Geochemical Indicators | Alkalinity | 126 | 105 | 133 | 140 | 140 | 115 | 120 |
| | Conductivity (ms/cm) | 335 | 565 | 257 | 348 | 269 | 310 | 362 |
| | ORP (mV) | -351 | -414.2 | -412.3 | -157.7 | -116 | -490.7 | -516.4 |
| | pH (unitless) | 6.0 | 6.06 | 6.12 | 6.29 | 5.9 | 5.92 | 5.93 |
| | Temperature (°C) | 15.7 | 15.56 | 14.9 | 16.0 | 16.63 | 16.22 | 14.88 |
| | Total Organic Carbon | 21 | 33 | 16 | 15 | 19 | 27 | 9.7 |

High Concentrations Compared to Background
Low Concentrations Compared to Background

**TABLE 6-3**
Equations for Calculating the Expressed Assimilative Capacity of BTEX through Biodegradation

| Biodegradation Pathway | Key Electron Acceptor or Metabolic Byproduct | Expressed Assimilative Capacity |
|---|---|---|
| Aerobic | $O_2$ | $0.32(C_B - C_P)$ |
| Denitrification | $NO_3^-$ | $0.21(C_B - C_P)$ |
| Manganese Reduction | $Mn^{+2}$ | $0.091(C_P - C_B)$ |
| Iron Reduction | $Fe^{+2}$ | $0.046(C_P - C_B)$ |
| Sulfate Reduction | $SO_4^{-2}$ | $0.21(C_B - C_P)$ |
| Methanogenesis | $CH_4$ | $1.28(C_P - C_B)$ |

Notes: $C_B$ = Background concentration of the key electron acceptor or metabolic byproduct
$C_P$ = Plume concentration of the key electron acceptor or metabolic byproduct
After Wiedemeier (1995)

**TABLE 6-4**
Observed Changes in Geochemical Concentrations and Calculated Expressed Assimilative Capacities for BTEX Biodegradation

| Location | Oxygen | Nitrate | Manganese | Iron | Sulfate | Methane |
|---|---|---|---|---|---|---|
| Background Wells | 0.7 | ND (0.5) | ND (0.5) | ND (0.5) | 15.5 | 0.0054 |
| Plume Well | 0.25 | ND (0.5) | ND (0.5) | 8.4 | 21.3 | 7.06 |
| EAC | 0.14 | 0 | 0 | 0.39 | 0 | 9.03 |

All measurement in mg/L

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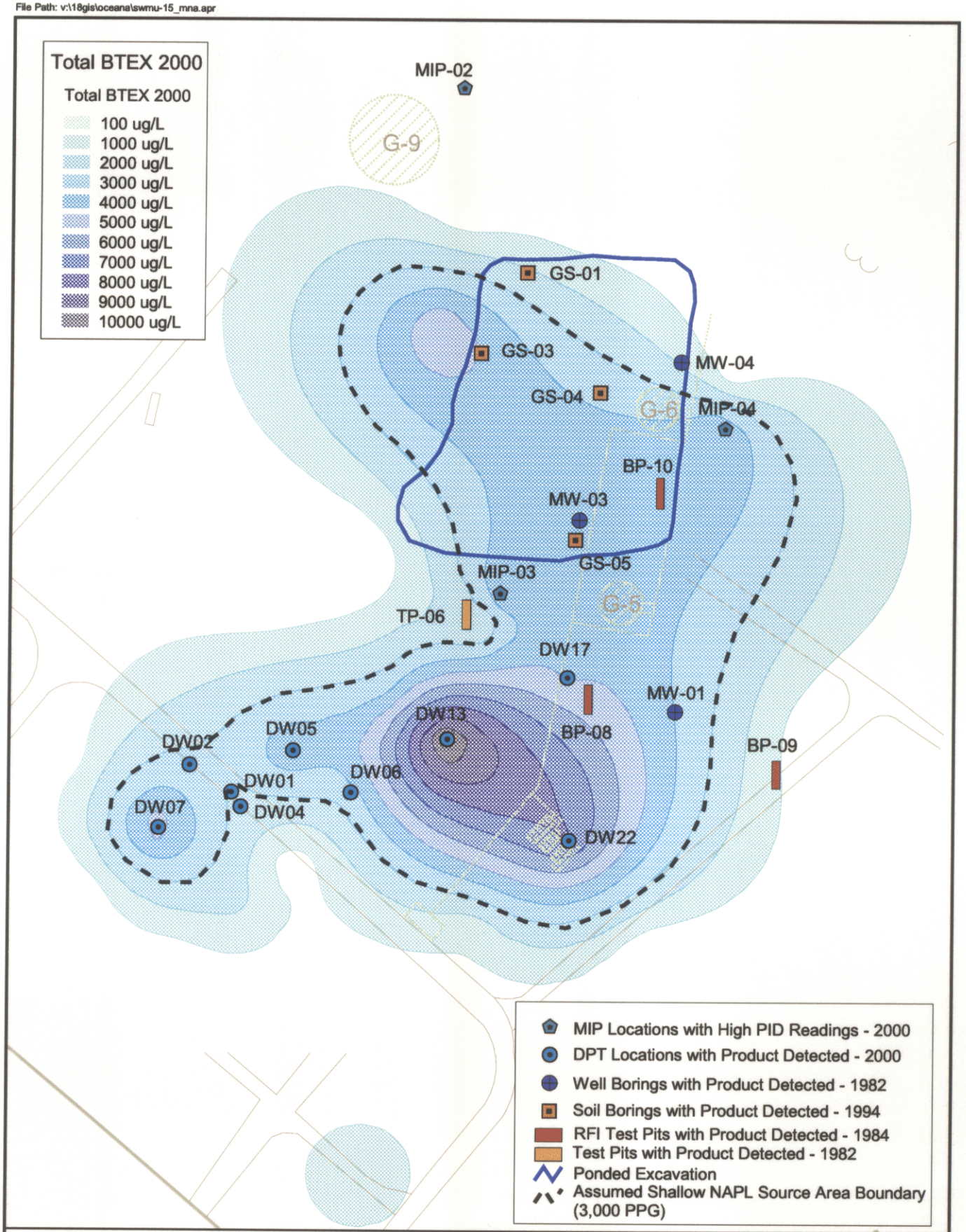



N W E S

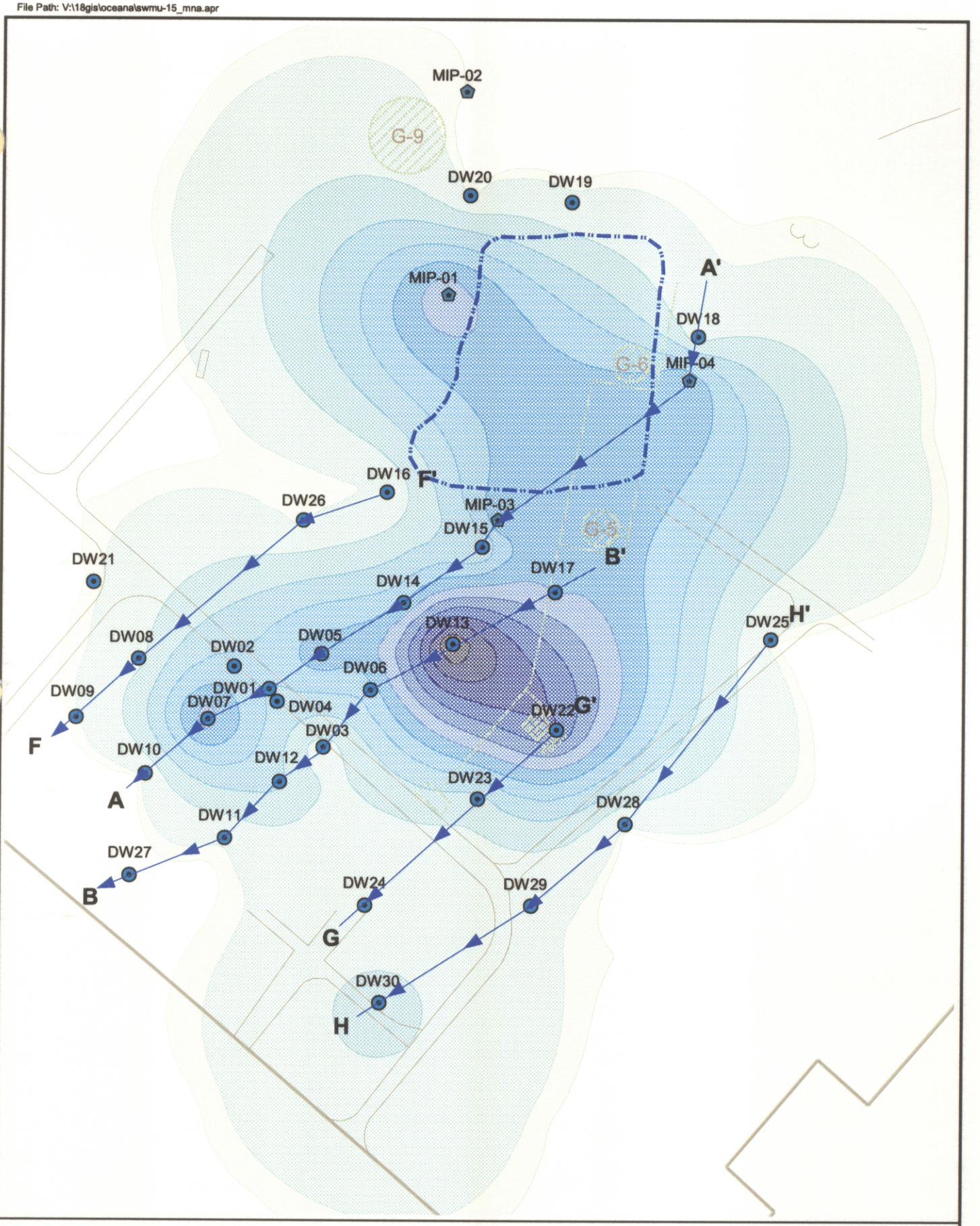
100 0 100 200 Feet

Figure 6-1
Historic Sample Locations where
Product has been Detected at SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2MHILL

00526 E BSY

File Path: V:\18gis\oceana\swmu-15_mna.apr

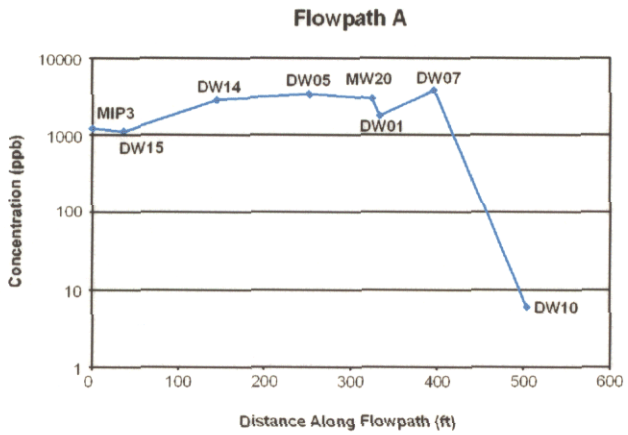


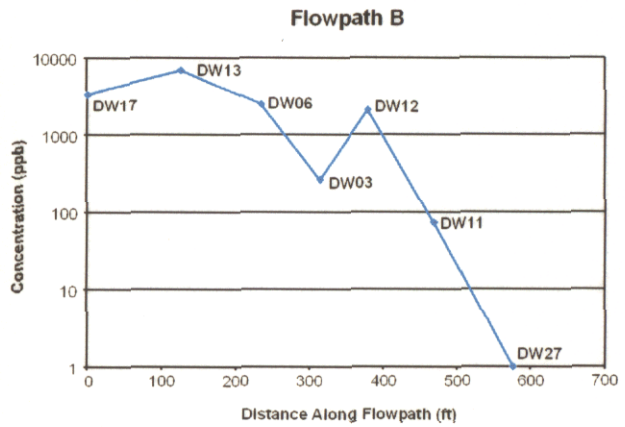

N
W E
S

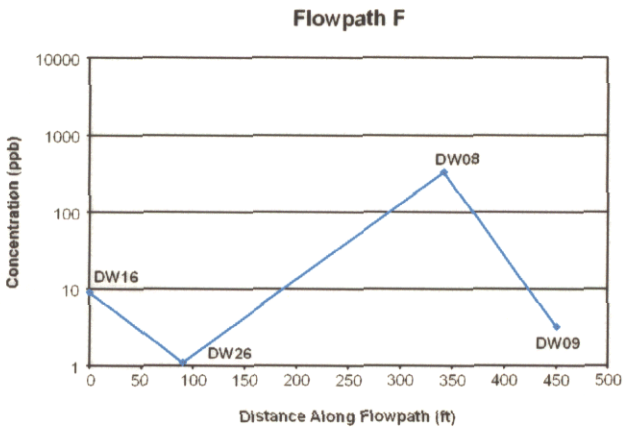
0 90 180 270 Feet

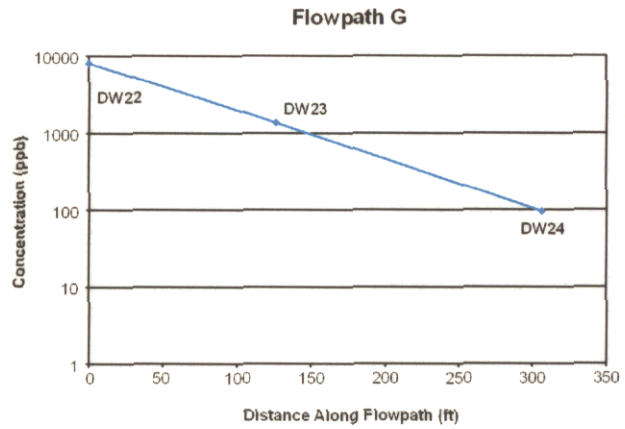
Figure 6-2
Modeled Groundwater Flowpaths - SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2M HILL



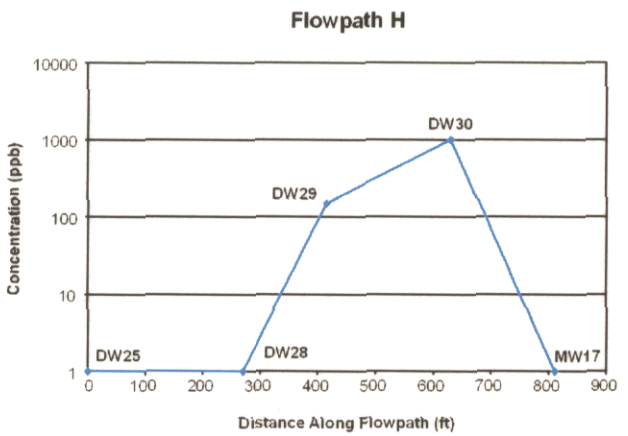




**Figure 6-3**

Benzene Concentrations Along Groundwater Flowpaths
NAS Oceana, Virginia Beach, Virginia

CH2MHILL

152830.F6 paths.hs 03/27/01 ancjb

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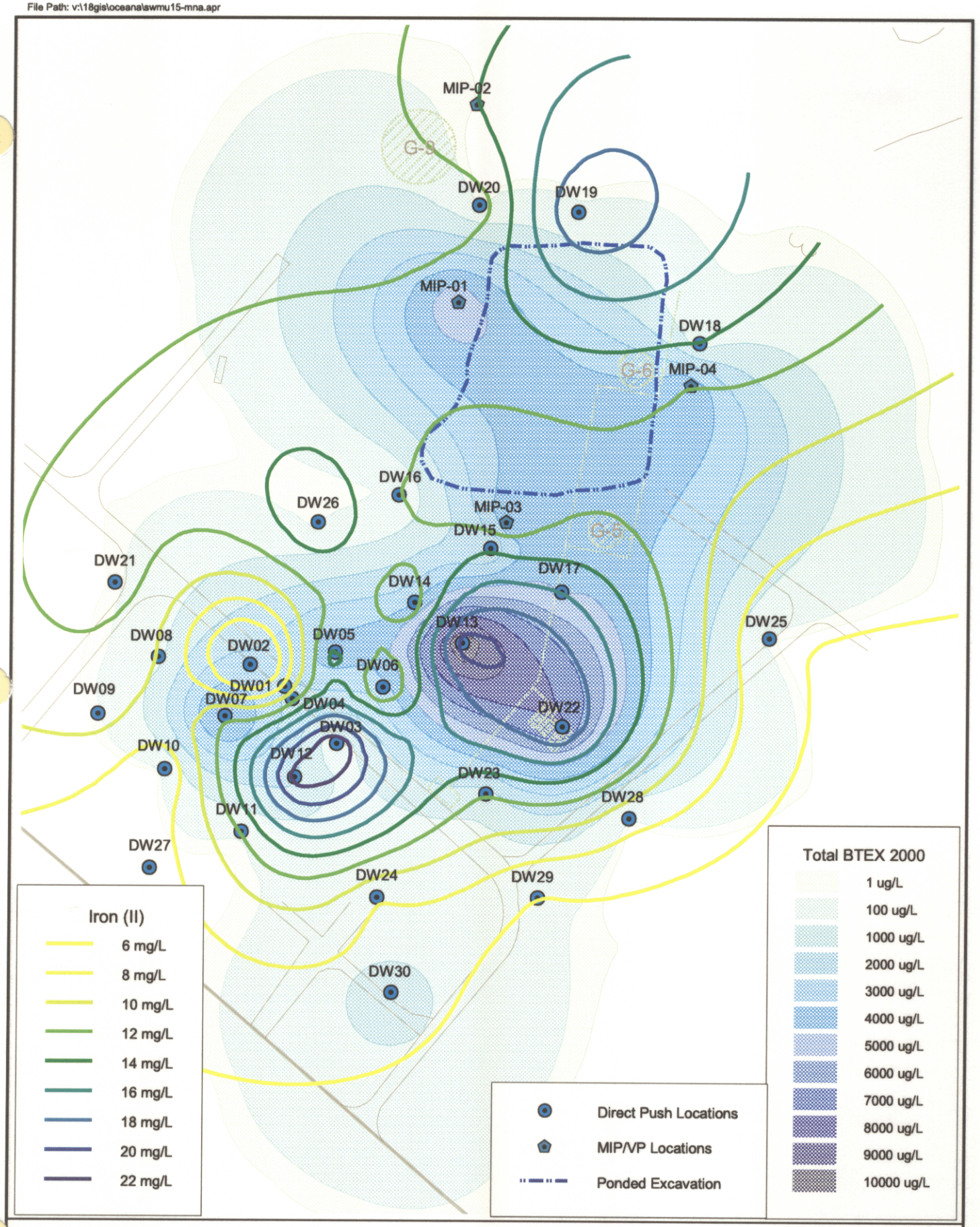


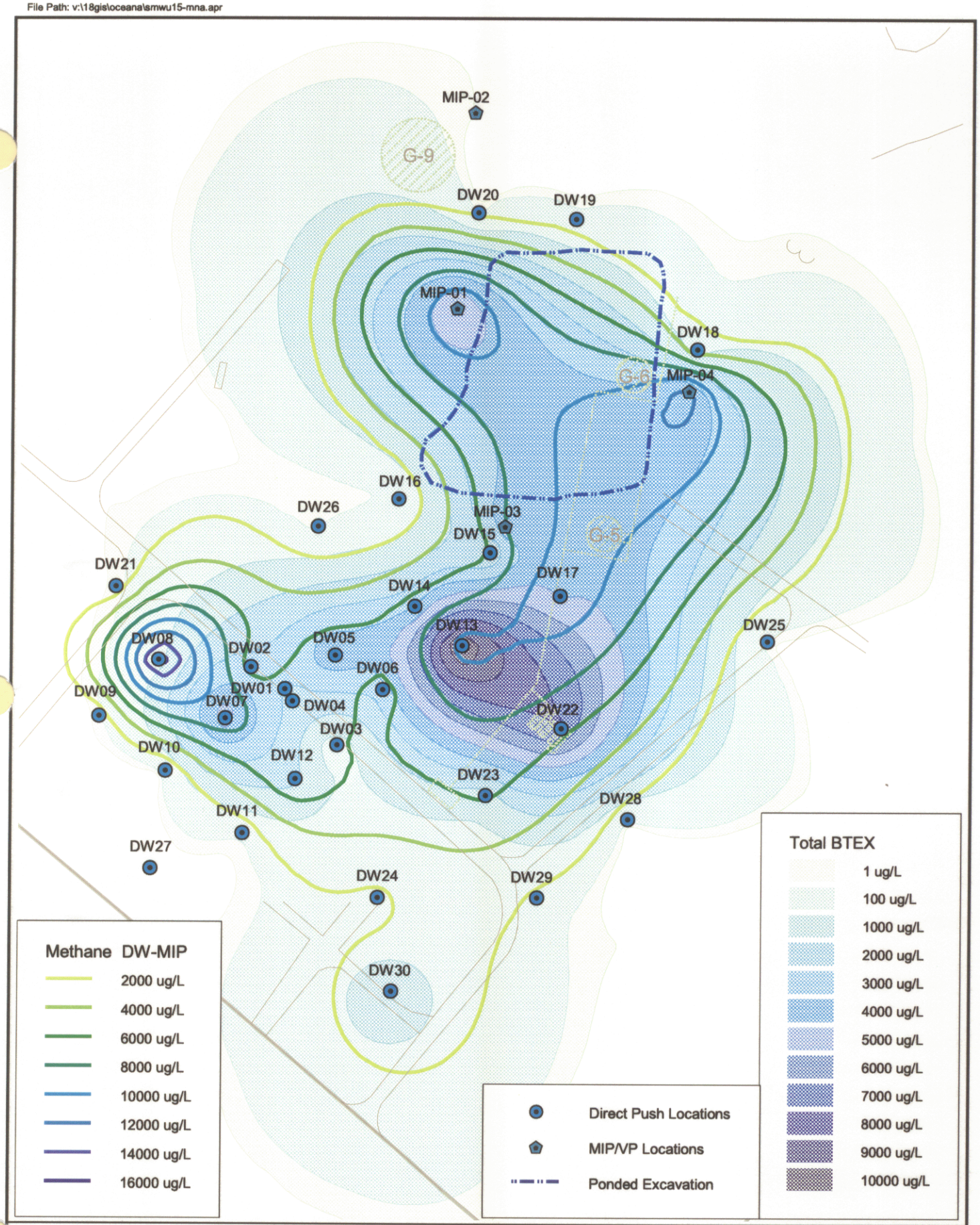

N
W E
S

0 80 160 240 Feet

Figure 6-4
Iron (II) and Total BTEX in Groundwater - SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2M HILL

File Path: v:\18gis\oceana\smwu15-mna.apr



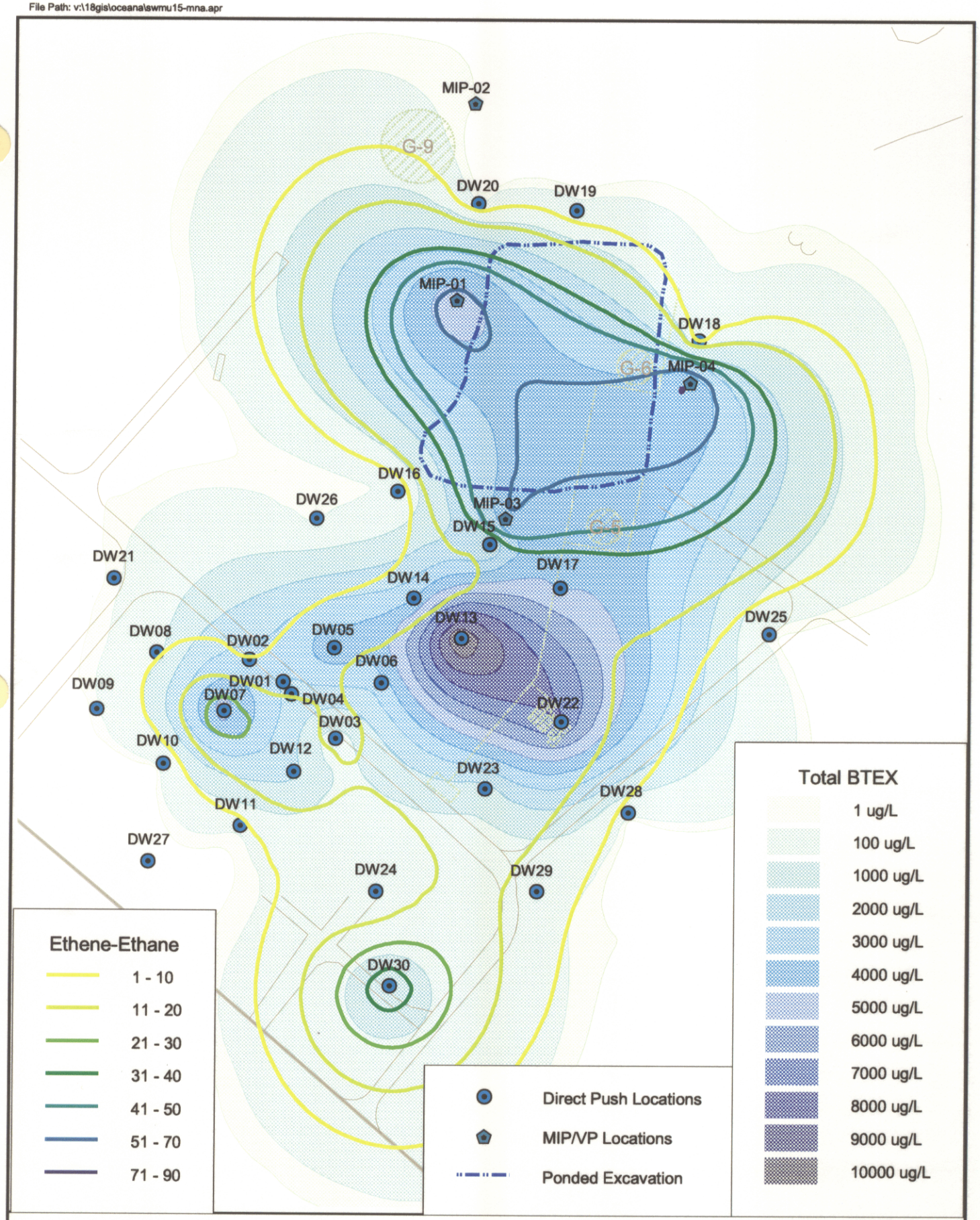

N
W E
S

0 80 160 240 Feet

Figure 6-5
Methane and Total BTEX in Groundwater - SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2M HILL

File Path: v:\18gis\oceana\swmu15-mna.apr



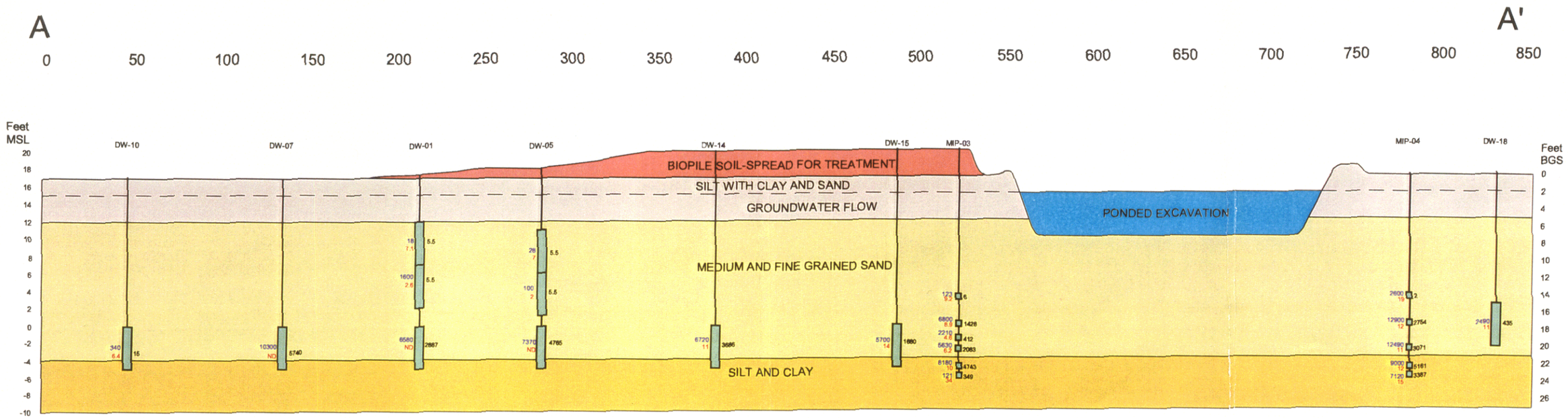

N W E S

0 80 160 240 Feet

Figure 6-6
Ethane, Ethene and Total BTEX in Groundwater - SWMU 15
NAS Oceana, Virginia Beach, Virginia

CH2M HILL

File Path: v:\18gis\oceana\fig 3-1 & 5-7 & 6-4 xsecs.apr




**LITHOLOGY**

- BIOPILE SOIL-SPREAD
- SILT W/CLAY AND SAND
- POND EXCAVATION
- MEDIUM-FINE GRAINED SAND
- SILT AND CLAY

**DPT SCREEN INTERVALS**

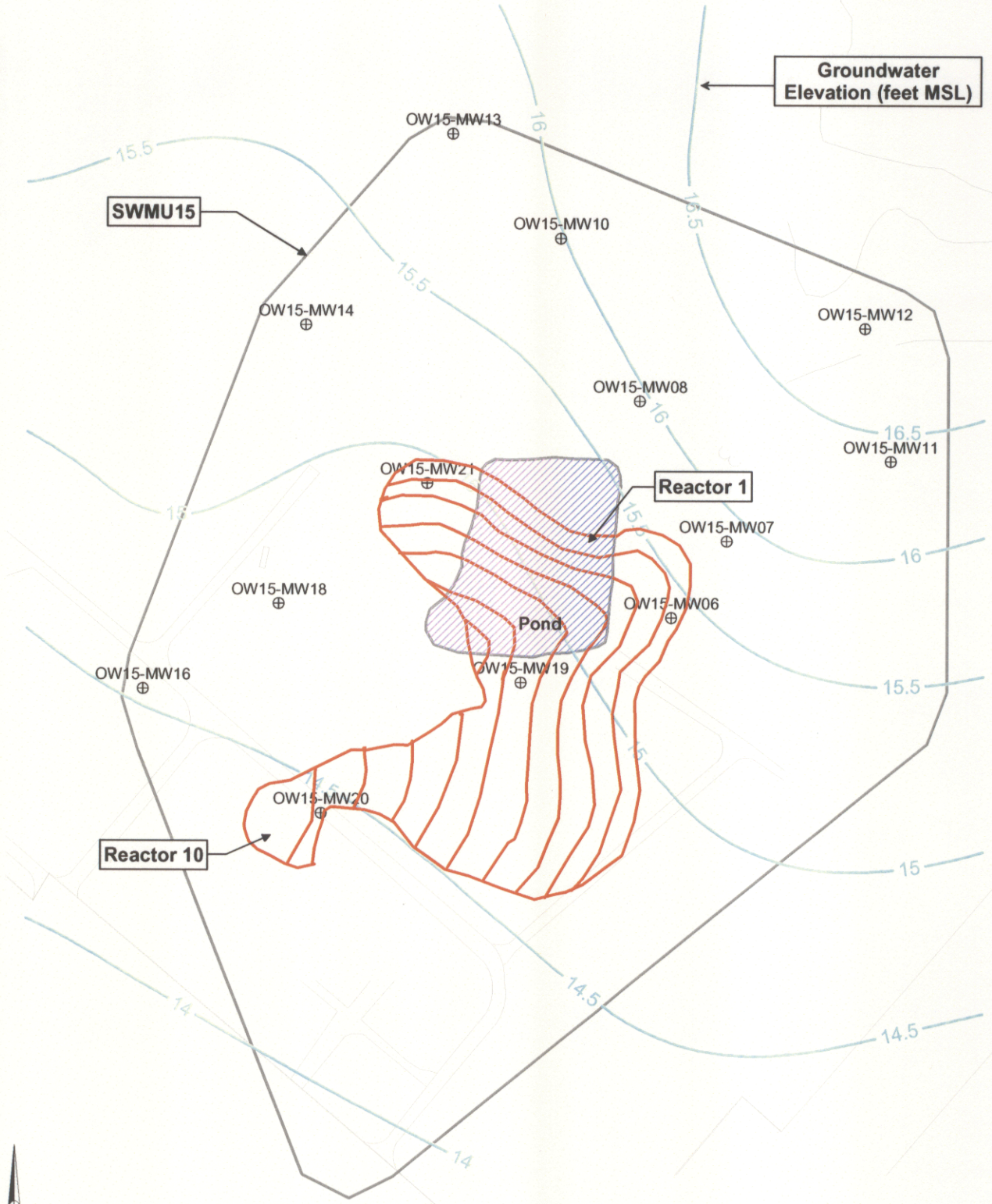
METHANE

IRON II

TOTAL BTEX

Figure 6-7
Methane, Iron (II), and Total BTEX Across
Cross Section A-A'
NAS Oceana, Virginia Beach, Virginia

CH2MHILL




0 feet 200 feet 400 feet

152630-26.SRF

**Figure 6-8**
**TTCU Reactor Configuration**
**Large Shallow Source**
**Benzene Half-Life = 300 Days**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL

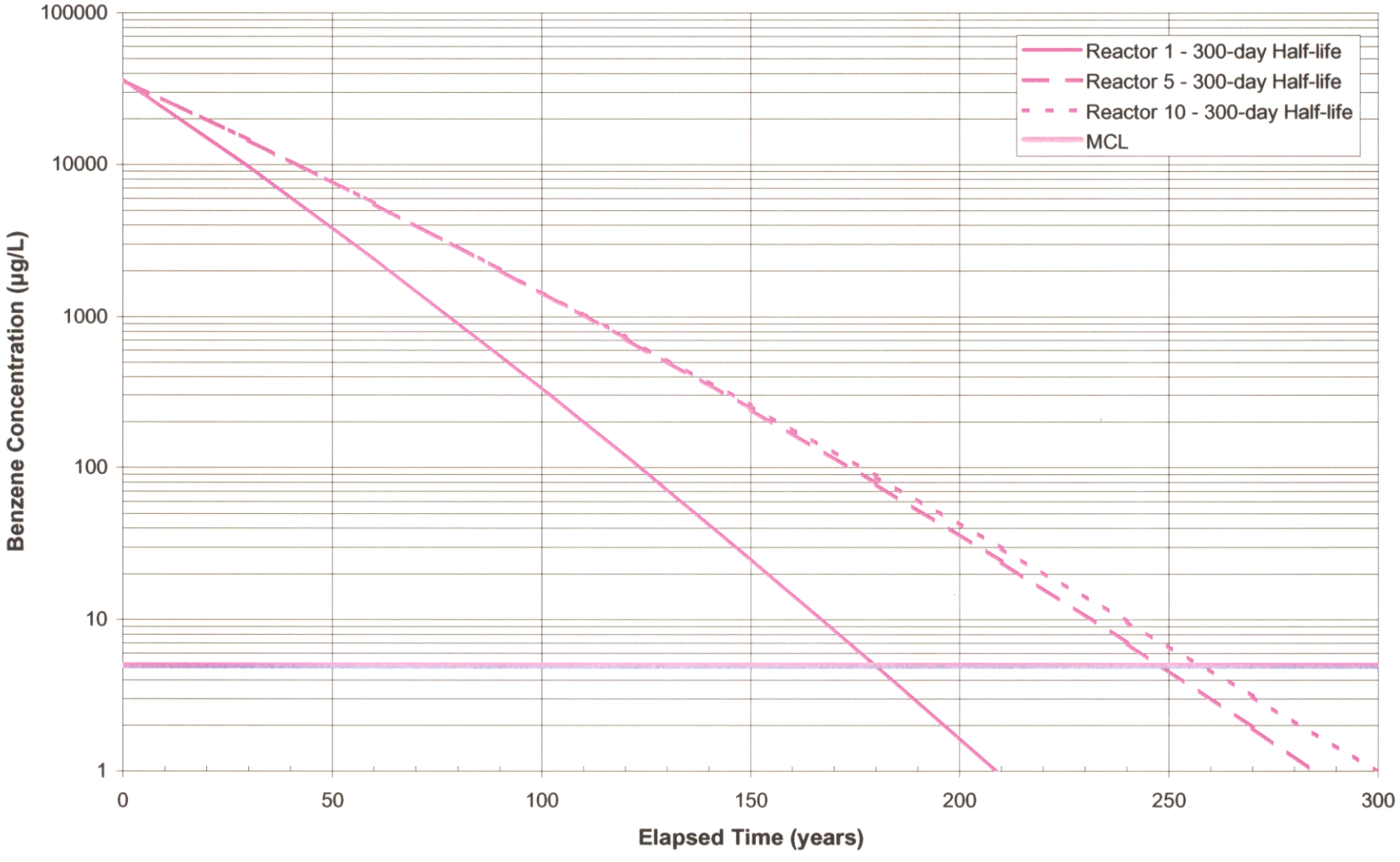



**Figure 6-9**
**Source Concentrations Over Time**
**Large Shallow Source with Biodegradation**
NAS Naval Air Station, Virgina Beach, Virginia

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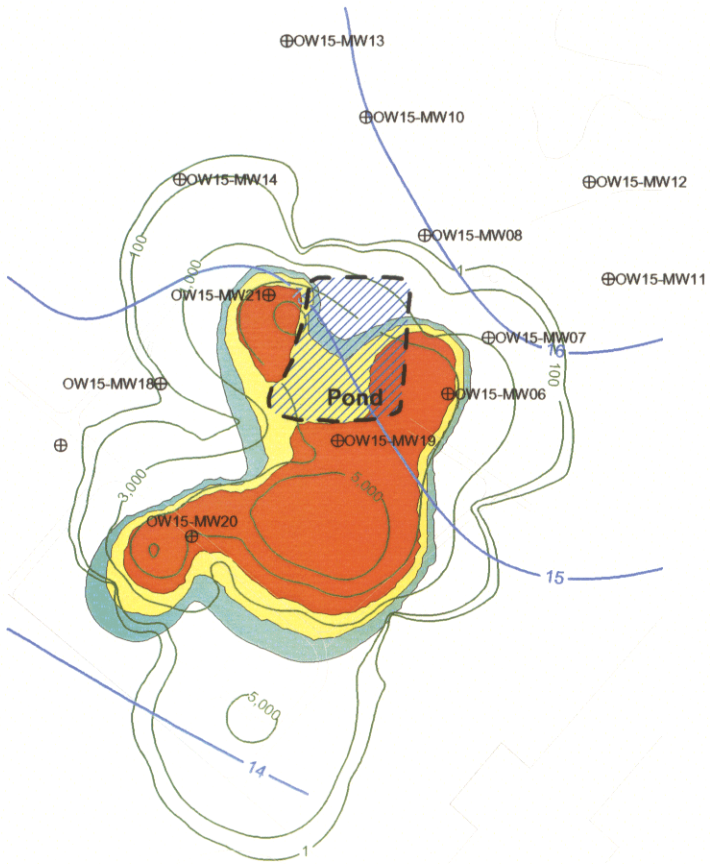
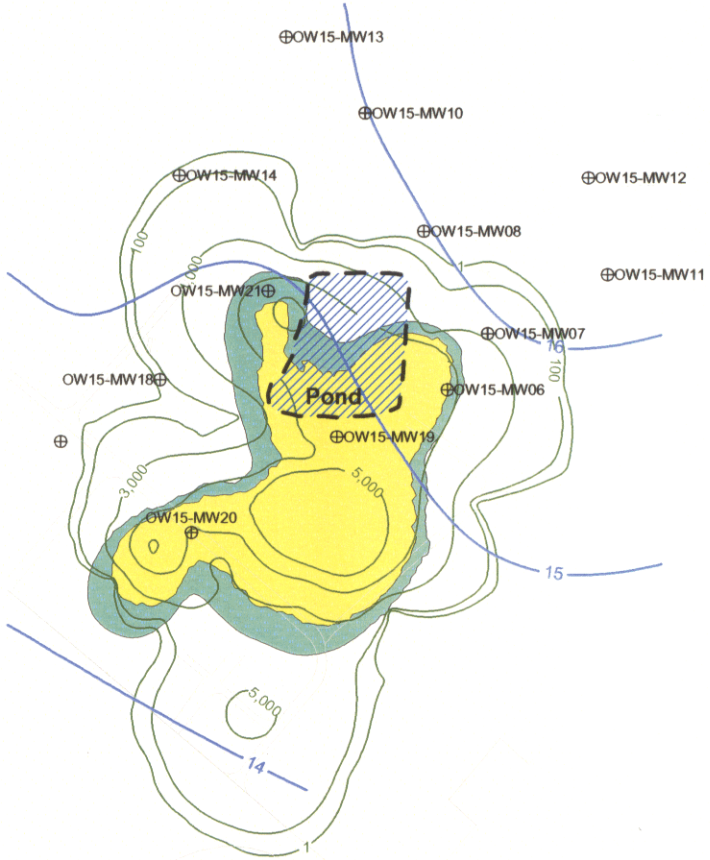
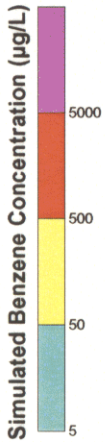
CH2MHILL




**Shallow Columbia Aquifer (4 to 12 feet BGS)**




**Deep Columbia Aquifer (12 to 20 feet BGS)**




**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

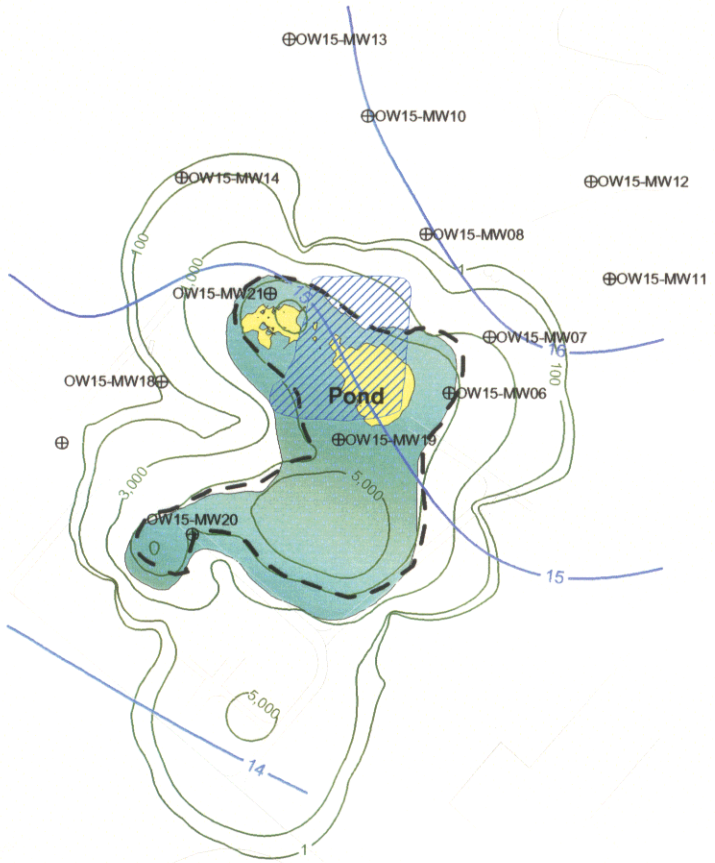
N

0 feet 350 feet 700 feet

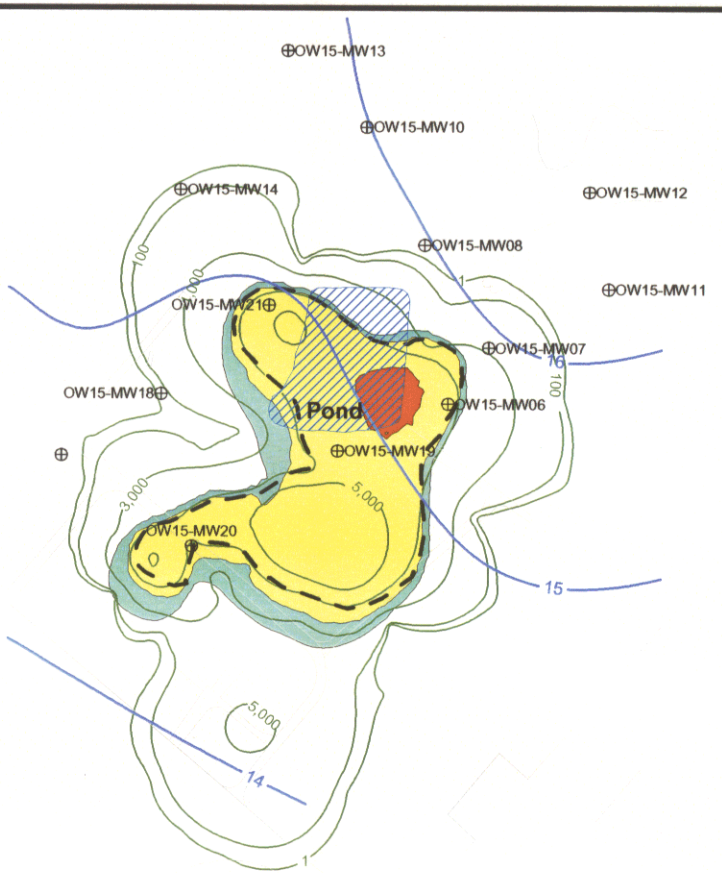
152630-02.SRF

**Figure 6-10**
**Simulated Benzene Concentrations in the Year 2000**
**(Shallow Source Only)**
**Benzene Half-Life = 300 Days**
NAS Naval Air Station, Virginia Beach, Virginia

