Naval Facilities Engineering Command

ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

CONTRACT REPORT
CR-04-002-ENV

ASSESSING THE FEASIBILITY OF DNAPL SOURCE ZONE REMEDIATION: REVIEW OF CASE STUDIES

by

GEOSYNTEC CONSULTANTS
130 Research Lane, Suite 2
Guelph, Ontario, Canada N1G 5G3

May 2004

Prepared for:

NAVAL FACILITIES ENGINEERING SERVICES CENTER
NFESC ESC 411
1100 23rd Ave
Port Hueneme, CA 93043

ASSESSING THE FEASIBILITY OF DNAPL SOURCE ZONE REMEDIATION: REVIEW OF CASE STUDIES

Prepared by:

GEOSYNTEC CONSULTANTS
130 Research Lane, Suite 2
Guelph, Ontario, Canada N1G 5G3
GeoSyntec Project Number TR0132
April 2004

EXECUTIVE SUMMARY

The Naval Facilities Engineering Services Center (NFESC) hired GeoSyntec Consultants (GeoSyntec) to conduct a survey of the application of chlorinated solvent dense non-aqueous phase liquid (DNAPL) source remediation technologies. The overall goal of this project was to gather information on the relative successes of remediation applications under different site conditions in order to initiate the development of guidelines on DNAPL source treatment. Members of the environmental community that had attempted to remediate DNAPL source zone areas were invited to participate in a web-based survey, which remained open for several months. Survey respondents were asked a number of questions dealing with site-specific issues (*e.g.,* geology, hydrogeology, contaminant distribution, monitoring network) and technology specific issues (*e.g.,* type of remedial technology, remediation stage, cost, treatment effectiveness). The number of survey respondents totaled 213. Of the 213, complete sets of data were obtained for 118 locations. Data from 21 published case studies was also entered into the survey. This report also includes a brief overview of chlorinated solvent DNAPL contamination and remediation processes (Section 2).

The data compiled from the survey was analyzed to detect correlations between remedial application success and site conditions. The data is presented in detail in Section 4 of the report. The following observations and correlations were established upon data analysis:

- *Site Characteristics*: The majority of the sites had areal extents of 10,000 ft^2 to 100,000 ft^2 and the volume impacted was greater than 100,000 ft^3. A large number (89%) of the sites consisted of unconsolidated material and the minority (11%) had consolidated material. Within the unconsolidated material sites, 39% of them comprised sandy soils, 19% silt, and 15% clay soils.

- *Source Zone Characteristics*: The majority of the locations had chlorinated ethenes in the source zone area but some had a combination of other DNAPLs (chloroethanes, chloromethanes and chlorobenzenes). The median concentrations reported at these locations were 56mg/L and 100 mg/L for PCE and TCE, respectively. Of the 75 sites with DNAPL distribution data, 83% had residual DNAPL, 61% had sorbed DNAPL, 44% had pooled DNAPL, 40% had DNAPL diffused into low K layers and 11% had DNAPL trapped in dead-end fractures. The average survey respondent reported having a maximum DNAPL depth between 10 to 100 ft bgs. However, close to 8% of the users reported having source zone areas between 100 to >1,000ft bgs. Approximately one third of the survey users (31%) reported having an irregular shape source zone area. Others reported cylindrical, rectangular and triangular source zone areas.

- *DNAPL Source Zone Remedial Technologies Used*: A number of technologies were applied to remediate DNAPL source zones. Thermal technologies, *in situ*

chemical oxidation and bioremediation were each used in roughly 20% of the cases. Dual Phase extraction and excavation were used at 11% and 9% of the locations respectively. Surfactant flushing and zero valent iron (ZVI) were also used at a few locations.

- <u>*Remediation Cost*</u>: The average cost for full-scale applications was $2.8M, with the largest cost being a $15M water/DNAPL dual-phase treatment (on-going) at a site with a DNAPL impacted zone that was in the range of 100,000 to 1,000,000 ft^2. The lowest cost for full-scale applications was $75K for a bioremediation application and a ZVI application, both at small sites. The majority of the pilot tests cost less than $0.5M with no cost greater than $2M. Thermal treatment, pump and treat, and dual-phase extraction applications appeared to be significantly more expensive than chemical oxidation cases on large sites.

- <u>*Treatment Duration*</u>: Estimated treatment durations were as follows: Dual Phase Extraction: 60 years; Pump & Treat: 158 years; Chemical Oxidation: ~4 years; Thermal Technologies: ~4 years; ZVI Technologies: ~4 years; and Bioremediation: ~4 years. Treatment duration was estimated based on 16 full-scale applications both on-going and completed.

- <u>*Evaluating Success*</u>: Evaluating success at the survey locations was difficult since a rigorous statistical analysis was not conducted due to budget limitations. Hence, success criteria were established based on estimated mass removal, decrease in mass flux and the occurrence of rebound. Only one remediation application, a chemical oxidation using permanganate, met the most stringent criteria for evaluating success (>80% mass removal, >81% reduction in mass flux, and no rebound). This site was a pilot scale demonstration in sand with a controlled DNAPL release. If the success criteria are relaxed slightly to include >61% reduction in mass flux then an additional remediation application (bioremediation) is added. This site was also a pilot scale application conducted in sand.
    - <u>*Mass Removal*</u>: Fourteen (14) locations had ≥80% source mass removal and of these, 4 sites claimed to have 100% source mass removal (one excavation pilot test, one thermal six-phase heating and one thermal conductive heating [both full-scale], and one chemical oxidation pilot test using permanganate). Of the 4 sites with 100% mass removal, three had unknown mass flux reduction and/or unknown rebound.

    - <u>*Mass Flux*</u>: Thirteen (13) locations had ≥81% reduction in mass flux. The 13 cases include 5 thermal six phase heating applications (1 full scale), 2 permanganate and 2 Fenton's applications, 2 bioremediation applications, 1 surfactant and 1 steam application.

- *Success v. Media*: None of the technology applications in consolidated material were deemed to be successful. This may be due to the fact that only 11% of the locations included in the survey had consolidated media, but it may also be due to the fact that remediating source zone areas in consolidated material remains a big challenge.

- *Meeting MCLs*: None of the remediation attempts presented in this survey/review achieved MCLs or regulatory site closure. Meeting MCLs was not always the reason source reduction was attempted, and there are other tangible and intangible criteria that are used to interpret success.

The data collected from this survey suggests that DNAPL remediation efficacy is extremely difficult to gauge, and although employing aggressive remedial technologies cannot achieve site closure, significant mass removal can be achieved.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (CONT'D)

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

1 INTRODUCTION

GeoSyntec Consultants (GeoSyntec) was retained by the Naval Facilities Engineering Services Center (NFESC) to conduct a survey of the application of chlorinated solvent dense non-aqueous phase liquid (DNAPL) source remediation technologies. The overall goal of this project was to assist NFESC to initiate the development of guidelines on DNAPL source treatment by gathering information on current technologies used to treat DNAPL sources and their relative successes under various site conditions.

1.1 Objectives

The development of promising source zone treatment technologies has changed the conventional belief that DNAPL removal is often “technically impracticable”. Although obtaining maximum contaminant levels (MCLs) near and within source areas after the application of DNAPL treatment technologies has proven to be an elusive goal, ongoing development and testing of innovative remedial technologies suggest that source zone remediation can cause significant reduction of mass discharge and dissolved phase concentrations of volatile organic compounds (VOCs) from source areas. However, the selection of a source zone remedial technology that is cost effective and will produce the best results within the specified time frame for a specific site is not a simple task. The advantages and limitations associated with source remediation must be carefully considered in order to have reasonable expectations for the remediation. Limitations of remedial technologies due to such things as geologic heterogeneities, depth and lateral extent of contamination must be factored into the technology choice as well. Currently no guidelines for technology selection exist, and little information is available to provide direct comparisons of technology effectiveness for all site conditions. Guidelines for technology selection need to be developed to:

i) simplify the technology selection process;

ii) provide defensible arguments for: (*a*) technology selection; (*b*) development of official remedial objectives that can reasonably be met; and (*c*) defense for no action for source remediation where appropriate; and

iii) increase the overall effectiveness and minimize the costs of DNAPL remediation attempts by optimizing the chosen remedial technology to the site conditions.

This report represents the first step towards developing such guidelines through conducting a review of DNAPL treatment technologies that have been field-deployed.

As such, the objectives of the review of DNAPL remedial technologies outlined in this report were as follows:

i) a brief overview of chlorinated solvent DNAPL contamination and remediation processes (Section 2);

ii) an overview of how each DNAPL remediation technology removes DNAPL from the subsurface, the advantages and limitations of the technology, the range of site conditions where it may/may not be applicable, and information on technology application, including a summary of select published case studies (Section 3 and Appendix A);

iii) a review of data compiled from a web-based survey developed to collect information on field applications of DNAPL remediation, including some site characteristics, costs, and remedial effectiveness data (Section 4 and Appendices B, C and D);

iv) conclusions (Section 5); and

v) recommendations for further work based on the findings of our review and analysis (Section 6).

This report contains a compilation of published information, as well as information collected from survey respondents from all aspects of the groundwater community. The accuracy of the information and data collected from the survey and from the published case studies could not be independently verified for the majority of sites; however, the data was reviewed to identify obvious errors (as discussed in Section 4.2.1). The information is presented here as it was provided by the survey respondents.

1.2 Scope of Work and Report Organization

There are many technologies and approaches available to treat the vadose and dissolved phase contaminants derived from chlorinated organic solvent DNAPLs. However, the scope of work for the project was to address remedial technologies that are applied to treat DNAPL source areas only. The review of DNAPL remediation technologies was also limited to technologies that have been used to clean up contaminated sites with chlorinated solvent DNAPLs [*e.g.,* chlorinated ethenes such as trichloroethene (TCE), chlorinated ethanes such as 1,1,2-trichloroethane (1,1,2-TCA), chlorinated methanes such as dichloromethane (DCM), and chlorinated benzenes such as pentachlorobenzene (PeCB)] that are present beneath the watertable (*i.e.,* saturated zone). Technologies used to remediate other types of DNAPLs were not considered; neither were technologies used to target contamination originally present in the unsaturated zone.

Information was gathered on sites where the presence of DNAPL was either suspected or known.

A review of peer reviewed/gray published literature (Sections 2 and 3) was conducted to compile information on the following:

i) the mechanisms of DNAPL behavior in the subsurface;

ii) the theory and application of DNAPL remedial technologies that have been attempted in a field setting; and

iii) a review of published case studies.

A key effort of this project was the design of a web-based survey to collect information about DNAPL remedial applications at sites for which the data is not obtainable through the literature. Survey participants from the larger environmental community (*e.g.,* consultants, regulators, site owners, *etc*.) were solicited through a number of large email campaigns, and posting in widely distributed environmental newsletters and web pages. Data from published case studies was also entered into the survey, and the data compiled from the survey was analyzed to detect correlations between remedial application success and site conditions (Section 4). The information gathered from the literature review and the survey was used to evaluate whether sufficient information exists to develop technology selection criteria (Section 5) and to develop recommendations for further work in achieving this goal (Section 6).

2 OVERVIEW OF DNAPL REMEDIATION

An overview of the "DNAPL Paradigm", including background information on DNAPLs (Section 2.1) and their behaviour in the subsurface (Section 2.2) is presented below. Coupled with this overview is a discussion on the DNAPL remedial process, including removal mechanisms (Section 2.3) and remedial success parameters [*i.e.,* various definitions of "success" (Section 2.4.1), factors impacting remedial success (Section 2.4.2) and success metrics (Section 2.4.3)].

2.1 Background on DNAPLs

Federal and state regulations are one of the main drivers for undertaking remediation of contaminated groundwater sites. Remedial actions are also undertaken to eliminate long-term liability due to such things as human health impacts, diminution of property values, damage to natural resources, *etc*. Often the legal, regulatory and societal pressures to remediate contaminated sites within a relatively short time frame does not allow the responsible parties to fully understand the available technologies and set reasonably achievable remedial goals for a site. For groundwater that is considered to be a potential or actual source of drinking water, the standards for remediation are either maximum contaminant levels (MCLs) for regulated organic chemicals as specified under the Safe Drinking Water Act or risk-based concentrations based on site-specific human health risk assessments. However, obtaining these goals has proven elusive for chlorinated organic solvents, specifically chlorinated aliphatic hydrocarbons (CAHs) such as chlorinated ethenes / ethanes / methanes and chlorinated benzenes. CAHs are among the most common groundwater contaminants and, because of their physical characteristics (see Section 2.2 below), are also among the most difficult groundwater contaminants to remediate (Pankow and Cherry, 1996).

These CAHs are non-aqueous liquids that are denser than water, and are often used and released to the subsurface as "free-product" liquids (*i.e.,* DNAPLs). They are found at approximately 80% of all Superfund sites with groundwater contamination and are by far the most prevalent contaminants at Department of Defense (DoD) sites, occurring at more than 3,000 DoD sites in the United States (Environmental Protection Agency, 1997). Based on the NORM database (March 2003), the Navy has 867 chlorinated solvent impacted sites. Of the 399 sites impacted with TCE, it is estimated that 12% of the DoD sites have a DNAPL source remaining in the subsurface (based on groundwater TCE concentrations greater than 10 mg/L). Of the 213 sites impacted with PCE, it is estimated that 9% of the DoD sites have a DNAPL source remaining in the subsurface (based on groundwater PCE concentrations greater than 1.5 mg/L).

The recognition of the difficulties that cleanup of these CAHs pose resulted in the USEPA publishing many technical guidance documents on characterization and remediation of DNAPL sites, and to recognize that DNAPL remediation presents significant technical challenges. Section 2.4.2 outlines some of the factors impacting remedial effectiveness. In 1993, the USEPA published a guidance document on technical impracticability (TI) to be used for assessing the feasibility of meeting established performance goals at Superfund sites where remediation was considered impracticable from "an engineering perspective, taking cost into consideration" (EPA TI Guidance Document, 1993). However, since 1990, only about 50 TI waivers have been granted, out of over 1500 Superfund sites (USEPA Report of an Expert Panel, In Press).

The USEPA, the Department of Energy (DoE), the DoD and various private sector organizations have invested substantial resources in DNAPL investigations and remediation attempts. However, to date the most common remediation techniques used for DNAPL impacted sites are containment technologies, such as pump and treat, slurry walls or permeable reactive walls. These remedial technologies, although often effective at limiting the spread of contamination at these sites, require at a minimum long term monitoring and institutional controls and may require very large operation and maintenance costs. Pump and treat and other containment processes have not fully remediated sites with DNAPL source areas. Several technologies have been proven to remove mass from the source zone; however, without near complete source zone removal, few if any sites have been remediated to drinking water standards or background levels. The USEPA has commissioned an expert panel to evaluate the benefits of partial source removal. Advocates of partial source removal suggest that this would ultimately speed up the remedial activities, reduce long-term risks, and reduce the mass transfer of contaminants into the aquifer, which would lower groundwater concentrations and reduce plume size.

2.2 DNAPL Behavior in the Subsurface

A DNAPL released to the subsurface will seek phase equilibrium, a condition in which all acting influences are canceled by others, resulting in a stable, balanced, or unchanging system. The DNAPL will remain as a NAPL, adsorb to soil, dissolve in groundwater, or volatilize into soil gas to the extent defined by the physical and chemical properties of the individual CAH and the subsurface environment.

DNAPL movement through the subsurface is primarily governed by the conflicting forces of gravity and capillary forces. The primary driving force for DNAPL migration is gravity. DNAPLs are denser than water and thus will tend to mobilize downwards as opposed to spreading on the water table like hydrocarbons. As a result, a DNAPL released to the subsurface has the capacity to sink below the water table where it can provide a long-term source of contamination. The primary arresting force is the capillary force (P_c), which is dependent on the interfacial tension at the interface between the DNAPL and the water or air. The capillary force will vary with changes in the radius of curvature of the interface caused by variations in the soil pore size; small geological heterogeneities (often indistinguishable with site characterization methods) can have significant impact on the migration pathways taken by the DNAPL. This can lead to complicated DNAPL source zone architecture and significant DNAPL mass deeper and/or over greater lateral extent than expected.

As DNAPL travels through the subsurface, a small quantity is retained as residual saturation in every pore through which it flows; this portion of the DNAPL is referred to as residual DNAPL. As the DNAPL travels downward, it will accumulate on the top of soil layers or fractures with entry pressures (*i.e.,* the capillary pressure that must be exceeded for DNAPL to pass through a constricting pore throat into a pore) greater than the capillary pressure, forming a "pool". This pool will spread laterally until it either: *i*) reaches the edge of the confining layer; or *ii*) until sufficient height of free product is accumulated on the layer to exceed the entry pressure of the layer, at which point the DNAPL will enter the confining layer and continue to migrate downward. The architecture of the source may vary depending on the volume of DNAPL released, the geologic heterogeneity encountered, and the length of time since the release occurred, DNAPL is typically found as multiple horizontal layers or lenses, connected by vertical pathways at residual saturation with one ore more pools above fine grained layers. Only DNAPL that occurs in pools is considered to be potentially mobile under natural conditions. The mobility of residual and pooled DNAPL can be enhanced through a variety of remedial techniques, including heat or chemicals, which modify the interfacial tension between the water and the DNAPL. DNAPL can also be trapped in dead end pores or fractures, or diffused into low permeability layers.

2.3 DNAPL Remediation Processes

A number of DNAPL source zone technologies have been developed to optimize the mass transfer, *in situ* destruction and advective/dispersive DNAPL removal mechanisms. These technologies can be subdivided into three overall categories: DNAPL removal technologies, *in situ* destruction technologies, and source zone immobilization technologies.

Remediation is carried out by one of more of the following mechanisms:

i) **Dissolution:** Technologies dependent on dissolution rely on increasing the solubility of the contaminant through the use of chemical additives (surfactants and/or co-solvents) or by increasing the temperature (thermal technologies). The dissolved contaminant is then extracted with the groundwater and treated *ex situ* as in conventional pump and treat systems. Technologies employing this mechanism include surfactant and co-solvent flushing and the thermal technologies steam injection and three- and six-phase heating (also known as electrical resistive heating).

ii) **Displacement:** Technologies that involve displacement of the DNAPL either reduce the capillary forces by reducing the interfacial tension between the DNAPL and groundwater (through the use of surfactants, co-solvents or heat), or increase the driving forces through enhancing the gradient across the DNAPL (*e.g.,* dual-phase extraction). The DNAPL is extracted along with the groundwater and treated *ex situ*. Technologies employing this mechanism include surfactant and co-solvent flushing, dual-phase extraction, and the thermal technologies steam injection and three- and six-phase heating.

iii) **Volatilization:** Technologies designed to remove DNAPL *via* volatilization involve increasing the transfer of contaminants to the vapor phase and inducing the flow of vapor through the contaminated zone. The vapor is then extracted via wells for above ground treatment. It is possible to enhance the volatilization of the contaminants using heat. Technologies relying on this approach include the thermal technologies steam injection and three- and six-phase heating and dual-phase extraction.

iv) **Excavation:** Contaminated soil containing DNAPL is extracted and treated *ex situ*. Contaminants remaining in the groundwater as dissolved phase are not removed.

v) **Destruction:** *In situ* destruction technologies include technologies that destroy the contamination through chemical reaction or biodegradation. Most DNAPL components are relatively resistant to oxidation under naturally occurring conditions; however, through the addition of a strong oxidizer it is possible to degrade the contaminants. Most DNAPL components may be more readily broken down by reduction through the addition of a reducing compound such as zero valent iron (Fountain, 1998) or a chemical oxidant such as permanganate. Bioremediation is an *in situ* destruction process that involves the breakdown of contaminants through biologically-mediated reactions. This can occur naturally, be enhanced through the addition of an electron donor/acceptor, or be stimulated through the addition of both an active bacteria culture and an electron donor/acceptor. Technologies relying on this mechanism include the thermal technology electrical conductive heating, chemical oxidation, bioremediation and zero valent iron.

vi) **Immobilization:** Source zone immobilization does not actually remediate the DNAPL source zone but isolates the source from the surrounding environment, thereby mitigating risks. The source zone immobilization techniques include barrier wall, reactive barrier walls, pump and treat, and vitrification.

2.4 Remedial Success

2.4.1 Definition of Remedial Success

The definition of remedial success may change according to the site characteristics, regulatory demands, land use needs, *etc.* and may include the following factors:

i) **Mitigate Risk to the Environment:** Risk management may include either partial or complete DNAPL mass removal, plus the reduction of dissolved phase mass flux downgradient of the source area. Containment of dissolved plumes and/or source areas may also be a remedial goal. Remedial success is often evaluated in terms of meeting established cleanup goals that may be based on MCLs or risk-based levels intended to reduce the risk to human health and the environment.

ii) **Reasonable Treatment Duration/Application:** A remedial treatment method may be successful in terms of its ability to remove DNAPL mass from the subsurface; however, the time required to complete remediation may be unreasonably long. Restraints may be placed on the treatment duration by regulators or site owners who may wish to use the contaminated land for purposes that will be impacted by the presence of contamination. Also, ongoing invasive or disruptive remediation activities or systems may be undesirable for some site uses.

iii) **Reasonable Cost of Implementation:** Similarly, effective remedial treatments may be unreasonably expensive to implement at some sites. Two of the ways that treatment costs are evaluated are net present value (NPV) or cost to complete (CTC). For net present costs, often used in industry, the costs on a per year basis may be more appealing (*i.e.,* $250K per year for 100 yr) then a larger lump sum (*i.e.,* $5 million in one year) up front for faster remediation. However, the government more often looks at the cost to complete the remediation and would more likely select the $5 million over the $25 million. It is difficult to compare the cost of remediation methods based on prior experience at other sites, since cost is influenced by factors such as the size of treatment area (area and volume) as well as the amount of DNAPL mass targeted within that area. Unit cost measures (*e.g.,* cost per area, cost per volume, cost per unit mass) are a more effective means of comparing remedy costs**.**

2.4.2 Factors Impacting Remedial Effectiveness

A number of factors may have a significant impact on the effectiveness of the DNAPL remediation process. Many of these factors are listed below, along with brief discussions of their impact.

1) Inadequate delineation of the DNAPL location

One of the key factors in remediating DNAPL source zones is adequately defining the location and composition of the source, including both macro-scale and local distributions of DNAPL. However, as described in Section 2.2 above, the typical complex spatial distribution of DNAPLs in the subsurface makes determination of the actual DNAPL extent difficult. To collect sufficient data at the scale needed to identify the source zone, data must be collected on the order of meters to tens of meters and this is often costly and subject to error. Samples of the aqueous, gaseous, solid and immiscible phases need to be collected to determine the soluble, volatile, sorbing and immiscible components of the DNAPL.

Other limiting factors in the delineation of DNAPL source zones include the indirectness of the methods and the risk involved in direct source zone characterization. None of the remote sensing techniques developed for locating DNAPLS (*e.g.,* geophysical methods, partitioning interwell tracer tests, and natural radon abundance) have proven effective in defining the DNAPL extent at meaningful resolutions (Stroo *et al*., 2003). The use of source zone delineation and characterization methods that disturb the subsurface environment (*e.g.,* soil borings, groundwater samples) within DNAPL source zones is risky due to the possibility of creating a pathway for migration of mobile DNAPL. This could significantly worsen the contamination problem, particularly at sites where the DNAPL was contained by a low permeability layer.

2) Proper characterization of important physical and chemical site attributes

Not only is the DNAPL source architecture highly dependent on geologic heterogeneities, the performance of most technologies is also highly affected by these heterogeneities and therefore the hydrogeology of the contaminated volume must also be carefully determined (Fountain, 1998). In addition to the physical attributes of the source zone such as heterogeneity and hydrogeology, the chemical composition of the DNAPL is also important for the selection, design and performance of remedial technologies. The chemical composition of the NAPL affects properties like interfacial tension, viscosity, density, wettability, solubility, vapor pressure, Henry's Law constants, biodegradability, oxidation potential, and other properties that affect the performance and therefore the selection of different technologies.

3) Degree of reliance on dissolution or volatilization of DNAPL

For technologies that are dependent on the dissolution or volatilization of the DNAPL, the contaminant distribution is of additional importance. A number of factors will affect the degree to which DNAPL dissolution/volatilization can be accelerated in both porous and fractured geologic media, including the surface area of the DNAPL across which mass transfer can occur (*i.e.,* DNAPL present in pools versus residual) and the fraction of DNAPL stored in soil layers and/or fractures disconnected from the principal groundwater flow pathways. The specific interfacial surface area (surface area to volume ratio) of DNAPL pools is much lower than that of residual DNAPL; this is exaggerated in fractures due to the two-dimensional nature of fractures. For rocks with a porous matrix, significant diffusion of DNAPL into the rock matrix can occur (Parker *et al.,* 1994); removal of the DNAPL stored in the rock matrix is then limited by the rate of diffusion from the matrix. Similarly, low permeability soil layers or dead-end or hydraulically-disconnected fractures in bedrock can prevent advective removal of contaminants in the dissolved/vapor phase, which limits mass removal from DNAPL trapped in these locations. Destruction of the dissolved phase contaminant at the edge of the hydraulically-disconnected areas will accelerate dissolution and diffusion of the DNAPL from these locations.

When dissolution/volatilization of a pool of DNAPL by abiotic flushing is occurring, significant dissolution/volatilization will occur at only the leading edge of the DNAPL zone where clean water/air first contacts the DNAPL phase. Once the groundwater/air has bypassed the leading edge of the DNAPL, it contains dissolved phase/vapor contaminants. The driving force for dissolution/volatilization lowers beyond the leading edge, resulting in mass removal essentially only from the leading edge of the DNAPL zone.

4) Interaction at NAPL interfaces

Biological, physical and chemical interactions that occur at the interface between NAPLs and the aqueous phase can significantly impact source zone treatment effectiveness; however, these interactions are poorly understood (Stroo *et al.,* 2003). It is possible that degradation reactions that occur in the aqueous phase at the interface with DNAPL pools/residual can enhance interphase mass transfer by increasing concentration gradients and therefore increasing dissolution rates. Bioremediation has been shown to increase dissolution rates by 2 to 6.5 times the natural rates (*e.g.,* Yang and McCarty, 2001; Cope and Hughes, 2001; Carr *et al.,* 2000). Field and laboratory evidence indicates that *in situ* chemical oxidation (*i.e.,* permanganate) could increase dissolution rates by an order of magnitude more than the bioremediation rates (Schnarr *et al.*, 1998; MacKinnon and Thomson, 2002; Lee *et al.*, 2003). Alternatively, treatment rates may be increased further through the use of reagents that preferentially partition to the NAPL-water interface (Stroo *et al.*, 2003).

Since DNAPL degradation may occur over the entire DNAPL:water interface, interphase mass transfer is enhanced across the entire interface. The surface area:volume ratio of the DNAPL can impact remedial effectiveness and/or duration. A smaller surface:volume ratio (*e.g.,* DNAPL pools) results in less enhancement of the DNAPL dissolution than for a larger ratio (*e.g.,* residual). The enhancement in the DNAPL dissolution rate may decrease over time due to the formation of reaction products as films at the interface (*e.g.,* permanganate reaction with chlorinated solvents forming an insoluble manganese dioxide layer over the DNAPL/ water interface, MacKinnon and Thomson, 2002, Lee *et al.* 2003; biofilms forming near the DNAPL interface, Chu *et al.*, 2002). The impact of film formation is more pronounced where DNAPLs are distributed as pools, rather than as residual, due to the smaller interfacial area.

5) Degradation of groundwater quality (secondary groundwater quality issues)

While the removal of DNAPL mass from the subsurface will directly mitigate the chlorinated solvent contamination problem, the removal process may result in the generation of secondary groundwater quality issues, which may prevent the use of the groundwater as a source of drinking water for health or taste and odor reasons. For example, the strongly reducing conditions created by anaerobic biodegradation of chlorinated solvents may mobilize large quantities of dissolved iron and manganese in some aquifers. Addition of high concentrations of electron donors can results in high BOD (biological oxygen demand), and methane generation that can cause safety-related problems. Similarly, chemical oxidation using permanganate results in the formation of manganese dioxide precipitate, which may be significant at sites where large quantities of permanganate are used to treat large DNAPL masses. The manganese dioxide may reduce over time to dissolved manganese if aquifer conditions ever become reducing (*e.g.,* permanganate mass is consumed, and reducing groundwater influxes from upgradient). The use of zero-valent iron may result in high quantities of dissolved iron added to the groundwater. Impurities (*e.g.,* regulated metals) in amendments injected into the subsurface during remediation may create their own groundwater contamination problem where sufficient mass of the amendments are employed (*e.g.,* trace amounts of selenium contained in molasses, which is sometimes used as a nutrient to stimulate biodegradation). It is possible that these secondary groundwater impacts may mitigate over time and distance from the treatment zone; however, testing of any amendments added for regulated compounds as well as the treatment remedy over a smaller scale should be done to evaluate the potential for the formation of secondary groundwater issues.

6) *Use of multiple technologies to complete remediation*

Some remedial technologies can be effective at removing significant quantities of easily accessible DNAPL mass over a short time period (*e.g.,* surfactant/co-solvent flushing, chemical oxidation, multi-phase extraction); however, they can be prohibitively costly to use for removal of the remaining mass that is less accessible. In these situations, it may be beneficial to follow up the initial remedy with a second, less expensive and less aggressive remedy as a polishing step (*e.g.,* bioremediation or natural attenuation). When designing for the possibility of using "treatment trains", attention needs to be given to the long-term impacts on the aquifer caused by the primary treatment remedy. For example, chemical oxidation may produce extremely low pH conditions (Fenton's reagent), a highly oxidizing environment, and/or significant masses of precipitated manganese dioxide (permanganate) that could potentially become a long-term source of dissolved manganese if the groundwater environment becomes reducing in the future. Chemical oxidation can reduce specific microbial populations and thermal technologies can sterilize the soil. These conditions may inhibit microbial activity, which would impact the effectiveness of bioremediation or natural attenuation as secondary polishing remedies.

7) *Groundwater influx*

Sites with large groundwater velocities or a large influx of groundwater into the treatment area can negatively impact the effectiveness of remedial activities. Thermal treatments rely on maintaining the temperature of the aquifer at a specific level in order to effectively volatilize, mobilize and/or destroy DNAPL *in situ*. High influx of lower temperature groundwater can impact the ability to maintain the aquifer at the optimal temperature. High groundwater flux also can transport in additional electron acceptors or other compounds, which increase cost for bioremediation by requiring the addition of extra electron donors. On a positive note, high groundwater flux can be beneficial for flushing or flooding a site with treatment amendments or in pump and treat scenarios.

8) *Regulatory environment*

Regulatory cleanup levels are highly variable depending on factors such as location, and land use. Thus, a remedy that is acceptable at one site may not be acceptable at another. The definition of remedial objectives with all-or nothing end-points for DNAPL remediation has resulted in a limited number of DNAPL sites where source remediation technologies are being applied

2.4.3 Measurement of Remedial Success

Understanding how well technologies perform with specific site and source characteristics is required to optimize the remedial technology application, as well as the technology selection. To properly evaluate a source remediation technology, multiple metrics must be used to evaluate performance (EPA DNAPL panel, In Press), including the following:

i) **Estimates of DNAPL Mass Removed:** Measured or defined as either the contaminant mass recovered, an estimate of the mass destroyed during treatment or an estimate of the mass remaining after treatment. Direct measurement of both the mass remaining and mass destroyed *in situ* is often not feasible. DNAPL mass initially present and remaining post-treatment may be the more important parameters, but are very difficult to quantify. Methods such as soil coring, partitioning inter-well tracer tests, geophysical methods, inference from dissolved phase concentrations, or push-in samplers and sensors may provide rough estimates of DNAPL mass present; however, costly detailed sampling is required at many sites due to the typical sporadic distribution of DNAPL in the subsurface. For *in situ* destruction technologies, the estimate of the mass destroyed must be inferred from other data (*e.g.,* the formation of degradation products, changes in groundwater concentrations, soil boring samples, differences in pre- and post-treatment partitioning tracer tests) and again is dependent on the initial mass estimate. For treatment technologies that remove mass and treat *ex situ,* a measurement of the total mass recovered can be obtained. This can be used to then assume the mass remaining, but this value is dependent on the accuracy of the initial estimate of mass.

ii) **Changes in Dissolved Phase Concentrations and Mass Flux:** The easiest metric to implement. The DNAPL mass remaining may be inferred from the dissolved phase concentration; however, this estimate is typically inaccurate since the relationship between DNAPL mass and dissolved phase concentrations is nonlinear. Dissolved phase data can also be sensitive to a number of outside factors that can lead to variabilities in space and time, including: (*i*) precipitation recharge; (*ii*) temporal changes in groundwater flow direction; (*iii*) external influences on the aquifer (*e.g.,* pumping); (*iv*) variability in the sampling method; and (*v*) rebound after treatment. The type of well installation used to obtain groundwater samples may also impact the sample data at sites with depth-variable contamination profiles due to dilution with less contaminated water.

iii) **Changes in the DNAPL Distribution, Composition, and Properties:** Changes in the DNAPL other than mass reduction may occur throughout the course of remedial treatment; these changes can be monitored to evaluate remedial progress. Specifically, these changes include: (*i*)

DNAPL mobilization; (*ii*) changes in DNAPL composition; and (*iii*) changes in the DNAPL properties (*e.g.*, interfacial tension, solubility, volatility, *etc*.).

iv) **Secondary Impacts on the Aquifer Geochemistry and Biochemistry:** A more indirect measure of remedial success can be determined through the monitoring of secondary impacts on aquifer conditions. Many remedial methods affect the geochemistry of the aquifer. Examples of potential impacts include changes in the following parameters: (*i*) microbial populations; (*ii*) pH and oxidation-reduction potential (ORP); (*iii*) dissolved metal concentrations; (*iv*) groundwater temperature; (*v*) sulfate reduction; and (*vi*) production of degradation byproducts.

Not all metrics are appropriate for all technologies, and the optimal combination of metrics will depend on the chosen remedial technology(ies), aquifer hydrogeology characteristics, and contaminant properties (EPA DNAPL panel, In Press).

3 OVERVIEW OF DNAPL REMEDIAL TECHNOLOGIES

An important step in the process of developing technology selection criteria, is to understand the theory behind each remedial technology, the advantages and disadvantages of each technology, and the factors affecting implementation. This section contains a brief overview of this information for the following DNAPL remedial technologies:

i) surfactant/co-solvent flushing (Section 3.1);

ii) bioremediation (Section 3.2);

iii) chemical oxidation (Section 3.3);

iv) a number of thermal technologies (Section 3.4);

v) multi-phase extraction (Section 3.5); and

vi) zero-valent iron (Section 3.6).

Appendix A contains a limited number of case studies of each technology. These case studies are included to highlight some of the challenges and advantages associated with each technology, as well as to include examples of how each technology performed for various site characteristics. The information presented in each case study includes a summary of relevant site characteristics, technology application approaches, remedial goals, and lessons learned from each site.

3.1 Surfactant and Co-Solvent Flushing

Surfactant flushing (or surfactant-enhanced aquifer remediation [SEAR]) and co-solvent flushing are chemical enhancements to pump and treat and involve injection of a chemical solution, flushing through a source zone and recovery of the injected solution and targeted DNAPL. The application of a surfactant or co-solvent flush results in DNAPL remediation through one or more of the following mechanisms:

i) Enhancement of the target chemicals' solubility by lowering the interfacial tension between water and the DNAPL;

ii) Mobilization of the DNAPL by lowering the DNAPL:water interfacial tension;

iii) Mobilization of the DNAPL by swelling the DNAPL volume and reducing its density as the added alcohol dissolves into the DNAPL (co-solvent only); and *iv)* Stimulation of *in situ* bioremediation after the initial chemical flush, as many surfactants and co-solvents can also act as electron donors.

When surfactants are flushed through a source zone, the concentration and specific interactions of that surfactant with the target chemical help to determine whether the surfactant will enhance solubility or mobility. These surfactants achieve enhanced solubility and/or mobility by reducing the interfacial tension between the DNAPL and the water phase through a process referred to as micellar solubilization. The surfactants used for aquifer flushing are typically anionic surfactants, as the anionic surfactant is less likely to be sorbed to the soil matrix then the cationic surfactant, and include alcohol ether sulfates, alkane sulfonates and sulfosuccinates. These surfactants consist of a water soluble head and an oil soluble tail, and at concentrations typical for remedial application, will coalesce into aggregations referred to as micelles. Micelles can be envisioned as spheres having a polar exterior (hydrophilic portion of surfactant) and nonpolar interior (hydrophobic moiety). The type of surfactant aggregation changes as the concentration of the surfactant changes. Solubilization of DNAPL into the micelles occurs for oil-in-water micro emulsions, resulting in enhanced DNAPL dissolution. At somewhat higher surfactant concentrations, the creation of an ultra-low interfacial tension can result in mobilization of the DNAPL. A water-in-oil micro emulsion may also be created in which the surfactant will partition into the DNAPL phase, which is undesirable as the surfactant is essentially lost into the DNAPL with little impact on the DNAPL's solubility or mobility.

Co-solvents are similar to surfactants in that they can alter the properties of solution interfaces to affect both the solubility and interfacial tension at the DNAPL:water interface. Co-solvents are miscible in both water and DNAPL and may partition preferentially into one or the other depending on the type of alcohol and DNAPL and the alcohol concentration. As a result, alcohols increase the solubility of many DNAPLs, and can increase the mobility of the DNAPL if used at sufficiently high concentration to lower the DNAPL:water interfacial tension to essentially zero. The low density of many alcohols used as co-solvents can make it more difficult to target specific geologic horizons below the water table. However, the DNAPL density will decrease as the lower density alcohol partitions into the DNAPL, which has the advantage of decreasing the likelihood of downward DNAPL mobilization.

Enhanced mobility is commonly used as the primary approach for remediation in cases where the DNAPL zone is underlain by a competent capillary barrier, such as a clay aquitard. DNAPL mobilization is considered particularly useful in cases where larger accumulations (such as pools) of DNAPL are known to exist in the aquifer. In cases where no competent capillary barrier exists, enhanced solubility from the DNAPL is the preferred surfactant flushing approach. Enhanced solubility is also considered to be preferable in cases where the DNAPL is fairly distributed in the aquifer, likely existing primarily as residual phase. In either case, hydraulic control during flushing is essential for application of this technology.

The advantages of surfactant and co-solvent flushing include the following:

i) **DNAPL removal can be rapid:** Significant amount of DNAPL mass can be removed, typically within 4 to 15 pore volume flushes (CH2M Hill, 1997);

ii) **Effective DNAPL removal:** Large amounts of DNAPL may be extracted from the subsurface during treatment; and

iii) **Biodegradation may be stimulated:** Amendments remaining in the subsurface post-flushing may act as electron donors and stimulate biodegradation of any remaining contamination.

Disadvantages associated with surfactant and/or co-solvent flushing include:

i) **There may be a risk of undesirable DNAPL mobilization:** The magnitude of the risk is dependent on site geology (*i.e.*, confining layers may mitigate the risk in some situations) and the type and concentration of surfactant/co-solvent used (*i.e.,* the use of a low density co-solvent may mitigate risk by decreasing the density of the DNAPL after partitioning into it).

ii) **Handling of the extracted fluids may be problematic:** Surfactants are generally not recyclable, thus requiring disposal or *ex situ* treatment. Co-solvents can also be difficult to separate from extracted DNAPL due to its miscibility with the DNAPL.

iii) **Achieving the targeted flush may be difficult:** Soil heterogeneity can impact the ability to deliver the amendments evenly throughout the targeted zone, resulting in uneven DNAPL removal. *In situ* dilution and dispersion can result in *in situ* amendment concentrations varying from the targeted concentrations, which may change the resulting DNAPL behavior from that desired (*e.g.,* dilution of alcohol may result in DNAPL solubilization rather than mobilization, or dilution of surfactants may result in the surfactant partitioning into the DNAPL rather than DNAPL dissolution into surfactant micelles).

