DRAFT FINAL TECHNOLOGY EVALUATION OPERABLE UNIT 16 (OU 16) SITE 93 MCB CAMP LEJEUNE NC (DRAFT ACTING AS FINAL)

1/1/2003

CH2M HILL

DRAFT FINAL

Technology Evaluation
Operable Unit No. 16 (Site 93)
Marine Corps Base
Camp Lejeune, North Carolina

Prepared for

Department of the Navy

Atlantic Division
Naval Facilities Engineering Command

Norfolk, Virginia

Contract No. N62470-95-D-6007
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Prepared by

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January 30, 2003

174057.TS.ED.93

Kirk Stevens
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Code: EV23
1510 Gilbert St., Bldg. No. N26
Norfolk, VA 23511-2699

Subject: Site 93 Technology Evaluation

Dear Kirk:

CH2MHILL is please to submit the draft final version of the Site 93 Technology Evaluation under CTO 253. Copies of the documents have been sent to the following: MCB Camp Lejeune, US Environmental Protection Agency, NC Department of Environment and Natural Resources, Naval Environmental Health Center, Shaw Environmental Group, and Baker Environmental.

If you have any questions or comments, feel free to contact me at (704) 329-0073 x291.

Sincerely,

CH2M HILL

Christopher Bozzini

Christopher F. Bozzini, P.E.
Project Manager

CLT\Site 93 draft final tech eval cover letter.doc

c: Rick Raines, MCB Camp Lejeune
Randy McElveen, NCDENR
Charlie Stehman, NCDENR, Wilmington
Gena Townsend, EPA Region 4 (2 copies)
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Ron Kenyon, Shaw Group
Rich Bonelli, Baker Environmental
Scott Bailey, CH2M HILL

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EXECUTIVE SUMMARY

A technical evaluation (TE) of potential remedial technologies was prepared to facilitate the selection of an effective approach for treatability (pilot) testing at Site 93. This TE is not intended to be an exhaustive review of all remediation technologies, but rather a focused review of technologies that are potentially effective for source area treatment. The evaluation includes innovative strategies for *in-situ* groundwater remediation that may not have been used at Camp Lejeune, but are considered promising or "emerging" technologies. This study is a follow-on to the April 2002 Feasibility Study for Site 93.

The Partnering Team has requested targeting "hot spot" remediation. Localized areas of relatively elevated concentrations have been defined at Site 93 as target VOC concentrations greater than one or two orders of magnitude in excess of applicable and relevant standards. Groundwater impacts are most concentrated at shallow depth (approximately 15-19 feet), corresponding to the depth of the discontinuous Belgrade formation. The maximum depth of any groundwater contamination is approximately 30 feet below grade. In addition, contamination has not reached Edwards Creek, as a line of sample points between the site and the creek were non-detect.

Five technologies using differing delivery methods best suited for the substrate were evaluated. Test cost, including one year of operation are summarized below. The five technologies evaluated were: 1) hydrogen sparging using horizontal wells; 2) zero valent iron injection; 3) permanganate injection; 4) enhanced bioremediation using emulsified vegetable oil; and 5) enhanced bioremediation using sodium lactate.

Option	Test Cost
1 - Hydrogen Sparge	$382,000
2 - Zero Valent Iron	$227,000
3 – Permanganate	$240,000
4 – Enhanced Bioremediation using Vegetable Oil	$224,000
5 – Enhanced Bioremediation using Sodium Lactate	$266,000

Based on the comparison of technologies, permanganate, zero-valent iron and enhanced bioremediation are considered effective and implementable technologies at Site 93. Enhanced bioremediation is recommended for pilot scale implementation. Due to the DCE build up, enhanced bioremediation should push the attenuation process to completion. Due to the slow release of carbon by vegetable oil, emulsified vegetable oil injection is recommended over sodium lactate injection.

The recommended approach for implementing vegetable oil at Site 93 is to treat two different target areas. Two areas were chosen to test delivery materials. The two target areas are located around 93-MW06 and 93-MW08. Vegetable oil would be injected using a Geoprobe at four points around 93-MW06 and pneumatic fracturing would be used for the injection at the four points around 93-MW06. As shown in Figures 4-1 and 4-2, the location and spacing of the injection points relative to the target area is the same for 93-MW06 as for 93-MW08. Addressing two different target areas, using the same spacing between injection points and distance from the target monitoring well, allows a comparison to be made about the effectiveness of the two different methods of injection for delivering vegetable oil. Because maintenance requirements are essentially non-existent for both types of injection (aside from routine monitoring), the evaluation period may be continued for more than one year. The evaluation will help to establish the long-term effectiveness of each method of injection. If results of the pilot study are favorable, vegetable oil can be applied to other areas of the Site 93 plume using the more effective method of injection.

1.0 Introduction

1.1 Purpose of the Technology Evaluation

This Technology Evaluation (TE) identifies remedial technologies appropriate for pilot testing at Site 93. Effectiveness of the technology in reducing the concentration of dissolved phase chlorinated solvents will be evaluated. This document is not intended to be an exhaustive review of all available comprehensive remediation options, but rather a focused review of options that can be demonstrated in the field for the purpose of source area or "hot spot" treatment. Emphasis was placed on innovative remedial strategies which may not have been attempted at Camp Lejeune in the past, but which are considered promising or "emerging" technologies, specifically for the purpose of *in-situ* groundwater remediation.

This report should aid the Camp Lejeune Partnering Team in selecting the remedial technology or technologies to be tested in the field as part of a pilot study. The methodology for this pilot study will be documented in the Treatability Study Work Plan.

1.2 Report Organization

This Technology Evaluation consists of the following sections, including this introductory section:

1.0 **Introduction** – Presents the purpose of the Technology Evaluation for this site.

2.0 **Site Information** – Provides an overview of the site history, geology, hydrogeology, and contamination.

3.0 **Location of Hot Spots for Technology Evaluation** – Defines "hot spot" and identifies the hot spot targeted for this evaluation.

4.0 **Remedial Technologies Evaluation** – Presents the factors used in selecting a remedial technology, classes of technologies, the selected technologies, and a cost analysis.

5.0 **Predictive Modeling** – Details the objectives, approach, and results from BIOCHLOR modeling.

6.0 **Conclusions and Recommendations** – Discusses the conclusions and recommendations resulting from the evaluation of the selected technologies against the objectives of the TE.

7.0 **References** – Lists the references used in this document.

All figures are in a separate section.

2.0 Site Information

Site 93, part of Operable Unit (OU) Number (No.) 16, is located in the Camp Geiger section of Camp Lejeune (Figure 2-1). Site 93 is located near Building TC-942 at the intersection of Ninth and "E" Streets. The site area is relatively flat and covered by asphalt, gravel and grass. The eastern portion of the site is wooded and slopes gently toward Edwards Creek. Ground surface elevations are approximately 5 to 20 feet above mean seal level (msl) in the vicinity of the site.

Background information for Site 93 is contained in the *Remedial Investigation of Operable Unit 16 (Sites 89 and 93)* (Baker Environmental, June 1998) and the *Site 93 Additional Plume Characterization Letter Report* (Baker Environmental, April 2002).

2.1 Site History

Site 93 contains several areas of contamination that have been investigated under the underground storage tank (UST) Investigation Program starting in 1995 and the Installation Restoration (IR) Program in 1996. Originally, the focus of the site investigation was on a small area near the southwest corner of Building TC-942 that formerly contained a 550-gallon UST used to store waste oil. This UST was removed in 1993. Subsequent investigations have revealed several contaminant plumes throughout the site, spanning from the original UST to the barracks area.

A Remedial Investigation (RI) was conducted in 1996 and 1997. The results of the RI indicated limited site-related soil contamination, chlorinated solvent (primarily trichloroethene [TCE]) contamination in the shallow and intermediate aquifer zones.

Long Term Monitoring (LTM) of groundwater at Site 93 was initiated in April 1999 and is ongoing. Groundwater samples are analyzed for contaminants of concern (COCs) including tetrachloroethene (PCE), TCE, trans-1,2-dichloroethene (trans-1,2-DCE), cis-1,2-dichloroethene (cis-1,2-DCE), and vinyl chloride (VC), as well as natural attenuation parameters.

In 2001, Baker Environmental conducted a preliminary natural attenuation evaluation (NAE) at Site 93. The results of the NAE indicated limited natural attenuation of chlorinated solvents was occurring at the site as evidenced by the presence of reductive dechlorination byproducts.

The need for additional plume characterization was decided upon during the November 2001 Partnering Meeting. The objective of the meeting was to further delineate groundwater contamination, characterize hot spot contamination areas, and collect additional aquifer data to support the selection of an active remedial system at Site 93. Baker Environmental conducted additional plume characterization activities during January and February 2002.

2.2 Site Geology and Hydrogeology

The Site 93 RI report (Baker Environmental, 1998) provides details regarding local geology and the occurrence of surface water and groundwater resources at Site 93. The following is a brief summary of these features.

2.2.1 Geology

Site 93 is located in the Atlantic Coastal Plain physiographic province of North Carolina. The Base is underlain by seven sand and limestone units separated by units which include the surficial, Castle Hayne, Beaufort, Peedee, Black Creek, and the upper and lower Cape Fear lithologic units. During the RI, the Undifferentiated and River Bend Formations were identified. The Belgrade Formation did not appear to be consistent at Site 93, however, a description of this unit has been included. Figures 2-2 and 2-3 show a cross-sectional diagram of the stratigraphy at Site 93.

The Undifferentiated Formation is comprised of loose to medium dense sands and soft to medium stiff clay. This formation is comprised of several units of Holocene and Pleistocene ages and can consist of a fine to coarse sand, with lesser amounts of silt and clay. At Site 93, this formation typically extends to a depth between 20 and 30 feet below ground surface (bgs). The silt and clay lenses present within this formation may be correlated to the regional geology as the Belgrade Formation, or Castle Hayne confining unit.

The Belgrade Formation is comprised of fine sand with some shell fragments, silt, and clay of the Miocene age. Identifying this formation at Site 93 was difficult due to its inconsistency. The inconsistent nature of the Belgrade Formation suggests that a significant hydraulic connection exists between the Undifferentiated Formation and the upper portions of the River Bend Formation. At best, the Belgrade Formation at Site 93 can be classified as a semi-confining unit or a "retarding layer", as it is laterally discontinuous and does not exhibit completely confining conditions to the River Bend Formation below.

Beneath the Undifferentiated Formation and the limited Belgrade Formation lies the River Bend Formation (upper portion of the Castle Hayne aquifer). This unit, which is predominantly composed of dense to very dense shell and fossil fragments interbedded with calcareous sands, is present at approximately 25 to 50 feet bgs.

The geologic information indicates a definite hydraulic connection between the surficial aquifer and the underlying Castle Hayne aquifer. This connection is likely attributable to the discontinuous nature of the Castle Hayne confining unit rather than hydraulic conductivity through the unit. Hydrogeologic information from the RI report for this site as well as other nearby sites at Camp Geiger indicate that the Castle Hayne confining unit is non-existent or limited in lateral extent. Also, vertical hydraulic conductivity measurements indicate that the Castle Hayne confining unit exhibits a low hydraulic conductivity.

2.2.2 Hydrogeology

The surficial aquifer resides within the Undifferentiated Formation, the Castle Hayne confining unit resides within the Belgrade Formation, and the Castle Hayne aquifer resides within the River Bend Formation. The surficial aquifer is approximately 18 to 23 feet thick and begins approximately one to five bgs. The thickness of the Castle Hayne confining layer is 4 to 7 feet. A definite confining layer separating the surficial aquifer from the Castle Hayne aquifer is not present at Site 93.

During the remedial investigation, groundwater levels within RI monitoring wells ranged from 2.15 feet below msl to 13.52 feet above msl. Groundwater level measurements for Site 93 are presented within the RI. The most recent groundwater elevation data and approximate flow directions have been illustrated on Figure 2-4.

The groundwater elevation data suggest that the flow patterns observed for the surficial and upper portions of the Castle Hayne aquifer display similar trends. Overall, elevations are higher in the northern portion of the site, with decreasing elevations in the direction of Edwards Creek and in the wooded area to the east. Groundwater flow in the surficial aquifer shows a pronounced localized flow to the east as Edwards Creek serves as a groundwater discharge boundary. Edwards Creek effects flow within the surficial aquifer and upper portions of the Castle Hayne aquifer more than in the deeper portion of the aquifer. Groundwater flow in the upper portions of the Castle Hayne is affected somewhat by the local discharge area of Edwards Creek. The New River, located east of the site, influences the groundwater flow of the deeper portions of the Castle Hayne aquifer, causing groundwater at depth to move east, toward the river.

Groundwater head differentials between the shallow and intermediate wells were evaluated to determine if a vertical component of flow underlies the site. In general, elevations in shallow temporary wells were greater than the associated elevation in the intermediate temporary wells. This data demonstrates a downward component of groundwater movement from the surficial aquifer to the Castle Hayne aquifer north of Edwards Creek. This information supports the assumption that in the area of Site 93, the Castle Hayne aquifer is unconfined.

The estimated hydraulic conductivity (K value) at Site 93 is similar to the K values from Site 89, which is adjacent to Site 93. The hydraulic conductivity from the shallow wells at Site 89 was 0.0029 cm/s. The average hydraulic conductivity in the intermediate well was 0.023 cm/s, one order of magnitude greater than the values measured in the shallow wells. The hydraulic gradient at Site 93 is approximately 0.004 ft/ft. Based on these measurements and an assumed porosity of 0.2, the velocity in the surficial aquifer is estimated to be on the order of 60 ft/yr.

2.3 Site Contamination

Five VOCs were detected in the groundwater samples during the RI which was conducted in 1996 and 1997. They included: chloroform, cis-1, 2-DCE, PCE, trans-1, 2-DCE, and TCE. TCE was the most frequently detected VOC in groundwater, with the highest concentrations coming from the gravel parking area, immediately south of Building TC-942 and the location of the UST. Other compounds which exceeded the Federal Maximum Contaminant Levels (MCLs) or the 2L standards, included chloroform, cis-1, 2-DCE, and PCE.

Bis (2-ethylhexyl)phthalate and naphthalene were the most common semivolatile organic compound (SVOCs) detected at Site 93. Pesticides and PCBs were not detected in any of the monitoring wells during the RI.

The following inorganic constituents were detected above the MCLs and the 2L standards: iron, manganese, and lead. The background levels of metals are consistently high across the Base (at sites other than 93) due to natural site conditions as reported in the Baker RI; therefore, metals have not been considered to be contaminants of concern and consequently were not addressed in the FS. A statistical analysis of site data in relation to the background study done by Baker in 2002 is needed.

Site 93 groundwater contamination was concentrated in the shallow aquifer in the vicinity of the UST, near Building TC-942. Low concentrations of VOCs were detected in samples collected from the intermediate groundwater monitoring wells, demonstrating that some vertical migration had occurred. However, more recent groundwater characterization sampling events have illustrated multiple contaminant plumes present in three vertical zones within Site 93.

PCE, TCE, cis-1,2-DCE, trans-1,2-DCE, and VC were detected in many of the groundwater samples collected during the additional plume characterization in early 2002. Contaminant concentrations exceeded 2L Standards at several locations. The following compounds exceeded 2L Standards: PCE, TCE, cis-1,2-DCE, and trans-1,2-DCE.

Figure 2-5 shows the horizontal extent of PCE in groundwater. Figure 2-6 shows the horizontal extent of TCE in groundwater. Figures 2-5 and 2-6 are based on geoprobe plume delineation and groundwater long-term monitoring. The greatest vertical extent of contaminant distribution is shown in the vertical cross section (cross section location shown on Figure 2-2) on Figure 2-7. These figures include data collected during LTM. Table 2-1 summarizes the results from the April 2002 LTM.

TABLE 2-1
April 2002 LTM Results for Site 93 (Detects Only)

	2L STD.	93-MW05	93-MW06	93-MW08	93-MW09
Cis-1,2-DCE	70	91	580	130	32
Trans-1,2-DCE	70	43	220	51	8
TCE	2.8	46	180	61	3 J
PCE	0.7	5 U	95	120	5 U
1,1,2,2-PCA	0.17	5 U	34	5 U	5 U
1,1,2-TCA	---	5 U	10	5 U	5 U
VC	0.015	2 U	10	4	2 U
Total CVOCs	---	180	1,129	246	43

All results are µg/L
U – Not Detected, Detection Limit Provided

Groundwater impacts are most concentrated at shallow depth (approximately 5-19 feet), corresponding to the depth of the discontinuous Belgrade formation. The LTM data shows higher concentrations than found during the plume delineation work and indicates that cis-1,2-DCE is the predominant compound. The wells in the LTM program are screened from 5-15 feet bgs. The maximum depth of groundwater impacts is approximately 30 feet below grade. However, concentrations at this depth are only slightly above regulatory limits. Contamination has not reached Edwards Creek, as a line of down gradient sample points between the site and the creek did not detect any VOCs.