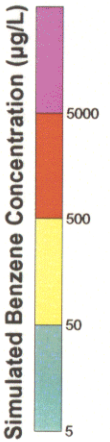
CH2MHILL




**Shallow Columbia Aquifer (4 to 12 feet BGS)**




**Deep Columbia Aquifer (12 to 20 feet BGS)**




**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

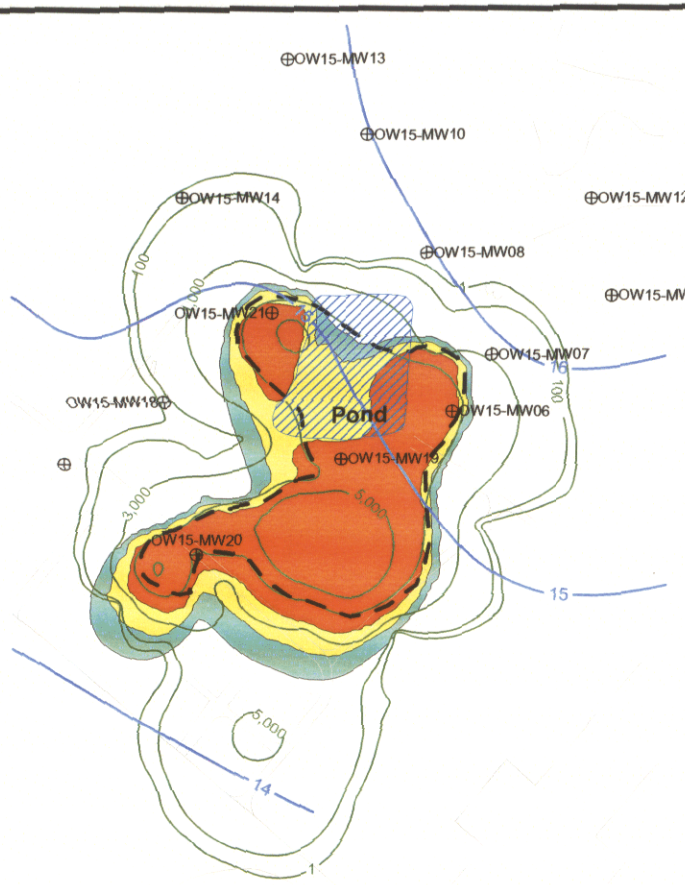
N

0 feet 350 feet 700 feet

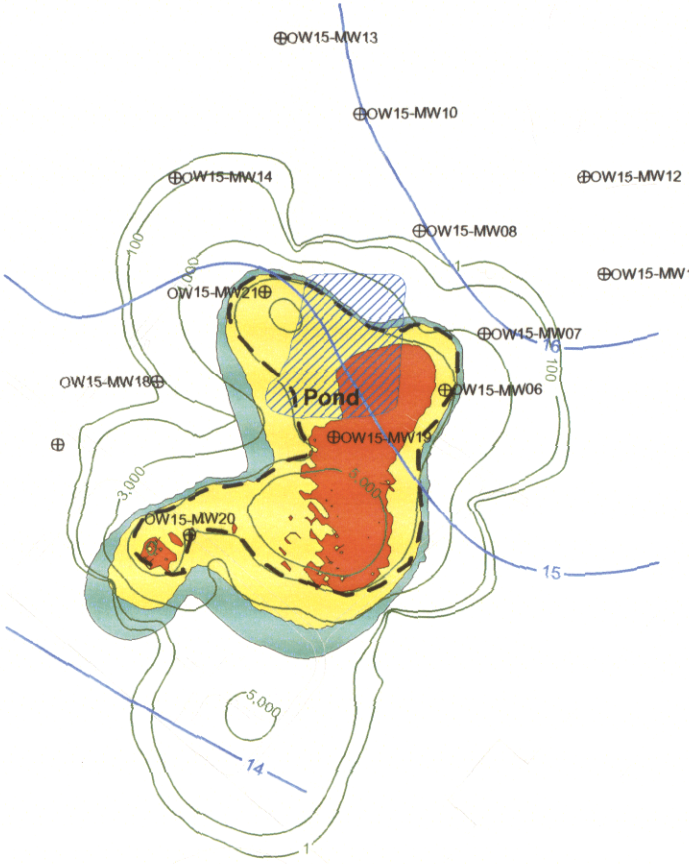
152630-03.SRF

**Figure 6-11**
**Simulated Benzene Concentrations in the Year 2000**
**(Deep Source Only)**
**Benzene Half-Life = 300 Days**
NAS Naval Air Station, Virginia Beach, Virginia

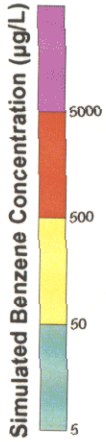
CH2MHILL




Shallow Columbia Aquifer (4 to 12 feet BGS)

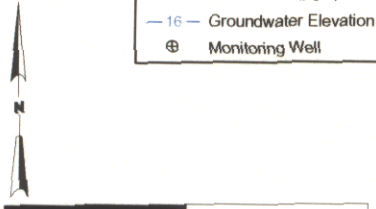



Deep Columbia Aquifer (12 to 20 feet BGS)




**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- Monitoring Well




152630-04.SRF

**Figure 6-12**
**Simulated Benzene Concentrations in the Year 2000**
**(Shallow and Deep Source)**
**Benzene Half-Life = 300 Days**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL

# 7. Lines of Evidence Not Supporting Natural Attenuation

An alternative hypothesis to the one presented in Section 6 is that the contaminant source (NAPL-contaminated soil) was effectively removed by the excavation in 1996 and the BTEX remaining at the site is limited to what is dissolved in the groundwater and adsorbed to the soil. Given the high concentrations of benzene that have been detected at the site, this scenario would infer that biodegradation of benzene is minimal or not occurring at all. The lines of evidence that support the hypothesis that natural attenuation is not occurring at SWMU 15 includes high contaminant concentrations that persist over time and over several hundred feet downgradient of the assumed source area, and geochemical data that may indicate the contaminant plume is not at steady state and has not "broken through" to all of the monitoring wells along a flowpath.

## 7.1 Conceptual Site Model for Excavated NAPL Source Area and Dissolved-Phase Plume Distribution

Soil sampling was performed in May 1996 to delineate the source area in the vicinity of former tanks G-5, G-6 and G-9. Results from a leaching model had indicated that benzene in soil above 91 µg/kg would leach to the groundwater at concentrations exceeding the MCL of 5 µg/L. Figure 2-10 shows the soil sample locations used to delineate the 100 µg/kg isoconcentration contour that was used as a boundary for soil excavation. Soil samples collected outside of the boundary line were reported as non-detect, with the exception of one sample at 63 µg/kg on the southeast side of former tank G-9. In August 1996, approximately 18,000 cubic yards of soil were excavated over an area of approximately 2 acres and a depth of 7 feet and remediated onsite in two biopiles.

The conceptual site model for this scenario is that residual NAPL formerly existed within the area with soil benzene concentrations above 100 µg/kg, and that the NAPL-contaminated soil was completely excavated in 1996. Once the residual NAPL was removed, benzene would only be present adsorbed to the soil at concentrations less than 100 µg/kg and dissolved in the groundwater. Figure 7-1 depicts the NAPL source and dissolved-phase plume areas used for this scenario.

## 7.2 Documented Contaminant Changes at the Site

### 7.2.1 Changes at Specific Groundwater Monitoring Locations over Time

As discussed in Section 6, there are not many wells at SWMU 15 where temporal data are available to evaluate changes or stability in groundwater contaminant levels. The results summarized in Table 5-2 indicate that several wells that had high levels of BTEX during 1994 were either destroyed during the soil excavation and construction of the biopile.

Well MW-20 was installed in 1999 to replace well MW-15 which was destroyed during excavation and on-site treatment of the soil in the source area. MW-15 was screened from 5 to 20 feet bgs and MW-20 is screened from 3 to 18 feet. The last time MW-15 was sampled, in October of 1994, the benzene concentration was 270 μg/L and total BTEX was 544 μg/L. In February 2000, MW-20 had a benzene concentration of 3,010 μg/L and a total BTEX concentration of 4,456 μg/L. The increase in benzene concentration may indicate that contaminated groundwater has migrated to the vicinity of MW-20 from the former source area at the ponded excavation, or from a secondary source area that may be located east of MW-20.

### 7.2.2 Changes Along Groundwater Flowpaths

Along the groundwater flowpaths described in Figures 6-2 and 6-3, benzene concentrations are consistently high along Flowpaths A and B over a distance of approximately 400 feet, and then the concentrations diminish to low or non-detectable levels over the next 100 to 200 feet. Under the premise that natural attenuation is not occurring, the consistently high benzene concentrations along these flowpaths are interpreted to be due to advective transport away from the source area without biodegradation. The decrease in concentrations near the downgradient edge of the plume is interpreted to be the result of benzene beginning to reach those areas but not yet fully broken through to create steady-state conditions. A rough check on this interpretation can be made by estimating the travel time from the source (assumed to be the excavation area) to the sampling locations exhibiting decreasing benzene concentrations. Assuming an average groundwater velocity of 20 feet per year, the time required for the plume to travel 400 feet is approximately 20 years. This would indicate that the fuel release occurred at the end of the time period that the tank farm was active (from mid-1950's to mid-1970's).

A comparison was made between benzene and toluene, ethylbenzene, and xylene concentrations along the flowpaths. Table 7-1 summarizes all the Year 2000 BTEX results for wells along Flowpaths A, B, and G. Along Flowpath A, toluene and ethylbenzene are at relatively low concentrations compared to benzene. Xylene concentrations increase from 170 μg/L at MIP-03 to 1,300 μg/L at DW-07, similar to the increase in benzene concentrations from 1,230 μg/L at MIP-03 to 3,320 μg/L at DW-07. This suggests that biodegradation of xylenes is low. Both benzene and xylenes decrease to low levels at DW-10, which may indicate that the plume has not yet broken through at this well. These data for Flowpath A suggest that toluene and ethylbenzene have biodegraded whereas benzene and xylenes have not.

A different picture is found when examining BTEX concentrations along Flowpaths B and G. Along Flowpath B, benzene concentrations are high between wells DW-17 and DW-12, while xylene concentrations appear to steadily decrease along the flowpath. Toluene and ethylbenzene concentrations are relatively low at all wells. This suggests that biodegradation of toluene, ethylbenzene and xylenes is occurring, while benzene is not biodegrading (or is biodegrading slowly). Along Flowpath G, benzene is high at DW-22 and DW-23, but toluene, ethylbenzene, and xylenes are low.

Overall, these data for three flowpaths suggest that toluene and ethylbenzene have already biodegraded and that xylenes biodegrade slowly like benzene along one flowpath, and faster than benzene along two other flowpaths.

## 7.3 Geochemical Indicators that Suggest the Plume is Not at Steady State

The contaminated groundwater plume has consistently high concentrations of methane in areas with high benzene concentrations (Table 7-1). As discussed in Section 6, elevated methane concentrations are the result of methanogenesis, an anaerobic biodegradation process. If methane is taken as a conservative tracer for the plume, then the high methane concentrations indicate that the plume has reached DW-07 along Flowpath A, DW-12 along Flowpath B, and DW-23 along Flowpath G, but possibly has not broken through to the wells further downgradient where the methane concentrations are greatly reduced. This suggests that the benzene plume may not yet be at steady state and is still in an expansion phase.

## 7.4 Groundwater Modeling Without Biodegradation

### 7.4.1 Modeling Overview

The three-dimensional, screening-level, groundwater model described in Appendix J was also used to evaluate benzene fate and transport for the case where it was assumed that no biodegradation of benzene was occurring in the source areas or the aquifer. Some of the questions evaluated for this scenario are:

- Can the benzene distribution reported in the 2000 sampling results be replicated assuming a smaller residual NAPL source area that was excavated in 1996?
- Does the size of the benzene plume indicate that biodegradation is not occurring?
- How long will the benzene persist if there is no biodegradation occurring?

A series of three model simulations were performed using the three-dimensional numerical model described in Appendix J to gain insight into whether the observed distribution of contamination at the site suggests that benzene biodegradation is not occurring in the aquifer. These simulations either assume a shallow LNAPL source located within the upper two feet of the Columbia Aquifer, a deep LNAPL source located near the bottom of the Columbia Aquifer within the upper two feet of the silt/clay aquitard, or a combination of the two. For simulations containing a shallow source, it was assumed that the source was present at the site for 30 years (1965-1995) and that the entire shallow source was excavated in 1996. All of the simulations described below assume that no benzene biodegradation occurs within the source areas or the aquifer. The details of the model simulations are described below.

1 A simulation assuming a shallow NAPL source term located in the uppermost two feet of the Columbia Aquifer. The extent of the source term is assumed to extend throughout the footprint of the excavation area (See Figure 7-1). The source concentration declines over time according to the three-phase TTCU tool described in Appendix J. It was assumed that the source was present at the site for 30 years (1965-1995) and that the entire shallow source was excavated in 1996

2 A simulation that assumes an NAPL source near the bottom of the Columbia Aquifer within the upper two feet of the silt/clay aquitard. The extent of the source term is

defined by the extent of observed BTEX concentrations in groundwater above 3,000 μg/L (Figure 6-1). The source concentration declines over time according to the three-phase TTCU tool described in Appendix J.

3 A simulation that combines the shallow and deep sources described for the first two simulations. The concentration in both sources declines over time according to the three-phase TTCU tool described in Appendix J.

### 7.4.2 Modeling Results

The first simulation assumes a shallow NAPL source area with declining concentrations over time based on the assumptions contained in the TTCU model, and an extent coincident with the footprint of the pond excavation. The configuration of the source reactors is shown in Figure 7-2, and the decline in source concentrations at Reactors 1, 5, and 10 are shown in Figure 7-3. Note that in the absence of biodegradation, the benzene source is very persistent, remaining at very high concentrations for hundreds of years. The simulated distribution of benzene in the shallow and deep portions of the Columbia Aquifer in the year 2000 is shown on Figure 7-4. The overall extent of the plume predicted by this simulation is slightly smaller than that observed in the field. The simulations results suggest that in the absence of biodegradation, the contamination leaving the source zone spreads through the full thickness of the Columbia Aquifer, resulting in a very similar benzene distribution in both the shallow and deep portions of the aquifer (Figure 7-4). Water quality data collected at the site suggests that benzene concentrations are higher in the deeper portions of the Columbia Aquifer and are relatively low or non-detect at intermediate depths. Only a few shallow (water table) groundwater samples have been collected over the investigation area, and the actual distribution of benzene in the shallow groundwater is poorly defined.

The second simulation assumes a deep NAPL source area with declining concentrations over time based on the assumptions contained in the TTCU model described Appendix J. The reactor configuration is shown in Figure 6-8, and the decline in source concentrations at Reactors 1, 5, and 10 are shown in Figure 7-3. The model prediction of benzene concentrations in the year 2000 in both the shallow and deep portions of the Columbia Aquifer is shown on Figure 7-5. Due to the larger assumed source extent, the simulated plume more closely approximates the observed plume extent in the field. However, as mentioned above, the assumption that no biodegradation is occurring results in the plume spreading vertically throughout the full thickness of the Columbia Aquifer.

The final simulation assumes a combination of the source areas described in the first two simulations above. The forecast benzene plume in the year 2000 for both the shallow and deep portions of the Columbia Aquifer is shown on Figure 7-6. Due to the larger assumed lower source zone, the predicted plume extent for this simulation agrees quite well with that observed in the field. The benzene plume resulting from these two source areas is very similar in the lower portion of the aquifer to what was predicted in run number 2 above. The upper portion of the plume is an aggregate of the upper source behavior near the excavation area and the lower source behavior in areas further downgradient.

In summary, the simulations assuming no biodegradation and a source area with an extent similar to the footprint of the excavation at SWMU 15 predict a plume extent slightly smaller than that observed the field. Model runs assuming a larger deep source area

produce simulated plumes more similar to those observed in the field. However, all simulations assuming no biodegradation predict a contaminant plume that spreads through the full thickness of the aquifer. This predicted benzene distribution is not consistent with the available water quality data from the site.

## 7.5 Conclusions and Recommendations for Scenario Not Supporting Natural Attenuation

### 7.5.1 Conclusions

In this section, several evaluations were performed to evaluate the alternative hypothesis that natural attenuation of benzene is not occurring at SWMU 15. The following conclusions support this alternative hypothesis:

- Soil sampling performed as part of the Phase II RCRA Facility Investigation indicated that NAPL-contaminated soil was present in the former tank farm area east of former tank G-6 (Figure 2-10). The contaminated soils were excavated from this area in 1996 to remove the NAPL source.
- High concentrations of benzene (ranging between 1,120 and 8,090 μg/L) are present in groundwater up to 400 feet downgradient of the excavation area. A rough estimate of the time required for the plume to travel 400 feet is approximately 20 years, which would indicate that the fuel release occurred at the end of the time period that the tank farm was active (for mid-1950's to mid-1970's).
- A well installed in 1999 (MW-20) to replace another well that was destroyed during the excavation and on-site treatment of soil in the source area (MW-15) had significantly higher benzene concentrations in February 2000 than in October 1994. The increase in benzene concentration may indicate that contaminated groundwater has migrated to the vicinity of MW-20 from the former excavated source area.
- High concentrations of methane are coincident with high benzene levels in the plume. If the methane is used as a tracer compound for the plume, the absence of high levels of methane downgradient of the benzene plume may indicate that the plume has not yet broken through to the downgradient wells.
- Groundwater modeling assuming a shallow NAPL source that is completely removed in 1996 and no biodegradation of benzene simulates a plume that is slightly smaller than what is observed in field data. The addition of a deep NAPL source near the base of the Columbia Aquifer more closely approximates the observed plume extent in the field. However, all simulations that assume no biodegradation of benzene predict a contaminant plume that spreads throughout the entire thickness of the Columbia Aquifer, which is not consistent with the vertical benzene distribution observed in the field data.

### 7.5.2 Recommendations

As discussed in the conceptual site models for Sections 6 and 7, the interpretation as to whether or not benzene biodegradation is occurring at SWMU 15 depends on how NAPL is distributed in the subsurface and whether any NAPL sources are currently present at the site

and contributing to groundwater contamination. Additional soil and groundwater sampling as recommended in Section 6.5.2 could be used to confirm the presence or absence of NAPL outside of the area that was excavated in 1996. If no NAPL is detected in these further investigations, then the benzene plume may be expected to continue to migrate away from the site. Some remedial alternatives for this scenario are further evaluated in Section 8.

**TABLE 7-1**
BTEX and Methane Concentrations Along Flowpath Wells

| Well ID | Benzene | Toluene | Ethylbenzene | Xylenes (m+p) | Methane |
|---|---|---|---|---|---|
| **Flowpath A** | | | | | |
| MIP03 | 1230 | 3.1 | 24 | 170 | NA |
| DW15 | 1120 | <300 | <200 | 210 | 5700 |
| DW14 | 2870 | 10 | 19 | 784 | 6720 |
| DW05 | 3410 | <17 | 13 | 1330 | 7370 |
| MW20 | 3010 | 16 | <40 | 1430 | 7060 |
| DW01 | 1800 | 12 | 21 | 1050 | 6580 |
| DW07 | 3320 | <300 | <200 | 1300 | 9200 |
| DW10 | 5.8 | <3 | <2 | 5 | 310 |
| **Flowpath B** | | | | | |
| DW17 | 3350 | 16 | 28 | 1578 | 11400 |
| DW13 | 6910 | 41 | 47 | 4230 | 10600 |
| DW06 | 2500 | <300 | <200 | 486 | 5340 |
| DW03 | 261 | <30 | <20 | 138 | 6080 |
| DW12 | 2118 | 26 | 41 | 130 | 7910 |
| DW11 | 73 | <3 | <2 | 30 | 790 |
| DW27 | <2 | <3 | <2 | 1.4 | 54.2 |
| **Flowpath G** | | | | | |
| DW22 | 8090 | 10.1 | 35 | 9.6 | 6350 |
| DW23 | 1380 | 2 | 3.5 | 112 | 6250 |
| DW24 | 97 | <3 | <2 | 59 | 1610 |

Note: Units are µg/L

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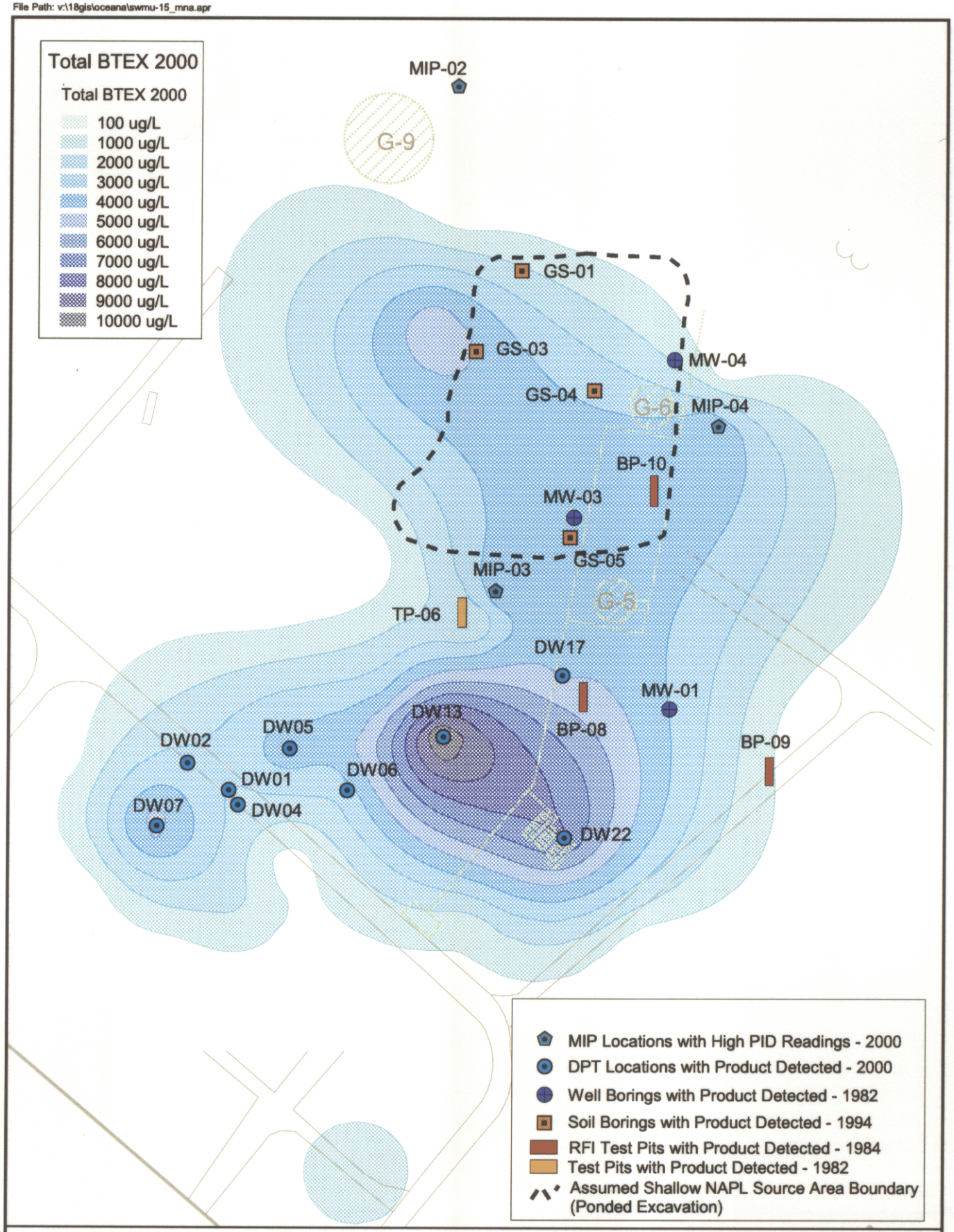


N W E S

100 0 100 200 Feet

Figure 7-1
Historic Sample Locations where Product has been Detected at SWMU 15
NAS Oceana, Virginia Beach, Virginia

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00526 E B64

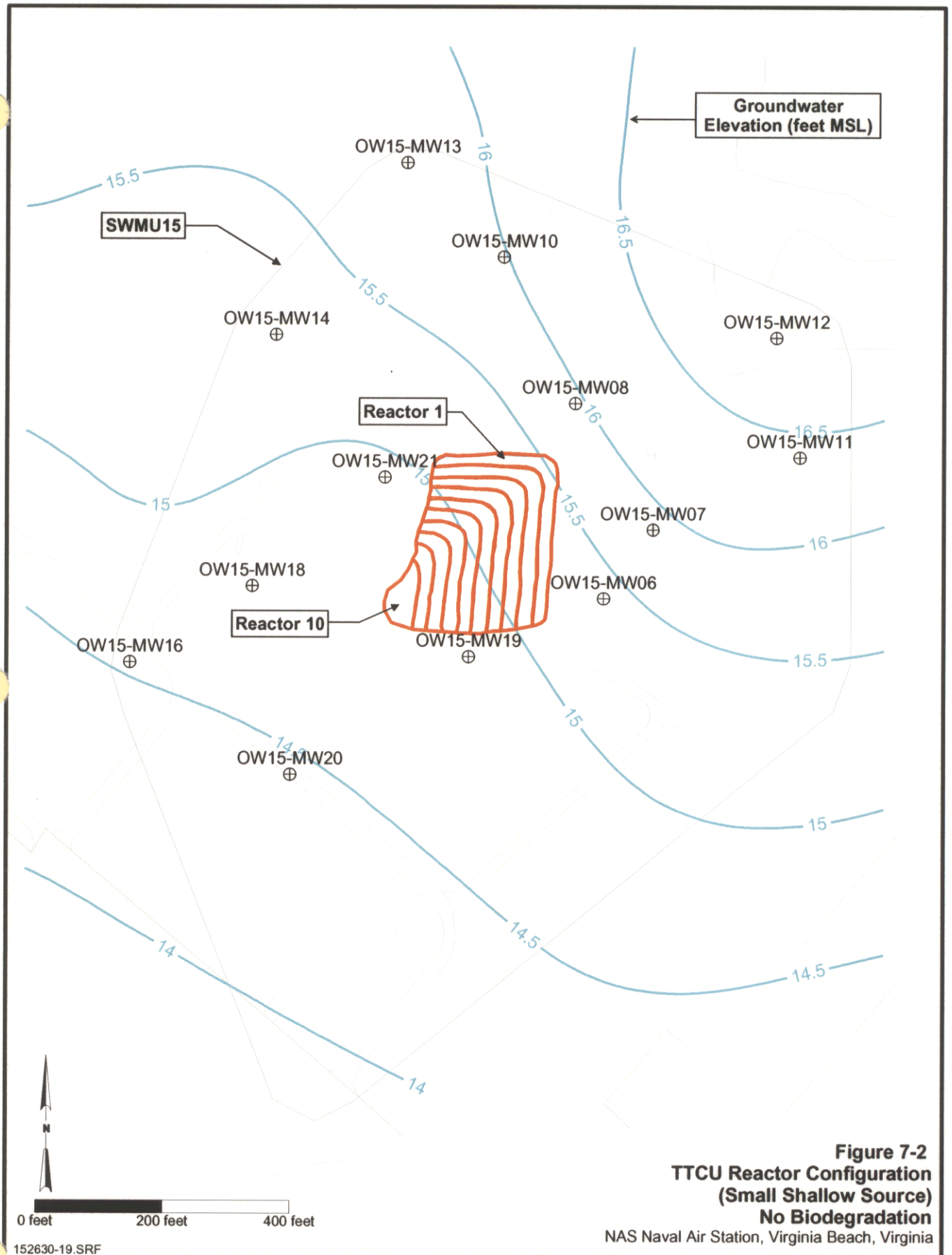


**Figure 7-2**
**TTCU Reactor Configuration**
**(Small Shallow Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

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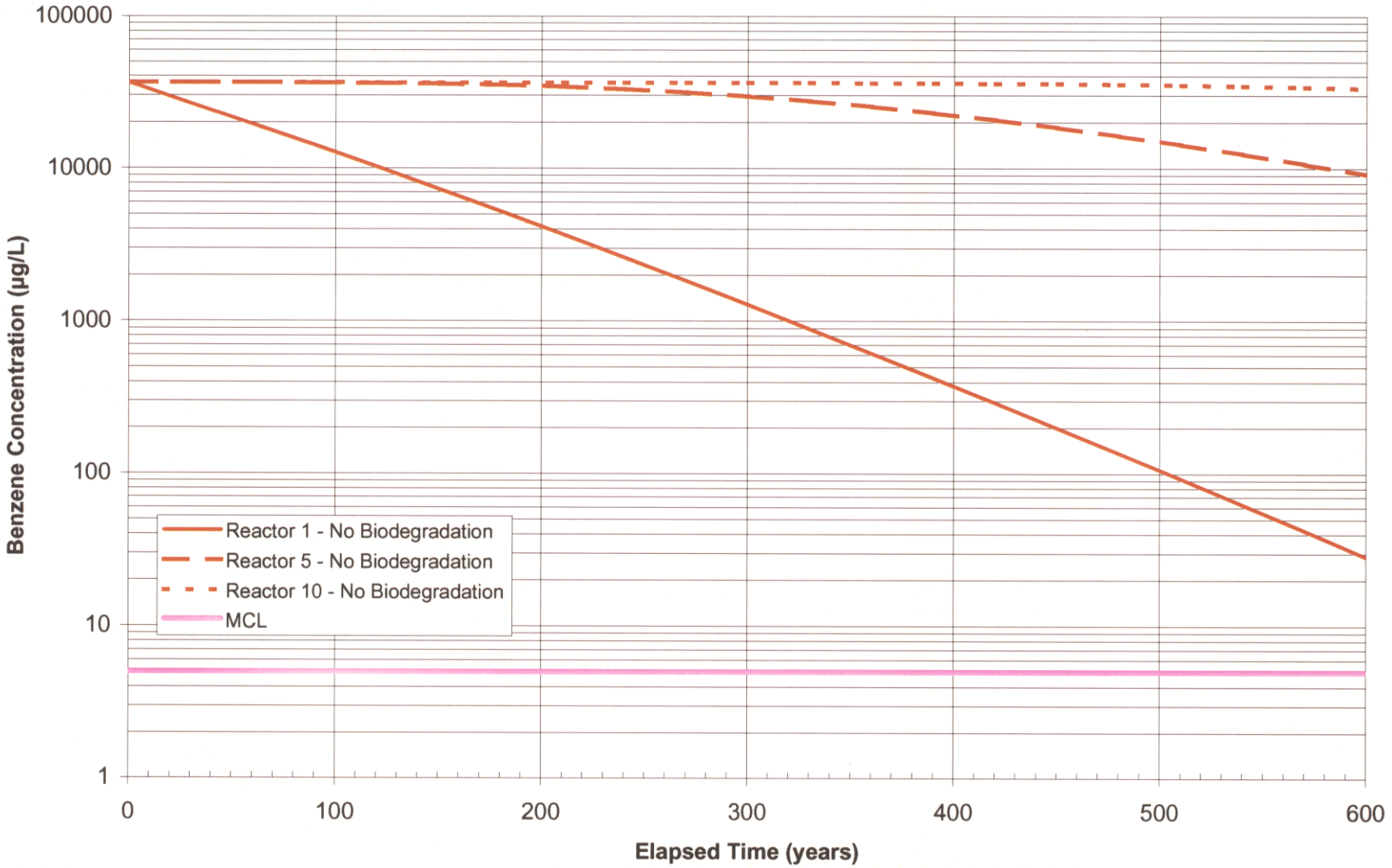


**Figure 7-3**
**Source Concentrations Over Time**
**Small Shallow Source with No Biodegradation**
NAS Naval Air Station, Virgina Beach, Virginia

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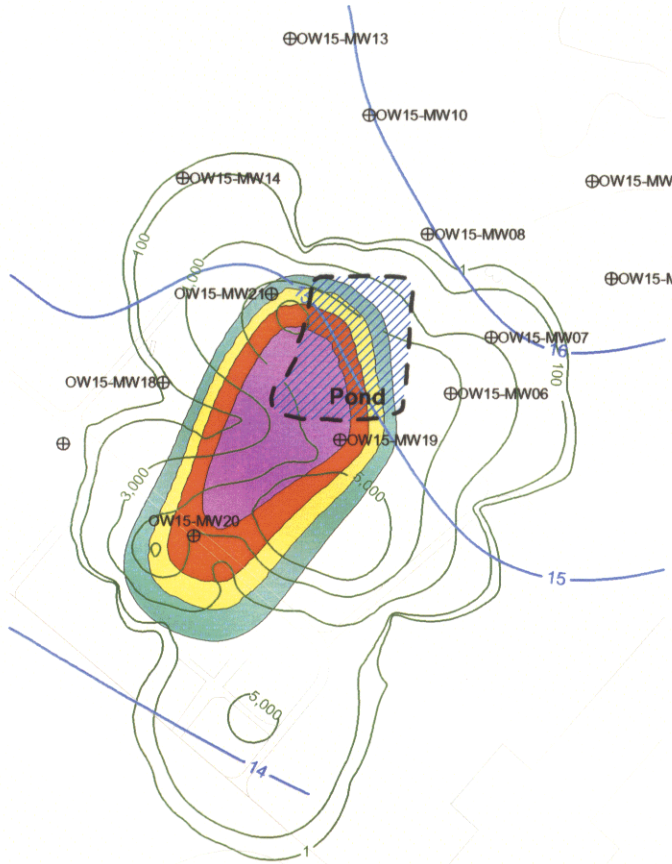
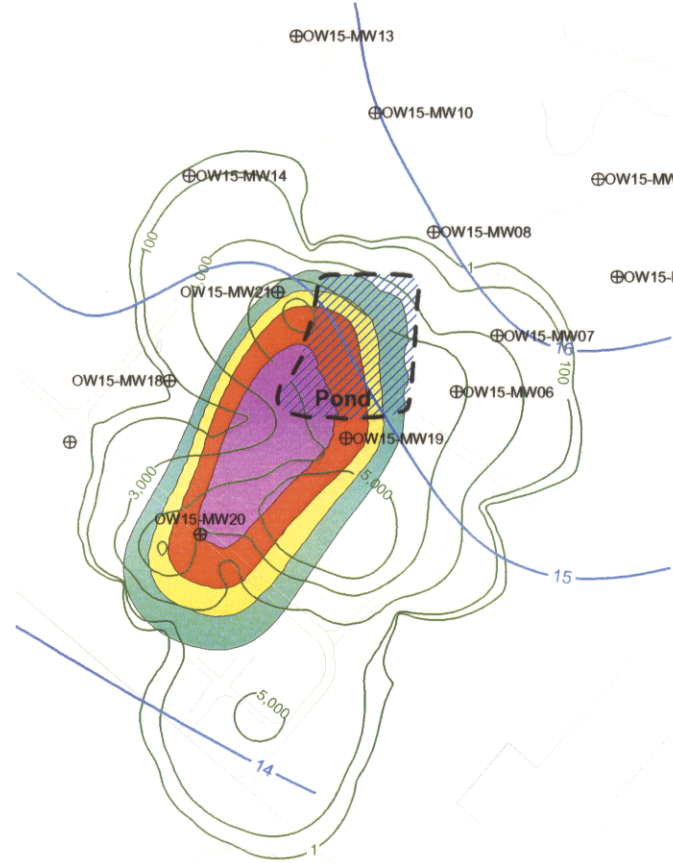
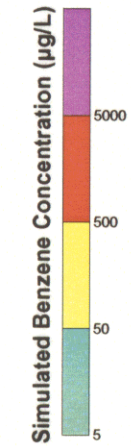



**Shallow Columbia Aquifer (4 to 12 feet BGS)**

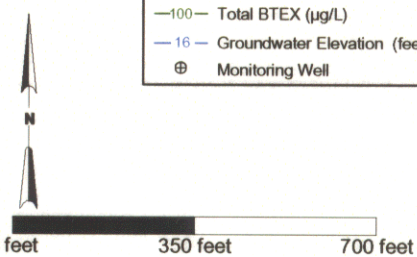



**Deep Columbia Aquifer (12 to 20 feet BGS)**




**Legend:**

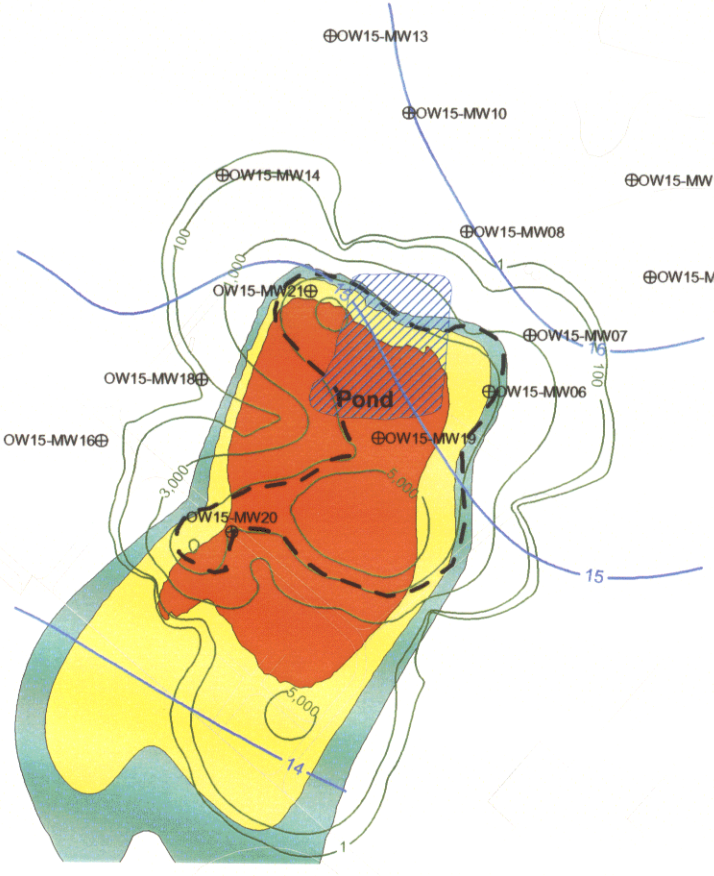
- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- Monitoring Well



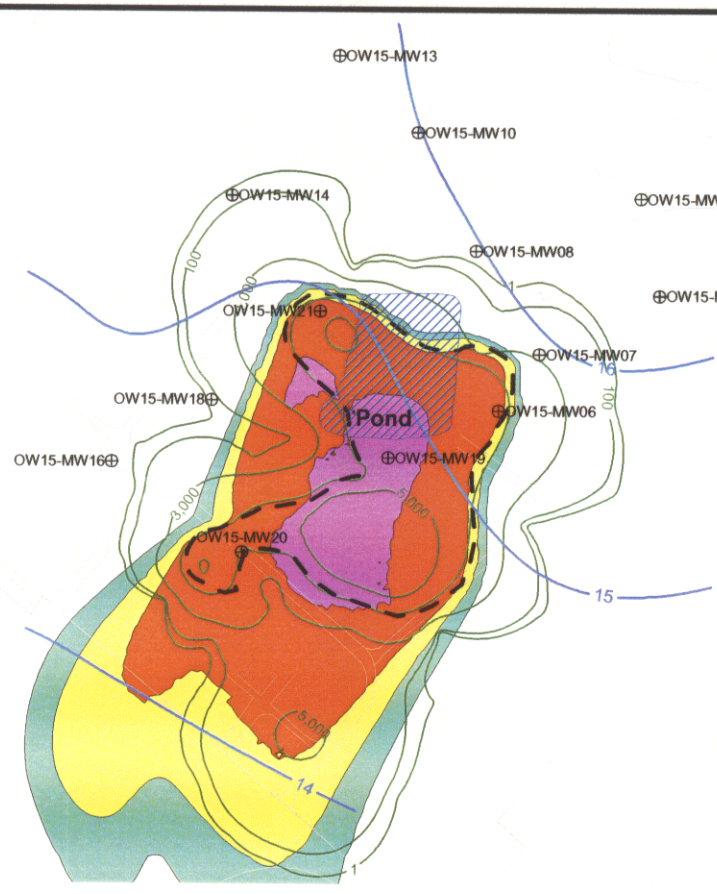

152630-05.SRF

**Figure 7-4**
**Simulated Benzene Concentrations in the Year 2000**
**(Shallow Source Only)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

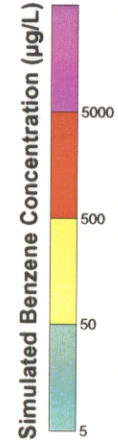
CH2MHILL




Shallow Columbia Aquifer (4 to 12 feet BGS)

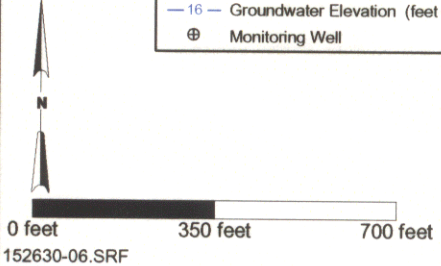



Deep Columbia Aquifer (12 to 20 feet BGS)




**Legend:**

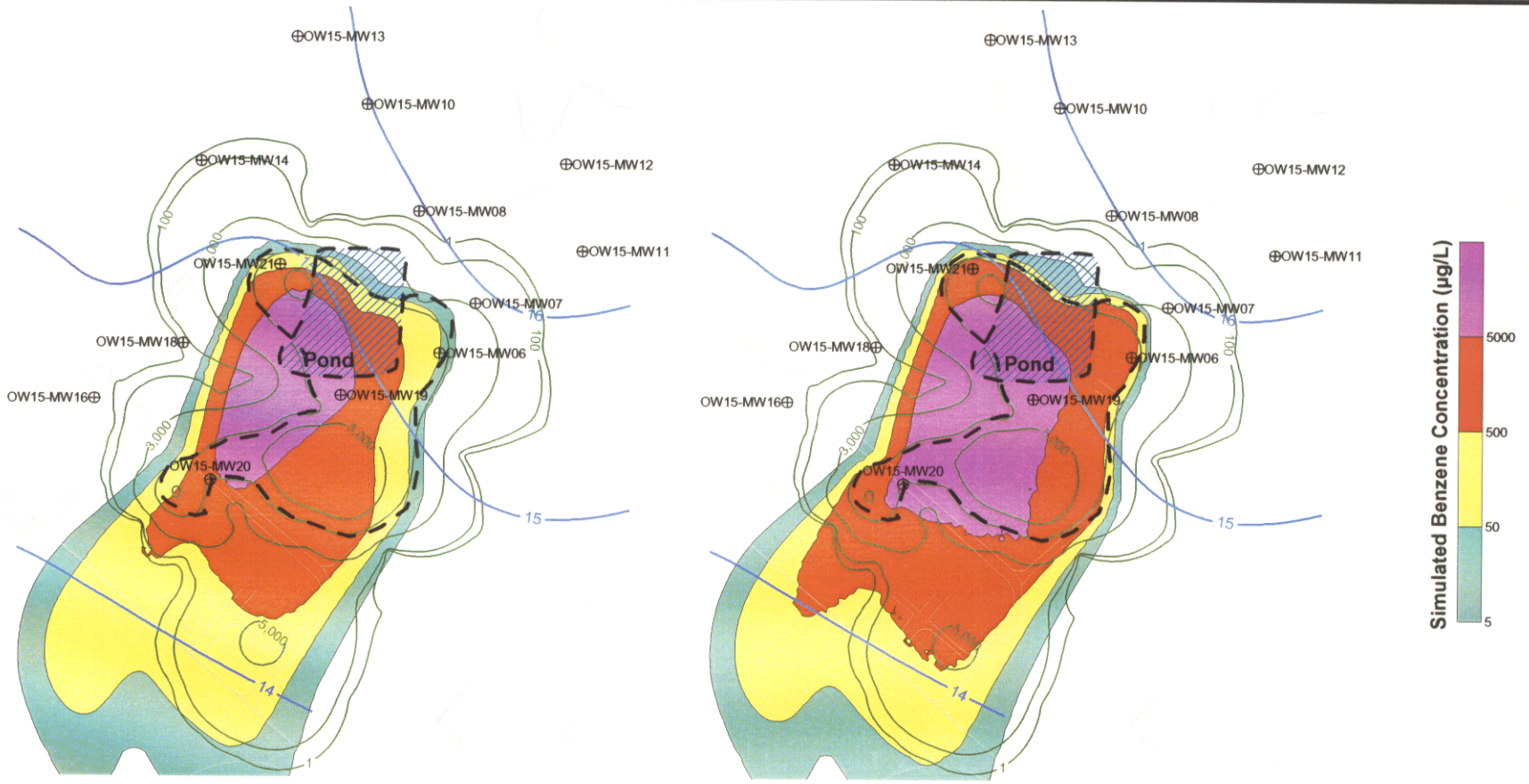
- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well




152630-06.SRF

**Figure 7-5**
**Simulated Benzene Concentrations in the Year 2000**
**(Deep Source Only)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL




**Shallow Columbia Aquifer (4 to 12 feet BGS)**

**Deep Columbia Aquifer (12 to 20 feet BGS)**

**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

N

0 feet 350 feet 700 feet

152630-07.SRF

**Figure 7-6**
**Simulated Benzene Concentrations in the Year 2000**
**(Shallow and Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

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# 8. Groundwater Modeling of Remedial Alternatives

This section describes groundwater flow and solute transport modeling of three remedial alternatives for SWMU 15 – no action, a downgradient reactive curtain of an oxygen release compound, and groundwater plume containment through surface water extraction from the ponded excavation.