3.2 Bioremediation

Biodegradation accelerates the remediation of DNAPL source areas through several major processes, including:

i) Dechlorination of the parent chlorinated solvents (*e.g.,* PCE, 1,1,2,2-PCA) in the dissolved phase near the DNAPL/water interface steepens the dissolution gradient and increases the overall mass transfer of the solvent from the DNAPL to the dissolved phase (Carr *et al.,* 2000; Cope and Hughes, 2001), thus depleting the DNAPL at a faster rate; and

ii) Dechlorination of the parent chlorinated solvents to species that have higher saturated solubilities and thus faster dissolution rates; therefore resulting in a directly proportional increase in the dissolution rate and decrease in the DNAPL longevity (Carr *et al.,* 2000; Cope and Hughes, 2001).

The maximum enhancement of DNAPL removal is primarily based upon the total effective surface area over which biodegradation can occur, biodegradation rate, and the partitioning behavior of the terminal chlorinated ethene. Other factors include the rate of groundwater flow, the nutrient availability, the concentration of alternate electron acceptors, if biofilms form near the water:DNAPL interface and the parent CAH and degradation product solubility.

Chlorinated solvents can be biodegraded through four mechanisms: (*i*) reductive dechlorination; (*ii*) aerobic cometabolism; (*iii*) anaerobic oxidation; and (*iv*) direct oxidation. Reductive dechlorination involves the sequential replacement of chlorine atoms on the organic molecule by hydrogen atoms. The reaction occurs primarily under anaerobic and reducing redox conditions that typically favor methanogenesis, although reductive dechlorination has been observed in bulk aerobic aquifers (the activity occurs within anaerobic micro-habitats). The chlorinated VOCs serve as electron acceptors for the halorespiring bacteria that carry out these degradation reactions; simple organic carbon compounds (*e.g*., alcohols, fatty acids, sugars, petroleum hydrocarbons and natural organic carbon substances such as humic/fulvic acids) can serve as electron donors. Reductive dechlorination is the principal mechanism for biodegradation of most highly chlorinated compounds such as PCE, TCE, TCA and CTC.

A variation of sequential reductive dechlorination is dihaloelimination which involves the removal of two chloride atoms and the formation of ethene with a carbon–carbon double bond. Like reductive dechlorination, this reaction occurs under anaerobic and reducing redox conditions, although methanogenesis may not be required. Again, like reductive dechlorination, chlorinated VOCs will serve as electron acceptors for the bacteria that carry out these degradation reactions, while simple organic carbon compounds (*e.g.*, alcohols, fatty acids, sugars, petroleum hydrocarbons and natural organic carbon substances such as humic/fulvic acids) can serve as electron donors.

Cometabolic reactions can occur under aerobic and anaerobic conditions. Aerobic cometabolism of chlorinated organic compounds results in their oxidization to CO_2, water and chloride by non-specific microbial oxygenase enzymes produced by a variety of aerobic microorganisms. Typical cometabolites that induce enzymes that react with chlorinated VOCs include methane, ammonia, ethene, toluene and phenol. Aerobic cometabolism can occur naturally at the fringes of the plumes where redox conditions transition from anaerobic to aerobic, and a suitable cometabolite, oxygen, and the target VOC are mixed in relatively balanced proportions. Anaerobic cometabolism can occur as part of the halo-respiration process, or reactions with other highly reduced proteins used in methyl-transfer reactions. Halo-respiration will produce reduced forms of the parent VOC, and these reduced forms can react with the same enzymes that produced it. The microorganism may gain energy from the initial dechlorination steps, but not the cometabolic step.

Of the above processes, reductive dechlorination will be the most applicable for the treatment of most chlorinated solvent DNAPLs for the following reasons:

i) **Energetically favorable:** microorganisms that cometabolize chlorinated solvents do not derive energy or carbon from the process. In contrast, halorespiring microorganisms derive significant energy during dechlorination. Anaerobic and direct oxidation reactions are also energetically favorable, but only occur for lower chlorinated solvents (*e.g.,* dichloroethenes, vinyl chloride, 1,2-dichloroethane) and will not be significant within a DNAPL source area where higher chlorinated solvents (*e.g.*, PCE, TCE) dominate.

ii) **Limited solubility constraints:** nutrients used to stimulate or support reductive dechlorination (electron donors such as sugars, alcohols, fatty acids that are fermented to hydrogen and used for reductive dechlorination) are more soluble than the chlorinated solvents, so can be applied in amounts that equal or exceed reductive dechlorination demand, and that create concentration gradients that encourage microbial growth near or at the DNAPL:water interface (Chu *et al.*, 2003).

iii) **Relative insensitivity to high concentrations:** whereas non-dechlorinating microorganisms that compete for hydrogen are inhibited at concentrations approaching the aqueous solubility limit of PCE/TCE, dechlorinating microorganisms are not. Therefore, DNAPL source areas provide a unique environment within which halorespirers have a competitive advantage. A corollary to this advantage is an improved cost effectiveness of nutrient addition because a greater percentage of the hydrogen produced during the fermentation of added electron donors is consumed by dechlorinating microorganisms and not wasted in support of other microbial processes such as methanogenesis (Yang and McCarty, 1998 and 2000).

The advantages of bioremediation include the following:

i) **Cost-effectiveness:** Operating and maintenance costs can be relatively low, and equivalent to very simple groundwater extraction and treatment systems that only require air-stripping with no off-gas treatment.

ii) **The ability to combine with other technologies:** Bioremediation can work synergistically with other DNAPL treatment technologies (*e.g*., surfactant/co-solvent flushing, emulsified nano-scale iron) to speed up DNAPL treatment, or be used as a polishing step to cost effectively remove residual DNAPL left behind from more aggressive technologies.

iii) **Reduction in treatment duration:** Studies have suggested that bioremediation could increase the mass removal rate by an order of magnitude, with a corresponding reduction in time to achieve remedial goals (*e.g.,* a 100 year pump and treat scenario is reduced to 10 years).

Disadvantages of bioremediation include the following:

i) **Impacts to secondary groundwater quality:** Secondary water quality effects are related to the creation of lower reduction-oxidation conditions that may result in the solubilization of metals, such as iron and manganese above their secondary water quality limits, or the release of arsenic, a known carcinogen and toxic compound. Hydrogen sulfide can be created during the reduction of sulfate, and methane can degas from the groundwater and build up in the vadose zone forming an explosion hazard. In addition, there can be transient or steady-state production of toxic degradation byproducts (*e.g*., VC) where required microbial communities do not exist.

ii) **There may be some safety and handling issues:** Several types of electron donors are flammable (*e.g.,* alcohols) and require specialized containers for storage and procedures for handling.

iii) **Biofouling of injection wells:** Well fouling from the formation of biofilms and precipitation of inorganic species inside and outside of biofilms can be extremely problematic depending on the site geochemistry, and can result in significant O&M costs.

3.3 Chemical Oxidation

In situ chemical oxidation (ISCO) has been shown to destroy or degrade an extensive variety of hazardous wastes in groundwater and soil. ISCO refers to a group of specific technologies that each use specific combinations of oxidants and delivery techniques. Various oxidants have been used in laboratory and field applications to aggressively destroy chlorinated solvent DNAPLs, including permanganate (MnO_4^-), ozone, and Fenton's reagent (a combination of hydrogen peroxide [H_2O_2] and a ferrous iron catalyst). The oxidants react with the contaminants and convert them to innocuous compounds commonly found in nature such as carbon dioxide (CO_2), water and inorganic chloride. Some of the organic contaminants that can be treated using ISCO include BTEX (benzene, toluene, ethylbenzene, and xylenes), chlorinated solvents (*e.g.*, PCE, TCE), MTBE (methyl-ter-butyl-ether), and PAH (polyaromatic hydrocarbons) compounds. Permanganate has really only been shown to be effective at degrading chlorinated ethenes. Fenton's reagent has been used to degrade most chlorinated compounds with the exception of chlorinated methanes.

Similar to biodegradation, chemical oxidation accelerates the remediation of DNAPL source areas through dechlorination of the chlorinated solvents in the dissolved phase near the DNAPL/water interface. The destruction of the dissolved DNAPL at the interface steepens the dissolution gradient, increasing the overall mass transfer of the solvent from the DNAPL to the dissolved phase, and thus depleting the DNAPL at a faster rate. The maximum enhancement of DNAPL removal is primarily based upon the total effective surface area over which oxidation can occur and the reaction rate. Other factors include effective delivery of the oxidant to the contaminated media, consumption of the oxidant by other organic material in the aquifer, and the CAH solubility.

Fenton's Reagent

The basis of the Fenton's technology involves free radical generation and direct oxidation with hydrogen peroxide. Hydrogen peroxide is an effective oxidizing agent; however, to achieve contaminant reduction in a reasonable time, iron or iron salts are used as a catalyst (the combination is referred to as Fenton's reagent). Fenton's reagent chemistry (equation 3.1) is well documented as a method for producing hydroxyl radicals by reaction of peroxide (H_2O_2) and ferrous iron (Fe^{2+}) (ITRC, 2001). The basic reaction is as follows:

$$H_2O_2 + Fe^{2+} \Rightarrow Fe^{2+} + OH^- + OH\bullet \qquad (3.1)$$

The hydroxyl radicals ($OH\bullet$) serve as powerful, effective and nonspecific oxidizing agents. There are many reactions that occur during the oxidation of a contaminant and either ferrous or ferric iron can react with the peroxide to produce oxidizing radicals:

$$RHX + H_2O_2 <==> H_2O + CO_2 + H^+ + X^- \qquad (3.2)$$

where RHX represents an organic compound and X represents a halide (such as chloride). Compounds such as TCE and PCE are converted to CO_2, water and hydrogen and chloride ions.

An effective treatment stoichiometry for *in situ* Fenton's is influenced by variables such as pH, contaminant concentrations, and total organic carbon (TOC) (Kakarla *et al.,* 2002). A pH in the range of 3 to 4 is ideal for free radical generation (Watts *et al*., 1990), which is impractical to maintain under field conditions due to the enormous buffering capacity associated with most native soils. It has been demonstrated that free radical generation and contaminant oxidation can be promoted without acid addition using a modified Fenton's process that uses iron catalysts, which are effectively chelated in the pH range of 5 to 7, and a stabilized hydrogen peroxide (Kakarla *et al*., 2002). Fenton's reagent produces a strong reaction, which is not persistent in the subsurface and thus can be difficult to distribute to the source area.

Ozone

Ozone (O_3) is one of the strongest oxidants available for ISCO (ITRC, 2001). Ozone can oxidize organic contaminants by either direct oxidization by ozone or by generation of free radical intermediates. The hydroxyl radicals are nonselective oxidizers that rapidly attack organic contaminants and break down their carbon-to-carbon bonds. Ozone can oxidize compound such as aromatics and chlorinated alkenes, although oxidation by hydroxyl radicals is faster than oxidation by ozone itself (ITRC, 2001).

Permanganate

Permanganate is an oxidizing agent that has an affinity for oxidizing organic compounds containing carbon-carbon (C=C) double bonds, aldehyde groups or hydroxyl groups (ITRC, 2001). The reaction between permanganate and chlorinated ethenes involves an electrophilic attack on the ethene's C=C double bonds and the formation of a cyclic hypomanganate ester. Rapid hydrolysis of the cyclic ester results in the production of carbon dioxide (CO_2). There are two forms of permanganate, potassium permanganate ($KMnO_4$) and sodium permanganate ($NaMnO_4$). The stoichiometric reactions describing the oxidation of TCE and PCE by MnO_4^- are given by Yan and Schwartz (1999):

$$C_2Cl_3H + 2MnO_4^- \rightarrow 2CO_2(g) + 2MnO_2(s) + 3Cl^- + H^+ \qquad (3.3)$$

$$3C_2Cl_4 + 4MnO_4^- + 4H_2O \rightarrow 6CO_2(g) + 4MnO_2(s) + 12Cl^- + 8H^+ \qquad (3.4)$$

where PCE and TCE are presented by their chemical formulae C_2Cl_4 and C_2Cl_3H, respectively. This reaction indicates that oxidation of these compounds by MnO_4^- is accompanied by the production of manganese dioxide (MnO_2) solid, CO_2 gas, hydrogen (H^+) and chloride (Cl^-). In comparison to Fenton's reagent, permanganate is a weaker oxidant; however, it is more persistent in the subsurface and therefore may be better able to target the source area.

The effectiveness of ISCO treatment is influenced by the following factors:

i) **Adequate contact between oxidants and contaminants must be achieved:** Subsurface heterogeneities, preferential flowpaths, or low soil permeability can result in uneven flushing of the oxidant through the subsurface, resulting in untreated contaminants.

ii) **Groundwater geochemistry can impact oxidant consumption:** An understanding of the geochemical conditions at the site is essential since the applied reagents could be consumed by natural organic matter or dissolved iron rather than the contaminants, resulting in poorer than expected treatment. Groundwater geochemistry may also need to be adjusted to more optimal conditions prior to treatment (*e.g.,* lowering of pH during application of Fenton's reagent).

iii) **Design of the oxidant delivery approach:** In order to achieve adequate contact between the oxidant and the contamination, an adequate fraction of the pore-volume of the target area must be filled or flushed with the oxidant. However, care must be taken not to displace the contamination with excessive amounts of oxidant injection.

iv) **Oxidant concentration:** Oxidant concentrations need to be high enough to meet the natural oxidant demand of the aquifer, as well as the demand of any contaminant encountered during flushing. However, excessive concentrations of oxidant are not desirable due to potential impacts on secondary groundwater quality (*e.g.*, color, pH, dissolved metals) and higher costs.

v) **Initial DNAPL distribution:** Nearly all residual DNAPL mass can be destroyed *in situ* with an expectation of a comparable level of mass flux reduction (Thomson *et al*., 2000). In comparison, it is likely that a lower level of mass removal and mass flux reduction may be achieved for pooled DNAPL accumulations (Thomson *et al.,* 2000). The differences in mass flux removal are primarily due to the difference in the DNAPL-water interfacial surface area.

The advantages and disadvantages of the various chemical oxidation methods are as follows:

Fenton's Reagent

Advantages:

i) The oxidant materials are inexpensive and readily available.

ii) A wide range of chemicals including chlorinated solvents, polyaromatic hydrocarbons and petroleum products can be treated.

Disadvantages:

i) The technology is limited by the interference of subsurface impurities and carbonate since bicarbonate and organic matter will create competing reactions that hinder performance.

ii) An extremely exothermic reaction occurs, which can create safety and handling issues.

iii) Groundwater pH post-treatment can be quite low (<5), which can effectively sterilize the soil and limit secondary treatment choices.

Ozone

Advantages:

i) The gaseous nature of ozone allows for ease of delivery through the vadose zone compared with the liquid oxidants (Looney and Falta, 2000).

Disadvantages:

i) The half-life of ozone substantially limits its ability to migrate through the soil, thus this oxidant is generally considered useful only for small scale or vadose zone applications.

ii) Ozone generation system requires a large capital investment.

iii) Ozone can be an indoor air quality issue.

iv) Ozone is highly reactive with aquifer solids and groundwater constituents.

Permanganate

Advantages:

i) Permanganate is less reactive with aquifer solids than other oxidants, resulting in improved oxidant delivery to the target contaminants due to its persistence.

ii) It is typically more stable and safer to handle than Fenton's reagent, does not require pH adjustment with concentrated acid and produces less heat and insoluble gas in the treatment zone.

Disadvantages:

i) Permanganate treats a narrower range of contaminants than the other oxidants. Although it can treat chlorinated ethenes, permanganate is not effective at treating chlorinated ethanes and may have limited effectiveness against BTEX.

ii) Permanganate can be expensive.

iii) Permeability reductions can occur near DNAPL source zones due to the formation of MnO_2 precipitates (*e.g.,* MacKinnon and Thomson, 2000; Dai and Reitsma, 2002; Lee *et al*., 2003) and/or rapid production of $CO_2(g)$ (Dai and Reitsma, 2002), resulting in less effective treatment over time.

iv) Recirculation systems are prone to fouling with MnO_2 precipitates.

v) Strongly oxidizing conditions are created that can persist post-treatment, which may impact the effectiveness or choice of polishing technology (if required).

vi) Dissolved metals mobilization may occur in some aquifers, depending on the mineral content of the geological material present.

vii) Manganese precipitated as MnO_2 may mobilize as dissolved manganese if the groundwater geochemistry becomes reducing upon termination of the treatment.

3.4 Thermal Technologies

The thermal technologies that are most commonly applied for remediation of DNAPLs include steam flushing, electrical resistance heating (ERH; both three-phase and six-phase heating) and electrical conductive heating (ECH; also referred to as *in situ* thermal desorption and thermal conductive heating). While there are a number of other thermal technologies including *in situ* vitrification, radio frequency heating and hot-air injection, these are not commonly applied and were not cited in any of the survey's responses; thus we have not included specific details for these technologies in this document.

All thermal technologies involve increasing the soil and groundwater temperature in the target area. Heating can result in DNAPL remediation through enhancement of both extraction and *in situ* destruction processes through the following mechanisms (Udell & Stewart, 1998; Battelle, 2002; Stegemeier and Vinegar, 2001; Roote, 2003; USEPA, 1999):

i) increasing vapor pressure and volatilization rates of low boiling point chemicals;

ii) conversion of groundwater to steam and subsequent steam distillation of target chemicals;

iii) desorption of target chemicals from sorption sites;

iv) decreases in viscosity of separate phase chemicals which can increase mobility;

v) increases in soil permeability through partial (steam, ERH) or complete drying (ECH) of the soil matrix;

vi) increases in both aqueous solubility and aqueous and gaseous molecular diffusion coefficients to increase dissolution and diffusion rates;

vii) enhanced *in situ* biodegradation of target chemicals in the case of moderate (typically <100°C) temperature increases;

viii) *in situ* thermal destruction of target chemicals through hydrous pyrolysis/oxidation, particularly when higher temperatures are applied (i.e. greater than 100°C); and *ix)* physical displacement of DNAPL mobilized by active flushing of the target zone due to the induced gradient from SVE and/or steam injection.

ERH and steam flushing rely on the water to transport heat, and therefore are only effective while soil moisture remains. In contrast, ECH is achieved through heating of the soil, and therefore can be applied at much higher temperatures to achieve DNAPL remediation (Roote, 2003; Stegemeier and Vinegar, 2001). ECH and ERH are suitable for application in both high and low permeability media (*i.e.* clays), as the thermal conductivity of soils tends to be fairly uniform as compared to hydraulic permeabilities. As steam flushing is reliant on hydraulic transport, it is less applicable to low permeability media. For all thermal technologies, groundwater influx into the treatment zone is a key factor in the successful application of the technology as this material needs to be heated to continue the remedial process. In cases where groundwater velocities or surface recharge is high, resulting in a high influx of unheated groundwater into the treatment zone, special controls (extraction wells) may be required so that the thermal technology can be effective in maintaining adequate heat in the treatment zone. If controls are likely to be insufficient for limiting groundwater influx then thermal technologies may not be applicable to the site.

Advantages of the various thermal technologies include the following:

i) **Potential for rapid remediation:** DNAPLs may be removed within months to years, in comparison to the years to decades for less aggressive (*e.g.,* bioremediation, chemical oxidation) technologies.

ii) **Effective in low permeability media:** ERH and ECH technologies rely primarily on electrical and heat conduction, which is less sensitive to heterogeneities in soil permeability as the thermal conductivity of soils tends to be fairly uniform as compared to hydraulic permeabilities. Steam flushing is primarily reliant on hydraulic transport to remove the DNAPLs, this method is less effective for low permeability media (Roote, 2003).

Disadvantages of the thermal technologies include:

i) **Relatively high cost:** Both capital expenditures and operations and maintenance can be costly. Capital expenditures typically include above ground infrastructure to generate steam/heat/electricity for subsurface application, soil vapor treatment, extracted groundwater treatment, piping and off-gas control; below ground infrastructure includes a high density of application points and temperature monitoring points. Operation and maintenance costs are dominated by the power requirements to generate steam/heat/electricity to the subsurface.

ii) **Health and safety is a concern:** The equipment used to generate the thermal effect requires careful handling and, for ERH, the application area must be treated as an exclusion zone (no entry) to avoid electrocution risks (Battelle, 1999). In addition, the vapors generated during the remedial program can transport to ground surface resulting in potential exposure to operators as well as the surrounding area. Thermal applications typically have ground surface emission controls as well as air monitoring to limit the potential for exposure.

iii) **Undesired mobilization of DNAPL can occur:** An increase in the temperature during the thermal technology application can lead to changes in contaminant transport properties (viscosity, solubility, diffusion coefficients) that can result in spreading of the DNAPL outside of the original defined source area (Kaslusky and Udell, 2002). Careful treatment design can minimize the degree of DNAPL remobilization.

iv) **Sterilization of the soil can occur:** Typically, the application of heat-based remediation technologies will increase the subsurface soil and groundwater temperatures to above $65^{o}C$ for extended time periods (several months to a year), which will effectively sterilize the soil in the treatment area. This will impact the effectiveness of microbially-dependent post-treatment polishing remedies (*e.g.,* natural attenuation, bioremediation; Dettmer, 2002).

v) **Formation of undesired intermediates:** Chlorinated ethenes can be reactive at relatively moderate temperatures and form chlorinated intermediates that can persist. For example, the formation of hexchlorobutadiene or other toxic compounds (Constanza et al., 2003a, b).

3.5 Zero-Valent Iron

Zero-valent iron (ZVI) has traditionally been used in the treatment of groundwater plumes as part of permeable reactive barriers. ZVI technologies that are now being tested and applied for remediation of DNAPLs include direct injection of particulate iron, mixing of iron with clay slurries or incorporating nano-scale ZVI into an oil emulsion prior to injection.

ZVI in close proximity to DNAPL source areas accelerates the remediation of DNAPL source areas through several major processes, including:

i) DNAPL partitions into oil droplets containing nano-scale ZVI within them. The DNAPL reacts with the iron causing dechlorination of the parent chlorinated solvents (*e.g.,* PCE, 1,1,2,2-PCA). Encapsulation of ZVI inside of a hydrophobic fluid allows the iron to be in closer contact with the DNAPL, thus reducing the influence of the size and accessibility of the DNAPL/water interface on the DNAPL removal rate.

ii) Dechlorination of the parent chlorinated solvents in the dissolved phase near the DNAPL/water interface steepens the dissolution gradient and increases the overall mass transfer of the solvent from the DNAPL to the dissolved phase, depleting the DNAPL at a faster rate; and

iii) Dechlorination of the parent chlorinated solvents to species that have higher saturated solubilities and thus faster dissolution rates; therefore resulting in a directly proportional increase in the dissolution rate and decrease in the DNAPL longevity.

Laboratory and field research has demonstrated that zero-valent metals will reductively dehalogenate dissolved chlorinated solvents such as PCE and TCE to ethene (Gillham and O'Hannesin, 1994; Gillham 1995; Roberts *et al.,* 1996). The main dehalogenation reaction pathways occurring at the iron surface require excess electrons produced from the corrosion of the zero-valent iron in water as follows:

$$Fe^0 \rightarrow Fe^{2+} + 2e^- \qquad (3.5)$$

$$Fe^{2+}_{(surface)} \rightarrow Fe^{3+}_{(aqueous)} + e^- \qquad (3.6)$$

Hydrogen gas is produced as well as OH^-, which results in an increase in the pH of the surrounding water according to the following reaction:

$$2H_2O + 2\ e^- \rightarrow H_{2(gas)} + 2OH^- \qquad (3.7)$$

Some portion of the chlorinated ethenes are degraded by a step wise dehalogenation process according to:

$$RCl + H^+ + 2e^- \rightarrow RH + Cl^- \qquad (3.8)$$

In the dehalogenation step (equation 3.8), the "R" represents the molecular group to which the chlorine atom is attached (*e.g.,* for TCE, "R" corresponds to CCl_2CH). For complete dehalogenation of TCE, reaction (3.8) must occur three times, with the end product being ethene. Through this process, the target chemicals undergo sequential dechlorination steps, resulting in the formation of non-chlorinated hydrocarbon products (*e.g.,* ethene, ethane, and straight chain hydrocarbons). The degradation of TCE can also occur via β-elimination where TCE is converted to chloroacetylene, which is dehalogenated to acetylene. Acetylene is subsequently degraded to ethene and ethane.

For all direct applications of ZVI, destruction of the DNAPL can be fairly rapid, especially with the use of nano-scale iron (Choe *et al.*, 2001). When ZVI is used with a clay slurry or as EZVI, there is a reduction in contaminant migration during treatment through reduced groundwater flow and partitioning into the oil phase, respectively (Liberati 2003; O'Hara *et al.*, 2003; Wadley and Gilham, 2003). ZVI can be applied in low permeability and consolidated media through the use of an injection technology that will also cause either fracturing or enhanced mixing such as pneumatic or hydraulic fracturing (Chen and Markesic, 2001). Due to the redox conditions that are developed with the application of ZVI, favorable conditions for follow on polishing treatments can exist.

Advantages of ZVI technologies include the following:

i) **Destruction of the DNAPL can potentially be rapid:** This is particularly true where nano-scale ZVI is used due to the large surface area of the iron particles that are available for reaction with the DNAPL (Choe *et al.*, 2001).

ii) **Reduction of contaminant migration during treatment:** For the EZVI method, the DNAPL will tend to partition into the injected oil, resulting in an immediate reduction in mass flux downstream of the source area. The oil slowly degrades over time, creating electron donors and stimulating biodegradation of the DNAPL, further mitigating contaminant migration (O'Hara *et al.,* 2003). For ZVI mixed with clay, the clay reduces the permeability of the soil and therefore reduces the groundwater flow (Liberati 2003; Wadley and Gilham, 2003).

iii) **Effective in low permeability media:** Depending on the methods used to distribute the ZVI in the subsurface, ZVI and EZVI can be applied at low permeability sites within created fractures (*i.e.,* pneumatic or hydraulic fracturing and injection).

iv) **Creates conditions that are amenable to the use of polishing technologies:** ZVI can create favorable conditions (*e.g.,* strongly reducing environment) for organisms that would mediate biological degradation for a bioremediation or natural attenuation remedy. The EZVI method has the added benefit of stimulating bioremediation.

Disadvantages of the ZVI remedial technologies include:

i) **Spreading of DNAPL may occur:** DNAPL mobilization may occur during the direct injection of ZVI when large injection fluid volumes are used. This risk can be limited through the use of engineered controls such as injection pattern design.

ii) **Cost of consumables can be high:** Only a limited number of manufacturers of nano-scale iron exist worldwide, and nano-scale iron can therefore be expensive.

3.6 Dual Phase/Multiphase Extraction

Multiphase extraction (MPE) was developed as an extension of the soil vapor extraction (SVE) technology, which is commonly used to remediate source zones in the vadose zone. The terms dual phase and MPE are used interchangeably in this document.

MPE technology involves the application of a vacuum at one or more wells to extract groundwater, DNAPL and/or vapor from a source area. During the operation of MPE systems, DNAPL remediation is achieved through one or more of the following mechanisms:

i) Enhanced groundwater flushing through the source area results in increased dissolution rates from DNAPL and total mass extracted from the aquifer;

ii) Mobilization and recovery of DNAPL phase due to the vacuum extraction; and,

iii) Volatilization and extraction of exposed DNAPL in areas where the water table has been depressed.

MPE is a technology of many synonyms, these various synonyms have arrived from applications in different industries (i.e. oil industry) and differences in the application approach for MPE, as summarized in Table 3.1. In some cases the names are associated with a specific trademark or patent on some component of the MPE application approach. Table 3.2 outlines the optimal conditions for application of an MPE approach.

The advantages of an MPE approach include the following (EPA, 1999):

i) **Effective on moderate to low permeability soils:** It is easier to achieve and maintain a vacuum for lower permeability soils.

ii) **Total fluids recovery is optimized:** Minimal drawdown and thus free product smearing, and aquifer transmissivity is maximized at the wellhead.

The disadvantages of an MPE approach include:

i) **Energy demands are high:** Vacuum pumps and/or blowers are required, which require a lot of energy to operate.

ii) ***Ex situ* treatment of extracted fluids may be difficult:** NAPL emulsions and VOC-laden vapors require treatment.

iii) **Initial start-up and adjustment periods are required:** These may be prolonged.

iv) **Capital costs can be high:** *Ex situ* treatment infrastructure is required along with vacuum extraction equipment.

v) **Treatment may be limited to shallower depths:** Depth limitations apply.

4 SURVEY RESULTS

The successful translation of technology theory to the field is dependent on a number of factors. The relative impact of these factors on the remedial success of a technology can only be assessed through a performance evaluation under a wide range of site conditions. This information was compiled through a review of DNAPL remediation case studies, which is presented in this section. Section 4.1 presents an overview of the methods used and the data collected during the review process. Section 4.2 includes a summary of the information compiled, and an analysis of the data to determine whether trends exist with respect to site characteristics, cost, and technology success.

4.1 Survey and Literature Data Collection Methods

Information on specific DNAPL remediation case studies was collected using two approaches:

i) A web-based survey was developed to compile a database of information on various aspects of DNAPL remediation that could impact the technology selection process (Section 4.1.1); and

ii) A review of the literature and existing publicly available case study databases was performed to collect information from published case studies (Section 4.1.2). The details of these case studies were then entered into the web-based survey to add this information to the database.

4.1.1 Web-Based Survey

The type of information collected using the survey included the following information:

i) site location, survey respondent role in the remediation community, the remedial technology applied, and stage of remediation;

ii) the site characteristics specifically outlining the geology, hydrogeology, and groundwater geochemistry of a site;

iii) the DNAPL source zone characteristics including its composition, location, size of aquifer impacted by DNAPL, and DNAPL distribution;

iv) the cost and duration of treatment; and

v) various remedial success parameters.

Screen shots of the actual survey questions are contained in Appendix B. Details of the information collected are included in Section 4.2

The objectives of the survey were as follows:

i) Collect information on innovative and demonstrated source remediation technologies (*e.g.,* thermal, chemical oxidation, surfactant flushing, bioremediation, excavation, *etc.*) that have been tested or applied at chlorinated solvents DNAPL contaminated sites;

ii) Obtain multiple perspective views of each technology application by encouraging personnel from all levels of the environmental field to participate in the survey; and

iii) Obtain enough information to allow for evaluation of technology performance and impact of site characteristics, while at the same time limiting the amount of time required to enter data into the survey to a reasonable effort.

The survey of case studies was posted on the world wide web for a total of six months and the information package with the web link was emailed to approximately 700 people, mailed to over 3,000 people and posted on a number of web pages and news letters including:

i) the Environmental Protection Agency (EPA) clu-in.org Tech Direct newsletter, which was sent to over 15,000 people;

ii) the Battelle conference web page;

iii) the Interstate Technology Regulatory Council (ITRC) web page;

iv) and the Environmental Security Technology Certification Program (ESTCP) web page.

Targeted survey respondents included: Department of Defense (DoD) remedial project managers (RPMs), non-DoD RPMs, site owners, technology vendors, environmental consultants, academics and regulators. A total of 192 representatives from all areas of the remediation community accessed the survey and provided some site information (*i.e.,* a minimum of a site name); however, only a portion of these (61 out of 192 survey respondents) specified either a technology or technology specific information. In addition to individuals logging into the survey and entering information, GeoSyntec entered data into the survey from 21 published case studies (see Section 4.1.2 below). Including the published case studies as individual survey respondents increases the total number of survey respondents to 213, and the number of respondents who specified a technology to 82.

Figure 4.1 presents a summary of the survey respondents by their role in the groundwater remediation community. Consultants represented the largest percentage of the respondents (35%), followed by the published case studies (26%), DoD RPMs (16%), site owners/RPMs (12%), vendors (9%), and regulators (2%). Notably absent from the respondents who specified a technology (see Figure 4.1) was members of the academic community; however, there are still representatives of all other areas of the remediation community.

Figure 4.2 shows the geographical distribution of the sites entered into the survey. The majority of sites were located in the United States, with a small number in Canada and one from Australia.

4.1.2 Review of the Literature

Case study information was also obtained from a review of the published literature, which included peer-reviewed and grey literature from a number of journals, conference proceedings, regulatory documents, vendor web pages and the following publicly available databases:

i) Remediation and Characterization Technology Database (EPA REACH IT);

ii) Federal Remediation Technologies Roundtable (FRTR) Case Studies;

iii) Field Applications of *In Situ* Remediation Technologies: Permeable Reactive Barriers;

iv) Fractured Bedrock Focus Area;

v) *In Situ* Thermal Treatment Site Profile Database;

vi) Innovative Remediation Technologies: Field-Scale Demonstration Projects in North America;

vii) State Coalition for Remediation of Drycleaners;

viii) Superfund Cleanup Technologies; and

ix) Technology Focus: The Remediation Technology Information Center.

Information from case studies with more complete data available, and where it was obvious that the treatment of DNAPL was attempted, were entered into the survey database. A total of 21 case studies were inputted by GeoSyntec personnel. Table C.35 identifies the 21 sites and the technologies that were applied at each site.

4.2 Data Quality

4.2.1 Data Information Check

The data from the survey and case studies included in this report were not screened to verify their validity except for the following:

i) **Outliers:** Obvious outliers (*e.g.,* abnormally small treatment volumes, or groundwater chemistry orders of magnitude above solubility limits) were either corrected where the correction was obvious [*e.g.,* the user selected the wrong unit of measure (*e.g.,* concentrations above the solubility limits), modify the chosen units of measure], the survey respondent was contacted to verify the data, or were omitted in the analysis where the correct data was not obvious/verifiable. In total, data was omitted once for a volume of <1 ft^3, and 12 sites had the units changed for the dissolved groundwater chemistry values (*e.g.,* groundwater data over solubility limits).

ii) **Duplicate information:** Where duplication of site and technology information occurred, an attempt was made to determine which of the datasets provided was the most complete. Only the more complete dataset was included in the analysis, except where duplicate information may be of interest (*e.g.,* information on the perception of success of a remedial technology at a particular site entered by two survey respondents representing different roles in the remedial process, such as consultant and regulator). There were a total of three sites with multiple entries, one site had three individuals entering data and the other two sites each had two individuals entering data.

4.3 Summary of Survey Results

There was considerable data collected on the site geology/lithology, hydrogeology, geochemistry, monitoring methods, DNAPL composition, distribution and other source zone characteristics and characterization methods. The information summarized in this section highlights the major trends and conclusions drawn from the data collected and the overall performance of the applied technologies. Appendix C and D respectively present detailed summaries of all of the data collected from the survey on a question by question basis, and an interpretation of the data in terms of trends observed in impacts of site characteristics on technology performance/selection, costs, and treatment duration. Tables and figures with detailed breakdowns of the data entered into the survey, sorted by technology, are included in Appendices C and D respectively.

The following caveats are implicit in the data summary provided below:

i) Variations in the number of total data available for each survey question arise due to the following:

- one survey respondent can enter data for multiple sites;
- one individual site location can have data for multiple technology applications; and
- few survey questions required answers before allowing the respondent to proceed forward through the survey, resulting in variable totals per question.

ii) For ease of discussion, the term "site" is used here to refer to a unique combination of site location and technology application. One site location may have multiple technology applications, either used sequentially or targeting different portions of the DNAPL source area(s); however, each technology application is treated as a separate site.

iii) Given the limited amount of available data on field applications of DNAPL remediation, the data collected may not be a statistically significant representation of all field applications. In place of the rigorous statistical analysis, we have opted instead to present the data as collected, and note prominent trends and correlations between factors where the data exists. It should be noted, however, that our conclusions may be impacted by the small data sample size, and are therefore not necessarily representative of all DNAPL sites.

4.3.1 Remedial Technologies Identified in Survey

Survey respondents were asked to specify the technology that was applied at their site and the stage of remediation. Remedial technologies were specified for 118 of the sites entered into the survey. For purposes of analysis, remedial technologies that employed similar principles for DNAPL removal were combined under one "primary technology" (*e.g.,* chemical oxidation using permanganate or Fenton's reagent were defined under the same primary technology of chemical oxidation). Figure 4.3 illustrates the distribution of technologies.

Bioremediation, thermal and chemical oxidation were the most often applied technologies (21%, 23%, and 21%, respectively). Surfactant flushing and ZVI technologies were the least applied technologies (3.4% and 5%, respectively). No information was collected in the survey on sites where co-solvent flushing was applied. Information was also provided for dual-phase extraction, excavation, pump and treat, and 6 undefined other technologies.

Table 4.1 and Figure 4.3 provides a summary of the breakdown of the primary technologies: thermal, chemical oxidation, dual-phase extraction, other, and zero-valent iron into "secondary" technology descriptions that represent variations of the primary technology. Of the thermal technologies, resistive heating (six- and three-phase) and steam flushing were the most frequently applied, whereas conductive heating and low-temperature six-phase heating were each applied at one site. Of the chemical oxidation technologies, permanganate appears to be the most frequently chosen oxidant, while data for only one ozone treatment site was entered into the survey. There does not appear to be a preferred method for dual-phase extraction approaches. Of the zero-valent iron variations, non-specified use of ZVI was the most frequently applied alternative. EZVI using nano-scale iron is still in the development stage with only one pilot test completed to date.

Survey respondents were asked to specify, from a range of options, their reasons for selecting a particular technology. Appendices C and D contain detailed breakdowns of the responses.

Survey respondents were asked to specify the stage of remediation for each site (*i.e.,* pilot *versus* full-scale and completed *versus* ongoing). Of 80 total DNAPL treatment attempts, 31 were full-scale applications and 49 were pilot tests. Data was collected for only 2 full-scale systems and 33 pilot tests where the remediation was considered to be complete and post-treatment monitoring was not on-going.

4.3.2 Aquifer Geology/Lithology

The aquifer geology data collected with the survey consisted of the type of media (consolidated versus unconsolidated), degree of fracturing, heterogeneity and matrix permeability. These data are summarized in detail in Section 1 of Appendix C. DNAPL source areas were predominantly located in unconsolidated media (89%), with sand being most prevalent (45%) (Table 4.2, Figure 4.4). Only 11% had predominantly consolidated media in the source area.

Section 2.1 of Appendix D presents the interpretation of geology and hydrogeology on technology choice and performance. The technologies chosen for the following predominant source area lithologies were:

i) **Only unconsolidated media:** dual phase extraction, pump and treat, and surfactant flushing.

ii) **One sedimentary rock site, remainder only unconsolidated media:** excavation, ZVI and thermal.

iii) **Large range of geologic media types, including both unconsolidated and consolidated:** bioremediation and chemical oxidation.

A number of interesting trends arise from the analysis of technology performance with respect to site geology/lithology (Section 2.1 of Appendix D). For example, sites with consolidated media were generally described as follows:

i) no successful fractured bedrock sites are reported;

ii) no one entered data of estimates of the DNAPL source mass removal at a fractured bedrock site;

iii) neither of the fractured bedrock sites with estimates of mass flux observed any reduction in mass flux; and

iv) the occurrence of post-treatment rebound was unknown.

In comparison, sites with predominantly unconsolidated media could be described as follows:

i) 28 of 43 sites with unconsolidated media were perceived to be successfully remediated, with the remaining almost one-third perceived to be fairly successful (one poor success as well);

ii) 59% of 20 sites had a >90% reduction in the DNAPL source mass, with the majority of the remainder (90% in total) experiencing at least a 50% reduction in DNAPL mass;

iii) the majority (68% of 19 sites) of the sites had a mass flux reduction of 80 to 100%, with only one site experiencing less than a 40% decrease; and

iv) 14 of 20 sites did not experience post-treatment rebound.

4.3.3 Aquifer Hydrogeology

The aquifer hydrogeology data collected with the survey are summarized in Section 2 of Appendix C. Section 2.2 of Appendix D presents the interpretation of geology and hydrogeology on technology choice and performance.

Section 2.2 of Appendix D contains an analysis of the impact of the aquifer hydrogeology on remedial success. No trends in the data are discernible, likely due more to a lack of data than a lack of impact of the hydrogeology. The breakdown of the remainder of the success parameters is not shown, since the data available for these factors are even fewer in number.