Figures

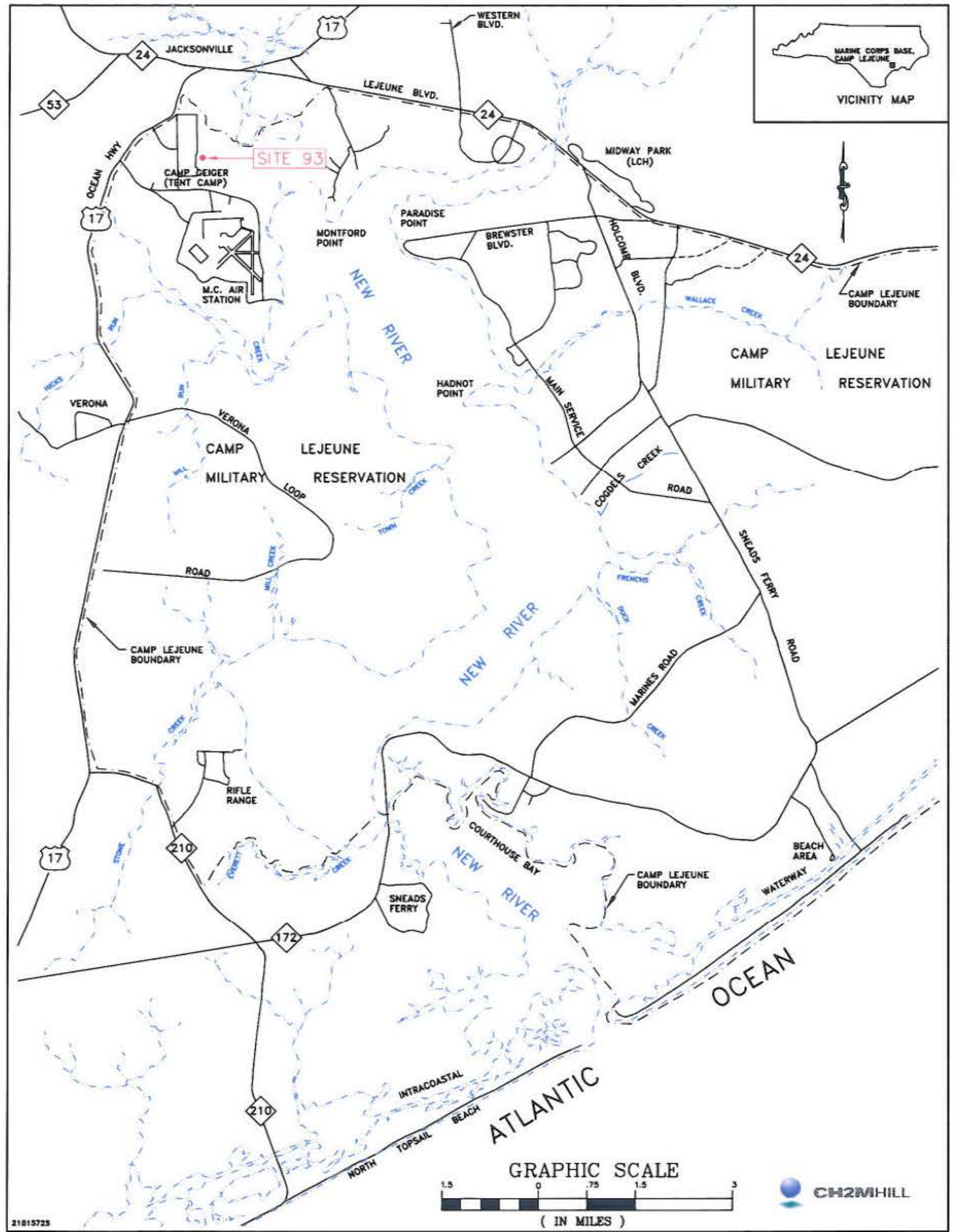
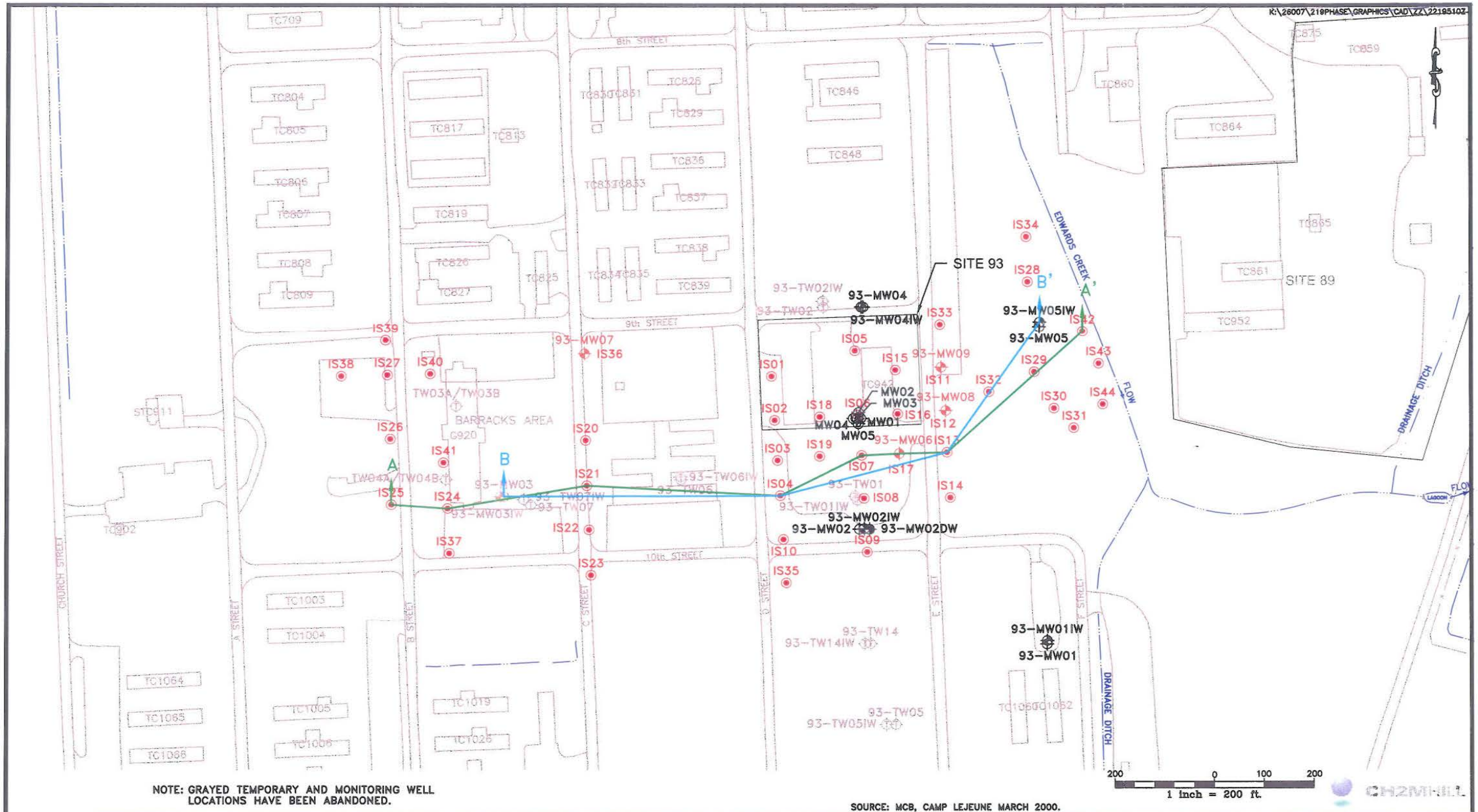


FIGURE 2–1
LOCATION MAP – SITE 93
TECHNOLOGY EVALUATION REPORT
CTO – 0253
MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA



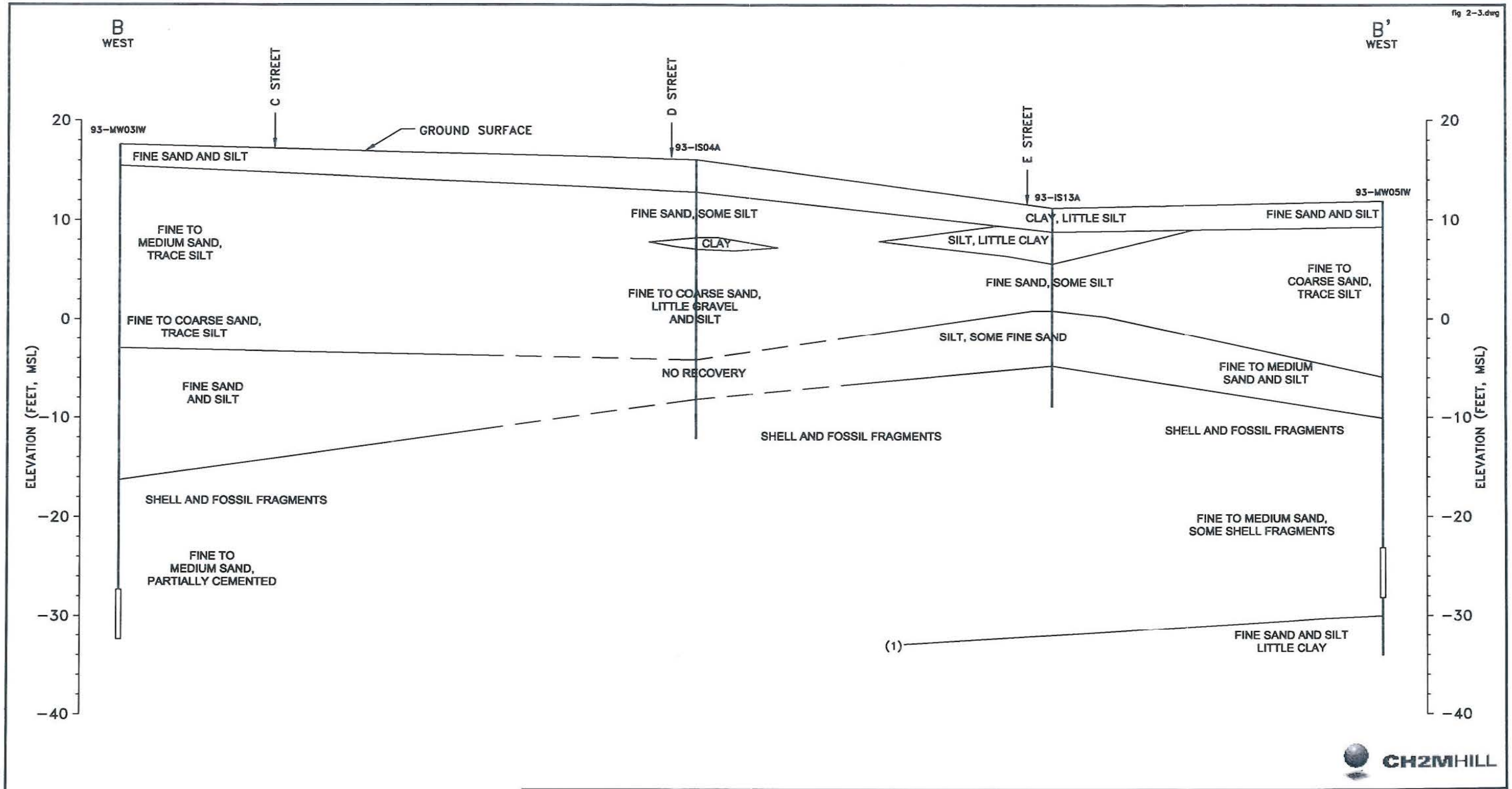
NOTE: GRAYED TEMPORARY AND MONITORING WELL LOCATIONS HAVE BEEN ABANDONED.

SOURCE: MCB, CAMP LEJEUNE MARCH 2000.

LEGEND

Symbol	Description
93-MW01	SHALLOW GROUNDWATER MONITORING WELL LOCATION (1997 RI)
93-MW01IW	INTERMEDIATE GROUNDWATER MONITORING WELL LOCATION (1997 RI)
93-MW02DW	DEEP GROUNDWATER MONITORING WELL LOCATION (1997 RI)
93-TW05	TEMPORARY GROUNDWATER MONITORING WELL LOCATION (1997 RI)
93-MW07	SHALLOW GROUNDWATER MONITORING WELL LOCATION (2002 ADDITIONAL PLUME CHARACTERIZATION)
IS01	BORING LOCATION (2002 ADDITIONAL PLUME CHARACTERIZATION)
MW01	SHALLOW GROUNDWATER MONITORING WELL (1995 SITE CREEK)
A — A'	CONTAMINANT PLUME CROSS SECTION
B — B'	GEOLOGIC CROSS SECTION

FIGURE 2-2
CROSS SECTION LOCATION MAP
OPERABLE UNIT NO. 16 – SITE 93
TECHNOLOGY EVALUATION REPORT
CTO – 0253
MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA

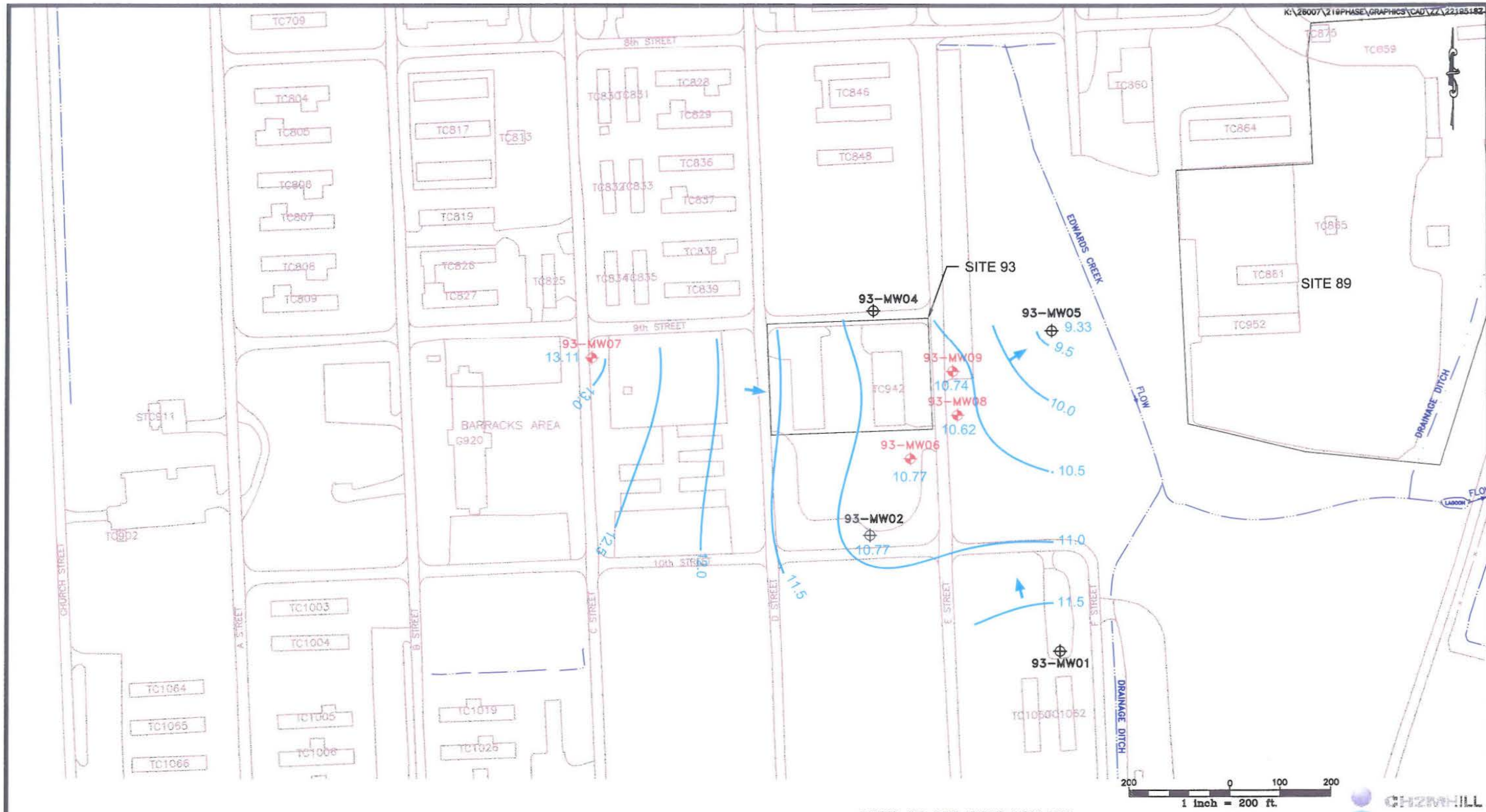


THE SOIL BORING INFORMATION IS CONSIDERED TO BE REPRESENTATIVE OF SUBSURFACE CONDITIONS AT THE RESPECTIVE BORING LOCATIONS. SUBSURFACE CONDITIONS INTERPOLATED BETWEEN BORINGS ARE ESTIMATED BASED ON ACCEPTED SOIL ENGINEERING PRINCIPLES AND GEOLOGIC JUDGEMENT.