## 8.1 Modeling Scenarios

### 8.1.1 No Action

This alternative serves as a baseline for the other two alternatives. Two no action simulations were performed, one assuming a 300-day benzene half-life and the other assuming no biodegradation is occurring.

The no action simulation assuming a 300-day benzene half-life is a continuation of the third run described in Section 6 (Figure 6-12), with both a shallow and a deep source. The boundary of the shallow and deep benzene source areas are shown on Figure 6-1. Unlike the scenarios presented in Section 6, this simulation predicts the future benzene distributions at 5, 15, and 30 years from the year 2000.

The no action simulation assuming no biodegradation is a continuation of the third run described in Section 7, with both a shallow and a deep source. The boundary of the shallow source is shown in Figure 7-1 and the boundary of the deep benzene source is shown on Figure 6-1. This simulation also predicts the future benzene distributions at 5, 15, and 30 years from the year 2000.

A mechanism resulting in high benzene concentrations in the aquitard materials beneath the shallow aquifer has not been identified. However, field data indicate high concentrations of benzene are prevalent at the base of the Columbia aquifer. The TTCU tool described in Appendix J was used to estimate the declining concentrations in both the shallow and deep source terms over time.

### 8.1.2 Downgradient Reactive Curtain

This alternative simulates the effect of an oxygenated reactive curtain on the benzene plume. A curtain of a compound such as Oxygen Release Compound™ (ORC) could be injected at the location shown on Figure 8-1. The effect of the curtain would be to induce strongly aerobic conditions, resulting in aerobic biodegradation of benzene. The reactive curtain is represented in the model as a 10-foot wide zone reaching from the water table to the bottom of the Columbia Aquifer. The half-life of benzene that passes through the curtain was simulated as 1.4 days, which is the maximum unenhanced aerobic biodegradation rate for field studies reported by Suarez et al. (1999). The remainder of the aquifer experiences no biodegradation. The initial concentrations for this run were obtained from the model

simulation described previously assuming a shallow and deep NAPL source and no biodegradation (Figure 7-6). Model results were selected for the Year 2000.

### 8.1.3 Surface Water Extraction

This alternative simulates the effect of controlling plume migration by pumping water from the ponded excavation at rates that keep the pond dewatered (12.5 gpm). This condition is represented in the MODFLOW model by a series of drain boundary conditions with a bottom elevation of 10 ft-MSL. There is no biodegradation in this simulation. The initial concentrations for this run were obtained from the model simulation described previously assuming a shallow and deep NAPL source and no biodegradation (Figure 7-6). Model results were selected for the Year 2000.

### 8.1.4 Reactive Curtain with Surface Water Extraction

This alternative combines the features of both the surface water extraction and the reactive curtain alternatives described above. The initial concentrations for this run were obtained from the model simulation described previously assuming a shallow and deep NAPL source and no biodegradation (Figure 7-6). There is no biodegradation in this simulation other than at the reactive curtain. Model results were selected for the Year 2000.

## 8.2 Predictive Modeling Assumptions

The predictive solute transport modeling performed for this section is based on certain simplifying assumptions. These assumptions are listed below.

- The presence of a shallow and deep NAPL source was assumed for these simulations. The TTCU tool was used to estimate concentrations within these source areas, which are the same as the shallow and deep source areas described in Sections 6 and 7.
- Dewatering the pond may not be as effective as simulated here. The model may overestimate the ability of the Columbia Aquifer to transmit water to the pond. Conversely, the model may underpredict the amount of pumping required to keep the pond dewatered. This is a subject of high uncertainty in the model.

## 8.3 Remedial Alternative Modeling Results

### 8.3.1 No Action with Biodegradation

The continued development of a groundwater plume from shallow and deep benzene sources assuming a benzene half-life of 300 days is shown at 5, 15, and 30 years in Figures 8-2 through and 8-4. These figures present the simulated benzene concentrations in both the shallow and deep portions of the Columbia Aquifer. Due to biodegradation, the extent of the benzene plume is predicted to remain fairly stable. Concentrations gradually decline within the plume as the source areas lose mass to biodegradation.

### 8.3.2 No Action without Biodegradation

The continued development of a groundwater plume from shallow and deep benzene sources assuming no biodegradation is shown at 5, 15, and 30 years in Figures 8-5 through and 8-7. These figures present the simulated benzene concentrations in both the shallow and deep portions of the Columbia Aquifer. The benzene plume travels south-southwest, eventually extending an additional 600 feet downgradient of the source, a total travel distance of approximately 1200 feet over the 65 years of historical and predictive simulation. Because no biodegradation is simulated, the benzene plume will continue to grow until the sources are depleted.

### 8.3.3 Downgradient Reactive Curtain

The interaction of the benzene plume with a reactive curtain is shown at 5, 15, and 30 years in Figures 8-8 through 8-10. These figures present the simulated benzene concentrations in both the shallow and deep portions of the Columbia Aquifer. At 5 years (Figure 8-8), the location of the reactive curtain is apparent as the plume is bifurcated with the primary source concentrations prevented from moving downgradient past the curtain, and the residual downgradient edge of the plume continuing to migrate to the southwest. It should be noted that the location of the reactive curtain was selected to prevent the migration of the highest concentrations of contaminants associated with the source areas from moving downgradient. If migration of the relatively low concentrations associated with the downgradient portion of the dissolved benzene plume is of concern, the reactive curtain could simply be relocated further downgradient to capture the remainder of the plume. The simulated benzene concentrations at later times are shown on Figures 8-9 and 8-10. It is apparent from these figures that the reactive curtain is effective at preventing the downgradient migration of source zone contamination while the downgradient detached portion of the plume continues to migrate to the south and west.

### 8.3.4 Surface Water Extraction

The effect of dewatering the pond at 5, 15, and 30 years is shown in Figures 8-11 through 8-13. These figures present the simulated benzene concentrations in both the shallow and deep portions of the Columbia Aquifer. A comparison with the no-action alternative indicates immediately obvious differences. The source area is entirely captured by surface water extraction, preventing further downgradient release of benzene mass. However, the downgradient portion of the plume escapes the groundwater depression, and continues to travel south-southwest. It is apparent from the figures that the surface water extraction results in a shallower hydraulic gradient in the downgradient portions of the plume, resulting in slower migration to the southwest.

### 8.3.5 Reactive Curtain with Surface Water Extraction

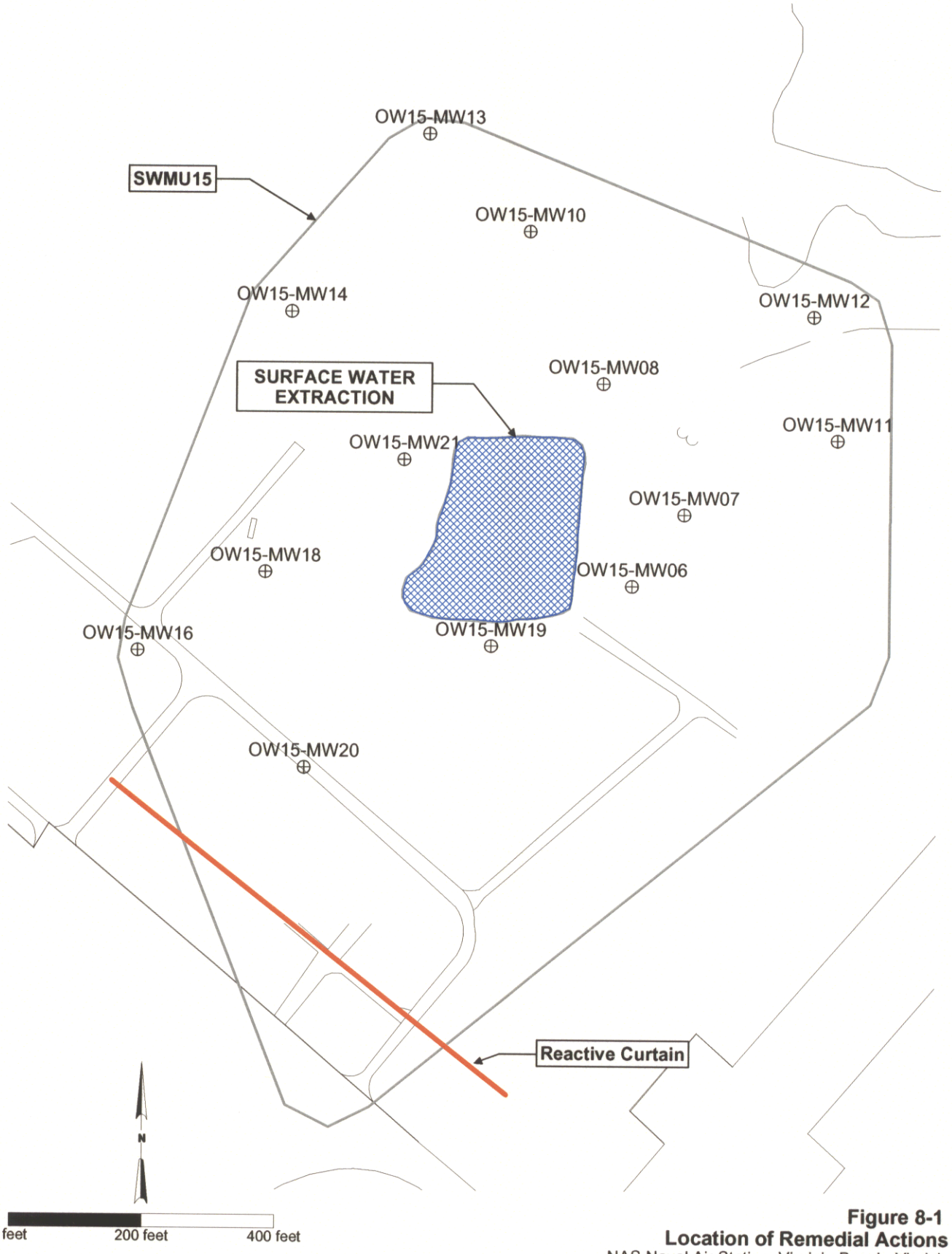
The interaction of the benzene plume with a reactive curtain and surface water extraction is shown at 5, 15, and 30 years in Figures 8-14 through 8-16. These figures present the simulated benzene concentrations in both the shallow and deep portions of the Columbia Aquifer. As in the surface water extraction simulation (Section 8.3.4), the source area is entirely captured by surface water extraction. At 5 years (Figure 8-14), the location of the reactive curtain is somewhat apparent, however the decreased groundwater velocity

resulting from pumping the pond prevents significant downgradient migration within the first 5 years of simulation. As additional time passes, the influence of the reactive curtain is more easily seen as the portion of the benzene plume downgradient of the reactive curtain continues to move to the southwest (Figures 8-15 and 8-16). It should be noted that the location of the reactive curtain was selected to prevent the migration of the highest concentrations of contaminants associated with the source areas from moving downgradient. If migration of the relatively low concentrations associated with the downgradient portion of the dissolved benzene plume is of concern, the reactive curtain could simply be relocated further downgradient to capture the remainder of the plume. It is apparent from these figures and previously discussed simulations that either the reactive curtain or surface water extraction is effective at preventing the downgradient migration of source zone contamination, and that combining the two remedial actions results in a duplication of effort.

## 8.4 Conclusions and Recommendations for Remedial Alternative Modeling

The following conclusions can be drawn from the predictive transport modeling at SWMU 15:

- If biodegradation is taking place at SWMU 15, the ultimate size of the benzene plume, both horizontally and vertically, is limited by the biodegradation rate. If the half-life is approximately 300 days, the maximum distance the plume will migrate is approximately 200 feet from the source.
- If no biodegradation is taking place, the benzene plume generated by either a shallow or deep source will eventually extend throughout the entire thickness of the Columbia Aquifer.
- If biodegradation is not taking place at SWMU 15, and there is substantial residual NAPL present in the subsurface, the source area will continue to contribute benzene to the groundwater for hundreds of years. The benzene plume will grow unless remedial action is taken or the plume reaches a natural discharge area.
- If a reactive curtain that induces effective bioremediation is installed and maintained, even benzene concentrations as high as 5000 $\mu g/L$ or more can be treated to below the MCL of 5 $\mu g/L$. If properly designed and implemented, such a reactive curtain is an effective barrier to benzene transport.
- Dewatering the pond at SWMU 15 can provide effective hydraulic control of the source area.
- Combining a reactive curtain with surface water extraction will likely result in redundant source control.
- A reactive curtain could be placed such that a plume of almost any downgradient extent could be entirely controlled, whereas surface water extraction has a limited area of influence. Therefore, if control of the entire benzene plume above MCLs is desired, a reactive curtain is a more suitable alternative.




152630-18.SRF

**Figure 8-1**
**Location of Remedial Actions**
NAS Naval Air Station, Virginia Beach, Virginia

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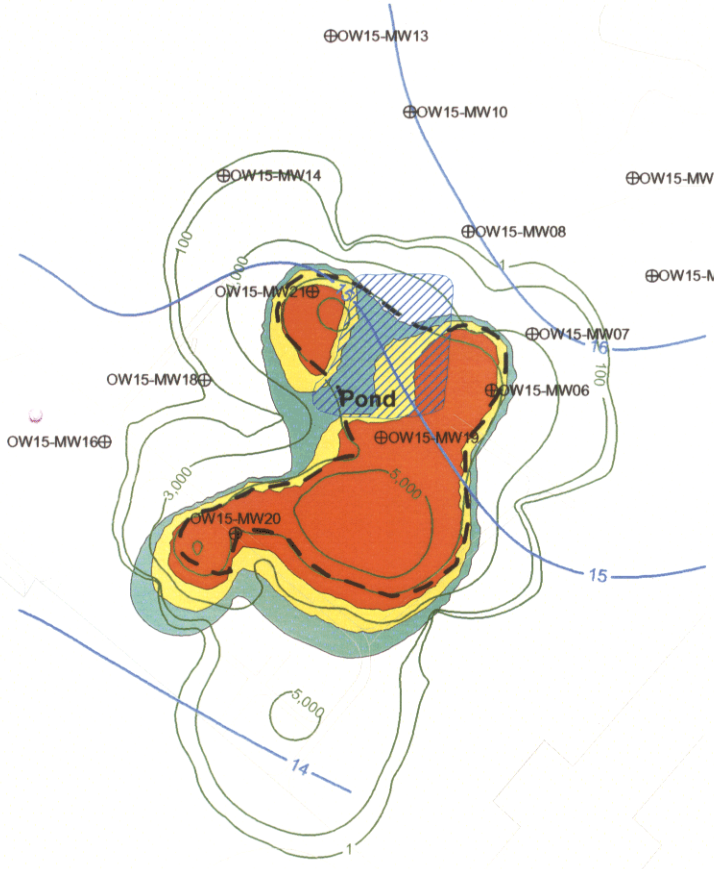
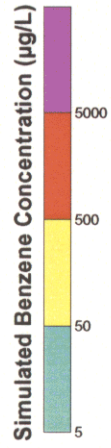



**Shallow Columbia Aquifer (4 to 12 feet BGS)**

**Deep Columbia Aquifer (12 to 20 feet BGS)**




**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- Monitoring Well

N

0 feet 350 feet 700 feet

152630-08.SRF

**Figure 8-2**
**Simulated Benzene Concentrations in 5 Years**
**No Action Alternative**
**(Large Shallow and Large Deep Source)**
**Benzene Half-Life = 300 Days**
NAS Naval Air Station, Virginia Beach, Virginia

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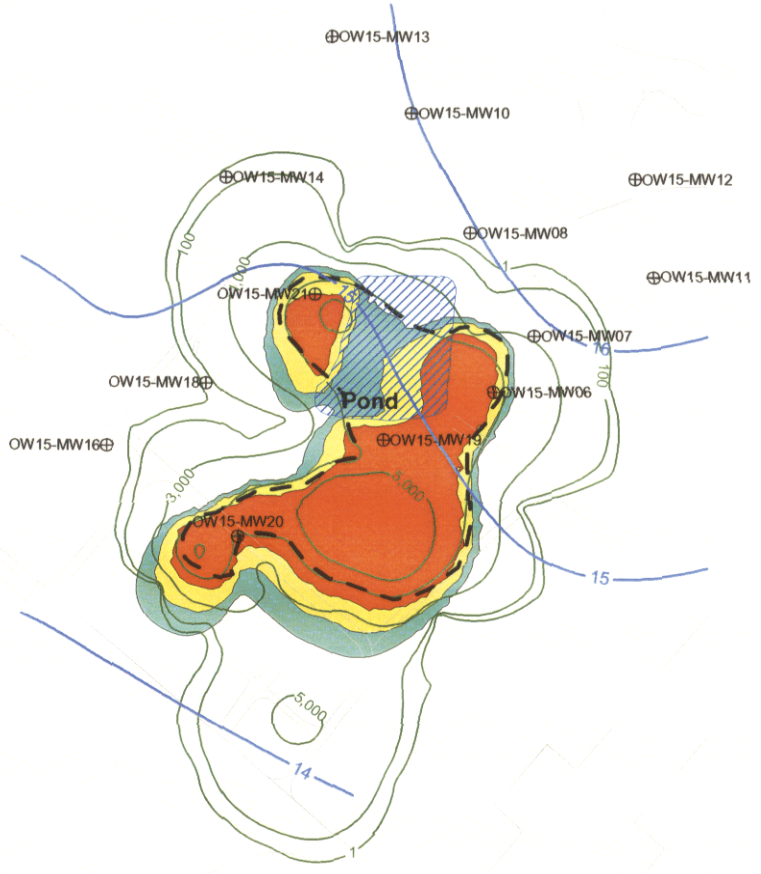
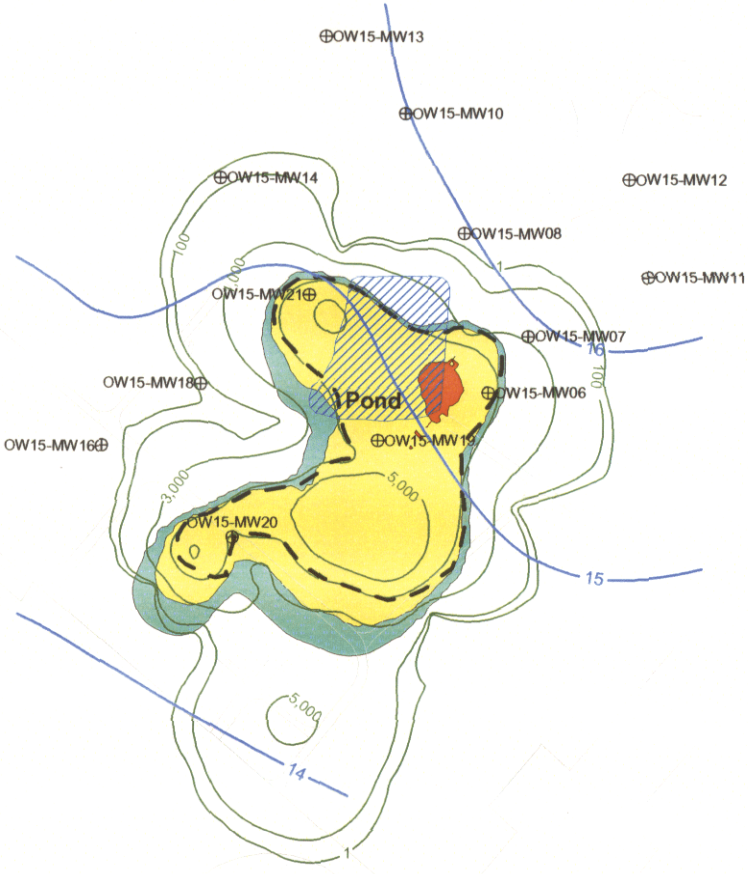
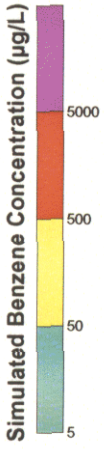



**Shallow Columbia Aquifer (4 to 12 feet BGS)**




**Deep Columbia Aquifer (12 to 20 feet BGS)**




**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

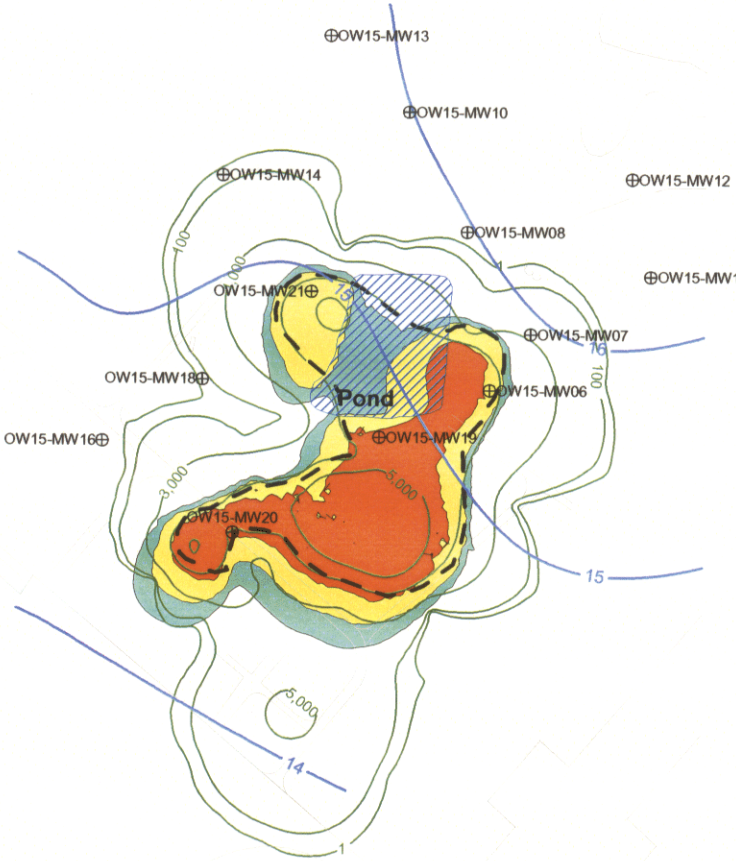
N

0 feet 350 feet 700 feet

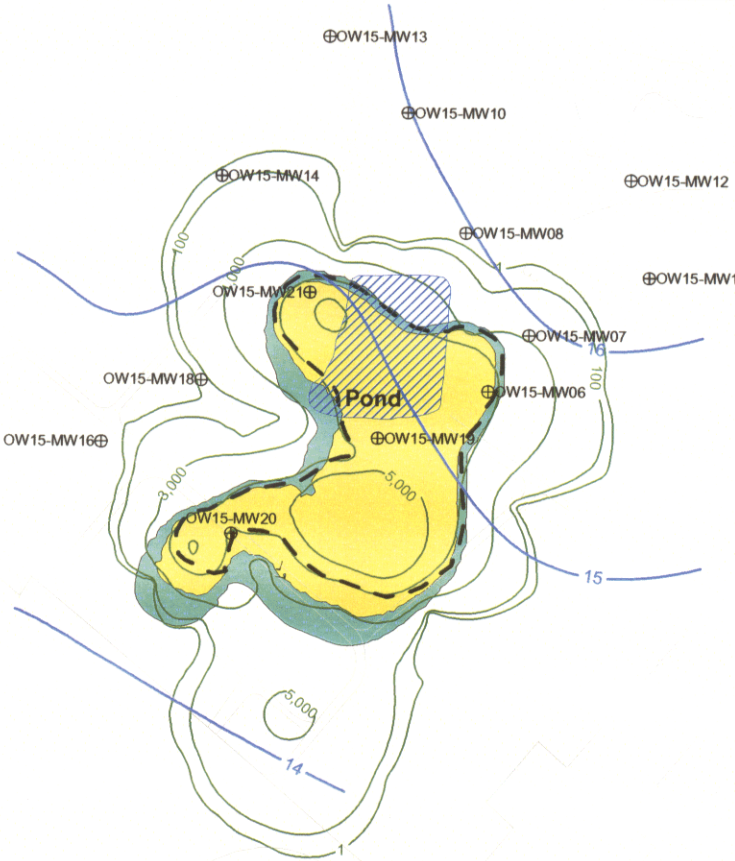
152630-09.SRF

**Figure 8-3**
**Simulated Benzene Concentrations in 15 Years**
**No Action Alternative**
**(Large Shallow and Large Deep Source)**
**Benzene Half-Life = 300 Days**
NAS Naval Air Station, Virginia Beach, Virginia

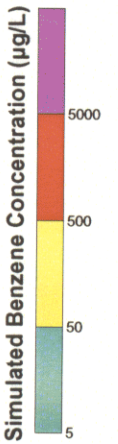
CH2MHILL




Shallow Columbia Aquifer (4 to 12 feet BGS)

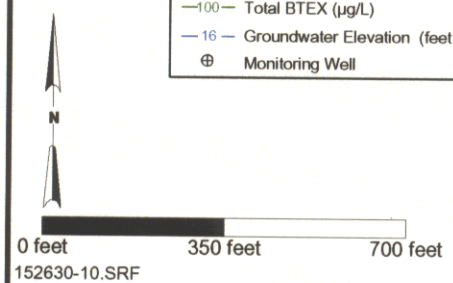



Deep Columbia Aquifer (12 to 20 feet BGS)




**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well




152630-10.SRF

**Figure 8-4**
**Simulated Benzene Concentrations in 30 Years**
**No Action Alternative**
**(Large Shallow and Large Deep Source)**
**Benzene Half-Life = 300 Days**
NAS Naval Air Station, Virginia Beach, Virginia

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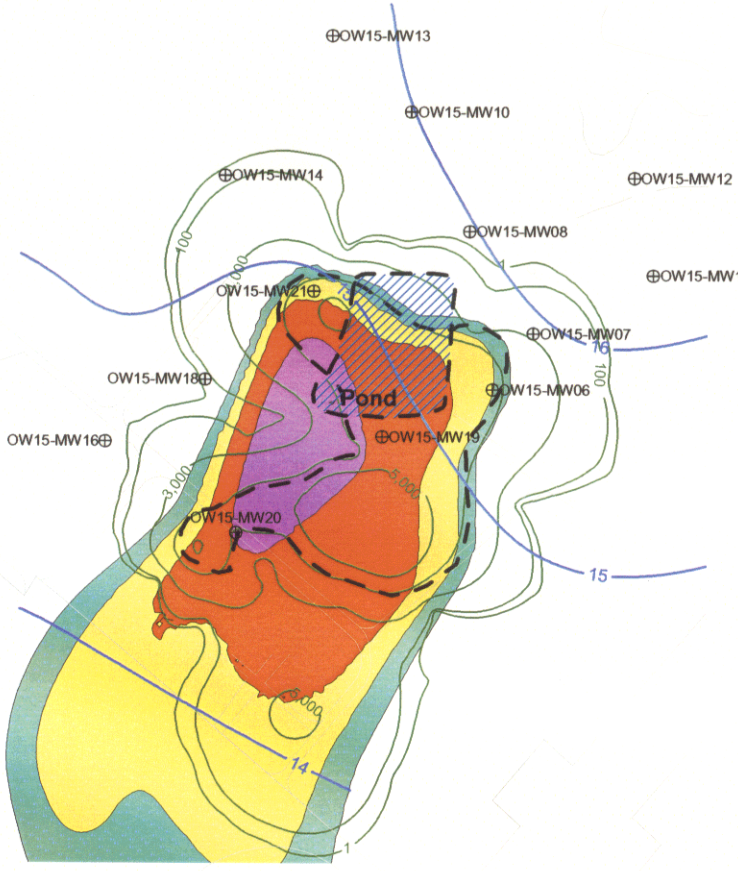
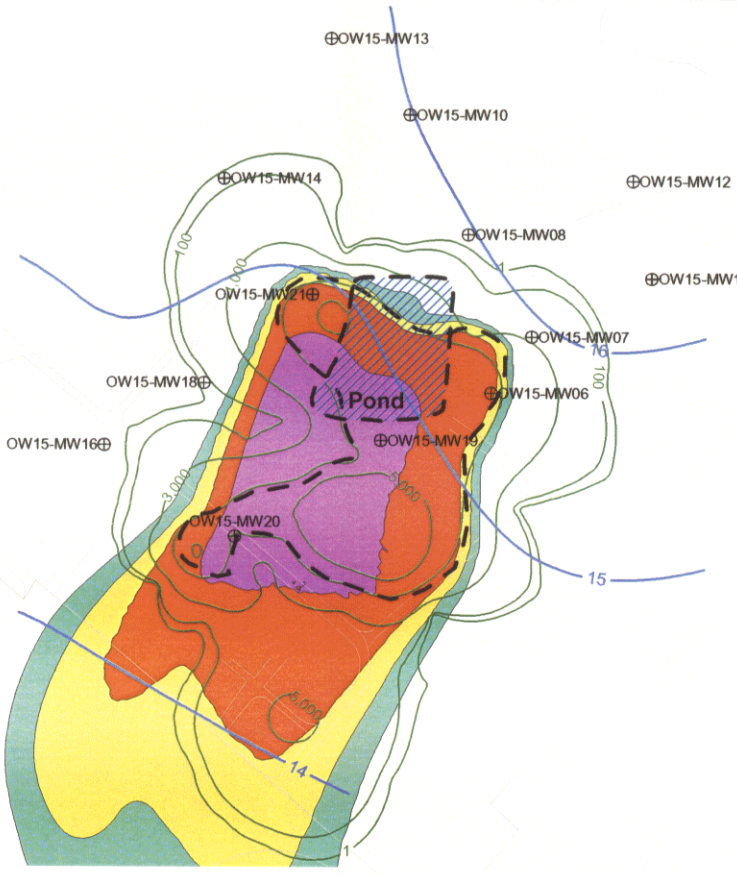
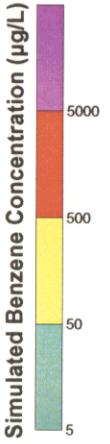



Shallow Columbia Aquifer (4 to 12 feet BGS)




Deep Columbia Aquifer (12 to 20 feet BGS)




**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

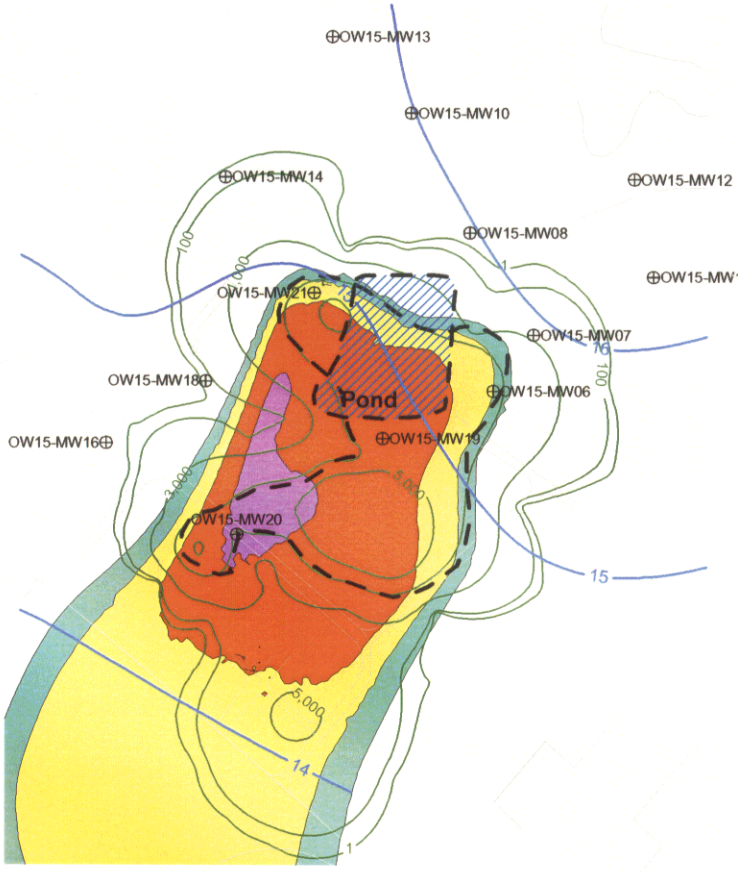
N

0 feet 350 feet 700 feet

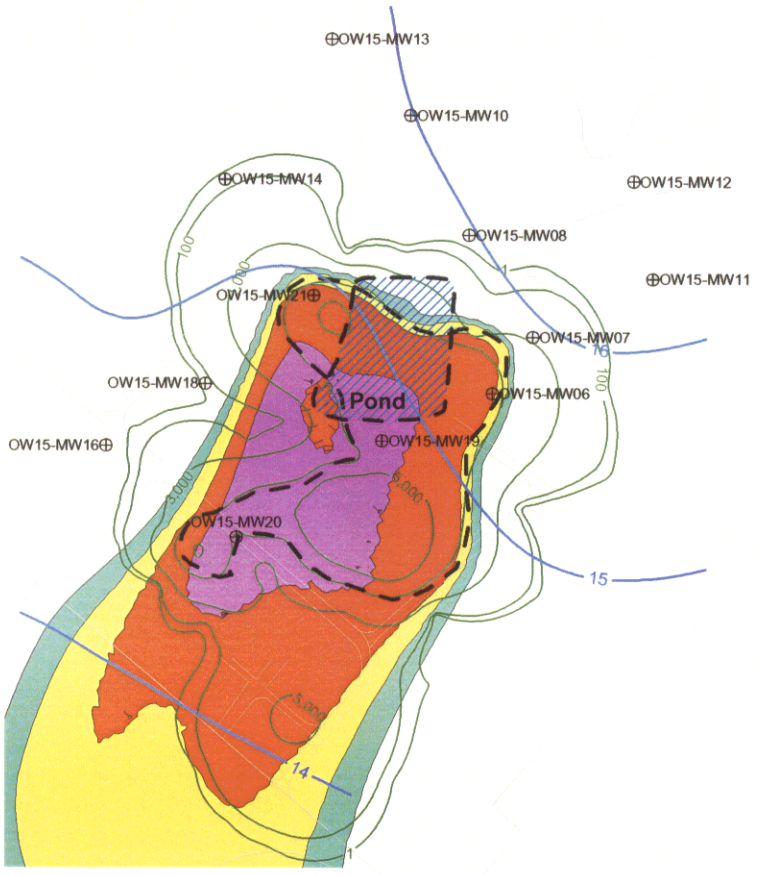
152630-11.SRF

**Figure 8-5**
**Simulated Benzene Concentrations in 5 Years**
**No Action Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

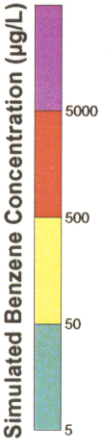
CH2MHILL




Shallow Columbia Aquifer (4 to 12 feet BGS)




Deep Columbia Aquifer (12 to 20 feet BGS)




**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- Monitoring Well

N

0 feet 350 feet 700 feet

152630-12.SRF

**Figure 8-6**
**Simulated Benzene Concentrations in 15 Years**
**No Action Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

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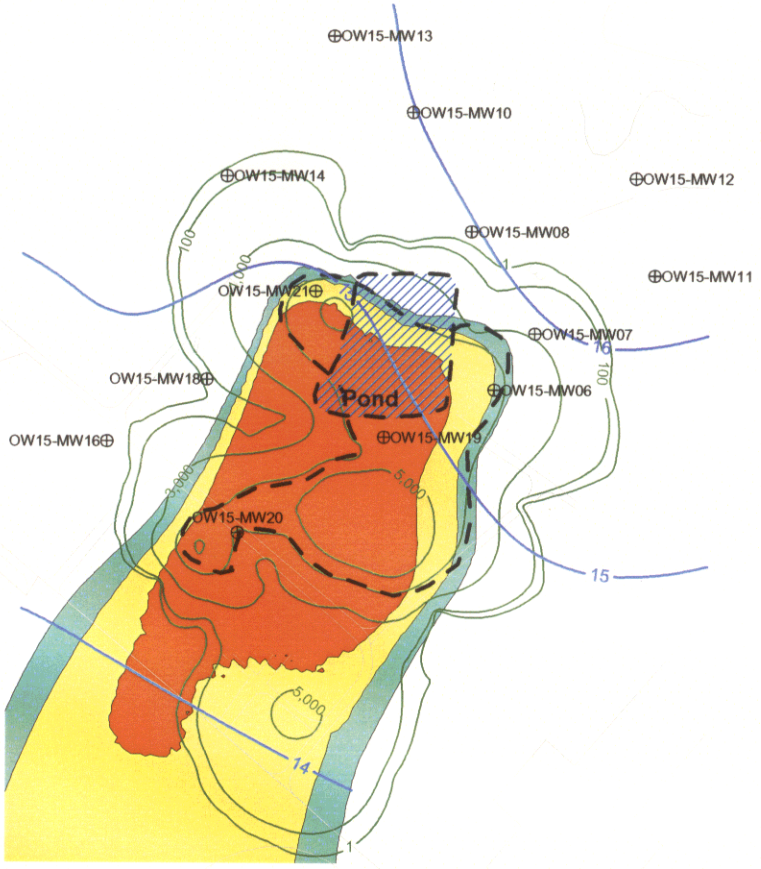
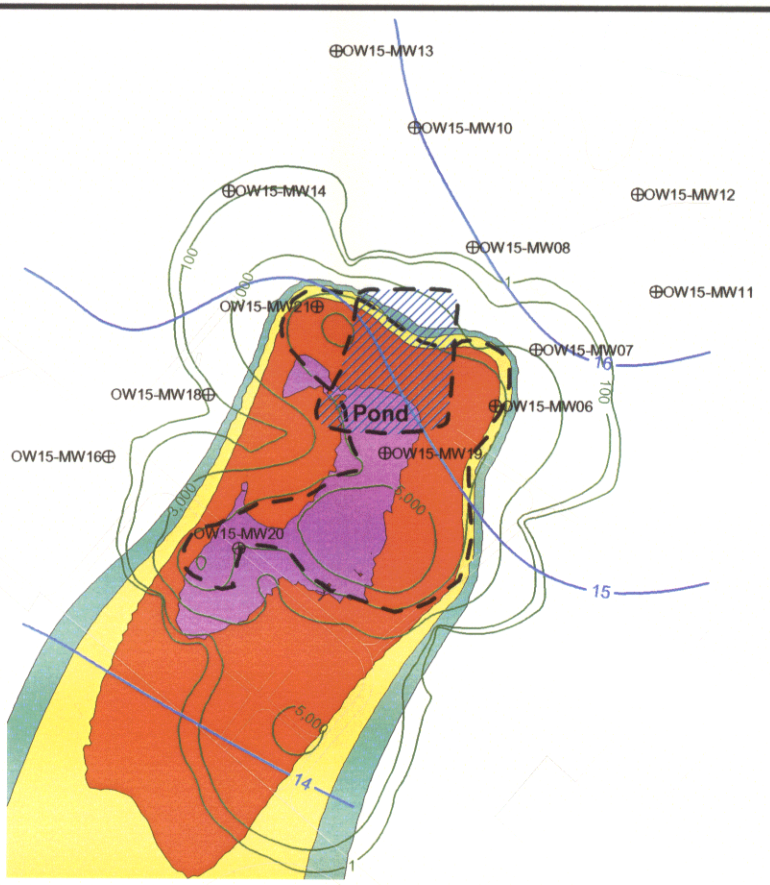
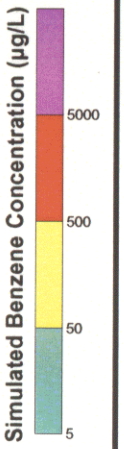



Shallow Columbia Aquifer (4 to 12 feet BGS)




Deep Columbia Aquifer (12 to 20 feet BGS)




**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

N

0 feet 350 feet 700 feet

152630-13.SRF

**Figure 8-7**
**Simulated Benzene Concentrations in 30 Years**
**No Action Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