4.3.4 DNAPL Source Zone Characteristics

A series of questions were asked in the survey pertaining directly to the DNAPL source zone. These included the following:

i) Source area chemistry (*i.e.,* DNAPL contaminant profiles, groundwater geochemistry);

ii) Size and distribution parameters of the DNAPL impacted zone (*i.e.,* areal extent, volume, maximum depth of the DNAPL, DNAPL distribution and shape); and

iii) DNAPL mass estimation (*i.e.,* methods of determining presence and mass, and an estimation of pre-remediation DNAPL mass).

4.3.4.1 Source Area Chemistry

Section 3 of Appendix C contains a summary of the composition of the DNAPL and dissolved phase data. A total of 75 sites had both technology and DNAPL composition data specified. Figures 4.5 and 4.6 illustrate the breakdown of the sites with a specified technology by the DNAPL composition. A total of 80 sites had groundwater chemistry data specified. The majority (68%) of the sites were impacted with only chlorinated ethenes; a smaller percentage had mixed DNAPL compositions (29%). Four sites did not have chlorinated ethenes, of which three of the sites had DNAPL consisting solely of chloroethanes and one site had both chloromethanes and chlorobenzenes. As expected, the groundwater contaminant data was similar to the breakdown of the DNAPL composition data.

Section 2.3.1 of Appendix D contains an analysis of the distribution of technologies with DNAPL and dissolved phase composition. The conclusions may be summarized as follows:

i) Bioremediation, thermal, excavation and dual phase extraction were applied at sites contaminated with all four groups of DNAPLs;

ii) ZVI and surfactant flushing were applied at sites with only chloroethene contamination; and

iii) Chemical oxidation was applied at sites with chloroethenes, chloroethanes, and chloromethanes as components of the DNAPL, and also at sites with these components plus chlorobenzenes as dissolved phase contamination. The two sites without chloroethenes were sites impacted by chloroethanes; at each of these sites, remediation was undertaken by chemical oxidation using Fenton's Reagent.

Section 3 of Appendix C also contains a breakdown of the dissolved phase groundwater contaminant data by the maximum, minimum, average and median concentrations, along with a comparison to the single-component solubility of each compound (*i.e.,* the theoretical maximum concentration that may be achieved from dissolution of DNAPL).

4.3.4.2 Source Area Size and Distribution Parameters

Section 3 of Appendix C contains the details on the data collected on the areal extent and volume of the DNAPL-impacted zone, the maximum depth of the DNAPL, and the DNAPL distribution. Section 2.3 of Appendix D provides an analysis of these factors with respect to technology choice and effectiveness. A summary of the findings is included below:

Areal extent of the DNAPL Impacted Zone

Areal extent ranged from 0.001 ft^2 to over 1,000,000 ft^2, but the majority (31 % of 75 sites) had a DNAPL areal extent of 10,000 to 100,000 ft^2. Sites with areal extents less than 100 ft^2 were generally technology demonstrations; the accuracy of the one site with an area less than 1 ft^2 could not be independently verified. Areal extent was unknown for 48 (39%) of 123 sites.

On a per technology basis, bioremediation and chemical oxidation have been applied at the largest range in areal extent. Of the 7 sites with areal extents of source zones greater than 1,000,000 ft^2, three of the sites were remediated using excavation, two with dual phase extraction and one each with bioremediation and thermal. There are no obvious trends in the success data in terms of the areal extent.

Volume of the DNAPL Impacted Zone

The volume of the DNAPL impacted zone was unknown for 55 (47%) of the 123 sites. The responses ranged from 1 ft^3 to over 1,000,000 ft^3, but the majority (67% of 63 sites) of the sites had a DNAPL impacted volume of greater than 100,000 ft^3.

Chemical oxidation and excavation have been applied at sites with the largest range in volumes of DNAPL impacted soil, followed by bioremediation and dual phase extraction. Thermal treatments have been mainly applied at sites with greater than 100,000 ft^3 volume of DNAPL impacted soils. There were no trends in the success data with respect to DNAPL volume.

Maximum DNAPL Depth

The maximum depth of the DNAPL zone was unknown for 43 (36%) of 118 sites that information was provided for .The responses ranged from 1 ft to 10,000 ft bgs, however, the majority (77% of 77 sites) of the sites had a DNAPL depth between 10 and 100 ft bgs.

Bioremediation has been applied at sites with the greatest depths of DNAPL distribution. Chemical oxidation, thermal, and excavation have also been applied at sites with deep DNAPL sources. Correlation with success data are presented in Appendix D.

DNAPL Distribution

One of the questions in the survey asked how the DNAPL was distributed in the subsurface, in pools, as residual, sorbed to the soil particles, diffused into low K layers (rock matrix or clay) or in dead-end fractures. The respondents were asked to choose all of the parameters that applied to their site, resulting in greater than 100% totals. Of the 179 responses to this question representing 75 sites, the majority of the sites had residual (83%) or sorbed (61%) DNAPL. Of the remainder of the responses, 44% of the sites had pooled DNAPL, 40% had DNAPL diffused into low K layers and only 11% had DNAPL trapped in dead-end fractures.

Surfactant flushing was applied at sites with DNAPL present as either pools or at residual saturation, whereas bioremediation, chemical oxidation, dual phase extraction and excavation were attempted at sites with DNAPL distributed in all of the classifications. No trends were observed with respect to DNAPL distribution and success parameters.

4.3.4.3 DNAPL Detection and Mass Estimation

Table 4.3 provides a summary of the methods used to identify DNAPL presence and shows that 2 of a total of 122 sites did not estimate the presence of DNAPL. DNAPL presence at these 122 sites was most frequently inferred from groundwater chemistry and site history (at 69 and 63 sites, respectively). However, known spills and direct observation of DNAPL in wells and soil samples were used at a large number of sites as well (32, 30 and 37 sites respectively).

Section 2.3.7 of Appendix D contains a summary of the relative frequency that each DNAPL sampling method is used at a site.

Section 2.3.7 of Appendix D also contains a discussion of the correlation between the various remedial success parameters and the sampling method used to detect and locate the DNAPL source area. While it should be noted that there was minimal data available to analyze, it is interesting to note that at the sites where the treatment was perceived to be successful, the average method for locating the DNAPL source area consisted of an approximately even mixture of fully-screened monitoring wells, nested monitoring wells, depth-discrete samples and soil samples. Conversely, the less successful sites predominantly used fully-screened monitoring wells on average.

4.3.5 Treatment Cost

Survey respondents were asked to specify the costs (in US dollars) for design and implementation of the remediation, omitting the costs required for the initial site characterization. The DNAPL treatment cost data from all sites is shown in a histogram in Figure 4.7, and summarized in Table 4.4. The costs in Table 4.4 and Figure 4.7 are broken down into the scale of treatment (*i.e.,* full-scale *versus* pilot test) as well as the size of the DNAPL impacted zone (small applications had areas < 10,000 ft^2 and volumes < 100,000 ft^3; large applications had areas > 10,000 ft^2 and volumes > 100,000 ft^3).

Cost data was provided for 16 sites at which full-scale treatment was either completed (1 site), treatment was complete but post-treatment monitoring was on-going (6 sites), or treatment was on-going (9 sites). The average cost for all of the 16 full-scale applications was $2.8M. Full-scale applications on smaller sites had costs that were generally an order of magnitude smaller than the larger sites. Of the large, full-scale applications, remedial treatment costs were generally in the millions of dollars, with the largest cost being a $15M water/DNAPL dual-phase treatment (on-going) at a site with a DNAPL impacted zone that was in the range of 100,000 to 1,000,000 ft^2. The smallest cost was reported as being $75K at two sites where full-scale treatment was completed and post-treatment monitoring was ongoing. The sites were a ZVI treatment for a site with a DNAPL impacted zone that was in the range of 100 to 1,000 ft^2 and a bioremediation treatment with an unknown size. Thermal, pump and treat and dual-phase extraction applications appeared to be significantly more expensive than the chemical oxidation applications on large sites; however, these costs will be strongly impacted by the actual size of the targeted treatment zone, and therefore do not necessarily reflect all sites.

Data was also collected for a total of 31 pilot tests, of which the majority of the tests were completed (all but 3 sites). None of the pilot tests had costs greater than \$2M, with the majority being less than \$0.5M. It should be noted that a significant portion of the pilot tests under \$0.5M were small-scale (<1,000 ft^2) technology demonstrations/field research projects. If the technology demonstrations are removed from the count, the pilot test costs were generally within the range of \$150,000 to\$2M. The breakdown of costs data is presented in Appendix D.

Unit costs based on the area and volume of the DNAPL impacted zone of the aquifer and DNAPL mass removed were calculated for the full-scale applications to provide a fairer basis for cost comparison between technologies (see Section 1.2.1 of Appendix D). However, the lack of data prevented any meaningful comparison between technologies. The unit costs appeared to be affected by the size of the DNAPL impacted zone, with smaller sites having much larger unit costs.

4.3.6 Treatment Duration

Section 1.2.2 in Appendix D outlines the treatment duration data. No trend in the pilot test data is discernible, except perhaps that bioremediation pilot tests were generally longer than the remaining technologies. The one conclusion that can be drawn from the comparison of full-scale applications is the significant difference between the duration of the remedial technologies that employ *in situ* destruction or enhancement of the DNAPL mobilization/flushing mechanisms (*e.g.,* bioremediation, chemical oxidation, excavation, thermal and ZVI technologies) versus that of technologies that rely on flushing as the principal DNAPL removal mechanism (*i.e.,* pump and treat and dual-phase extraction). The expected treatment durations of the three sites using water/DNAPL dual-phase extraction and pump and treat were 45 and 75 years (dual-phase) to 158 years (pump and treat). The remainder of the technologies had expected durations of less than 4 years. It should be noted that pump and treat has been used on that site for five years to date, while the two dual-phase extraction sites have been in operation for 10 and 15 years, and are still operating.

4.3.7 Technology Performance Evaluation

Several remedial effectiveness criteria were evaluated to determine what impact technology choice and site characteristics may have on the degree of success of remediation. General technology performance criteria included the following:

i) the perception of technology effectiveness and performance (Section 4.3.7.1) ; and

ii) factors impacting remedial performance (Section 4.3.7.2).

More specific technology performance criteria were also evaluated, including the following:

i) extent of DNAPL mass removal (Section 4.3.7.3);

ii) decrease of mass flux (Section 4.3.7.4);

iii) occurrence of rebound of dissolved phase concentrations (Section 4.3.7.5);

iv) achievement of remedial goals and/or site closure (Section 4.3.7.6); and

v) impacts to secondary groundwater quality (section 4.3.7.7).

DNAPL remediation technologies may be effective in terms of only one or more of the above criteria; however, the most effective technology would meet all criteria. Therefore, each technology was also evaluated in how well it met all criteria (Section 4.3.7.8).

4.3.7.1 Perception of Technology Effectiveness

Section 1.3.1 of Appendix D contains a detailed analysis of the rating of technology performance at each site. Table 4.5 and Figure 4.8 summarize the perceived success of the technology applications. The conclusions are summarized below:

i) Of the sites where success was evaluated, more than 50% of the sites were rated successful for bioremediation (78% of 9 sites), chemical oxidation using Fenton's reagent (63% of 8 sites), excavation (75% of 4 sites), ZVI (67% of 3 sites), and thermal (100% of 4 sites of six-phase heating, 50% of 2 sites of steam flushing, and 100% of 1 site each of conductive and low-temperature six-phase heating) technologies.

ii) Only bioremediation, excavation and thermal technologies (six-phase, conductive and low-temperature six-phase heating) were rated successful for more than 75% of the sites.

iii) Technologies that were predominantly rated as having a fair success were chemical oxidation using permanganate (57% of 7 sites), surfactant flushing (100% of 2 sites), the thermal technology resistive heating (1 site), and EZVI (1 site).

iv) The three sites using dual-phase water/air extraction had ratings of good, fair and poor successes.

There was not enough data to discern any correlation between role in the environmental community and perception of success. Survey respondents were also asked to rate their technology according to a list of effectiveness criteria, which are summarized in Section 1.3.1 of Appendix D.

4.3.7.2 Factors Impacting Remedial Effectiveness

Section 1.3.2 of Appendix D provides a summary of specific limitations of each technology. Also included in Section 1.3.2 of Appendix D is a summary of the impact of external factors (e.g., presence of site infrastructure, proximity to surface water, etc.) on remedial effectiveness. No trends were apparent, other than that most technologies were impacted by budget/remediation costs.

4.3.7.3 DNAPL Mass Removal

Table 4.6 and Figure 4.9 summarize the source mass removal data that were specified by respondents to the survey. Section 1.3.3 of Appendix D contains a detailed summary of the data and analysis. There were a total of 20 sites with source mass removal data. The majority (70%) of sites had >80% mass removal. The technologies used at these sites were chemical oxidation (2 permanganate, 4 Fenton's reagent), thermal (one each of six phase heating, steam and conductive heating), excavation (3 total), surfactant flushing (1 site) and bioremediation (1 site).

Only four sites achieved 100% mass removal (one excavation pilot test, one six-phase and one conductive heating [both full-scale], and one chemical oxidation pilot test using permanganate). Of these sites, rebound was not evaluated at two (50%) of the sites; the DNAPL was present only as residual in three (75%) of the sites and had an unknown distribution at the fourth. Two (50%) of the sites were full-scale treatments (one with post-treatment monitoring ongoing) and two (50%) of the sites were pilot-scale treatments.

DNAPL/air dual-phase extraction performed poorly with less than 10% mass removal. The low-temperature six-phase heating pilot test also performed poorly in terms of mass removal; however, it should be noted that this pilot test was terminated prematurely in order to focus on another remedial technology. Therefore, the extent of DNAPL mass removal does not necessarily reflect what may have been achieved if the pilot test had continued.

4.3.7.4 Mass Flux Decrease

Table 4.7 and Figure 4.10 summarize the mass flux data that were specified by respondents to the survey. Section 1.3.4 of Appendix D contains a detailed overview of the data and analysis. There were a total of 21 sites with mass flux decrease data. The majority (62%) of sites had a mass flux decrease greater than 80%. The technologies applied at these sites included chemical oxidation (2 each permanganate and Fenton's reagent), thermal applications (5 six phase heating and 1 steam), bioremediation (2), and surfactant flushing (1). However, rebound was evaluated at only three of these 13 sites (two with no rebound, one with rebound). The DNAPL distribution was unknown for eight sites and present as residual at four sites and residual and sorbed at one site. All but one site were pilot scale treatments.

In comparison, 86% of sites had a mass flux decrease greater than 50%. The only technologies that did not achieve >80% mass flux decrease in at least half of the sites were excavation and EZVI. Two sites had no mass flux decreases (chemical oxidation using permanganate was applied at one, excavation the other). Both of these technologies were targeting DNAPL in a predominantly fractured bedrock environment. The excavation was on-going. Success had not yet been evaluated for the chemical oxidation application and the excavation site was considered a fair success.

Mass flux as a performance metric for DNAPL remediation is still relatively new and its use as a performance metric to evaluate source depletion technologies is not generally accepted practice (EPA DNAPL Panel, In Press). Contaminant mass flux is the locally defined contaminant discharge per unit area (mass per unit area per time). It is possible that a number of the survey responses about measured decreases in mass flux were actually more applicable to either a decrease in mass discharge or in groundwater concentrations.

4.3.7.5 Post-Treatment Monitoring and Rebound of Dissolved Phase Concentrations

For many of the parameters used to evaluate success, a certain level of post-treatment monitoring is necessary to determine whether the level of mass decrease or reduction in mass flux was a permanent change or a temporary change due to things such as dilution. Table 4.8 summarizes the post-treatment monitoring stage data that were specified by respondents to the survey. Post-treatment monitoring was generally terminated within 4 years (29 of 31 sites). One site had monitoring on-going for 10 years. Section 5 in Appendix C provides more details on the data.

Table 4.9 and Figure 4.11 summarize the rebound data (see Section 1.3.5 in Appendix D for more details). There were a total of 21 sites with rebound data. The majority (67%) of sites did not have rebound occur. The technologies where rebound did occur were permanganate (83% of 6 sites), excavation (50% of 2 sites), and low-temperature six-phase heating (100% of 1 sites). Again, it should be emphasized that the low-temperature six-phase heating site was a pilot test that was terminated prematurely; therefore, the occurrence of rebound does not necessarily reflect the result of a completed application. Of the sites with rebound, four (57%) had DNAPL present in pools and two (29%) had DNAPL diffused into low K layers. However, of the 14 sites with no observed rebound, three sites (21%) had DNAPL in pools and four (29%) had DNAPL diffused into low K layers so DNAPL distribution may not be a good indicator on its own for evaluating the difficulty of achieving success.

4.3.7.6 Achievement of Remedial Goals and Site Closure

Survey respondents were only asked to evaluate success based on source mass removal, mass flux decrease, rebound and perceived success. Subsequent to the closure of the survey, an email request was sent out to the 53 participants who provided success data asking them the following questions:

i) State whether they achieved dissolved phase concentrations reduced to less than maximum concentration levels (MCLs) upon completion of the remediation scheme.

ii) If MCLs were achieved, state the stage of treatment (*i.e.,* pilot test versus full-scale) and the length of post treatment monitoring.

iii) If MCLs were not achieved, were remedial goals met?

iv) If MCLs were not achieved, but regulatory closure was, state how regulatory closure of the site was achieved.

In total, 8 sites had responses to these questions. Although out of the 53 sites, 4 sites were believed to have had 100% source mass removal and 13 sites had greater than 81% mass flux reduction, only one site claimed to have achieved MCLs after remediation. The site where MCLs were achieved was an excavation application with silt as the dominant lithology; however, the site did not achieve regulatory goals with respect to cis 1,2-DCE which has an MCL of 70 ppb and a site clean up goal of 5 ppb. The post remediation monitoring is ongoing, several years after the completion of remediation.

As a number of the sites were pilot scale demonstrations, achieving MCLs and site closure would not be expected at that stage of remediation. Of the 8 responses to the questions about MCLs, five stated that the pilot scale remediation attempts did meet the project goals, which were set above MCLs. Of these, two were bioremediation applications, one was a dual phase application, one was a permanganate application that is now going to full scale and one is an application of six phase heating that is now going to full scale. Of the remaining two sites, one was a Fenton's application which did not achieve remedial goals or MCLs and one was a full scale application of bioremediation were MCLs and regulatory closure are expected to be achieved within three years.

4.3.7.7 Impacts to Secondary Groundwater Quality

Table 4.10 provides a list of the secondary groundwater quality parameters that the survey respondents had to choose from, of which they were to check all that apply. Figure 4.12 summarizes the secondary groundwater impacts sorted by technology. Section 1.3.7 in Appendix D contains a more detailed discussion of the data, broken down by technology.

In general the most prevalent secondary groundwater impacts included: 1) generation/mobilization of undesirable compounds; 2) changes in groundwater aesthetic parameters 3) changes in soil hydraulic properties; and, 4) changes in DNAPL distribution.

In general, bioremediation, chemical oxidation (particularly permanganate) and dual phase extraction had the most secondary groundwater issues identified, although some of them were noted to be temporary (*i.e.*, groundwater color changes with the application of permanganate).

4.3.7.8 Overall Technology Performance

It is possible for remediation at a site to meet one or more of the success criteria, yet fail to meet other criteria. For example, a large amount of DNAPL mass may be removed from the subsurface, but rebound may occur coupled with insignificant mass flux decrease. The optimal result from remedial activities would be a large amount of DNAPL mass removed, significant mass flux reduction, and no post-treatment rebound of dissolved phase concentrations. To evaluate the level of success that was achieved for various combinations of site conditions and technologies, the sites were sorted according to varying degrees of each success criteria. Sites with “unknown” responses to any of the success criteria eliminated the site from consideration. The following results were found:

i) **Greater than 80% mass removal AND a greater than 61% reduction in mass flux AND no observed rebound AND a perceived success:** Only two sites met the most stringent of the success criteria. Bioremediation and chemical oxidation (permanganate) were applied at these sites. Both sites had sandy aquifers and were pilot-scale applications.

ii) **80% mass removal AND a greater than 61% reduction in flux AND perceived a success:** Four sites met these criteria, with the technologies being chemical oxidation (permanganate – two sites), bioremediation (one site) and excavation (one site). All four sites had sandy aquifers. All but the site with excavation were pilot-scale applications.

iii) **80% mass removal AND a greater than 61% reduction:** Six sites in total met these criteria, with the technologies applied being chemical oxidation (permanganate – two sites), bioremediation (one site), excavation (one site), surfactant flushing (one site) and thermal six-phase heating (one site). All sites except for the surfactant flush had sandy aquifers; the surfactant flush was conducted in a clay aquifer. Only the excavation and the thermal six phase heating were full-scale applications, the remaining were pilot-scale.

iv) **80% mass removal AND no observed rebound AND a perceived success:** Seven sites met these criteria. These sites include the three chemical oxidation sites (one permanganate, two Fenton's reagent), one bioremediation, two thermal applications (steam and conductive heating) and one excavation. If the perceived success criterion is removed from this evaluation, another chemical oxidation application (Fenton's reagent) is included. The sites were all unconsolidated, and the lithologies comprised three sand, three clay and one silt sites. Five of the sites were completed full scale applications and two were pilot scale applications.

v) **Greater than 61% reduction in flux AND no observed rebound AND a perceived success:** Two bioremediation, one chemical oxidation (permanganate), and one thermal (six phase heating) sites met these criteria (four in total). Two of the sites had sandy aquifers, the other two had clay. Two of the applications were full scale and two were pilot scale.

The two predominant trends that appear to be consistent throughout all sites that met all degrees of success criteria were:

i) Not one of the "successful" sites had remediation applied in unconsolidated media. The prevalent lithology was sand, with some sites with predominantly clay.

ii) The majority of the "successful" sites were applied at the pilot-scale. Only excavation and thermal technologies met even the least stringent of the criteria for full-scale applications.

5 CONCLUSIONS

The principal goal for this review and survey of chlorinated solvent DNAPL remediation case studies was to gather information on the current technologies used to treat DNAPL sources and their relative success to provide the first step towards developing technology selection guidelines. The following general conclusions can be made from the gathered data.

- The web-based survey proved to be a useful tool for collecting and compiling a cross section of case study data, in a consistent manner that reflected the impressions of users and reviewers of performance data.

- DNAPL source zone remediation has been attempted at a wide range of sites using a number of different technologies with varying success. Although remediation of source areas to below MCLs is an elusive goal, ongoing development and testing of innovative remedial technologies suggests that source zone remediation can cause significant reduction of mass discharge and dissolved phase concentrations of volatile organic compounds (VOCs) from source areas.

- Thermal remediation technologies are among the most common DNAPL treatment technologies; however, the use of innovative technologies is becoming more common. Based on the results of the survey, thermal technologies were the most often applied, chemical oxidation was a close second along with a surprising number of bioremediation applications (23%, 21%, and 21%, respectively). Surfactant flushing and ZVI technologies were the least applied technologies (3.4% and 5%, respectively). Information was also provided for dual-phase extraction, excavation, pump and treat, and 6 undefined other technologies. No information was collected in the survey on sites where co-solvent flushing was applied.

- DNAPL-impacted sites range greatly in size, with areal extents from <100 ft^2 to over 100,000 ft^2 and volumes from <10 ft^3 to >1,000,000 ft^3. The majority of the sites had a DNAPL areal extent of 10,000 to 100,000 ft^2 and a DNAPL impacted aquifer volume of greater than 100,000 ft^3. Many of the sites for which data was collected were pilot scale demonstrations. Sites with areal extents less than 100 ft^2 were generally technology demonstrations and the sizes of the site reported in the survey are not necessarily indicative of the extent of DNAPL contamination at the site. Of the 123 sites with data on the DNAPL areal extent, 48 (39%) said that the areal extent was unknown and 55 (46.6%) said that the volume was unknown.

- A key parameter when designing a remediation strategy is the DNAPL distribution in the subsurface. Although the most common distribution form for DNAPL is as residual or sorbed mass (83% and 61%, respectively based on survey responses), a large percentage (44%) of the sites estimated that DNAPL was present in the subsurface as pools. In addition, 40% had DNAPL diffused into low K layers and 11% had DNAPL trapped in dead-end fractures.

- The use of mass flux (*i.e.*, the locally defined contaminant discharge per unit area) as a performance metric to evaluate source depletion technologies is still relatively new and is not a generally accepted practice. However there were a total of 21 responses with a measured decrease in mass flux observed after remediation. Although 2 sites (10%) had 0% decrease in mass flux, 13 sites (62%) had 81% to 100% decreases in mass flux. . It is possible that a number of the responses about a measured decrease in mass flux were actually more applicable to either a decrease in mass discharge or a decrease in groundwater concentrations.

- Lithology/geology, hydrogeology and DNAPL source zone architecture (size, depth, distribution, *etc.*) are all parameters that impacted successful DNAPL remediation; however, information on these factors was either unknown or not measured for a large percentage of the case example responses. The impact of these parameters on the success of DNAPL remediation appears to be unknown or ignored by vendors, regulators, or users of these technologies.

- None of the remediation attempts presented in this survey/review achieved MCLs or regulatory site closure.

- Although meeting MCLs is not always the reason source reduction is attempted, there are other tangible and intangible benefits, such as mass removal, regulatory favor, risk reduction, which can be derived from such an attempt.

- Although remediation was perceived to be successful at 28 sites:
    - Only one remediation (4%) application, a chemical oxidation case using permanganate), met the most stringent criteria for evaluating success). This site was a pilot scale demonstration in a sand with an emplaced DNAPL source.

  - Two (2) cases (9.5%) met criteria of >61% reduction in mass flux, the prior chemical oxidation case and an additional bioremediation application. Both sites are pilot scale applications conducted in sand.

  - Fourteen (14) sites (67%) had ≥80% source mass removal and only 4 sites (19%) claimed to have 100% source mass removal. Of the 4 sites with 100% mass removal, three had unknown mass flux reduction and/or unknown rebound.

  - Thirteen (13) sites (62%) had ≥81% reduction in mass flux.

- Full-scale applications typically cost millions of dollars, with the largest cost being a \$15M water/DNAPL dual-phase treatment (on-going) at a site with a DNAPL impacted zone that was in the range of 100,000 to 1,000,000 ft^2. None of the pilot tests had costs greater than \$2M, with the majority being less than \$0.5M.

- In terms of treatment duration, from the comparison of full-scale applications there is a significant difference between the duration of the remedial technologies that employ in situ destruction or enhancement of the DNAPL mobilization/flushing mechanisms (e.g., bioremediation, chemical oxidation, excavation, thermal and ZVI technologies) versus that of technologies that rely on flushing as the principal DNAPL removal mechanism (i.e., pump and treat and dual-phase extraction). The expected treatment durations for technologies relying on flushing ranged from 45 to 158 years in comparison with the remainder of the technologies which had expected durations of less than 4 years.

The data collected from this survey suggests that DNAPL remediation efficacy is extremely difficult to gauge, and although employing aggressive remedial technologies has not achieved site closure, significant mass removal can be achieved.

6 RECOMMENDATIONS

To further refine the benefit of source treatment requires that:

i) **Update the status of on-going field applications to expand upon the database.** The following list contains suggestions as to how to do this:

- Follow up on sites listed as ongoing in the survey to track progress, and on sites with incomplete data.
- Expand on the case study data collection, either through re-releasing the web-based survey for public input, continuing to review the literature for case study information, and/or directly targeting particular sites and obtaining case study information through site personnel interviews. Insufficient amounts of data were collected for much of the information requested, which can result in the results not being statistically significant.

ii) **Collecting data on a finer scale to allow statistical data analysis.** Data was collected using "ranges" of input values that where selected by the user. The selection of ranges reduces the ability to quantify factors that affect remedial performance and predict success, such as correlation between technology performance metrics (*e.g.,* remedial success and lithology).

iii) **Collaborate with others collecting this type of information to pool resources and share data.** Partnering with EPA, the ITRC, and others to aid in filling in data gaps or collecting data on a finer scale. The combined efforts will help to improve the state of the knowledge and help to streamline the remediation process.

7 REFERENCES

Abriola, L.M., C.D. Drummond, K.M. Rathfelder, L.D. Lemke, E.J. Hahn, and K.D. Pennell (2000). Surfactant enhanced remediation: application of numerical models in pilot test design. *In* Groundwater 2000, Proc. Of the International Conference on Groundwater Research, Copenhagen, Denmark, 6-8 June 2000, *P.L. Bjerg, et al., eds., 33-36, A.A. Balkema, Rotterdam, The Netherlands.*

Abriola, L.M., C.D. Drummond, L.D. Lemke, K.M. Rathfelder, K.D. Pennell, E. Petrovskis, and G. Daniels (2001). Surfactant enhanced remediation: application of mathematical models in the design and evaluation of a pilot test*. In* Groundwater Quality 2001, Pre-prints of the Third International Conference on Groundwater Quality, 18-21 June, University of Sheffield, United Kingdom, *6-8.*

Baker, Ralph S., and Myron Kuhlman 2002. A Description Of The Mechanisms Of In-Situ Thermal Destruction (ISTD) Reactions. in H. Al-Ekabi (Ed.), Current Practices in Oxidation and Reduction Technologies for Soil and Groundwater, and presented at the 2nd International Conf. on Oxidation and Reduction Technologies for Soil and Groundwater, ORTs-2, Toronto, Ontario, Canada, Nov. 17-21, 2002.

Battelle, 2002. Steam Injection Treatment of a DNAPL Source Zone at Launch Complex 34, Cape Canaveral Air Station. Draft Final Technology Evaluation Report. August 20 2002

Battelle, 2003. Demonstration of Resistive Heating Treatment of DNAPL Source Zone at Launch Complex 34 in Cape Canaveral Air Force Station, Florida. Final Innovative Technology Evaluation Report. February 19, 2003.

Battelle and Duke Engineering Services, 2002. NFESC Technical Report TR-2206-ENV: Surfactant-Enhanced Aquifer Remediation (SEAR) Design Manual. April, 2002.

Carr, C.S., S.Garg, and J.B. Hughes, 2000. Effect of dechlorinating bacteria on the longevity and composition of PCE-containing nonaqueous phase liquids under equilibrium dissolution conditions, Environ. Sci. and Tech., 34(6), 1088-1094.

CH2M HILL, 1997. Technology Practices Manual for Surfactants and Cosolvents. February, 1997.

Chen, S., Markesic S. (2001) An innovative Approach to the Emplacement of Zero-Valent Iron for the Treatment of Chlorinated Volatile Organic Compounds Presented at the 1st International Conference on Oxidation Reduction Technologies for Insitu Treatment of Soil & Groundwater, Niagra Falls.

Choe S., Lee S-H., Chang Y.-Y., Hwang K-Y., and Khim J. 2001. Rapid Reductive Destruction of Hazardous organic compounds by nanoscale Fe^o. Chemosphere 42 (2001) 267-372.

Chu, M., P.K. Kitanidis, and P.L. McCarty, 2003. Effects of biomass accumulation on biologically enhanced dissolution of a PCE pool: a numerical simulation. *Journal of Contaminant Hydrology*, 65:75-100.

Costanza, J, K.D. Pennell, J.A. Mulholland 2003a. Laboratory Study on the Transformation of Organic Contaminants Under Thermal Source Zone Removal Conditions. In Proceedings of the 2003 Georgia Water Resources Conference, April 23-24, Athens, GA.

Costanza, J, K.D. Pennell, J.A. Mulholland, and E.L. Davis. 2003b. Systematic laboratory study on the transformation of organic contaminants under thermal source zone removal conditions. Platform presentation 225th American Chemical Society Meeting, March 23-27, New Orleans, LA.

Cope, N., and J.B. Hughes, 2001. Biologically-enhanced removal of PCE from NAPL source zones, Environ. Sci. and Tech., 35(10), 2014-2020.

Dai, Q., and S. Reitsma, 2002. Two-dimensional experimental studies of permanganate flushing of pooled DNAPL, in the proceedings of the Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May, 2002.

Dettmer, Karen, 2002. A Discussion of the Effects of Thermal Remediation Treatments on Microbial Degradation Processes. August 2002 for U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response Technology Innovation Office Washington, DC www.clu-in.org

Drummond, C.D., L.D. Lemke, K.M. Rathfelder, E.J. Hahn and L.M. Abriola (2000). Simulation of surfactant-enhanced PCE recovery at a pilot test field site. *In* Treating Dense Nonaqueous-Phase Liquids (DNAPLs): Remediation of Chlorinated and Recalcitrant Compounds *(ed. By G.B. Wickramanayake, A.R. Gavaskar, and N. Gupta). 77-84, Battelle Press, Columbus.*

Edwards, E.A. and E.E. Cox, 1997. Field and laboratory studies of sequential anaerobic-aerobic chlorinated solvent biodegradation, Accepted for publication in the proceedings of the Fourth International *In situ* and On-Site Bioremediation Symposium, New Orleans, LA. April 1997.

Ellis, D.E., E.J. Lutz, J.M. Odom, R.J. Buchanan Jr., and C.L. Bartlett, 2001. Bioaugmentation for accelerated *in situ* anaerobic bioremediation, Environ. Sci. and Tech., accepted for publication.

Falta, R.W., C.M. Lee, S.E. Brame, E. Roeder, J.T. Coates, and C. Wright. Field Test of High Molecular Weight Alcohol Flushing for Subsurface NAPL Remediation, Water Resources Research, Vol. 35, No. 7, July, 1999.

Fountain, J.C., 1998. Technologies for Dense Nonaqueous-Phase Liquid Source Zone Remediation. Groundwater Remediation Technology Analysis Center: Pittsburgh, PA.

Gilham, R.W. 1995. Resurgence of research concerning organic transformations enhanced by zero-valent metals and potential application in remediation of contaminated groundwater. Natl. Meet. – Am. Chem. Soc. Div Environ Chem. 1995., 35, 691-694.

Gillham R.W., S.F. O'Hannesin. 1994. Enhanced degradation of halogenated aliphatics by zero-valent iron. Ground Water 32(6), 958-967.

958.

Hood, E.D., 2000. *Permanganate Flushing of DNAPL Source Zones: Experimental and Numerical Investigation*, Ph.D. Thesis, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario.

Hood, E.D., N.R. Thomson, and G.J. Farquhar, 1997. *In situ* oxidation: an innovative treatment strategy to remediate trichloroethylene and perchloroethlyene DNAPLs in porous media, in the proceedings of The 6th Symposium on Groundwater and Soil Contamination, Montreal, Quebec.

Hood, E.D., N.R. Thomson, D. Grossi and G.J. Farquhar, Experimental determination of the kinetic rate law for oxidation of perchloroethylene by potassium permanganate, Chemosphere, 40(12):1383-1388, 1999.

Interstate Technology and Regulatory Cooperation (ITRC) 2001. Technical and Regulatory Guidance for *In situ* Chemical Oxidation of Contaminated Soil and Groundwater. Prepared by the *In situ* Chemical Oxidation Work Team. June 2001.

IT Corporation, 2000. *In situ* Oxidation Demonstration Test Final Report Treatment Cell C Launch Complex 34 DNAPL Source Zone Oxidation Project.

Jawitz, J.W., R.K. Sillan, M.D. Annable, P.S.C. Rao, K. Warner. 2000. *In situ* Alcohol Flushing of a DNAPL Source Zone at a Dry Cleaner Site. Environmental Science & Technology, 2000, 34, pp. 3733-3739.

Kakarla, Prada K., Andrews T., Greenberg R.S., Zervas D.S., 2002. Modified Fenton’s Processes for In-Situ Chemical Oxidation – Laboratory and Field Evaluation. Remediation Autumn 2002. 23-36.

Kaslusky, S.F., Udell, K.S.. 2002. A theoretical model of air and steam co-injection to prevent the downward migration of DNAPLs during steam-enhanced extraction. Journal of Contaminant Hydrology 55(2002) 213-232.

Lee, E.S., Y. Seol, Y.C. Fang, and F.W. Schwartz, 2003. Destruction efficiency and dynamics reaction fronts associated with the permanganate oxidation of trichloroethylene, Environmental Science and Technology, 37(11):2540-2546.

Liberati, Michael R. 2003. Use of ZVI and Clay for Source Zone Remediation. Presented at RTDF Permeable Reactive Barriers (PRBs) Action Team Meeting, Niagara Falls, NY. October 15-16, 2003.

Looney, B.B., R.W. Falta, 2000. Vadose Zone Science and Technology Solutions. Editors. Battelle Press.

MacKinnon, L.K., and Thomson, N.R., 2002. Laboratory-scale *in situ* chemical oxidation of a perchloroethylene pool using permanganate, Journal of Contaminant Hydrology, 56:49-74.

Major, D.W., E.E. Cox, E. Edwards, and P.W. Hare, 1995. Intrinsic dechlorination of trichloroethene to ethene in a bedrock aquifer, Intrinsic Bioremediation, R.E. Hinchee, J.T. Wilson, and D.C. Downey (eds), Battelle Press, Columbus, OH, 197-203.

Major, D.W., E.H. Hodgins, and B.J. Butler, 1991. Field and laboratory evidence of *in situ* biotransformation of tetrachloroethene to ethene and ethane at a chemical transfer facility in North Toronto, *In situ* and on Site Bioreclamation, R. Hinchee and R. Olfenbuttel (Eds.), Buttersworth-Heineman, Stoneham, MA.

Nelson, M.D., B.L. Parker, T.A. Al, J.A. Cherry, and D. Loomer, 2001. Geochemical reactions resulting from *in situ* oxidation of PCE-DNAPL by KMnO4 in a sandy aquifer, Environ. Sci. and Technol., 35, 1266-1275.

O'Hara, Suzanne, Thomas Krug, David Major, Jackie Quinn, Cherie Geiger, and Chris Clausen. 2003. Performance Evaluation of Dehalogenation of DNAPLs Using Emulsified ZVI. Presented at RTDF Permeable Reactive Barriers (PRBs) Action Team Meeting, Niagara Falls, NY. October 15-16, 2003.

Pankow, J.F. and J.A. Cherry. 1996. Dense Chlorinated Solvents and Other DNAPLs in Groundwater, Editors. Waterloo Press.

Roberts, L.A., L.A. Totten, W.A. Arnold, D. R. Burris, and T.J. Campbell. 1996. Reductive Elimination of Chlorinated Ethylenes by Zero Valent Metals. Env. Sci. and Tech. Vol 30 No. 8.

Roeder, E., R.W. Falta, C.M.Lee, and J.T. Coates, DNAPL to LNAPL Transitions During Horizontal Cosolvent Flooding, Groundwater Monitoring and Remediation, Winter, 2001.

Roote, Diane. 2003. *In situ* Thermal-Enhanced Remediation Technologies, Prepared for U.S. D.O.E., September 2003

Schroth, M.H., M. Oostrom, T.W. Wietsma, and J.D. Istok, *In situ* oxidation of trichloroethene by permanganate: effects on porous medium hydraulic properties, Journal of Contaminant Hydrology, 50:79-98.

Shoemaker, Steve, Richard Landis. 2002. Results of the Kinston Jetted PRB and Source Treatment. Presented at RTDF Permeable Reactive Barriers Workshop, November 6, 2002.

Stegemeier, George L. and Harold J. Vinegar. 2001. Thermal Conduction Heating For In-Situ Thermal Desorption Of Soils Hazardous & Radioactive Waste Treatment Technologies Handbook, Ch. 4.6-1, Oh, Chang H. (Ed.) Copyright 2001, CRC Press, Boca Raton, Florida.

Stroo, H.F., Unger M., Ward C.H., Kavanaugh M.C., Vogel C., Leeson A., Marqusee J., Smith B.P., 2003. Remediation Chlorinated Solvent Source Zones. Env. Sci. and Tech., June 1, 2003. 225A - 230A.

Thermal Remediation Services, Inc.. White Paper: Three-Phase Heating? Six-Phase Heating? Which is Better? [rev 2001; cited 2003 Nov 20]. Available from: http://www.thermalrs.com/TRSPages/WhitePapers.html.