NOTE: (1) INFORMATION FROM NEARBY WELL 93-MW02IW SUGGESTS CONTACT AT THIS ELEVATION.

FIGURE 2-3
CROSS SECTION B-B'
OPERABLE UNIT NO. 16 - SITE 93
TECHNOLOGY EVALUATION REPORT
CTO - 0253

MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA

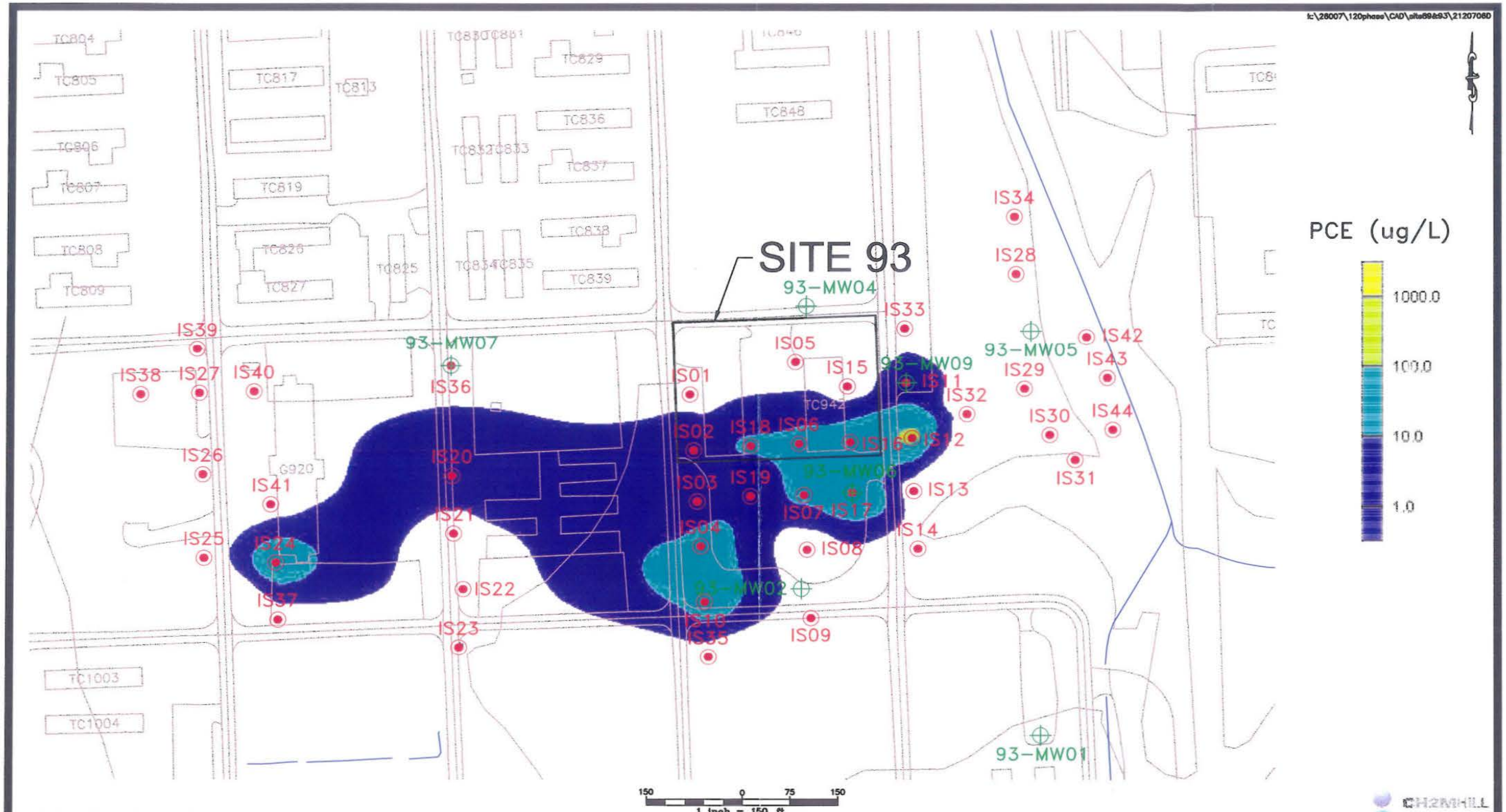


SOURCE: MCB, CAMP LEJEUNE MARCH 2000.

LEGEND

- 93-MW01 – SHALLOW GROUNDWATER MONITORING WELL (1997 RI)
- 93-MW07 – SHALLOW GROUNDWATER MONITORING WELL LOCATION (2002 ADDITIONAL PLUME CHARACTERIZATION)
- 11.0 – ISOELEVATION CONTOUR LINE
- GROUNDWATER FLOW DIRECTION

FIGURE 2-4
GROUNDWATER CONTOUR MAP
OPERABLE UNIT NO. 16 – SITE 93
TECHNOLOGY EVALUATION REPORT
CTO – 0253
MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA



SOURCE: MCB, CAMP LEJEUNE, MARCH 2000

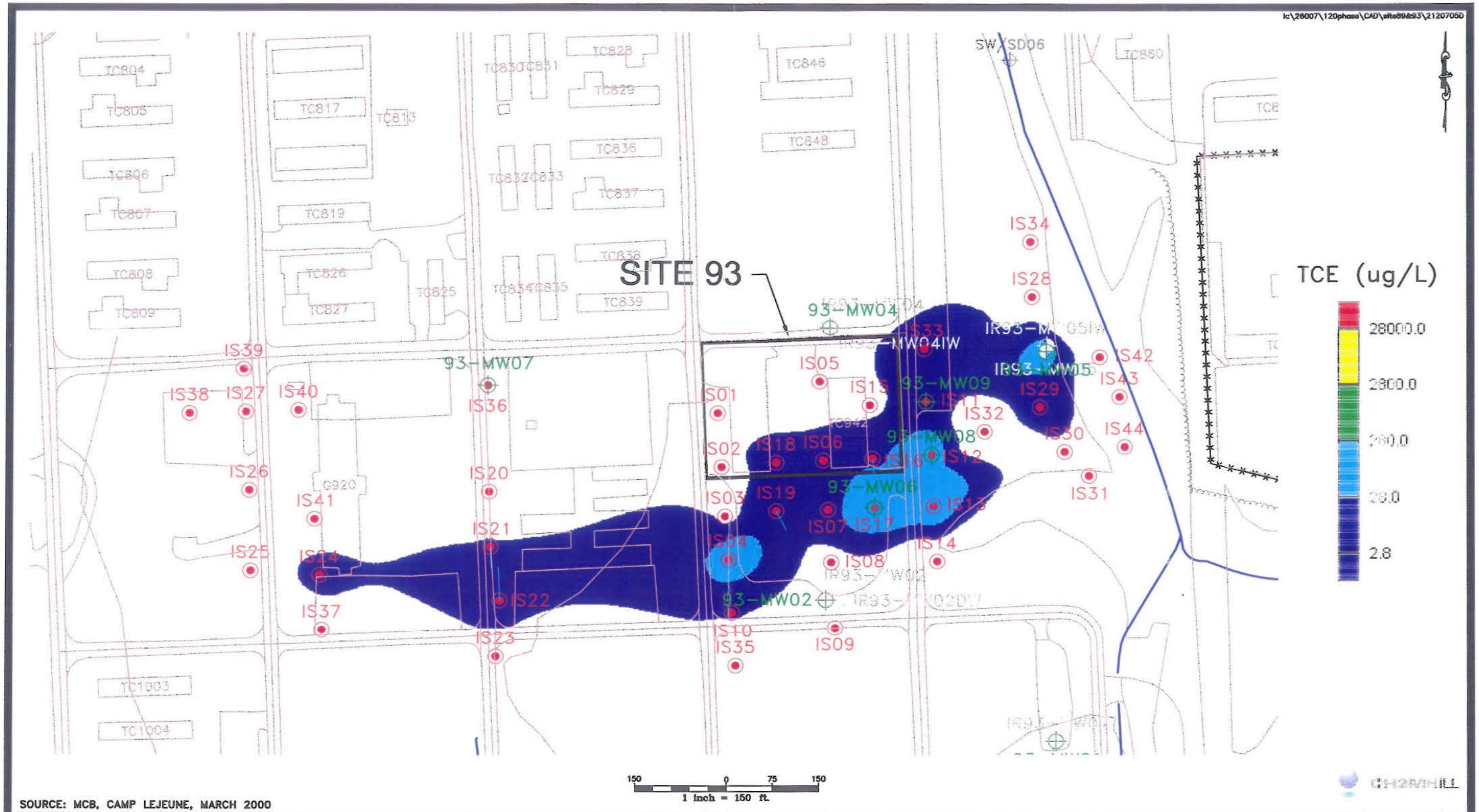
LEGEND

⊕ – SHALLOW GROUNDWATER MONITORING WELL (<20 FEET)

● – GEOPROBE BORING LOCATION (2002 ADDITIONAL PLUME CHARACTERIZATION)

NOTE:
– LOCATIONS SHOWN IN BLACK REGULAR FONT ARE NOT INCLUDED IN THE MONITORING PROGRAM.
– LOCATIONS SHOWN IN GREEN FONT ARE INCLUDED IN THE MONITORING PROGRAM.

FIGURE 2–5
EXTENT OF PCE IN GROUNDWATER
OPERABLE UNIT NO. 16 – SITE 93
TECHNOLOGY EVALUATION REPORT–CTO 253
MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA



SOURCE: MCB, CAMP LEJEUNE, MARCH 2000

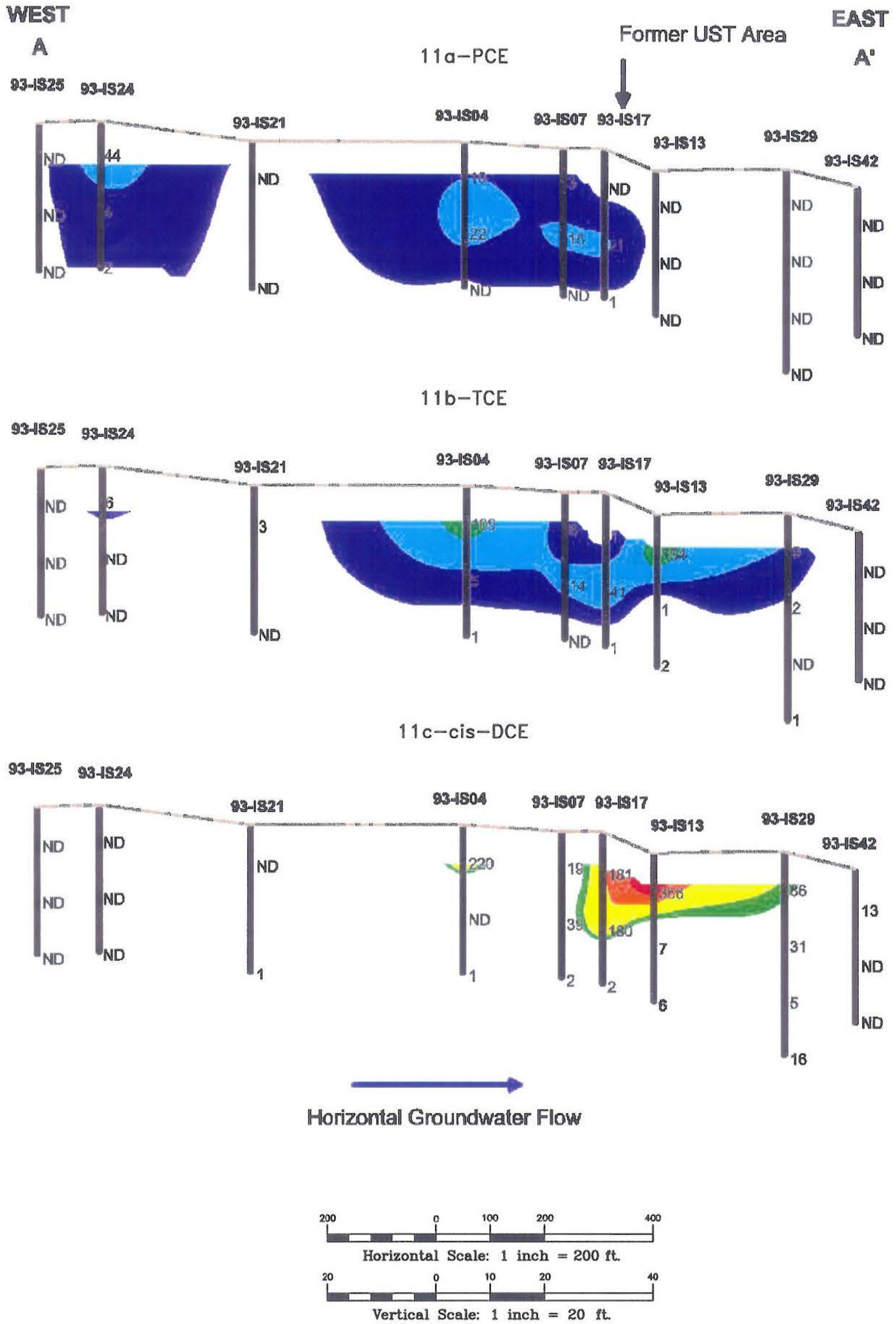
LEGEND

⊕ – SHALLOW GROUNDWATER MONITORING WELL (<20 FEET)

◉ – GEOPROBE BORING LOCATION (2002 ADDITIONAL PLUME CHARACTERIZATION)

NOTE:
– LOCATIONS SHOWN IN BLACK REGULAR FONT ARE NOT INCLUDED IN THE MONITORING PROGRAM.
– LOCATIONS SHOWN IN GREEN FONT ARE INCLUDED IN THE MONITORING PROGRAM.

FIGURE 2-6
EXTENT OF TCE IN GROUNDWATER
OPERABLE UNIT NO. 16 – SITE 93
TECHNOLOGY EVALUATION REPORT-CTO 253
MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA



LEGEND

- 400 ug/L
- 300 ug/L
- 200 ug/L
- 100 ug/L
- 70 ug/L (cis 1,2 DCE) 80 ug/L (PCE & TCE)
- 10 ug/L
- 2.0 ug/L (TCE) 1 ug/L (PCE)

FIGURE 2–7
CROSS SECTION A–A'
OPERABLE UNIT NO. 16 – SITE 93
TECHNOLOGY EVALUATION REPORT
CTO – 0253
MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA

3.0 Location of Hot Spots for Technology Evaluation

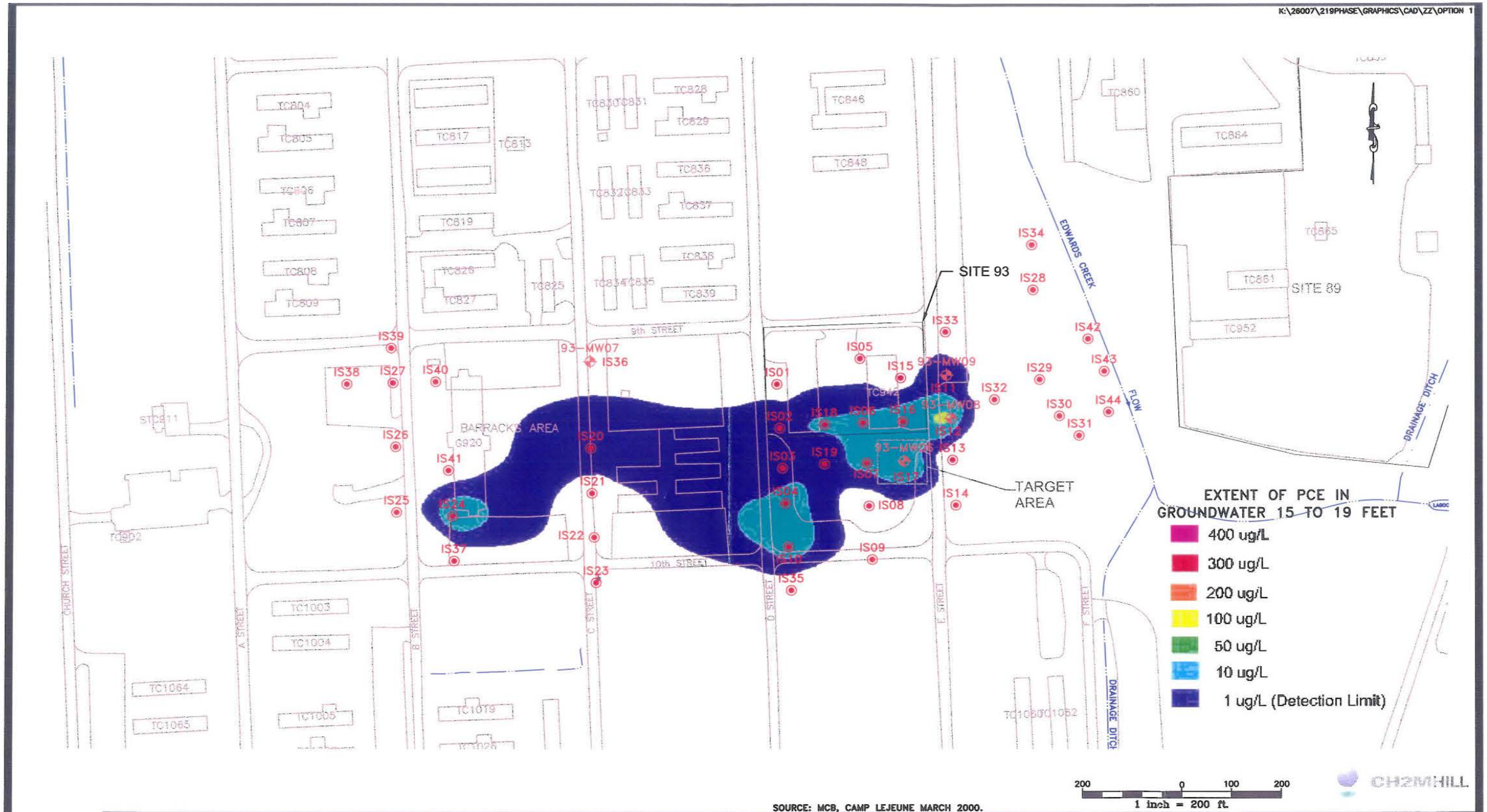
3.1 Defining "Hot Spots"

Based on engineering judgment, a "hot spot" is generally considered to be an area containing COC concentrations significantly greater than the areas around it. In general, a "hot spot" could be greater than 100 μg/L or 1000 μg/L or orders of magnitude greater than a regulatory standard. The North Carolina groundwater standard for PCE is 0.7 μg/L, TCE 2.8 μg/L and cis-1,2-DCE 70 μg/L.