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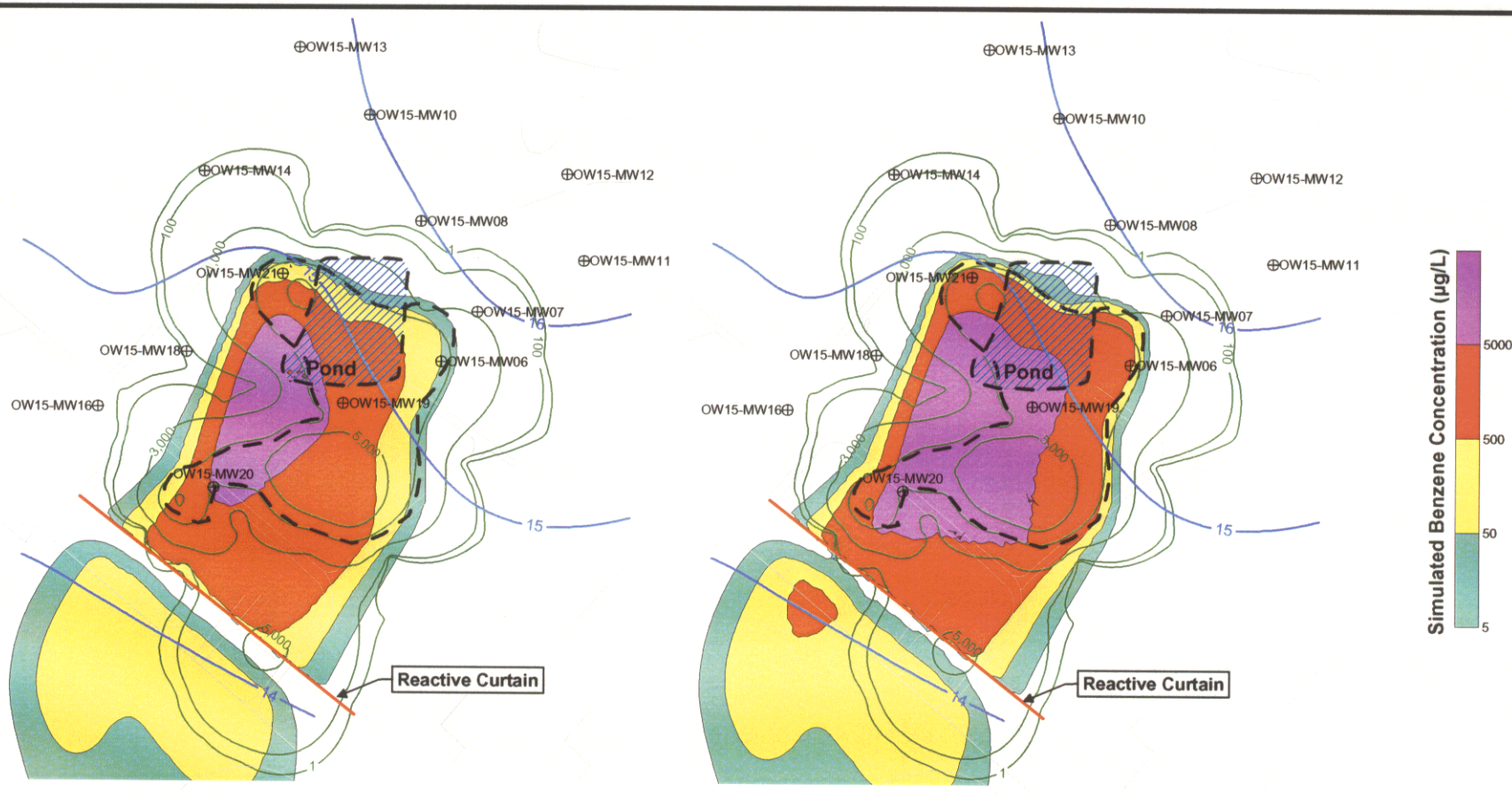


Shallow Columbia Aquifer (4 to 12 feet BGS)

Deep Columbia Aquifer (12 to 20 feet BGS)

**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- Monitoring Well

N

0 feet 350 feet 700 feet

152630-14.SRF

**Figure 8-8**
**Simulated Benzene Concentrations in 5 Years**
**Downgradient Reactive Curtain Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

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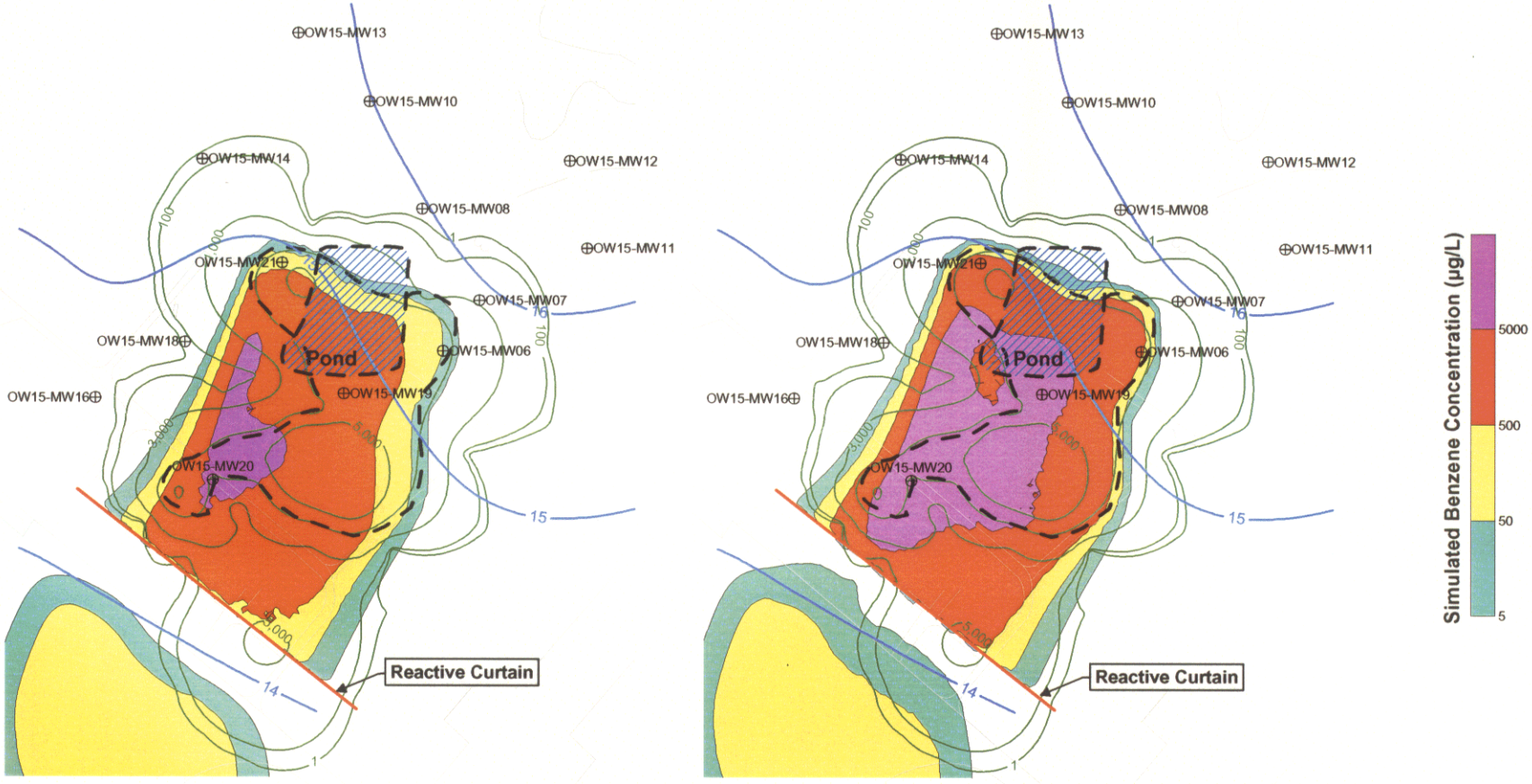


Shallow Columbia Aquifer (4 to 12 feet BGS)

Deep Columbia Aquifer (12 to 20 feet BGS)

**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

N

0 feet 350 feet 700 feet

152630-15.SRF

**Figure 8-9**
**Simulated Benzene Concentrations in 15 Years**
**Downgradient Reactive Curtain Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

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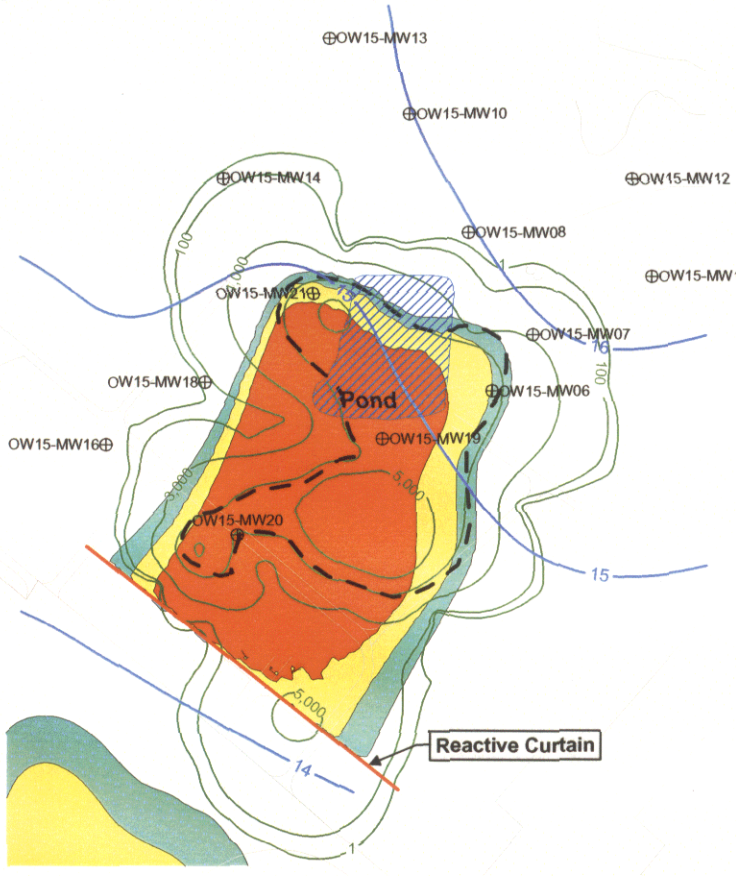
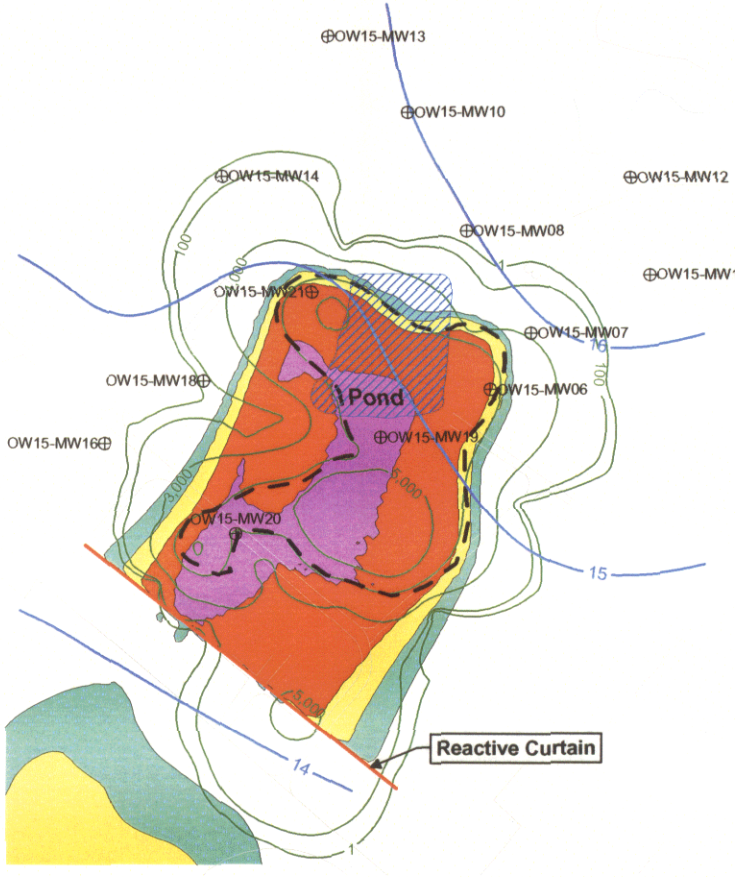
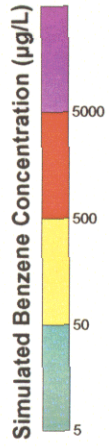



Shallow Columbia Aquifer (4 to 12 feet BGS)

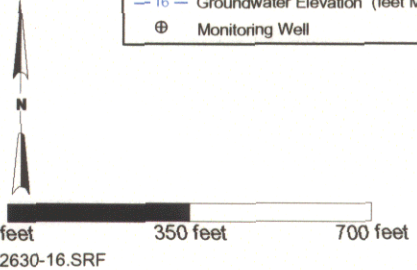



Deep Columbia Aquifer (12 to 20 feet BGS)




**Legend:**

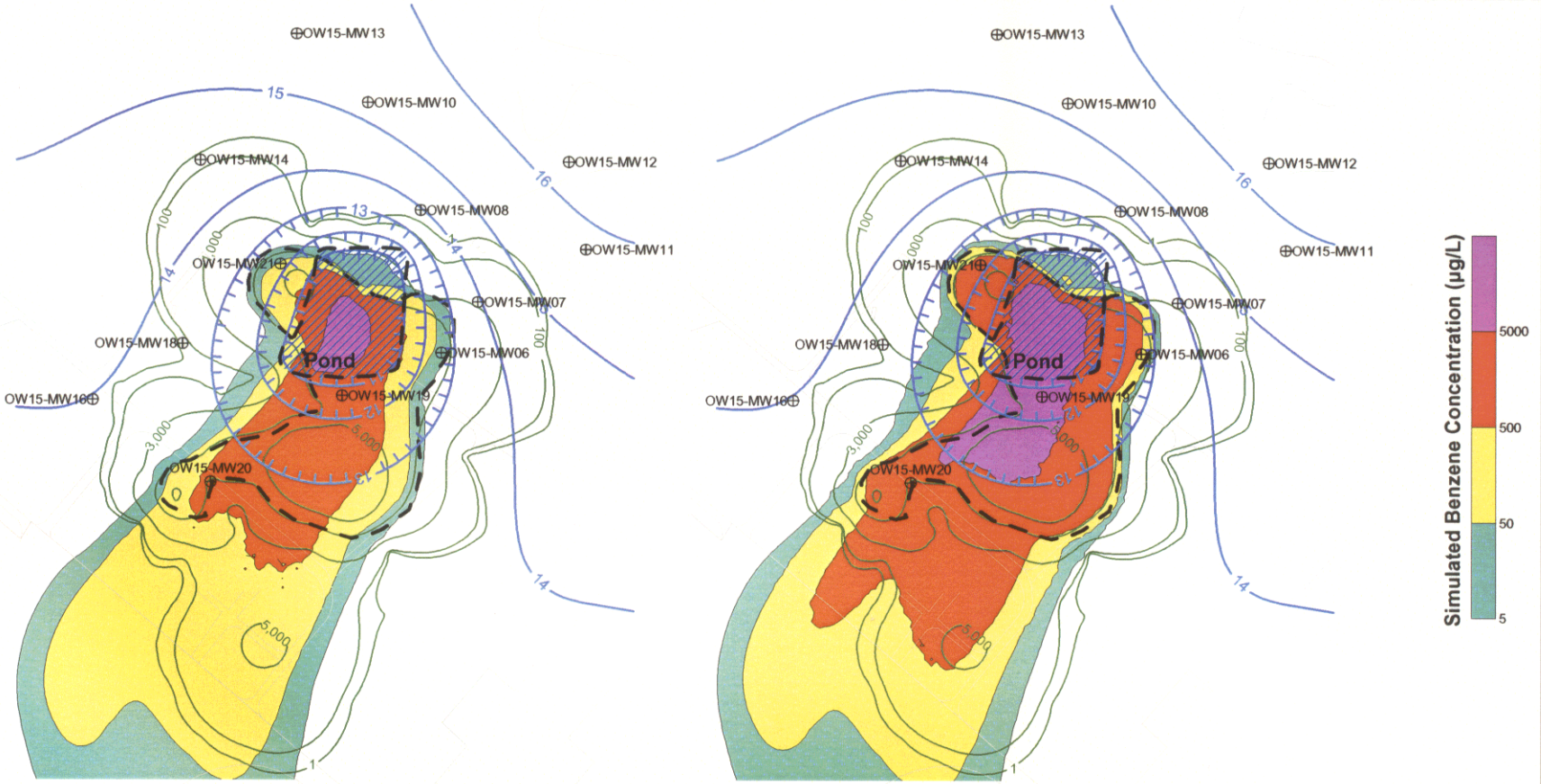
- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well




152630-16.SRF

**Figure 8-10**
**Simulated Benzene Concentrations in 30 Years**
**Downgradient Reactive Curtain Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL




**Shallow Columbia Aquifer (4 to 12 feet BGS)**

**Deep Columbia Aquifer (12 to 20 feet BGS)**

**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- Monitoring Well

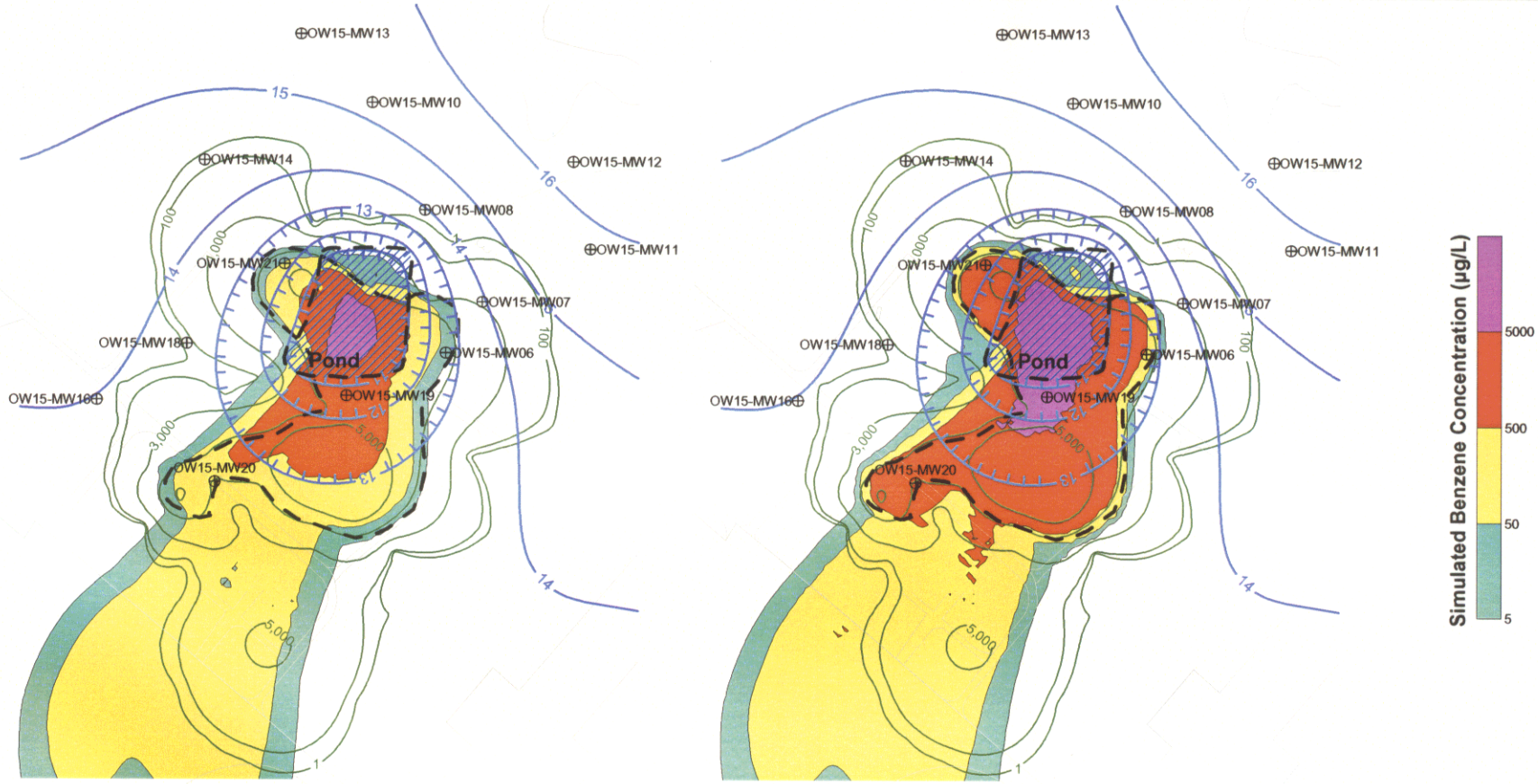
N

0 feet 350 feet 700 feet

152630-20.SRF

**Figure 8-11**
**Simulated Benzene Concentrations in 5 Years**
**Surface Water Extraction Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL




**Shallow Columbia Aquifer (4 to 12 feet BGS)**

**Deep Columbia Aquifer (12 to 20 feet BGS)**

**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

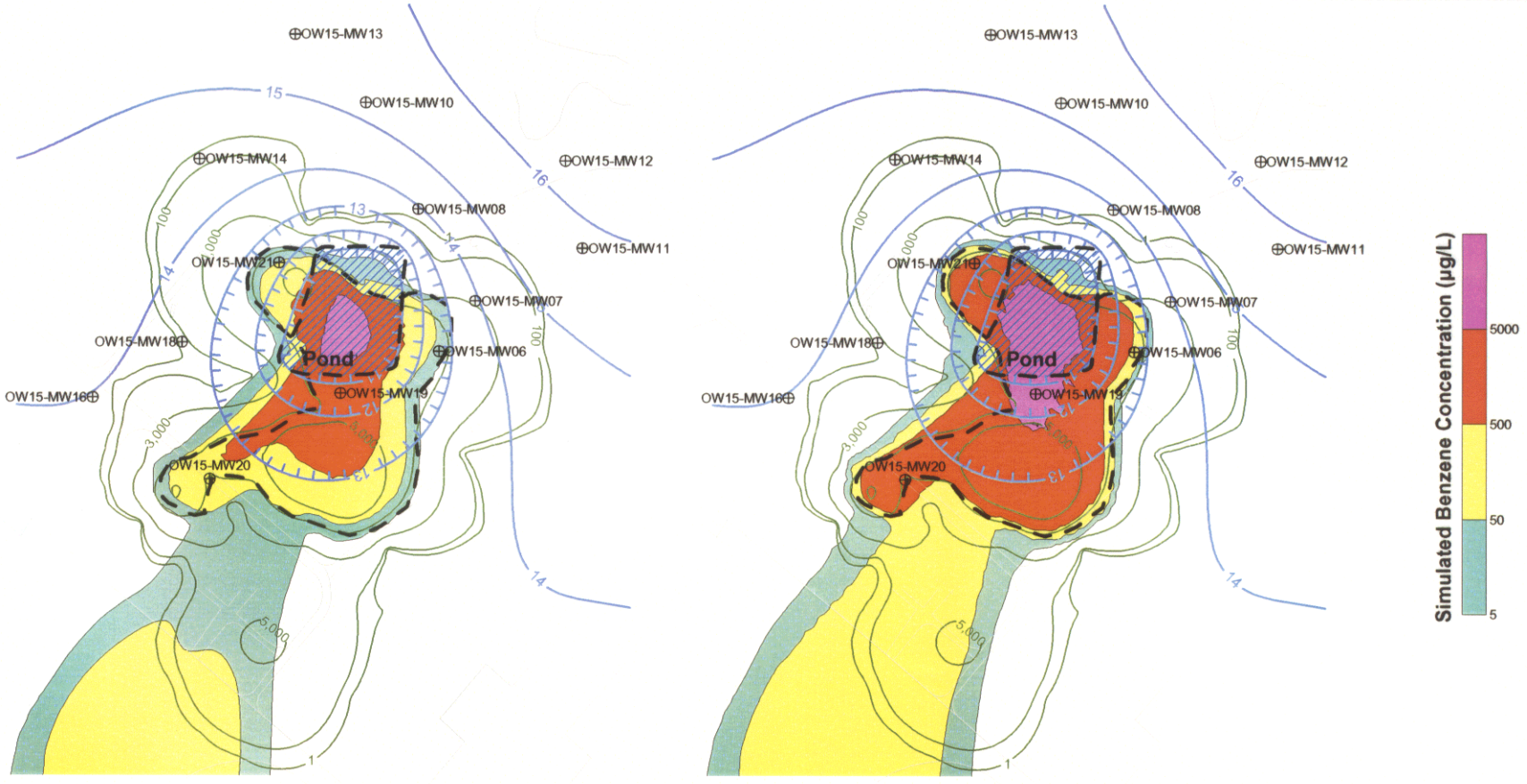
N

0 feet 350 feet 700 feet

152630-21.SRF

**Figure 8-12**
**Simulated Benzene Concentrations in 15 Years**
**Surface Water Extraction Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL




**Shallow Columbia Aquifer (4 to 12 feet BGS)**

**Deep Columbia Aquifer (12 to 20 feet BGS)**

**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- Monitoring Well

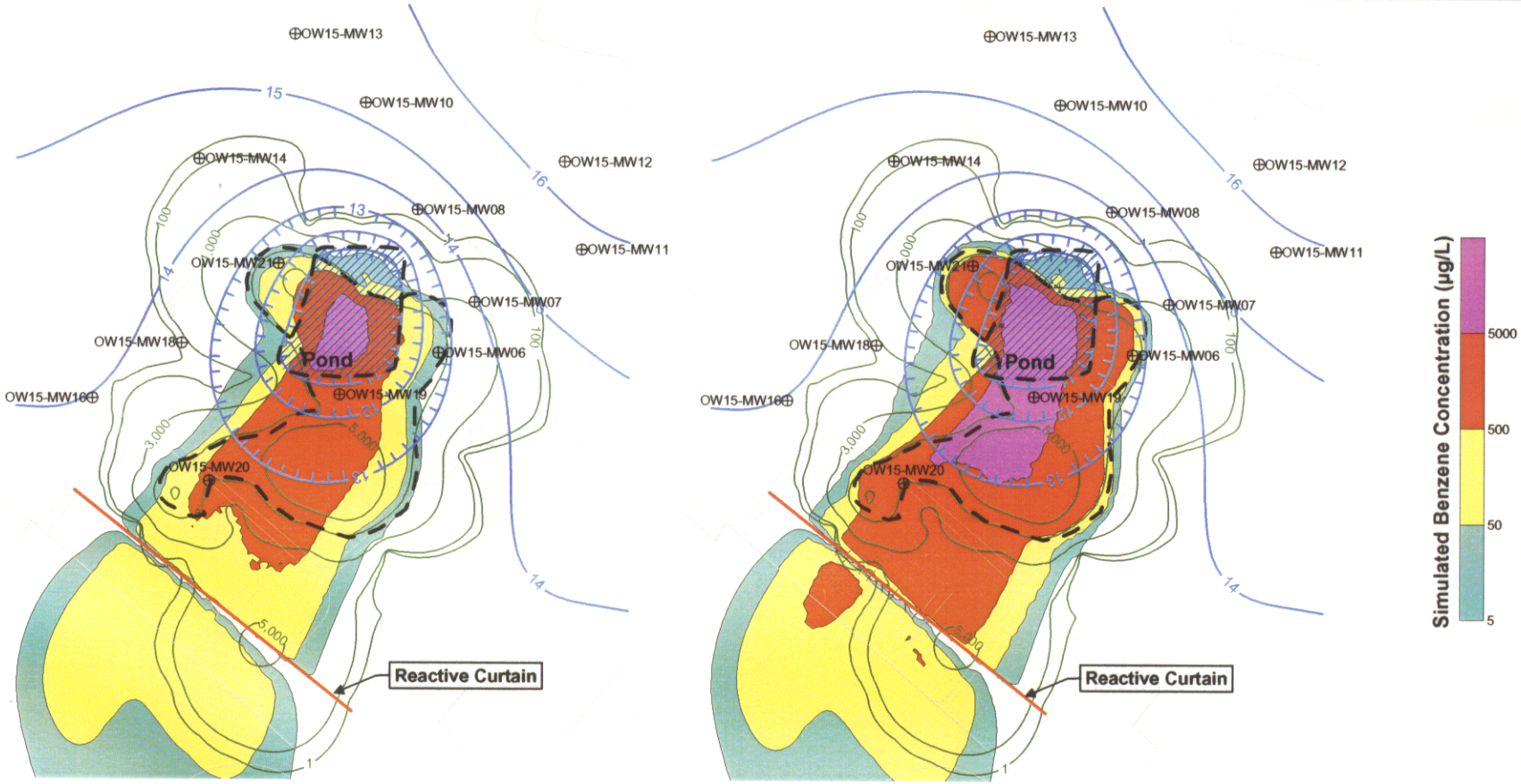
N

0 feet 350 feet 700 feet

152630-22.SRF

**Figure 8-13**
**Simulated Benzene Concentrations in 30 Years**
**Surface Water Extraction Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL




**Shallow Columbia Aquifer (4 to 12 feet BGS)**

**Deep Columbia Aquifer (12 to 20 feet BGS)**

**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

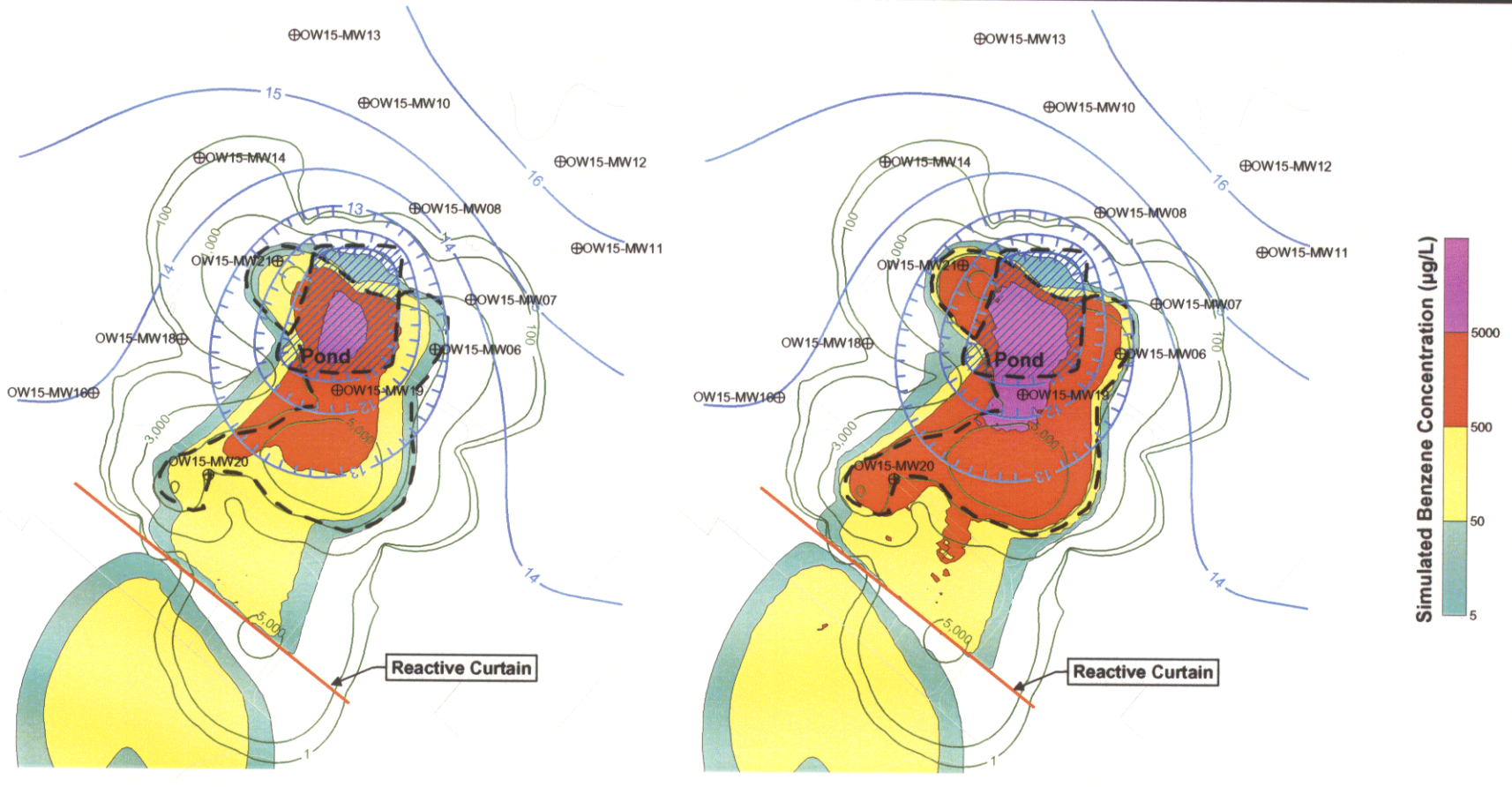
N

0 feet 350 feet 700 feet

152630-23.SRF

**Figure 8-14**
**Simulated Benzene Concentrations in 5 Years**
**Reactive Curtain with Surface Water Extraction Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL




**Shallow Columbia Aquifer (4 to 12 feet BGS)**

**Deep Columbia Aquifer (12 to 20 feet BGS)**

**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

N

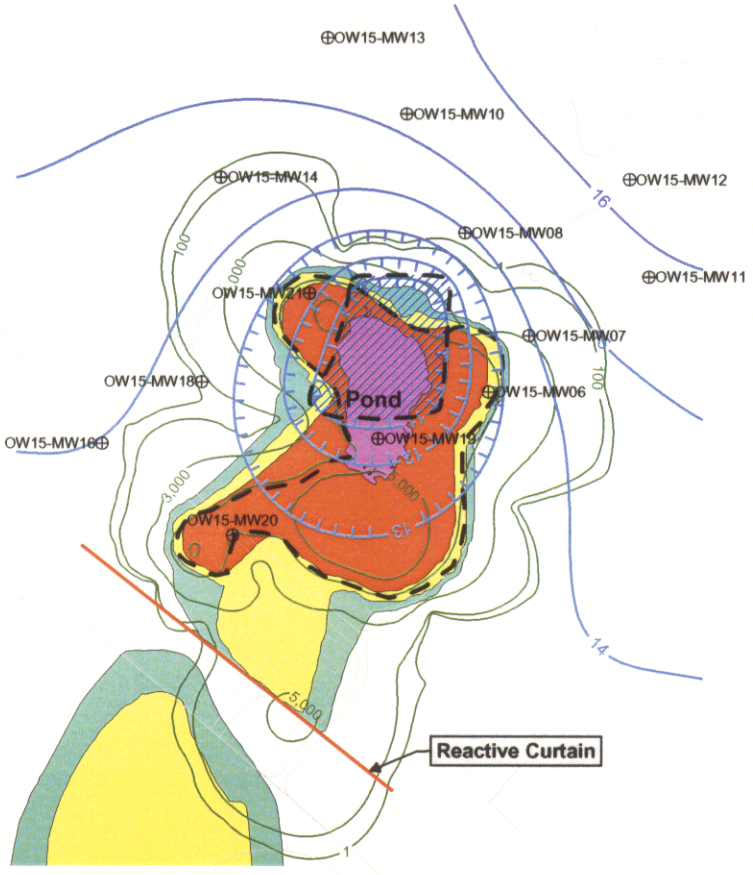
0 feet 350 feet 700 feet

152630-24.SRF

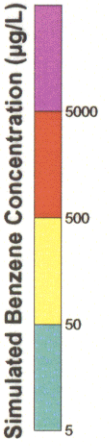
**Figure 8-15**
**Simulated Benzene Concentrations in 15 Years**
**Reactive Curtain with Surface Water Extraction Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL

Shallow Columbia Aquifer (4 to 12 feet BGS)




Deep Columbia Aquifer (12 to 20 feet BGS)




**Legend:**

- Source Zone
- 100 Total BTEX (µg/L)
- 16 Groundwater Elevation (feet MSL)
- ⊕ Monitoring Well

N

0 feet 350 feet 700 feet

152630-25.SRF

**Figure 8-16**
**Simulated Benzene Concentrations in 30 Years**
**Reactive Curtain with Surface Water Extraction Alternative**
**(Small Shallow and Large Deep Source)**
**No Biodegradation**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL

# 9. Uncertainties

Uncertainties in this study revolve around physical characterization. They are: horizontal and vertical plume delineation, source area determinations, and groundwater flow directions and velocity. These areas of uncertainty are addressed below.

## 9.1 Horizontal and Vertical Plume Delineation

The primary uncertainties regarding the physical characterization of the BTEX contaminant plume involve whether the entire plume was characterized. The horizontal and vertical boundaries of the plume were determined using results of direct push samples collected at various depths within the Columbia Aquifer. For shallow depths, samples were collected at the first four DPT locations (DW01 to DW04) at the interval from 5 to 10 feet deep, and at DW05 from the interval of 7 to 12 feet deep. BTEX concentrations at the water table of these locations were very low or non-detect (ranging from ND to 4.9 μg/L), whereas high BTEX concentrations were detected near the bottom of the Columbia Aquifer (ranging from 339 to 4,756 μg/L). Based on the apparent low contamination at the shallow depths of the first five DPT locations, sampling at the remaining 25 DPT locations was focused on deeper intervals near the bottom of the Columbia Aquifer. It cannot be known with certainty that shallow, water-table contamination is not present at the remaining 25 DPT locations. Evidence of contamination at the water table was seen in the PID and FID results at MIP-02, MIP-03, and MIP-04, outside the boundaries of the excavation area; however, the tight, silty soils near the surface prevented the collection of confirmational groundwater samples.

Near the base of the aquifer where elevated BTEX constituents were detected, an effort was made in the field to adjust the total depth of DPT samples based upon fluctuations in topography, to facilitate the monitoring of the base of the aquifer. At several plume-perimeter DPT sampling locations, the screen was pushed to a depth of 15 to 20 feet below ground surface, 2 to 3 feet above the base of the aquifer. The sample locations where this occurred are DW18, DW19, DW21, DW24, DW25, DW26, and DW27. Cross section analysis has indicated that these samples were collected at a depth unsuitable to monitor the highest levels of contamination. Therefore, the analytical results at these locations are likely to be biased low relative to a sample collected 2 to 3 feet deeper into the aquifer. However, in many instances, adjacent perimeter samples that were collected at the base of the aquifer produced similar results. Therefore, the horizontal extent of the plume is interpreted to be characterized sufficiently to satisfy the goals of this study.

The one location where the horizontal extent is uncertain is at the southernmost end of the plume at location DW30. Total BTEX greater than 1,000 μg/L was detected there. Two circumstances could account for this anomalous high detection. The plume is expected to be sinuous in nature with fingers of contamination moving through the subsurface strata. Either the detection at DW30 represents the detection of one of those fingers or the location at DW30 represents a minor former source area. Shallow groundwater at this approximate location was sampled in 1995 in conjunction with the CMS investigation (GP-30). Results indicate the presence of xylenes, DCE, and vinyl chloride, whereas, groundwater sampled

further upgradient toward the known source area had no detects of BTEX constituents. This information supports an interpretation that the area around DW30 could be a small former source area.

## 9.2 Source Area Determination

Another uncertainty regarding the physical characterization of the plume is whether there is one large NAPL source area which has produced a large dissolved-phase contaminant plume or several NAPL source areas with dissolved-phase plumes that have coalesced. The major source area identified in the RFIs and CMS was excavated. It is reasonable to assume that the product flowed laterally in the subsurface in hydraulically downgradient directions. The extent to which this might have occurred is unknown. Residual NAPL appears to exist in shallow and deep sections of the aquifer adjacent to the ponded excavation, based upon physical observation of sheens on sampled groundwater. NAPL was also detected in groundwater as sheens at several sampling locations south and southwest of the excavation. These sheens could be the result of subsurface migration of the product or could be associated with secondary and tertiary source areas. The most significant of these potential additional source areas is in the vicinity of DW13 and DW22, where total BTEX concentrations exceed 11,000 µg/L. This area was not characterized historically and it is bisected by the pipeline from the tank farm that leads to the former pump house location. Two other potential source areas are located near DPT sample locations DW07 and DW30. Correct delineation of the source area is imperative in obtaining an accurate estimate of contaminant cleanup time. An error in delineating the edge of the residual NAPL plume could severely over-or underestimate the remediation time required.

## 9.3 Groundwater Flow Directions and Velocity

The groundwater flow directions at this SWMU have varied historically from southerly to northerly due to the flat nature of the topography and the proximity of the SWMU to a groundwater divide. Groundwater flows southerly across the remainder of the base with the exception of localized flow into surface water bodies. At SWMU 15, southerly groundwater flow is interpreted to be the prevailing flow direction based upon historic benzene plume migration from the excavated source area and historic water table elevation determinations. However, the gradient seems to shift depending upon the amount of precipitation, with lower precipitation favoring a southerly flow direction. The fluctuations of the water table elevations at the site also cause a fluctuation of the gradient and the groundwater velocity. When the gradient increases, then the velocity will also increase, leading to a decrease in the time necessary for contaminant cleanup. Additional periodic monitoring of water table elevations is necessary to further characterization the fluctuation in flow direction and to obtain a more accurate estimate of the time required for contaminant cleanup.

# 10. Conclusions and Recommendations

This report presents the results of the groundwater investigation of the Columbia Aquifer at SWMU 15, an abandoned fuel tank farm, to determine the potential for natural attenuation of BTEX constituents, which had been released into the soil and shallow groundwater at the site. The main emphasis of this study was to evaluate the potential for naturally occurring degradation mechanisms to reduce dissolved-phase fuel-hydrocarbon concentrations in groundwater to levels that are protective of human health and the environment.

The Navy collected groundwater and soil samples at the SWMU. Physical and chemical data collected during this investigation were supplemented with data collected during previous remedial investigations, a corrective measures study, and a source area removal action. The BTEX contamination was characterized horizontally and vertically using DPT and MIP technology. Groundwater quality analytical results indicate that elevated concentrations of benzene, toluene, ethylbenzene, and xylenes exist within the Columbia Aquifer and surrounding confining units at SWMU 15. Benzene and xylenes are the primary constituents detected in the volatile fraction. Toluene and ethylbenzene apparently have, for the most part, biodegraded.

The Columbia Aquifer, comprised of a fine-to medium-grained sand layer approximately 16 feet thick, is semi-confined between surficial and basal layers of silt and clay. Discrete-depth groundwater sampling and MIP survey results indicated that elevated BTEX constituents occur near the bottom of the Columbia Aquifer in the uppermost silt and clay layers of the basal confining unit. Some volatile hydrocarbon contamination was detected in the surficial confining unit as well. A residual NAPL is suspected in the zones of maximum contamination composed of BTEX and non-BTEX constituents of various degraded fuels. The residual NAPL, bound up in the low-permeability silt and clay, is not likely to migrate.

Two hypotheses were evaluated for the conceptual site model of contaminant distribution and biodegradation at SWMU 15:

- **Hypothesis 1** – NAPL is present downgradient of the excavation area and high benzene concentrations are maintained by dissolution from the NAPL to the aqueous phase.
- **Hypothesis 2** – All NAPL was removed from the site through excavation of the soils at the former tank farm area in 1996, and all of the benzene currently detected in groundwater is considered to be in a dissolved-phase plume.

The conclusions regarding the occurrence of natural attenuation at SWMU 15 are very different depending on which hypothesis is used. If NAPL is present, the aqueous concentrations of benzene and other fuel components are maintained by dissolution from the NAPL phase. A decrease in concentration consistent with natural attenuation processes would only be observed downgradient of the NAPL source zone in the dissolved-phase plume. If all of the NAPL was removed from the site during the soil excavation in 1996, then the high benzene concentrations that have been observed up to 400 feet downgradient of the excavation area suggests that benzene is not biodegrading.

Field data was collected and evaluated to determine the potential for natural attenuation at SWMU 15. The follow conclusions support the "weight of evidence" that BTEX is naturally attenuating at this site:

- Elevated levels of benzene in groundwater appear to be caused by residual NAPL at the water table and at the base of the Columbia Aquifer, up to several hundred feet south of the former tank farm area that was excavated in 1996. The evidence for NAPL includes field observations of free product sheen on groundwater samples from wells and test pits, and benzene concentrations that are near the theoretical effective solubility for dissolved-phase benzene in contact with NAPL.
- BTEX compounds attenuate from greater than 1,000 μg/L near the edges of the apparent NAPL source area to less than 10 μg/L within 200 feet along groundwater flowpaths.
- Temporal data at well MW-07, located east of former tank G-6, indicates that benzene and xylenes decreased from 300 and 80 μg/L in 1994 to non-detect in 2000
- Changes in electron acceptor and metabolic byproduct concentrations between the contaminated plume and reference background locations suggests that biodegradation of BTEX compounds is occurring, with iron reduction and methanogenesis being the likely dominant processes.
- The calculated first-order biodegradation rate constant for benzene ranges from 0.0006 to 0.0036 $day^{-1}$ (half-lives of 192 to 1136 days). The average biodegradation rate is approximately 0.0023 $day^{-1}$ (half-life of 300 days).
- Groundwater modeling simulations assuming a relatively large NAPL area and a benzene biodegradation half-life of 300 days produce simulated plumes that reasonably match the observed plume extent in the field.

The following conclusions support the alternative hypothesis that natural attenuation of benzene is not occurring at SWMU 15:

- Soil sampling performed as part of the Phase II RCRA Facility Investigation indicated that NAPL-contaminated soil was present in the former tank farm area east of former tank G-6 (Figure 2-10). The contaminated soils were excavated from this area in 1996 to remove the NAPL source.
- High concentrations of benzene (ranging between 1,120 and 8,090 μg/L) are present in groundwater up to 400 feet downgradient of the excavation area. A rough estimate of the time required for the plume to travel 400 feet is approximately 20 years, which would indicate that the fuel release occurred at the end of the time period that the tank farm was active (for mid-1950's to mid-1970's).
- A well installed in 1999 (MW-20) to replace another well that was destroyed during the excavation and on-site treatment of soil in the source area (MW-15) had significantly higher benzene concentrations in February 2000 than in October 1994. The increase in benzene concentration may indicate that contaminated groundwater has migrated to the vicinity of MW-20 from the former excavated source area.