Udell, K.S. & L.D. Stewart. 1998.Combined steam injection and vacuum extraction for aquifer cleanup. Subsurface Contamination by Immiscible Fluids pp. 327-335

U.S. Army Corps of Engineers, 1999. Engineering and Design: Multi-Phase Extraction. EM 1110-1-4010, 1 June 1999.

U.S. Department of Energy, 2003. Pinellas Environmental Restoration Project: Northeast Site Area A NAPL Remediation Final Report. GJO-2003-482-TAC, GJO PIN 13.12.10. September 2003.

U.S. Department of Energy, 1999a. Innovative Technology Summary Report; *In situ* Chemical Oxidation Using Potassium Permanganate. DOE/EM-0496. September 1999.

U.S. Department of Energy, 1999b. Innovative Technology Summary Report; Fenton’s Reagent. DOE/EM-0484. October 1999.

U.S. Environmental Protection Agency. (U.S. EPA). 1993. Guidance for Evaluating the Technical Impracticability of Groundwater Restoration. OSWER Directive 9234.2-25.

U.S. EPA 1997. Cleanup of the Nation's Waste Sites: Markets and Technology Trends. EPA 542-R-96-005; U.S. Government Printing Office: Washington DC, 1997.

U.S. EPA, 1999. Multi-Phase Extraction: State-of-the-Practice. EPA-542-R-99-004, June, 1999.

U.S. EPA. In Press. The DNAPL Remediation Challenge: Is there a Case for Source Depletion? Edited by Michael C. Kavanaugh, and P. Suresh C. Rao, Expert Panel In Press.

Vinegar, H.J., Stegemeier, G.L., Stevenson, J.D., Carl, F.G., and Dudley, R.J. (1999), "In-Situ Thermal Desorption of Soils Impacted with Chlorinated Solvents," Paper #99-450, presented at the Air and Waste Management Association Annual Meeting, St. Louis, June 22.

Wadley, Sharon L.S., Robert W. Gillham. 2003. Laboratory and Field Investigations of DNAPL Source Zone Remediation Using Granular Iron. Presented at RTDF Permeable Reactive Barriers (PRBs) Action Team Meeting, Niagara Falls, NY. October 15-16, 2003.

Watts, R.J., Udell, M.D., Rauch, P.A., and Leung, S.W. 1990. Treatment of pentachlorophenol-contaminated soils using Fenton's reagent. *Hazardous Waste Hazardous Materials, 7(4), 335-345.*

Yan, Y.E., and F.W. Schwartz, 1999. Oxidative degradation and kinetics of chlorinated ethylenes by potassium permanganate, J. Contam. Hydrol., 37, 343-365.

Yang, Y., and P. L. McCarty, 1998. Competition for hydrogen within a chlorinated solvent dehalogenating mixed culture, Environmental Science and Technology, 32 (22): 3591- 3597.

Yang, Y., and P.L. McCarty, 2000. Biologically enhanced dissolution of tetrachloroethene DNAPL, Environ. Sci. and Technol. 34(14)2979-2984.

Table 3.1: MPE Terms and Configurations (EPA, 1999; USACE, 1999)

Term	Configuration
Dual Phase Extraction	▪ Non-specific MPE term
Drop-Tube Entrainment Extraction	▪ Single pump configuration
Well-Screen Entrainment Extraction	▪ Extraction of vapor and groundwater from a sealed well with induced vacuum. Groundwater is aspirated into the vapor stream at the well screen.
High-Vacuum Dual Phase Extraction (HVDPE)	▪ Two pump configuration with a submersible pump for groundwater recovery. High vacuum application (18 to 26 in Hg)
Low-Vacuum Dual Phase Extraction (LVDPE)	▪ Low permeability, fractured systems ▪ Two pump configuration with a submersible pump for groundwater recovery. Low vacuum application (2 to 12 in Hg)
Two-Phase Extraction (TPE)	▪ Single pump configuration with high vacuum application (18 to 26 in Hg)
Bioslurping	▪ Single pump configuration with high vacuum application (18 to 26 in Hg), generally applied to LNAPLs
VE/GE (“Veggie”); Downhole-Pump Extraction	▪ Two pump configuration with a submersible pump for groundwater recovery
Vacuum Enhanced Pumping (VEP)	▪ Non-specific MPE term
Vacuum Enhanced Recovery (VER)	▪ Non-specific MPE term

Table 3.2: Optimal Conditions for Multiphase Extraction (from p. 13, EPA, 1999)

Parameter	Optimal Conditions for MPE
Hydraulic Conductivity	▪ Moderate to low (K=10^{-3} to 10^{-5} cm/s)
Transmissivity	▪ Low (≤ 500 gpd/ft)
Geologic Setting	▪ Sands to clays
Vadose Zone Soil Permeability to Air	▪ Moderate to low (k<1 darcy)
Formation Characteristics	▪ Low permeability, fractured systems ▪ Interbedded sand and clay stringers ▪ Limited saturated thickness ▪ Shallow water table ▪ Thick capillary zone (up to several feet) ▪ Perched NAPL or groundwater layers
Drawdown/Recovery Rate	▪ Conditions producing steep or high drawdown in wells ▪ Low groundwater recovery rates achieved with conventional pumping
Contaminant Vapor Pressure	▪ > 1 mm Hg at 20°C
Contaminant Volatility	▪ >0.01 at 20°C ▪ >2x10-4 atm m^3/mol at 20°C

Table 4.1: Breakdown of Primary Technologies

Primary Technology	**Secondary Technology**	**Number of Sites Where Technology was Applied**
Thermal	Six-Phase Heating	10
	Steam	8
	Three-Phase Heating	5
	Resistive Heating	2
	Conductive Heating	1
	Low-Temp Six-Phase	1
Chemical Oxidation	Permanganate	15
	Fenton's Reagent	9
	Ozone	1
Dual-Phase Extraction	Water/DNAPL	5
	Water/air	5
	DNAPL/air	3
Other	Undefined	6
	Pump and Treat	1
Zero-Valent Iron	Zero-Valent Iron	4
	EZVI/Nano-Scale Iron	1
	ZVI/Clay Source Treatment	1

Table 4.2: Summary of the breakdown of the predominant geologic material in the source area.

Aquifer Media Type	Lithology		Sites with Unspecified Technology	Sites with Technology Specified	Total Sites
Consolidated	Metamorphic	Metabasalt	0	1	1 (50.0%)
		Metashale	0	0	0 (0.0%)
		Other	0	1	1 (50.0%)
		TOTAL	**0**	**2**	**2 (12.5%)**
	Sedimentary	Shale	1	5	6 (54.5%)
		Sandstone	0	0	0 (0.0%)
		Limestone (non-karstic)	1	0	1 (9.1%)
		Limestone (karstic)	0	3	3 (27.3%)
		Other	0	1	1 (9.1%)
		TOTAL	**2**	**9**	**11 (68.8%)**
	Igneous	Granitic	0	1	1 (100%)
		Basaltic	0	0	0 (0.0%)
		Intermediate	0	0	0 (0.0%)
		Other	0	0	0 (0.0%)
		TOTAL	**0**	**1**	**1 (6.3%)**
	Unknown	**TOTAL**	**1**	**1**	**2 (12.5%)**
	TOTAL		**3**	**13**	**16 (11.1%)**
Unconsolidated	Gravel		0	8	8 (6.3%)
	Sand		12	45	57 (44.5%)
	Till		1	7	8 (6.3%)
	Silt		7	22	29 (22.7%)
	Clay		4	18	22 (17.2%)
	Unknown		0	4	4 (3.1%)
	TOTAL		**24**	**104**	**128 (88.9%)**

Table 4.3: Number of Methods Used to determine DNAPL Presence

Method	**Number of Sites With Unspecified Technology**	**Number of Sites With Technology Specified**	**Total Sites**
Site history	1	62	63 (51.6%)
Known spill(s)	0	32	32 (26.2%)
Inferred from dissolved contaminant concentrations	1	68	69 (56.6%)
Direct observation of DNAPL in soil sample	0	37	37 (30.3%)
Extracted from monitoring wells	1	30	31 (25.4%)
Membrane Interface Probe	0	10	10 (8.2%)
Ribbon NAPL Samplers/FLuTEs	0	2	2 (1.6%)
Partitioning tracers	0	5	5 (4.1%)
Presence not estimated	0	2	2 (1.6%)
Total Number of Sites	**5**	**117**	**122**

Table 4.4: Summary of Remedial Cost Data

Treatment Scale	**Total Cost (USD)**	**Size of DNAPL Zone**[a]			**TOTAL SITES**
		Small	**Large**	**Unknown**	
Full-Scale	<\$0.5M	3	2	2	7
	\$0.5M to \$1M	0	1	0	1
	\$1M to \$2M	0	2	0	2
	\$2M to \$4M	0	2	0	2
	\$4M to \$10M	0	2	1	3
	>\$10M	0	1	0	1
	Total	**3**	**10**	**3**	**16**
Pilot Test	<\$0.5M	10	3	3	16
	\$0.5M to \$1M	1	8	2	11
	\$1M to \$2M	1	2	1	4
	\$2M to \$4M	0	0	0	0
	\$4M to \$10M	0	0	0	0
	>\$10M	0	0	0	0
	Total	**12**	**13**	**6**	**31**

[a] DNAPL zone size classifications were:
small = area < 10,000 ft^2 and volume < 100,000 ft^3
large = area > 10,000 ft^2 and volume > 100,000 ft^3.

TABLE 4.5
SUCCESS EVALUATION WITH ONLY PERCEIVED SUCCESS
Navy Review of Case Studies

			DNAPL Distribution						
Perceived Success	Technology	Lithology	Dead-end fractures	Diffused into Low K Layers	In pools	Residual	Sorbed	Stage	Post Treatment Monitoring
Success	Dual Phase-Water/air extraction	Till		X		X	X	Pilot test completed	
Success	Bioremediation	Sand						Pilot test completed	
Success	Bioremediation	Clay		X		X	X	Pilot test completed	
Success	Bioremediation	Sand		X		X	X	Pilot test completed	On going
Success	Chemical Oxidation-Fenton's Reagent	Sand						Full-scale completed	On going
Success	ZVI -Zero-valent iron	Sand				X	X	Full-scale completed	On going
Success	Thermal-Six phase heating	Silt			X	X		Pilot test completed	On going
Success	Bioremediation	Sand				X		Pilot test completed	On going
Fair Success	Dual Phase-Water/air extraction	Gravel						Pilot test completed	
Fair Success	Chemical Oxidation-Permanganate	Sand						Pilot test completed	
Fair Success	Thermal-Resistive heating	Clay					X	Pilot test completed	

TABLE 4.6
SUCCESS EVALUATION IN TERMS OF SOURCE MASS REMOVAL
Navy Review of Case Studies

						DNAPL Distribution						
Source mass removal	**Technology**	**Mass Flux Decrease**	**Rebound**	**Perceived Success**	**Lithology**	**Dead-end fractures**	**Diffused Into Low K Layers**	**In pools**	**Residual**	**Sorbed**	**Stage**	**Post Treatment Monitoring**
100%	Chemical Oxidation-Permanganate	81-100%	No	Success	Sand				X		Pilot test completed	
	Thermal-Six phase heating	81-100%	Unknown	Not yet evaluated	Sand						Full-scale completed	On going
	Thermal- Conductive Heating	Unknown	No	Success	Clay				X		Full-scale completed	
	Excavation	Unknown	Unknown	Success	Sand				X		Pilot test completed	
>90%	Surfactant Flushing	81-100%	Unknown	Fair Success	Clay				X		Pilot test completed	
	Chemical Oxidation-Permanganate	81-100%	Yes	Success	Sand				X	X	Pilot test completed	
	Bioremediation	61-80%	No	Success	Sand						Pilot test completed	On-going
	Excavation	Unknown	No	Success	Silt		X	X	X	X	Full-scale completed	On-going
	Chemical Oxidation-Fenton's Reagent	Unknown	No	Success	Clay		X		X	X	Full-scale completed	On-going
	Thermal-Steam	Unknown	No	Success	Clay		X				Full-scale completed	On-going
	Chemical Oxidation-Fenton's Reagent	Unknown	No	Success	Sand						Full-scale completed	On-going
>80 <90%	Excavation	61-80%	Yes	Success	Sand		X		X	X	Full-scale completed	On-going
	Chemical Oxidation-Fenton's Reagent	Unknown	No	Fair Success	Silt				X		Pilot test completed	
	Chemical Oxidation-Fenton's Reagent	Unknown	Unknown	Success	Silt						Full-scale completed	
>50 <80%	Thermal-Steam	81-100%	Unknown	Fair Success	Sand				X		Pilot test completed	
	Chemical Oxidation-Permanganate	Unknown	Yes	Fair Success	Sand			X	X	X	Pilot test completed	
>25<50	Chemical Oxidation-Permanganate	61-80%	Yes	Fair Success	Sand			X	X	X	Pilot test completed	
	ZVI - EZVI/nano-scale iron	41-60%	No	Fair Success	Sand			X	X		Pilot test completed	
>10<25	Thermal - Low temp-six phase heating	Unknown	Yes	Success	Silt			X	X	X	Pilot test completed	
<10	Dual Phase-DNAPL/air extraction	Unknown	Unknown	Poor Success	Silt		X	X	X	X	Pilot test completed	On going

TABLE 4.7
SUCCESS EVALUATED IN TERMS OF MASS FLUX DECREASE
Navy Review of Case Studies

						DNAPL Distribution						
Mass Flux Decrease	**Technology**	**Source Mass Removal**	**Rebound**	**Perceived Success**	**Lithology**	**Dead-end Fractures**	**Diffused Into Low K Llayers**	**In pools**	**Residual**	**Sorbed**	**Stage**	**Post Treatment Monitoring**
81-100%	Chemical Oxidation-Permanganate	100%	No	Success	Sand				X		Pilot test completed	
	Thermal-Six phase heating	100%	Unknown	Not yet evaluated	Sand						Full-scale completed	On going
	Surfactant Flushing	>90%	Unknown	Fair Success	Clay				X		Pilot test completed	
	Chemical Oxidation-Permanganate	>90%	Yes	Success	Sand				X	X	Pilot test completed	
	Thermal-Steam	>50 <80%	Unknown	Fair Success	Sand				X		Pilot test completed	
	Thermal-Six phase heating	Unknown	No	Success	Clay						Pilot test completed	
	Chemical Oxidation-Fenton's Reagent	Unknown	Unknown	Fair Success	Unknown						Pilot test completed	
	Bioremediation	Unknown	Unknown	Fair Success	Unknown						Pilot test completed	
	Bioremediation	Unknown	Unknown	Fair Success	Sand						Pilot test completed	
	Chemical Oxidation-Fenton's Reagent	Unknown	Unknown	Not yet evaluated	Gravel						Pilot test completed	
	Thermal-Six phase heating	Unknown	Unknown	Success	Unknown						Pilot test completed	
	Thermal-Six phase heating	Unknown	Unknown	Not yet evaluated	Till						Pilot test completed	
	Thermal-Six phase heating	Unknown	Unknown	Success	Clay				X		Pilot test completed	
61-80%	Bioremediation	>90%	No	Success	Sand						Pilot test completed	On going
	Excavation	>80 <90%	Yes	Success	Sand		X		X	X	Full-scale completed	On going
	Chemical Oxidation-Permanganate	>25 <50%	Yes	Fair Success	Sand			X	X	X	Pilot test completed	
	Bioremediation	Unknown	No	Success	Clay						Full-scale completed	On going
	Surfactant Flushing	Unknown	Unknown	Fair Success	Silt			X			Pilot test completed	
41-60%	ZVI - EZVI/nano-scale iron	>25 <50%	No	Fair Success	Sand			X	X		Pilot test completed	
0%	Chemical Oxidation-Permanganate	Unknown	Unknown	Not yet evaluated	Metamorphic						Pilot test completed	
	Excavation	Unknown	Unknown	Fair Success	Limestone	X	X		X	X	Full-scale completed	On going

Table 4.8: Summary of Post –Treatment Monitoring Stage

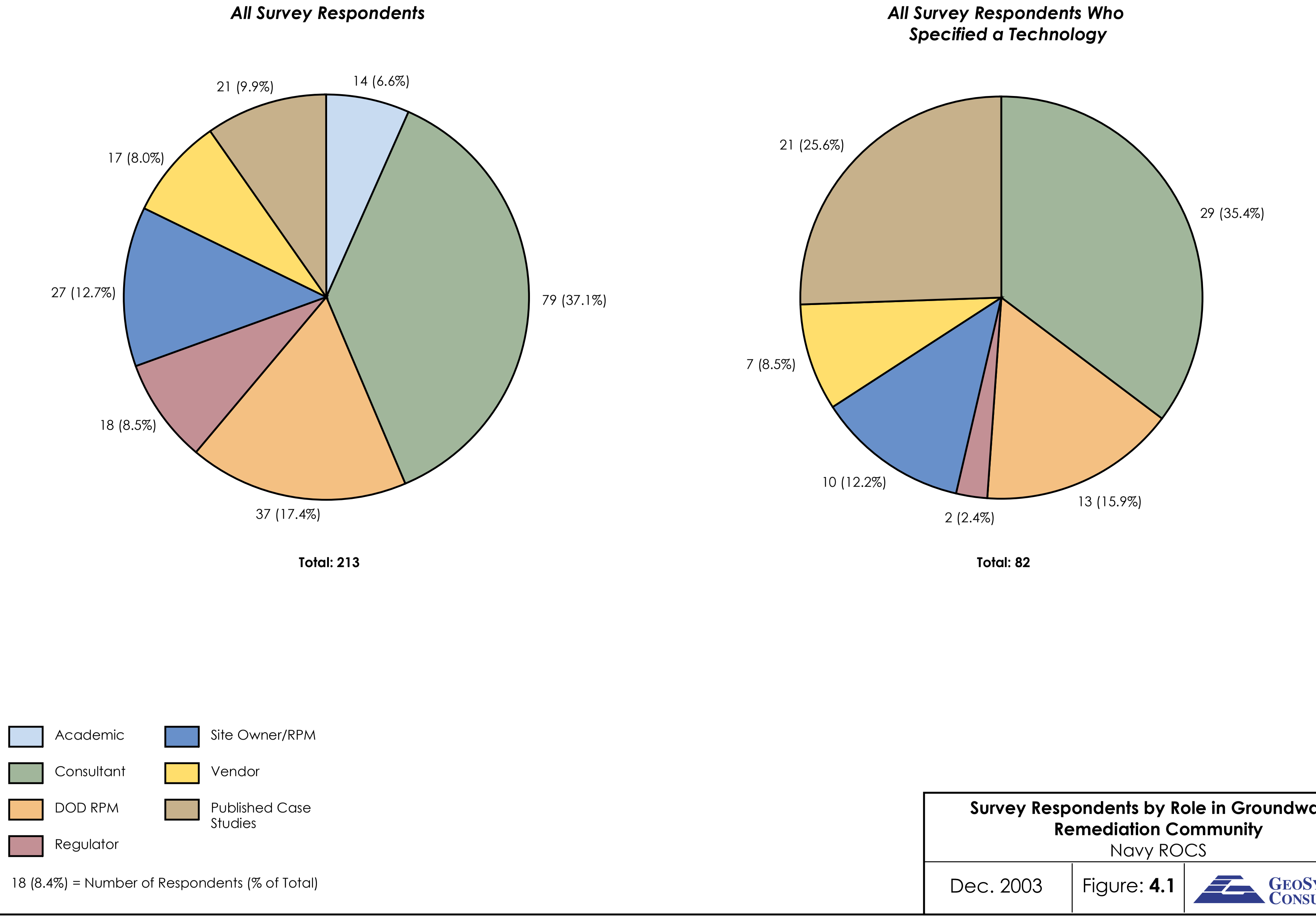
Post –Treatment Monitoring Stage	**Number of Sites**
Completed	25 (47.2%)
Ongoing	13 (24.5%)
Not Conducted	15 (28.3%)
Total	**53**

TABLE 4.9
SUCCESS EVALUATED IN TERMS OF REBOUND
Navy Review of Case Studies

						DNAPL Distribution						
Rebound	**Technology**	**Source Mass Removal**	**Mass Flux Decrease**	**Perceived Success**	**Lithology**	**Dead-end fractures**	**Diffused into Low K Layers**	**In pools**	**Residual**	**Sorbed**	**Stage**	**Post Treatment Monitoring**
Yes	Chemical Oxidation-Permanganate	>90%	81-100%	Success	Sand				X	X	Pilot test completed	
	Chemical Oxidation-Permanganate	Unknown	Unknown	Success	Shale	X	X	X	X	X	Pilot test completed	
	Excavation	>80 <90%	61-80%	Success	Sand		X		X	X	Full-scale completed	On going
	Chemical Oxidation-Permanganate	>50 <80%	Unknown	Fair Success	Sand			X	X	X	Pilot test completed	
	Chemical Oxidation-Permanganate	>25 <50%	61-80%	Fair Success	Sand			X	X	X	Pilot test completed	
	Thermal - Low temp-six phase heating	>10 <25%	Unknown	Success	Silt			X	X	X	Pilot test completed	
	Chemical Oxidation-Permanganate	Unknown	Unknown	Fair Success	Gravel						Pilot test completed	
No	Chemical Oxidation-Permanganate	100%	81-100%	Success	Sand				X		Pilot test completed	
	Other - Conductive Heating	100%	Unknown	Success	Clay				X		Full-scale completed	
	Bioremediation	>90%	61-80%	Success	Sand						Pilot test completed	On going
	Excavation	>90%	Unknown	Success	Silt		X	X	X	X	Full-scale completed	On going
	Chemical Oxidation-Fenton's Reagent	>90%	Unknown	Success	Clay		X		X	X	Full-scale completed	On going
	Thermal-Steam	>90%	Unknown	Success	Clay		X				Full-scale completed	On going
	Chemical Oxidation-Fenton's Reagent	>90%	Unknown	Success	Sand						Full-scale completed	On going
	Chemical Oxidation-Fenton's Reagent	>80 <90%	Unknown	Fair Success	Silt				X		Pilot test completed	
	ZVI - EZVI/nano-scale iron	>25 <50%	41-60%	Fair Success	Sand			X	X		Pilot test completed	
	Thermal-Six phase heating	Unknown	81-100%	Success	Clay						Pilot test completed	
	Bioremediation	Unknown	61-80%	Success	Clay						Full-scale completed	On going
	Bioremediation	Unknown	Unknown	Success	Sand		X	X	X	X	Pilot test completed	On going
	Chemical Oxidation-Fenton's Reagent	Unknown	Unknown	Success	Gravel						Pilot test completed	
	ZVI -Zero-valent iron	Unknown	Unknown	Success	Sand				X	X	Pilot test completed	

Table 4.10: Summary of impacts to secondary groundwater quality data.

Secondary Groundwater Quality Indicator	Number of Sites With The Indicator Selected
Methane generation	8 (22.8%)
Hydrogen sulfide generation	1 (2.9%)
Dissolved iron generation	7 (20.0%)
Dissolved manganese generation	7 (20.0%)
Elevated concentration of other metals	8 (22.9%)
Increased Biochemical Oxygen Demand	4 (11.4%)
Change in pH	7 (20.0%)
Reduced soil porosity	6 (17.1%)
Change in hydraulic conductivity	5 (14.3%)
Change in groundwater color	8 (22.9%)
Increased dissolved solids	3 (8.6%)
Redistribution of DNAPL	4 (11.4%)
Increase in source area volume	0 (0.0%)
Decrease in source area volume	12 (34.3%)
Other	5 (14.3%)
TOTAL SITES WITH SECONDARY GROUNDWATER IMPACTS	**35**



Survey Respondents by Role in Groundwater Remediation Community

Navy ROCS

Dec. 2003

Figure: **4.1**

GeoSyntec Consultants

pie graphs_groups.ai

Number of sites in Survey by location

Not shown:

Alaska - 3

Australia - 1

Canada - 8

Number of sites in Survey with specified technology by location

Not shown:

Alaska - 3

Australia - 1

Canada - 4

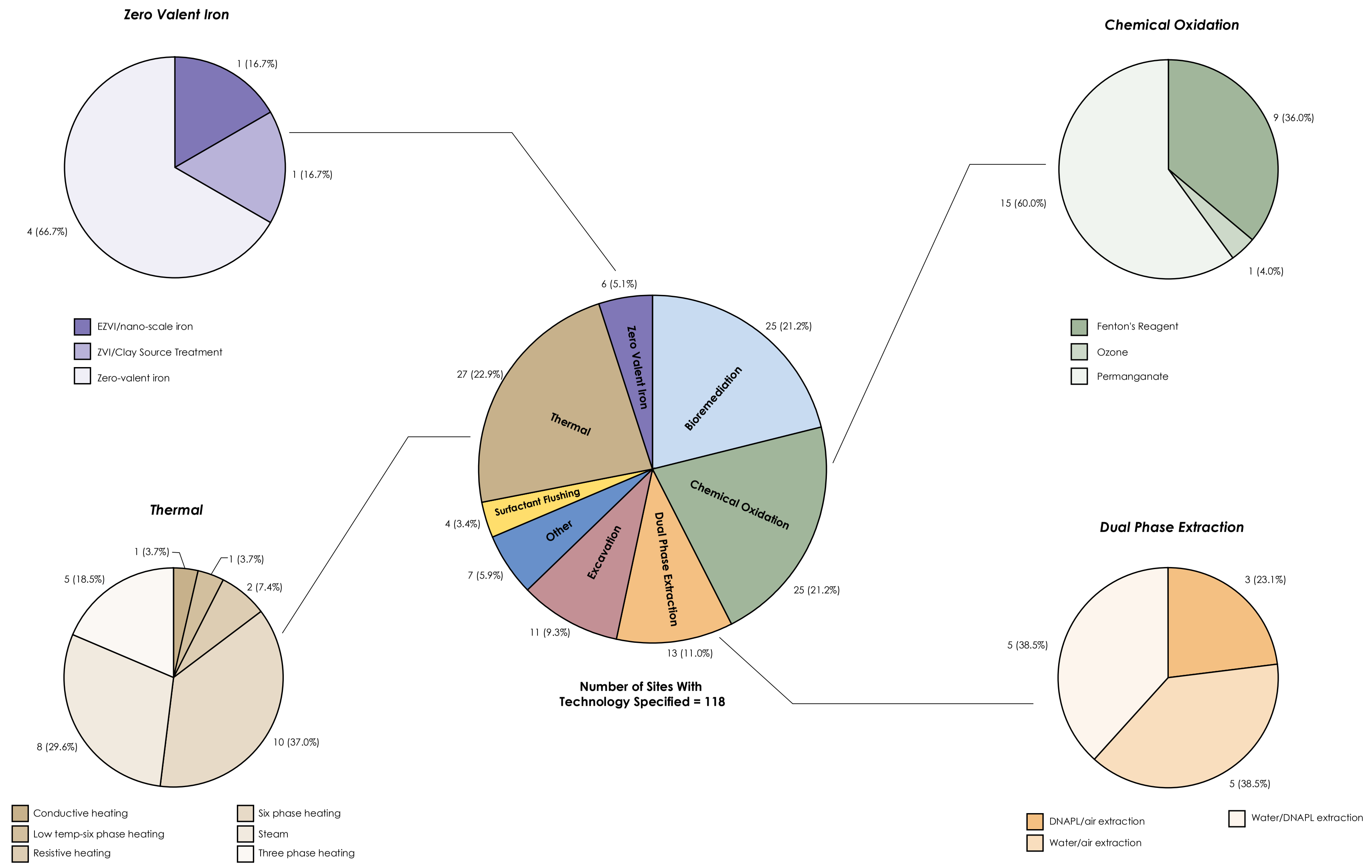
Location of Sites
Navy ROCS

Feb. 2004

Figure: **4.2**

GeoSyntec Consultants

location of sites.ai



Notes: The "other" category consists of 6 undefined technologies, and one site where pump and treat was applied.

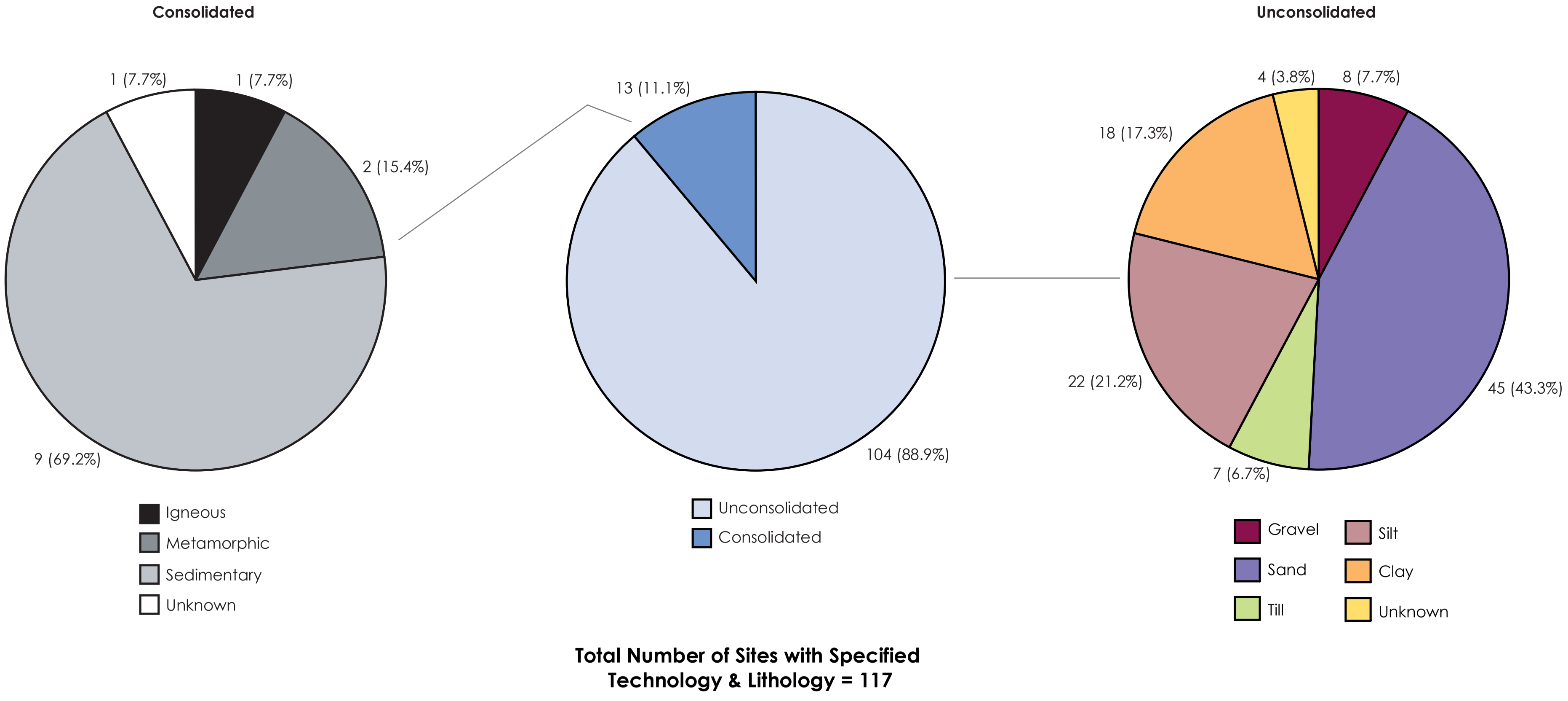
11 (9.0%) = Number of Sites (% of total sites with technology specified)

Number of Sites with Technology
Data Entered in the Survey
Navy ROCS

Dec. 2003

Figure: **4.3**

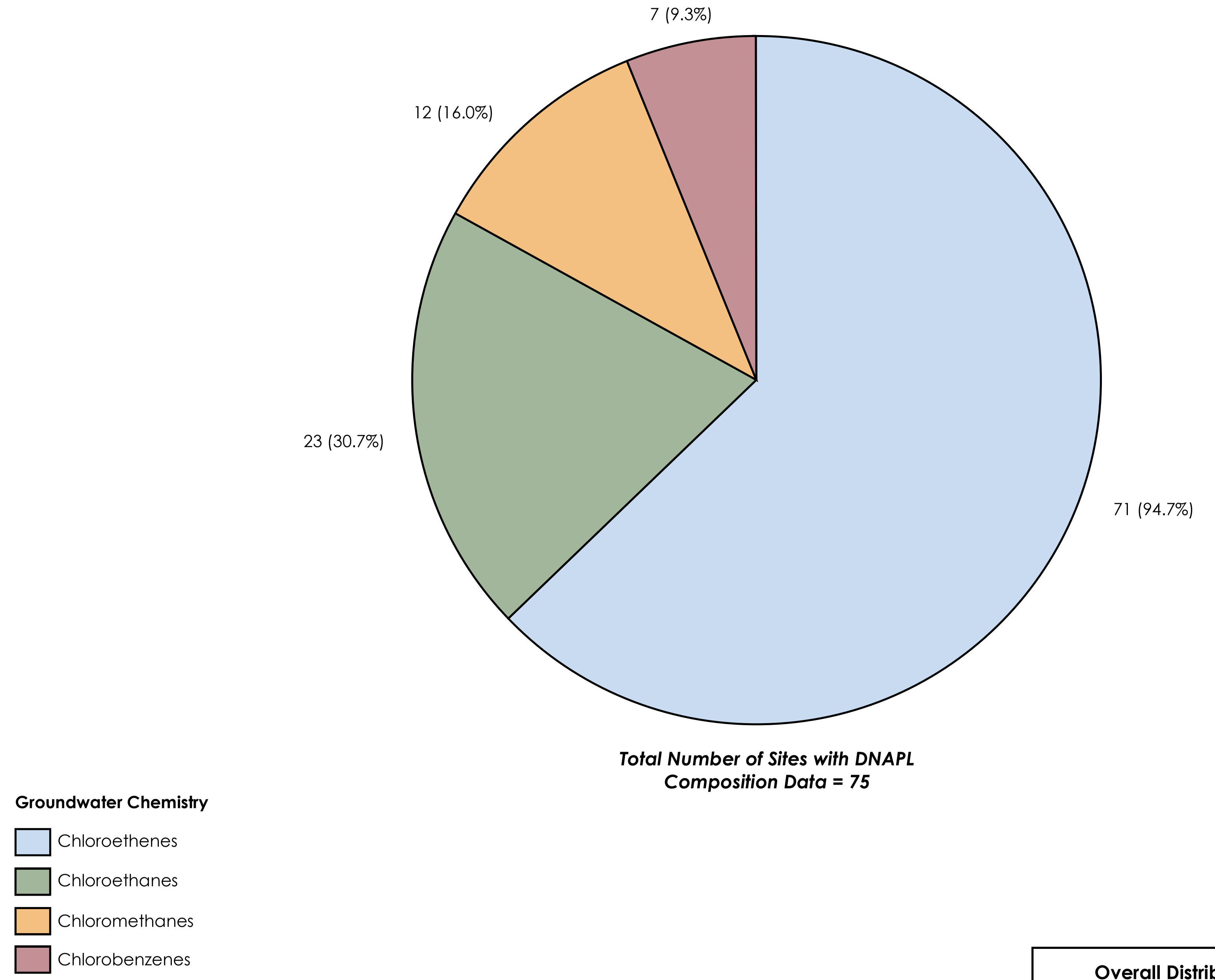
pie graphs_groups.ai



13 (11.1%) = Number of Sites (% of Total)

Number of Sites With Lithology Data Entered Into Survey
Navy ROCS

Dec. 2003	Figure: **4.4**	GeoSyntec Consultants



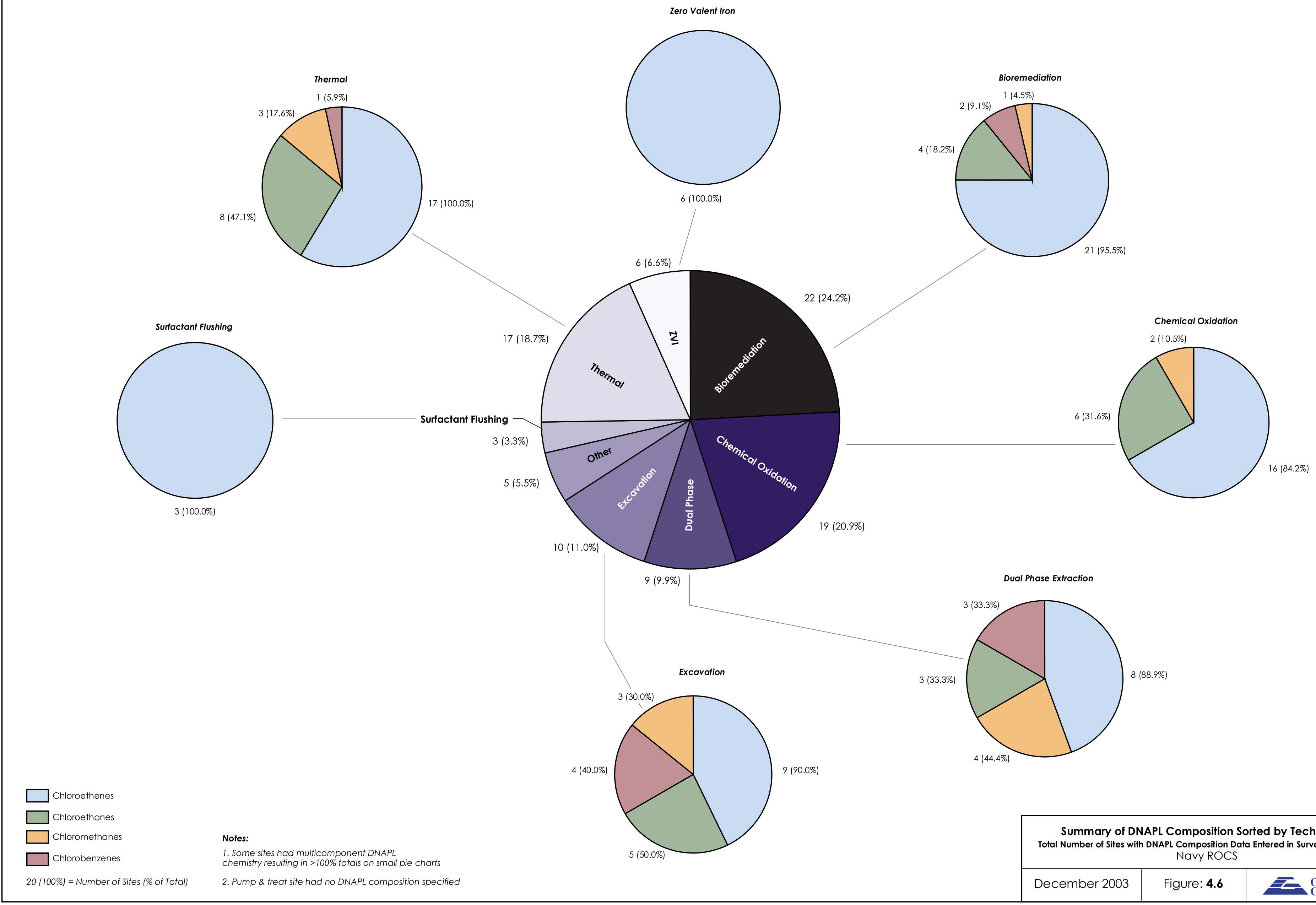
Note: Some sites had multicomponent DNAPL resulting in >100% total

12 (16.0%) = Number of Sites (% of Total)

Overall Distribution of DNAPL Composition
Navy ROCS

Dec. 2003 | Figure: **4.5** | GeoSyntec Consultants

pie graphs_groups.ai



Notes:

1. Some sites had multicomponent DNAPL chemistry resulting in >100% totals on small pie charts

2. Pump & treat site had no DNAPL composition specified

Summary of DNAPL Composition Sorted by Technology

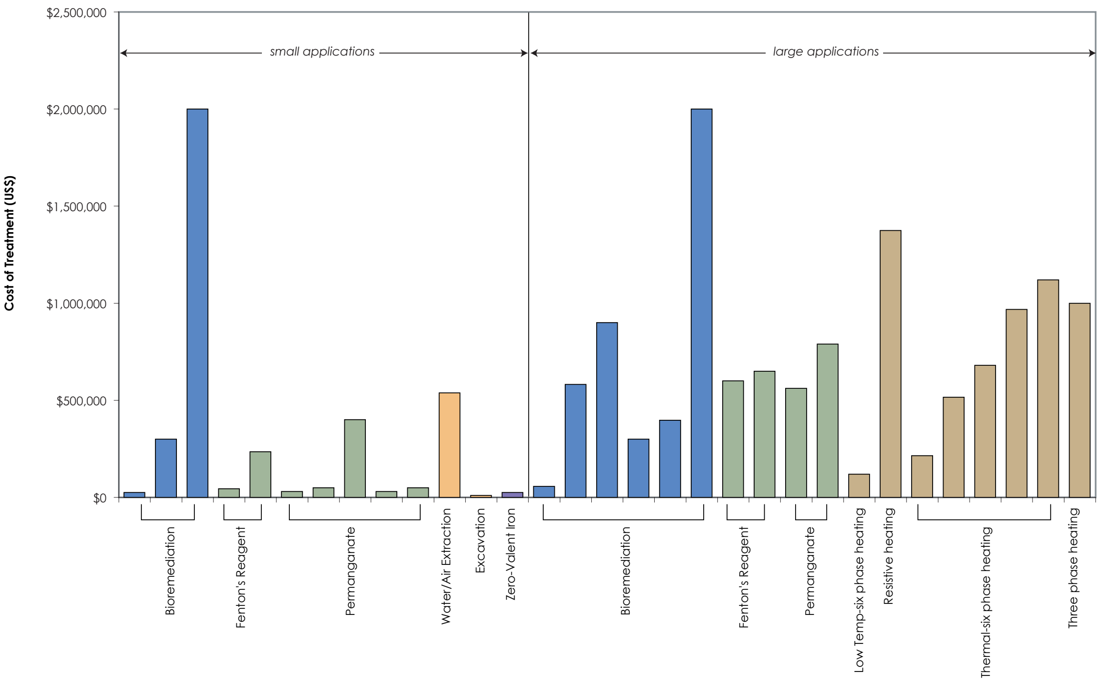
Total Number of Sites with DNAPL Composition Data Entered in Survey (Center Pie)

Navy ROCS

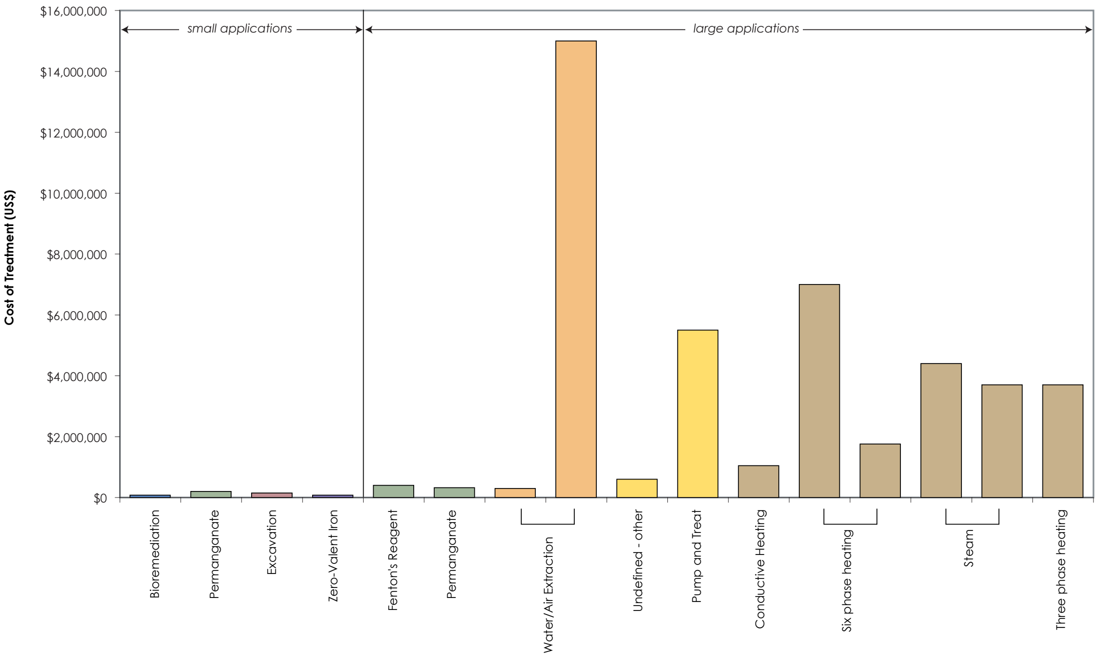
December 2003 | Figure: **4.6** | GeoSyntec Consultants

pie graphs_groups.ai

Pilot-Test Applications



Full-Scale Applications



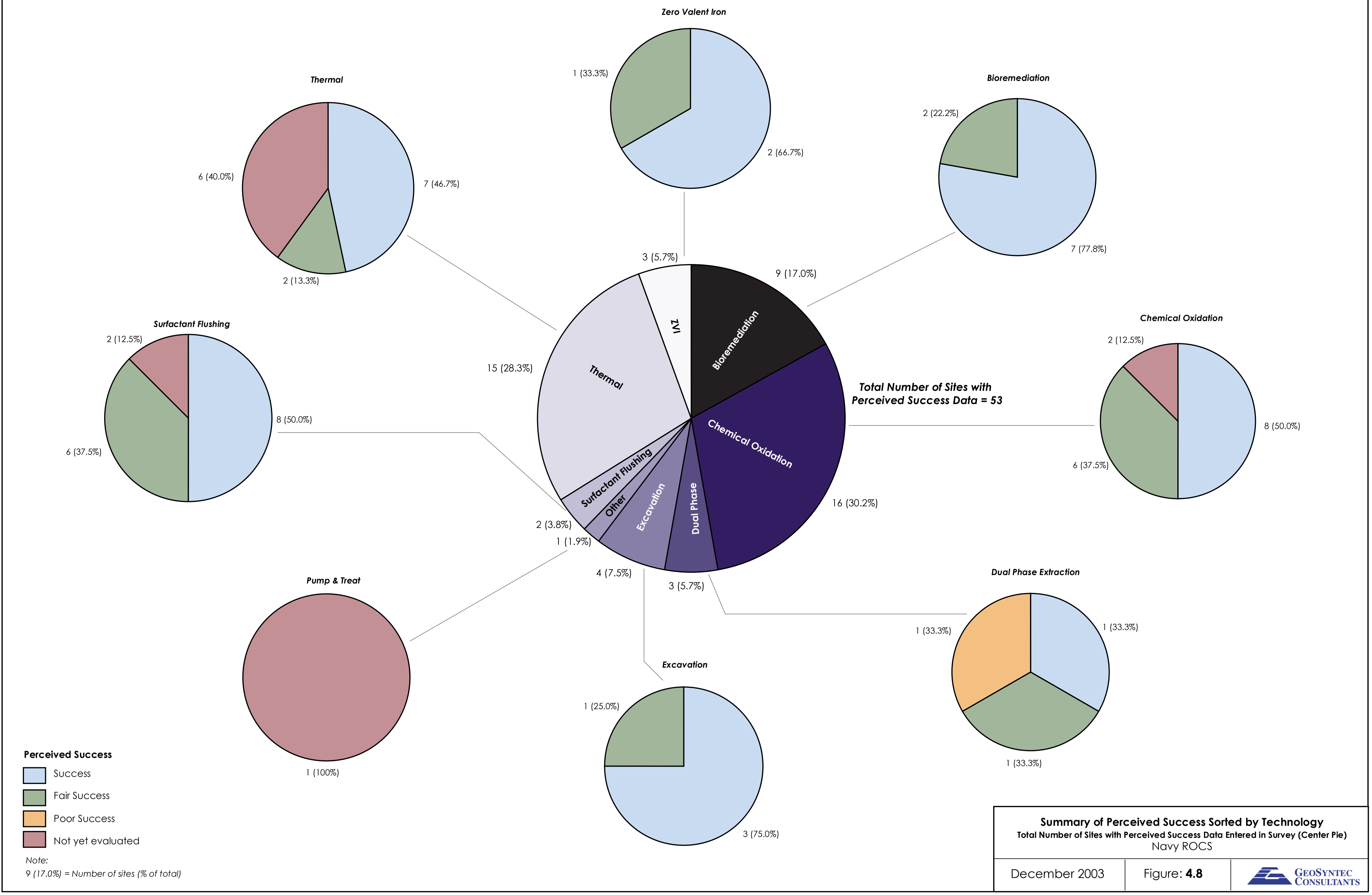
Technology Legend

🟦 Bioremediation	🟫 Thermal
🟩 Chemical Oxidation	🟥 Excavation
🟪 Zero Valent Iron	🟨 Pump and Treat
🟧 Dual Phase Extraction	

bar graphs_groups.ai

Actual Cost of Technology Applications
Navy ROCS

Dec. 2003
Figure: **4.7**
GeoSyntec Consultants

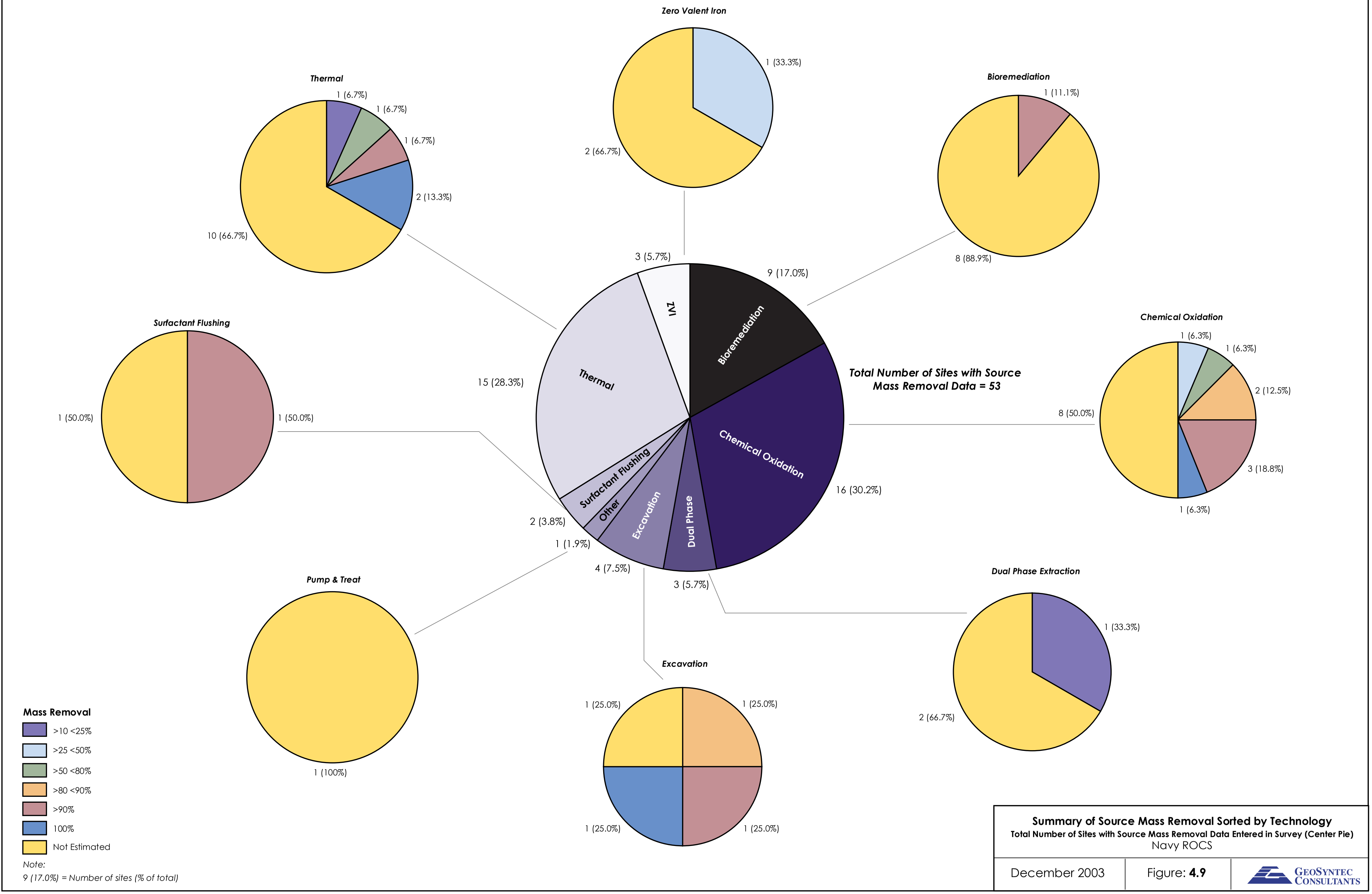


Summary of Perceived Success Sorted by Technology

Total Number of Sites with Perceived Success Data Entered in Survey (Center Pie)

Navy ROCS

December 2003 | Figure: **4.8** | GeoSyntec Consultants



Note:
9 (17.0%) = Number of sites (% of total)

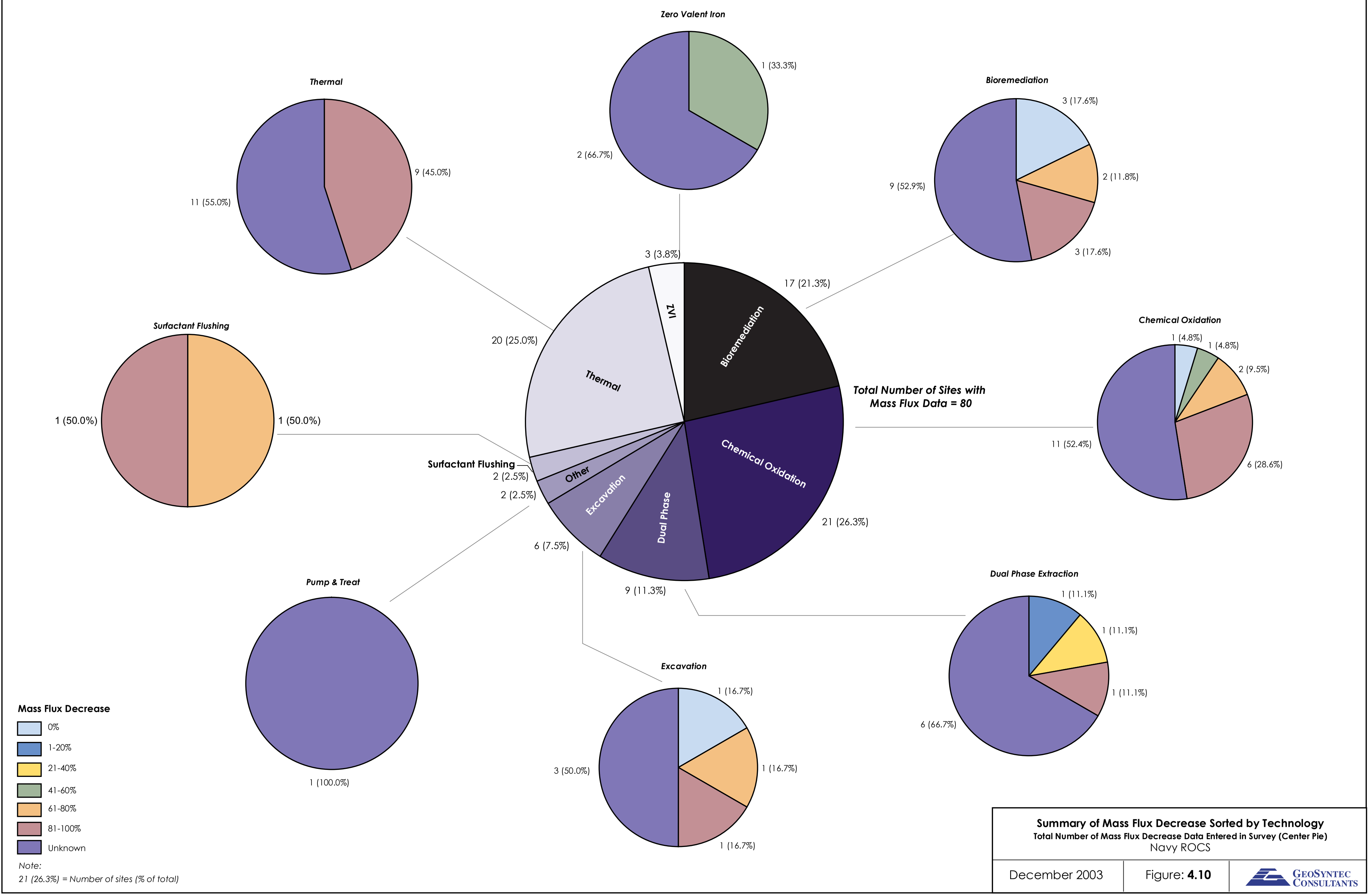
Summary of Source Mass Removal Sorted by Technology
Total Number of Sites with Source Mass Removal Data Entered in Survey (Center Pie)
Navy ROCS

December 2003

Figure: **4.9**

GeoSyntec Consultants

pie graphs_groups.ai



Note:
21 (26.3%) = Number of sites (% of total)

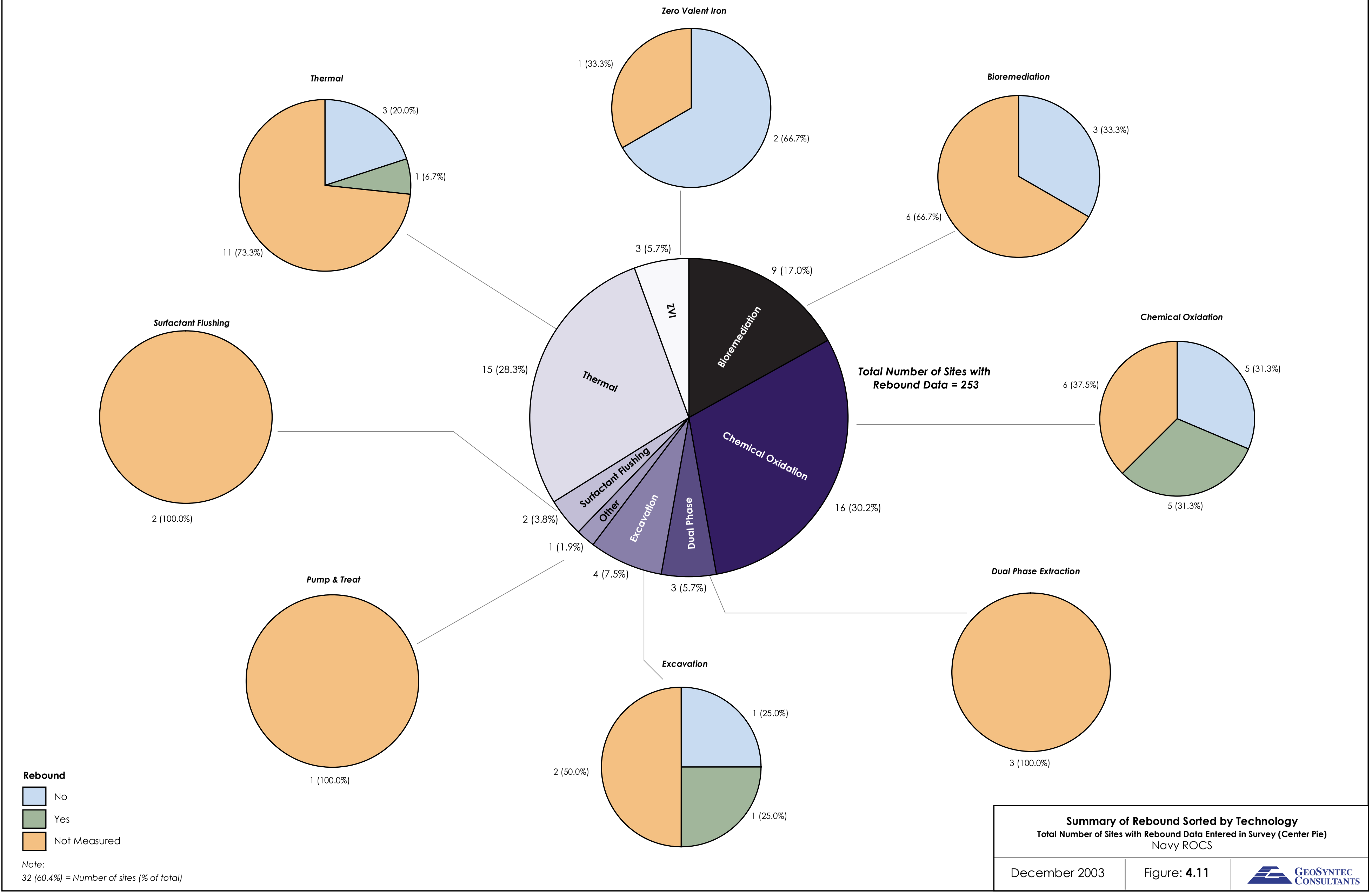
Summary of Mass Flux Decrease Sorted by Technology
Total Number of Mass Flux Decrease Data Entered in Survey (Center Pie)
Navy ROCS

December 2003

Figure: **4.10**

GeoSyntec Consultants

pie graphs_groups.ai



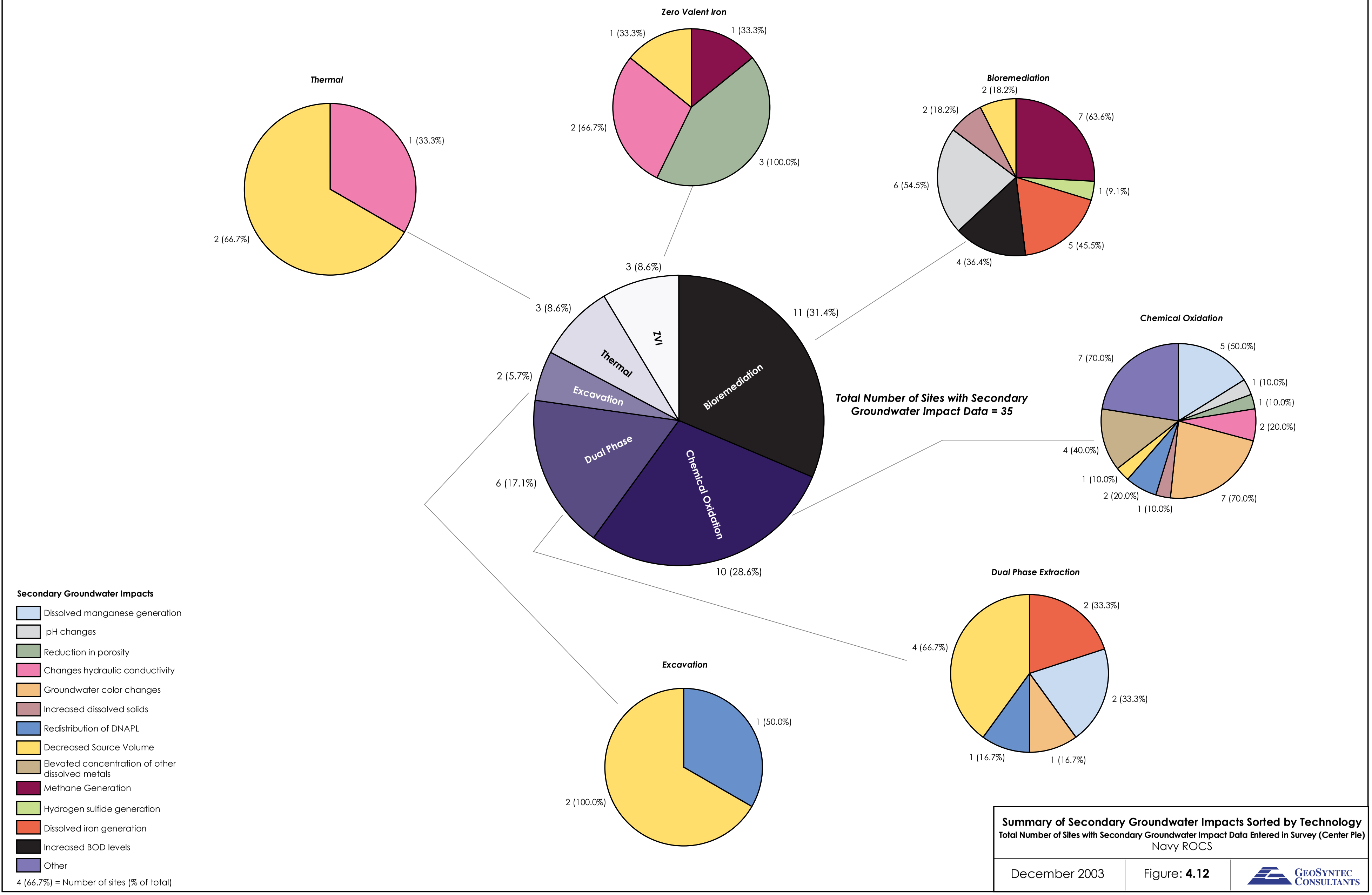
Note:
32 (60.4%) = Number of sites (% of total)

Summary of Rebound Sorted by Technology

Total Number of Sites with Rebound Data Entered in Survey (Center Pie)

Navy ROCS

December 2003 | Figure: **4.11** | GeoSyntec Consultants



Secondary Groundwater Impacts

- Dissolved manganese generation
- pH changes
- Reduction in porosity
- Changes hydraulic conductivity
- Groundwater color changes
- Increased dissolved solids
- Redistribution of DNAPL
- Decreased Source Volume
- Elevated concentration of other dissolved metals
- Methane Generation
- Hydrogen sulfide generation
- Dissolved iron generation
- Increased BOD levels
- Other

4 (66.7%) = Number of sites (% of total)

Summary of Secondary Groundwater Impacts Sorted by Technology

Total Number of Sites with Secondary Groundwater Impact Data Entered in Survey (Center Pie)

Navy ROCS

December 2003 | Figure: **4.12** | GeoSyntec Consultants

pie graphs_groups.ai

APPENDIX A

Case Studies

APPENDIX A: Case Studies

Appendix A contains a limited number of case studies per technology discussed in Section 3. These case studies are included to highlight some of the challenges and advantages associated with each technology, as well as to include examples of how each technology performed for various site characteristics. The information presented in each case study includes a summary of relevant site characteristics, technology application approaches, remedial goals, and lessons learned from each site.

1 Surfactant/Co-Solvent Flushing

One case study each of surfactant and co-solvent flushing are summarized below. The first case study is an outline of the application of a SEAR (surfactant enhanced aquifer remediation) at the Bachman Road Site in Oscada, MI, as described in the U.S EPA report *The DNAPL Remediation Challenge: Is there a Case for Source Depletion?* (In Press) The second case study is an outline of the application of co-solvent (alcohol) flushing at the Sages dry cleaner Site in Jacksonville, FL, as described by Jawiz *et al.* (2000). Table A.1 summarizes the site conditions and remedial activities at the site. Sections 1.1 and 1.2 below include summaries of the treatment operation and lessons learned from each application.

Table A.1: Summary of Surfactant and Co-solvent Case Studies

Parameter	Bachman Road Site	Sages Dry Cleaner Site
Technology description	SEAR for solubilization of source zone	Alcohol flushing of source zone
Soil type	Fine to medium grained glacial outwash sands	Fine to very fine sand to 9 m bgs; very fine to silty sand to 10.7 m bgs; thin clay layer at 10.7 m bgs; very fine to silty sand below
Hydraulic conductivity	15-150 ft per day	6 m/day in fine to very fine sand 3 m/day in very fine to silty sand
Hydraulic gradient	not provided	not provided
Depth to groundwater	11 ft bgs	not provided; source zone saturated
Well yield	not provided	Total system flow 15.1 L/min (3 injection wells; 6 recovery wells)
Contaminants of concern	PCE	PCE

Parameter	**Bachman Road Site**	**Sages Dry Cleaner Site**
NAPL evidence	PCE concentration in groundwater to 88ppm; Free phase in one well and two soil sub-samples from coring	Free-phase in one supply well; groundwater concentration from 70 to 150 mg/L; 196 pre-treatment soil samples with average concentration of 2.8 mg/g
Volume treated	7,500 ft^3	2150 ft^3
Area treated	20 x 25 ft	9 x 24 ft
Depth treated	11-26 ft bgs	7.6 to 9.9 m bgs
DNAPL mass targeted	not provided	Estimated from pre-treatment soil samples as 42 L (67 kg)
Remediation Infrastructure	One extraction well, three injection wells, with three surfactant injection wells between the extraction and injection wells	Three central injection wells; 6 perimeter extraction wells; 7 multilevels (5 each); 2 pore volumes of alcohol added; MPPE above ground treatment system
Remediation Duration	November 1996 to October 1998	8 days active flushing
Remedial Costs	Design and installation $300,000 O&M, reporting, analytical $450,000 Carbon disposal $100,000	not provided
Performance results:		
1) met remedial goals	✓	✓ (removal of substantial fraction of DNAPL)
2) exceeded remedial goals		
3) met MCLs in at least some areas		
4) treatment efficiencies: TCE, etc.	Aqueous VOC concentrations decreased from 4,000 μg/L to 650 μg/L; 1164 lbs TCE mass removed	~60% by soil core and partitioning tracer test
5) DNAPL mass remaining	not quantified	~40%

1.1 Case Study 1: Bachman Road Site, Oscada MI

General operation of the application of SEAR proceeded as follows:

i) Groundwater extraction well operation was initiated at 19.7 L/min followed shortly by startup of three groundwater injection wells (1.9 L/min each). Three surfactant injection wells, placed between the injection and extraction wells were not initially used.

ii) Surfactant injection was preceded by a short-term partitioning tracer test to estimate PCE mass.

iii) Injection of a 6% (by volume) Tween 80 solution into all three surfactant injection wells over 5 days.

iv) Operation of one surfactant injection well was then discontinued, and surfactant addition continued into the other two injection wells for an additional 5 days.

v) In total, 1.5 pore volumes of surfactant solution were added.

vi) Water injection was continued for an additional 2 days after surfactant addition.

vii) The extraction well was operated for an additional month to ensure surfactant and solubilized DNAPL capture.

Hydraulic capture of the solubilized DNAPL was demonstrated with >95% capture of the injected surfactant. Multi-level sampler measurements confirmed the surfactant sweep. A two order of magnitude reduction in groundwater concentrations from multi-level samplers was observed post-demonstration. Post-demonstration degradation products have been observed, suggesting that the surfactant flood stimulated microbial activity. Based upon the results of the pilot test, a full scale application of the technology was being designed at the time of the report.

The predominant lesson learned during the technology application was the importance of complete source zone characterization, since the presence of an untreated upgradient source zone resulted in relatively high PCE concentrations at the extraction well post-demonstration.

1.2 Case Study 2: Sages Dry Cleaner Site, Jacksonville, Fl.

General operation of the application of the alcohol flush proceeded as follows:

i) Pre- and post-demonstration coring and partitioning tracer tests were conducted to evaluate the presence and distribution of PCE in the source zone.

ii) Three injection wells and six extraction wells were used to create hydraulic capture of the source area, with a 2:1 extraction to injection ratio. Injection wells were screened 0.3 m deeper to enhance extraction of the DNAPL. Injection wells were fitted with packers over this period to focus alcohol injection into areas of highest DNAPL saturation, with water injected above the packer.

iii) The ethanol concentration was gradually increased to 95% over the first 10 hours of injection to minimize fluid density differences between injected and resident fluids.

iv) Packers were set at 0.3 m from the bottom of the well for the first 6 hours to flush alcohol immediately below the deepest DNAPL to create a barrier to downward mobilization.

v) Packers were then raised at a rate of approximately 15 cm/hr to maximum heights of 1.7 m at two injection wells and 0.9 m at the third injection well.

vi) After 70 hours of flushing, the packers were lowered back down to 0.3 m at the same rate.

vii) A total of 34 kL (2 pore volumes) of 95% ethanol was delivered into the three injection wells during a period of about 3 days.

viii) Water flooding was initiated at 3.5 days and continued for 4.5 days (4.48 pore volumes).

ix) The total volume flushed was 76 kL of water and ethanol, combined.

x) Monitoring of the demonstration area for biological enhancement was continuing at the time the report was issued.

The remedial goals of the demonstration were as follows:

i) Removal of a significant amount of PCE mass from the source area;

ii) Maximize the efficiency of the DNAPL extraction;

iii) Minimize the potential for DNAPL mobilization; and

iv) Minimize waste disposal costs.

These goals were generally met by the demonstration, although waste costs were increased by the volume of groundwater extracted to ensure hydraulic capture.

Lessons learned during the technology application included the following:

i) High extraction to injection fluid ratio dilutes the extracted fluid, requiring additional treatment capacity and cost.

ii) Results of the pre-demonstration monitoring indicated that the architecture of the DNAPL was discretely distributed, which made it likely that a flushing technology would be inefficient, emphasizing the importance of source zone characterization prior to technology selection.

2 Bioremediation

Two case studies of field applications of enhanced *in situ* bioremediation (EISB) are summarized below. The first case study is the application of EISB to treat a DNAPL source area within overburden and bedrock at the Caldwell Trucking Superfund Site in New Jersey as described by Finn *et al,*(2003). The second case study was conducted at the NASA LC 34 complex in Florida (Battelle, in press). Several applied field demonstrations have recently been completed or are currently being conducted to assess EISB of DNAPL source areas in both porous and fractured bedrock media. Table A.2 summarizes the site conditions and remedial activities at these sites.

Table A.2 Summary of Bioremediation Case Studies

Parameter	Caldwell Trucking	NASA LC34
Technology description	EISB + bioaugmentation with KB-1 ™. Donors used: methanol, ethanol lactate Design: batch addition	EISB + bioaugmentation with KB-1™. Donor used: ethanol Design: recirculation
Soil type	Overburden: basal sand and gravel Bedrock: fractured basalt	Sand
Hydraulic conductivity	Overburden: geomean 1x10-3 cm/sec Bedrock: geomean 2.4x10-5 cm/sec	5.3x10-3 cm/sec
Hydraulic gradient	Overbuden: 0.011 ft/ft Bedrock: 0.017 to 0.56 ft/ft	<0.0001
Depth to groundwater	15 to 20 feet bgs	4 ft
Contaminants of concern	PCE, TCE, 1,1,1-TCA	TCE, cis-DCE, VC
NAPL evidence	60% of aqueous saturation for TCE	Direct measurement of soil concentrations indicative of DNAPL; groundwater concentration at solubility in some locations; known history of TCE DNAPL release into the aquifer
Volume treated	Ca. 16,000 cubic yards	22 ft x 20 ft x 10 ft =4,400 cu. ft (163 cu yd)
Area treated	120x60 ft^2	440 ft^2
Depth treated	120 feet bgs	16 to 26 ft bgs
DNAPL mass targeted	Yes	Yes
Remediation infrastructure	7 injection wells (multi-level) 7 monitoring wells	3 injection and 3 extraction wells, 30 monitoring points
Remediation duration	Pre-full scale evaluation 30 months- currently on-going	Pilot August 2002 to October 2003 (completed)

Parameter	Caldwell Trucking	NASA LC34
Performance results	PCE and TCE: 99.8% reduction from 27,000 ug/L to 50 ug/L; and 680,000 ug/L to 1,400 ug/L, respectively. Corresponding increase in cDCE. VC, and ethene. cDCE and VC are declining, ethene increasing; Result is the expected ROD amendment replacing P&T with bioremediation to treat source area.	Independent determination that VOCs were non-detect in soil within the treatment zone; No evidence that total VOC concentrations as high as 291 mg/L inhibited biodegradation; Ethene concentrations in excess of the stoichiometric chloroethene concentrations measured during the Baseline phase were observed in some performance monitoring wells, suggesting that biodegradation resulted in a mass transfer enhancement; Limited methanogenesis was observed during electron donor addition; Molecular techniques indicated that methanogenic Archaebacteria were not present. Some methanogenesis was observed following bioaugmentation.

3 Chemical Oxidation

One case study each of field applications of permanganate and Fenton's reagent technology are summarized below. No case study was found where ozone was used to treat a chlorinated solvent DNAPL source zone below the water table.

The first case study is an outline of the pilot-scale application of Fenton's reagent at the Savannah River Site in Aiken, South Carolina (US DOE, 1999a). The second case study is a summary of a potassium permanganate pilot test conducted at the Portsmouth Gaseous Diffusion Plant in Piketon, Ohio (US DOE, 1999b). Table A.3 summarizes the site conditions and remedial activities at both of these sites. Sections 3.1 to 3.2 below include summaries of the treatment operation and lessons learned from each application.

Table A.3: Summary of Chemical Oxidation Case Studies

Parameter	Savannah River Site	Portsmouth Gaseous Diffusion Plant
Technology description	Fenton's Reagent	Potassium Permanganate
Soil type	permeable sands with low fines alternating with clayey sand and clay units	silt and clay layer (25 to 30 ft thick), overlying sand and gravel (2 to 10 ft thick),

Parameter	Savannah River Site	Portsmouth Gaseous Diffusion Plant
Hydraulic conductivity	not provided	20 ft/day for horizontal well tests and between 24 and 411 ft/day for vertical well tests
Depth to groundwater	130 ft bgs	not provided
Contaminants of concern	TCE and PCE - DNAPL composition 95% TCE and 5 % PCE	TCE
NAPL evidence	Observed DNAPL in bottom of wells; groundwater concentrations of 120 mg/l PCE and 21 mg/l TCE	Observed DNAPL in wells; 700 mg/l TCE in groundwater.
Volume treated	68,702 ft^3	119,000 ft^3
Area treated	50 X 50 ft^2	90 x 220 ft^2
Depth treated	124 to 152 ft bgs	~30 to 35 ft bgs
DNAPL mass targeted	600 lbs	273 lbs of TCE
Remediation infrastructure	▪ 4 injection wells; ▪ 3 groundwater monitoring wells; ▪ 3 vadose zone monitors; ▪ proprietary injection process	▪ 2 horizontal recirculation wells – 1 injection one extraction well each 220 ft long; ▪ 22 boreholes for pre-demonstration concentrations; ▪ 14 monitoring wells ▪ above ground mixing system including solids feeder, mixing tank and jet pump into well
Remediation duration	6 day period of injection	approximately 30 days
Remedial costs	$511,115 site preparation and operation activities, drilling, construction, operations, sampling, pre and post demonstration characterization, demobilization and reporting and project management.	$562,000 for project management, pre-demonstration characterization, remediation operations and oxidant recirculation, resistivity monitoring, and post demonstration characterization and demobilization
Performance results:	94% destruction of total VOCs,	points where TCE was non-detect but

Parameter	Savannah River Site	Portsmouth Gaseous Diffusion Plant
	95% PCE and 88% TCE	distribution not uniform

3.1 Case Study 1: Fenton's reagent at the Savannah River Site in Aiken, South Carolina.

All italicized text in this section is taken directly from *Innovative Technology Summary Report DOE/EM-0484 Fenton's Reagent*. October 1999*)*.

General operation of the Fenton's reagent application at Savannah River proceeded as follows:

i) *The site selected for the demonstration was an area of approximately 50 foot (ft) by 50 ft adjacent to a known source of DNAPL; a small DNAPL plume located below the water table was treated over a 6-day period.*

ii) *The catalyst solution of 100 parts per million (ppm) ferrous sulfate, pH-adjusted with concentrated sulfuric acid, was initially injected into the subsurface to ensure adequate migration into the formation, while the groundwater pH was adjusted to between 4 and 6.*

iii) *Subsequent injection of the* H_2O_2 *and catalyst utilized a patented mixing and injection process. Injections were conducted in batch mode with one batch injected per day.*

iv) *Following 6 days of injection, the site was characterized to determine treatment efficiency.*

Average contaminant concentrations in the treatment area groundwater were 119.49 mg/l PCE and 21.31 mg/l TCE before treatment and were reduced to 0.65 mg/l PCE and 0.07 mg/l TCE at completion of treatment. The estimated pre-test mass of DNAPL in the treatment zone was 593 lbs; the estimated post-test mass of DNAPL was 36 lbs.