3.2 Identification of "Hot Spot" Used in this Technology Evaluation

The focus of the pilot test will be at an area with the highest contaminant concentration. Based on inspection of PCE, TCE, and cis-1,2-DCE plume configurations, the primary target area was selected to be the area around 93-MW06. The results of the April 2002 LTM are a total VOC concentration of 1,129 μg/L with a cis-1,2-DCE concentration of 580 μg/L (2L std. = 70 μg/L), TCE concentration of 180 μg/L (2L std. = 2.8 μg/L), and PCE concentration of 95 μg/L (2L std. = 0.7 μg/L). The target area, approximately 30 feet by 30 feet around 93-MW06, is shown in Figure 3-1. A secondary target area around 93-MW08 was selected to compare injection methods for the enhanced bioremediation technologies

Figures



LEGEND

93-MW07 – SHALLOW GROUNDWATER MONITORING WELL LOCATION (2002 ADDITIONAL PLUME CHARACTERIZATION)

IS01 – BORING LOCATION (2002 ADDITIONAL PLUME CHARACTERIZATION)

PLOT DATE: 04/08/02

FIGURE 3–1
PILOT STUDY TARGET AREA
SITE 93 TECHNOLOGY EVALUATION REPORT
CTO – 0253
MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA

4.0 Remedial Technologies Evaluation

4.1 Factors in Selecting a Remedial Technology

This section describes the methodology used to determine remediation technologies for potential field or "pilot scale" treatability testing at Site 93. These factors include:

1) Site conditions
2) Nature and extent of contamination
3) Site constraints

Site Conditions

The site geology and hydrogeology and contaminated environmental media (soil, soil gas, groundwater) are factors in determining which remediation technologies are applicable to a site. This technology evaluation is focused only on groundwater since soil contaminant levels did not pose a risk and no source areas could be identified. Because of the unique characteristics of Site 93 (low permeability, heterogeneous saturated soil with a very thin overlying vadose zone), in conjunction with the stated goal of localized source area remediation, available technologies are limited. Description of the preferred technologies is described in Section 4.3. The site conditions were described in Section 2.2.

Nature and Extent of Contamination

The type, concentration, and spatial distribution of contaminants further narrow the remediation technologies that would be effective in reducing contaminant mass. Site 93 has a dissolved plume of chlorinated VOCs that is at a depth less than 30 feet bgs and predominantly at about 15 ft. A hot spot exists at 93-MW06 (1,129 µg/L total VOCs), while the remainder of the site has relatively low concentrations of VOCs. Concentrations are highest at shallow depths (5-15 ft bgs) and decrease with depth. These characteristics were discussed in Sections 2.3 and 3.2.

Site Constraints

Physical conditions may be present that limits the ability to implement particular technologies. These obstacles include buried infrastructure, buildings, paved areas, land use, and depth to contamination. Site 93 has one building (TC 942) that is currently in use and several paved areas. TC 942 will be close to the hot spot treatment area and will be a factor in selection of a technology and final placement of the pilot test area. Consideration was given to technologies that are minimally disruptive.

4.2 Classes of Technologies

In accordance with the criteria listed above, three general categories of remedial options were identified:

- Mass Transfer (stripping)
- Enhanced Biodegradation
- In-situ oxidation or reduction (chemical treatment)

Mass transfer technologies, such as air sparging and vacuum enhanced recovery, were not considered feasible at Site 93 due to the shallow depth of the water table, lack of surface cover (i.e. unpaved ground surface), low subsurface permeability and soil heterogeneity. Thermal treatment technologies are not considered cost effective for plumes that do not contain free phase product.

The two remaining technologies (enhanced biodegradation and in-situ oxidation or reduction) include two primary components:

1) Chemical/substrate delivery to the subsurface, possibly including a carrier fluid; and,
2) Chemical or substrate that will affect contaminant mass reduction by biological, chemical, or physical means.

Both components are described in the following sections. Substrate delivery is generally the most complex and difficult engineering problem at remediation sites.

4.3 Selected Technologies

Five technologies were selected for further evaluation based on consideration of the factors discussed in Section 4.1. Chemicals and substrates used to promote *in-situ* biodegradation, oxidation, and reduction can be injected in liquid or gaseous form. Options evaluated included hydrogen sparging, zero valent iron (ZVI), permanganate, vegetable oil and sodium lactate. Hydrogen sparging injects a mixture of hydrogen and nitrogen into the subsurface to induce biodegradation. ZVI degrades contaminants by chemical reduction through the injection of ZVI. Permanganate is an oxidation process where the chemical is injected into the formation to oxidize the target contaminants. Enhanced bioremediation through the injection of either vegetable oil or sodium lactate provides a carbon source for microbial growth and promotes the dehalogenation process.

ORC and HRC are scheduled to be pilot tested at Site 78; therefore, use of this compound at Site 93 would be somewhat redundant and reduce the Partnering Team's goal to increase first hand knowledge of a variety of *in situ* technologies.

Three methods of substrate delivery were examined. They are horizontal borings/wells, vertical borings/wells, and pneumatic fracturing (soil fracturing) with injection. Both vertical or horizontal borings/wells can be used for chemical or substrate delivery, and both have proven effective in the field. Vertical wells are more effective for small scale, shallow plumes while horizontal wells are more effective for large scale, deeper plumes. The localized, dilute nature of the groundwater plume at Site 93 favors a vertical well/boring approach.

Pneumatic fracturing is an alternative method of chemical/substrate delivery. Pneumatic fracturing offers the advantage of improved fracture density relative to hydraulic fracturing. Fracture density plays a key role in remediation speed and effectiveness at low permeability sites, as the time required for diffusive transport of the injected chemical is greatly influenced by the distance between fractures. The technique is used to introduce chemicals or biological substrates into moderate to low permeability formations. Soil fractures are created by injection of high-pressure (75-150 psi) nitrogen gas. However, pneumatic fracturing may not be effective at shallow depths (less than ten feet) due to the potential for short-circuiting or day lighting of injected material. At shallow depths, because of the lack of overburden pressure, the fractures tend to "bow" upwards relatively quickly, instead of remaining relatively horizontal at greater depths. For this reason, the "radius of influence" of injection is significantly smaller for shallow depths.

Hydraulic fracturing is not recommended because of possible impact to building foundations in the area. Hydraulic fracturing is also a relatively slow and inefficient process for multiple injections.

4.3.1 Hydrogen Sparging

Hydrogen sparging is a recently developed method to stimulate anaerobic halorespiration, a form of reductive dechlorination (RD). RD is a reaction in which the chlorinated solvents act as an electron acceptor and a chlorine atom is replaced with a hydrogen atom, which acts as the electron donor. For dechlorination to occur at low hydrogen concentrations, halorespirators must compete successfully with other hydrogen-using bacteria for the available hydrogen. However, recent studies (Newell, et al 1997) indicate that dechlorination is not affected by competition for electron donors at high hydrogen concentrations. Therefore, increasing the amount of hydrogen within a plume will result in increased halorespiration and reduce chlorinated solvent concentrations.

Sparging hydrogen periodically into the plume has been successfully demonstrated at the pilot scale level (Newell, et al 1997). The volume of hydrogen is kept small to reduce the potential for building up gas-phase hydrogen (bubbles) that would escape to the vadose zone. The frequency of the sparging pulse is set to maintain the concentration of hydrogen in the groundwater at a level that will support reductive dechlorination. In unmodified formations, the sparging wells must be approximately 10 to 15 feet apart to achieve effective distribution of the hydrogen. Fracturing is not required for substrate injection in the case of hydrogen gas injection, since the gas pressure will be sufficient to create fractures (channels) in conjunction with normal sparging activity.

Gas sparging allows for greater penetration of low permeability areas, relative to liquid injections, thus decreasing remediation "lag" time. Furthermore, direct injection of hydrogen is seen as a method to bypass the process of fermentation associated with conventional liquid substrates. The need for time consuming and costly re-injections is eliminated, and the system can be reactivated at any time to address "rebound" effects.

Applicability to Site 93

For most applications, hydrogen gas is stored on-site in large "tube trailers" or bundles of welding gas type vessels, either pre-mixed or blended with nitrogen on-site. Since the gas is under high pressure, a blower or compressor system is not required. The gas is metered directly into the sparge well(s) using an injection manifold, controlled by a programmable timer. Maintenance is negligible. The primary concern associated with hydrogen injection is the potential accumulation of fugitive gas in buildings, and/or production of by-products, such as hydrogen sulfide gas. Periodic monitoring would need to be conducted in area buildings during operation.

It is expected that low-volume pulsed biosparging would be effective at Site 93. The system could be fully automated to pulse hydrogen gas into the subsurface at a prescribed rate. Maintenance would be low. Fracturing is not required for hydrogen gas injection since the gas pressure will be sufficient to create fractures (channels) in conjunction with normal sparging activity. Biosparging could be implemented using a network of vertical wells and conveyance piping.

4.3.2 Zero Valent Iron/Colloidal Iron Injection with Pneumatic Fracturing

ZVI consists of pure iron metal granules or powder, which must be specially manufactured and packaged to prevent premature corrosion. Once released into the environment, oxidation of the iron under anaerobic conditions yields ferrous iron and hydrogen ions, both of which are reducing agents for chlorinated solvents. Use of ZVI in the remediation industry began in 1990, with the first use of permeable reactive barriers (PRB) to contain/treat groundwater plumes. Once in the ground, ZVI will slowly oxidize (corrode) and cause reduction of chlorinated solvents. Numerous iron permeable reactive barriers (PRBs) have been installed; many of which are still in place and working well.

The use of ZVI has since been expanded to comprehensive treatment of groundwater plumes. ARS Technologies (ARS) has developed the "Ferox^SM^" process. In contrast to PRBs, made of highly concentrated iron fillings distributed within a vertical zone 2 to 3 ft thick, the "Ferox^SM^" process involves high-pressure, pneumatic injection of tiny iron particles within individual soil borings. A slurry of ZVI powder and water (water amendment is optional for saturated zone applications) will be injected into the subsurface immediately after fracturing is completed, using nitrogen gas as a carrier fluid.

Pneumatic fracturing can be effective in dense/tight soils and heterogeneous conditions. This method is used to improve distribution of injected materials and increase spacing between borings. The "radius of influence" of ZVI injection using this technique has been verified in the field (using soil samples) to be about 15-20 ft.

Preliminary ARS research indicates that hydrogenation resulting from iron corrosion may stimulate anaerobic biological enhanced RD (ERD) in the subsurface, thus resulting in synergistic abiotic and biotic mediated electron transfer. Biological ERD is not likely with PRB systems because of high alkalinity, which is generally toxic to microorganisms.

Applicability to Site 93

ZVI consists of pure iron metal granules or powder, which must be specially manufactured and packaged to prevent premature corrosion. Once released into the environment, oxidation of the iron under anaerobic conditions yields ferrous iron and hydrogen ions, both of which are reducing agents for chlorinated solvents. The April 2002 LTM dissolved oxygen content measured in 93-MW06 was 0.25 mg/L, indicating anaerobic conditions. ZVI would be injected into the treatment area in a series of points at depths that intercept groundwater flow. The injection is expected to be a one-time event (one dose) due to the longevity of the iron, which is not consumed, is an immediate reaction. Also, since the iron is injected, there is no equipment or system to maintain.

4.3.3 Potassium Permanganate

Permanganate is an oxidizing agent with a unique affinity for organic compounds containing carbon double bonds, such as chlorinated alkenes like PCE and TCE. The oxidation strength and specificity of the permanganate ion improves its longevity, relative to non-specific oxidizers, such as OH^- radicals and ozone. However, the introduction of oxidant such as permanganate will alter the oxidation-reduction potential of the aquifer, to the point where biologically mediated RD may no longer be favorable. Strongly reducing conditions (ORP of –150 MV or less) are favored for optimal RD. Obviously, oxidants such as permanganate, which maintain significant longevity in the environment, will also interfere with RD for a longer period of time.

Although the oxidizing potential of the permanganate ion is less than Fenton's reagent or ozone, it is efficient and fast acting. Permanganate has reportedly accomplished greater than 99 percent removal of TCE within 2 hours under favorable conditions (Siegrist, 2000). Because of the relative stability of permanganate, it may persist in the environment for several months, depending on the natural oxidant demand of the subsurface. Furthermore, permanganate is effective over a broad range of pH: 3.5 to 12 (ITRC, 2001).

Field experiments (Siegrist, 2000) indicate diffusive transport of permanganate may improve remediation speed and effectiveness in "silty clay soils." During these experiments, which involved emplacement of permanganate particles mixed with mineral gel within hydraulic fractures, a diffusive zone of active permanganate ions up to 1.3 ft from the midpoint of the injection zone was measured. This zone of diffused permanganate remained active for up to 10 months following injection.

The reaction of permanganate ion with organic compounds is well documented to produce manganese dioxide (MnO_2), an insoluble precipitate, chloride, and either carbon dioxide or intermediate organic compounds. A typical reaction equation, in this case TCE, is presented below:

$$C_2HCl_3 + 2MnO_4^- \Rightarrow 3Cl^- + 2CO_2 + H^+ + 2MnO_2(s)$$

Manganese dioxide is a naturally occurring mineral found in soil in many areas of the country. Manganese dioxide/hydroxide, a gelatinous precipitate, will be formed as a consequence of permanganate reduction (which occurs as permanganate performs oxidation). For very high dose rates, accumulation of MNO_2 may result in "fouling" of injection well screens, and/or decreasing the natural hydraulic conductivity in the surrounding soil. Residual permanganate and/or manganese dioxide/hydroxide may also render the groundwater at a treated site unfit for human consumption in the future.

Applicability to Site 93

Permanganate has quick reaction rates and high destruction efficiencies; therefore, permanganate is considered feasible for treatment of chlorinated solvents at Site 93. Although the permanganate is fast acting, residual and/or intermediate compounds produced during RD may remain in the subsurface if either insufficient time or permanganate was provided for the reaction to proceed to completion. One drawback is the amount of permanganate needed. The estimated amount of potassium permanganate required to treat a 30 feet by 30 feet target area is 4,300 lbs. However, injecting more permanganate than needed may result in the overproduction of CO_2 and MnO_2 byproducts, which could hinder oxidant distribution. Re-injection may be necessary if oxidation of the chlorinated solvents is incomplete. The injection of several thousand gallons of liquid will also affect subsurface conditions.