- High concentrations of methane are coincident with high benzene levels in the plume. If the methane is used as a tracer compound for the plume, the absence of high levels of methane downgradient of the benzene plume may indicate that the plume has not yet broken through to the downgradient wells.
- Groundwater modeling assuming a shallow NAPL source that is completely removed in 1996 and no biodegradation of benzene simulates a plume that is slightly smaller than what is observed in field data. The addition of a deep NAPL source near the base of the Columbia Aquifer more closely approximates the observed plume extent in the field. However, all simulations that assume no biodegradation of benzene predict a contaminant plume that spreads throughout the entire thickness of the Columbia Aquifer, which is not consistent with the vertical benzene distribution observed in the field data.

Additional monitoring is recommended in order to effectively characterize the natural attenuation process. Additional soil and groundwater sampling could be used to confirm the presence or absence of NAPL outside of the area that was excavated in 1996. Confirmational soil and groundwater sampling would be performed at both shallow (water table) and deeper depths near the bottom of the Columbia Aquifer. If the presence of NAPL is verified, additional samples may be required to determine the downgradient edges of the NAPL source zone. If no NAPL is detected in these further investigations, then the benzene plume may be expected to continue to migrate away from the site.

If monitored natural attenuation is selected as a remedial action for SWMU 15, long-term monitoring of natural attenuation should include using permanent monitoring wells, strategically placed along a flow path within the contaminated zone. The Navy's MNA guidance documents recommend that several closely-spaced monitoring wells be installed along the axis of the plume to facilitate plume tracking. The following locations are recommended for installing long-term monitoring wells along one or more groundwater flowpaths for natural attenuation monitoring:

- One well at an uncontaminated upgradient location
- One well at the downgradient edge of the NAPL source zone, and
- Two or three wells within the downgradient dissolved-phase plume.

The monitoring wells should include nested, or "cluster" wells, which are screened at the water table and near the bottom of the Columbia Aquifer. Short screened intervals (i.e., 5 feet long) should be used to lessen the mixing of groundwater from different vertical zones of the aquifer. Groundwater would be sampled periodically to assess the rate at which biodegradation of BTEX is occurring. A detailed description of the proposed monitoring strategy would be documented in the feasibility study for SWMU 15. The schedule of monitoring and parameters to be sampled for would be documented in the SWMU 15 MNA section of the Long-Term Monitoring Plan for NAS Oceana. This document has not yet been updated to include this information.

Additional "sentinel" wells may be useful in uncontaminated groundwater locations further downgradient of the dissolved-phase plume to verify that the contamination is not spreading.

If natural attenuation is not found to be sufficient for remediating the petroleum release at SWMU 15, then additional measures would be warranted. Institutional controls and long-term monitoring may be appropriate if the contaminated groundwater plume is not expected to reach human or ecological receptors. Model simulations presented in this report show that either a reactive ORC curtain or surface water extraction of the ponded excavation area may be effective at preventing the downgradient migration of a contaminant plume. Additional field data, such as drawdown and water production estimates from aquifer pumping tests or evaluation of aerobic biodegradation rates in ORC treatment zones, would need to be collected during a treatability study or remedial design phase to evaluate the site-specific effectiveness of these technologies.

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# Appendix A
## Historical Groundwater Contamination Data – SWMU 15

**Appendix A-1**
**Historic Direct Push Groundwater Total BTEX**
**SWMU 15 - NAS Oceana**

| | Nov-92 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **15-GP1** | **15-GP2** | **15-GP3** | **15-GP4** | **15-GP5** | **15-GP6** | **15-GP7** | **15-GP8** | **15-GP9** | **15-GP10** | **15-GP11** | **15-GP12** |
| Benzene | 10 U | 6.3 | 86 | 10 U | 10 U | 16,000 | 10 U | 10 U | 10 U | 10 U | 10 U | 10 U |
| Toluene | 10 U | 4.3 | 32 | 10 U | 10 U | 6,900 | 10 U | 10 U | 10 U | 10 U | 10 U | 10 U |
| Ethylbenzene | 10 U | 3.7 | 10 U | U | 10 U | 13,000 | 10 U | 10 U | 10 U | 10 U | 10 U | 10 U |
| Total Xylene | 10 U | 15 | 3,300 | 10 U | 10 U | 22,000 | 10 U | 10 U | 10 U | 10 U | 10 U | 10 U |
| **Total BTEX** | **ND** | **29.3** | **3,418** | **ND** | **ND** | **57,900** | **ND** | **ND** | **ND** | **ND** | **ND** | **ND** |

| | Feb-94 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **15-GP13** | **15-GP14** | **15-GP15** | **15-GP16** | **15-GP17** | **15-GP18** | **15-GP19** | **15-GP20** |
| Benzene | 13,152 E | 109 | 923.3 | 857 | 3 J | 100 U | 5 U | 32 |
| Toluene | 11,527 E | 25 U | 25 U | 25 U | 5 U | 100 U | 5 U | 25 U |
| Ethylbenzene | 8,835 E | 359 | 706 | 527 | 5 U | 642 | 5 U | 15 J |
| Total Xylene | 60,434 E | 1,226 | 1,470 | 1,032 | 5 U | 1,038 | 5 U | 20 J |
| **Total BTEX** | **93,948** | **1,694** | **3,099** | **2,416** | **3** | **1,680** | **ND** | **67** |

| | Sep-94 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **15-GP21** | **15-GP22** | **15-GP23** | **15-GP24** | **15-GP25** | **15-GP26** | **15-GP27** | **15-GP28** | **15-GP29** |
| Benzene | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| Toluene | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| Ethylbenzene | 2 U | 2 U | 2 U | U | 2 U | 2 U | 2 U | 2 U | 2 U |
| Total Xylene | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| **Total BTEX** | **ND** | **ND** | **ND** | **ND** | **ND** | **ND** | **ND** | **ND** | **ND** |

| | Feb-95 | | | | |
|---|---|---|---|---|---|
| | **15-GP30** | **15-GP31** | **15-GP32** | **15-GP33** | **15-GP34** |
| Benzene | 2 U | 2 U | 2 U | 2 U | 2 U |
| Toluene | 2 U | 2 U | 2 U | 2 U | 2 U |
| Ethylbenzene | 2 U | 2 U | 2 U | 2 U | 2 U |
| Total Xylene | 19 | 4 U | 4 U | 4 U | 4 U |
| **Total BTEX** | **19** | **ND** | **ND** | **ND** | **ND** |

Highest Total BTEX Concentration observed in a Historic Direct Push Groundwater Sample

**Sample Depth**
All GP samples were collected with a hydraulic probe sampler at the water table....typically from 7 to 9 ft except 15-GP13 and 15-GP17 which were collected from 0 to 5 ft.

# Appendix B
## Validated Monitoring Well Data

**Table B-1**
**Detected MW Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date | OW15-MW06-R02<br>01/27/2000 | OW15-MW07-R02<br>01/28/2000 | OW15-MW07-R02-P<br>01/28/2000<br>Duplicate | OW15-MW08-R02<br>01/27/2000 | OW15-MW10-R02<br>01/28/2000 | OW15-MW11-R02<br>01/28/2000 | OW15-MW12-R02<br>01/28/2000 | OW15-MW13-R02<br>01/27/2000 | OW15-MW14-R02<br>01/27/2000 |
|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | |
| **Volatile Organic Compounds (UG/L)** | | | | | | | | | |
| BENZENE | 1.1 J | 2 U | 2 U | 2.4 | 2 U | 2 U | 2 U | 2 U | 2 U |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| M- AND P-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| O-XYLENE | 1.1 J | 2 U | 2 U | 1.6 J | 2 U | 2 U | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U |
| TRICHLOROETHENE | 2 J | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | | | | |
| ALKALINITY | 10 U | 10 U | 10 U | 10 U | 10 U | 10 U | NA | 10 U | 10 U |
| CHLORIDE | 63.5 | 31 | 31 | 17.4 | 10.2 | 15 | 8.7 | 12.2 | 10 |
| COND (MS/CM) | 197 | 275 | NA | 88 | 174 | 157 | 125 | 157 | 99 |
| DO | 1.47 | 0.2 | NA | 1.15 | 0.41 | 2.26 | 0.72 | 0.69 | 0.32 |
| ETHANE (NG/L) | 40 | 32 | 25 | 8 | 363 | 21 | 29 | 15 | 5 U |
| ETHENE (NG/L) | 5 U | 10 | 9 | 5 U | 38 | 17 | 38 | 5 U | 39 |
| IRON II | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| IRON III | 0.5 U | 0.9 | 1 | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 10.4 | 6.931 | 5.877 | 2.933 | 6.603 | 16.95 | 5.554 | 2.503 | 0.238 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 2.35 | 0.9 | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 4.3 | 4.94 | NA | 4.3 | 4.76 | 4.81 | 5.22 | 5.63 | 5.21 |
| REDOX (mV) | 248 | 162.2 | NA | 187.4 | 261.1 | 269.1 | 153.9 | 138.5 | 147 |
| SULFATE | 23.3 | 20 | 20 | 12.7 | 12.7 | 9.7 | 9.2 | 16.4 | 8.58 |
| SULFIDE | 0.1 | 0.1 | 0.1 | 0.08 | 0.1 | 0.09 | NA | 0.1 | 0.1 |
| TEMP (Celsius) | 7.2 | 9.1 | NA | 9.93 | 11 | 10.04 | 11.7 | 12.58 | 11.72 |
| TOTAL ORGANIC CARBON (TOC) | 7.2 | 5.8 | 6.2 | 4.8 | 4.9 | 2.2 | 4.6 | 2.6 | 13 |
| TURB (NTU) | 8.6 | 944.6 | NA | 539 | 976.5 | 883.1 | 17.8 | 33.3 | 108.5 |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

**Table B-1**
**Detected MW Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date<br>Chemical Name | OW15-MW16-R02<br>01/26/2000 | OW15-MW17-R02<br>01/29/2000 | OW15-MW18-R02<br>01/27/2000 | OW15-MW19-R02<br>01/28/2000 | OW15-MW20-R02<br>01/27/2000 | OW15-MW21-R02<br>01/29/2000 | OW15-MW21-R02-P<br>01/29/2000<br>Duplicate |
|---|---|---|---|---|---|---|---|
| **Volatile Organic Compounds (UG/L)** | | | | | | | |
| BENZENE | 2 U | 2 U | 2 U | 6.7 | 3,010 | 2 U | 2 U |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 9.8 | 40 U | 2 U | 2 U |
| M- AND P-XYLENE | 2 U | 2 U | 2 U | 5.3 | 1,430 | 2 U | 2 U |
| O-XYLENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| TOLUENE | 3 U | 3 U | 3 U | 3 U | 16 J | 3 U | 3 U |
| TRICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | | |
| ALKALINITY | 35 | 75 | 25 | 37 | 90 | 25 | 30 |
| CHLORIDE | 13 | 8.7 | 10.5 | 7.8 | 13.5 | 7.8 | 7.7 |
| COND (MS/CM) | 133.4 | 284 | 173 | 586 | 251 | 626 | NA |
| DO | 0.08 | 0.23 | 4.43 | 0.22 | 0.25 | 0.14 | NA |
| ETHANE (NG/L) | 57 | 1,415 | 182 | 1,808 | 19,726 | 611 | 580 |
| ETHENE (NG/L) | 5 U | 559 | 43 | 23 | 75 | 203 | 197 |
| IRON II | 1.9 | 7.9 | 0.55 | 14 U | 8.4 | 11 | 11 |
| IRON III | 0.5 U | 0.5 U | 0.5 U | 1.2 | 0.89 | 0.5 U | 0.5 U |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 | 0.5 U |
| METHANE (UG/L) | 25.90 | 15.6 | 180 | 390 | 7,060 | 12.46 | 10.34 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 8.78 | 6 | 5.77 | 6.15 | 5.46 | 6.02 | NA |
| REDOX (mV) | -37.3 | -350 | 67.7 | -47.5 | -113.7 | 81 | NA |
| SULFATE | 19 | 11.8 | 7.3 | 121 | 21.3 | 166 | 163 |
| SULFIDE | 0.12 | 0.14 | 0.09 | 0.1 | 0.22 | 0.15 | 0.15 |
| TEMP (Celsius) | 14.12 | 14.53 | 14.88 | 15.83 | 14.81 | 15.09 | NA |
| TOTAL ORGANIC CARBON (TOC) | 2 U | 3.2 | 4 | 4.2 | 1 | 2 U | 2 U |
| TURB (NTU) | NA | 820.1 | 1,803 | 1,831 | 1,160 | 985.6 | NA |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

Raw MW Groundwater Data
SWMU 15 - NAS Oceana

| Sample Date | OW15-MW06-R02 01/27/2000 | OW15-MW07-R02 01/28/2000 | OW15-MW07-R02-P 01/28/2000 | OW15-MW08-R02 01/27/2000 | OW15-MW10-R02 01/28/2000 | OW15-MW11-R02 01/28/2000 | OW15-MW12-R02 01/28/2000 | OW15-MW13-R02 01/27/2000 | OW15-MW14-R02 01/27/2000 |
|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | Duplicate | | | | | | |
| **Volatile Organic Compounds** (UG/L) | | | | | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BENZENE | 1.1 J | 2 U | 2 U | 2.4 | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMODICHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| M- AND P-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| METHYLENE CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| O-XYLENE | 1.1 J | 2 U | 2 U | 1.6 J | 2 U | 2 U | 2 U | 2 U | 2 U |
| STYRENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TETRACHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRICHLOROETHENE | 2 J | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| VINYL CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| **Geochemistry** (MG/L unless otherwise noted) | | | | | | | | | |
| ALKALINITY | 10 U | 10 U | 10 U | 10 U | 10 U | 10 U | NA | 10 U | 10 U |
| CHLORIDE | 63.5 | 31 | 31 | 17.4 | 10.2 | 15 | 8.7 | 12.2 | 10 |
| COND (MS/CM) | 197 | 275 | NA | 88 | 174 | 157 | 125 | 157 | 99 |
| DO | 1.47 | 0.2 | NA | 1.15 | 0.41 | 2.26 | 0.72 | 0.69 | 0.32 |
| ETHANE (NG/L) | 40 | 32 | 25 | 8 | 363 | 21 | 29 | 15 | 5 U |
| ETHENE (NG/L) | 5 U | 10 | 9 | 5 U | 38 | 17 | 38 | 5 U | 39 |
| IRON II | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| IRON III | 0.5 U | 0.9 | 1 | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 10.4 | 6.931 | 5.877 | 2.933 | 6.603 | 16.95 | 5.554 | 2.503 | 0.235 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 2.35 | 0.9 | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 4.3 | 4.94 | NA | 4.3 | 4.76 | 4.81 | 5.22 | 5.63 | 5.21 |
| REDOX (mV) | 248 | 162.2 | NA | 187.4 | 261.1 | 269.1 | 153.9 | 138.5 | 147 |
| SULFATE | 23.3 | 20 | 20 | 12.7 | 12.7 | 9.7 | 9.2 | 16.4 | 8.58 |
| SULFIDE | 0.1 | 0.1 | 0.1 | 0.08 | 0.1 | 0.09 | NA | 0.1 | 0.1 |
| TEMP (Celsius) | 7.2 | 9.1 | NA | 9.93 | 11 | 10.04 | 11.7 | 12.58 | 11.72 |
| TOTAL ORGANIC CARBON (TOC) | 7.2 | 5.8 | 6.2 | 4.8 | 4.9 | 2.2 | 4.6 | 2.6 | 13 |
| TURB (NTU) | -8.6 | 944.6 | NA | 539 | 976.5 | 883.1 | 17.8 | 33.3 | 108.5 |

NA - Not analyzed
B - Analyte not detected above associated blank

J - Reported value is estimated
U - Analyte not detected

Table B-2
Raw MW Groundwater Data
SWMU 15 - NAS Oceana

| Sample Date | OW15-MW16-R02 01/26/2000 | OW15-MW17-R02 01/29/2000 | OW15-MW18-R02 01/27/2000 | OW15-MW19-R02 01/28/2000 | OW15-MW20-R02 01/27/2000 | OW15-MW21-R02 01/29/2000 | OW15-MW21-R02-P 01/29/2000 |
|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | Duplicate |
| **Volatile Organic Compounds** (UG/L) | | | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| 1,1-DICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 3 U | 3 U | 60 U | 3 U | 3 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| BENZENE | 2 U | 2 U | 2 U | 6.7 | 3,010 | 2 U | 2 U |
| BROMODICHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| BROMOFORM | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| BROMOMETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| CHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| CHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| CHLOROFORM | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| CHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 9.8 | 40 U | 2 U | 2 U |
| M- AND P-XYLENE | 2 U | 2 U | 2 U | 5.3 | 1,430 | 2 U | 2 U |
| METHYLENE CHLORIDE | 2 U | 2 U | 2 U | 2 U | 58 U | 2 U | 2 U |
| O-XYLENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| STYRENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| TETRACHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| TOLUENE | 3 U | 3 U | 3 U | 3 U | 16 J | 3 U | 3 U |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| TRICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| VINYL CHLORIDE | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U |
| **Geochemistry** (MG/L unless otherwise noted) | | | | | | | |
| ALKALINITY | 35 | 75 | 25 | 37 | 90 | 25 | 30 |
| CHLORIDE | 13 | 5.7 | 10.5 | 7.8 | 13.5 | 7.8 | 7.7 |
| COND (MS/CM) | 133.4 | 284 | 173 | 536 | 251 | 626 | NA |
| DO | 0.08 | 0.23 | 4.43 | 0.22 | 0.25 | 0.14 | NA |
| ETHANE (NG/L) | 57 | 1,415 | 182 | 1,808 | 19,726 | 611 | 580 |
| ETHENE (NG/L) | 5 U | 559 | 43 | 23 | 75 | 203 | 197 |
| IRON II | 1.9 | 7.9 | 0.55 | 14 U | 8.4 | 11 | 11 |
| IRON III | 0.5 U | 0.5 U | 0.5 U | 1.2 | 0.891 | 0.5 U | 0.5 U |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 | 0.5 U |
| METHANE (UG/L) | 25.96 | 15.6 | 180 | 390 | 7,060 | 12.46 | 10.34 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 5.78 | 6 | 5.77 | 6.15 | 5.46 | 6.02 | NA |
| REDOX (mV) | -37.3 | -350 | 67.7 | -47.5 | -113.7 | -81 | NA |
| SULFATE | 19 | 11.8 | 7.3 | 121 | 21.3 | 166 | 163 |
| SULFIDE | 0.12 | 0.14 | 0.09 | 0.1 | 0.22 | 0.15 | 0.15 |
| TEMP (Celsius) | 14.12 | 14.53 | 14.88 | 15.83 | 14.81 | 15.09 | NA |
| TOTAL ORGANIC CARBON (TOC) | 2 U | 3.2 | 4 | 4.2 | 14 | 2 U | 2 U |
| TURB (NTU) | NA | 820.1 | 1,8[illegible] | 1,831 | 1,160 | 985.6 | NA |

NA - Not analyzed
B - Analyte not detected above associated blank

J - Reported value is estimated
U - Analyte not detected

# Appendix C
## Direct Push Analytical Data

**Appendix C-1**
**Detected Direct Push Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date | OW15-DW01-05<br>02/01/2000 | OW15-DW01-10<br>02/01/2000 | OW15-DW01-17<br>02/08/2000 | OW15-DW02-05<br>02/02/2000 | OW15-DW02-10<br>02/01/2000 | OW15-DW02-17<br>02/08/2000 | OW15-DW03-05<br>02/02/2000 | OW15-DW03-10<br>02/02/2000 | OW15-DW03-17<br>02/09/2000 |
|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | |
| **Volatile Organic Compounds (UG/L)** | | | | | | | | | |
| 1,1-DICHLOROETHANE | 2 U | 3.1 | 2.2 | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| BENZENE | 2 U | 2 U | 1,800 | 2 U | 2 U | 1,520 | 2 U | 2 U | 261 |
| ETHYLBENZENE | 2 U | 2 U | 21 | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| M- AND P-XYLENE | 2 U | 2 U | 1,050 | 2 U | 2 U | 1,710 | 2 U | 2 U | 138 |
| O-XYLENE | 2 U | 2 U | 3.8 | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| TOLUENE | 3 U | 3 U | 12 | 4.9 | 3 U | 60 U | 3 U | 3 U | 30 U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | | | | |
| ALKALINITY | 105 | 85 | 100 | 40 | 25 | 70 | 135 | 105 | 110 |
| CHLORIDE | 13 | 16 | 14 | 11.3 | 12 | 16 | 15 | 18 | 14 |
| COND (MS/CM) | 234 | 244 | 551 | 891 | 715 | 363 | NA | 487 | 561 |
| DO | 0.24 | 0.23 | 0.96 | NA | 0.35 | 1.87 | 0.25 | 0.52 | 0.5 |
| ETHANE (NG/L) | 102 | 2,025 | 15,218 | 55 | 494 | 8,980 | 346 | 465 | 10,994 |
| ETHENE (NG/L) | 63 | 70 | 199 | 89 | 59 | 173 | 125 | 70 | 186 |
| IRON II | 7.1 | 2.58 | 8 U | 0.93 | 8.8 | 0.5 U | 11 | 28 | 24 |
| IRON III | 1.1 | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 7 | 0.5 U | 1.2 | 1.3 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.64 | 0.8 | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 18.36 | 1,600 | 6,580 | 7,681 | 27 | 5,010 | 20,130 | 320 | 6,080 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 57 | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 5.93 | 5.78 | 5.97 | 6.31 | 5.34 | 5.82 | 5.9 | 5.99 | 6.19 |
| REDOX (mV) | -83.1 | -52.9 | -137.4 | 11.7 | -21.7 | -92.0 | -129.7 | -108 | -199.2 |
| SULFATE | 13 | 21 | 28 | 193 | 330 | 0.5 U | 37 | 105 | 25 |
| SULFIDE | 0.1 | 0.15 | 0.17 | 0.18 | 0.12 | 0.18 | 0.1 | 0.09 | 0.19 |
| TEMP (Celsius) | 11.41 | 13.41 | 13.84 | 9.1 | 12.94 | 14.16 | 10.68 | 11.95 | 15.26 |
| TOTAL ORGANIC CARBON (TOC) | 3.6 | 10 | 15 | 2.1 | 3.2 | 14 | 17 | 17 | 18 |
| TURB (NTU) | 5.6 | 486.2 | 1,819.1 | NA | 662.7 | 1,819.9 | 499.2 | 13.5 | 1,829.5 |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

**Appendix C-1**
**Detected Direct Push Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date | OW15-DW04-05<br>02/07/2000 | OW15-DW04-10<br>02/07/2000 | OW15-DW04-17<br>02/08/2000 | OW15-DW05-07<br>02/07/2000 | OW15-DW05-12<br>02/08/2000 | OW15-DW05-18<br>02/08/2000 | OW15-DW06-18<br>02/09/2000 | OW15-DW07-17<br>02/09/2000 | OW15-DW07-17-P<br>02/09/2000<br>Duplicate |
|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | |
| **Volatile Organic Compounds (UG/L)** | | | | | | | | | |
| 1,1-DICHLOROETHANE | 2 U | 4.3 | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| BENZENE | 2 U | 2 U | 1,920 | 2 U | 2 U | 3,410 | 2,500 | 3,320 | 3,840 |
| ETHYLBENZENE | 2 U | 2 U | 40 U | 2 U | 2 U | 13 | 200 U | 200 U | 200 U |
| M- AND P-XYLENE | 2 U | 2 U | 840 | 2 U | 2 U | 1,330 | 486 | 1,300 | 1,550 |
| O-XYLENE | 2 U | 2 U | 40 U | 2 U | 2 U | 3.3 | 200 U | 200 U | 200 U |
| TOLUENE | 3 U | 3 U | 60 U | 3 U | 3 U | 17 U | 300 U | 300 U | 300 U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | | | | |
| ALKALINITY | 105 | 85 | 120 | 40 | 33 | 120 | 37 | 75 | 75 |
| CHLORIDE | 14 | 18 | 15 | 17 | 13 | 15 | 11 | 12 | 12 |
| COND (MS/CM) | 473 | 525 | 510 | 175 | 345 | 262 | 87 | 439 | NA |
| DO | 0.43 | 0.52 | 0.54 | 0.54 | 0.3 | 0.33 | 0.42 | 0.2 | NA |
| ETHANE (NG/L) | 620 | 3,503 | 19,642 | 66 | 760 | 18,386 | 22,290 | 37,078 | 41,661 |
| ETHENE (NG/L) | 108 | 71 | 303 | 32 | 517 | 501 | 273 | 522 | 459 |
| IRON II | 19 | 11 U | 11 | 1 U | 7 | 15 | 9.3 | 12 U | 12 U |
| IRON III | 0.7 | 0.5 U | 0.8 | 0.5 U | 0.5 U | 0.9 | 0.5 | 0.8 | 0.6 U |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 1.2 | 0.5 U | 0.5 U |
| METHANE (UG/L) | 280 | 230 | 6,800 | 28 | 100 | 7,370 | 5,340 | 9,200 | 10,300 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 6.91 | 6.89 | 5.93 | 5.28 | 5.68 | 5.93 | 5.7 | 6.01 | NA |
| REDOX (mV) | -117 | -109.1 | -168.7 | -441.8 | -288.7 | -516.4 | -338.2 | -421.4 | NA |
| SULFATE | 33 | 40 | 11 | 31 | 116 | 2 | 400 | 0.5 U | 0.5 U |
| SULFIDE | 0.13 | 0.1 | 0.15 | 0.14 | 0.15 | 0.19 | 0.15 | 0.15 | 0.12 |
| TEMP (Celsius) | 12.14 | 13.3 | 14.56 | 13.43 | 14.56 | 14.88 | 15.15 | 14.82 | NA |
| TOTAL ORGANIC CARBON (TOC) | 7.3 | 12 | 18 | 5.35 | 4.6 | 17 | 11 | 17 | 16 |
| TURB (NTU) | 1,812 | 1,262 | NA | 59.7 | 571.6 | 437.2 | 82.2 | 1,826.1 | NA |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

**Appendix C-1**
**Detected Direct Push Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date | OW15-DW08-17<br>02/09/2000 | OW15-DW09-17<br>02/09/2000 | OW15-DW10-17<br>02/09/2000 | OW15-DW10-17-P<br>02/09/2000<br>Duplicate | OW15-DW11-17<br>02/09/2000 | OW15-DW12-17<br>02/10/2000 | OW15-DW13-20<br>02/10/2000 | OW15-DW14-20<br>02/10/2000 | OW15-DW15-20<br>02/09/2000 |
|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | |
| **Volatile Organic Compounds (UG/L)** | | | | | | | | | |
| 1,1-DICHLOROETHANE | 1.8 J | 2 U | 2 U | 2 U | 2 U | 3.6 | 2 U | 2 U | 200 U |
| BENZENE | 332 | 3.2 | 5.8 | 5.9 | 73 | 2,118 | 6,910 | 2,870 | 1,120 |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 41 E | 47 E | 19 | 200 U |
| M- AND P-XYLENE | 224 | 1.5 J | 5 | 5.3 | 30 | 130 E | 4,230 | 784 | 210 |
| O-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 6.1 | 2.9 | 200 U |
| TOLUENE | 1.7 J | 3 U | 3 U | 3 U | 3 U | 26 | 41 E | 10 | 300 U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | | | | |
| ALKALINITY | 50 | 90 | 35 | 40 | 40 | 135 | 105 | 95 | 70 |
| CHLORIDE | 18 | 14 | 12 | 12 | 14 | 12 | 16 | 15 | 12 |
| COND (MS/CM) | 155 | 166 | 272 | NA | 165 | 507 | 563 | 364 | 230 |
| DO | 0.29 | 0.27 | 0.26 | NA | 0.25 | 0.09 | 0.07 | 0.03 | 0.27 |
| ETHANE (NG/L) | 8,509 | 3,409 | 2,393 | 2,353 | 6,461 | 30,285 | 28,372 | 14,970 | 21,929 |
| ETHENE (NG/L) | 266 | 291 | 244 | 259 | 381 | 452 | 486 | 188 | 1,057 |
| IRON II | 10 | 11 | 6.4 | 5.7 | 12 | 23 | 21 | 11 | 14 |
| IRON III | 0.7 | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.9 | 1.3 | 0.8 | 0.5 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 17,300 | 670 | 310 | 340 | 790 | 7,910 | 10,600 | 6,720 | 5,700 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 6 | 5.94 | 5.83 | NA | 5.92 | 6.15 | 6.06 | 5.9 | 6.06 |
| REDOX (mV) | -356.2 | -411.9 | -448.9 | NA | -463.6 | -419.5 | -414.2 | -477.2 | -493.2 |
| SULFATE | 0.5 U | 13 | 16 | 16 | 17 | 0.5 U | 0.5 | 0.5 U | 3 |
| SULFIDE | 0.34 | 0.36 | 0.17 | 0.17 | 0.15 | 0.22 | 0.15 | 0.23 | 0.39 |
| TEMP (Celsius) | 15.44 | 15 | 15.14 | NA | 15.15 | 14.75 | 15.56 | 16.48 | 15.69 |
| TOTAL ORGANIC CARBON (TOC) | 5.5 | 8.3 | 2.8 | 2.6 | 8.8 | 15 | 33 | 25 | 13 |
| TURB (NTU) | 162.5 | 666.7 | 270.4 | NA | 171.2 | 650.9 | 1,830.0 | 898.9 | 443.2 |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

**Appendix C-1**
**Detected Direct Push Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date | OW15-DW16-18<br>02/09/2000 | OW15-DW17-20<br>02/10/2000 | OW15-DW18-15<br>02/10/2000 | OW15-DW19-15<br>02/10/2000 | OW15-DW20-18<br>02/10/2000 | OW15-DW21-15<br>02/10/2000 | OW15-DW22-20<br>02/14/2000 | OW15-DW23-20<br>02/14/2000 | OW15-DW24-15<br>02/14/2000 |
|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | |
| **Volatile Organic Compounds (UG/L)** | | | | | | | | | |
| 1,1-DICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BENZENE | 9 | 3,350 | 416 | 192 | 29 | 3.8 | 8,090 | 1,380 | 97 |
| ETHYLBENZENE | 8.2 | 28 | 5.4 | 0.7 J | 2 U | 2 U | 35 E | 3.5 | 2 U |
| M- AND P-XYLENE | 35 | 1,578 | 6.3 | 12 | 8.7 | 1 J | 9.6 | 112 E | 59 |
| O-XYLENE | 2 U | 3.8 | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 16 | 6 | 1.2 J | 3 U | 3 U | 10.1 | 2 J | 3 U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | | | | |
| ALKALINITY | 15 | 115 | 50 | 33 | 33 | 85 | 133 | 90 | 100 |
| CHLORIDE | 7.4 | 14 | 8 | 8.3 | 6.9 | 12 | 15 | 11 | 17 |
| COND (MS/CM) | 641 | 310 | 270 | 450 | 289 | 165 | 257 | 280 | 247 |
| DO | 0.02 | 0.4 | 0.27 | 0.03 | 0.38 | 0.42 | 0.32 | 0.28 | 0.28 |
| ETHANE (NG/L) | 1,169 | 17,997 | 6,150 | 5,601 | 4,685 | 1,807 | 29,424 | 29,170 | 8,156 |
| ETHENE (NG/L) | 383 | 354 | 718 | 201 | 128 | 217 | 277 | 525 | 301 |
| IRON II | 12 | 16 | 14 | 20 | 11 | 13 | 20 | 12 | 7.8 |
| IRON III | 0.7 | 1 | 1.2 | 1.3 | 1.1 | 0.8 | 1.7 | 1 | 0.6 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 | 0.5 | 0.6 |
| METHANE (UG/L) | 51 | 11,400 | 2,490 | 1,200 | 1,460 | 560 | 6,350 | 6,250 | 1,610 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 6.63 | 5.92 | 6.2 | 6.32 | 6.07 | 5.9 | 6.12 | 6.2 | 6.05 |
| REDOX (mV) | 438.9 | -490.7 | 330.7 | 375 | -222.4 | -304.6 | 412.3 | 489.4 | -465.2 |
| SULFATE | 184 | 0.5 | 70 | 97 | 109 | 7 | 0.5 U | 0.5 U | 0.5 |
| SULFIDE | 0.15 | 0.16 | 0.31 | 0.24 | 0.15 | 0.26 | 0.09 | 0.14 | 0.14 |
| TEMP (Celsius) | 16.62 | 16.22 | 16 | 16.75 | 15.94 | 15.58 | 14.9 | 15.84 | 14.55 |
| TOTAL ORGANIC CARBON (TOC) | 5.5 | 27 | 8.3 | 8.6 | 5 | 5.8 | 15 | 8.5 | 4.6 |
| TURB (NTU) | 1,836.1 | 104.2 | 428.1 | 1,039.1 | 70.1 | 666.6 | 27.4 | 33.1 | 20.7 |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

**Appendix C-1**
**Detected Direct Push Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date | OW15-DW25-15<br>02/14/2000 | | OW15-DW26-15<br>02/14/2000 | | OW15-DW27-15<br>02/14/2000 | | OW15-DW28-20<br>02/16/2000 | | OW15-DW29-20<br>02/16/2000 | | OW15-DW30-20<br>02/16/2000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | | | | |
| **Volatile Organic Compounds (UG/L)** | | | | | | | | | | | | |
| 1,1-DICHLOROETHANE | 2 | U | 2 | U | 2 | U | 8 | U | 20 | U | 20 | U |
| BENZENE | 2 | J | 1.1 | J | 2 | U | 8 | U | 150 | | 1,008 | |
| ETHYLBENZENE | 2 | U | 2 | U | 2 | U | 8 | U | 20 | U | 20 | U |
| M- AND P-XYLENE | 2 | U | 1.9 | J | 1.4 | J | 42 | | 79 | | 468 | |
| O-XYLENE | 2 | U | 2 | U | 2 | U | 8 | U | 20 | U | 20 | U |
| TOLUENE | 3 | U | 3 | U | 3 | U | 12 | U | 30 | U | 30 | U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | | | | | | | |
| ALKALINITY | 20 | | 20 | | 20 | | 75 | | 85 | | 100 | |
| CHLORIDE | 9.1 | | 7.8 | | 10 | | 11 | | 11 | | 14 | |
| COND (MS/CM) | 107 | | 353 | | 230 | | 108 | | 141 | | 144 | |
| DO | 0.29 | | 0 | | 0.05 | | 0.17 | | 0.1 | | 0.03 | |
| ETHANE (NG/L) | 143 | | 1,470 | | 855 | | 7,977 | | 16,599 | | 47,174 | |
| ETHENE (NG/L) | 100 | | 285 | | 297 | | 226 | | 152 | | 236 | |
| IRON II | 6.3 | | 16 | | 7.1 | | 8.7 | | 5.9 | | 7.5 | |
| IRON III | 0.5 | U | 0.6 | | 0.6 | | 0.5 | U | 0.7 | | 0.6 | |
| MANGANESE | 0.5 | U | 0.5 | U | 0.5 | U | 0.5 | U | 0.5 | U | 0.5 | U |
| METHANE (UG/L) | 21 | | 220 | | 54.17 | | 1,420 | | 1,760 | | 3,180 | |
| NITRATE | 0.5 | U | 0.5 | U | 0.5 | U | 0.5 | U | 0.5 | U | 0.5 | U |
| pH (unitless) | 5.63 | | 6.2 | | 5.75 | | 5.73 | | 6.06 | | 5.89 | |
| REDOX (mV) | -372.1 | | -390.9 | | -367.5 | | 229 | | 244.3 | | 259.3 | |
| SULFATE | 12 | | 90 | | 20 | | 7.3 | | 2.8 | | 5.7 | |
| SULFIDE | 0.1 | | 0.07 | | 0.1 | | 0.1 | | 0.17 | | 0.18 | |
| TEMP (Celsius) | 14.7 | | 16 | | 15.55 | | 16.03 | | 16.25 | | 15.49 | |
| TOTAL ORGANIC CARBON (TOC) | 4.6 | | 3.9 | | 2.9 | | 2.9 | | 6.9 | | 5.9 | |
| TURB (NTU) | 13.6 | | 224.3 | | 452.3 | | 1,835 | | 473.6 | | 1,832.2 | |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

Appendix C-2
Raw Direct Push Groundwater Data
SWMU 15 - NAS Oceana

| Sample Date | OW15-DW01-05 02/01/2000 | OW15-DW01-10 02/01/2000 | OW15-DW01-17 02/08/2000 | OW15-DW02-05 02/02/2000 | OW15-DW02-10 02/01/2000 | OW15-DW02-17 02/08/2000 | OW15-DW03-05 02/02/2000 | OW15-DW03-10 02/02/2000 | OW15-DW03-17 02/09/2000 |
|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | |
| **Volatile Organic Compounds** (UG/L) | | | | | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| 1,1-DICHLOROETHANE | 2 U | 3.1 | 2.2 | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 3 U | 3 U | 3 U | 60 U | 3 U | 3 U | 30 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| BENZENE | 2 U | 2 U | 1,800 | 2 U | 2 U | 1,520 | 2 U | 2 U | 261 |
| BROMODICHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| BROMOFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| BROMOMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| CHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| CHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| CHLOROFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| CHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| ETHYLBENZENE | 2 U | 2 U | 21 | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| M- AND P-XYLENE | 2 U | 2 U | 1,050 | 2 U | 2 U | 1,710 | 2 U | 2 U | 138 |
| METHYLENE CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| O-XYLENE | 2 U | 2 U | 3.8 | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| STYRENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| TETRACHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| TOLUENE | 3 U | 3 U | 12 | 4.9 | 3 U | 60 U | 3 U | 3 U | 30 U |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| TRICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| VINYL CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 40 U | 2 U | 2 U | 20 U |
| **Geochemistry** (MG/L unless otherwise noted) | | | | | | | | | |
| ALKALINITY | 105 | 85 | 100 | 40 | 25 | 70 | 135 | 105 | 110 |
| CHLORIDE | 13 | 16 | 14 | 11.3 | 12 | 16 | 15 | 18 | 14 |
| COND (MS/CM) | 234 | 244 | 551 | 891 | 715 | 363 | NA | 487 | 561 |
| DO | 0.24 | 0.23 | 0.96 | NA | 0.35 | 1.87 | 0.25 | 0.52 | 0.5 |
| ETHANE (NG/L) | 162 | 2,025 | 15,218 | 55 | 494 | 8,980 | 346 | 465 | 16,994 |
| ETHENE (NG/L) | 63 | 70 | 199 | 89 | 59 | 173 | 125 | 70 | 186 |
| IRON II | 7.1 | 2.58 | 8 U | 0.93 | 8.8 | 0.5 U | 11 | 28 | 24 |
| IRON III | 1.1 | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 7 | 0.5 U | 1.2 | 1.3 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.64 | 0.8 | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 18.36 | 1,600 | 6,580 | 7.681 | 27 | 5,010 | 20,130 | 320 | 6,080 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 57 | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 5.93 | 5.78 | 5.97 | 6.31 | 5.34 | 5.82 | 5.9 | 5.99 | 6.19 |
| REDOX (mV) | -83.1 | -52.9 | -137.4 | 11.7 | -21.7 | -920 | -129.7 | -108 | -199.2 |
| SULFATE | 13 | 21 | 28 | 193 | 330 | 0.5 U | 37 | 105 | 25 |
| SULFIDE | 0.1 | 0.15 | 0.17 | 0.18 | 0.12 | 0.18 | 0.1 | 0.09 | 0.19 |
| TEMP (Celsius) | 11.41 | 13.41 | 13.84 | 9.1 | 12.94 | 14.16 | 10.68 | 11.95 | 15.26 |
| TOTAL ORGANIC CARBON (TOC) | 3.6 | 10 | 15 | 2.1 | 3.2 | 14 | 17 | 17 | 18 |
| TURB (NTU) | 5.6 | 486.2 | 1,819.1 | NA | 662.7 | 1,819.9 | 499.2 | 13.5 | 1,829.5 |

NA - Not analyzed
B - Analyte not detected above associated blank

J - Reported value is estimated
U - Analyte not detected

Appendix C-2
Raw Direct Push Groundwater Data
SWMU 15 - NAS Oceana

| Sample Date | OW15-DW04-05 02/07/2000 | OW15-DW04-10 02/07/2000 | OW15-DW04-17 02/08/2000 | OW15-DW05-07 02/07/2000 | OW15-DW05-12 02/08/2000 | OW15-DW05-18 02/08/2000 | OW15-DW06-18 02/09/2000 | OW15-DW07-17 02/09/2000 | OW15-DW07-17-P 02/09/2000 |
|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | Duplicate |
| **Volatile Organic Compounds** (UG/L) | | | | | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| 1,1-DICHLOROETHANE | 2 U | 4.3 | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 60 U | 3 U | 3 U | 3 U | 300 U | 300 U | 300 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| BENZENE | 2 U | 2 U | 1,920 | 2 U | 2 U | 3,410 | 2,500 | 3,320 | 3,840 |
| BROMODICHLOROMETHANE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| BROMOFORM | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| BROMOMETHANE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| CHLOROBENZENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| CHLOROETHANE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| CHLOROFORM | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| CHLOROMETHANE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| ETHYLBENZENE | 2 U | 2 U | 40 U | 2 U | 2 U | 13 | 200 U | 200 U | 200 U |
| M- AND P-XYLENE | 2 U | 2 U | 840 | 2 U | 2 U | 1,330 | 486 | 1,300 | 1,550 |
| METHYLENE CHLORIDE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| O-XYLENE | 2 U | 2 U | 40 U | 2 U | 2 U | 3.3 | 200 U | 200 U | 200 U |
| STYRENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| TETRACHLOROETHENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| TOLUENE | 3 U | 3 U | 60 U | 3 U | 3 U | 17 U | 300 U | 300 U | 300 U |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| TRICHLOROETHENE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| VINYL CHLORIDE | 2 U | 2 U | 40 U | 2 U | 2 U | 2 U | 200 U | 200 U | 200 U |
| **Geochemistry** (MG/L unless otherwise noted) | | | | | | | | | |
| ALKALINITY | 105 | 85 | 120 | 40 | 33 | 120 | 37 | 75 | 75 |
| CHLORIDE | 14 | 18 | 15 | 17 | 13 | 15 | 11 | 12 | 12 |
| COND (MS/CM) | 473 | 525 | 510 | 175 | 345 | 262 | 87+ | 439 | NA |
| DO | 0.43 | 0.52 | 0.54 | 0.54 | 0.3 | 0.33 | 0.42 | 0.2 | NA |
| ETHANE (NG/L) | 620 | 3,503 | 19,642 | 66 | 760 | 18,386 | 22,290 | 37,078 | 41,661 |
| ETHENE (NG/L) | 108 | 71 | 303 | 32 | 517 | 501 | 273 | 522 | 459 |
| IRON II | 19 | 11 U | 11 | 1 U | 7 | 15 | 9.3 | 12 U | 12 U |
| IRON III | 0.7 | 0.5 U | 0.8 | 0.5 U | 0.5 U | 0.9 | 0.5 | 0.8 | 0.6 U |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 1.2 | 0.5 U | 0.5 U |
| METHANE (UG/L) | 280 | 230 | 6,800 | 28 | 100 | 7,370 | 5,340 | 9,200 | 10,300 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 6.91 | 6.89 | 5.93 | 5.28 | 5.68 | 5.93 | 5.7 | 6.01 | NA |
| REDOX (mV) | -117 | -109.1 | -168.7 | -441.8 | -288.7 | -516.4 | -338.2 | -421.4 | NA |
| SULFATE | 33 | 40 | 11 | 31 | 116 | 2 | 400 | 0.5 U | 0.5 U |
| SULFIDE | 0.13 | 0.1 | 0.15 | 0.14 | 0.15 | 0.19 | 0.15 | 0.15 | 0.12 |
| TEMP (Celsius) | 12.14 | 13.3 | 14.56 | 13.43 | 14.56 | 14.88 | 15.15 | 14.82 | NA |
| TOTAL ORGANIC CARBON (TOC) | 7.3 | 12 | 18 | 5.35 | 4.6 | 17 | 11 | 17 | |
| [illegible]B (NTU) | 1,812 | 1,262 | NA | 59.7 | 571.6 | 437.2 | 82.2 | 1,826.1 | |