Average pH was 5.71 before treatment and 2.44 at completion of treatment. Change in pH was due to addition of acid to maintain optimal oxidation conditions and, to some extent, due to production of CO_2 *from the oxidation process. After 17 months, pH has risen to 3.4 to 4.0.*

Average baseline groundwater temperature in the treatment zone was 19.2°C; this was raised to a maximum of 34.7°C by the oxidation process. Dissolved oxygen concentrations increased from an average of 9.3 mg/l before treatment to 24 mg/l after treatment. Average baseline chloride concentration was 3.61 mg/l; chloride reached a maximum of 24.33 mg/l at the completion of the treatment process. The increase in chloride concentration verified oxidation of PCE and TCE by the peroxide. Hydrogen peroxide concentrations in the monitoring wells ranged from approximately 2 to 5 ppm.

Monitoring of gases in the headspace of monitoring wells for CO_2*, PCE, and TCE during the injection process indicated:*

i) *Gases were escaping from water in the monitoring wells during injection due to the violent oxidation process.*

ii) *Carbon dioxide levels in these gases rose to over 3,500 ppmv (ambient* CO_2 *levels are approximately 300-400 ppmv). Elevated* CO_2 *levels verified DNAPL oxidation in the subsurface.*

iii) *PCE (from 0 to 190 ppmv) and TCE (0 to 80 ppmv) were evident in the vapor and can be attributed to sparging of water in the wells.*

Lessons learned during the technology application included the following:

Design Issues:

i) *The efficiency of the process increases at higher contaminant concentrations and decreases as target treatment levels become more stringent.*

ii) *Higher* H_2O_2 *concentrations provide faster reaction times, significantly greater removal of DNAPL type contaminants, but less efficient* H_2O_2 *use.*

iii) *Highly alkaline soils may require mineral acid addition to bring the pH into the optimal range.*

iv) *Organic carbon content may impact treatment because the hydroxyl radical is relatively nonselective. However, no significant effect was observed with contaminant levels of 500-2000 ppm with total organic carbon of 0.1 to 1.3 (Watts et al. 1994. "On site treatment of contaminated soils using hydrogen peroxide." Project Report T9234-06, Washington State Transport Center, Washington State University).*

v) For in situ groundwater treatment, the number and pattern of injectors and monitoring wells must be designed to ensure maximum coverage of the treatment zone. Because the cost is related to depth (cost per well was approximately $70/ft) and amount of DNAPL, the number and spacing of the wells becomes critical. The heterogeneity of the subsurface at the site will also control the number and spacing of wells required.

vi) Duration of operation is not a linear function of volume of DNAPL. Factors affecting the duration of the treatment include: permeability, heterogeneity, and geochemistry of the aquifer.

Implementation Considerations:

i) When implementing in situ oxidation using Fenton's Reagent, general operation considerations include:

  - *pH of the system must be between 3 and 6.*
  - *The rate of the reaction increases with increasing temperature (although the efficiency declines above 40 to 50°C*
  - *For most applications the valence of the iron salts used doesn't matter (+2 versus +3) nor does it matter whether a chloride or sulfate salt of the iron is used, although chlorine salts may generate high rates of chloride during application.*
  - *Due to oxidation of the subsurface, metals that are mobile under these conditions may be released at some sites. This should be considered during the technology selection process.*

ii) Implementation of this technology does not require permanent infrastructure, such as a permanent power source (temporary power is required), permanent water and chemical tanks, etc. Temporary power is required for operation of the system. This is much less expensive for the short duration of operation, typically less than 1 month and in many instances 1 to 2 weeks. Also required is a constant supply of water for process, as well as emergency, purposes. For remote sites where a distribution line with potable water is not available tanks for water storage are appropriate. During the demonstration, approximately 1000 gallons of water per day were used for a 6-day period.

iii) *The end products of in situ oxidation are very appealing. No waste is generated from the treatment process, and no material is brought to the surface.*

iv) *At complex sites in situ oxidation using Fenton's Reagent should be considered in tandem with other technologies. For example, if in situ bioremediation is considered as a polishing step, the pH should be held above 4.0 during the treatment operations.*

Needs for Future Development:

i) *The effects on the aquifer geochemistry and microbiology in the treatment zone need to be better understood. Because in situ oxidation is a very robust chemical reaction, a reasonable assumption is that most of the microbial population was destroyed during the reaction. The type of microbial activity that will return to the area and to what extent is not known.*

ii) *During the demonstration, the pH dropped dramatically from an average pH of 5.7 before treatment to 2.4 at completion of treatment. Post-test treatment has shown a very slow rebound of the groundwater pH. Three months after completion of the test, the groundwater pH remained at approximately 3.5.*

3.2 Case Study 2: Potassium permanganate pilot test conducted at the Portsmouth Gaseous Diffusion Plant in Piketon, Ohio.

All italicized text in the section is taken directly from: *Innovative Technology Summary Report DOE/EM-0496 In Situ Chemical Oxidation Using Potassium Permanganate.* September 1999.

General operation of the potassium permanganate pilot study to remove TCE DNAPL at the Portsmouth Gaseous Diffusion Plant (PORTS) proceeded as follows:

i) *The demonstration at PORTS was implemented using a pair of parallel horizontal wells with 200-foot (ft) screened sections located in a 5-ft thick silty, gravel aquifer within the center of a groundwater plume originating from a known source of DNAPL.*

ii) *Crystalline KMnO4 was added to groundwater extracted from the upgradient well and re-injected into the downgradient well approximately 90 feet from the extraction well.*

iii) *Oxidant solution (~2% KMnO4) was recirculated through the horizontal wells for approximately one month.*

iv) *Subsequent injection of KMnO4 into a nearby vertical well was conducted for 8 days to enhance uniform delivery of the oxidant in the region between the horizontal wells.*

Key results of the pilot test include:

i) *Lateral and vertical heterogeneities within the aquifer significantly impacted uniform delivery of the oxidant through the horizontal wells.*

ii) *Significant reductions in TCE were measured in both groundwater and soil samples in areas where the oxidant was delivered. During post-treatment sampling, TCE was not detected (< 5 parts per billion [ppb]) in samples collected from the monitoring wells and soil borings in locations where the oxidant had permeated. However, because oxidant delivery was not uniform, TCE was not reduced to non-detectable levels in all groundwater and soil samples.*

Lessons learned during the technology application included the following:

Design Issues

i) *The recirculation concept of introducing permanganate into the subsurface is viable. Oxidant injection without extraction is feasible; however, there is no control in the subsequent movement of the oxidant after its release. Hence, recirculation is likely a preferable mode of operation.*

ii) *Lateral heterogeneities impact the delivery of oxidants through the horizontal wells; whereas, vertical heterogeneities impact the delivery of oxidants through vertical wells.*

iii) *If a recirculation approach is used to deliver the oxidant to the subsurface, a system for handling precipitated solids may need to be* *incorporated into the treatment system for higher oxidant dosing rates and higher contaminant concentrations.*

iv) *Higher permanganate concentrations provide faster reaction times, significantly greater removal of DNAPL-type contaminants, but less-efficient oxidant use due to the natural oxidant demand of the subsurface.*

v) *Typical treatment ratios for reagent ($KMnO_4$) to contaminant are greater than 5:1 based on field and laboratory studies. The efficiency of the process increases at higher contaminant concentrations and decreases as target treatment levels become more stringent.*

vi) *Organic carbon content may impact treatment because the permanganate is relatively nonselective. However, no significant effect was observed with contaminant levels near 850 mg/l and total organic carbon of 0.1 to 1.3%.*

vii) *For in situ groundwater treatment, the number and pattern of injection and extraction wells and monitoring wells must be designed to ensure maximum coverage of the treatment zone. Because the cost is related to depth and amount of DNAPL, the number and spacing of the wells becomes critical.*

Implementation Considerations

i) *Formation Characteristics:*

  - *Soil and groundwater pH - Permanganate is effective over a pH range of 3 to 12 with an optimum near 7.*
  - *Soil and groundwater Eh - Background redox conditions must be defined to determine potential impacts on speciation and mobility of non-target metals.*
  - *Soil and groundwater TOC - Ambient TOC can exert a demand on oxidant. Low TOC (<0.5%) is preferred to limit such demand or excess reagent will be required. This will increase costs.*
  - *Soil and groundwater temperature - Temperature can impact reaction rates. Extremely low temperatures (e.g., < 10ºC) slow reaction rates appreciably; so higher temperatures are preferred.*

- *Soil and groundwater alkalinity and ionic strength - High carbonate alkalinity can impact free radical oxidation by scavenging the free radicals produced and limiting oxidation efficiency. High ionic strength (e.g., by salts) can reduce reaction rates.*

ii) *Contaminant Properties:*

- *Type and concentration - Applicable to unsaturated halocarbons (PCE, TCE, DCE), aromatics (BTEX), and polyaromatic hydrocarbons (phenols, naphthalene). May mobilize some redox sensitive metals in some settings.*
- *Presence of co-contaminants - May alter subsurface biogeochemistry and locally mobilize co-contaminants (e.g., redox sensitive metals such as Cr). Manganese oxides may sorb radionuclides.*

iii) *Treatment Process Characteristics:*

- *Delivered oxidant composition - High concentrations may be needed to deliver adequate oxidant mass in a limited volume that is advected in the system.*
- *Handling and Safety - Depending on concentrations and form, permanganate is a strong oxidizer and is incompatible with combustibles. Care is required during handling.*
- *Reactivity and effects on formation matrix - Permanganates can lead to some matrix plugging due to precipitation of MnO_2 solids.*

iv) *Injection and extraction wells may eventually become clogged from entrained silt, biological growth, mineral precipitates or other factors, but this effect appeared to be minor based on field demonstrations. Well and matrix clogging is expected to be more apparent during applications of oxidant injection/recirculation at higher oxidant concentrations and within areas of suspected DNAPL.*

Needs for Future Development

- *Natural oxidant demand within a treatment area as related to oxidant dosing requirements needs to be better understood.*

- *Optimization of the oxidant to contaminant ratio must be further evaluated. While lower oxidant concentrations have been shown to be effective in the field, the residual concentrations may not be sufficient to treat contaminants within lower permeability zones. Higher oxidant concentrations will provide better residual oxidant for diffusion into the lower permeability areas, but may result in less efficient oxidant used (residual oxidant will be consumed by the natural oxidant demand within the matrix).*

4 Thermal Technologies

Three case studies of field applications of three variations of the thermal technology are summarized below. The first case study is an outline of the application of a combination of steam flushing and electro-thermal dynamic stripping (ET-DSP^{TM}) completed at the Pinellas Environmental Restoration Project: Northeast Site Area A, Young-Rainey Science, Technology and Research Center in Largo, Florida (U.S. Department of Energy, 2003). The second case study is a summary of an ERH pilot test conducted at Launch Complex 34, Cape Canaveral, Florida (Battelle, 2003). The third case study summarizes the results from an ECH demonstration conducted at the Shell Technology Ventures site in Portland, Indiana (Vinegar *et al.,* 1999). Table A.4 summarizes the site conditions and remedial activities at each of these sites. Sections 4.1 and 4.2 below include summaries of the treatment operation and lessons learned from each application.

Table A.4: Summary of Thermal Technologies Case Studies

Parameter	**Pinellas Northeast Site Area A**	**Launch Complex 34, Cape Canaveral**	**Shell Technology Ventures**
Technology description	Steam flushing and ET-DSP™	Electrical Resistive Heating	Electrical Conductive Heating
Soil type	sand; silty clay with some visible gravel	fine to medium sized sand, clay and shell fragments	Fill 1to 7 feet bgs; till to 18 ft bgs; sand and gravel 18-30 ft bgs
Hydraulic conductivity	1X10^{-3} cm/s	1.3 to 2.3 ft/day	not provided; effective permeability 2.5 X 10^{-8} cm/s
Hydraulic gradient	very low	0.00009 to 0.00007 ft/ft	not provided
Depth to groundwater	1 to 6 ft bgs	4-5 ft bgs	22-25 ft bgs
Well yield	steam injection rates 100 to 5,000 lbs/hr vapor injection rates 1 to 10 scfm per well extraction rates during heating typically 30 gpm	not provided	not provided
Contaminants of concern	TCE, cis-1,2-DCE, methylene chloride, toluene, petroleum range organics	TCE	PCE, TCE in 1st area; 1,1-DCE in 2nd area
NAPL evidence	soil concentrations: TCE up to 1,000 mg/kg	soil concentrations: TCE greater than 300 mg/kg theoretical threshold for DNAPL	soil concentrations: PCE, TCE, 1,1-DCE, 3,500, 79 and 0.65 ppm, respectively
Volume treated	13,000 yd^3	not provided	6,500 tons
Area treated	10,000 ft^2	75 ft X 50 ft	1st area 7,500 ft^2; 2nd area 600 ft^2
Depth treated	ground surface to 35 ft bgs	ground surface to 45 ft bgs	ground surface to 18 ft bgs (1st area), 11 ft bgs (2nd area)
DNAPL mass targeted	3,000 lbs	24,889 lbs	not provided

Parameter	Pinellas Northeast Site Area A	Launch Complex 34, Cape Canaveral	Shell Technology Ventures
Remediation infrastructure	15 steam injection wells; 28 extraction wells; 21 combined steam-ET-DSP^{TM}; 2 deep ET-DSP^{TM} electrodes	13 electrodes; 12 SVE wells 4-6 ft bgs;	1st Area:136 heater /suction wells 2nd Area:18 heater/suction wells dewatering trench in 1st area to remove excess groundwater Temperature monitoring at 91 locations
Remediation duration	Sept. 26, 2002- Mar. 24, 2003	Aug. 18, 2000-Sept. 19, 2001	Completed during 1997
Remedial costs	$3,800,000 including design, permitting, drilling, construction, operations, sampling, waste disposal, demobilization and reporting.	$613,000 for demonstration and disposal; $255,000 for pre-demonstration characterization	not provided
Performance results:			
1) met remedial goals	✓	✓	✓
2) exceeded remedial goals	✓	✓	✓
3) met MCLs in at least some areas	✓		✓
4) treatment efficiencies: TCE, etc.	TCE: 99.986% Toluene: 99.888% Methylene chloride: 99.989% Cis-1,2-DCE: 99.852% TPH: 61%	TCE: 97%	lowest treatment efficiency 98.4% for PCE (calculated from soil analyses)
5) DNAPL mass remaining	1 lb	estimated at 3% of initial mass	mass estimates not provided

4.1 Case Study 1: Steam Flushing and Electro-Thermal Dynamic Stripping Process Applied at Pinellas Northeast Site Area A, Largo, Florida.

General operation of the application of steam flushing and electro-thermal dynamic stripping process proceeded as follows:

i) Hydraulic and pneumatic controls were established by liquid and vapor extraction.

ii) Heating of the perimeter and bottom, while maintaining hydraulic control was achieved one month later.

iii) Heating of all of Area A to the target temperature, using combined steam injection and ET-DSP, was achieved in the following two weeks, while maintaining hydraulic and pneumatic control.

iv) NAPL mass recovery continued under pressure cycling and mass removal optimization conditions for a further 3 months. Pressure cycling continued until recovery entered a "diminishing returns" pattern.

v) Cool-down and polishing, involving continued vapor and liquid extraction combined with air and cold water injection followed for a one month period.

As seen in Table A.4 above, the remedial action was deemed to have met or exceeded (below MCLs were achieved in many locations) the remedial objectives. The remedial objectives were to meet the cleanup criteria listed in Table 1 below within the specified time period (pp.5-6 and Table 1 of the source document (U.S DOE, 2003):

"Table 1. Contaminants of Concern and Remediation Goals"

Chemical	***Ground Water Cleanup Goal (μg/L)***	***Soil Cleanup Goal (μg/kg)***
TCE	*11,000*	*20,400*
Cis-1,2-DCE	*50,000*	*71,000*
Methylene Chloride	*20,000*	*227,000*
Toluene	*5,500*	*15,000*
TPH - FL-PRO	*50,000*	*2,500,000*

Hydraulic control of the NAPL and dissolved phase had to be achieved at all times, and the cleanup criteria had to be met for a 24 month period following cessation of remedial activities.

Lessons learned during the technology application included the following:

i) Reduction of the water discharge rate would be achievable by re-circulation of treated water, and/or lowering of the water addition rate to the treatment volume.

ii) The extraction wells were observed to rise during curing and operation, leading to well grout seals near the surface requiring repair and maintenance. It would be desirable to prevent this expansion and the resulting asphalt cracking around the wells.

iii) The air stripper had an average treatment efficiency of 73 percent, which is very low. The efficiency could be increased by the use of de-foaming agents, de-scaling agent, or other methods. Routine inspection and maintenance of the air stripper is necessary.

iv) The liquid GAC system experienced operational problems that included fouling by precipitation of inorganics, and potentially biological growth. More focus should be given to prevention of the formation of these. The vapor GAC system should be made more robust for the periods of peak VOC recovery in the V-1 stream. Options include:

- Design for total of subsurface vapors and air stripper off-gas;
- Include more GAC vessels or larger vessels; and
- Automate regeneration based on breakthrough monitoring.

v) The vapor treatment of vinyl chloride and methylene chloride were problematic. A different vapor treatment system should be considered (*e.g.*, thermal oxidation or catalytic oxidation).

vi) ERT was not effective at monitoring subsurface temperatures. The high dissolved solids in the ground water may have prevented the resistivity effects from temperature from being distinguishable, thus preventing ERT from being effective.

4.2 Case Study 2: ERH Applied at the LC34 site at Cape Canaveral, Florida.

ERH was applied in a pilot study at the site to remove TCE DNAPL. General operation of the application of ERH process proceeded as follows:

i) Pre-demonstration characterization of VOC concentrations in soil inside demonstration area.

ii) Heat application with concurrent SVE for 43 days, followed by a 77 day break in heat application due to hurricane damage to transformer.

iii) Second heat application with concurrent SVE for 98 days. Electrodes are upgraded during this period to enhance power input. This heating period was followed by a 48 day break due to rocket launches.

iv) Third heat application with concurrent SVE for 62 days.

v) Cool down and concurrent SVE for 79 days to evacuate any *in situ* TCE vapors during the cool-down phase.

vi) Post-demonstration soil samples collected to characterize VOC distribution in demonstration area.

The demonstration exceeded the remedial objective of 90% removal of VOC mass in the demonstration area, by achieving an average of 97% removal. However, there was some evidence that VOCs may have migrated outside of the demonstration area and VOC vapors were measured in the ambient air surrounding the demonstration area, indicating that the pneumatic and hydraulic controls for the demonstration were not sufficient to control VOC migration.

Lessons learned during the technology application included the following:

i) Cis-1,2-DCE was generated inside the demonstration area during the ERH application. The optimal enhancement of intrinsic bioremediation requires further study.

ii) There was some evidence that VOCs migrated outside of the demonstration area based upon post-demonstration sampling. A mechanism for channeling vertically migrating vapors through less conductive layers would have been useful in aiding the prevention of VOC migration. In addition, hydraulic and pneumatic control may have also helped.

iii) A novel electrode design, consisting of an electrical cable attached to a ground rod within a graphite fill proved ineffective at the site due to excessive rainfall.

iv) There was some loss of TCE to the ambient air during the heat application, indicating that the SVE system was not sufficiently efficient. The relatively shallow vadose zone may have played a role in vapor losses to the ground surface.

4.3 Case Study 3: ECH Process Applied at Shell Technology Ventures site in Portland, Indiana.

The ECH demonstration was conducted to remove PCE, TCE and 1,1-DCE from two areas at the site. General operation of ECH proceeded as follows:

i) Extraction of any liquids removable via pumping and/or SVE. A dewatering trench was installed after pumping failed to dewater one area of the demonstration area.

ii) Heating of soil for 40-60 days, with concurrent monitoring of *in situ* temperature and pressure distribution, HCl in off-gas (indicating extracted VOCs). Three quarters of the site reached steam superheat temperatures over this period, and all areas exceeded the boiling point of water.

iii) Soil sampling from 50 points to confirm VOC removal in coolest areas prior to shutdown of heating.

iv) Heating was discontinued and soil temperature was monitored for a six month period over which it decreased to below 100 ^{o}C.

v) Confirmatory soil sampling.

vi) Resodding of soil to accelerate natural revegetation.

The remedial action was deemed to meet the remedial objectives, with all samples below 0.5 ppm PCE and 0.02 ppm TCE. Soil samples collected along the perimeter of the demonstration area showed that contaminants were not spread outside of the heated area by the heat application.

Lessons learned during the technology application included the following:

i) High groundwater influx led to lower achieved temperature increases even with perimeter drains to control influx. However, steam distillation was sufficient to remove VOCs in this area.

ii) Heating of subsurface resulted in death of ground cover, which required resodding.

5 ZVI Case Studies

One case study each for field applications of zero-valent iron (ZVI) jetted as a slurry with clay and nano scale ZVI mixed into emulsified vegetable oil prior to injection (EZVI) are included below. The ZVI and clay slurry was a full-scale application at DuPont's Kinston plant, Kinston, NC (EPA, In Press). The EZVI case study describes a pilot scale application of EZVI at Launch Complex 34 Cape Canaveral Air Force Station, FL (O'Hara *et al*., 2003). Table A.5 summarizes the site conditions and remedial activities at the sites. Sections 5.1 and 5.2 below include summaries of the treatment operations and lessons learned from each application.

Table A.5 Summaries of ZVI Case Studies

Parameter	Launch Complex 34, Cape Canaveral	Kinston, NC
Technology description	EZVI with nano-scale ZVI	ZVI and clay slurry injection by jetting
Soil type	fine to medium sized sand, clay and shell fragments	15 – 18 ft of sand overlying confining mudstone layer
Hydraulic conductivity	1.3 to 2.3 ft/day	not provided; groundwater velocity 0.05 to 0.1 ft/d
Hydraulic gradient	0.00009 to 0.00007 ft/ft	not provided
Depth to groundwater	4-5 ft bgs	4-5 ft bgs
Well yield	not provided	not provided
Contaminants of	TCE	TCE

Parameter	Launch Complex 34, Cape Canaveral	Kinston, NC
concern		
NAPL evidence	soil concentrations: TCE greater than 300 mg/kg theoretical threshold for DNAPL	soil concentrations: TCE, from 10 to 100 mg/kg and groundwater concentrations of 50 to 60 mg/l
Volume treated	1080 ft^3	not provided
Area treated	9 ft X 15 ft	~30 ft diameter zone
Depth treated	16 to 24 ft bgs	ground surface to 18 ft bgs
DNAPL mass targeted	up to 46 kg	not provided
Remediation Infrastructure	▪ 8 injection wells; ▪ 4 recirculation wells ▪ 4 5-point multilevel monitoring wells; ▪ 7 monitoring wells ▪ 12 soil core locations	▪ 16 pre- and post-injection soil core locations ▪ monitoring wells ▪ 11 treatment (ZVI/Clay) columns emplaced ▪ low K cofferdam of jetted clay/ZVI surrounding source and treatment columns
Remediation Duration	EZVI injection was 3 days, post injection monitoring for 6 months	Completed during 1999
Remedial Costs	not provided	not provided

Parameter	Launch Complex 34, Cape Canaveral	Kinston, NC
Performance results:		
1) met remedial goals	✓	some goals met – mixing not as effective on a particle scale but on inches scale. Jetting appears to have effective in creating sufficient mixing through most of source zone
2) exceeded remedial goals	Where EZVI was present exceeded goal of 50% mass reduction	
3) met MCLs in at least some areas		
4) treatment efficiencies: TCE, etc.	TCE: ~58% based on soil cores ~56% based on mass flux reduction (up to 100% in zones with good EZVI distribution	
5) DNAPL mass remaining	estimated at 42% of initial mass	mass estimates not provided

5.1 Case Study 1: EZVI at LC34 Cape Canaveral Florida.

General operation of the application of EZVI process proceeded as follows:

i) A set of 6 pre-demonstration cores, sampled in 2-ft sections and fully extracted using methanol were collected within the 9.5 x 15 ft pilot test area to estimate DNAPL mass and distribution;

ii) A complete set of groundwater samples from four 5-point multilevel (20 samples) and five fully screen wells collected to get baseline groundwater conditions;

iii) Based on soil and groundwater concentrations the DNAPL was not evenly distributed through the treatment area. The bulk of the DNAPL mass appeared to be located in the southwest corner of the pilot test area and at depths of approximately 18 and 24 ft bgs.

iv) EZVI injected into 8 wells at two depth intervals (20 to 24 ft bgs and 16 to 20 ft bgs) using pressure pulse technology. Pressure pulse technology uses a process of periodic (*e.g.*, 1 pulse per second) large-impulse hydraulic excitations to introduce hydraulic strain energy into the formation to minimize fingering and help fluid flow.

v) Total of 750 gal of EZVI injected into treatment area.

vi) Approximately 1.5 months after injection, a set of interim cores were collected in the test cell to determine distribution of the EZVI and measure degradation.

vii) Groundwater samples were collected weekly from a subset of wells for a period of 4 months.

viii) A set of 6 post-demonstration cores were collected, sampled in 2-ft sections and fully extracted using methanol were collected within the 9.5 x 15 ft pilot test area to estimate post treatment DNAPL mass and distribution.

ix) A set of groundwater samples from all sampling points was collected to evaluate mass flux reduction.

As shown in the table above, the treatment goal of 50% reduction in TCE concentrations was met based on both the soil core results and groundwater results.

Lessons learned during the technology application included the following:

i) EZVI was not evenly distributed , with significant fingering and preferential flow paths;

ii) EZVI appeared to have traveled upwards from the injection depth intervals despite being a DNAPL;

iii) Oil and surfactant in the EZVI appeared to contribute significantly to the degradation observed due to enhanced biodegradation;

iv) Ongoing work on improving delivery mechanisms for the EZVI and investigation of the amount of contribution from biodegradation are needed.

5.2 Case Study 2: In-situ Treatment of a TCE Source Area Using a Jetted Slurry of ZVI and Clay at Dupont plant, Kinston, NC.

General operation of the application of ZVI/Clay slurry process proceeded as follows:

i) slurry consisted of 95% kaolinite and 5% Peerless ZVI on a dry weight basis;

ii) 11 columns were emplaced to depths from 15 to 18 ft bgs and column diameters estimated from 5 to 6 ft placed at centerline distances of 4 to 5 ft.

iii) a low K cofferdam was of jetted ZVI/clay was placed completed around the source area perimeter;

iv) cofferdam jetting centers placed 9 ft part to create interlocking panels;

Some of the remedial goals were met with the treatment (see Table A.5 above). Of the 13 post demonstration samples collected, only 2 showed significant TCE or breakdown products in the post-treatment cores. Direct observation indicated that intimate mixing on a particle scale was not achieved; however, there was slurry on the scale of inches distributed through the soil. Monitoring is ongoing to determine if groundwater concentrations will continue to decline.

6 Multi-Phase Extraction

A case study for a field application of multi-phase extraction (MPE) is summarized below. The case study is an outline of the application of a full scale multiphase extraction application at the 328 Site in Santa Clara, CA (U.S. EPA, 1999). Table A.6 summarizes the site conditions and remedial activities at the site. Section 6.1 below includes summaries of the treatment operation and lessons learned from the application.

Table A.6 Summary of MPE Case Study

Parameter	328 Site
Technology description	Dual Phase Extraction (single pump) with pneumatic fracturing of soil
Soil type	silty clay
Hydraulic conductivity	not provided

Parameter	**328 Site**
Hydraulic gradient	not provided
Depth to groundwater	9 ft bgs
Well yield	not provided
Contaminants of concern	TCE
NAPL evidence	TCE concentration in soil 46 mg/kg
Volume treated	16,000 yd^3
Area treated	0.5 acre
Depth treated	0-20 ft bgs
DNAPL mass targeted	not provided
Remediation Infrastructure	(#wells, monitoring points, etc.)
Remediation Duration	November 1996 to October 1998
Remedial Costs	Design and installation \$300,000 O&M, reporting, analytical \$450,000 Carbon disposal \$100,000
Performance results:	
1) met remedial goals	✓
2) exceeded remedial goals	
3) met MCLs in at least some areas	
4) treatment efficiencies: TCE, etc.	Aqueous VOC concentrations decreased from 4,000 µg/L to 650 µg/L; 1164 lbs TCE mass removed
5) DNAPL mass remaining	not quantified

6.1 Case Study 1: 328 Site, Santa Clara, CA

General operation of the application of MPE proceeded as follows:

i) Vacuum application and MPE initiated; clusters of extraction wells operated on a rotating basis.

ii) Pneumatic fracturing of source area wells to improve vapor extraction two months later while cluster operations of extraction wells continued. Fracturing was completed over a 5 month period.

iii) Continued operations focusing on areas of highest VOC concentrations for one year.

iv) Shutdown of MPE system for two months to observe rebound.

v) Restart and continued operation for one month. VOC extraction data suggested that remedial goals had been met.

vi) Confirmation soil sampling one month later. Preparation for system shutdown two months later.

Based upon the post-treatment soil and groundwater data, the remedial action was deemed to have met the remedial objectives. The remedial objectives were to remove the VOC source zone (U.S DOE, 2003).

Lessons learned during the technology application included the following:

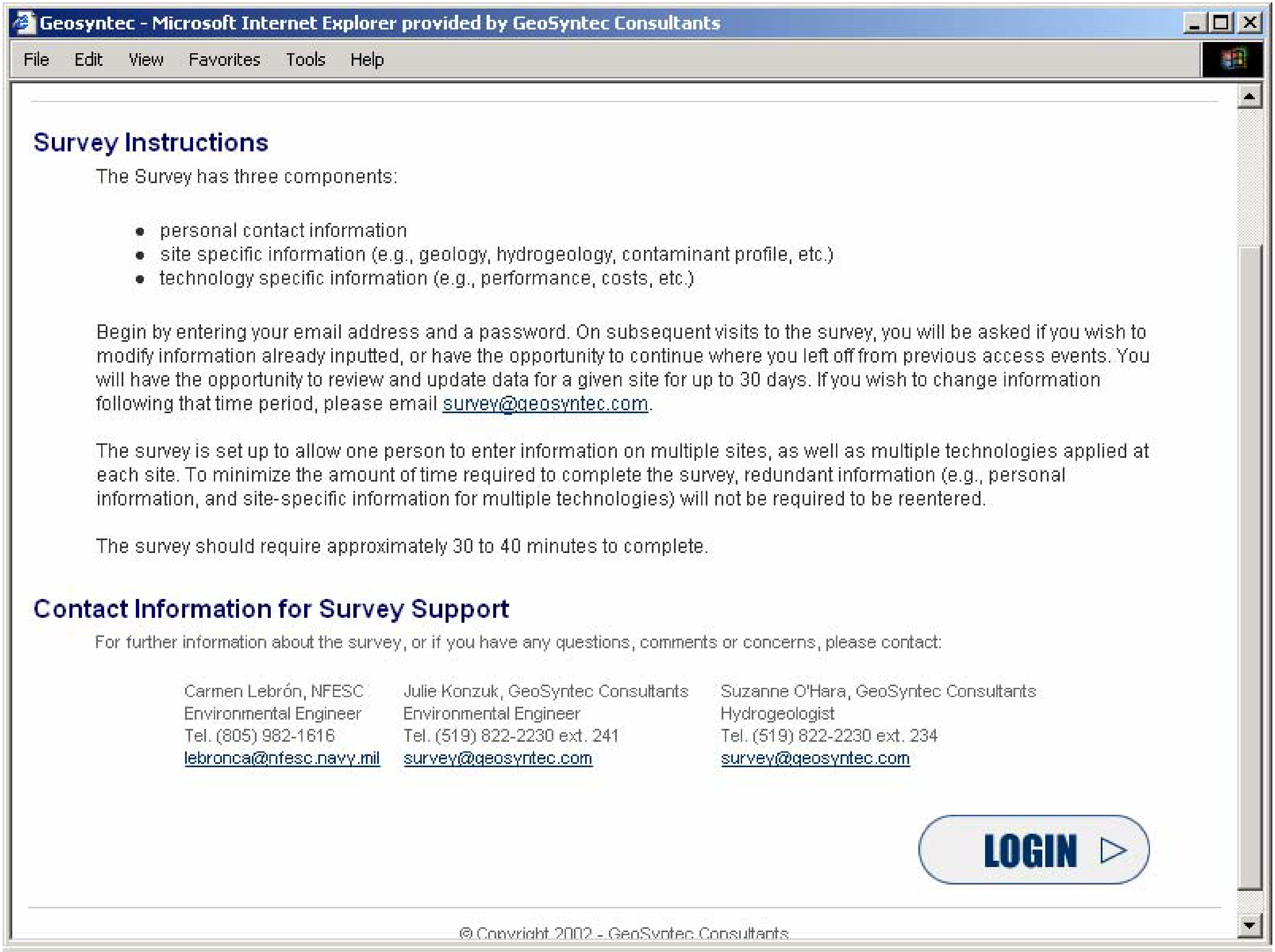
i) Pneumatic fracturing was a useful technique for enhancing vapor extraction rates;

ii) Groundwater extraction rates were much higher than anticipated by characterization efforts, necessitating a rotating schedule of well operation to meet the capacity of the groundwater treatment system. This emphasizes the importance of careful characterization and/or pilot testing of the technology for a given site to ensure proper design of the MPE application; and,

iii) The majority of mass extracted using MPE was treated in the vapor stream as opposed to the water stream. VOCs are commonly volatilized from extracted groundwater during MPE and thus sizing of vapor treatment should be based upon the expected mass of VOCs extracted from both phases.

APPENDIX B

Screen Shots of the Web Based Survey



Survey Instructions

The Survey has three components:

- personal contact information
- site specific information (e.g., geology, hydrogeology, contaminant profile, etc.)
- technology specific information (e.g., performance, costs, etc.)

Begin by entering your email address and a password. On subsequent visits to the survey, you will be asked if you wish to modify information already inputted, or have the opportunity to continue where you left off from previous access events. You will have the opportunity to review and update data for a given site for up to 30 days. If you wish to change information following that time period, please email survey@geosyntec.com.

The survey is set up to allow one person to enter information on multiple sites, as well as multiple technologies applied at each site. To minimize the amount of time required to complete the survey, redundant information (e.g., personal information, and site-specific information for multiple technologies) will not be required to be reentered.

The survey should require approximately 30 to 40 minutes to complete.

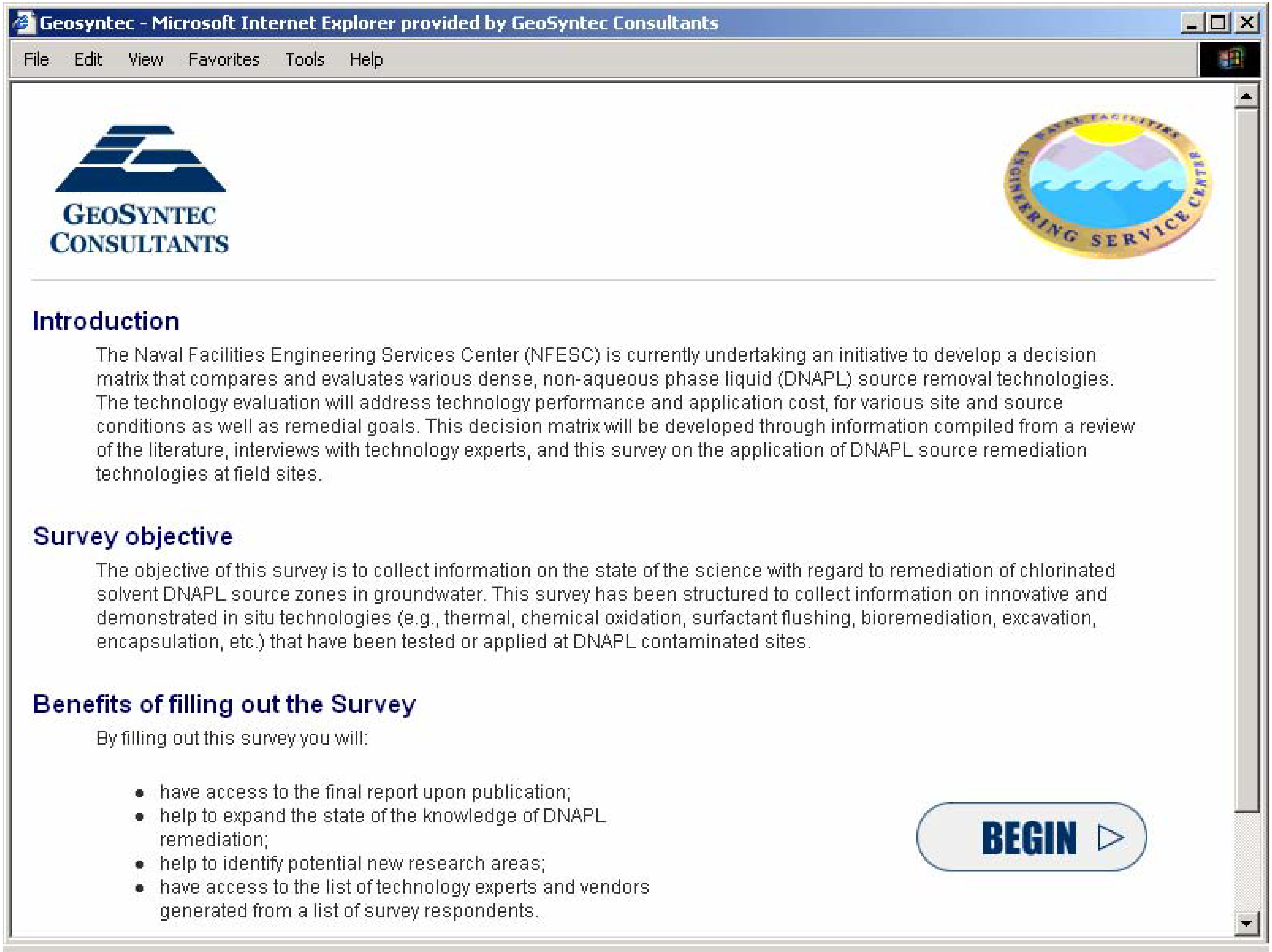
Contact Information for Survey Support

For further information about the survey, or if you have any questions, comments or concerns, please contact:

Carmen Lebrón, NFESC
Environmental Engineer
Tel. (805) 982-1616
lebronca@nfesc.navy.mil

Julie Konzuk, GeoSyntec Consultants
Environmental Engineer
Tel. (519) 822-2230 ext. 241
survey@geosyntec.com

Suzanne O'Hara, GeoSyntec Consultants
Hydrogeologist
Tel. (519) 822-2230 ext. 234
survey@geosyntec.com



Introduction

The Naval Facilities Engineering Services Center (NFESC) is currently undertaking an initiative to develop a decision matrix that compares and evaluates various dense, non-aqueous phase liquid (DNAPL) source removal technologies. The technology evaluation will address technology performance and application cost, for various site and source conditions as well as remedial goals. This decision matrix will be developed through information compiled from a review of the literature, interviews with technology experts, and this survey on the application of DNAPL source remediation technologies at field sites.