When contaminants are lodged within low conductivity materials, injection of aggressive, short-lived oxidation reagents would not be effective or efficient. Groundwater flow through these materials is very slow and contaminant transport may be diffusion limited. Because of the relatively low permeability and heterogeneity of the surficial aquifer, conventional fluid injections are not considered feasible without very close spacing of wells/borings. Borehole spacing of 6-12 feet (three to six foot radius) intervals is recommended by specialty remedial vendors, such as Regenesis (ORC™/HRC™) or BMS (Biox™). Pneumatic fracturing is effective as it creates a much larger zone of influence. The zone of influence resulting from pneumatic fracturing and injection is conservatively estimated to be 30 feet (15-foot radius from the injection point). The radius of influence of injection is smaller for shallow depths because of the orientation of the fractures and the potential for daylighting.

Similar to ZVI, $KMnO_4$ would be injected using nitrogen gas as a carrier fluid. Once the formation is fractured and gas flow has been established, a double diaphragm pump will be used to deliver the $KMnO_4$ solution (approximately 5% in water) into the nitrogen gas stream, causing it to "atomize" (i.e. become entrained in the gas as a fine mist). The combined gas and liquid stream will be injected into the formation. Typical gas flow rates will probably be within the range of 800 to 1200 scfm.

Short-lived oxidants would not spread from the injection zone; therefore, multiple injections would be needed at many locations to treat the entire plume. Periodic re-injection of reagents could be cost-prohibitive and maintenance intensive. Health and safety of workers and bystanders is at greater risk when dealing with multiple episodes of storing, handling, and injecting reactive chemicals.

4.3.4 Enhanced Bioremediation

Enhanced bioremediation through the injection of either vegetable oil or lactate provides a carbon source for microbial growth. Reductive dechlorination is a natural process in most groundwaters, but the rate of dechlorination is usually slow and may not be sustainable. In order to stimulate reductive dechlorination, large amounts of a suitable electron donor must be introduced to the site. Vegetable oil or lactate acts as an electron donor, while TCE acts as an electron acceptor. The addition of the electron donor drives redox conditions and accelerates the dehalogenation progression from TCE to DCE to VC and, finally, to ethene. In this process, hydrogen atoms are replacing chlorine atoms in the contaminant molecules, and when complete biodegradation occurs, the contaminants are broken down into innocuous compounds such as carbon dioxide and water.

The separate phase nature of vegetable oil allows for slow dissolution into groundwater thus making it a slow release carbon source. Only one injection at each point may be required due to this slow release. Vegetable oil is an inexpensive, innocuous carbon source that is not regulated as a contaminant by the United States Environmental Protection Agency (USEPA).

The injection of sodium lactate to accelerate the dechlorination of TCE is an emerging technology. Lactate is easily dispersible, possibly allowing for fewer injection points. In previous studies, an increased rate of dechlorination has occurred as far as 40 meters from the injection point (Sorenson, 2001). The rapid fermentation of lactate could require more frequent injections than with vegetable oil. However, as lactate ferments, it forms acetate and propionate which are also capable of accelerating dechlorination.

Applicability to Site 93

Enhanced bioremediation through injection of vegetable oil or sodium lactate under anaerobic conditions accelerates the progression of dechlorination of TCE to DCE to VC to ethene. The April 2002 LTM dissolved oxygen content measured in 93-MW06 was 0.25 mg/L, indicating anaerobic conditions.

The injection of vegetable oil is expected to be a one-time event (one dose) due to the slow carbon release of vegetable oil. Since the vegetable oil is injected, there is no equipment or system to maintain. Although a natural attenuation study has not been conducted at Site 93, vegetable oil is expected to accelerate the dechlorination process.

Sodium lactate would be injected in large quantities as often as once a month until contaminant concentrations are reduced to desired levels. No equipment or system maintenance would be required for sodium lactate injection.

The vegetable oil or sodium lactate would be injected into the treatment area in a series of points at depths that intercept groundwater flow. Injection through a well is an effective means of substrate delivery; however, use of pneumatic fracturing for injection may increase the radius of influence and/or increase the long term effectiveness of the treatment. An increase in the radius of influence could reduce the overall cost of treatment. Therefore, both types of injection are recommended if a pilot study using vegetable oil or sodium lactate is performed.

The recommended approach for implementing vegetable oil or sodium lactate at Site 93 is to treat two different target areas. The two target areas are located around 93-MW06 and 93-MW08. Vegetable oil or sodium lactate would be injected using pneumatic fracturing at four points installed in a series around 93-MW06. As shown in Figure 4-1, horizontal spacing between injections would be approximately 15 feet. Vegetable oil or lactate would be injected through injection wells at four points installed in a series around 93-MW08. As shown in Figure 4-2, the location and spacing of the injection points relative to the target area is the same as for 93-MW06. Addressing two different target areas, using the same spacing between points and distance from the centerpoint, allows a comparison to be made about the effectiveness of the two different methods of injection for delivering the substrate. Because maintenance requirements are essentially non-existent for vegetable oil injection (aside from routine monitoring), the evaluation period may be continued for more than one year. The evaluation will help to establish the long-term effectiveness of each method of injection. Sodium lactate injection would most likely require more than one injection, which would add to the overall project cost.

4.4 Cost Analysis

A cost analysis of the evaluated technologies was completed. The cost estimate contained in Appendix A is budgetary and is to be used for comparison purposes only. A comparison of the costs is presented in Table 4-1. All alternatives would have a similar monitoring component requiring the installation of new monitoring wells. The cost associated with injection of ZVI and monitoring for one year (including groundwater monitoring) is estimated to be $227,000. The corresponding cost for permanganate is $240,000. The cost for hydrogen sparging is estimated to be $382,000. The cost of vegetable oil injection is estimated to be $224,000, and the cost of sodium lactate injection is an estimated $266,000.

For the purpose of developing the hydrogen sparging, ZVI, and potassium permanganate cost estimates, it was assumed that the substrate or chemical of choice would be injected into approximately 8 borings/injection points from 6 to 25 feet bgs, surrounding 93-MW06. The vegetable oil and sodium lactate costs were estimated with the assumption that the substrate would be injected using pneumatic fracturing into 4 points from 6 to 25 feet bgs, surrounding 93-MW06, and injected into 4 points at the same depth interval, surrounding 93-MW08 as illustrated in Figures 4-1 and 4-2. A single injection event for ZVI, potassium permanganate, vegetable oil, and sodium lactate was assumed; follow-up injections may be required but were not accounted for in the cost estimate of this pilot study. The time frame for the field demonstration was assumed to be one year.

TABLE 4-1
Cost Comparison

Technology	Delivery Method	Capital Cost	Other Costs[1]	Total Cost
Hydrogen Sparging	Vertical Wells	$271,000	$111,000	$382,000
Zero Valent Iron	Pneumatic Fracturing	$170,000	$57,000	$227,000
Potassium Permanganate	Pneumatic Fracturing	$183,000	$57,000	$240,000
Vegetable Oil	Pneumatic Fracturing and Vertical Borings	$167,000	$57,000	$224,000
Sodium Lactate	Pneumatic Fracturing and Vertical Borings	$209,000	$57,000	$266,000

[1] Other costs include sampling, routine system operations and maintenance, consumables, and reporting.

The monitoring program would require the installation of six new monitoring wells. The new and existing wells would be sampled prior to treatment and then quarterly after treatment. Samples would be analyzed for VOCs, chlorides, and natural attenuation parameters.

Figures

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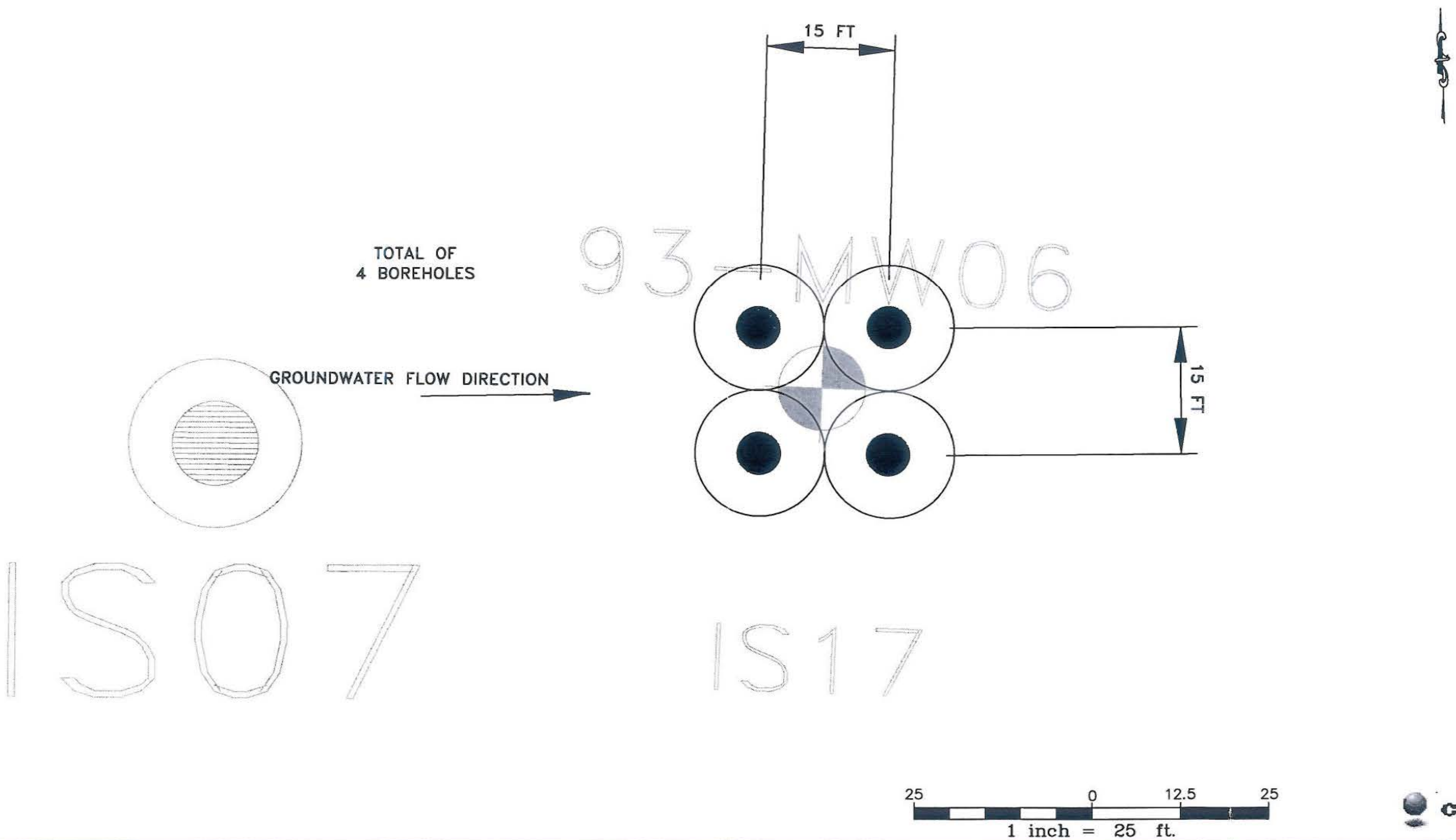


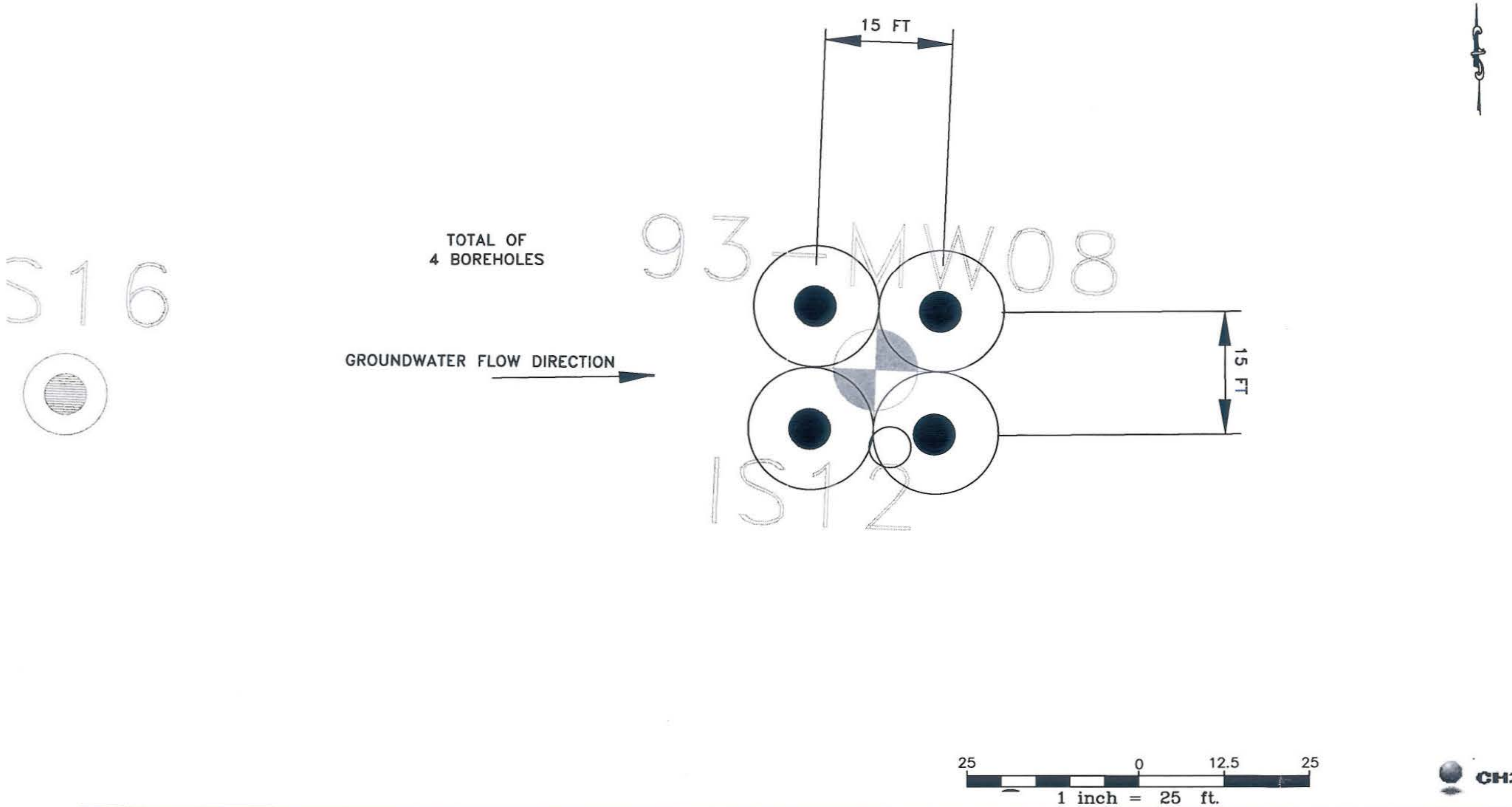
CH2MHILL

LEGEND

- EXPECTED RADIUS OF INFLUENCE AT DEPTHS BELOW 15 FT
- BOREHOLE LOCATION ADDRESSING DEPTHS FROM 6 TO 25 FT bgs

SOURCE: MCB, CAMP LEJEUNE MARCH 2000.

FIGURE 4–1
CONCEPTUAL LAYOUT OF INJECTION POINTS SURROUNDING 93–MW06
SITE 93 TECHNOLOGY EVALUATION REPORT
CTO – 0253
MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA



CH2MHILL

LEGEND

EXPECTED RADIUS OF INFLUENCE AT DEPTHS BELOW 15 FT

BOREHOLE LOCATION ADDRESSING DEPTHS FROM 6 TO 25 FT bgs

SOURCE: MCB, CAMP LEJEUNE MARCH 2000.

FIGURE 4–2
CONCEPTUAL LAYOUT OF INJECTION POINTS SURROUNDING 93–MW08
SITE 93 TECHNOLOGY EVALUATION REPORT
CTO – 0253
MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA

5.0 Predictive Modeling

5.1 Purpose and Objectives

BIOCHLOR (Aziz, 2001) is a screening tool that simulates remediation by natural attenuation at sites contaminated with chlorinated solvents. The model attempts to predict the maximum extent of dissolved-phase plume migration over time based on a known source area and actual or assumed site conditions. The maximum extent of plume migration is estimated both as solute transport without decay and as solute transport with biotransformation modeled as a sequential first-order decay process (reductive dechlorination). The model can then be used to compare the estimated plume migration to the location of potential receptors to determine if natural attenuation will remediate groundwater prior to impact, or to estimate the distance to a point of compliance. BIOCHLOR was used to estimate the reductive dechlorination of PCE and its daughter products over time given different source configurations. The model assumes a one-dimensional flow regime with three-dimensional dispersion.