NA - Not [illegible]zed
B - Analyte not detected above associated blank

J - Reporte[illegible]ue is estimated
U - Analyte not detected

Appendix C-2
Raw Direct Push Groundwater Data
SWMU 15 - NAS Oceana

| Sample Date | OW15-DW08-17 02/09/2000 | OW15-DW09-17 02/09/2000 | OW15-DW10-17 02/09/2000 | OW15-DW10-17-P 02/09/2000 | OW15-DW11-17 02/09/2000 | OW15-DW12-17 02/10/2000 | OW15-DW13-20 02/10/2000 | OW15-DW14-20 02/10/2000 | OW15-DW15-20 02/09/2000 |
|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | Duplicate | | | | | |
| **Volatile Organic Compounds (UG/L)** | | | | | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| 1,1-DICHLOROETHANE | 1.8 J | 2 U | 2 U | 2 U | 2 U | 3.6 | 2 U | 2 U | 200 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 300 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| BENZENE | 332 | 3.2 | 5.8 | 5.9 | 73 | 2,118 | 6,910 | 2,870 | 1,120 |
| BROMODICHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| BROMOFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| BROMOMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| CHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| CHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| CHLOROFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| CHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 41 E | 47 E | 19 | 200 U |
| M- AND P-XYLENE | 224 | 1.5 J | 5 | 5.3 | 30 | 130 E | 4,230 | 784 | 210 |
| METHYLENE CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| O-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 6.1 | 2.9 | 200 U |
| STYRENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| TETRACHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| TOLUENE | 1.7 J | 3 U | 3 U | 3 U | 3 U | 26 | 41 E | 10 | 300 U |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| TRICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| VINYL CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 200 U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | | | | |
| ALKALINITY | 50 | 90 | 35 | 40 | 40 | 135 | 105 | 95 | 70 |
| CHLORIDE | 18 | 14 | 12 | 12 | 14 | 12 | 16 | 15 | 12 |
| COND (MS/CM) | 155 | 166 | 272 | NA | 165 | 507 | 563 | 364 | 230 |
| DO | 0.29 | 0.27 | 0.26 | NA | 0.25 | 0.09 | 0.07 | 0.03 | 0.27 |
| ETHANE (NG/L) | 8,509 | 3,409 | 2,393 | 2,353 | 6,461 | 30,285 | 28,372 | 14,970 | 21,929 |
| ETHENE (NG/L) | 266 | 291 | 244 | 259 | 381 | 452 | 486 | 188 | 1,057 |
| IRON II | 10 | 11 | 6.4 | 5.7 | 12 | 23 | 21 | 11 | 14 |
| IRON III | 0.7 | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.9 | 1.3 | 0.8 | 0.5 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 17,300 | 670 | 310 | 340 | 790 | 7,910 | 10,600 | 6,720 | 5,700 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 6 | 5.94 | 5.83 | NA | 5.92 | 6.15 | 6.06 | 5.9 | 6.06 |
| REDOX (mV) | -456.2 | -411.9 | -448.9 | NA | -463.6 | -419.5 | -414.2 | -477.2 | -493.2 |
| SULFATE | 0.5 U | 13 | 16 | 16 | 17 | 0.5 U | 0.5 | 0.5 U | 3 |
| SULFIDE | 0.34 | 0.36 | 0.17 | 0.17 | 0.15 | 0.22 | 0.15 | 0.23 | 0.39 |
| TEMP (Celsius) | 15.44 | 15 | 15.14 | NA | 15.15 | 14.75 | 15.56 | 16.48 | 15.69 |
| TOTAL ORGANIC CARBON (TOC) | 5.5 | 8.3 | 2.8 | 2.6 | 8.8 | 15 | 33 | 25 | 13 |
| TURB (NTU) | 162.5 | 666.7 | 270.4 | NA | 171.2 | 650.9 | 1,830.0 | 898.9 | 443.2 |

NA - Not analyzed
B - Analyte not detected above associated blank

J - Reported value is estimated
U - Analyte not detected

Appendix C-2
Raw Direct Push Groundwater Data
SWMU 15 - NAS Oceana

| Sample Date | OW15-DW16-18 02/09/2000 | OW15-DW17-20 02/10/2000 | OW15-DW18-15 02/10/2000 | OW15-DW19-15 02/10/2000 | OW15-DW20-18 02/10/2000 | OW15-DW21-15 02/10/2000 | OW15-DW22-20 02/14/2000 | OW15-DW23-20 02/14/2000 | OW15-DW24-15 02/14/2000 |
|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | |
| **Volatile Organic Compounds** (UG/L) | | | | | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BENZENE | 9 | 3,350 | 416 | 192 | 29 | 3.8 | 8,090 | 1,380 | 97 |
| BROMODICHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| ETHYLBENZENE | 8.2 | 28 | 5.4 | 0.7 J | 2 U | 2 U | 35 E | 3.5 | 2 U |
| M- AND P-XYLENE | 35 | 1,578 | 6.3 | 12 | 8.7 | 1 J | 9.6 | 112 E | 59 |
| METHYLENE CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| O-XYLENE | 2 U | 3.8 | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| STYRENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TETRACHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 16 | 6 | 1.2 J | 3 U | 3 U | 10.1 | 2 J | 3 U |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| VINYL CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| **Geochemistry** (MG/L unless otherwise noted) | | | | | | | | | |
| ALKALINITY | 15 | 115 | 50 | 33 | 33 | 85 | 133 | 90 | 100 |
| CHLORIDE | 7.4 | 14 | 8 | 8.3 | 6.9 | 12 | 15 | 11 | 17 |
| COND (MS/CM) | 641 | 310 | 270 | 450 | 289 | 165 | 257 | 280 | 247 |
| DO | 0.02 | 0.4 | 0.27 | 0.03 | 0.38 | 0.42 | 0.32 | 0.28 | 0.28 |
| ETHANE (NG/L) | 1,169 | 17,997 | 6,150 | 5,601 | 4,685 | 1,807 | 29,424 | 29,170 | 8,156 |
| ETHENE (NG/L) | 383 | 354 | 718 | 201 | 128 | 217 | 277 | 525 | 301 |
| IRON II | 12 | 16 | 14 | 20 | 11 | 13 | 20 | 12 | 7.8 |
| IRON III | 0.7 | 1 | 1.2 | 1.3 | 1.1 | 0.8 | 1.7 | 1 | 0.6 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 | 0.5 | 0.6 |
| METHANE (UG/L) | 51 | 11,400 | 2,490 | 1,200 | 1,460 | 560 | 6,350 | 6,250 | 1,610 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 6.63 | 5.92 | 6.2 | 6.32 | 6.07 | 5.9 | 6.12 | 6.2 | 6.05 |
| REDOX (mV) | -438.9 | -490.7 | -330.7 | -375 | -222.4 | -304.6 | -412.3 | -489.4 | -465.2 |
| SULFATE | 184 | 0.5 | 70 | 97 | 109 | 7 | 0.5 U | 0.5 U | 0.5 |
| SULFIDE | 0.15 | 0.16 | 0.31 | 0.24 | 0.15 | 0.26 | 0.09 | 0.14 | 0.14 |
| TEMP (Celsius) | 16.62 | 16.22 | 16 | 16.75 | 15.94 | 15.58 | 14.9 | 15.84 | 14.55 |
| TOTAL ORGANIC CARBON (TOC) | 5.5 | 27 | 8.3 | 8.6 | 5 | 5.8 | 15 | 8.5 | 4.6 |
| [illegible] (NTU) | 1,836.1 | 104.2 | 428.1 | [illegible]039.1 | 70.1 | 666.6 | 27.4 | 33.1 | 20.[illegible] |

NA - Not a[illegible]d
B - Analyte not detected above associated blank

J - Reported [illegible] is estimated
U - Analyte not detected

Appendix C-2
Raw Direct Push Groundwater Data
SWMU 15 - NAS Oceana

| Sample Date | OW15-DW25-15 02/14/2000 | OW15-DW26-15 02/14/2000 | OW15-DW27-15 02/14/2000 | OW15-DW28-20 02/16/2000 | OW15-DW29-20 02/16/2000 | OW15-DW30-20 02/16/2000 |
|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | |
| **Volatile Organic Compounds (UG/L)** | | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| 1,1-DICHLOROETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 3 U | 12 U | 30 U | 30 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| BENZENE | 2 J | 1.1 J | 2 U | 8 U | 150 | 1,008 |
| BROMODICHLOROMETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| BROMOFORM | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| BROMOMETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| CHLOROBENZENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| CHLOROETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| CHLOROFORM | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| CHLOROMETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| M- AND P-XYLENE | 2 U | 1.9 J | 1.4 J | 42 | 79 | 468 |
| METHYLENE CHLORIDE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| O-XYLENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| STYRENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| TETRACHLOROETHENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| TOLUENE | 3 U | 3 U | 3 U | 12 U | 30 U | 30 U |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| TRICHLOROETHENE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| VINYL CHLORIDE | 2 U | 2 U | 2 U | 8 U | 20 U | 20 U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | |
| ALKALINITY | 20 | 20 | 20 | 75 | 85 | 100 |
| CHLORIDE | 9.1 | 7.8 | 10 | 11 | 11 | 14 |
| COND (MS/CM) | 107 | 353 | 230 | 108 | 141 | 144 |
| DO | 0.29 | 0 | 0.05 | 0.17 | 0.1 | 0.03 |
| ETHANE (NG/L) | 143 | 1,470 | 855 | 7,977 | 16,599 | 47,174 |
| ETHENE (NG/L) | 100 | 285 | 297 | 226 | 152 | 236 |
| IRON II | 6.3 | 16 | 7.1 | 8.7 | 5.9 | 7.5 |
| IRON III | 0.5 U | 0.6 | 0.6 | 0.5 U | 0.7 | 0.6 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 21 | 220 | 54.17 | 1,420 | 1,760 | 3,180 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| pH (unitless) | 5.63 | 6.2 | 5.75 | 5.73 | 6.06 | 5.89 |
| REDOX (mV) | -372.1 | -390.9 | -367.5 | -229 | -244.3 | -259.3 |
| SULFATE | 12 | 90 | 20 | 7.3 | 2.8 | 5.7 |
| SULFIDE | 0.1 | 0.07 | 0.1 | 0.1 | 0.17 | 0.18 |
| TEMP (Celsius) | 14.7 | 16 | 15.55 | 16.03 | 16.25 | 15.49 |
| TOTAL ORGANIC CARBON (TOC) | 4.6 | 3.9 | 2.9 | 2.9 | 6.9 | 5.9 |
| TURB (NTU) | 13.6 | 224.3 | 452.3 | 1,835 | 473.6 | 1,832.2 |

NA - Not analyzed
B - Analyte not detected above associated blank

J - Reported value is estimated
U - Analyte not detected

# Appendix D
## MIP/VP Analytical Groundwater Data

**Table D-1**
**Detected MIP Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date | OW15-MIP01-06<br>02/15/2000 | OW15-MIP01-10<br>02/15/2000 | OW15-MIP01-14<br>02/16/2000 | OW15-MIP01-17<br>02/16/2000 | OW15-MIP01-20<br>02/16/2000 | OW15-MIP01-22<br>02/17/2000 | OW15-MIP01-23<br>02/17/2000 | OW15-MIP01-25<br>02/17/2000 | OW15-MIP01-26<br>02/17/2000 | OW15-MIP02-11<br>02/25/2000 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | | |
| **Volatile Organic Compounds** (UG/L) | | | | | | | | | | |
| BENZENE | 0.9 J | 2 U | 2 U | 2 U | 81 | 5,920 | 3,980 | 227 | 39 | 2 U |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 16 | 35 | 2.6 | 2 U | 2 U |
| M- AND P-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 14 | 28 | 1.6 J | 2 U | 2 U |
| O-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2.9 | 2.6 | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 3 U | 3 U | 3 U | 3 U | 7.8 | 7.4 | 1.1 J | 1.3 J | 3 U |
| **Geochemistry** (MG/L unless otherwise noted) | | | | | | | | | | |
| ALKALINITY | 13 | 10 U | 45 | 28 | 65 | 140 | 140 | 16 | 70 | 17 |
| CHLORIDE | 16 | 7.6 | 8.5 | 7.9 | 10 | 11 | 12 | 9 | 16 | 9.4 |
| COND (MS/CM) | 289 | 415 | 466 | 200 | 177 | 349 | 293 | 415 | NA | 134 |
| DO | 0.33 | 0.36 | 0.18 | 0.28 | 5.5 | 0.26 | 0.36 | 4.73 | NA | 0 |
| ETHANE (NG/L) | 76 | 74 | 231 | 1,355 | 659 | 48,821 | 79,212 | 2,016 | 1,242 | 70 |
| ETHENE (NG/L) | 59 | 58 | 47 | 28 | 19 | 155 | 72 | 503 | 354 | 72 |
| IRON II | 0.5 U | 16 | 14 | 4.2 | 2.3 | 13 | 14 | 4.6 | 0.5 U | 3.9 |
| IRON III | 0.5 U | 0.6 | 0.9 | 0.5 U | 0.6 | 0.8 | 0.9 | 0.7 | 0.5 U | 0.5 U |
| MANGANESE | 0.5 U | 1 | 1 | 0.5 U | 0.5 U | 0.6 | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 6.7 | 6,702 | 6,503 | 171 | 109 J | 12,160 | 16650 | 130.2 | 200.6 | 56.21 |
| NITRATE | 7.2 | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| PH (unitless) | 5.47 | 5.53 | 5.82 | 6.24 | 6.55 | 6.29 | 6.07 | 6.47 | NA | 5.31 |
| REDOX (mV) | 10.4 | -29.7 | -81.9 | -115.3 | -128.1 | -157.7 | -127.6 | -152.1 | NA | -74.5 |
| SULFATE | 87 | 210 | 234 | 61 | 8.2 | 53 | 0.5 U | 196 | 12 | 26 |
| SULFIDE | 0.1 | 0.1 | 0.11 | 0.11 | 0.15 | 0.14 | 0.15 | 0.12 | 0.12 | 0.19 |
| TEMP (Celsius) | 13.31 | 14.48 | 15.94 | 17.48 | 16.36 | 16.11 | 16.46 | 14.89 | NA | 14.01 |
| TOTAL ORGANIC CARBON (TOC) | 4.3 | 3.2 | 2 U | 3.1 | 6.9 | 15 | 19 | 3.1 | NA | 3.5 |
| TURB (NTU) | 349.7 | 83.2 | 385.2 | 584 | 237.5 | 121.6 | 85.4 | 1466.2 | NA | 96.2 |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

**Table D-1**
**Detected MIP Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date<br>Chemical Name | OW15-MIP02-11-P<br>02/25/2000<br>Duplicate | OW15-MIP02-14<br>02/25/2000 | OW15-MIP02-17<br>02/25/2000 | OW15-MIP02-17-P<br>02/25/2000<br>Duplicate | OW15-MIP02-20<br>02/25/2000 | OW15-MIP02-22<br>02/25/2000 | OW15-MIP02-23<br>02/25/2000 | OW15-MIP02-29<br>02/25/2000 | OW15-MIP03-11<br>02/17/2000 | OW15-MIP03-11-P<br>02/17/2000<br>Duplicate |
|---|---|---|---|---|---|---|---|---|---|---|
| **Volatile Organic Compounds (UG/L)** | | | | | | | | | | |
| BENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 4.3 | 2 U | 2.2 | 1.8 J |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 4.5 | 2.1 | 2 U | 2 U | 2 U |
| M- AND P-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 8.4 | 6.9 | 2.9 J | 2 U | 2 U |
| O-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | | | | | |
| ALKALINITY | 20 | 10 U | 10 U | 10 U | 60 | 85 | 70 | 90 | 35 | 40 |
| CHLORIDE | 9.2 | 7.5 | 9.7 | 9.9 | 9.3 | 9.7 | 11 | 18 | 8.7 | 8.7 |
| COND (MS/CM) | NA | 262 | 202 | NA | 227 | 216 | NA | NA | 297 | NA |
| DO | NA | 0 | 0 | NA | 0 | 0 | NA | NA | 0.2 | NA |
| ETHANE (NG/L) | 39 | 74 | 451 | 1,276 | 2,545 | 6,321 | 1,758 | 5,493 | 3,491 | 3,510 |
| ETHENE (NG/L) | 26 | 5 U | 78 | 660 | 380 | 316 | 276 | 2,343 | 49 | 42 |
| IRON II | 3.9 | 5.6 | 11 | 10 | 10 | 14 | 0.6 | 18 | 19 | 17 |
| IRON III | 0.5 U | 0.5 U | 0.9 | 0.5 U | 0.6 | 0.5 | 0.5 U | 0.9 | 1.2 | 0.6 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.6 | 0.8 | 0.7 |
| METHANE (UG/L) | 41.82 | 15.54 | 120 | 64.73 | 350 | 1,200 | 340 | 84.37 | 1,970 | 1,900 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| PH (unitless) | NA | 5.22 | 5.99 | NA | 5.65 | 5.69 | NA | NA | 6.12 | NA |
| REDOX (mV) | NA | 72.2 | -5.7 | NA | -10.1 | -11.2 | NA | NA | -135.8 | NA |
| SULFATE | 27 | 116 | 68 | 69 | 38 | 8.3 | 2.9 | 11 | 100 | 100 |
| SULFIDE | 0.19 | 0.16 | 0.35 | 0.3 | 0.14 | 0.15 | 0.15 | 0.19 | 0.12 | 0.12 |
| TEMP (Celsius) | NA | 15.2 | 18.88 | NA | 18.47 | 15.26 | NA | NA | 14.15 | NA |
| TOTAL ORGANIC CARBON (TOC) | 2.8 | 2.5 | 7.4 | 5.2 | 8.1 | 4.8 | 12 | 9.6 | 6.3 | 8 |
| TURB (NTU) | NA | 142 | 169.1 | NA | 215.7 | 1,636 | NA | NA | 837.1 | NA |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

**Table D-1**
**Detected MIP Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date | OW15-MIP03-14<br>02/18/2000 | OW15-MIP03-17<br>02/18/2000 | OW15-MIP03-20<br>02/21/2000 | OW15-MIP03-22<br>02/21/2000 | OW15-MIP03-23<br>02/21/2000 | OW15-MIP03-25<br>02/22/2000 | OW15-MIP03-26<br>02/22/2000 | OW15-MIP04-07<br>02/22/2000 | OW15-MIP04-11<br>02/22/2000 | OW15-MIP04-11-P<br>02/22/2000<br>Duplicate |
|---|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | | |
| **Volatile Organic Compounds (UG/L)** | | | | | | | | | | |
| BENZENE | 2 U | 2 U | 1,230 | 328 | 1,820 | 4,340 | 304 | 2 U | 2 U | 2 U |
| ETHYLBENZENE | 2 U | 2 U | 24 | 6.2 | 15 | 27 | 4.8 | 2 U | 2 U | 2 U |
| M- AND P-XYLENE | 2 U | 2 U | 170 | 76 | 243 | 364 | 38 | 2 U | 2 U | 2 U |
| O-XYLENE | 2 U | 2 U | 2 U | 2 U | 1.3 J | 4.2 | 2 U | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 3 U | 3.1 | 3 U | 3.3 | 7.8 | 3 U | 3 U | 3 U | 3 U |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | | | | | | |
| ALKALINITY | 25 | 10 U | 95 | 60 | 98 | 58 | 85 | 110 | 18 | 20 |
| CHLORIDE | 7.5 | 7.7 | 13 | 10 | 12 | 15 | 18 | 18 | 8.2 | 8.2 |
| COND (MS/CM) | 370 | 355 | 199 | 150 | 175 | 271 | 357 | 349 | 354 | NA |
| DO | 0.36 | 0.23 | 0.39 | 7.46 | NA | 0.36 | 0.42 | 0.04 | 6.07 | NA |
| ETHANE (NG/L) | 886 | 505 | 27,238 | 9,559 | 35,282 | 71,904 | 1,624 | 1,912 | 914 | 914 |
| ETHENE (NG/L) | 41 | 41 | 482 | 108 | 332 | 535 | 425 | 33 | 44 | 32 |
| IRON II | 6.4 | 9.2 | 8.9 | 4.6 | 6.2 | 10 | 34 | 38 | 30 | 28 |
| IRON III | 0.5 U | 0.5 U | 0.5 | 0.7 | 0.5 U | 0.5 | 1 | 1.3 | 0.7 | 0.7 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 1 | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 230 | 123 | 6,800 | 2,210 | 5,630 | 8,180 | 121 | 480 | 200 | 190 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| PH (unitless) | 6.18 | 6.17 | 5.85 | 5.97 | 5.77 | 6.27 | 6.4 | 6.2 | 6.18 | NA |
| REDOX (mV) | -102.4 | -99.2 | -235.9 | -132.5 | -164.6 | -153.4 | -134.9 | -157 | -127.8 | NA |
| SULFATE | 179 | 174 | 0.5 U | 2.7 | 0.5 U | 0.5 U | 44 | 14 | 152 | 154 |
| SULFIDE | 0.14 | 0.15 | 0.12 | 0.14 | 0.15 | 0.15 | 0.13 | 0.12 | 0.1 | 0.09 |
| TEMP (Celsius) | 14.51 | 15.27 | 16.24 | 15.39 | 16.31 | 16.42 | 16.67 | 12.79 | 14.5 | NA |
| TOTAL ORGANIC CARBON (TOC) | 3.3 | 2.2 | 13 | 9 | 28 | 23 | 9.4 | 31 | 6.7 | 5.3 |
| TURB (NTU) | 78.3 | 99.3 | 121.9 | 308.7 | 219.4 | 1637.4 | 1837.8 | 237.6 | 16.5 | NA |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

**Table D-1**
**Detected MIP Groundwater Data**
**SWMU 15 - NAS Oceana**

| Sample ID<br>Sample Date | OW15-MIP04-14<br>02/23/2000 | OW15-MIP04-17<br>02/23/2000 | OW15-MIP04-20<br>02/23/2000 | OW15-MIP04-22<br>02/23/2000 | OW15-MIP04-23<br>02/23/2000 |
|---|---|---|---|---|---|
| **Chemical Name** | | | | | |
| **Volatile Organic Compounds (UG/L)** | | | | | |
| BENZENE | 2 U | 2,700 | 3,030 | 5,000 | 3,260 |
| ETHYLBENZENE | 2 U | 14 | 21 | 13 | 10 |
| M- AND P-XYLENE | 2 U | 35 | 11 | 136 B | 106 B |
| O-XYLENE | 2 U | 2 U | 3.1 | 2 U | 2 U |
| TOLUENE | 3 U | 3.5 | 5.5 | 12 | 9.5 |
| **Geochemistry (MG/L unless otherwise noted)** | | | | | |
| ALKALINITY | 45 | 120 | 140 | 125 | 120 |
| CHLORIDE | 8.5 | 9.9 | 11 | 13 | 13 |
| COND (MS/CM) | 277 | 265 | 284 | 269 | 336 |
| DO | 3.37 | 0.2 | 0.15 | 1.57 | 1.11 |
| ETHANE (NG/L) | 5,132 | 29,931 | 65,626 | 89,723 | 73,852 |
| ETHENE (NG/L) | 67 | 126 | 103 | 3749 | 5992 |
| IRON II | 19 | 12 | 11 | 12 | 15 |
| IRON III | 0.6 | 0.5 U | 0.5 U | 0.5 | 0.9 |
| MANGANESE | 0.6 | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 2,600 | 12,910 | 12,490 | 9,000 | 7,120 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| PH (unitless) | 6.31 | 6.04 | 5.89 | 5.9 | 6.05 |
| REDOX (mV) | -170 | -120.4 | -94.6 | -82.6 | -116 |
| SULFATE | 82 | 3.7 | 1.1 | 0.5 U | 11 |
| SULFIDE | 0.17 | 0.15 | 0.11 | 0.12 | 0.1 |
| TEMP (Celsius) | 14.85 | 15.77 | 15.93 | 16.53 | 16.27 |
| TOTAL ORGANIC CARBON (TOC) | 5.1 | 16 | 16 | 19 | 20 |
| TURB (NTU) | 35.2 | 331 | 25.1 | 140.5 | 1,835.7 |

NA - Not analyzed
B - Analyte not detected above associated blank
J - Reported value is estimated
U - Analyte not detected

D-2

## Raw MIP Groundwater Data
## SWMU 15 - NAS Oceana

| Sample Date | OW15-MIP01-06 02/15/2000 | OW15-MIP01-10 02/15/2000 | OW15-MIP01-14 02/16/2000 | OW15-MIP01-17 02/16/2000 | OW15-MIP01-20 02/16/2000 | OW15-MIP01-22 02/17/2000 | OW15-MIP01-23 02/17/2000 | OW15-MIP01-25 02/17/2000 | OW15-MIP01-26 02/17/2000 | OW15-MIP02-11 02/25/2000 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | | |
| **Volatile Organic Compounds** (UG/L) | | | | | | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BENZENE | 0.9 J | 2 U | 2 U | 2 U | 81 | 5,920 | 3,980 | 227 | 39 | 2 U |
| BROMODICHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | NA | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 16 | 35 E | 2.6 | 2 U | 2 U |
| M- AND P-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 14 | 28 | 1.6 J | 2 U | 2 U |
| METHYLENE CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| O-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2.9 | 2.6 | 2 U | 2 U | 2 U |
| STYRENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TETRACHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 3 U | 3 U | 3 U | 3 U | 7.8 | 7.4 | 1.1 J | 1.3 J | 3 U |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| VINYL CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| **Geochemistry** (MG/L unless otherwise noted) | | | | | | | | | | |
| ALKALINITY | 13 | 10 U | 45 | 28 | 65 | 140 | 140 | 16 | 70 | 17 |
| CHLORIDE | 10 | 7.6 | 8.5 | 7.9 | 10 | 11 | 12 | 9 | 16 | 9.4 |
| COND (MS/CM) | 289 | 415 | 460 | 200 | 177 | 349 | 293 | 415 | NA | 134 |
| DO | 0.33 | 0.36 | 0.18 | 0.28 | 5.5 | 0.26 | 0.36 | 4.73 | NA | 0 |
| ETHANE (NG/L) | 76 | 74 | 231 | 1,355 | 659 | 48,821 | 79,212 | 2,016 | 1,242 | 70 |
| ETHENE (NG/L) | 59 | 58 | 47 | 28 | 19 | 155 | 72 | 503 | 354 | 72 |
| IRON II | 0.5 U | 16 | 14 | 4.2 | 2.3 | 13 | 14 | 4.6 | 0.5 U | 3.9 |
| IRON III | 0.5 U | 0.6 | 0.9 | 0.5 U | 0.6 | 0.8 | 0.9 | 0.7 | 0.5 U | 0.5 U |
| MANGANESE | 0.5 U | 1 | 1 | 0.5 U | 0.5 U | 0.6 | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 6.7 | 6.702 | 6.503 | 171 | 109.1 | 12160 | 16650 | 130.2 | 200.6 | 56.21 |
| NITRATE | 7.2 | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| PH (unitless) | 5.47 | 5.53 | 5.82 | 6.24 | 6.55 | 6.29 | 6.07 | 6.47 | NA | 5.31 |
| REDOX (mV) | 10.4 | -29.7 | -81.9 | -115.3 | -128.1 | -157.7 | -127.6 | -152.1 | NA | 74.5 |
| SULFATE | 87 | 210 | 234 | 61 | 8.2 | 52 | 0.5 U | 196 | 12 | 26 |
| SULFIDE | 0.1 | 0.1 | 0.11 | 0.11 | 0.15 | 0.14 | 0.15 | 0.12 | 0.12 | 0.19 |
| TEMP (Celsius) | 13.31 | 14.48 | 15.94 | 17.48 | 16.36 | 16.11 | 16.46 | 14.89 | NA | 14.01 |
| TOTAL ORGANIC CARBON (TOC) | 4.3 | 2.2 | 2 U | 3.1 | 6.9 | 15 | 19 | 3.1 | NA | 3.5 |
| TURB (NTU) | 349.7 | 83.2 | 385.2 | 584 | 237.5 | 121.6 | 85.4 | 1466.2 | NA | 196.2 |

NA - Not analyzed
B - Analyte not detected above associated blank

J - Reported value is estimated
U - Analyte not detected

# Table D-2
## Raw MIP Groundwater Data
## SWMU 15 - NAS Oceana

| Sample Date | OW15-MIP02-11-P 02/25/2000 | OW15-MIP02-14 02/25/2000 | OW15-MIP02-17 02/25/2000 | OW15-MIP02-17-P 02/25/2000 | OW15-MIP02-20 02/25/2000 | OW15-MIP02-22 02/25/2000 | OW15-MIP02-23 02/25/2000 | OW15-MIP02-29 02/25/2000 | OW15-MIP03-11 02/17/2000 | OW15-MIP03-11-P 02/17/2000 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | Duplicate | | | Duplicate | | | | | | Duplicate |
| **Volatile Organic Compounds** (UG/L) | | | | | | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 4.3 | 2 U | 2.2 | 1.8 J |
| BROMODICHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| ETHYLBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 4.5 | 2.1 | 2 U | 2 U | 2 U |
| M- AND P-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 8.4 | 6.9 | 2.9 J | 2 U | 2 U |
| METHYLENE CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| O-XYLENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| STYRENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TETRACHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| VINYL CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| **Geochemistry** (MG/L unless otherwise noted) | | | | | | | | | | |
| ALKALINITY | 20 | 10 U | 10 U | 10 U | 60 | 85 | 70 | 90 | 35 | 40 |
| CHLORIDE | 9.2 | 7.5 | 9.7 | 9.9 | 9.3 | 9.7 | 11 | 18 | 8.7 | 8.7 |
| COND (MS/CM) | NA | 262 | 202 | NA | 227 | 216 | NA | NA | 297 | NA |
| DO | NA | 0 | 0 | NA | 0 | 0 | NA | NA | 0.2 | NA |
| ETHANE (NG/L) | 39 | 74 | 451 | 1,276 | 2,545 | 6,321 | 1,758 | 5,493 | 3,491 | 3,510 |
| ETHENE (NG/L) | 26 | 5 U | 78 | 660 | 380 | 316 | 275 | 2,343 | 49 | 42 |
| IRON II | 3.9 | 5.6 | 11 | 10 | 10 | 14 | 0.6 | 18 | 19 | 17 |
| IRON III | 0.5 U | 0.5 U | 0.9 | 0.5 U | 0.6 | 0.5 | 0.5 U | 0.9 | 1.2 | 0.6 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.6 | 0.5 | 0.7 |
| METHANE (UG/L) | 41.82 | 15.54 | 120 | 64.73 | 350 | 1,200 | 340 | 84.37 | 1,970 | 1,900 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| PH (unitless) | NA | 5.22 | 5.99 | NA | 5.65 | 5.69 | NA | NA | 6.12 | NA |
| REDOX (mV) | NA | 72.2 | -5.7 | NA | 10.1 | -11.2 | NA | NA | -135.8 | NA |
| SULFATE | 27 | 116 | 68 | 69 | 38 | 8.3 | 2.9 | 11 | 100 | 100 |
| SULFIDE | 0.19 | 0.16 | 0.33 | 0.3 | 0.14 | 0.13 | 0.15 | 0.19 | 0.12 | 0.12 |
| TEMP (Celsius) | NA | 15.2 | 18.88 | NA | 18.47 | 15.26 | NA | NA | 14.15 | NA |
| TOTAL ORGANIC CARBON (TOC) | 2.8 | 2.5 | 7.4 | 5.2 | 8.1 | 4.8 | 12 | 9.6 | 6.3 | 8 |
| TURB (NTU) | NA | 142 | [illegible] | [illegible] | 215.7 | 1,636 | NA | NA | 877.1 | NA |

NA - Not ana[illegible]
B - Analyte not detected above associated blank

J - Reported va[illegible] estimated
U - Analyte not detected

## Table D-2
## Raw MIP Groundwater Data
## SWMU 15 - NAS Oceana

| Sample Date | OW15-MIP03-14 02/18/2000 | OW15-MIP03-17 02/18/2000 | OW15-MIP03-20 02/21/2000 | OW15-MIP03-22 02/21/2000 | OW15-MIP03-23 02/21/2000 | OW15-MIP03-25 02/22/2000 | OW15-MIP03-26 02/22/2000 | OW15-MIP04-07 02/22/2000 | OW15-MIP04-11 02/22/2000 | OW15-MIP04-11-P 02/22/2000 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Chemical Name** | | | | | | | | | | Duplicate |
| **Volatile Organic Compounds** (UG/L) | | | | | | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U | 3 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BENZENE | 2 U | 2 U | 1,230 | 328 | 1,820 | 4,340 | 304 | 2 U | 2 U | 2 U |
| BROMODICHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROFORM | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| ETHYLBENZENE | 2 U | 2 U | 24 | 6.2 | 15 | 27 | 4.8 | 2 U | 2 U | 2 U |
| M- AND P-XYLENE | 2 U | 2 U | 170 J | 76 | 243 | 364 | 38 | 2 U | 2 U | 2 U |
| METHYLENE CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| O-XYLENE | 2 U | 2 U | 2 U | 2 U | 1.3 J | 4.2 | 2 U | 2 U | 2 U | 2 U |
| STYRENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TETRACHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 3 U | 3.1 | 3 U | 3.3 | 7.8 | 3 U | 3 U | 3 U | 3 U |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| VINYL CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U | 2 U |
| **Geochemistry** (MG/L unless otherwise noted) | | | | | | | | | | |
| ALKALINITY | 25 | 10 U | 95 | 60 | 98 | 58 | 85 | 110 | 18 | 20 |
| CHLORIDE | 7.5 | 7.7 | 13 | 10 | 12 | 15 | 18 | 18 | 8.2 | 8.2 |
| COND (MS/CM) | 370 | 355 | 199 | 150 | 175 | 271 | 357 | 349 | 354 | NA |
| DO | 0.36 | 0.23 | 0.39 | 7.46 | NA | 0.36 | 0.42 | 0.04 | 6.67 | NA |
| ETHANE (NG/L) | 886 | 505 | 27,238 | 9,559 | 35,282 | 71,904 | 1,624 | 1,912 | 914 | 914 |
| ETHENE (NG/L) | 41 | 41 | 482 | 108 | 332 | 535 | 425 | 33 | 44 | 32 |
| IRON II | 6.4 | 9.2 | 8.9 | 4.6 | 6.2 | 10 | 34 | 38 | 30 | 28 |
| IRON III | 0.5 U | 0.5 U | 0.5 | 0.7 | 0.5 U | 0.5 | 1 | 1.3 | 0.7 | 0.7 |
| MANGANESE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 1 | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 230 | 123 | 6,800 | 2,210 | 5,630 | 8,180 | 121 | 480 | 200 | 190 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| PH (unitless) | 6.18 | 6.17 | 5.85 | 5.97 | 5.77 | 6.27 | 6.4 | 6.2 | 6.18 | NA |
| REDOX (mV) | -102.4 | -99.2 | -235.9 | -132.5 | -164.6 | -153.4 | -134.9 | -157 | -127.8 | NA |
| SULFATE | 179 | 174 | 0.5 U | 2.7 | 0.5 U | 0.5 U | 44 | 14 | 152 | 154 |
| SULFIDE | 0.14 | 0.15 | 0.12 | 0.14 | 0.15 | 0.15 | 0.13 | 0.12 | 0.1 | 0.09 |
| TEMP (Celsius) | 14.51 | 15.27 | 16.24 | 15.39 | 16.31 | 16.42 | 16.67 | 12.79 | 14.5 | NA |
| TOTAL ORGANIC CARBON (TOC) | 3.3 | 2.2 | 13 | 9 | 28 | 23 | 9.4 | 31 | 6.7 | 5.3 |
| TURB (NTU) | 78.3 | 99.3 | 121.9 | 308.7 | 219.4 | 1637.4 | 1837.8 | 237.6 | 16.5 | NA |

NA - Not analyzed
B - Analyte not detected above associated blank

J - Reported value is estimated
U - Analyte not detected

## Table D-2
## Raw MIP Groundwater Data
## SWMU 15 - NAS Oceana

| Sample Date | OW15-MIP04-14 02/23/2000 | OW15-MIP04-17 02/23/2000 | OW15-MIP04-20 02/23/2000 | OW15-MIP04-22 02/23/2000 | OW15-MIP04-23 02/23/2000 |
|---|---|---|---|---|---|
| **Chemical Name** | | | | | |
| **Volatile Organic Compounds** (UG/L) | | | | | |
| 1,1,1-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2,2-TETRACHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1,2-TRICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,1-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2,4-TRICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DIBROMOETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,2-DICHLOROETHANE | 3 U | 3 U | 3 U | 3 U | 3 U |
| 1,3-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| 1,4-DICHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| BENZENE | 2 U | 2,700 | 3,030 | 5,000 | 3,260 |
| BROMODICHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOFORM | 2 U | 2 U | 2 U | 2 U | 2 U |
| BROMOMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| CARBON TETRACHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROBENZENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROFORM | 2 U | 2 U | 2 U | 2 U | 2 U |
| CHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| CIS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| DIBROMOCHLOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| DICHLORODIFLUOROMETHANE | 2 U | 2 U | 2 U | 2 U | 2 U |
| ETHYLBENZENE | 2 U | 14 | 21 | 13 | 10 |
| M- AND P-XYLENE | 2 U | 35 | 11 | 136 E | 106 E |
| METHYLENE CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U |
| O-XYLENE | 2 U | 2 U | 3.1 | 2 U | 2 U |
| STYRENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| TETRACHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| TOLUENE | 3 U | 3.5 | 5.5 | 12 | 9.5 |
| TRANS-1,2-DICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRANS-1,3-DICHLOROPROPENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| TRICHLOROETHENE | 2 U | 2 U | 2 U | 2 U | 2 U |
| VINYL CHLORIDE | 2 U | 2 U | 2 U | 2 U | 2 U |
| **Geochemistry** (MG/L unless otherwise noted) | | | | | |
| ALKALINITY | 45 | 120 | 140 | 125 | 120 |
| CHLORIDE | 8.5 | 9.9 | 11 | 13 | 13 |
| COND (MS/CM) | 277 | 265 | 284 | 269 | 336 |
| DO | 3.37 | 0.2 | 0.15 | 1.57 | 1.11 |
| ETHANE (NG/L) | 5,132 | 29,931 | 65,626 | 89,723 | 73,852 |
| ETHENE (NG/L) | 67 | 126 | 103 | 3749 | 5992 |
| IRON II | 19 | 12 | 11 | 12 | 15 |
| IRON III | 0.6 | 0.5 U | 0.5 U | 0.5 | 0.9 |
| MANGANESE | 0.6 | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| METHANE (UG/L) | 2,600 | 12,910 | 12,490 | 9,000 | 7,120 |
| NITRATE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| NITRITE | 0.5 U | 0.5 U | 0.5 U | 0.5 U | 0.5 U |
| PH (unitless) | 6.31 | 6.04 | 5.89 | 5.9 | 6.05 |
| REDOX (mV) | -170 | -120.4 | -94.6 | -82.6 | -116 |
| SULFATE | 82 | 3.7 | 1.1 | 0.5 U | 11 |
| SULFIDE | 0.17 | 0.15 | 0.11 | 0.12 | 0.1 |
| TEMP (Celsius) | 14.85 | 15.77 | 15.93 | 16.63 | 16.27 |
| TOTAL ORGANIC CARBON (TOC) | 5.1 | 16 | 16 | 19 | 20 |
| TURB (NTU) | 35.2 | 331 | 125.1 | 140.5 | 1,835.7 |

NA - Not analyzed
B - Analyte not detected above associated blank

J - Reported value is estimated
U - Analyte not detected

# Appendix E
## TPH Soil Sampling Results and Laboratory Summary Sheet

MANTECH

MEMORANDUM
MANTECH ENVIRONMENTAL RESEARCH SERVICES CORP.
Environmental Science

**Ref:** 00-AS23
**Contract #:** 68-C-98-138

**To:** [redacted]

**From:** Aaron Shook

**Thru:** D.D. Fine

**Subject:** Service Request SFTA-1-84

**Date:** June 19, 2000

**Copies:** R.L. Cosby
G.B. Smith
J.L. Seeley
P. Wang

Attached is the report for the GC analysis of 27 samples submitted under Service Request # SFTA-1-84. The samples were analyzed for TPH as JP-4 jet fuel. Quality control data is tabulated within the body of the report.

All values are reported to three (3) significant figures. Please refer to the notes at the bottom left of each report page for explanations of symbols or abbreviations that are placed in cells without numerical values.

Samples were received April 14th. Determinations were performed June 15, 2000. A modified version of RSKSOP-72, Rev. #1, dated December 13, 1991 was used to analyze all samples.