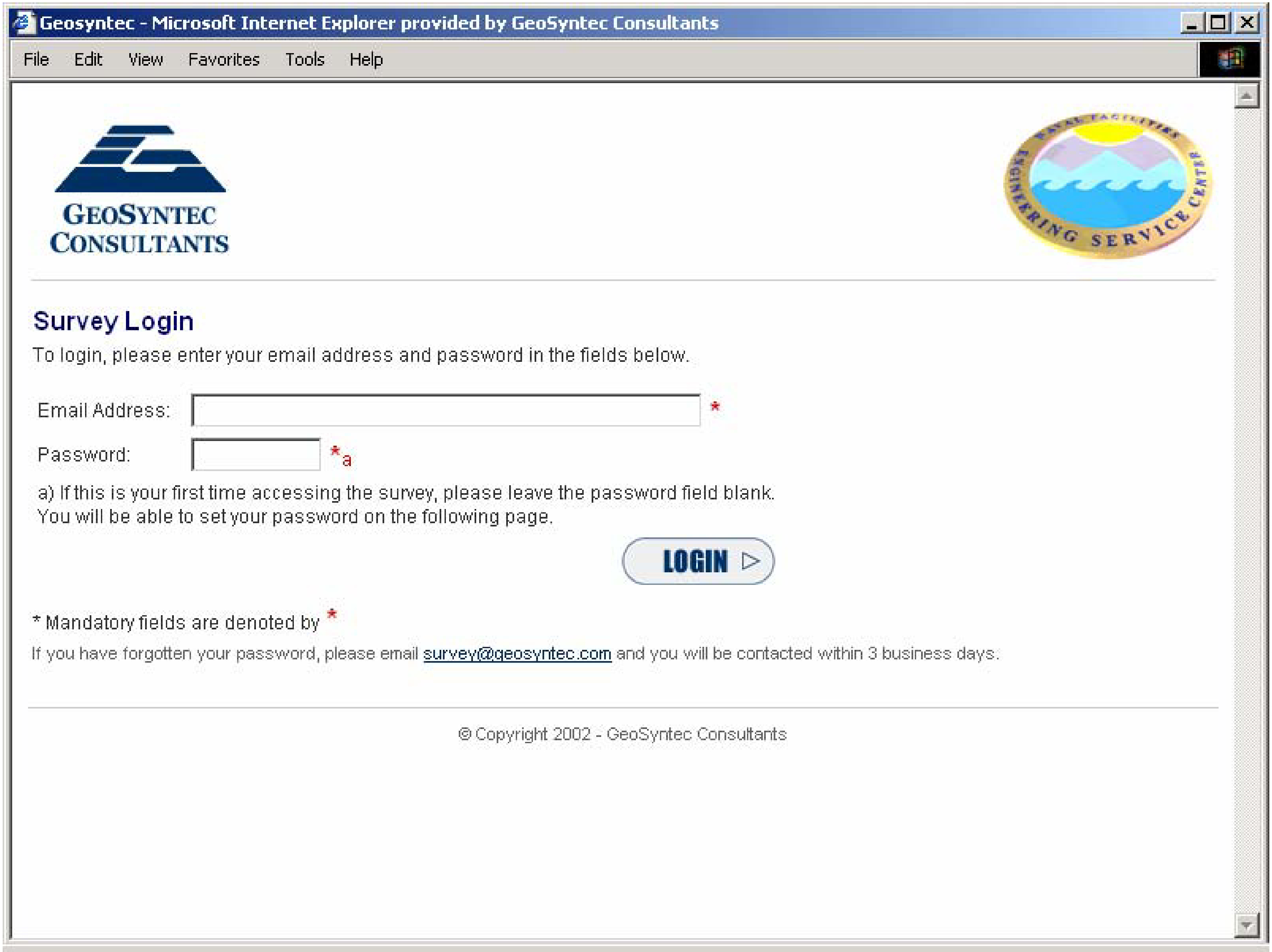
Survey objective

The objective of this survey is to collect information on the state of the science with regard to remediation of chlorinated solvent DNAPL source zones in groundwater. This survey has been structured to collect information on innovative and demonstrated in situ technologies (e.g., thermal, chemical oxidation, surfactant flushing, bioremediation, excavation, encapsulation, etc.) that have been tested or applied at DNAPL contaminated sites.

Benefits of filling out the Survey

By filling out this survey you will:

- have access to the final report upon publication;
- help to expand the state of the knowledge of DNAPL remediation;
- help to identify potential new research areas;
- have access to the list of technology experts and vendors generated from a list of survey respondents.



Survey Login

To login, please enter your email address and password in the fields below.

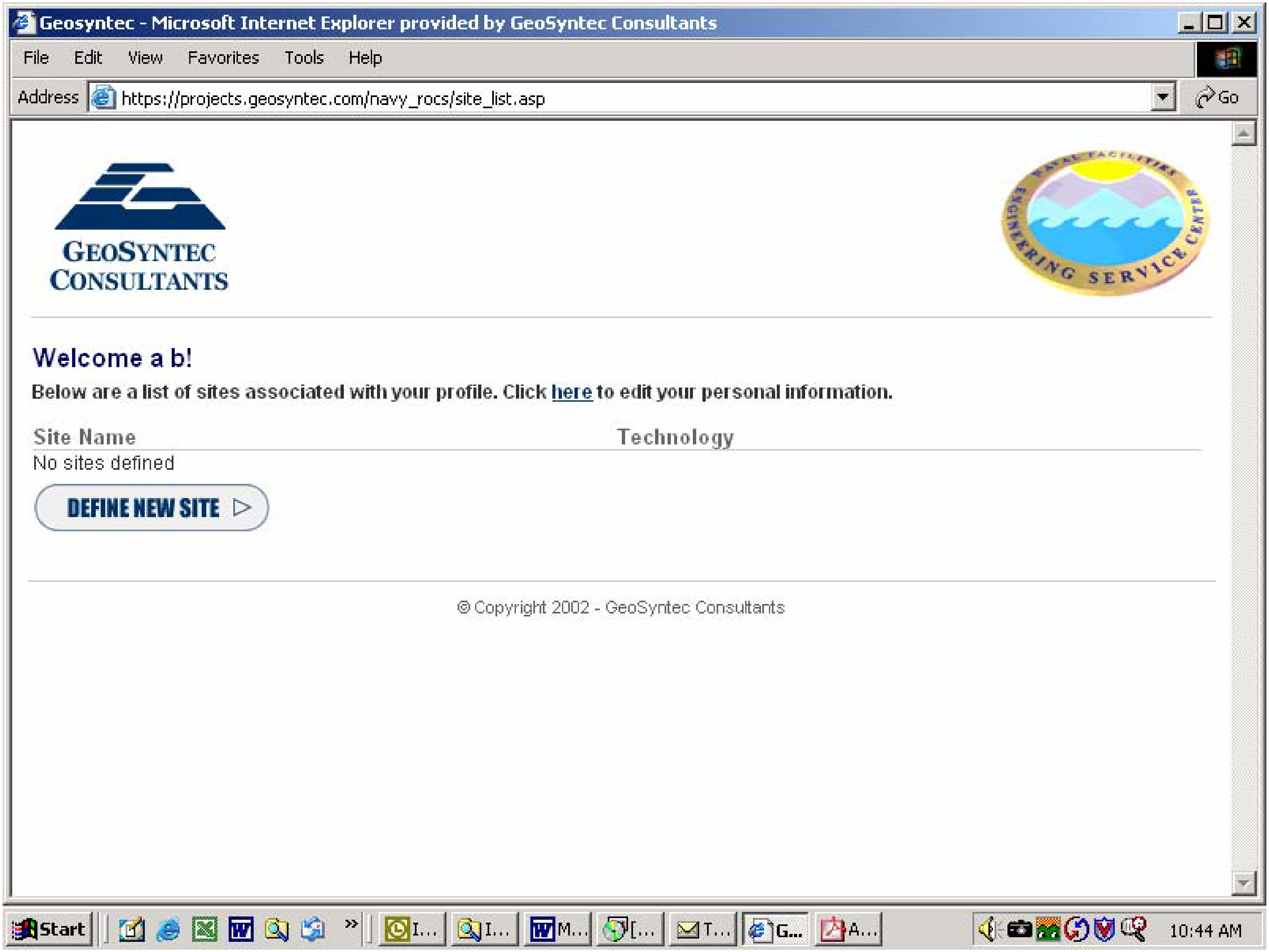
Email Address: ☐ *

Password: ☐ *a

a) If this is your first time accessing the survey, please leave the password field blank.
You will be able to set your password on the following page.

* Mandatory fields are denoted by *

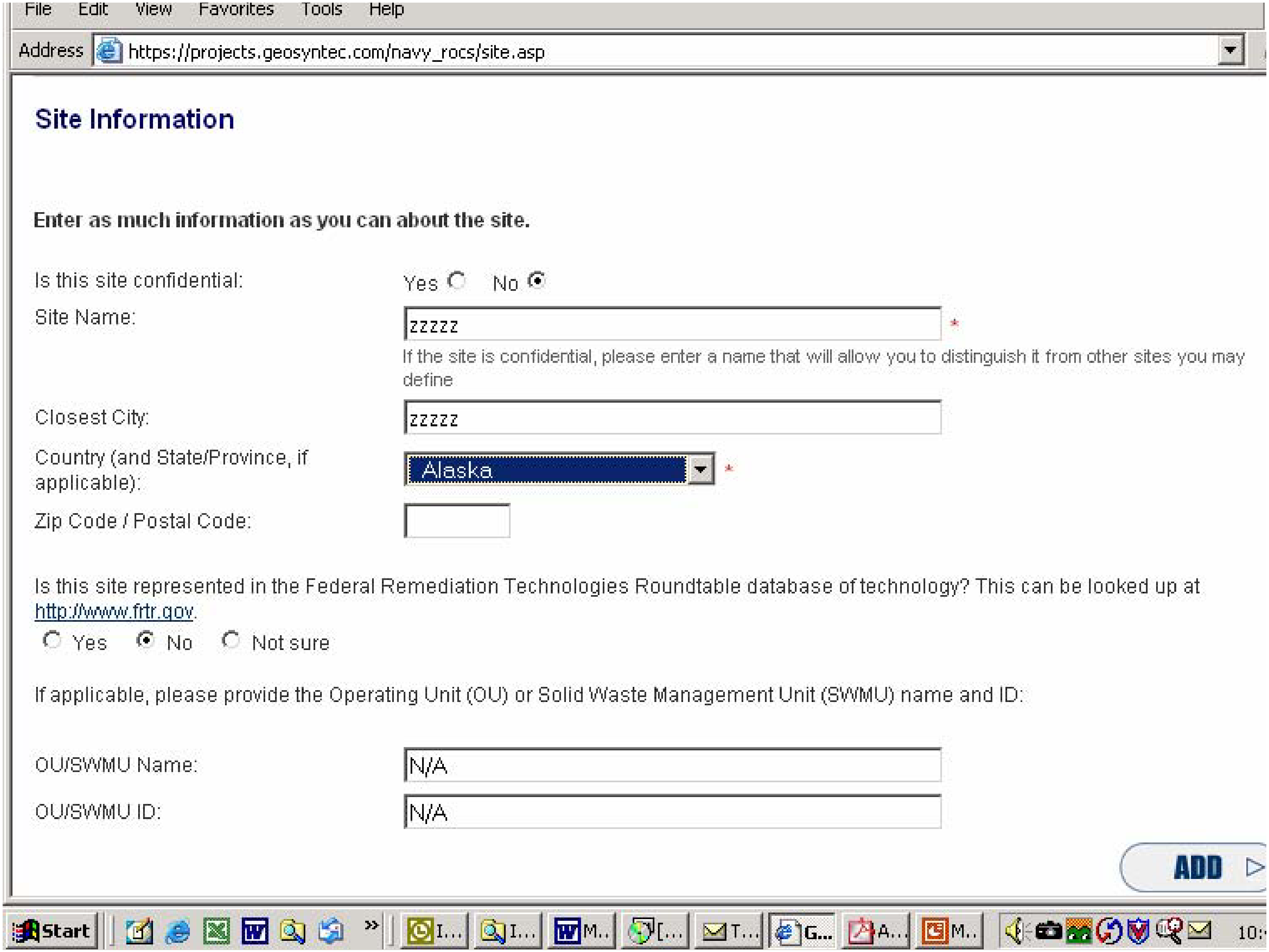
If you have forgotten your password, please email survey@geosyntec.com and you will be contacted within 3 business days.



Welcome a b!

Below are a list of sites associated with your profile. Click here to edit your personal information.

Site Name	Technology
No sites defined	



Site Information

Enter as much information as you can about the site.

Is this site confidential: Yes ○ No ●

Site Name: zzzzz *

If the site is confidential, please enter a name that will allow you to distinguish it from other sites you may define

Closest City: zzzzz

Country (and State/Province, if applicable): Alaska *

Zip Code / Postal Code:

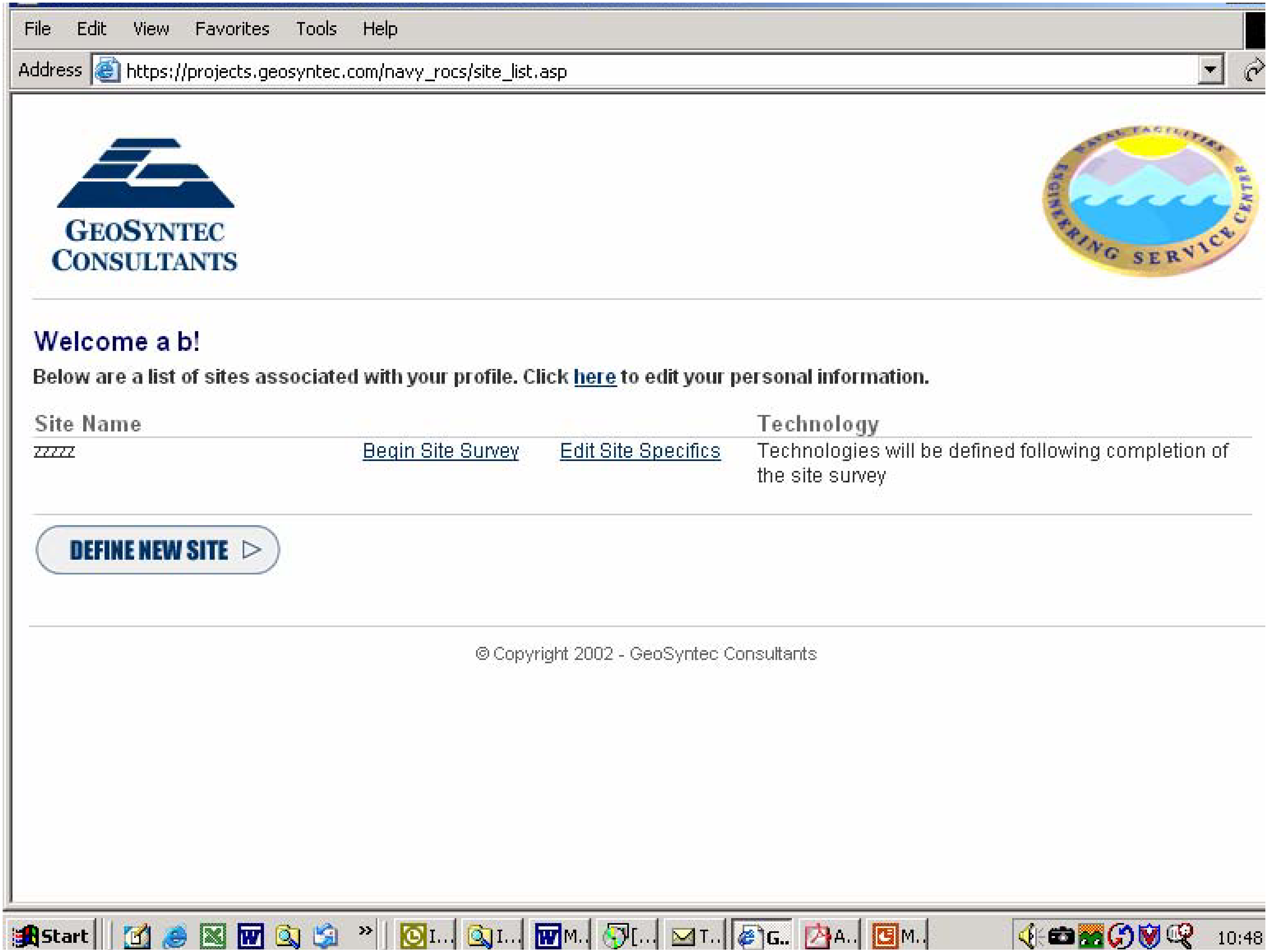
Is this site represented in the Federal Remediation Technologies Roundtable database of technology? This can be looked up at http://www.frtr.gov.

○ Yes ● No ○ Not sure

If applicable, please provide the Operating Unit (OU) or Solid Waste Management Unit (SWMU) name and ID:

OU/SWMU Name: N/A

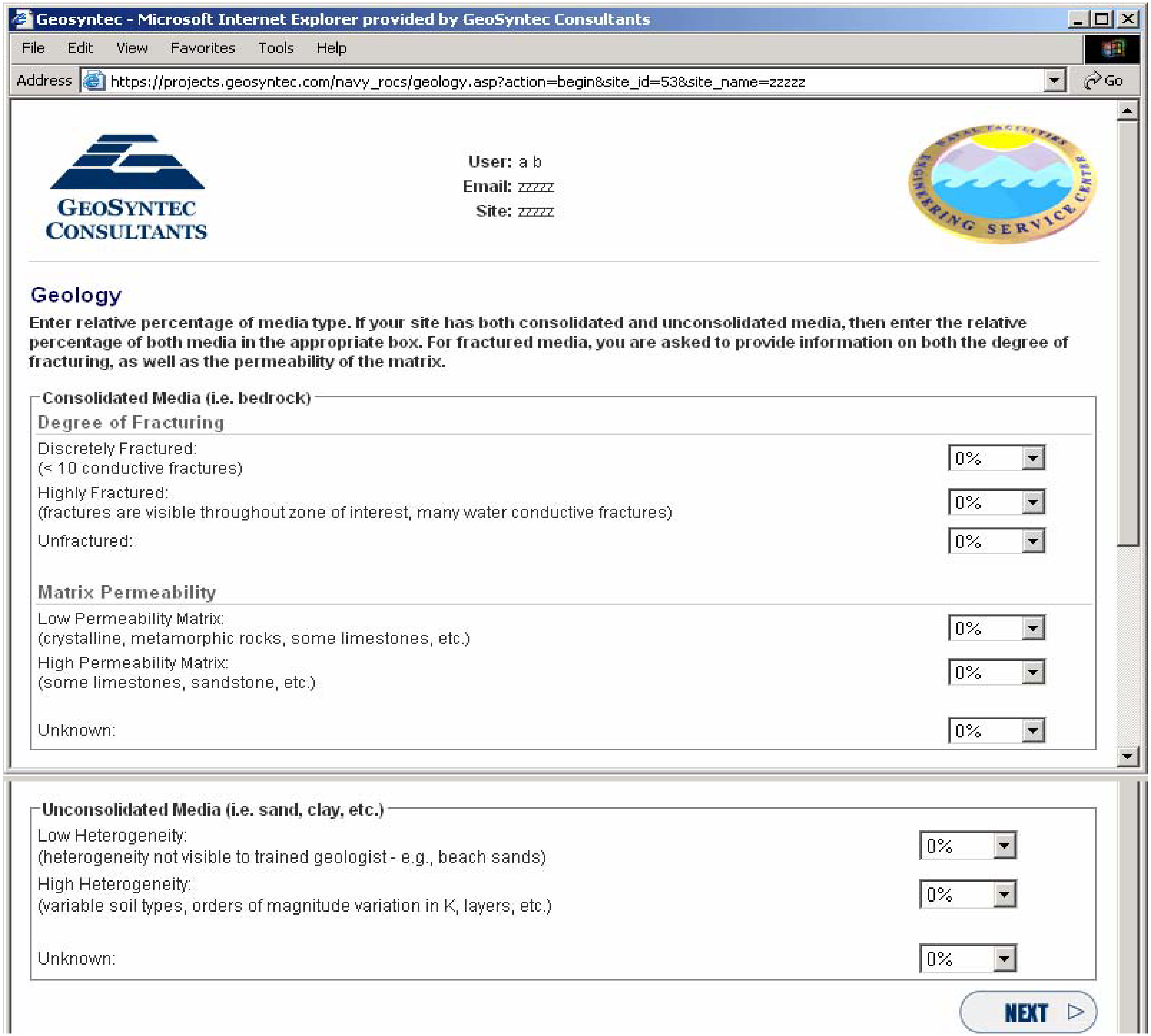
OU/SWMU ID: N/A



Welcome a b!

Below are a list of sites associated with your profile. Click here to edit your personal information.

Site Name			Technology
zzzzz	Begin Site Survey	Edit Site Specifics	Technologies will be defined following completion of the site survey



https://projects.geosyntec.com/navy_rocs/geology.asp?action=begin&site_id=53&site_name=zzzzz

User: a b
Email: zzzzz
Site: zzzzz

Geology

Enter relative percentage of media type. If your site has both consolidated and unconsolidated media, then enter the relative percentage of both media in the appropriate box. For fractured media, you are asked to provide information on both the degree of fracturing, as well as the permeability of the matrix.

Consolidated Media (i.e. bedrock)

Degree of Fracturing

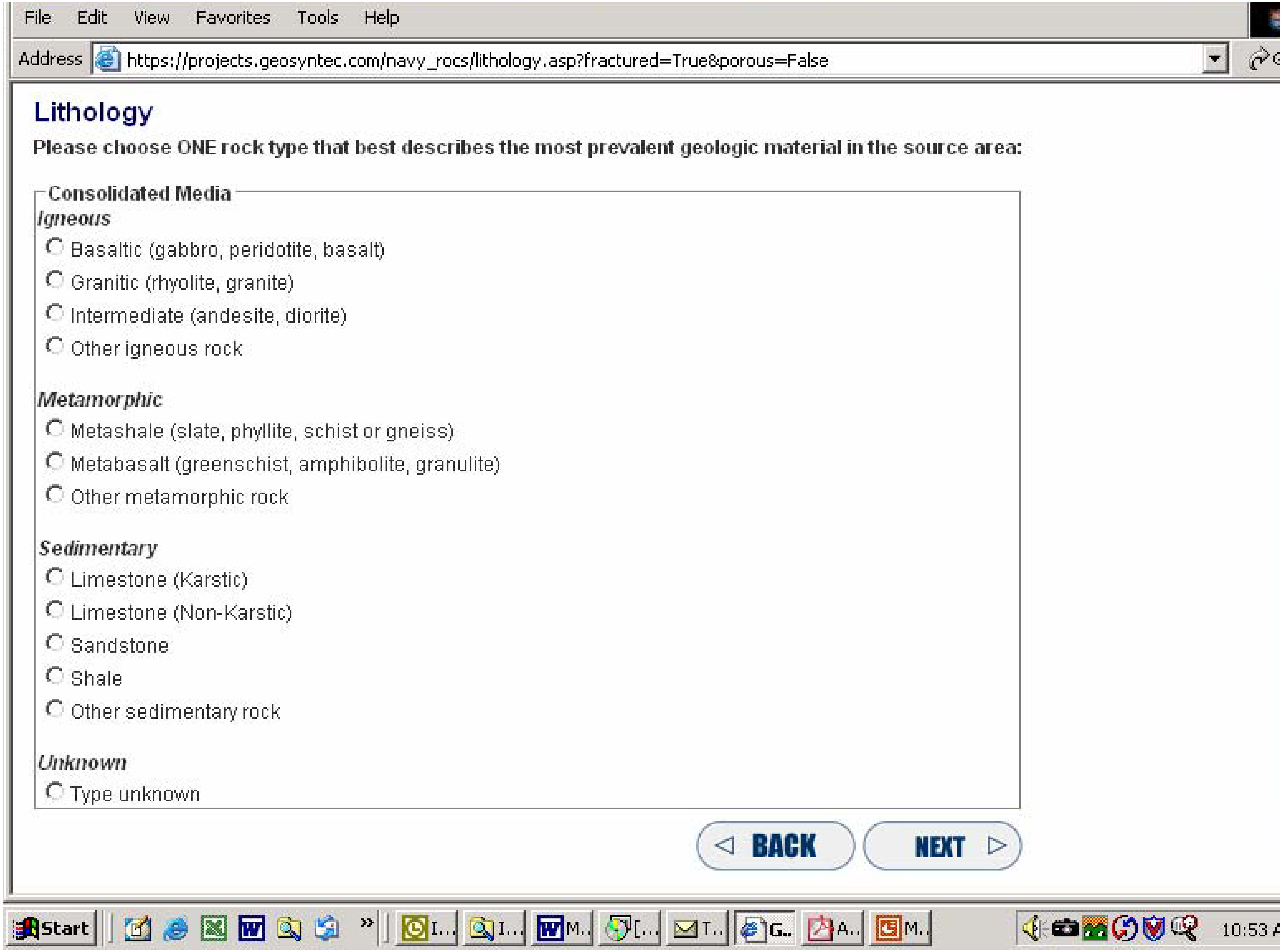
Discretely Fractured: (< 10 conductive fractures) 0%
Highly Fractured: (fractures are visible throughout zone of interest, many water conductive fractures) 0%
Unfractured: 0%

Matrix Permeability

Low Permeability Matrix: (crystalline, metamorphic rocks, some limestones, etc.) 0%
High Permeability Matrix: (some limestones, sandstone, etc.) 0%
Unknown: 0%

Unconsolidated Media (i.e. sand, clay, etc.)

Low Heterogeneity: (heterogeneity not visible to trained geologist - e.g., beach sands) 0%
High Heterogeneity: (variable soil types, orders of magnitude variation in K, layers, etc.) 0%
Unknown: 0%



https://projects.geosyntec.com/navy_rocs/lithology.asp?fractured=True&porous=False

Lithology

Please choose ONE rock type that best describes the most prevalent geologic material in the source area:

Consolidated Media

Igneous

○ Basaltic (gabbro, peridotite, basalt)
○ Granitic (rhyolite, granite)
○ Intermediate (andesite, diorite)
○ Other igneous rock

Metamorphic

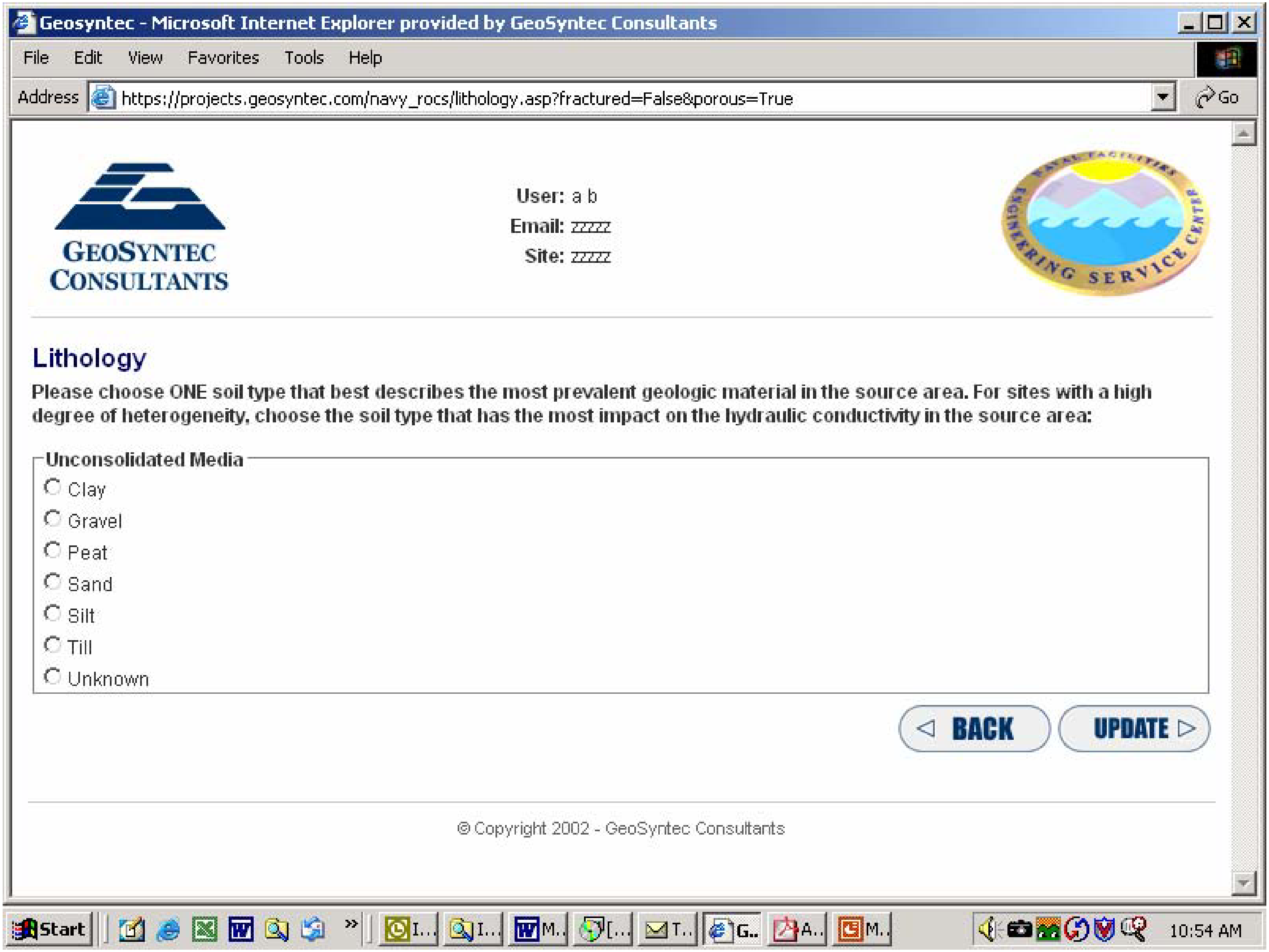
○ Metashale (slate, phyllite, schist or gneiss)
○ Metabasalt (greenschist, amphibolite, granulite)
○ Other metamorphic rock

Sedimentary

○ Limestone (Karstic)
○ Limestone (Non-Karstic)
○ Sandstone
○ Shale
○ Other sedimentary rock

Unknown

○ Type unknown



User: a b

Email: zzzzz

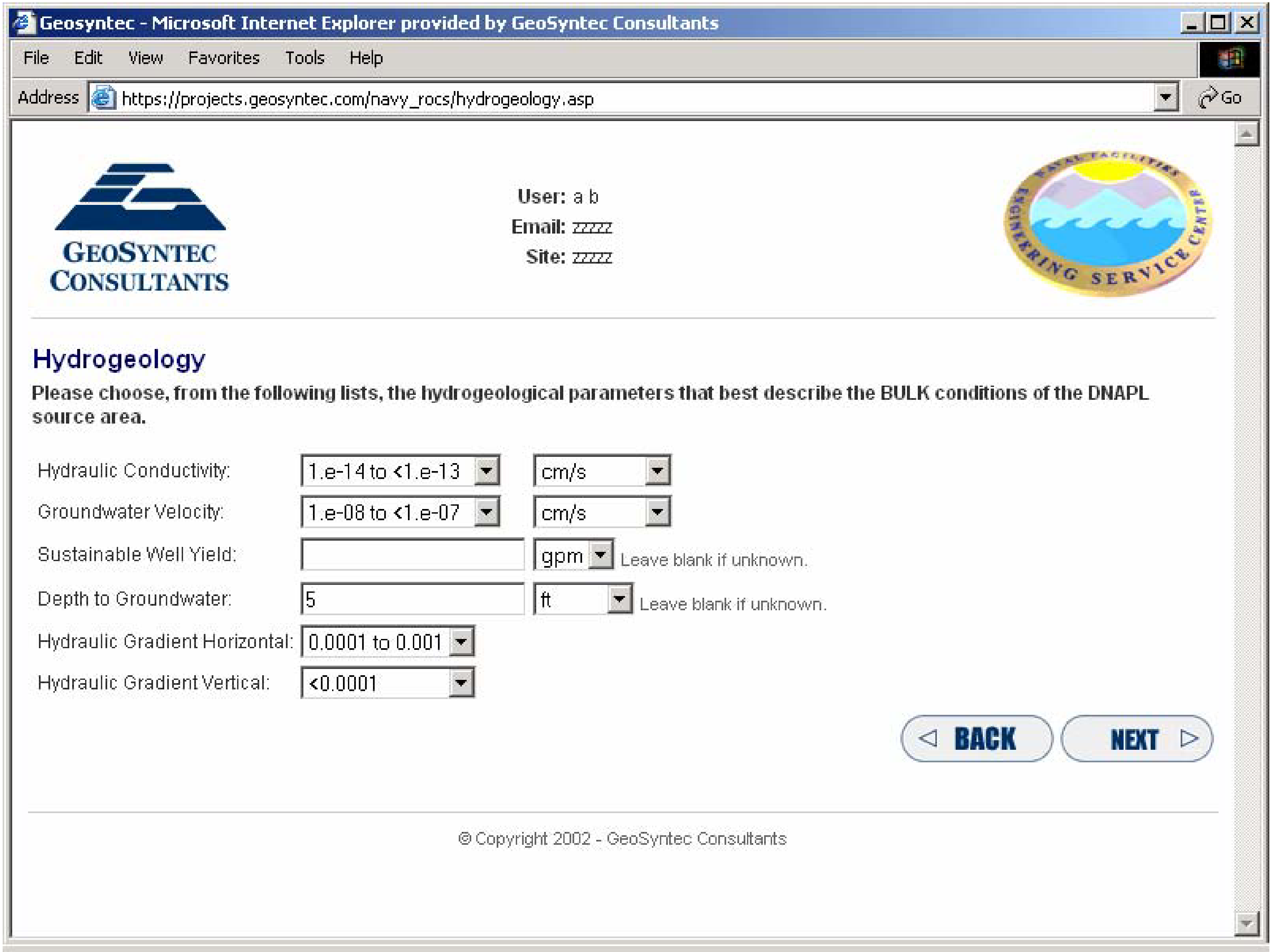
Site: zzzzz

Lithology

Please choose ONE soil type that best describes the most prevalent geologic material in the source area. For sites with a high degree of heterogeneity, choose the soil type that has the most impact on the hydraulic conductivity in the source area:

Unconsolidated Media

○ Clay
○ Gravel
○ Peat
○ Sand
○ Silt
○ Till
○ Unknown



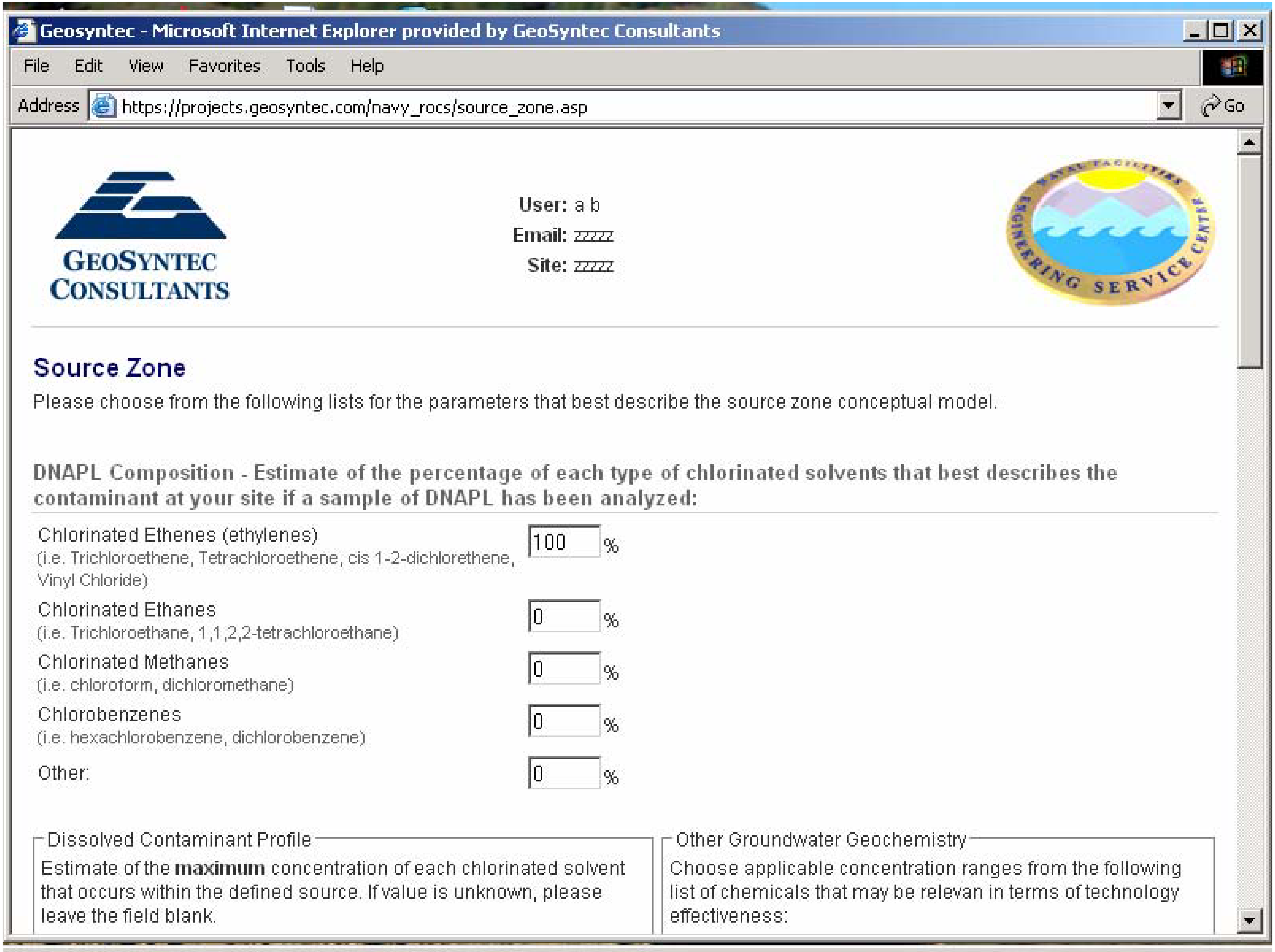
https://projects.geosyntec.com/navy_rocs/hydrogeology.asp

User: a b
Email: zzzzz
Site: zzzzz

Hydrogeology

Please choose, from the following lists, the hydrogeological parameters that best describe the BULK conditions of the DNAPL source area.

Hydraulic Conductivity:	1.e-14 to <1.e-13	cm/s	
Groundwater Velocity:	1.e-08 to <1.e-07	cm/s	
Sustainable Well Yield:		gpm	Leave blank if unknown.
Depth to Groundwater:	5	ft	Leave blank if unknown.
Hydraulic Gradient Horizontal:	0.0001 to 0.001		
Hydraulic Gradient Vertical:	<0.0001		



User: a b
Email: zzzzz
Site: zzzzz

Source Zone

Please choose from the following lists for the parameters that best describe the source zone conceptual model.