The BIOCHLOR model does not account for specific types of remediation, so assumptions as to the results of particular remedial efforts are used as inputs. This type of evaluation is helpful in determining the level to remediate groundwater in the most contaminated areas of the site (hot spots) while leaving the remainder to naturally attenuate. The hot spot at Site 93 contain PCE, TCE, and DCE at 95 µg/L, 180 µg/L, and 800 µg/L, respectively. Assuming the hot spot is remediated to practicable concentrations, natural attenuation processes may be able to remediate the remaining dissolved concentrations to NC groundwater standards within a reasonable timeframe and within an acceptable distance from the source area.

BIOCHLOR is not a fate and transport model, but a screening tool used to determine if remediation by natural attenuation is feasible at a site. Due to the assumptive nature of the modeling scenarios, the success of any single or combination of remedial approaches described in the following sections cannot be implied nor guaranteed. The results should be viewed qualitatively and any conclusions drawn carefully.

5.2 Methodology

The objective of this modeling effort is to estimate a period of time required for the plume to reach steady state, and to estimate the maximum extent of dissolved-phase plume migration under steady state conditions. This information will allow the user to estimate the location of a point of compliance (distance required to reach the 2L Standards) under different combinations of active and passive remediation scenarios. A conservative approach was taken by assuming a constant source concentration for each remedial scenario and using maximum concentrations as inputs, i.e. the PCE, TCE, and DCE concentrations in 93-MW06. Several input parameters were assumed to be the same as those presented earlier in this report. However, the majority of the input parameters (including dispersion and adsorption parameters) were estimated using BIOCHLOR commonly used values. The basic input parameters for BIOCHLOR 2.2 that were used in this modeling effort are contained in Appendix B.

Four scenarios of remedial action were modeled.

1) No action

2) 50% reduction in the source zone from treatment

3) 75% reduction in the source zone from treatment

4) 90% reduction in the source zone from treatment

5.3 Assumptions

The following input parameters were assumed using BIOCHLOR commonly used values while modeling Site 93: Seepage velocity, adsorption components, and source zone options. Seepage velocity was calculated by BIOCHLOR, resulting in a seepage velocity of 268 ft/yr. Previous Site 93 reports estimated groundwater seepage velocity to be approximately 60 ft/yr. To conservatively model plume migration, 268 ft/yr was used. All components in the adsorption input section, including soil bulk density, fraction of organic carbon, and constituent partition coefficients, were assumed using either BIOCHLOR commonly used values or literature values. Although a continuous source is not expected to exist at Site 93, the continuous source option was selected as an input parameter due to the lack of analytical data showing source-zone reductions over time. Using the continuous source option will result in a more conservative estimation of plume migration.

5.4 Calibration

The model was calibrated to actual field data to determine biotransformation rates (first order decay coefficients) for PCE, TCE, DCE, and VC. Data from test well 93-TW-01 (collected in 1996) was used for inputs as source zone concentration data. Field data collected in January 2002 was input into the Field Data for Comparison input section. The January 2002 field data consisted of data from monitoring points IS-07, IS-17, IS-12, IS-32, IS-29, and IS-42, which are located 50, 105, 230, 325, 425, and 560 feet from the calibration source well, respectively. The model was then run in the Centerline mode using a simulation time of 5 years (1996 to January 2002) to determine first order decay coefficients using trial and error. The model was calibrated using a modeled area length of 600 feet, the distance from the calibration source area (TW-01) to the creek. Once the model was calibrated and decay coefficients were established, the source zone concentrations were modified to reflect current source zone concentrations and the model was run under four scenarios including no action, 50%, 75%, and 90% reduction in source zone concentrations.

5.5 Results

Following calibration, BIOCHLOR was run under four scenarios using a modeled area length of 450 feet, the distance from the 93-MW06 source area to the creek. Scenario 1, no remedial action in the source zone, estimates that the plume will reach steady state conditions after approximately 14 years and PCE concentrations above the 2L standards will extend approximately 1,400 feet northeast of the source area. This model implies that a no action alternative would result in chlorinated solvent impact to the creek. Scenario 4, 90% reduction of the source zone concentrations, estimates that the plume will reach steady state conditions after approximately 7 years and concentrations of all chlorinated solvents other than PCE will be below the 2L Standards within 450 feet of the source zone. The results of the modeled scenarios are summarized in Table 5-1. The input and output associated with the scenarios is presented in Appendix B.

TABLE 5-1

BIOCHLOR Modeling Results

Scenario	Source Reduction (treatment efficiency)	Time to Steady State (years)	Distance to 2L Standards			
			PCE	TCE	DCE	VC
1	No treatment	14	1,400	650	450	625
2	50%	13	1,175	500	350	500
3	75%	10	950	350	225	400
4	90%	7	650	225	100	250

Distance from source area to creek is approximately 450 ft

6.0 Conclusions and Recommendations

6.1 Conclusions

Five potential options for a pilot study at Site 93 were developed based on the evaluation of technologies: hydrogen gas sparging using vertical well/boring (injection) points, permanganate injection with pneumatic fracturing, zero valent iron injection with pneumatic fracturing, vegetable oil injection with pneumatic fracturing, and sodium lactate injection with pneumatic fracturing. The five technologies were compared based on effectiveness, implementability, and cost of installation and one year of operation.

Effectiveness

Components of a technology's effectiveness include:

1) Health and safety issues.
2) Ability to treat contaminants by reducing toxicity, mobility, or volume.
3) Longevity of the chemical(s) in the subsurface, and possible need for re-injection(s).

Based on these issues, vegetable oil and ZVI are the most effective of the five options. Vegetable oil is a proven electron donor to promote dechlorination of TCE, can be injected with pneumatic fracturing, is a slow releaser of carbon, and has minimal health and safety issues. ZVI is a proven reductant for chlorinated VOCs, can be injected with pneumatic fracturing, is persistent in the environment, and has minimal health and safety issues (except for working with dusts). Sodium lactate is a feasible option, but due to its solubility and dispersivity, multiple injections may be required. Hydrogen and permanganate should work well, however, longevity and health and safety issues are more of an issue with these technologies when compared to vegetable oil (i.e., they will require continual or multiple injections, additional hazards with chemical use, etc.). Hydrogen sparging is also hindered by potential health and safety concerns (in terms of potential gas accumulation within buildings) and/or production of by-products, such as hydrogen sulfide gas. Hydrogen sparging is the least tested approach.

Implementability

The main aspects of implementability are the ability to construct, operate, and maintain and the availability of supplies and vendors, if needed. Of the five technologies, hydrogen sparging is considered the most difficult to implement and maintain due to the complex system of vertical wells and conveyance piping. Vegetable oil or sodium lactate injection through wells are the easiest options to implement. ZVI, permanganate, vegetable oil and sodium lactate using fracture induced delivery, are considered evenly matched in terms of implementability and are not much more difficult than vegetable oil injection through wells. However, a large volume of permanganate is typically required and multiple injections may be necessary. Multiple injections may also be required using sodium lactate. Vendors and supplies are available for each technology.

Cost

While vegetable oil and sodium lactate use the same delivery methods (pneumatic fracturing and injection wells), there is a marked difference in estimates due to the cost of the substrate. The cost for the vegetable oil injection is comparable to ZVI. ZVI and permanganate, using pneumatic fracturing, are similarly priced since the same delivery method would be employed with the only difference being the cost of the substrate material. Hydrogen sparging is the most expensive of the five options, due to equipment requirements and installation expenditures. Details of the cost estimates are provided in Appendix A.

6.2 Recommendations

Based on the comparison of technologies, enhanced bioremediation is recommended for pilot scale implementation. Enhanced bioremediation is recommended because natural attenuation appears to be stalling at DCE and treatment costs are lower. Due to the slow release of carbon by vegetable oil, vegetable oil injection is recommended over sodium lactate injection.

The recommended approach for implementing vegetable oil at Site 93 is to treat two different target areas. The two target areas are located around 93-MW06 and 93-MW08. Vegetable oil would be injected using pneumatic fracturing at four points, installed in a series, around 93-MW06. As shown in Figure 4-1, horizontal spacing between injections would be approximately 15 feet. Vegetable oil would also be injected through injection wells at four points, installed in a series, around 93-MW08. As shown in Figure 4-2, the location and spacing of the injection points relative to the target area is the same as for 93-MW06. Addressing two different target areas, using the same spacing between injections and distance from the target monitoring well, allows a comparison to be made about the effectiveness of the two different methods of injection for delivering vegetable oil. Because maintenance requirements are essentially non-existent for both types of injection (aside from routine monitoring), the evaluation period may be continued for more than one year. The evaluation will help to establish the long term effectiveness of each method of injection. If results of the pilot study are favorable, vegetable oil can be applied to other areas of the Site 93 plume using the favored method of injection.

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COST ESTIMATE FOR HYDROGEN SPARGING USING VERTICAL SPARGE POINTS

SITE 93, Camp Lejeune

CH2M HILL Project No. 174057.TS.ED.93

CAPITAL COSTS

Description	Qty Unit	Unit Cost	Cost	Comments
Mobilization/Demobilization- Subcontractor				
Equipment Prep, Mobilization, Demobilization	1 LS	$15,000.00	$15,000.00	Based on verbal estimate by Starr Environmental
Conceptual Design Report	1 LS	$15,000.00	$15,000.00	Based on verbal estimate by Starr Environmental
Submittals, Work Plan, HASP	1 LS	$10,000.00	$10,000.00	Based on verbal estimate by Starr Environmental
Subtotal Mobilization/Demobilization			$40,000.00	
Construction - Subcontractor				
Monitoring Well Installation Subcontractor	6 wells	$1,500.00	$9,000.00	
Installation of eight vertical sparge points	8 wells	$1,500.00	$12,000.00	
Misc. Field Piping/Manifolding	1 LS	$15,000.00	$15,000.00	
Protective Enclosure	1 LS	$18,000.00	$18,000.00	
Hydrogen Biosparging Equipment and Installation	1 LS	$123,000.00	$123,000.00	Based on lump sum estimate by Groundwater Science, Inc.
Subtotal *Construction*			$177,000.00	
Construction - CH2M Hill				
Project Management				
Project Manager	50 hours	$71.04	$3,552.00	
Work Plans, Permits, Initial Reports				
Senior Engineer	25 hours	$87.61	$2,190.25	
Project Manager	80 hours	$71.04	$5,683.20	
Associate Engineer	140 hours	$57.69	$8,076.60	
Vertical Sparge Point Installation				
Project Manager	4 hours	$71.04	$284.16	
Associate Engineer	24 hours	$57.69	$1,384.56	
Field Geologist	60 hours	$43.58	$2,614.80	
Monitoring Well Installation				
Project Manager	4 hours	$71.04	$284.16	
Associate Engineer	0 hours	$57.69	$0.00	
Field Geologist	50 hours	$43.58	$2,179.00	
Hydrogen Sparge Equipment Installation & Start-Up				
Project Manager	4 hours	$71.04	$284.16	
Associate Engineer	40 hours	$57.69	$2,307.60	
Field Geologist	50 hours	$43.58	$2,179.00	
System De-Commissioning, Post-Sampling, and Final Report				
Senior Engineer	25 hours	$87.61	$2,190.25	
Project Manager	25 hours	$71.04	$1,776.00	
Associate Engineer	80 hours	$57.69	$4,615.20	
Field Geologist	120 hours	$43.58	$5,229.60	
Subtotal *Professional Services*			$44,830.54	
Equipment and Expenses				
Per Diem (Incl. Truck Rental)	16 days	$150.00	$2,400.00	
Monitoring Well Surveying	1 LS	$2,000.00	$2,000.00	
Investigation Derived Waste	1 LS	$150.00	$150.00	
Misc. Sampling Equipment and Supplies	1 LS	$5,000.00	$5,000.00	
Subtotal *Equipment and Expenses*			$9,550.00	
Subtotal *Construction - CH2M HILL*			$54,380.54	
TOTAL CAPITAL COST			**$271,380.54**	

YEAR 1 OPERATIONS AND MAINTENANCE

Item/Activity	Qty Unit	Unit Cost	Cost	Comments
Groundwater Sampling (Baseline and 5 Events after Startup - Assume 12 Monitoring Wells)				
Sample Labor	6 event	$4,000.00	$24,000.00	
Sample Analysis - Subcontractor	6 event	$1,500.00	$9,000.00	12 samples/round incl. QA/QC
Sampling Supplies	6 event	$200.00	$1,200.00	
GW Sampling Equipment Rental	6 event	$1,000.00	$6,000.00	
Subtotal *Baseline Groundwater Sampling*			$40,200.00	
Reporting (Construction Completion Report and 5 Events Reports)				
Reporting Labor (event reports)	6 rpts	$2,000.00	$12,000.00	
Reporting Labor (construction completion report)	1 rpt	$5,000.00	$5,000.00	
Subtotal *Reporting*			$17,000.00	
Routine System O&M				
Project Management	12 mo	$900.00	$10,800.00	
Technician Labor	12 mo	$2,200.00	$26,400.00	
O&M Supplies	1 ls	$2,000.00	$2,000.00	
Subtotal *Routine System O&M*			$28,400.00	
Consumables				
Hydrogen (4 "welding gas" type vessels, ~1000 ft3, ultra high purity grade hydrogen per week)	52 wks	$240.00	$12,480.00	
Nitrogen (assume 500 gallon liquid N2 per month or 45,000 ft3 of gas phase N2)	12 mos	$840.00	$10,080.00	
Cylinder rental	12 mo	$100.00	$1,200.00	
Electrical usage	1 year	$2,000.00	$2,000.00	
Subtotal *Consumables*			$25,760.00	
TOTAL YEAR 1 OPERATIONS AND MAINTENANCE COST			**$111,360.00**	
TOTAL ESTIMATE OF COSTS			***$382,740.54***	

COST ESTIMATE for CHEMICAL REDUCTION USING VERTICAL BORINGS

SITE 93, Camp Lejeune

CH2M HILL Project No. 174057.TS.ED.93

CAPITAL COSTS					
Description	Qty	Unit	Unit Cost	Cost	Comments
Mob/Demob/Construction- Subcontractor					
Injection of chemical reductant (ZVI), into a total of 8 borings, from 6 to 25 feet bgs	1	LS	$110,000.00	$110,000.00	Based on written quote by ARS Technologies
includes:submittals (Work Plan, HASP), Field Prep and Analysis					
Field Implementation Labor, Decon, & Reporting					
Monitoring Well Installation Subcontractor	6	wells	$1,500.00	$9,000.00	
Subtotal *Mob/Demob/Construction*				$119,000.00	
Construction - CH2M Hill					
Project Management					
Project Manager	50	hours	$71.04	$3,552.00	
Work Plans, Permits, Initial Reports					
Senior Engineer	25	hours	$87.61	$2,190.25	
Project Manager	80	hours	$71.04	$5,683.20	
Associate Engineer	140	hours	$57.69	$8,076.60	
Monitoring Well Installation					
Project Manager	4	hours	$71.04	$284.16	
Associate Engineer	0	hours	$57.69	$0.00	
Field Geologist	50	hours	$43.58	$2,179.00	
Field Implementation					
Project Manager	4	hours	$71.04	$284.16	
Associate Engineer	20	hours	$57.69	$1,153.80	
Field Geologist	120	hours	$43.58	$5,229.60	
Post-Sampling and Final Report					
Senior Engineer	25	hours	$87.61	$2,190.25	
Project Manager	25	hours	$71.04	$1,776.00	
Associate Engineer	80	hours	$57.69	$4,615.20	
Field Geologist	120	hours	$43.58	$5,229.60	
Subtotal *Professional Services*				$42,443.82	
Equipment and Expenses					
Per Diem (Incl. Truck Rental)	10	days	$150.00	$1,500.00	
Monitoring Well Surveying	1	LS	$2,000.00	$2,000.00	
Investigation Derived Waste	1	LS	$150.00	$150.00	
Misc. Sampling Equipment and Supplies	1	LS	$5,000.00	$5,000.00	
Subtotal *Equipment and Expenses*				$8,650.00	
Subtotal *Construction - CH2M HILL*				$51,093.82	
TOTAL CAPITAL COST				**$170,093.82**	