ManTech Environmental Research Services Corporation

R.S. Kerr Environmental Research Center, P.O. Box 1198, 919 Kerr Research Drive
Ada, Oklahoma 74821-1198 580-436-8660 FAX 580-436-8501

Analyzed by: Aaron Shook
Samples Analyzed: 6/15/00
Samples Recieved: 4/14/00

TPH/Oceana NAS
SFTA-1-84
Wilson


6/19/00

| Sample ID | Dilution Factor | TPH (ng/ul) | TPH/Soil (ug/g) |
|---|---|---|---|
| MeCl2 Blank | 1 | nd | nd |
| 5000 ppm TPH | 1 | 5.07E+03 | na |
| M1P01 6.5 - 7.0 | 1 | nd | nd |
| M1P01 7.5 - 8.0 | 1 | nd | nd |
| M1P01 22.0 - 22.5 | 1 | nd | nd |
| M1P01 23.0 - 23.5 | 1 | nd | nd |
| M1P01 24.5 - 25.0 | 1 | nd | nd |
| M1P01 25.5 - 26.0 | 1 | nd | nd |
| M1P02 6.0 - 6.5 | 1 | blq | blq |
| M1P02 7.0 - 7.5 | 1 | 1.56E+03 | 4.61E+02 |
| M1P02 22.5 - 23.0 | 1 | nd | nd |
| M1P02 23.5 - 24.0 | 1 | nd | nd |
| MeCl2 Blank | 1 | nd | nd |
| 50000 ppm TPH | 1 | 5.02E+04 | na |
| M1P03 5.0 - 5.5 | 1 | nd | nd |
| M1P03 6.0 - 6.5 | 1 | nd | nd |
| M1P03 21.5 - 22.0 | 1 | nd | nd |
| M1P03 22.5-23.0 | 1 | nd | nd |
| M1P03 23.0 - 23.5 | 1 | nd | nd |
| M1P03 24.0 - 24.5 | 1 | nd | nd |
| M1P03 25.5 - 26.0 | 1 | nd | nd |
| M1P03 26.0 - 26.5 | 1 | nd | nd |
| M1P03 27.0 - 27.5 | 1 | nd | nd |
| M1P04 6.5 - 7.0 | 1 | nd | nd |
| MeCl2 Blank | 1 | nd | nd |
| 12500 ppm TPH | 1 | 1.12E+04 | na |
| M1P04 7.5 - 8.0 | 1 | nd | nd |
| M1P04 17.0 - 17.5 | 1 | nd | nd |
| M1P04 18.5 - 19.0 | 1 | nd | nd |
| M1P04 19.5 - 20.0 | 1 | nd | nd |
| M1P04 21.0 - 21.5 | 1 | nd | nd |
| M1P04 22.0 - 22.5 | 1 | nd | nd |
| Field Blank | 1 | nd | nd |
| 1000 ppm TPH | 1 | 1.09E+03 | na |

nd - none detected
na - not applicable
MeCl2 - methylene chloride
TPH- total petroleum hydrocarbons
blq - below level of quantitation (< 1000 ppm total TPH)

# Appendix F
## Summary of Geochemical Data from the February 2000 Sampling Event

**Appendix F**
**January 2000 Geochemistry Data**
**SWMU 15 - NAS Oceana**

| Well | BTEX | Alk | DO | Fe+2 | Mn | Methane | Nitrate | pH | Redox | Sulfate | Temp | TOC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Background Wells*** | | | | | | | | | | | | |
| MW06 | 0.0022 | 5 | 1.47 | 0.25 | 0.25 | 0.0104 | 0.25 | 4.3 | 248 | 23.3 | 7.2 | 7.2 |
| MW07 | 0.001 | 5 | 0.2 | 0.25 | 0.25 | 0.006931 | 0.25 | 4.94 | 162.2 | 20 | 9.1 | 5.8 |
| MW08 | 0.004 | 5 | 1.15 | 0.25 | 0.25 | 0.002933 | 0.25 | 4.3 | 187 | 12.7 | 9.93 | 4.8 |
| MW10 | 0.001 | 5 | 0.41 | 0.25 | 0.25 | 0.006603 | 2.35 | 4.76 | 261.1 | 12.7 | 11 | 4.9 |
| MW14 | 0.001 | 5 | 0.32 | 0.25 | 0.25 | 0.000235 | 0.25 | 5.21 | 147 | 8.58 | 11.72 | 13 |
| ***Mean*** | *0.00184* | *5* | *0.71* | *0.25* | *0.25* | *0.00542* | *0.67* | *4.702* | *201.06* | *15.456* | *9.79* | *7.14* |
| ***Low Contamination Wells*** | | | | | | | | | | | | |
| MW16 | 0.001 | 35 | 0.08 | 1.9 | 0.25 | 0.02596 | 0.25 | 5.78 | -37.3 | 19 | 14.12 | 1 |
| MW18 | 0.001 | 25 | 4.43 | 0.55 | 0.25 | 0.18 | 0.5 | 5.77 | 67.7 | 7.3 | 14.88 | 4 |
| MW19 | 0.0218 | 37 | 0.22 | 7 | 0.25 | 0.39 | 0.25 | 6.15 | -47.5 | 121 | 15.83 | 4.2 |
| ***Mean*** | *0.007933* | *32.33333* | *1.576667* | *3.15* | *0.25* | *0.198653* | *0.333333* | *5.9* | *-5.7* | *49.1* | *14.94333* | *3.066667* |
| ***High Contamination Wells*** | | | | | | | | | | | | |
| MW20 | 4.456 | 90 | 0.25 | 8.4 | 0.25 | 7.06 | 0.25 | 5.46 | -113.7 | 21.3 | 14.81 | 14 |
| ***Delta Between Plume and Background Wells*** | | | | | | | | | | | | |
| | *4.45416* | *85* | *-0.46* | *8.15* | *0* | *7.05458* | *-0.42* | *0.758* | *-314.76* | *5.844* | *5.02* | *6.86* |

Note: Shaded values were non-detect and were assumed to be one-half of the reported detection limit values

# Appendix G

## Summary of Intrinsic Remediation Constants for Benzene

Summary of Intrinsic Remediation Rate Constants for Benzene
SWMU 15 - NAS Oceana

| Flowpath | Slope ($k/v_x$) [$ft^{-1}$] | Groundwater Velocity ($v_x$) [ft/d] | Retardation Factor (R) | Contaminant Velocity ($v_c$) [ft/d] | Longitudinal Dispersivity ($\alpha$) [ft] | Attenuation Rate Const. (k) [$d^{-1}$] | Biodeg Rate Const. ($\lambda$) [$d^{-1}$] | Biodeg Half-life [d] | $\lambda/k$ Ratio [%] |
|---|---|---|---|---|---|---|---|---|---|
| ***Hypothesis 1 Wells (Plume Downgradient of NAPL)*** | | | | | | | | | |
| Flowpath A | 0.06 | 0.05 | 1.377 | 0.0363 | 11 | 0.0030 | 0.0036 | 192 | 121% |
| Flowpath B | 0.0387 | 0.05 | 1.377 | 0.0363 | 11 | 0.0019 | 0.0020 | 346 | 104% |
| Flowpath F | 0.043 | 0.05 | 1.377 | 0.0363 | 11 | 0.0022 | 0.0023 | 301 | 107% |
| Flowpath G | 0.0145 | 0.05 | 1.377 | 0.0363 | 11 | 0.0007 | 0.0006 | 1136 | 84% |
| Flowpath H | 0.0384 | 0.05 | 1.377 | 0.0363 | 11 | 0.0019 | 0.0020 | 350 | 103% |
| ***Hypothesis 2 Wells (No NAPL Plume)*** | | | | | | | | | |
| Flowpath A | -0.0025 | 0.05 | 1.377 | 0.0363 | 11 | -0.0001 | -0.0001 | -7854 | 71% |
| Flowpath B | 0.0045 | 0.05 | 1.377 | 0.0363 | 11 | 0.0002 | 0.0002 | 4043 | 76% |
| Flowpath G | 0.014 | 0.05 | 1.377 | 0.0363 | 11 | 0.0007 | 0.0006 | 1182 | 84% |
| Flowpath H | -0.0184 | 0.05 | 1.377 | 0.0363 | 11 | -0.0009 | -0.0005 | -1301 | 58% |

Reference: Buscheck and Alcantar (1995)

# Appendix H
## Calculated Retardation Factor

Appendix H
Calculated Retardation Factor
SWMU 15 - NAS Oceana

| Compound | Soil Org-C/Water Partition Coefficient ($K_{oc}$) [L/kg][a] | Porosity (n) | Bulk Density ($\rho_b$) [kg/L] | Soil Organic Carbon Fraction ($f_{oc}$) | Retardation Factor (R) |
|---|---|---|---|---|---|
| Benzene | 58.9 | 0.25 | 1.602 | 0.001 | 1.377 |

[a]Koc Source: TPH Working Group (1996)

# Appendix I

## Linear Regression Slope Calculations for the Five Flow Paths

Six I
Linear Regre... Slope Calculations
SWMU 15 - NAS Oceana

### Flowpath A

| Well ID | Distance Along Flowpath [ft] | Benzene | Methane |
|---|---|---|---|
| MIP3 | 0 | 1230.0 | NA |
| DW15 | 36 | 1120.0 | 5700.0 |
| DW14 | 144 | 2870.0 | 6720.0 |
| DW05 | 252 | 3410.0 | 7370.0 |
| MW20 | 324 | 3010.0 | 7060.0 |
| DW01 | 333 | 1800.0 | 6580.0 |
| DW07 | 396 | 3840.0 | 9200.0 |
| DW10 | 504 | 5.9 | 310.0 |

### Flowpath B

| Well ID | Distance Along Flowpath [ft] | Benzene | Methane |
|---|---|---|---|
| DW17 | 0 | 3350.0 | 11400.0 |
| DW13 | 126 | 6910.0 | 10600.0 |
| DW06 | 234 | 2500.0 | 5340.0 |
| DW03 | 315 | 261.0 | 6080.0 |
| DW12 | 378 | 2118.0 | 7910.0 |
| DW11 | 468 | 73.0 | 790.0 |
| DW27 | 576 | 1.0 | 54.2 |

### Flowpath F

| Well ID | Distance Along Flowpath [ft] | Benzene | Methane |
|---|---|---|---|
| DW16 | 0 | 9.0 | 51.0 |
| DW26 | 90 | 1.1 | 220.0 |
| DW08 | 342 | 332.0 | 17300.0 |
| DW09 | 450 | 3.2 | 670.0 |

### Flowpath G

| Well ID | Distance Along Flowpath [ft] | Benzene | Methane |
|---|---|---|---|
| DW22 | 0 | 8090.0 | 6350.0 |
| DW23 | 126 | 1380.0 | 6250.0 |
| DW24 | 306 | 97.0 | 1610.0 |

### Flowpath H

| Well ID | Distance Along Flowpath [ft] | Benzene | Methane |
|---|---|---|---|
| DW25 | 0 | 1.0 | 21.0 |
| DW28 | 270 | 1.0 | 1420.0 |
| DW29 | 414 | 150.0 | 1760.0 |
| DW30 | 630 | 1008.0 | 3180.0 |
| MW17 | 810 | 1.0 | 15.6 |

## Hypothesis 1 Scenario: Assuming NAPL is present downgradient of excavation area and steady state dissolved-phase plume begins where high benzene levels begin to decrease

**Natural Log Data (DW07 to DW10)**

| | | |
|---|---|---|
| DW07 | 396 | 8.2532 |
| DW10 | 504 | 1.7750 |

**Linear regression**

| | |
|---|---|
| Slope | -0.0600 |
| Y-int | 32.0069 |
| $r^2$ | 1.0000 |

**Hypothesis 1 Reg**

| | | |
|---|---|---|
| DW07 | 396 | 3840.0 |
| DW10 | 504 | 5.9 |

**Natural Log Data (DW12 to DW27)**

| | | |
|---|---|---|
| DW12 | 378 | 7.6582 |
| DW11 | 468 | 4.2905 |
| DW27 | 576 | 0.0000 |

**Linear regression**

| | |
|---|---|
| Slope | -0.0387 |
| Y-int | 22.3326 |
| $r^2$ | 0.9997 |

**Hypothesis 1 Reg**

| | | |
|---|---|---|
| DW12 | 378 | 2206.790 |
| DW11 | 468 | 67.706 |
| DW27 | 576 | 1.035 |

**Natural Log Data (DW08 to DW09)**

| | | |
|---|---|---|
| DW08 | 342 | 5.8051 |
| DW09 | 450 | 1.1632 |

**Linear regression**

| | |
|---|---|
| Slope | -0.0430 |
| Y-int | 20.5048 |
| $r^2$ | 1.0000 |

**Hypothesis 1 Reg**

| | | |
|---|---|---|
| DW08 | 342 | 332.0 |
| DW09 | 450 | 3.2 |

**Natural Log Data (DW22 to DW24)**

| | | |
|---|---|---|
| DW22 | 0 | 8.9984 |
| DW23 | 126 | 7.2298 |
| DW24 | 306 | 4.5747 |

**Linear regression**

| | |
|---|---|
| Slope | -0.0145 |
| Y-int | 9.0189 |
| $r^2$ | 0.9998 |

**Hypothesis 1 Reg**

| | | |
|---|---|---|
| DW22 | 0 | 8258.036 |
| DW23 | 126 | 1332.604 |
| DW24 | 306 | 98.406 |

**Natural Log Data (DW30 to MW17)**

| | | |
|---|---|---|
| DW30 | 630 | 6.9157 |
| MW17 | 810 | 0.0000 |

**Linear regression**

| | |
|---|---|
| Slope | -0.0384 |
| Y-int | 31.1208 |
| $r^2$ | 1.0000 |

**Hypothesis 1 Reg**

| | | |
|---|---|---|
| DW30 | 630 | 1008.0 |
| MW17 | 810 | 1.0 |

## Hypothesis 2 Scenario: Assuming no NAPL present downgradient of excavation area and steady state biodegradation occurs only where high methane levels are present

**Natural Log Data (MIP3 to DW07)**

| | | |
|---|---|---|
| MIP3 | 0 | 7.1 |
| DW15 | 36 | 7.0 |
| DW14 | 144 | 8.0 |
| DW05 | 252 | 8.1 |
| MW20 | 324 | 8.0 |
| DW01 | 333 | 7.5 |
| DW07 | 396 | 8.3 |

**Linear regression**

| | |
|---|---|
| Slope | 0.0025 |
| Y-int | 7.1872 |
| $r^2$ | 0.5849 |

**Hypothesis 2 Reg**

| | | |
|---|---|---|
| MIP3 | 0 | 1322.5 |
| DW15 | 36 | 1445.9 |
| DW14 | 144 | 1889.6 |
| DW05 | 252 | 2469.5 |
| MW20 | 324 | 2951.8 |
| DW01 | 333 | 3018.4 |
| DW07 | 396 | 3528.5 |

**Natural Log Data (DW17 to DW12)**

| | | |
|---|---|---|
| DW17 | 0 | 8.1 |
| DW13 | 126 | 8.8 |
| DW06 | 234 | 7.8 |
| DW03 | 315 | 5.6 |
| DW12 | 378 | 7.7 |

**Linear regression**

| | |
|---|---|
| Slope | -0.0045 |
| Y-int | 8.5529 |
| $r^2$ | 0.3097 |

**Hypothesis 2 Reg**

| | | |
|---|---|---|
| DW17 | 0 | 5181.9 |
| DW13 | 126 | 2931.6 |
| DW06 | 234 | 1799.1 |
| DW03 | 315 | 1247.5 |
| DW12 | 378 | 938.3 |

Not Calculated (does not meet assumptions)

**Natural Log Data (DW22 to DW23)**

| | | |
|---|---|---|
| DW22 | 0 | 9.0 |
| DW23 | 126 | 7.2 |

**Linear regression**

| | |
|---|---|
| Slope | -0.0140 |
| Y-int | 8.9984 |
| $r^2$ | 1.0000 |

**Hypothesis 2 Reg**

| | | |
|---|---|---|
| DW22 | 0 | 8090.0 |
| DW23 | 126 | 1380.0 |

**Natural Log Data (DW28 to DW30)**

| | | |
|---|---|---|
| DW28 | 270 | 0.0 |
| DW29 | 414 | 5.0 |
| DW30 | 630 | 6.9 |

**Linear regression**

| | |
|---|---|
| Slope | 0.0184 |
| Y-int | -4.0794 |
| $r^2$ | 0.8702 |

**Hypothesis 2 Reg**

| | | |
|---|---|---|
| DW28 | 270 | 2.4 |
| DW29 | 414 | 34.3 |
| DW30 | 630 | 1819.5 |

* Note: Shaded values were non-detect and are assumed to be one-half the reported detection limit value

# Appendix J
## Groundwater Model Descriptions

APPENDIX J

# Groundwater Model Descriptions

## Introduction

Groundwater modeling for SWMU 15 was performed using a combination of several models and equations to simulate different components of the aquifer system. The components that were modeled include:

- Groundwater flow using a three-dimensional MODFLOW model
- Contaminant transport using MT3DMS to simulate advection, dispersion, retardation, and chemical reactions in three dimensions
- Free product and residual NAPL source decay rate using a three-phase (NAPL, soil and water) model called the Time To Clean Up (TTCU) tool to predict the effects of solubility and dissolved-phase biodegradation within the source area on the persistence of free product and residual NAPL
- Adsorbed contaminant source decay rate using a two-phase (soil and water) model to predict the contaminant partitioning between the soil and water
- Dissolved-phase decay rate using the Buscheck and Alcantar equation to estimate the first-order contaminant biodegradation rate

Each of these models is described in greater detail below.

## Groundwater Flow Model

The groundwater flow model developed to support this modeling effort was constructed using the three-dimensional finite-difference code MODFLOW written by the United States Geological Survey (USGS) (McDonald and Harbaugh, 1988). This is a universally accepted model that has been extensively benchmarked and verified in the literature. The model developed for this evaluation consists of 183 rows, 185 columns, and 6 layers. The total modeled area is approximately 14,500 acres. The model grid spacing is 10 feet by 10 feet in areas of contamination and increases to 500 feet by 500 feet moving out to the model boundaries. The extent of the model grid is presented as Figure J-1.

The extent of the model grid was chosen to include the entire Oceana NAS and extend out to natural hydrologic features. The lateral boundary conditions are constant head boundaries that coincide with London Bridge Creek to the west and south, Eastern Lynnhaven River and Linkhorn Bay to the north, and Great Neck Creek to the west. The top boundary of the model is a specified flux boundary that represents the recharge of precipitation. Over most of the model area an annual average recharge rate of 4.4 inches per year was assumed. However, no recharge was assumed over the runway area, and concentrated recharge of 22 inches/year was assumed for the stormwater drainage ditches located in the vicinity of SWMU 15. The bottom boundary of the model, at a depth of 150

feet, extends an arbitrary 100 feet into the regional aquifer beneath the shallow alluvial aquifer at the site. This boundary was assumed to be a no-flow boundary.

The groundwater flow model was developed as a 6-layer model. The uppermost layer was simulated as an unconfined layer with a saturated thickness of 2 feet. Layer 4 was also given a 2-foot thickness. These layers were assigned such small thickness to allow representation of the smear zone contamination present near the water table in layer 1 and the observed deeper source at the base of the surficial aquifer. This approach will be more fully discussed in the solute transport section of this report. The assumed thickness of each model layer is presented in Table J-1.

**TABLE J-1**
Thickness of MODFLOW Model Layers

| Model Layer | Saturated Layer Thickness (ft) | Depth (feet bgs) |
|---|---|---|
| 1 | 2 | 0 to 4 |
| 2 | 8 | 4 to 12 |
| 3 | 8 | 12 to 20 |
| 4 | 2 | 20 to 22 |
| 5 | 30 | 22 to 52 |
| 6 | 100 | 52 to 152 |

bgs = Below Ground Surface

London Bridge Creek and Great Neck Creek were simulated in the model using the standard river package available in MODFLOW. The river package calculates flow between the river and the groundwater aquifer based on user specified values of the vertical hydraulic conductivity of the riverbed sediments, and the thickness of the riverbed. The model calculates leakage to or from the river based on the difference in head between the river stage and the head in the adjacent aquifer. The assumed hydraulic properties of the river and the aquifer were developed during the calibration process that will be described in the next section.

## Flow Model Calibration

The first step in applying a groundwater flow model to evaluate conditions at a site is to calibrate the model. Calibration is the process of performing model simulations and comparing the simulated water levels, gradients and groundwater flow directions with those measured in the field. As this model is a steady-state model, a single groundwater flow field was selected as a calibration target. The most complete water level data set available, that includes groundwater elevations from not only SWMU 15, but also SWMU-1, SWMU-2B and SWMU-2C was collected in late February 2001. Although groundwater conditions at the site do exhibit transient behavior over the course of the year, this selected flow field is consistent with the overall plume migration direction (southwest), and as such

is a reasonable average groundwater condition for the site. A comparison of the measured groundwater elevations at the site in late February 2001 and the simulated steady state groundwater elevations predicted by the model are presented in Figure J-2. An exact match between simulated and measured groundwater levels would occur along the 45-degree line shown. This figure demonstrates fairly close agreement between simulated and measured groundwater levels across the NAS.

### Aquifer Properties Estimated From Calibration Runs

During the calibration effort, the influence of various aquifer properties on predicted groundwater levels was evaluated by performing limited sensitivity analyses on each parameter. The value of each aquifer parameter selected for use in the model simulations presented herein was obtained by minimizing the error between simulated and observed groundwater elevations, but also by comparing the selected values with available field measurements as well as professional judgement. The assumed aquifer properties that were estimated during the calibration effort are summarized in Table J-2. The source of each parameter estimate is also included in Table J-2.

**TABLE J-2**
Summary of Aquifer Parameters

| Aquifer Property | Value in Calibrated Model | Source |
|---|---|---|
| Aquifer Horizontal Hydraulic Conductivity | 6.5 feet/day | Calibration Parameter |
| Aquifer Vertical Hydraulic Conductivity | 0.65 feet/day | Calibration Parameter |
| Aquitard Horizontal Hydraulic Conductivity | 0.05 feet/day | Calibration Parameter |
| Aquitard Vertical Hydraulic Conductivity | 0.005 feet/day | Calibration Parameter |
| Riverbed Vertical Hydraulic Conductivity | 0.1 feet/day | Calibration Parameter |

## Solute Transport Model

To evaluate and compare various potential remedial actions for the SWMU 15 site, a solute transport model was developed. This solute transport model utilizes an independent source zone persistence model documented under separate cover (CH2M HILL, 2000), and predicts the downgradient groundwater concentrations that will persist over time given various remedial actions in the source area.

### Solute Transport Model Description

The solute transport model used to evaluate the movement of contamination in SWMU 15 is the MT3DMS transport model (Zheng, et. al., 1999). MT3DMS is a three-dimensional computer code for simulating advection, dispersion, retardation, and chemical reactions in groundwater flow systems. It was developed to be used in conjunction with a block-centered finite-difference groundwater flow model such as MODFLOW, that was used in this study. The characteristics of a simulated groundwater flow field from a calibrated groundwater flow model are retrieved by MT3DMS and used to simulate dissolved phase

contaminant transport through the groundwater flow field. As a result, the main assumption incorporated into MT3DMS is that changes in the contaminant concentration field will not significantly affect the groundwater flow field.

The solute transport model simulations described herein focus on the contaminant benzene. While other contaminants of concern are present within the hydrocarbon source areas, benzene is the most mobile and has the lowest action level, and therefore drives the selection of an effective remedy.

To simulate the movement of dissolved contaminants through an alluvial aquifer, it is necessary to make assumptions regarding the characteristics of the contaminant itself as well as the characteristics of the aquifer through which it moves. A summary of the parameters assumed in the solute transport model, along with the sources of the parameter estimates, are included in Table J-3.

**TABLE J-3**
Summary of Contaminant Transport Simulation Parameters

| Aquifer Property | Value Assumed in Model | Source |
|---|---|---|
| Benzene Half-Life (Anaerobic) | 300 days | Field Data |
| Benzene Half-Life (Aerobic) | 1.4 days | Literature Value – (Rafai, et. al., 1998) |
| Benzene Octanol-Water Partition Coefficient ($K_{oc}$) | 58.9 ml/gram | Literature Value – TPH Working Group (1996) |
| Fraction of Organic Carbon in Aquifer ($f_{oc}$) | 0.001 | Estimated |
| Aquifer Bulk Density | 1.602 g/cm$^3$ | Field Testing |
| Total Porosity | 0.25 | Field Testing |
| Source Area Benzene Concentrations | Variable | Time to Clean Up Tool |

# Source Term Decay Rate Model

Source-area cleanup time was estimated using a screening model recently developed by CH2M HILL (2000). The spreadsheet model, described as the Time To Clean Up (TTCU) tool, predicts the effects of solubility and dissolved-phase biodegradation within the source area and calculates the time required for the remediation of selected petroleum hydrocarbon fractions using site-specific contaminant information.

The duration of cleanup at a petroleum-contaminated source area depends on the amount (mass) of contaminant present and the rate at which contaminant is dissolved (and transported downgradient) and biodegraded (destroyed). The most significant unknown for the SWMU 15 evaluation was the mass of contaminant present. On the basis of existing site information, it is currently not known whether site contaminants are present only as dissolved and adsorbed, or whether residual fuel (liquid) is also present. The TTCU tool was developed to assess source conditions in the presence of residual and free-phase NAPL

(three phases present: water, dissolved NAPL plume, residual /free-phase NAPL). In order to compare cleanup time in the case where NAPL is not present (only two phases present: water, dissolved NAPL plume), a new "two-phase" module was developed. In order to keep the discussion succinct, the discussion of results for this assessment is limited to benzene. Results from previous assessments at petroleum-contaminated sites indicate that benzene is often the best indicator contaminant.

## Two-Phase Modeling Approach

The two-phase model calculates the disappearance of benzene mass (over time) within a representative volume of aquifer material. The user provides a starting benzene concentration in groundwater, and the mass of benzene within the groundwater and adsorbed to soil are calculated. The partitioning between the dissolved phase and the adsorbed phase is represented by a linear distribution coefficient that assumes that the amount of contaminant sorbed is directly proportional to the concentration of the contaminant in solution. The equation for calculating equilibrium conditions between the dissolved and sorbed phases is:

$$S=K_dC$$

Where:

S = amount of contaminant sorbed to soil (milligrams [mg]/kilogram [kg] soil)

C = amount of contaminant dissolved in groundwater (mg/liter [L] groundwater)

$K_d$ = distribution coefficient = $K_{oc} \times f_{oc}$

$K_{oc}$ = organic carbon partition coefficient

$f_{oc}$ = fraction of organic carbon in the soil

Equilibrium soil benzene concentrations were calculated for soil $f_{oc}$ values of 0.01 (1% total organic carbon (TOC) content) and 0.001 (0.1% TOC). The TOC for SWMU 15 soil is assumed to fall within this selected range.

The total mass of benzene within the representative volume is calculated using assumptions of porosity and soil bulk density. The assumptions used and example calculations are presented in Table J-4.

**Table J-4**
**Two-Phase Partitioning and Biodegradation**
**SWMU 15 - NAS Oceana**

| | |
|---|---|
| Bulk Density (lbs/ft^3) | 100 |
| Bulk Density (g/cm^3 or kg/L) | 1.6 |
| Sp. G | 2.65 |
| Porosity | 0.4 |
| Initial Benzene Concentration (mg/L) | 10 |
| foc (fraction) | 0.001 |
| koc (L/kg) | 58.9 |
| kd | 0.0589 |
| Half Life (days) | 479 |
| Reaction Rate Constant k (/day) | -0.00144676 |
| Groundwater Velocity (ft/day) | Not Used |
| Time Step (days) | 6 |

| Elapsed Time (years)* | Dissolved Benzene Concentration (mg/L) | Dissolved Benzene Mass (mg/L porous media) | Adsorbed Benzene Concentration (mg/kg) | Adsorbed Benzene Mass (mg/L porous media) | Total Benzene Mass (mg/L porous media) | Mass Lost to Biodegradation In Time Step (mg/L porous media) | Cumulative Mass Lost to Biodegradation (mg/L porous media) |
|---|---|---|---|---|---|---|---|
| 0.6904 | 7.21E+00 | 2.85E+00 | 4.25E-01 | 2.65E-01 | 3.12E+00 | 2.47E-02 | 1.23E+00 |
| 0.7068 | 7.16E+00 | 2.83E+00 | 4.21E-01 | 2.63E-01 | 3.09E+00 | 2.45E-02 | 1.25E+00 |
| 0.7233 | 7.10E+00 | 2.81E+00 | 4.18E-01 | 2.61E-01 | 3.07E+00 | 2.43E-02 | 1.28E+00 |
| 0.7397 | 7.04E+00 | 2.78E+00 | 4.15E-01 | 2.59E-01 | 3.04E+00 | 2.41E-02 | 1.30E+00 |
| 0.7562 | 6.99E+00 | 2.76E+00 | 4.12E-01 | 2.57E-01 | 3.02E+00 | 2.40E-02 | 1.33E+00 |
| 0.7726 | 6.93E+00 | 2.74E+00 | 4.08E-01 | 2.55E-01 | 2.99E+00 | 2.38E-02 | 1.35E+00 |
| 0.7890 | 6.88E+00 | 2.72E+00 | 4.05E-01 | 2.53E-01 | 2.97E+00 | 2.36E-02 | 1.37E+00 |
| 0.8055 | 6.82E+00 | 2.70E+00 | 4.02E-01 | 2.51E-01 | 2.95E+00 | 2.34E-02 | 1.40E+00 |
| 0.8219 | 6.77E+00 | 2.67E+00 | 3.99E-01 | 2.49E-01 | 2.92E+00 | 2.32E-02 | 1.42E+00 |
| 0.8384 | 6.71E+00 | 2.65E+00 | 3.95E-01 | 2.47E-01 | 2.90E+00 | 2.30E-02 | 1.44E+00 |
| 0.8548 | 6.66E+00 | 2.63E+00 | 3.92E-01 | 2.45E-01 | 2.88E+00 | 2.28E-02 | 1.47E+00 |
| 0.8712 | 6.61E+00 | 2.61E+00 | 3.89E-01 | 2.43E-01 | 2.85E+00 | 2.27E-02 | 1.49E+00 |
| 0.8877 | 6.56E+00 | 2.59E+00 | 3.86E-01 | 2.41E-01 | 2.83E+00 | 2.25E-02 | 1.51E+00 |
| 0.9041 | 6.50E+00 | 2.57E+00 | 3.83E-01 | 2.39E-01 | 2.81E+00 | 2.23E-02 | 1.53E+00 |
| 0.9205 | 6.45E+00 | 2.55E+00 | 3.80E-01 | 2.37E-01 | 2.79E+00 | 2.21E-02 | 1.56E+00 |
| 0.9370 | 6.40E+00 | 2.53E+00 | 3.77E-01 | 2.35E-01 | 2.77E+00 | 2.19E-02 | 1.58E+00 |
| 0.9534 | 6.35E+00 | 2.51E+00 | 3.74E-01 | 2.33E-01 | 2.74E+00 | 2.18E-02 | 1.60E+00 |
| 0.9699 | 6.30E+00 | 2.49E+00 | 3.71E-01 | 2.32E-01 | 2.72E+00 | 2.16E-02 | 1.62E+00 |
| 0.9863 | 6.25E+00 | 2.47E+00 | 3.68E-01 | 2.30E-01 | 2.70E+00 | 2.14E-02 | 1.64E+00 |
| 1.0027 | 6.20E+00 | 2.45E+00 | 3.65E-01 | 2.28E-01 | 2.68E+00 | 2.13E-02 | 1.66E+00 |
| 2.0055 | 3.81E+00 | 1.51E+00 | 2.25E-01 | 1.40E-01 | 1.65E+00 | 1.31E-02 | 2.69E+00 |
| 3.0082 | 2.35E+00 | 9.27E-01 | 1.38E-01 | 8.62E-02 | 1.01E+00 | 8.04E-03 | 3.31E+00 |
| 4.0110 | 1.44E+00 | 5.70E-01 | 8.50E-02 | 5.30E-02 | 6.23E-01 | 4.95E-03 | 3.70E+00 |
| 5.0137 | 8.87E-01 | 3.51E-01 | 5.23E-02 | 3.26E-02 | 3.83E-01 | 3.04E-03 | 3.94E+00 |
| 6.0000 | 5.50E-01 | 2.17E-01 | 3.24E-02 | 2.02E-02 | 2.38E-01 | 1.89E-03 | 4.08E+00 |
| 7.0027 | 3.38E-01 | 1.34E-01 | 1.99E-02 | 1.24E-02 | 1.46E-01 | 1.16E-03 | 4.18E+00 |
| 8.0055 | 2.08E-01 | 8.22E-02 | 1.23E-02 | 7.65E-03 | 8.99E-02 | 7.13E-04 | 4.23E+00 |
| 9.0082 | 1.28E-01 | 5.06E-02 | 7.54E-03 | 4.70E-03 | 5.53E-02 | 4.39E-04 | 4.27E+00 |
| 10.0110 | 7.87E-02 | 3.11E-02 | 4.64E-03 | 2.89E-03 | 3.40E-02 | 2.70E-04 | 4.29E+00 |
| 11.0137 | 4.84E-02 | 1.91E-02 | 2.85E-03 | 1.78E-03 | 2.09E-02 | 1.66E-04 | 4.30E+00 |
| 12.0000 | 3.00E-02 | 1.19E-02 | 1.77E-03 | 1.10E-03 | 1.30E-02 | 1.03E-04 | 4.31E+00 |
| 13.0027 | 1.85E-02 | 7.30E-03 | 1.09E-03 | 6.78E-04 | 7.98E-03 | 6.33E-05 | 4.31E+00 |
| 14.0055 | 1.14E-02 | 4.49E-03 | 6.69E-04 | 4.17E-04 | 4.91E-03 | 3.89E-05 | 4.32E+00 |
| 15.0082 | 6.98E-03 | 2.76E-03 | 4.11E-04 | 2.57E-04 | 3.02E-03 | 2.39E-05 | 4.32E+00 |
| 16.0110 | 4.30E-03 | 1.70E-03 | 2.53E-04 | 1.58E-04 | 1.86E-03 | 1.47E-05 | 4.32E+00 |
| 17.0137 | 2.64E-03 | 1.04E-03 | 1.56E-04 | 9.71E-05 | 1.14E-03 | 9.06E-06 | 4.32E+00 |
| 18.0000 | 1.64E-03 | 6.47E-04 | 9.65E-05 | 6.02E-05 | 7.08E-04 | 5.62E-06 | 4.32E+00 |
| 19.0027 | 1.01E-03 | 3.98E-04 | 5.93E-05 | 3.70E-05 | 4.35E-04 | 3.45E-06 | 4.32E+00 |

*Representative times steps shown for brevity.

Intrinsic biodegradation removes benzene mass from the unit volume of aquifer. The rate of benzene biodegradation is assumed to be a first-order function of the benzene dissolved concentration as follows:

$$C_t = C_o e^{-k_b t}$$

Where:

$C_t$ = dissolved benzene concentration at time t (mg/L)

$C_o$ = original dissolved benzene concentration (mg/L). It is arbitrarily assumed that benzene has an original concentration of 10 mg/L for this assessment.

$k_b$ = first order benzene biodecay rate ($day^{-1}$)

t = model time step (days)

The benzene biodegradation rate used for this assessment was obtained from site data according to the procedures described in the dissolved-phase plume evaluation section below. A biodegradation rate ($k_b$)of 0.0023 $day^{-1}$ (300 day ½ life) was used in the two-phase and three phase assessment.

The mass of benzene degraded is calculated during each time step, and is subtracted from the total mass. The new equilibrium benzene concentrations in groundwater and adsorbed to soil are recalculated. The model keeps track of how benzene concentrations change over time within the representative volume of the aquifer. This iterative process is repeated until benzene concentrations fall below cleanup goals.

## Three-Phase Modeling Approach

The three-phase spreadsheet is designed to calculate changes in hydrocarbon concentrations in NAPL-contaminated source area soils and groundwater during natural attenuation. For this assessment it is assumed that NAPL is present at SWMU 15. Due to the complexity of the three-phase spreadsheets, only a summary description is presented in this report. A complete description of the three-phase spreadsheet is presented in the TTCU report (CH2M HILL, 2000).

The remediation of saturated zone hydrocarbon-contaminated soils by dissolution is driven by the tendency to maintain equilibrium between NAPL and aqueous-phase hydrocarbon concentrations. The dissolved equilibrium concentrations of each hydrocarbon fraction are calculated following Raoult's Law which states:

> Dissolved concentration of hydrocarbon fraction B = pure-phase solubility of B * mole fraction of B in the NAPL mixture.

Note that in source areas with residual NAPL in the soil, the contaminant mass in the aqueous phase and adsorbed phase is generally very small compared to the mass in the NAPL phase. Because the contaminant mass in the NAPL is so much greater, the contaminant concentrations in groundwater are assumed to be governed entirely by Raoult's Law.

Hydrocarbons are removed from the source area via dissolution and transport in the groundwater, and biodegradation. The mass of hydrocarbon transported from the source

zone (reactor) by dissolution during a time step is characterized by using the dissolved equilibrium concentration as follows:

> Reactor "n" mass lost to dissolution = (equilibrium concentration in reactor n – concentration in upgradient reactor n-1) * groundwater velocity * porosity * cross sectional area * time

The mass of hydrocarbon removed by intrinsic biodegradation is calculated using the relationships described for the two-phase model. The three-phase model was run for $k_b$ = 0.0023 $day^{-1}$ (300 day ½ life). The three-phase spreadsheet requires that the soil volume containing residual or (or mobile) NAPL, and the NAPL chemical characteristics, be defined. For SWMU 15, the following assumptions were used for these parameters:

- The area of residual NAPL extends over an area 600 feet downgradient of the former excavation. The source area length is parallel to the groundwater flow direction. The source area has a depth of 13 feet.
- The NAPL is fresh gasoline with chemical characteristics as summarized in publications by the Total Petroleum Hydrocarbon Criteria Working Group (1996).

The chemical constituents in gasoline were separated into the aromatic and aliphatic chemical groups as shown in Table J-5. Because the concentration of NAPL in soil at SWMU 15 (if present) is unknown, a range of gasoline soil concentrations was selected for model runs as follows:

- 5,000 mg/kg
- 10,000 mg/kg

The selected soil gasoline range is thought to reasonably represent soil concentrations that would be expected in the field if residual NAPL were present.

The three-phase model keeps track of how groundwater benzene concentrations change over time within each of 10 "cascade reactors" situated in the source area and arranged parallel to the groundwater flow direction. Results presented in the following section correspond to the groundwater conditions within the 10th reactor which would be at the downgradient edge of the assumed source area.

The model results are presented in Figure J-3. The model results are presented as a plot of benzene concentration in groundwater as a function of time since contaminants reached the aquifer. Figure J-3 summarizes results from the two-phase and three-phase models run using a benzene biodegradation rate of 0.0023 $day^{-1}$. The duration until benzene concentration falls below 0.005 mg/L (MCL) is defined as the cleanup time. As shown by the figure, the two-phase model ($f_{oc}$ = 0.001) predicts benzene concentration in groundwater will be reduced to below cleanup goals in less than 10 years of intrinsic remediation. In contrast, assuming residual NAPL is present (10,000-mg/kg gasoline in soil), the three-phase model predicts benzene will reach cleanup goals after approximately 200 to 300 years. Appendix G contains a summary of intrinsic remediation constants for benzene.

The results suggest that the time needed for intrinsic remediation of benzene in the presence of residual NAPL will be significantly longer than if no NAPL is present.

## Table J-5
## Gasoline TPHWG Fuel Sample
## Selected Aromatic and Aliphatic Fraction Concentrations and Chemical Properties

| Fraction | Median Equivalent Carbon | Percent of Mass | Initial Concentrations at 10,000 mg/kg TPH | ln MW | Molecular Weight | Moles | Initial Mole Fraction | Log10 Solubility | Single Component Solubility (mg/L) | Raoult's Law Solubility (mg/L) | Log10 Vapor Pressure | Single Component Vapor Pressure (atm) | Raoult's Law Vapor Prsssure (atm) | Henry's Constant ($cm^3/cm^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Aromatics*** | | | | | | | | | | | | | | |
| 1,2-dichloroethane | NA | 0 | 0 | | 99 | 0 | 0 | | 8690 | 0 | | 0.084 | 0 | 0.045 |
| 1,2-dibromoethane | NA | 0 | 0 | | 188 | 0 | 0 | | 3400 | 0 | | 0.015 | 0 | 0.013 |
| $C_5$-$C_7$ | 6.5 | 1.9 | 190 | 4.53 | 78 | 0.002 | 0.025 | 2.3 | 1750 | 43.1 | -0.95 | 0.13 | 3.2E-03 | 0.26 |
| $C_7$-$C_8$ | 7.58 | 8.1 | 810 | 4.63 | 92 | 0.009 | 0.089 | 2.1 | 526 | 46.7 | -1.5 | 0.038 | 3.4E-03 | 0.30 |
| $C_8$-$C_9$ | 8.63 | 10.7 | 1070 | 4.71 | 106 | 0.010 | 0.102 | 1.9 | 173 | 17.6 | -2.0 | 0.0081 | 8.3E-04 | 0.22 |
| $C_9$-$C_{10}$ | 9.5 | 9.52 | 952 | 4.77 | 118 | 0.008 | 0.081 | 1.7 | 50.7 | 4.1 | -2.5 | 0.0035 | 2.9E-04 | 0.37 |
| $C_{10}$-$C_{13}$ | 14 | 9.31 | 931 | 5.03 | 152 | 0.006 | 0.062 | 0.8 | 5.8 | 0.4 | -4.7 | 2.0E-05 | 1.2E-06 | 0.024 |
| $C_{13}$-$C_{16}$ | 20 | 0 | 0 | 5.26 | 192 | 0 | 0 | -0.5 | 0.32 | 0 | -6.5 | 3.3E-07 | 0 | 0.0090 |
| $C_{16}$-$C_{19}$ | 26 | 0 | 0 | 5.43 | 228 | 0 | 0 | -1.8 | 0.017 | 0 | -8.6 | 2.3E-09 | 0 | 0.0013 |
| $C_{19}$-$C_{24}$ | 33.5 | 0 | 0 | 5.59 | 268 | 0 | 0 | -3.3 | 0.0005 | 0 | -11.3 | 4.6E-12 | 0 | 0.00012 |
| ***Aromatics Subtotal*** | | **39.53** | **3953** | | | **0.035** | | | | **111.9** | | | **0.0077** | |
| ***Aliphatics*** | | | | | | | | | | | | | | |
| $C_5$-$C_7$ | 6 | 44.35 | 4435 | 4.48 | 88 | 0.050 | 0.509 | 1.2 | 15.8 | 8.1 | -0.7 | 0.20 | 0.10 | 49.5 |
| $C_7$-$C_{10}$ | 8.5 | 16.12 | 1612 | 4.82 | 123 | 0.013 | 0.132 | -0.2 | 0.67 | 0.09 | -2.0 | 0.011 | 0.0015 | 92.5 |
| $C_{10}$-$C_{13}$ | 11.5 | 0 | 0 | 5.11 | 166 | 0 | 0 | -1.8 | 0.015 | 0 | -3.5 | 3.5E-04 | 0 | 175.1 |
| $C_{13}$-$C_{16}$ | 14.5 | 0 | 0 | 5.33 | 207 | 0 | 0 | -3.5 | 0.00033 | 0 | -4.5 | 3.2E-05 | 0 | 872.9 |
| $C_{16}$-$C_{19}$ | 17.5 | 0 | 0 | 5.52 | 249 | 0 | 0 | -5.1 | 0.0000075 | 0 | -5.6 | 2.6E-06 | 0 | 3892.2 |
| $C_{19}$-$C_{24}$ | 21.5 | 0 | 0 | 5.72 | 304 | 0 | 0 | -7.3 | 4.7E-08 | 0 | -7.0 | 9.5E-08 | 0 | 27347.4 |
| ***Aliphatics Subtotal*** | | **60.47** | **6047** | | | **0.063** | | | | **8.2** | | | **0.10** | |
| ***Total Hydrocarbon*** | | **100** | **10000** | | | **0.099** | | | | **120.1** | | | **0.11** | |
| ***GRO ($C_5$ to $C_{10}$)*** | | | **9069** | | | | | | | **119.7** | | | **0.11** | |
| ***DRO ($C_{10}$ to $C_{25}$)*** | | | **931** | | | | | | | **0.4** | | | **1.2E-06** | |
| ***TAH (BTEX)*** | | | **2070** | | | | | | | **107.4** | | | **7.4E-03** | |
| ***TAQH (BTEX+NAPTHALENES +TRIMETHYLBENZENES)*** | | | **3022.11** | | | | | | | **111.5** | | | **7.7E-03** | |

## Table J-5
## Gasoline TPHWG Fuel Sample
## Selected Aromatic and Aliphatic Fraction Concentrations and Chemical Properties

| Fraction | Henry's Constant (atm $m^3$/mole) | Diffusion Coefficient in Air (Dia) ($cm^2$/sec) | Diffusion Coefficient in Water (Diw) ($cm^2$/sec) | Log $_{10}$ $K_{oc}$ | $K_{oc}$ (ml/g) | Coventional $K_D$ (=$K_{oc}$*0.001) | Vadose $C_{sat}$ (mg/kg) (foc=0.001) | Saturated $C_{sat}$ (mg/kg) (foc=0.001) | Example Compounds |
|---|---|---|---|---|---|---|---|---|---|
| ***Aromatics*** | | | | | | | | | |
| 1,2-dichloroethane | 0.0011 | | | 1.5 | 30.2 | 0.0302 | 0 | 0 | |
| 1,2-dibromoethane | 0.00032 | | | 1.8 | 57 | 0.057 | 0 | 0 | |
| $C_5$-$C_7$ | 0.0058 | 0.088 | 0.00001 | 3.0 | 58.9 | 0.0589 | 7.0 | 10.6 | Benzene |
| $C_7$-$C_8$ | 0.0067 | 0.087 | 0.00001 | 3.1 | 182 | 0.182 | 13.5 | 17.3 | Toluene |
| $C_8$-$C_9$ | 0.0050 | 0.08 | 0.00001 | 3.2 | 278 | 0.278 | 6.6 | 8.2 | Ethylbenzene & Xylene |
| $C_9$-$C_{10}$ | 0.0083 | 0.1 | 0.00001 | 3.3 | 1778.3 | 1.8 | 7.8 | 8.1 | Trimethylbenzenes, Methyl-Ethylbenzenes |
| $C_{10}$-$C_{13}$ | 0.00053 | 0.1 | 0.00001 | 3.7 | 5011.9 | 5.0 | 1.8 | 1.9 | Naphthalenes |
| $C_{13}$-$C_{16}$ | 0.00020 | 0.1 | 0.00001 | 4.3 | 19952.6 | 20.0 | 0 | 0 | |
| $C_{16}$-$C_{19}$ | 3.0E-05 | 0.1 | 0.00001 | 4.9 | 79432.8 | 79.4 | 0 | 0 | |
| $C_{19}$-$C_{24}$ | 2.7E-06 | 0.1 | 0.00001 | 5.7 | 446683.6 | 446.7 | 0 | 0 | |
| ***Aromatics Subtotal*** | | | | | | | **36.8** | **46.0** | |
| ***Aliphatics*** | | | | | | | | | |
| $C_5$-$C_7$ | 1.1 | 0.1 | 0.00001 | 3.1 | 1349.0 | 1.3 | 56.9 | 12.4 | Pentane, Hexane, Heptane, Branched Chain Alkanes (Isopentane), Cycloalkanes, Straight Chain Alkenes |
| $C_7$-$C_{10}$ | 2.1 | 0.1 | 0.00001 | 4.3 | 17988.7 | 18.0 | 2.5 | 1.6 | Octane, Nonane, Decane, Branched Chain Alkanes, Cycloalkanes |
| $C_{10}$-$C_{13}$ | 3.9 | 0.1 | 0.00001 | 5.6 | 402717.0 | 402.7 | 0 | 0 | Undecane, Dodecane, Tridecane, Branched Chain Alkanes |
| $C_{13}$-$C_{16}$ | 19.6 | 0.1 | 0.00001 | 7.0 | 9015711.4 | 9015.7 | 0 | 0 | Tetradecane, Pentadecane, Hexadecane, Branched Chain Alkanes |
| $C_{16}$-$C_{19}$ | 87.2 | 0.1 | 0.00001 | 8.3 | 201836636.4 | 201836.6 | 0 | 0 | Heptadecane, Octadecane, Nonadecane, Branched Chain Alkanes |
| $C_{19}$-$C_{24}$ | 613.0 | 0.1 | 0.00001 | 10.1 | 12735030810.2 | 12735030.8 | 0 | 0 | Eicosane, Heneicosane, Docosane, Tetracosane, Branched Chain Alkanes |
| ***Aliphatics Subtotal*** | | | | | | | **59.4** | **14.0** | |
| ***Total Hydrocarbon*** | | | | | | | **96.2** | **60.1** | |
| ***GRO ($C_5$ to $C_{10}$)*** | | | | | | | **94.4** | **58.2** | |
| ***DRO ($C_{10}$ to $C_{25}$)*** | | | | | | | **1.8** | **1.9** | |
| ***TAH (BTEX)*** | | | | | | | **27.2** | **36.1** | |
| ***TAQH (BTEX+NAPTHALENES +TRIMETHYLBENZENES)*** | | | | | | | **35.0** | **44.2** | |

Benzene cleanup time is sensitive to biodecay rate. At sites like SWMU 15 with a moderately low groundwater flux, cleanup time changes linearly with benzene half life for both models: doubling the decay half life roughly doubles the expected benzene cleanup time. At sites with greater groundwater flux, a greater fraction of the mass is removed via dissolution and downgradient transport in a shorter time, which de-emphasizes the effect of biodegradation alone.