YEAR 1 OPERATIONS AND MAINTENANCE					
Item/Activity	Qty	Unit	Unit Cost	Cost	Comments
Groundwater Sampling (Baseline and 5 Events after Startup - Assume 12 Monitoring Wells)					
Sample Labor	6	event	$4,000.00	$24,000.00	
Sample Analysis - Subcontractor	6	event	$1,500.00	$9,000.00	12 samples/round incl. QA/QC
Sampling Supplies	6	event	$200.00	$1,200.00	
GW Sampling Equipment Rental	6	event	$1,000.00	$6,000.00	
Subtotal *Baseline Groundwater Sampling*				$40,200.00	
Reporting (Construction Completion Report and 5 Events Reports)					
Reporting Labor (event reports)	6	rpts	$2,000.00	$12,000.00	
Reporting Labor (construction completion report)	1	rpt	$5,000.00	$5,000.00	
Subtotal *Reporting*				$17,000.00	
TOTAL YEAR 1 OPERATIONS AND MAINTENANCE COST				**$57,200.00**	

TOTAL ESTIMATE OF COSTS ***$227,293.82***

COST ESTIMATE for CHEMICAL OXIDATION USING VERTICAL BORINGS

SITE 93, Camp Lejeune

CH2M HILL Project No. 174057.TS.ED.93

CAPITAL COSTS

Description	Qty	Unit	Unit Cost	Cost	Comments
Mob/Demob/Construction- Subcontractor					
Injection of chemical oxidant (permanganate),	1	LS	$115,000.00	$115,000.00	Based on written quote by ARS Technologies
total of 8 borings, from 6 to 25 feet bgs					
includes:submittals (Work Plan, HASP), Field Prep and Analysis					
Field Implementation Labor, Decon, & Reporting					
TOD Laboratory Treatability Study	1	LS	$5,000.00	$5,000.00	Based on written quote by ARS Technologies
Monitoring Well Installation Subcontractor	6	wells	$1,500.00	$9,000.00	
Subtotal *Mob/Demob/Construction*				$129,000.00	
Construction - CH2M Hill					
Project Management					
Project Manager	50	hours	$71.04	$3,552.00	
Work Plans, Permits, Initial Reports					
Senior Engineer	25	hours	$87.61	$2,190.25	
Project Manager	80	hours	$71.04	$5,683.20	
Associate Engineer	140	hours	$57.69	$8,076.60	
Monitoring Well Installation					
Project Manager	4	hours	$71.04	$284.16	
Associate Engineer	0	hours	$57.69	$0.00	
Field Geologist	50	hours	$43.58	$2,179.00	
Field Implementation					
Project Manager	4	hours	$71.04	$284.16	
Associate Engineer	24	hours	$57.69	$1,384.56	
Field Geologist	140	hours	$43.58	$6,101.20	
Post-Sampling and Final Report					
Senior Engineer	25	hours	$87.61	$2,190.25	
Project Manager	50	hours	$71.04	$3,552.00	
Associate Engineer	80	hours	$57.69	$4,615.20	
Field Geologist	120	hours	$43.58	$5,229.60	
Subtotal *Professional Services*				$45,322.18	
Equipment and Expenses					
Per Diem (Incl. Truck Rental)	10	days	$150.00	$1,500.00	
Monitoring Well Surveying	1	LS	$2,000.00	$2,000.00	
Investigation Derived Waste	1	LS	$150.00	$150.00	
Misc. Sampling Equipment and Supplies	1	LS	$5,000.00	$5,000.00	
Subtotal *Equipment and Expenses*				$8,650.00	
Subtotal *Construction - CH2M HILL*				$53,972.18	
TOTAL CAPITAL COST				**$182,972.18**	

YEAR 1 OPERATIONS AND MAINTENANCE

Item/Activity	Qty	Unit	Unit Cost	Cost	Comments
Groundwater Sampling (Baseline and 5 Events after Startup - Assume 12 Monitoring Wells)					
Sample Labor	6	event	$4,000.00	$24,000.00	
Sample Analysis - Subcontractor	6	event	$1,500.00	$9,000.00	12 samples/round incl. QA/QC
Sampling Supplies	6	event	$200.00	$1,200.00	
GW Sampling Equipment Rental	6	event	$1,000.00	$6,000.00	
Subtotal *Baseline Groundwater Sampling*				$40,200.00	
Reporting (Construction Completion Report and 5 Events Reports)					
Reporting Labor (event reports)	6	rpts	$2,000.00	$12,000.00	
Reporting Labor (construction completion report)	1	rpt	$5,000.00	$5,000.00	
Subtotal *Reporting*				$17,000.00	
TOTAL YEAR 1 OPERATIONS AND MAINTENANCE COST				**$57,200.00**	

TOTAL ESTIMATE OF COSTS		***$240,172.18***

COST ESTIMATE for VEGETABLE OIL USING VERTICAL BORINGS

SITE 93, Camp Lejeune

CH2M HILL Project No. 174057.TS.ED.93

CAPITAL COSTS

Description	Qty	Unit	Unit Cost	Cost	Comments
Mob/Demob/Construction- Subcontractor					
Pneumatic fracturing and injection of vegetable oil into 4 borings, from 6 to 25 feet bgs includes:submittals (Work Plan, HASP), Field Prep and Analysis Field Implementation Labor, Decon, & Reporting	1	LS	$60,000.00	$60,000.00	Based on written quote by ARS Technologies
Vegetable oil for injection into total of 8 borings	62300	lb	$0.38	$23,674.00	Based on Memphis Depot project costs
Misc injection equipment and supplies	1	LS	$25,000.00	$25,000.00	Based on Memphis Depot project costs
Geoprobe	2	days	$1,500.00	$3,000.00	
Monitoring Well Installation Subcontractor	6	wells	$1,500.00	$9,000.00	
Subtotal *Mob/Demob/Construction*				$120,674.00	
Construction - CH2M Hill					
Project Management					
Project Manager	50	hours	$71.04	$3,552.00	
Work Plans, Conceptual Design, Permits, Initial Reports					
Senior Engineer	32	hours	$87.61	$2,803.52	
Project Manager	80	hours	$71.04	$5,683.20	
Associate Engineer	160	hours	$57.69	$9,230.40	
Monitoring Well Installation					
Project Manager	2	hours	$71.04	$142.08	
Associate Engineer	0	hours	$57.69	$0.00	
Field Geologist	48	hours	$43.58	$2,091.84	
Field Implementation					
Project Manager	2	hours	$71.04	$142.08	
Associate Engineer	24	hours	$57.69	$1,384.56	
Field Geologist	80	hours	$43.58	$3,486.40	
Post-Sampling and Final Report					
Senior Engineer	12	hours	$87.61	$1,051.32	
Project Manager	12	hours	$71.04	$852.48	
Associate Engineer	60	hours	$57.69	$3,461.40	
Field Geologist	80	hours	$43.58	$3,486.40	
Subtotal *Professional Services*				$37,367.68	
Equipment and Expenses					
Per Diem (Incl. Truck Rental)	10	days	$150.00	$1,500.00	
Monitoring Well Surveying	1	LS	$2,000.00	$2,000.00	
Investigation Derived Waste	1	LS	$150.00	$150.00	
Misc. Sampling Equipment and Supplies	1	LS	$5,000.00	$5,000.00	
Subtotal *Equipment and Expenses*				$8,650.00	
Subtotal *Construction - CH2M HILL*				$46,017.68	
TOTAL CAPITAL COST				**$166,691.68**	

YEAR 1 OPERATIONS AND MAINTENANCE

Item/Activity	Qty	Unit	Unit Cost	Cost	Comments
Groundwater Sampling (Baseline and 5 Events after Startup - Assume 12 Monitoring Wells)					
Sample Labor	6	event	$4,000.00	$24,000.00	
Sample Analysis - Subcontractor	6	event	$1,500.00	$9,000.00	12 samples/round incl. QA/QC
Sampling Supplies	6	event	$200.00	$1,200.00	
GW Sampling Equipment Rental	6	event	$1,000.00	$6,000.00	
Subtotal *Baseline Groundwater Sampling*				$40,200.00	
Reporting (Construction Completion Report and 5 Events Reports)					
Reporting Labor (event reports)	6	rpts	$2,000.00	$12,000.00	
Reporting Labor (construction completion report)	1	rpt	$5,000.00	$5,000.00	
Subtotal *Reporting*				$17,000.00	
TOTAL YEAR 1 OPERATIONS AND MAINTENANCE COST				**$57,200.00**	

TOTAL ESTIMATE OF COSTS ***$223,891.68***

COST ESTIMATE for SODIUM LACTATE USING VERTICAL BORINGS

SITE 93, Camp Lejeune

CH2M HILL Project No. 174057.TS.ED.93

CAPITAL COSTS

Description	Qty Unit	Unit Cost	Cost	Comments
Construction - Subcontractor				
Monitoring Well Installation Subcontractor	6 wells	$1,500.00	$9,000.00	
Pneumatic Fracturing at 4 points	4 points	$10,000.00	$40,000.00	Based on email quote by ARS Technologies
Sodium lactate for injection into a total of 8 borings, from 6 to 25 feet bgs	110646 lb	$0.78	$86,303.88	Based on Memphis Depot project costs
Misc injection equipment and supplies	1 LS	$25,000.00	$25,000.00	Based on Memphis Depot project costs
Geoprobe	2 days	$1,500.00	$3,000.00	
Subtotal *Construction*			$163,303.88	
Construction - CH2M Hill				
Project Management				
Project Manager	50 hours	$71.04	$3,552.00	
Work Plans, Conceptual Design, Permits, Initial Reports				
Senior Engineer	32 hours	$87.61	$2,803.52	
Project Manager	80 hours	$71.04	$5,683.20	
Associate Engineer	160 hours	$57.69	$9,230.40	
Monitoring Well Installation				
Project Manager	2 hours	$71.04	$142.08	
Associate Engineer	0 hours	$57.69	$0.00	
Field Geologist	48 hours	$43.58	$2,091.84	
Field Implementation				
Project Manager	8 hours	$71.04	$568.32	
Associate Engineer	36 hours	$57.69	$2,076.84	
Field Geologist	50 hours	$43.58	$2,179.00	
Post-Sampling and Final Report				
Senior Engineer	12 hours	$87.61	$1,051.32	
Project Manager	12 hours	$71.04	$852.48	
Associate Engineer	60 hours	$57.69	$3,461.40	
Field Geologist	80 hours	$43.58	$3,486.40	
Subtotal *Professional Services*			$37,178.80	
Equipment and Expenses				
Per Diem (Incl. Truck Rental)	10 days	$150.00	$1,500.00	
Monitoring Well Surveying	1 LS	$2,000.00	$2,000.00	
Investigation Derived Waste	1 LS	$150.00	$150.00	
Misc. Sampling Equipment and Supplies	1 LS	$5,000.00	$5,000.00	
Subtotal *Equipment and Expenses*			$8,650.00	
Subtotal *Construction - CH2M HILL*			$45,828.80	
TOTAL CAPITAL COST			**$209,132.68**	

YEAR 1 OPERATIONS AND MAINTENANCE

Item/Activity	Qty Unit	Unit Cost	Cost	Comments
Groundwater Sampling (Baseline and 5 Events after Startup - Assume 12 Monitoring Wells)				
Sample Labor	6 event	$4,000.00	$24,000.00	
Sample Analysis - Subcontractor	6 event	$1,500.00	$9,000.00	12 samples/round incl. QA/QC
Sampling Supplies	6 event	$200.00	$1,200.00	
GW Sampling Equipment Rental	6 event	$1,000.00	$6,000.00	
Subtotal *Baseline Groundwater Sampling*			$40,200.00	
Reporting (Construction Completion Report and 5 Events Reports)				
Reporting Labor (event reports)	6 rpts	$2,000.00	$12,000.00	
Reporting Labor (construction completion report)	1 rpt	$5,000.00	$5,000.00	
Subtotal *Reporting*			$17,000.00	
TOTAL YEAR 1 OPERATIONS AND MAINTENANCE COST			**$57,200.00**	

TOTAL ESTIMATE OF COSTS ***$266,332.68***

BIOCHLOR Natural Attenuation Decision Support System

Version 2.2

Excel '97

Run Name
Camp Lejeune
Site 93 CAL

Data Input Instructions:

115 → 1. Enter value directly....or

or 2. Calculate by filling in gray 0.02 cells. Press Enter, then (C)

(To restore formulas, hit "Restore Formulas" button)

Variable* → Data used directly in model.

Test if Biotransformation is Occurring → Natural Attenuation Screening Protocol

TYPE OF CHLORINATED SOLVENT: Ethenes ● Ethanes ○

1. ADVECTION

Seepage Velocity*	Vs	268.0	(ft/yr)
or			
Hydraulic Conductivity	K	1.3E-02	(cm/sec)
Hydraulic Gradient	i	0.004	(ft/ft)
Effective Porosity	n	0.2	(-)

2. DISPERSION

Alpha x*	13.971	(ft)
(Alpha y) / (Alpha x)*	0.33	(-)
(Alpha z) / (Alpha x)*	5.E-02	(-)

Calc. Alpha x

3. ADSORPTION

Retardation Factor* → R

or

Soil Bulk Density, rho	1.7	(kg/L)
FractionOrganicCarbon, foc	1.0E-3	(-)

Partition Coefficient

	Koc		R	
PCE	426	(L/kg)	4.62	(-)
TCE	130	(L/kg)	2.11	(-)
DCE	125	(L/kg)	2.06	(-)
VC	30	(L/kg)	1.25	(-)
ETH	302	(L/kg)	3.57	(-)
Common R (used in model)* =			2.11	

4. BIOTRANSFORMATION -1st Order Decay Coefficient*

Zone 1	λ (1/yr)	half-life (yrs)	Yield
PCE → TCE	0.635		0.79
TCE → DCE	3.875		0.74
DCE → VC	1.740		0.64
VC → ETH	19.500		0.45

Zone 2	λ (1/yr)	half-life (yrs)
PCE → TCE	0.000	
TCE → DCE	0.000	
DCE → VC	0.000	
VC → ETH	0.000	

λ HELP

5. GENERAL

Simulation Time*	5	(yr)
Modeled Area Width*	300	(ft)
Modeled Area Length*	600	(ft)
Zone 1 Length*	600	(ft)
Zone 2 Length*	0	(ft)

L W

Zone 2= L - Zone 1

6. SOURCE DATA TYPE: Continuous Single Planar

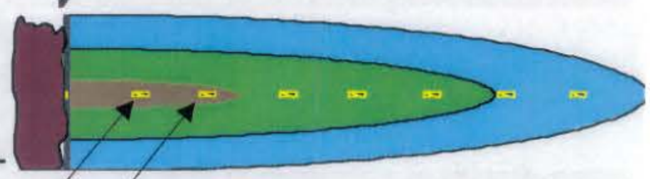
Source Options

Source Thickness in Sat. Zone* 20 (ft)

	Y1
Width* (ft)	250

Conc. (mg/L)*	C1	k_s* (1/yr)
PCE	.016	0
TCE	.394	0
DCE	.232	0
VC		0
ETH		0

Vertical Plane Source: Determine Source Well Location and Input Solvent Concentrations



View of Plume Looking Down

Observed Centerline Conc. at Monitoring Wells

7. FIELD DATA FOR COMPARISON

PCE Conc. (mg/L)	.015	.021	.02	.0	.0	.0						
TCE Conc. (mg/L)	.014	.041	.015	.0	.002	.0						
DCE Conc. (mg/L)	.039	.18	.09	.075	.031	.0						
VC Conc. (mg/L)	0.0	.001	.0	.001	.002	.0						
ETH Conc. (mg/L)												
Distance from Source (ft)	50	105	230	325	425	560						
Date Data Collected	2002											

8. CHOOSE TYPE OF OUTPUT TO SEE:

RUN CENTERLINE | RUN ARRAY | Help | Restore Formulas | RESET | SEE OUTPUT | Paste Example

BIOCHLOR Natural Attenuation Decision Support System

Version 2.2
Excel '97

Run Name
Camp Lejeune
Site 93 Scn 1

Data Input Instructions:

115 → 1. Enter value directly....or
↑ or ↗ 2. Calculate by filling in gray
0.02 cells. Press Enter, then (C)
(To restore formulas, hit "Restore Formulas" button)
Variable* → Data used directly in model.

Test if Biotransformation is Occurring → Natural Attenuation Screening Protocol

TYPE OF CHLORINATED SOLVENT: Ethenes ◉ Ethanes ○

1. ADVECTION

Seepage Velocity*	Vs	268.0	(ft/yr)
or			
Hydraulic Conductivity	K	1.3E-02	(cm/sec)
Hydraulic Gradient	i	0.004	(ft/ft)
Effective Porosity	n	0.2	(-)

2. DISPERSION

Alpha x*	13.971	(ft)
(Alpha y) / (Alpha x)*	0.33	(-)
(Alpha z) / (Alpha x)*	5.E-02	(-)

Calc. Alpha x

3. ADSORPTION

Retardation Factor* → R

or

Soil Bulk Density, rho	1.7	(kg/L)
FractionOrganicCarbon, foc	1.0E-3	(-)

Partition Coefficient	Koc		R	
PCE	426	(L/kg)	4.62	(-)
TCE	130	(L/kg)	2.11	(-)
DCE	125	(L/kg)	2.06	(-)
VC	30	(L/kg)	1.25	(-)
ETH	302	(L/kg)	3.57	(-)

Common R (used in model)* = 2.11

4. BIOTRANSFORMATION -1st Order Decay Coefficient*

Zone 1	λ (1/yr)	half-life (yrs)	Yield
PCE → TCE	0.635		0.79
TCE → DCE	3.875		0.74
DCE → VC	1.740		0.64
VC → ETH	19.500		0.45

Zone 2	λ (1/yr)	half-life (yrs)
PCE → TCE	0.000	
TCE → DCE	0.000	
DCE → VC	0.000	
VC → ETH	0.000	

λ HELP

5. GENERAL

Simulation Time*	1000	(yr)
Modeled Area Width*	300	(ft)
Modeled Area Length*	1500	(ft)
Zone 1 Length*	1500	(ft)
Zone 2 Length*	0	(ft)

L, W

Zone 2= L - Zone 1

6. SOURCE DATA TYPE: Continuous Single Planar

Source Options

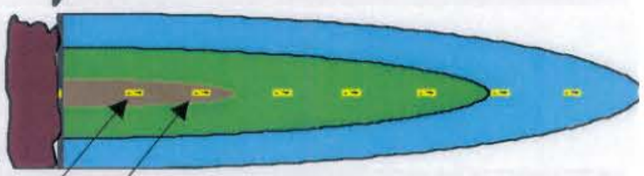
Vertical Plane Source: Determine Source Well Location and Input Solvent Concentrations

Source Thickness in Sat. Zone* 20 (ft)

Y1

Width* (ft) 250

Conc. (mg/L)*	C1	k_s* (1/yr)
PCE	.095	0
TCE	.18	0
DCE	.8	0
VC	.01	0
ETH		0



View of Plume Looking Down

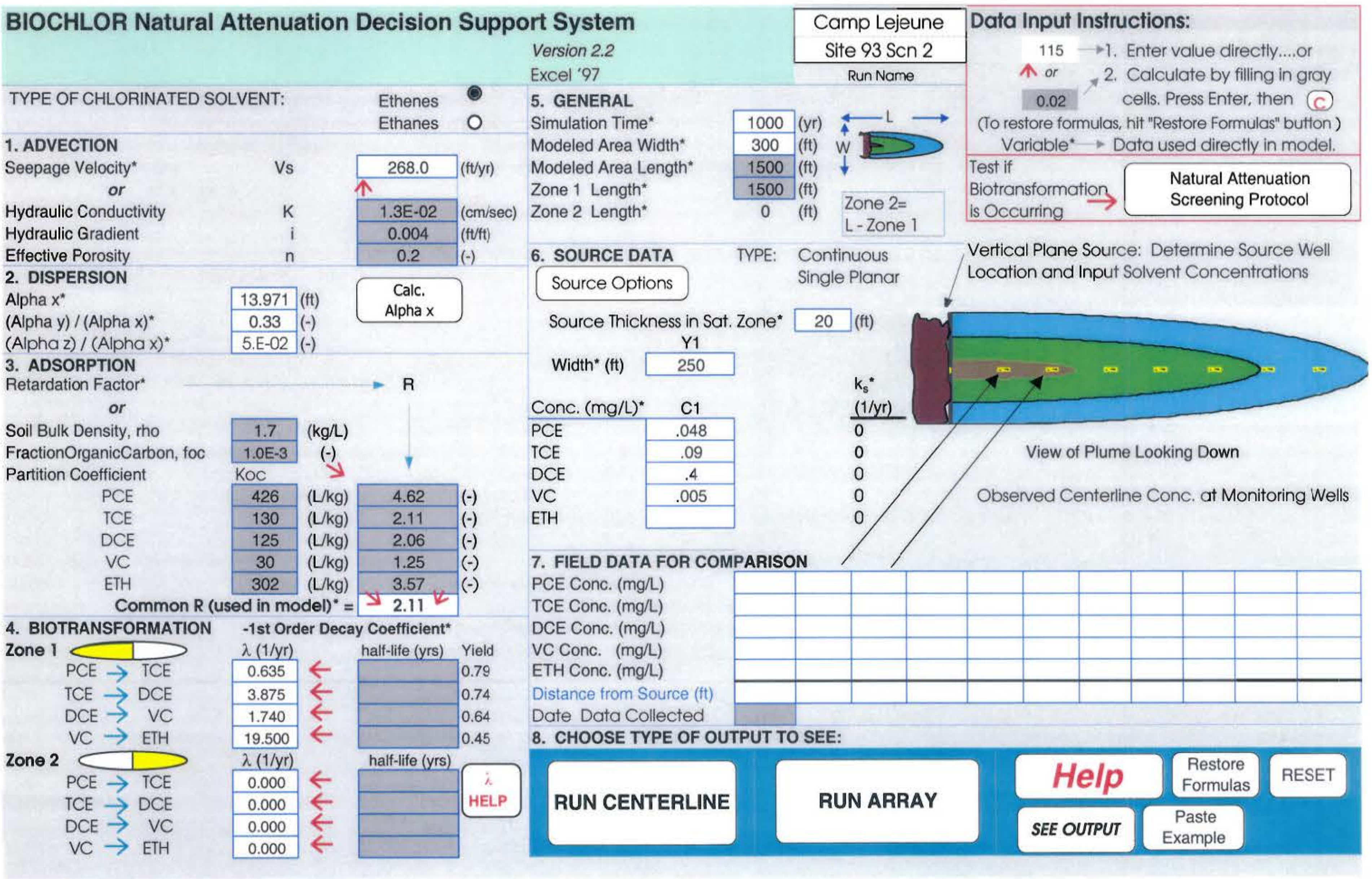
Observed Centerline Conc. at Monitoring Wells

7. FIELD DATA FOR COMPARISON

PCE Conc. (mg/L)											
TCE Conc. (mg/L)											
DCE Conc. (mg/L)											
VC Conc. (mg/L)											
ETH Conc. (mg/L)											
Distance from Source (ft)											
Date Data Collected											

8. CHOOSE TYPE OF OUTPUT TO SEE:

RUN CENTERLINE | RUN ARRAY | Help | Restore Formulas | RESET | SEE OUTPUT | Paste Example


BIOCHLOR Natural Attenuation Decision Support System
Version 2.2
Excel '97
Camp Lejeune
Site 93 Scn 2
Run Name
Data Input Instructions:
115 1. Enter value directly....or
or 2. Calculate by filling in gray
0.02 cells. Press Enter, then C
(To restore formulas, hit "Restore Formulas" button)
Variable* Data used directly in model.
Test if Biotransformation is Occurring
Natural Attenuation Screening Protocol
TYPE OF CHLORINATED SOLVENT: Ethenes Ethanes
1. ADVECTION
Seepage Velocity* Vs 268.0 (ft/yr)
or
Hydraulic Conductivity K 1.3E-02 (cm/sec)
Hydraulic Gradient i 0.004 (ft/ft)
Effective Porosity n 0.2 (-)
2. DISPERSION
Alpha x* 13.971 (ft)
(Alpha y) / (Alpha x)* 0.33 (-)
(Alpha z) / (Alpha x)* 5.E-02 (-)
Calc. Alpha x
3. ADSORPTION
Retardation Factor* R
or
Soil Bulk Density, rho 1.7 (kg/L)
FractionOrganicCarbon, foc 1.0E-3 (-)
Partition Coefficient Koc
PCE 426 (L/kg) 4.62 (-)
TCE 130 (L/kg) 2.11 (-)
DCE 125 (L/kg) 2.06 (-)
VC 30 (L/kg) 1.25 (-)
ETH 302 (L/kg) 3.57 (-)
Common R (used in model)* = 2.11
4. BIOTRANSFORMATION -1st Order Decay Coefficient*
Zone 1 λ (1/yr) half-life (yrs) Yield
PCE → TCE 0.635 0.79
TCE → DCE 3.875 0.74
DCE → VC 1.740 0.64
VC → ETH 19.500 0.45
Zone 2 λ (1/yr) half-life (yrs)
PCE → TCE 0.000
TCE → DCE 0.000
DCE → VC 0.000
VC → ETH 0.000
λ HELP
5. GENERAL
Simulation Time* 1000 (yr)
Modeled Area Width* 300 (ft)
Modeled Area Length* 1500 (ft)
Zone 1 Length* 1500 (ft)
Zone 2 Length* 0 (ft)
Zone 2= L - Zone 1
L
W
6. SOURCE DATA TYPE: Continuous Single Planar
Source Options
Source Thickness in Sat. Zone* 20 (ft)
Y1
Width* (ft) 250
Conc. (mg/L)* C1
PCE .048
TCE .09
DCE .4
VC .005
ETH
ks* (1/yr)
0
0
0
0
0
Vertical Plane Source: Determine Source Well Location and Input Solvent Concentrations
View of Plume Looking Down
Observed Centerline Conc. at Monitoring Wells
7. FIELD DATA FOR COMPARISON
PCE Conc. (mg/L)
TCE Conc. (mg/L)
DCE Conc. (mg/L)
VC Conc. (mg/L)
ETH Conc. (mg/L)
Distance from Source (ft)
Date Data Collected
8. CHOOSE TYPE OF OUTPUT TO SEE:
RUN CENTERLINE
RUN ARRAY
Help
SEE OUTPUT
Restore Formulas
Paste Example
RESET

BIOCHLOR Natural Attenuation Decision Support System

Version 2.2
Excel '97

Camp Lejeune
Site 93 Scn 3
Run Name

Data Input Instructions:

115 → 1. Enter value directly....or
or 0.02 → 2. Calculate by filling in gray cells. Press Enter, then (C)
(To restore formulas, hit "Restore Formulas" button)
Variable* → Data used directly in model.

Test if Biotransformation is Occurring → Natural Attenuation Screening Protocol

TYPE OF CHLORINATED SOLVENT: Ethenes ● Ethanes ○

1. ADVECTION

Seepage Velocity*	Vs	268.0	(ft/yr)
or			
Hydraulic Conductivity	K	1.3E-02	(cm/sec)
Hydraulic Gradient	i	0.004	(ft/ft)
Effective Porosity	n	0.2	(-)

2. DISPERSION

Alpha x*	13.971	(ft)
(Alpha y) / (Alpha x)*	0.33	(-)
(Alpha z) / (Alpha x)*	5.E-02	(-)

Calc. Alpha x

3. ADSORPTION

Retardation Factor* → R

or

Soil Bulk Density, rho	1.7	(kg/L)		
FractionOrganicCarbon, foc	1.0E-3	(-)		
Partition Coefficient	Koc			
PCE	426	(L/kg)	4.62	(-)
TCE	130	(L/kg)	2.11	(-)
DCE	125	(L/kg)	2.06	(-)
VC	30	(L/kg)	1.25	(-)
ETH	302	(L/kg)	3.57	(-)

Common R (used in model)* = 2.11

4. BIOTRANSFORMATION

-1st Order Decay Coefficient*

Zone 1

	λ (1/yr)	half-life (yrs)	Yield
PCE → TCE	0.635		0.79
TCE → DCE	3.875		0.74
DCE → VC	1.740		0.64
VC → ETH	19.500		0.45

Zone 2

	λ (1/yr)	half-life (yrs)
PCE → TCE	0.000	
TCE → DCE	0.000	
DCE → VC	0.000	
VC → ETH	0.000	

λ HELP

5. GENERAL

Simulation Time*	1000	(yr)
Modeled Area Width*	300	(ft)
Modeled Area Length*	1500	(ft)
Zone 1 Length*	1500	(ft)
Zone 2 Length*	0	(ft)

Zone 2= L - Zone 1

6. SOURCE DATA

TYPE: Continuous Single Planar

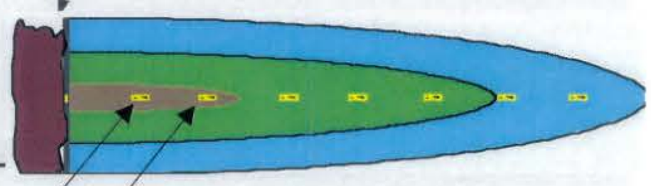
Source Options

Source Thickness in Sat. Zone* 20 (ft)

Width* (ft) Y1: 250

Conc. (mg/L)*	C1	k_s* (1/yr)
PCE	.024	0
TCE	.045	0
DCE	.2	0
VC	.003	0
ETH		0

Vertical Plane Source: Determine Source Well Location and Input Solvent Concentrations



View of Plume Looking Down

Observed Centerline Conc. at Monitoring Wells

7. FIELD DATA FOR COMPARISON

PCE Conc. (mg/L)											
TCE Conc. (mg/L)											
DCE Conc. (mg/L)											
VC Conc. (mg/L)											
ETH Conc. (mg/L)											
Distance from Source (ft)											
Date Data Collected											

8. CHOOSE TYPE OF OUTPUT TO SEE:

RUN CENTERLINE | RUN ARRAY | Help | Restore Formulas | RESET | SEE OUTPUT | Paste Example

BIOCHLOR Natural Attenuation Decision Support System

Version 2.2
Excel '97

Camp Lejeune
Site 93 Scn 4
Run Name

Data Input Instructions:

115 → 1. Enter value directly....or
or 2. Calculate by filling in gray cells. Press Enter, then (C)
0.02
(To restore formulas, hit "Restore Formulas" button)
Variable* → Data used directly in model.

Test if Biotransformation is Occurring → Natural Attenuation Screening Protocol

TYPE OF CHLORINATED SOLVENT: Ethenes ◉ Ethanes ○

1. ADVECTION

Seepage Velocity*	Vs	268.0	(ft/yr)
or			
Hydraulic Conductivity	K	1.3E-02	(cm/sec)
Hydraulic Gradient	i	0.004	(ft/ft)
Effective Porosity	n	0.2	(-)

2. DISPERSION

Alpha x*	13.971	(ft)
(Alpha y) / (Alpha x)*	0.33	(-)
(Alpha z) / (Alpha x)*	5.E-02	(-)

Calc. Alpha x

3. ADSORPTION

Retardation Factor* → R

or

Soil Bulk Density, rho	1.7	(kg/L)		
FractionOrganicCarbon, foc	1.0E-3	(-)		
Partition Coefficient	Koc			
PCE	426	(L/kg)	4.62	(-)
TCE	130	(L/kg)	2.11	(-)
DCE	125	(L/kg)	2.06	(-)
VC	30	(L/kg)	1.25	(-)
ETH	302	(L/kg)	3.57	(-)

Common R (used in model)* = 2.11

4. BIOTRANSFORMATION

-1st Order Decay Coefficient*

Zone 1

	λ (1/yr)	half-life (yrs)	Yield
PCE → TCE	0.635		0.79
TCE → DCE	3.875		0.74
DCE → VC	1.740		0.64
VC → ETH	19.500		0.45

Zone 2

	λ (1/yr)	half-life (yrs)
PCE → TCE	0.000	
TCE → DCE	0.000	
DCE → VC	0.000	
VC → ETH	0.000	

λ HELP

5. GENERAL

Simulation Time*	1000	(yr)
Modeled Area Width*	300	(ft)
Modeled Area Length*	1500	(ft)
Zone 1 Length*	1500	(ft)
Zone 2 Length*	0	(ft)

L W
Zone 2= L - Zone 1

6. SOURCE DATA

TYPE: Continuous Single Planar

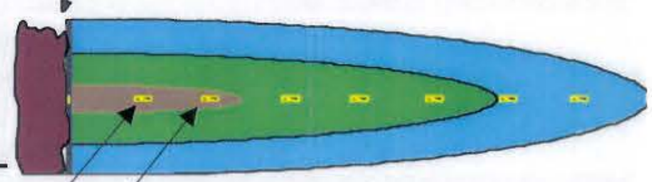
Source Options

Source Thickness in Sat. Zone* 20 (ft)

Y1
Width* (ft) 250

Conc. (mg/L)*	C1	k_s* (1/yr)
PCE	.01	0
TCE	.018	0
DCE	.08	0
VC	.001	0
ETH		0

Vertical Plane Source: Determine Source Well Location and Input Solvent Concentrations



View of Plume Looking Down

Observed Centerline Conc. at Monitoring Wells

7. FIELD DATA FOR COMPARISON

PCE Conc. (mg/L)											
TCE Conc. (mg/L)											
DCE Conc. (mg/L)											
VC Conc. (mg/L)											
ETH Conc. (mg/L)											
Distance from Source (ft)											
Date Data Collected											

8. CHOOSE TYPE OF OUTPUT TO SEE:

RUN CENTERLINE | RUN ARRAY | Help | Restore Formulas | RESET | SEE OUTPUT | Paste Example