Soil organic carbon content affects predicted cleanup time for the two-phase model. High $f_{oc}$ values in soil cause a greater mass of benzene in the adsorbed phase. A greater total hydrocarbon mass in the system tends to increase predicted cleanup time.

Benzene cleanup time is also linearly proportional to gasoline concentration in soil (three-phase model). By doubling the soil concentration, the mass of benzene is doubled, as is the cleanup time.

Estimates of benzene cleanup time at the SWMU 15 source area are constrained by our understanding of the site conditions. The model inputs were selected to include a reasonable range of values expected at the site. The model is likely to be conservative, and overestimates actual cleanup time at the site. Conservative assumptions include the following:

- The product is all gasoline. The actual NAPL may consist of a mixture of fuels, which would tend to reduce the resulting benzene concentration in groundwater. It is important to note that the highest benzene concentrations occur when the NAPL first contacts the groundwater. Benzene concentrations predicted by the model at 40 to 50 years into the simulation would be expected to reflect today's conditions.
- The source area is uniformly contaminated at the concentration modeled (5,000 mg/kg or 10,000 mg/kg). In reality, the soil concentrations at the site likely vary widely. The TTCU model does not currently handle a mixture of contamination concentrations.
- The source area is a uniform block of contamination. It is probable the source area is actually discontinuous, and likely consists of pockets of clean next to pockets of contaminated. A discontinuous source zone has less mass, and will tend to be remediated more quickly.
- It is assumed that volatilization from the source area to the atmosphere does not occur. This is a typical assumption for deep contaminant sources. However, for very long cleanup times, the mass of contaminant lost to volatilization may become significant.

# Dissolved-Phase Biodegradation Rate Evaluation

The major processes that affect the concentration of dissolved petroleum hydrocarbons are advection, dispersion, sorption, and biodegradation. Buscheck and Alcantar (1995) developed an equation to solve for $\lambda$, the first-order biodegradation rate, as a measure of intrinsic bioremediation. Input variables to this calculation include the overall attenuation rate (k), longitudinal dispersivity ($\alpha_x$), linear groundwater velocity ($v_x$), and linear contaminant velocity ($v_c$), to solve for $\lambda$ by the following equation:

$$\lambda = \left(\frac{v_c}{4\alpha_x}\right)\left(\left[1 + 2\alpha_x\left(\frac{k}{v_x}\right)\right]^2 - 1\right)$$

The Buscheck and Alcantar equation was used to evaluate dissolved-phase first-order biodegradation rates for benzene at the SWMU 15 site. The five groundwater flowpaths used in this analysis are pictured in Figure 6-2. Flowpaths are plume transects that flow from areas of high concentration to areas of low concentration in the direction of the predominant groundwater flow. The term $k/v_x$ was determined from the slope of the benzene concentration versus distance along the groundwater flowpaths when plotted on a log-linear graph. The log-linear graphs for each of the five groundwater flowpaths are provided in Figures J-4 through J-8. Linear regression slope calculations are tabulated in Appendix I. The data points for performing the linear regression were selected according to two hypothetical scenarios:

- **Hypothesis 1** – NAPL is present downgradient of the excavation area and high benzene concentrations are maintained by dissolution from the NAPL to the aqueous phase. Biodegradation rates in the dissolved-phase plume are calculated from the point along the flowpaths where high benzene levels begin to decrease.
- **Hypothesis 2** – All NAPL was removed from the site through excavation of the soils at the former tank farm area in 1996, and all of the benzene currently detected in groundwater is considered to be in a dissolved-phase plume. The benzene plume may not yet have broken through to the furthest downgradient wells along the flowpaths. Using methane as a plume tracer, biodegradation rates are only calculated for wells that have high methane concentrations (indication that the plume has broken through to these wells).

For example, Flowpath B monitoring points DW17, DW13, DW06, and DW12 have benzene concentrations ranging between 2,118 and 6,910 ug/L and methane concentrations ranging between 5,340 and 11,400 ug/L. Under Hypothesis 1, these wells are considered to be within a source area where the groundwater is in contact with residual NAPL. Downgradient of DW12, wells DW11 and DW27 have lower benzene concentrations, which suggests that these monitoring points are outside of the source area and within the dissolved-phase plume. Under Hypothesis 2, the high methane concentrations between wells DW17 and DW12 indicate that the benzene plume has reached at least as far has DW12, whereas the lower methane concentrations in DW11 and DW27 indicates that the plume may not have broken through to these wells.

In general, it is desirable to have three or more points along a flowpath within the dissolved phase plume for determining the slope of the regression line. In several cases, only two points were used because they were the only wells considered appropriately located within the dissolved phase plume for this evaluation.

The portions of the flowpaths that appeared to be within the dissolved-phase plume for Hypothesis 1 (NAPL present) were as follows:

- Flowpath A: DW07 to DW10
- Flowpath B: DW12 to DW27

- Flowpath F: DW08 to DW09
- Flowpath G: DW22 to DW24
- Flowpath H: DW30 to MW17

The dissolved-phase benzene concentrations are shown to attenuate rapidly in the plume along Flowpaths A, B, F, and H, and are estimated to be less than 1 μg/L within 200 feet of the downgradient edge of the source area. The slope of the linear regression line for Flowpath G data appears to be an outlier since it is not as steep, and may indicate that the monitoring points are not optimally placed near the edge of the source area and within the dissolved-phase plume. In several cases, only one well is located within the dissolved-phase plume along a given flowpath. Additional wells installed along the downgradient plume would give improved estimates of the biodegradation rates.

The portions of the flowpaths that appeared to be within the dissolved-phase plume for Hypothesis 2 (no NAPL present) were as follows:

- Flowpath A: MIP3 to DW07
- Flowpath B: DW17 to DW12
- Flowpath F: DW08
- Flowpath G: DW22 to DW23
- Flowpath H: DW28 to MW30

No overall pattern appears for benzene concentrations along the flowpaths under Hypothesis 2. Along Flowpath A, benzene concentrations increase slightly between MIP3 and DW07 (Figure J-4). Along Flowpath B, benzene concentrations decrease between DW17 and DW12 (Figure J-5). For Flowpath F, only one well, DW08, meets the conditions of high methane concentrations for Hypothesis 2, so a slope cannot be calculated. For Flowpath G, the decrease in benzene is the same as for the Hypothesis 1 case (Figure J-7). For Flowpath H, benzene concentrations increase sharply between DW28 and DW30.

Table J-6 summarizes the input values used to solve for the overall attenuation and biodegradation rates observed at the SWMU 15 site. The linear groundwater velocity, $v_x$, of 0.05 ft/day was estimated from the assumed hydraulic conductivity for medium to fine-grained sand ($4.1 \times 10^{-3}$ to $8.5 \times 10^{-4}$ cm/sec), effective porosity (0.25), and average gradient (0.0015 ft/ft). The $R_f$ value of 1.377 was calculated based on a literature value for $k_{oc}$ (58.9 L/kg; TPH Working Group, 1996), the effective porosity (0.25), an assumed bulk density (100 lbs/cf or 1.602 grams per cubic centimeter [g/cm$^3$] and soil organic carbon (1,000 mg/kg or 0.1%). Longitudinal dispersivity is a scale-dependent variable that has considerable uncertainty; a value of 11 was calculated assuming a dissolved-phase plume length ($L_p$) of 200 feet and the following equation from Xu and Eckstein (1995):

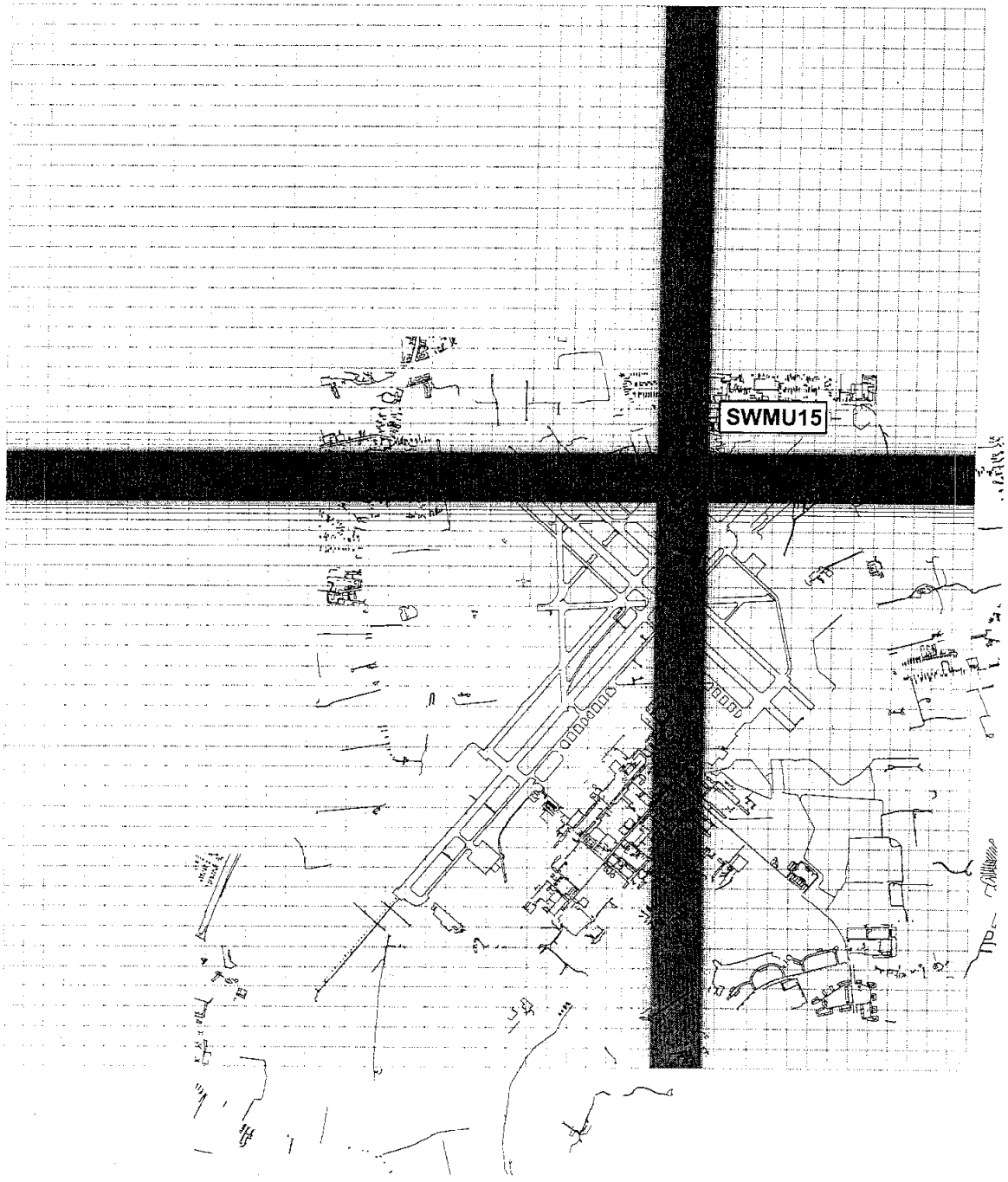
$$\alpha_x = 3.28 \times 0.83 \times \left[ \log_{10}\left( \frac{L_p}{3.28} \right) \right]^{2.414}$$

Under Hypothesis 1 (NAPL present), the resulting first-order biodegradation rate constants for benzene range between 0.0006 and 0.0036 $day^{-1}$ (half-lives between 192 and 1,136 days). The average biodegradation rate, excluding the result from Flowpath G which appears to be an outlier, is 0.0023 $day^{-1}$ (half-life of 300 days). This falls within the range of literature values for field and in-situ studies of anaerobic benzene biodegradation rates reported by Suarez and Rifai (1999), which ranged between 0.00001 and 0.023 and had a mean value of 0.003 $day^{-1}$ (half-life of 231 days).

Under Hypothesis 2 (no NAPL present), the calculated first-order biodegradation rates are very small or negative (half lives of –7854 to 4043 days). This supports a conclusion that benzene biodegradation does not appear to be occurring if no NAPL is present at the site.

**TABLE J-6**
Overall Attenuation and First-Order Biodegradation Rates for Benzene

| Flowpath | Slope, $k/v_x$ ($ft^{-1}$) | Groundwater Velocity, $v_x$ (ft/d) | Retardation Coef, $R_f$ | Contaminant Velocity, $v_c$ (ft/d) | Dispersivity $\alpha_x$ (ft) | Attenuation Rate, k ($day^{-1}$) | Biodeg. Rate, $\lambda$ ($day^{-1}$) | Biodeg Half-life (days) |
|---|---|---|---|---|---|---|---|---|
| ***Hypothesis 1 Wells (Plume downgradient of NAPL)*** | | | | | | | | |
| Flowpath A | 0.0600 | 0.05 | 1.377 | 0.0363 | 11 | 0.0030 | 0.0036 | 192 |
| Flowpath B | 0.0387 | 0.05 | 1.377 | 0.0363 | 11 | 0.0019 | 0.0020 | 346 |
| Flowpath F | 0.0430 | 0.05 | 1.377 | 0.0363 | 11 | 0.0022 | 0.0023 | 301 |
| Flowpath G | 0.0145 | 0.05 | 1.377 | 0.0363 | 11 | 0.0007 | 0.0006 | 1136 |
| Flowpath H | 0.0384 | 0.05 | 1.377 | 0.0363 | 11 | 0.0019 | 0.0020 | 350 |
| ***Hypothesis 2 Wells (No NAPL Present)*** | | | | | | | | |
| Flowpath A | - 0.0025 | 0.05 | 1.377 | 0.0363 | 11 | - 0.0001 | - 0.0001 | - 7854 |
| Flowpath B | 0.0045 | 0.05 | 1.377 | 0.0363 | 11 | 0.0002 | 0.0002 | 4043 |
| Flowpath G | 0.0140 | 0.05 | 1.377 | 0.0363 | 11 | 0.0007 | 0.0006 | 1182 |
| Flowpath H | - 0.0184 | 0.05 | 1.377 | 0.0363 | 11 | - 0.0009 | - 0.0005 | - 1301 |




N

0 feet 4,000 feet 8,000 feet

152630-01.SRF

**Figure J-1**
**Extent of Model Grid**
NAS Naval Air Station, Virginia Beach, Virginia

CH2MHILL

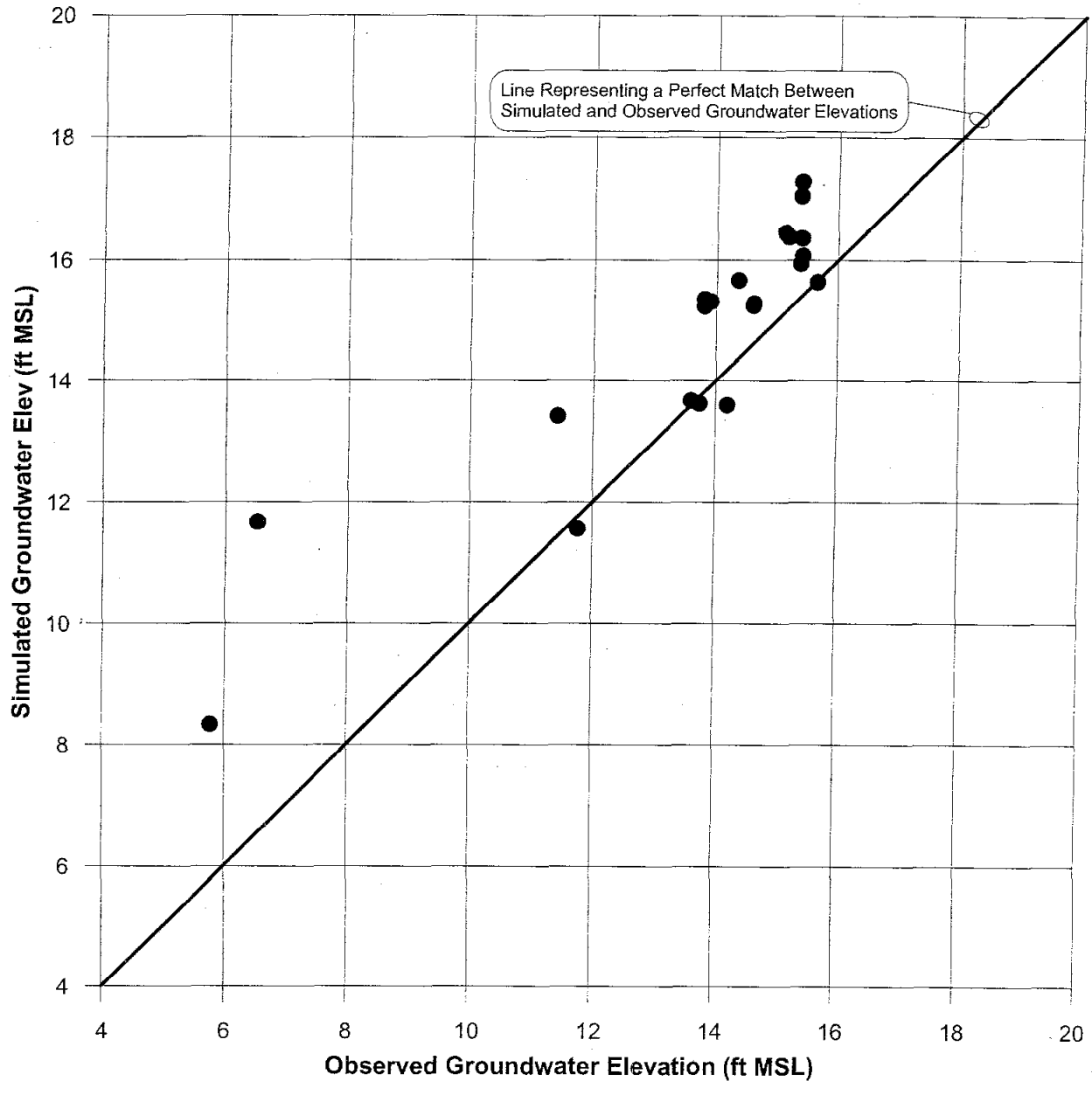



**Figure J-2**
**Simulated Versus Observed Groundwater Elevation**
NAS Naval Air Station, Virginia Beach, Virginia

152630-01.GRF

CH2MHILL

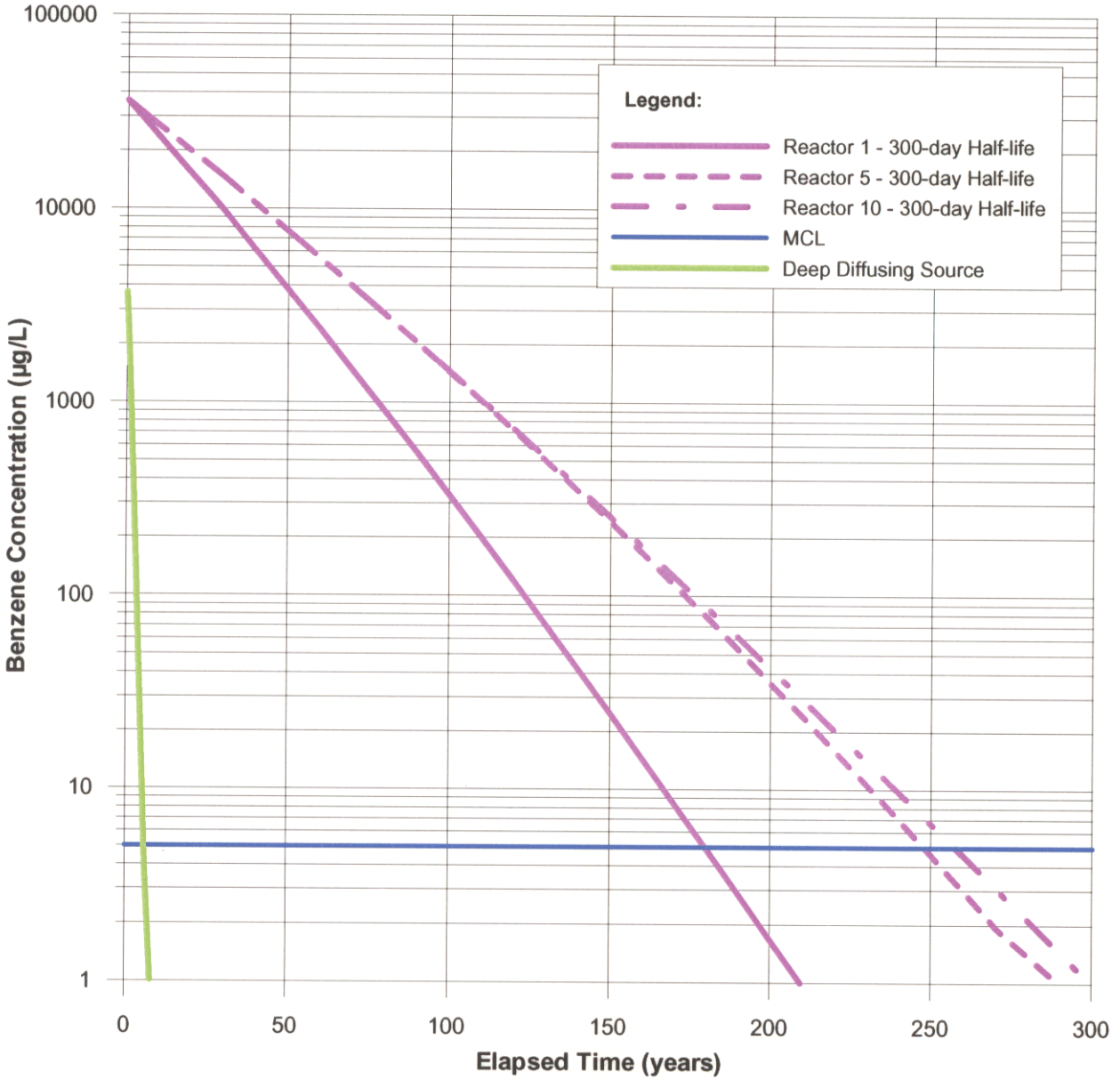



**Figure J-3**
**Benzene Concentration Versus Time**
**Three-Phase vs. Two-Phase Model**

NAS Naval Air Station, Virginia Beach, Virginia

152630-02.GRF

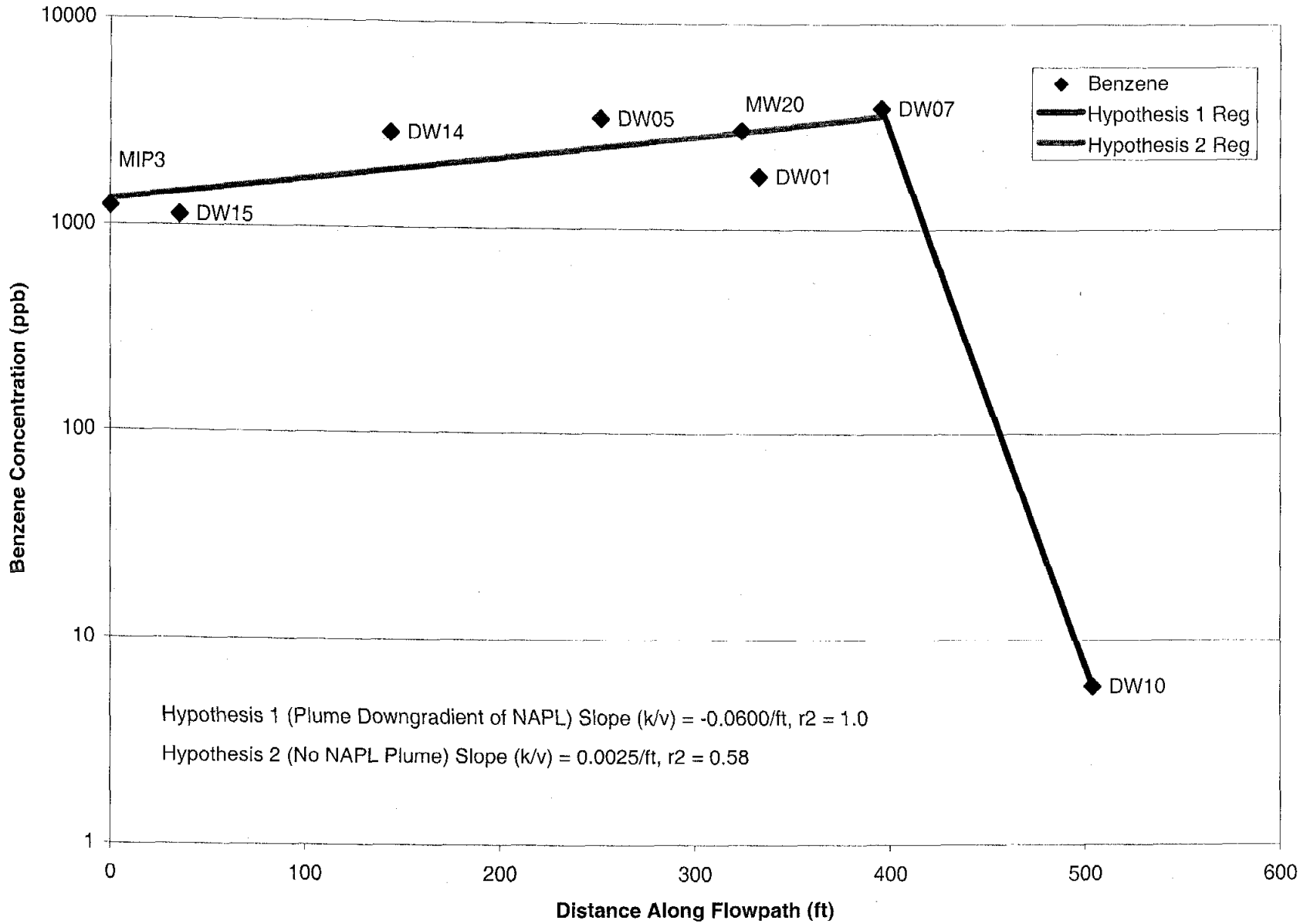
CH2MHILL

00526E084

Fi J-4

Benzene Concentration vs. Distance Along Flowpath A

SWMU 15 - NAS Oceana



e J-5

Benzene Concentration vs. Distance Along Flowpath B

SWMU 15 - NAS Oceana

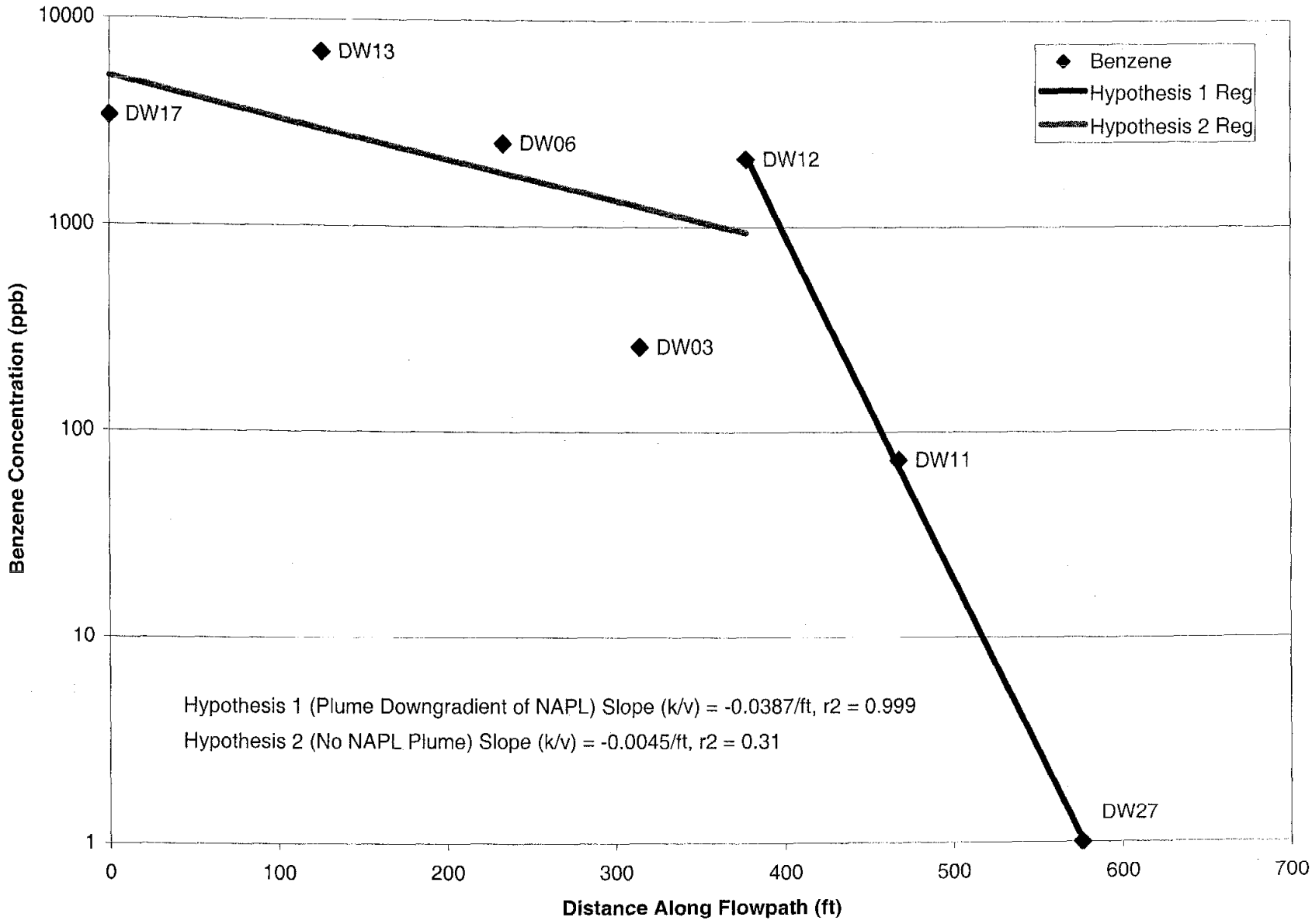
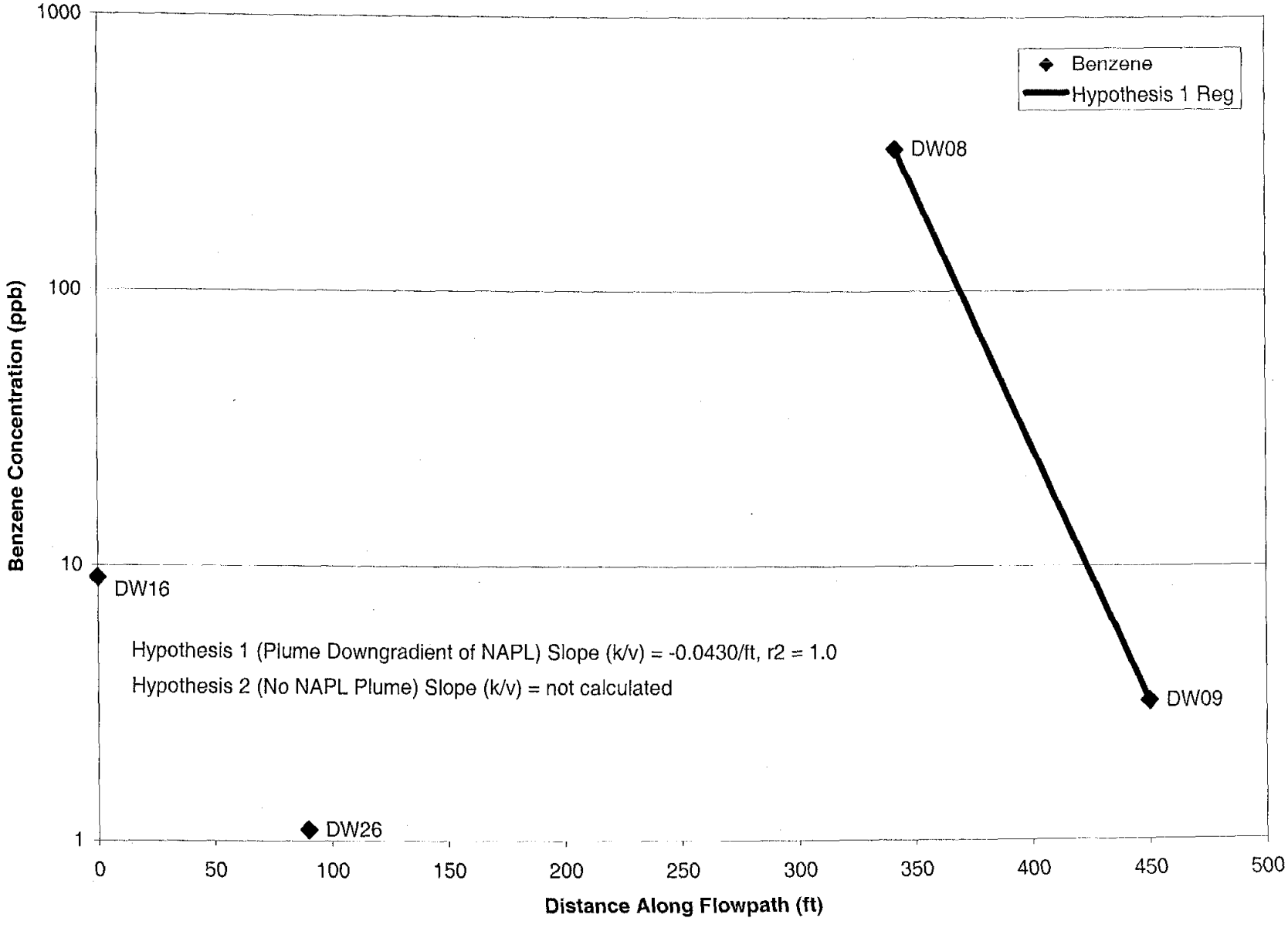


Fig J-6
Benzene Concentration vs. Distance Along Flowpath F
SWMU 15 - NAS Oceana



F J-7

Benzene Concentration vs. Distance Along Flowpath G

SWMU 15 - NAS Oceana

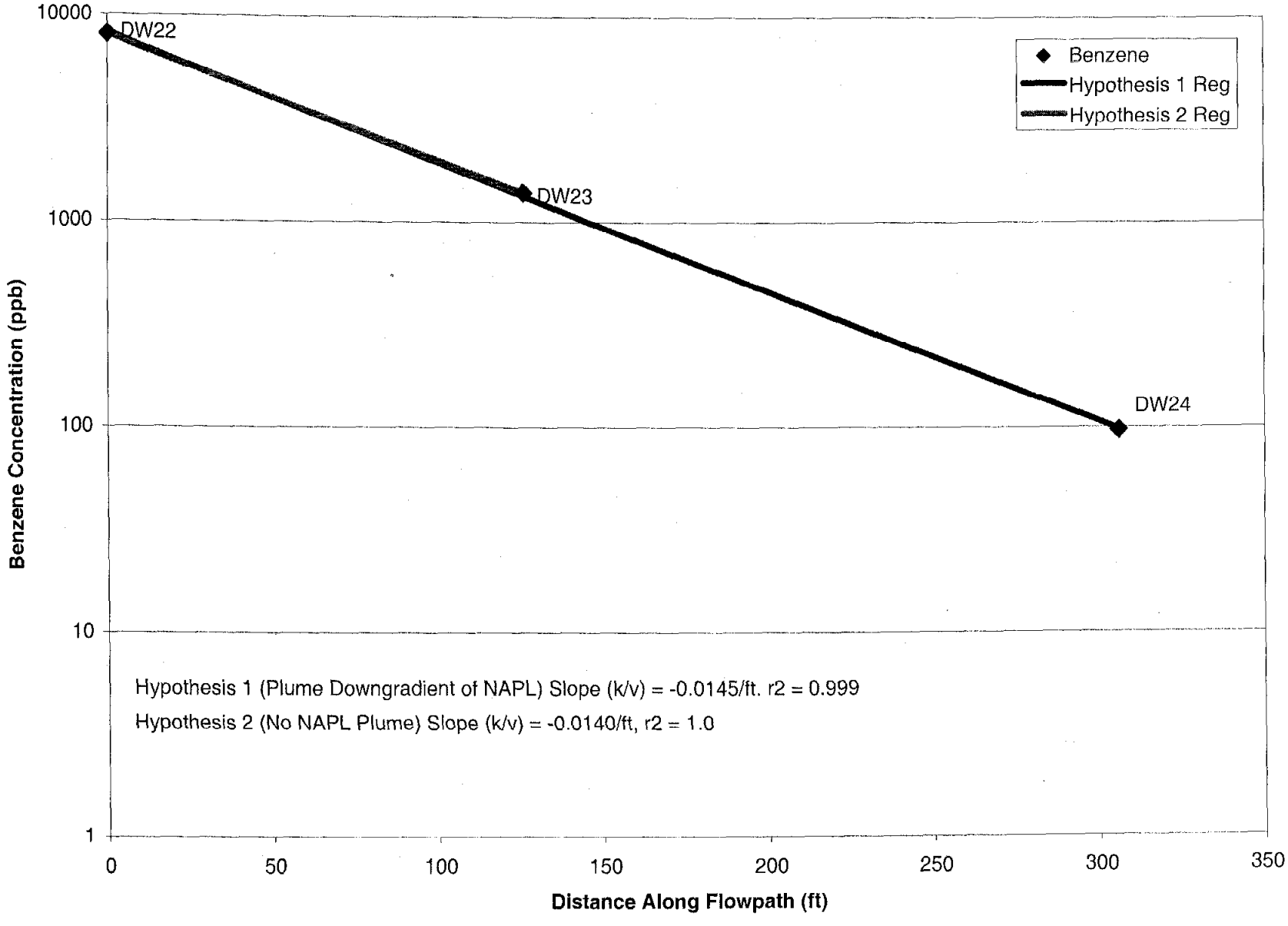
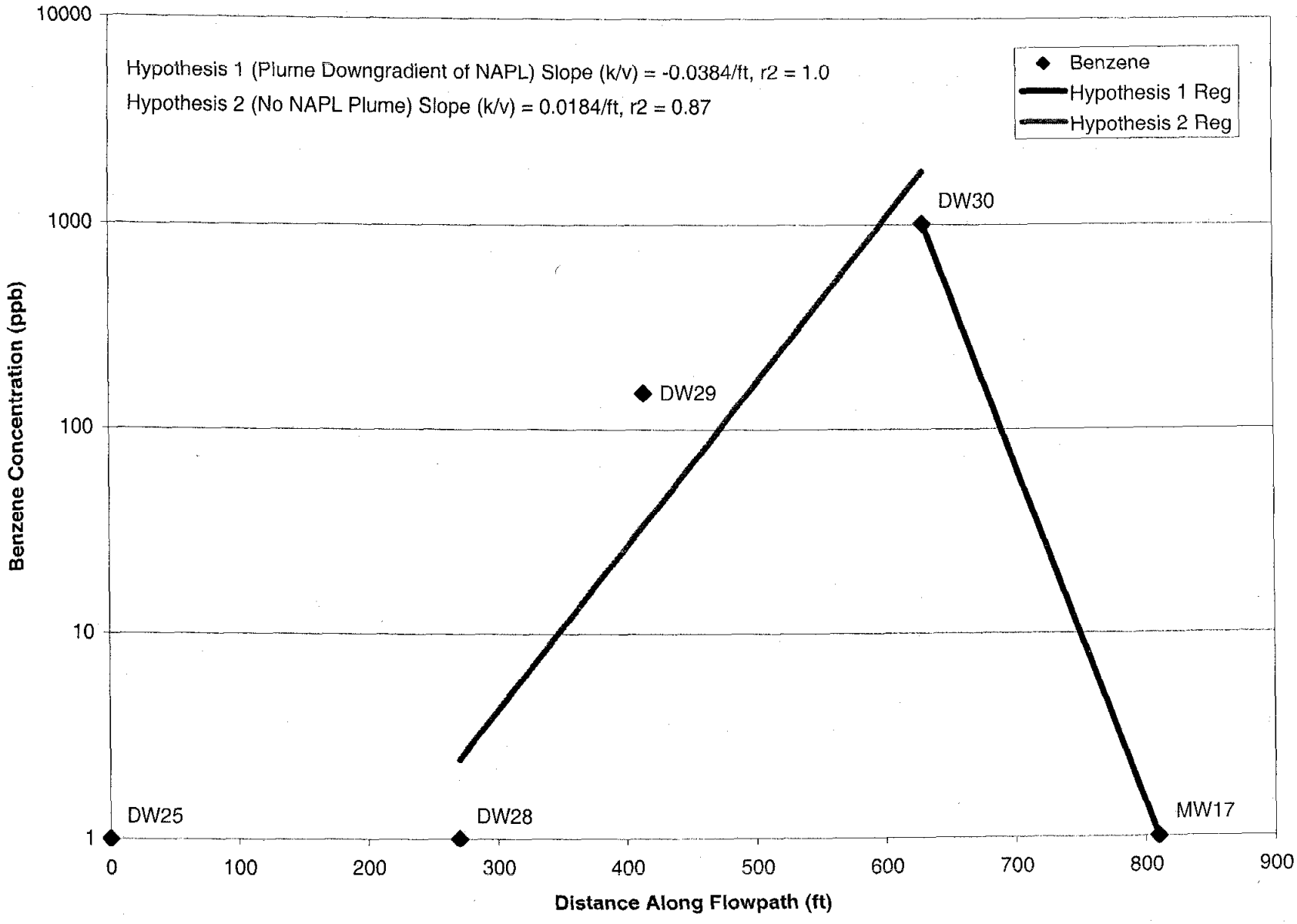



Figure J-8
Benzene Concentration vs. Distance Along Flowpath H
SWMU 15 - NAS Oceana