DNAPL Composition - Estimate of the percentage of each type of chlorinated solvents that best describes the contaminant at your site if a sample of DNAPL has been analyzed:

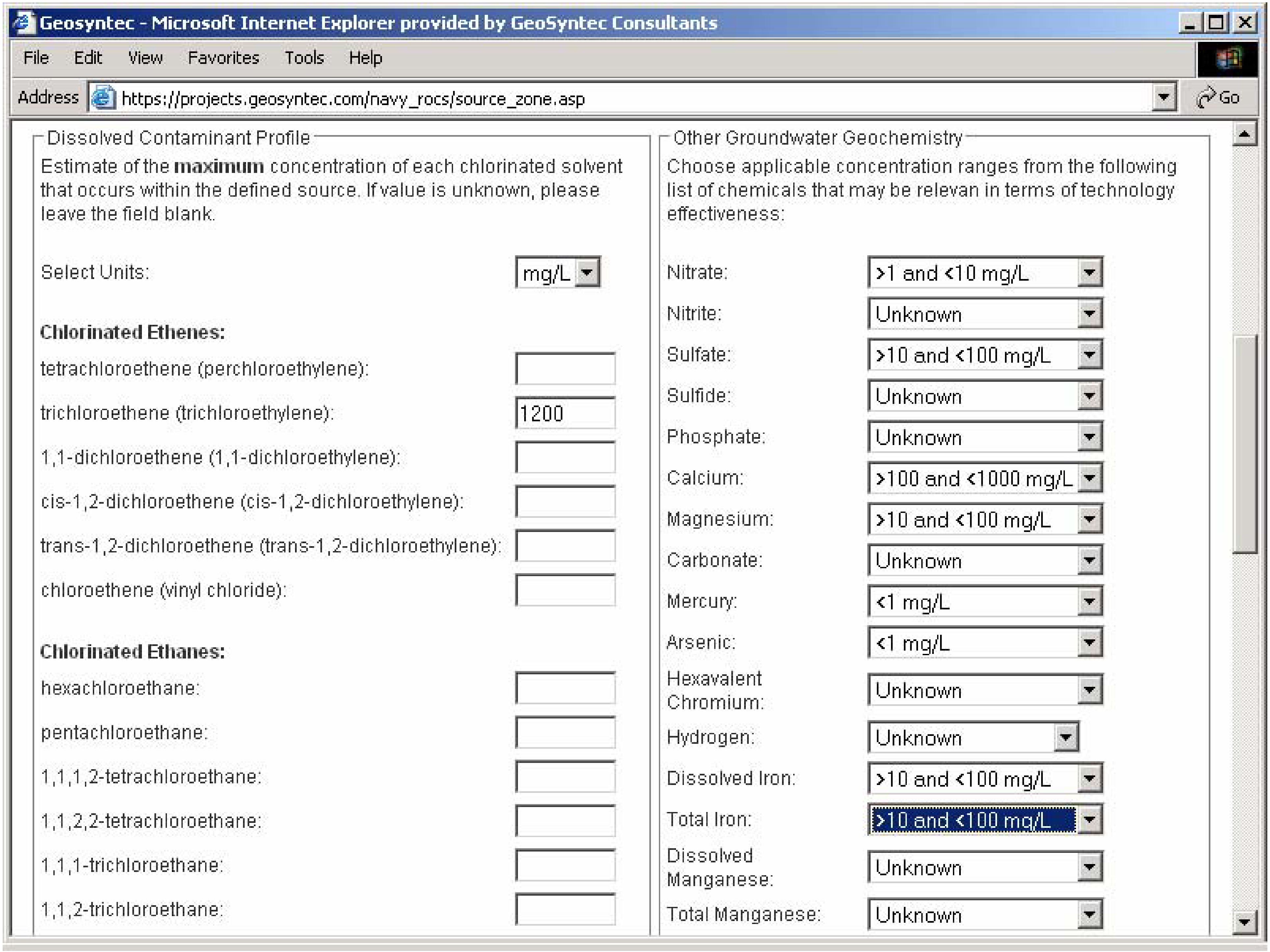
Chlorinated Ethenes (ethylenes) (i.e. Trichloroethene, Tetrachloroethene, cis 1-2-dichlorethene, Vinyl Chloride)	100 %
Chlorinated Ethanes (i.e. Trichloroethane, 1,1,2,2-tetrachloroethane)	0 %
Chlorinated Methanes (i.e. chloroform, dichloromethane)	0 %
Chlorobenzenes (i.e. hexachlorobenzene, dichlorobenzene)	0 %
Other:	0 %

Dissolved Contaminant Profile

Estimate of the **maximum** concentration of each chlorinated solvent that occurs within the defined source. If value is unknown, please leave the field blank.

Other Groundwater Geochemistry

Choose applicable concentration ranges from the following list of chemicals that may be relevan in terms of technology effectiveness:



Dissolved Contaminant Profile

Estimate of the **maximum** concentration of each chlorinated solvent that occurs within the defined source. If value is unknown, please leave the field blank.

Select Units: mg/L

Chlorinated Ethenes:

tetrachloroethene (perchloroethylene):

trichloroethene (trichloroethylene): 1200

1,1-dichloroethene (1,1-dichloroethylene):

cis-1,2-dichloroethene (cis-1,2-dichloroethylene):

trans-1,2-dichloroethene (trans-1,2-dichloroethylene):

chloroethene (vinyl chloride):

Chlorinated Ethanes:

hexachloroethane:

pentachloroethane:

1,1,1,2-tetrachloroethane:

1,1,2,2-tetrachloroethane:

1,1,1-trichloroethane:

1,1,2-trichloroethane:

Other Groundwater Geochemistry

Choose applicable concentration ranges from the following list of chemicals that may be relevan in terms of technology effectiveness:

Nitrate: >1 and <10 mg/L

Nitrite: Unknown

Sulfate: >10 and <100 mg/L

Sulfide: Unknown

Phosphate: Unknown

Calcium: >100 and <1000 mg/L

Magnesium: >10 and <100 mg/L

Carbonate: Unknown

Mercury: <1 mg/L

Arsenic: <1 mg/L

Hexavalent Chromium: Unknown

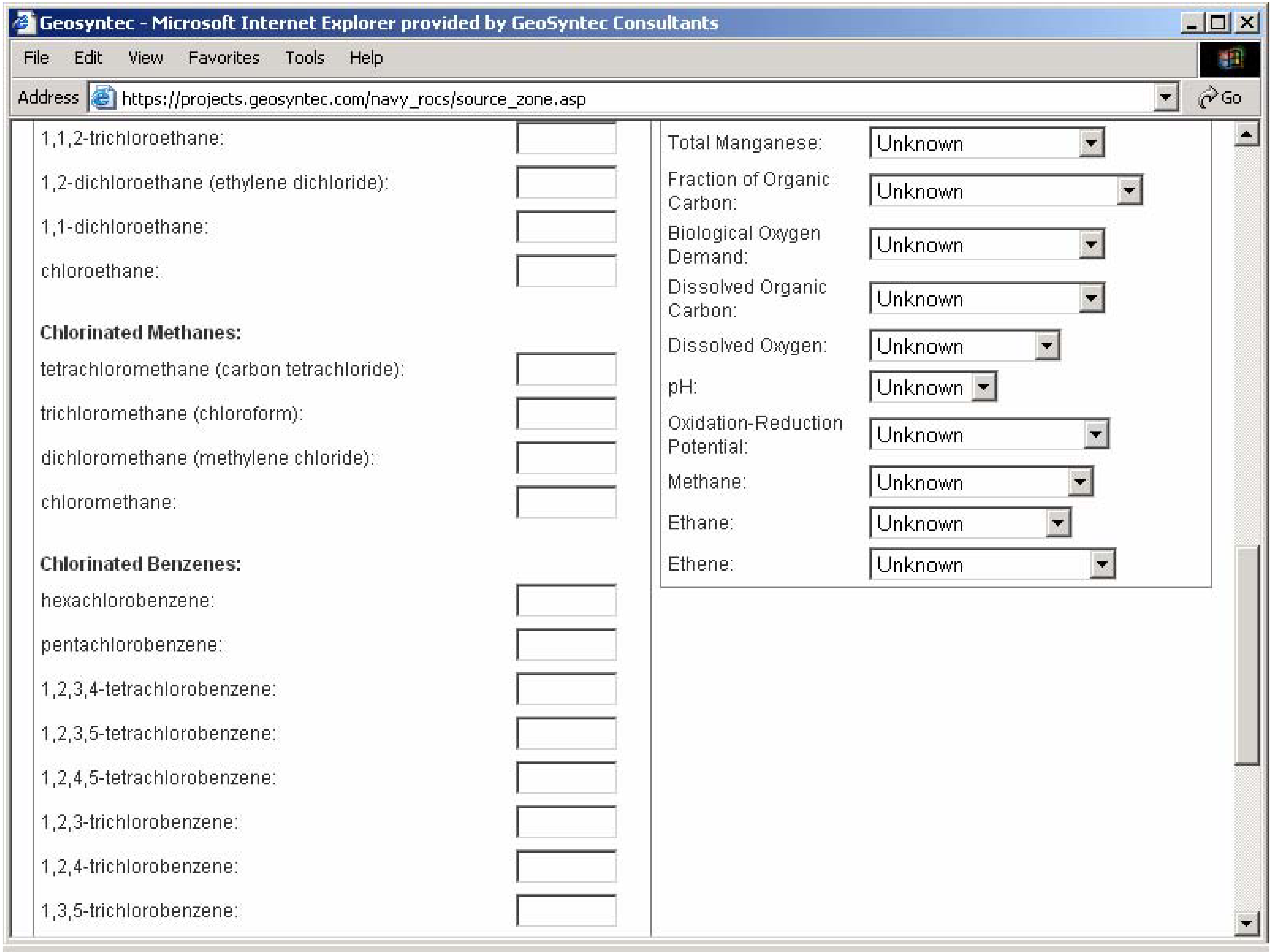
Hydrogen: Unknown

Dissolved Iron: >10 and <100 mg/L

Total Iron: >10 and <100 mg/L

Dissolved Manganese: Unknown

Total Manganese: Unknown



1,1,2-trichloroethane:

1,2-dichloroethane (ethylene dichloride):

1,1-dichloroethane:

chloroethane:

Chlorinated Methanes:

tetrachloromethane (carbon tetrachloride):

trichloromethane (chloroform):

dichloromethane (methylene chloride):

chloromethane:

Chlorinated Benzenes:

hexachlorobenzene:

pentachlorobenzene:

1,2,3,4-tetrachlorobenzene:

1,2,3,5-tetrachlorobenzene:

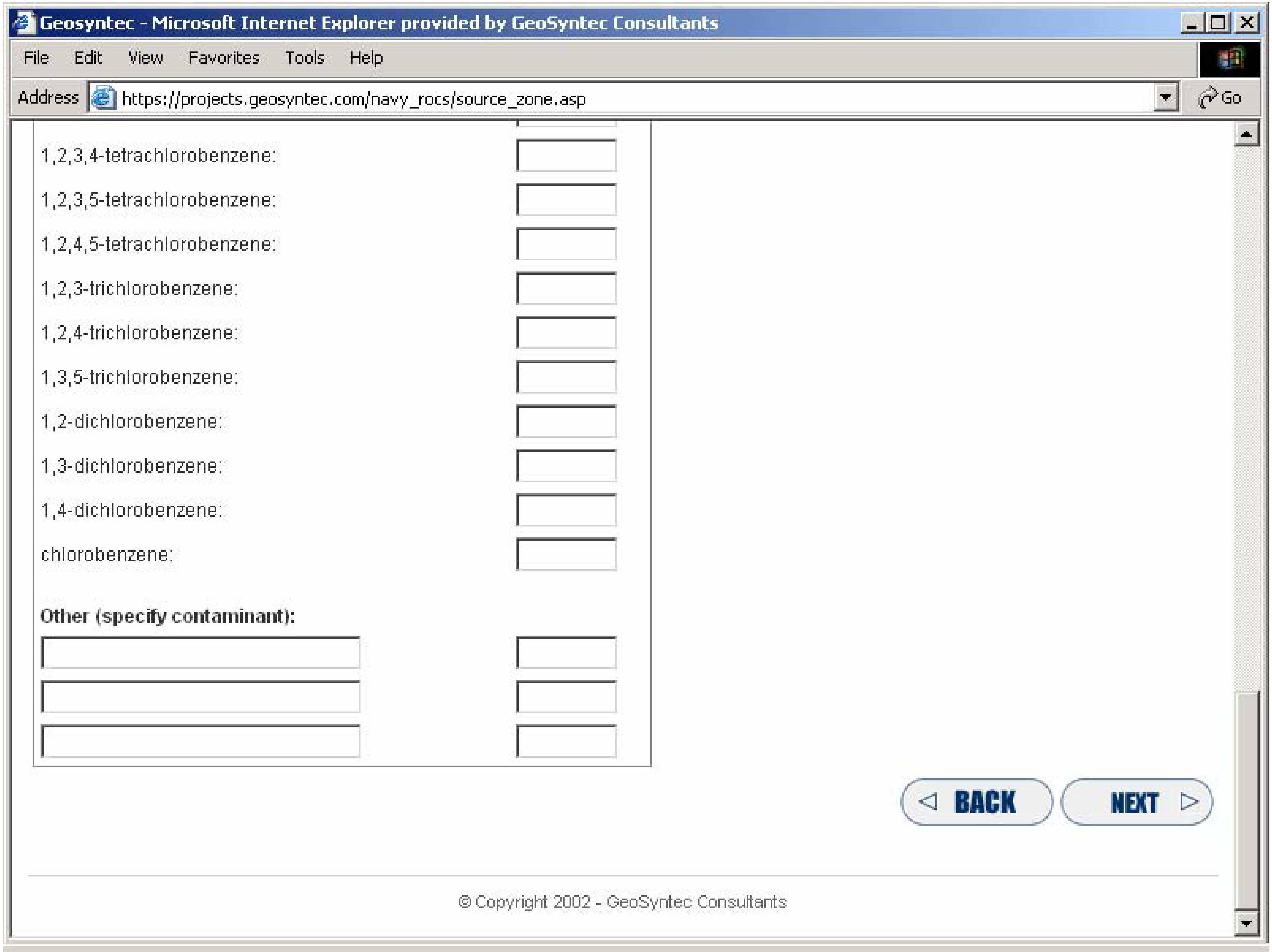
1,2,4,5-tetrachlorobenzene:

1,2,3-trichlorobenzene:

1,2,4-trichlorobenzene:

1,3,5-trichlorobenzene:

Total Manganese:	Unknown
Fraction of Organic Carbon:	Unknown
Biological Oxygen Demand:	Unknown
Dissolved Organic Carbon:	Unknown
Dissolved Oxygen:	Unknown
pH:	Unknown
Oxidation-Reduction Potential:	Unknown
Methane:	Unknown
Ethane:	Unknown
Ethene:	Unknown



1,2,3,4-tetrachlorobenzene:

1,2,3,5-tetrachlorobenzene:

1,2,4,5-tetrachlorobenzene:

1,2,3-trichlorobenzene:

1,2,4-trichlorobenzene:

1,3,5-trichlorobenzene:

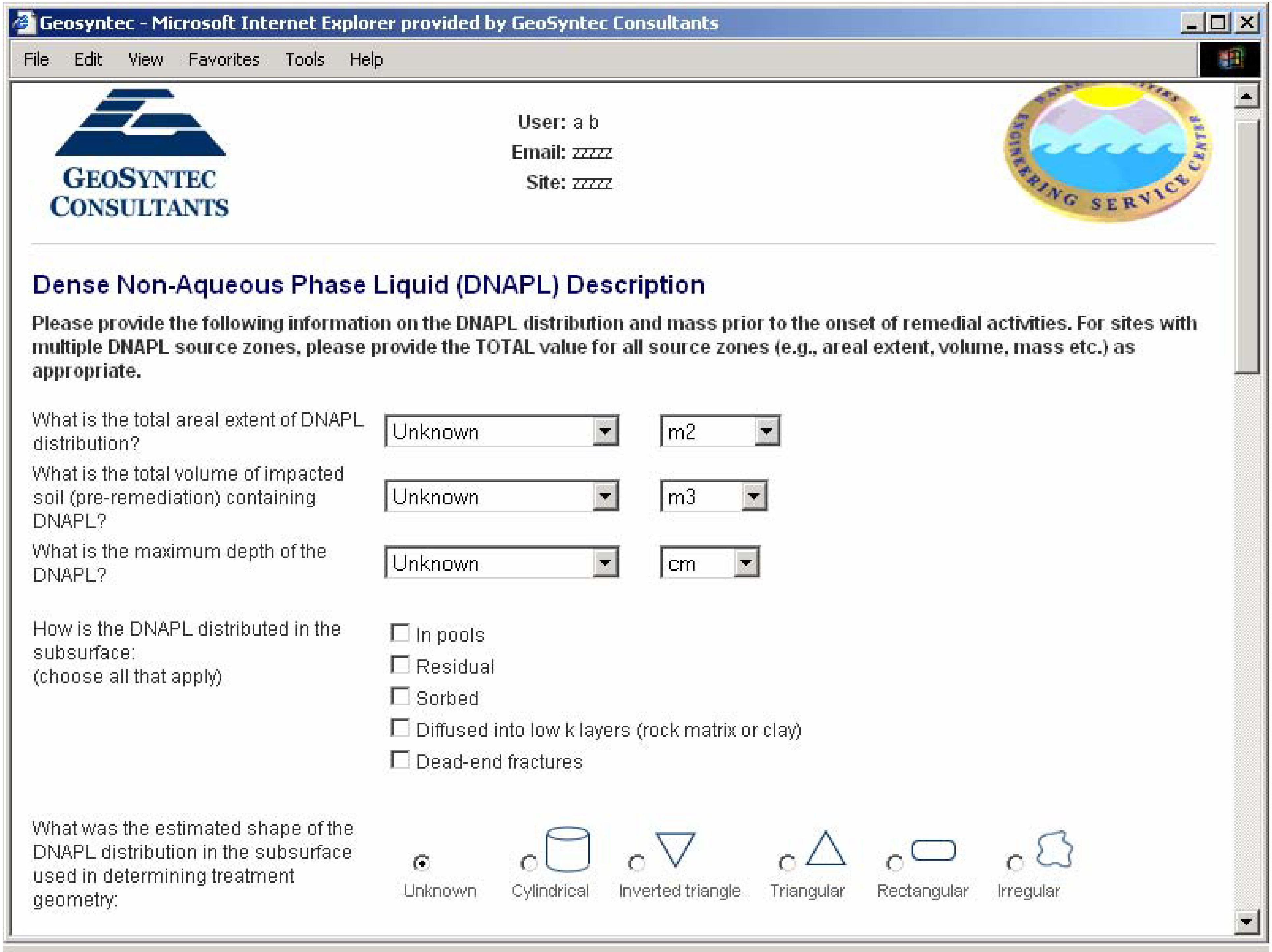
1,2-dichlorobenzene:

1,3-dichlorobenzene:

1,4-dichlorobenzene:

chlorobenzene:

Other (specify contaminant):



User: a b
Email: zzzzz
Site: zzzzz

Dense Non-Aqueous Phase Liquid (DNAPL) Description

Please provide the following information on the DNAPL distribution and mass prior to the onset of remedial activities. For sites with multiple DNAPL source zones, please provide the TOTAL value for all source zones (e.g., areal extent, volume, mass etc.) as appropriate.

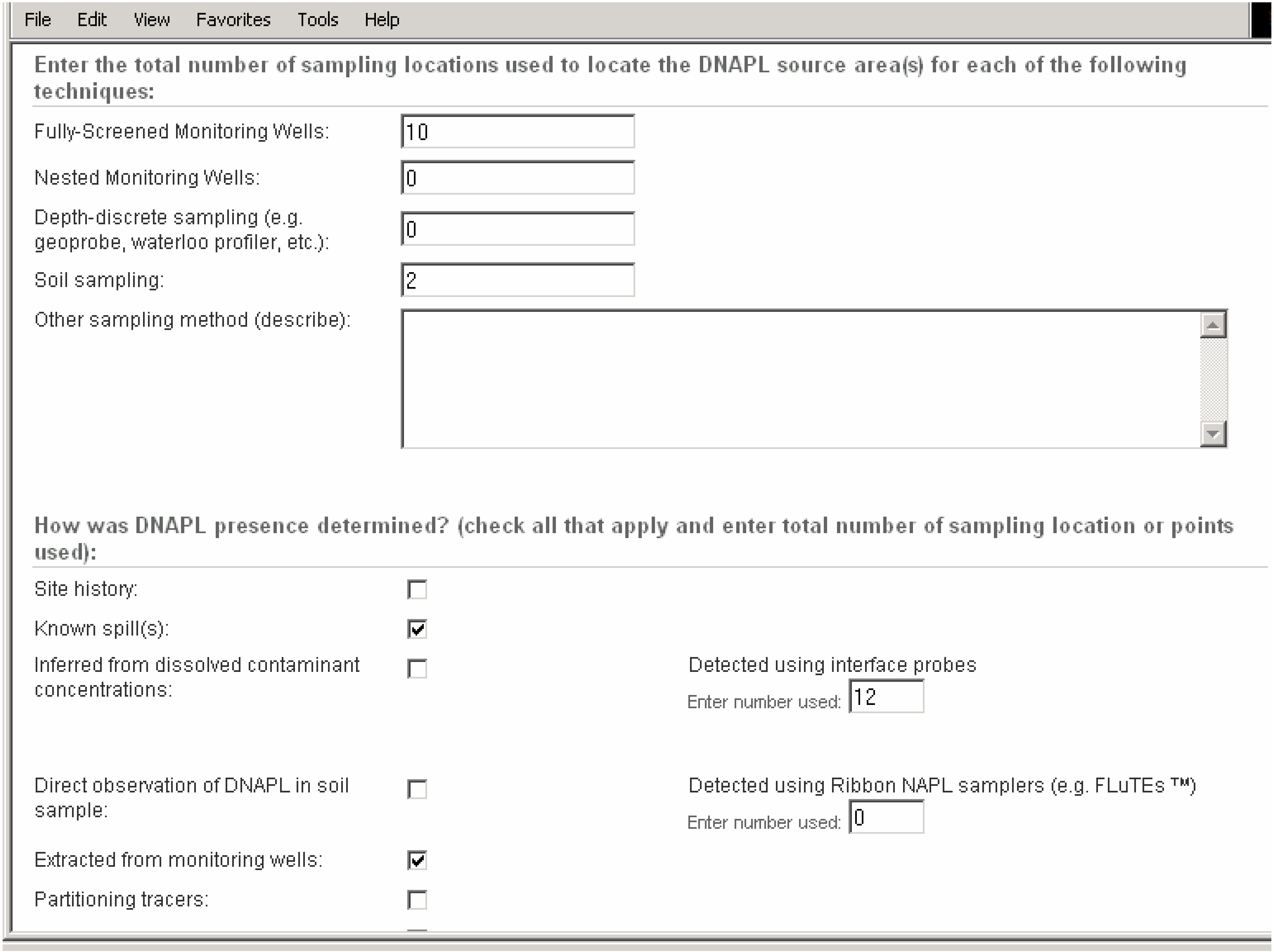
What is the total areal extent of DNAPL distribution?	Unknown	m2
What is the total volume of impacted soil (pre-remediation) containing DNAPL?	Unknown	m3
What is the maximum depth of the DNAPL?	Unknown	cm

How is the DNAPL distributed in the subsurface:
(choose all that apply)

- ☐ In pools
- ☐ Residual
- ☐ Sorbed
- ☐ Diffused into low k layers (rock matrix or clay)
- ☐ Dead-end fractures

What was the estimated shape of the DNAPL distribution in the subsurface used in determining treatment geometry:

● Unknown ○ Cylindrical ○ Inverted triangle ○ Triangular ○ Rectangular ○ Irregular



Enter the total number of sampling locations used to locate the DNAPL source area(s) for each of the following techniques:

Fully-Screened Monitoring Wells: 10

Nested Monitoring Wells: 0

Depth-discrete sampling (e.g. geoprobe, waterloo profiler, etc.): 0

Soil sampling: 2

Other sampling method (describe):

How was DNAPL presence determined? (check all that apply and enter total number of sampling location or points used):

Site history: ☐

Known spill(s): ☑

Inferred from dissolved contaminant concentrations: ☐

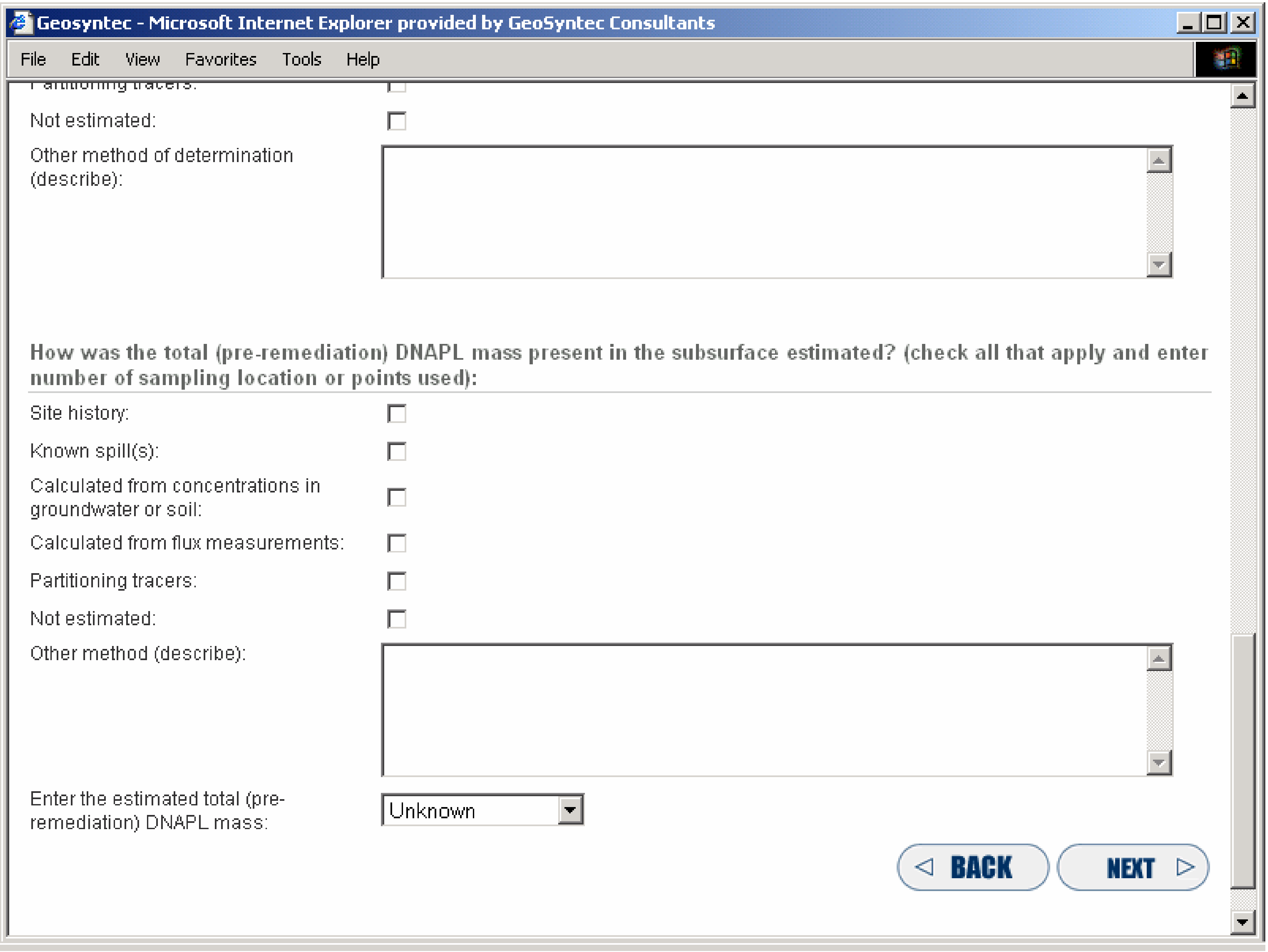
Detected using interface probes
Enter number used: 12

Direct observation of DNAPL in soil sample: ☐

Detected using Ribbon NAPL samplers (e.g. FLuTEs ™)
Enter number used: 0

Extracted from monitoring wells: ☑

Partitioning tracers: ☐



Partitioning tracers: ☐

Not estimated: ☐

Other method of determination (describe):

How was the total (pre-remediation) DNAPL mass present in the subsurface estimated? (check all that apply and enter number of sampling location or points used):

Site history: ☐

Known spill(s): ☐

Calculated from concentrations in groundwater or soil: ☐

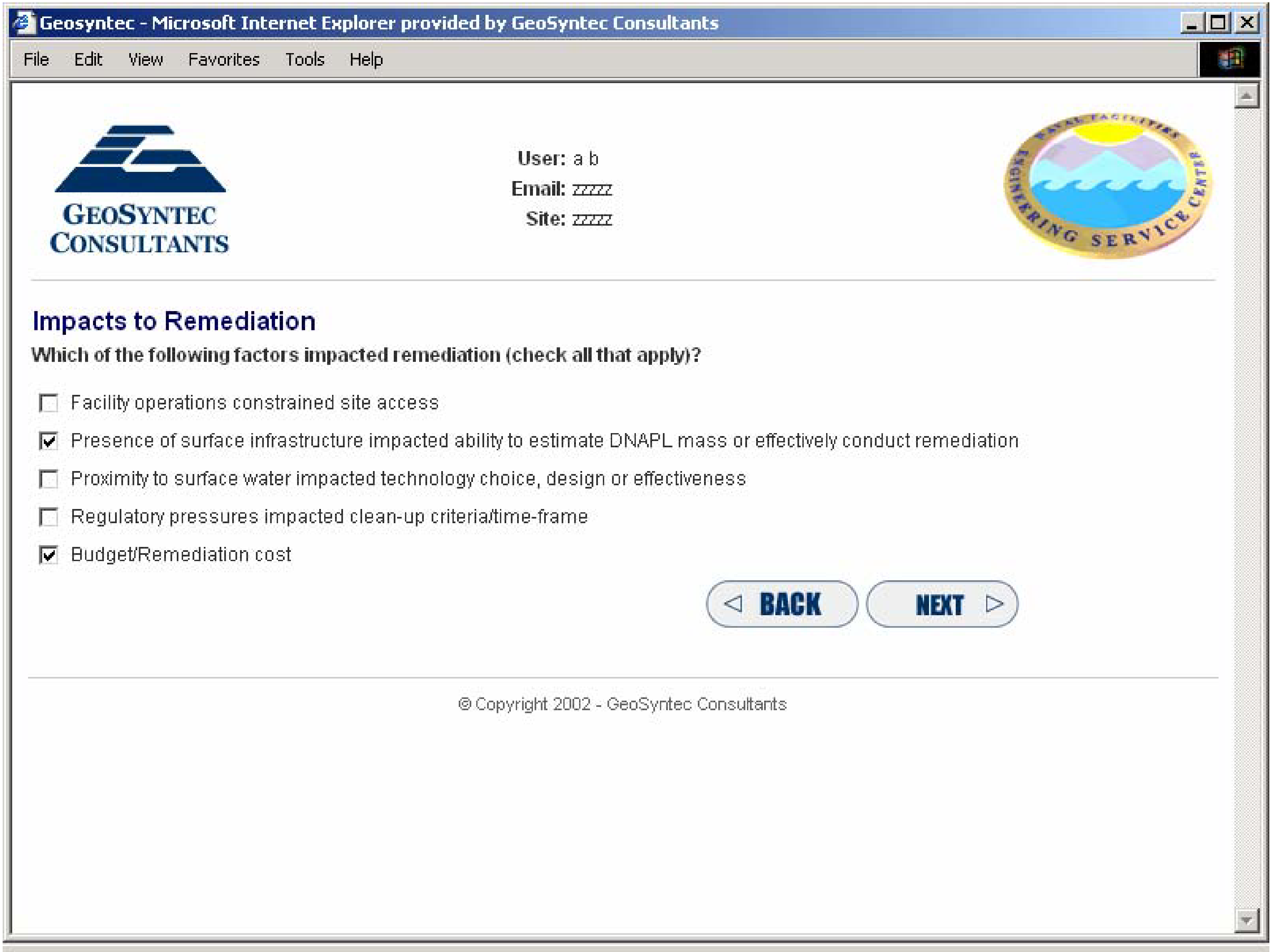
Calculated from flux measurements: ☐

Partitioning tracers: ☐

Not estimated: ☐

Other method (describe):

Enter the estimated total (pre-remediation) DNAPL mass: Unknown

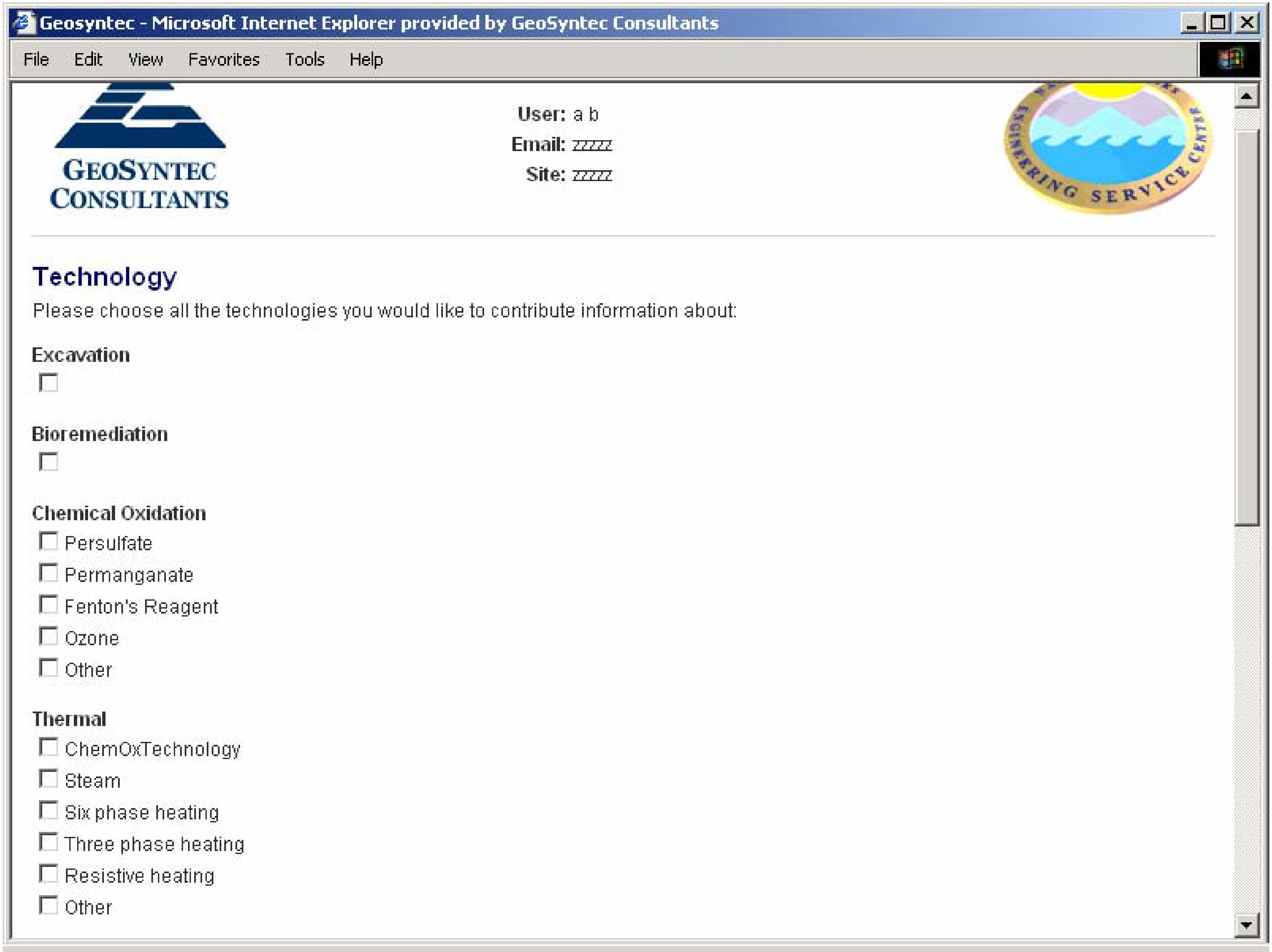


User: a b
Email: zzzzz
Site: zzzzz

Impacts to Remediation

Which of the following factors impacted remediation (check all that apply)?

- ☐ Facility operations constrained site access
- ☑ Presence of surface infrastructure impacted ability to estimate DNAPL mass or effectively conduct remediation
- ☐ Proximity to surface water impacted technology choice, design or effectiveness
- ☐ Regulatory pressures impacted clean-up criteria/time-frame
- ☑ Budget/Remediation cost



User: a b
Email: zzzzz
Site: zzzzz

Technology

Please choose all the technologies you would like to contribute information about:

Excavation

☐

Bioremediation

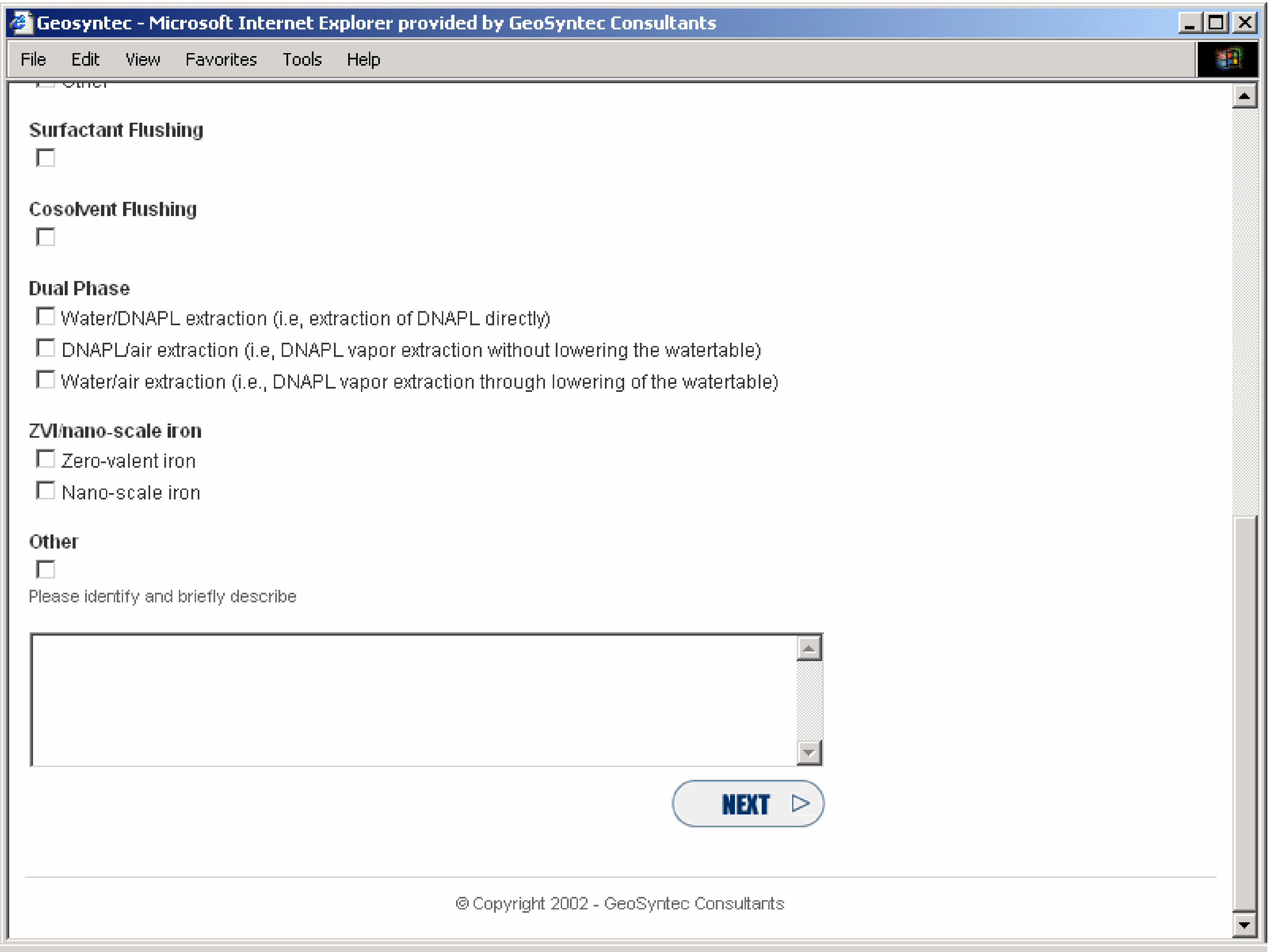
☐

Chemical Oxidation

☐ Persulfate
☐ Permanganate
☐ Fenton's Reagent
☐ Ozone
☐ Other

Thermal

☐ ChemOxTechnology
☐ Steam
☐ Six phase heating
☐ Three phase heating
☐ Resistive heating
☐ Other



Surfactant Flushing

☐

Cosolvent Flushing

☐

Dual Phase

☐ Water/DNAPL extraction (i.e, extraction of DNAPL directly)
☐ DNAPL/air extraction (i.e, DNAPL vapor extraction without lowering the watertable)
☐ Water/air extraction (i.e., DNAPL vapor extraction through lowering of the watertable)

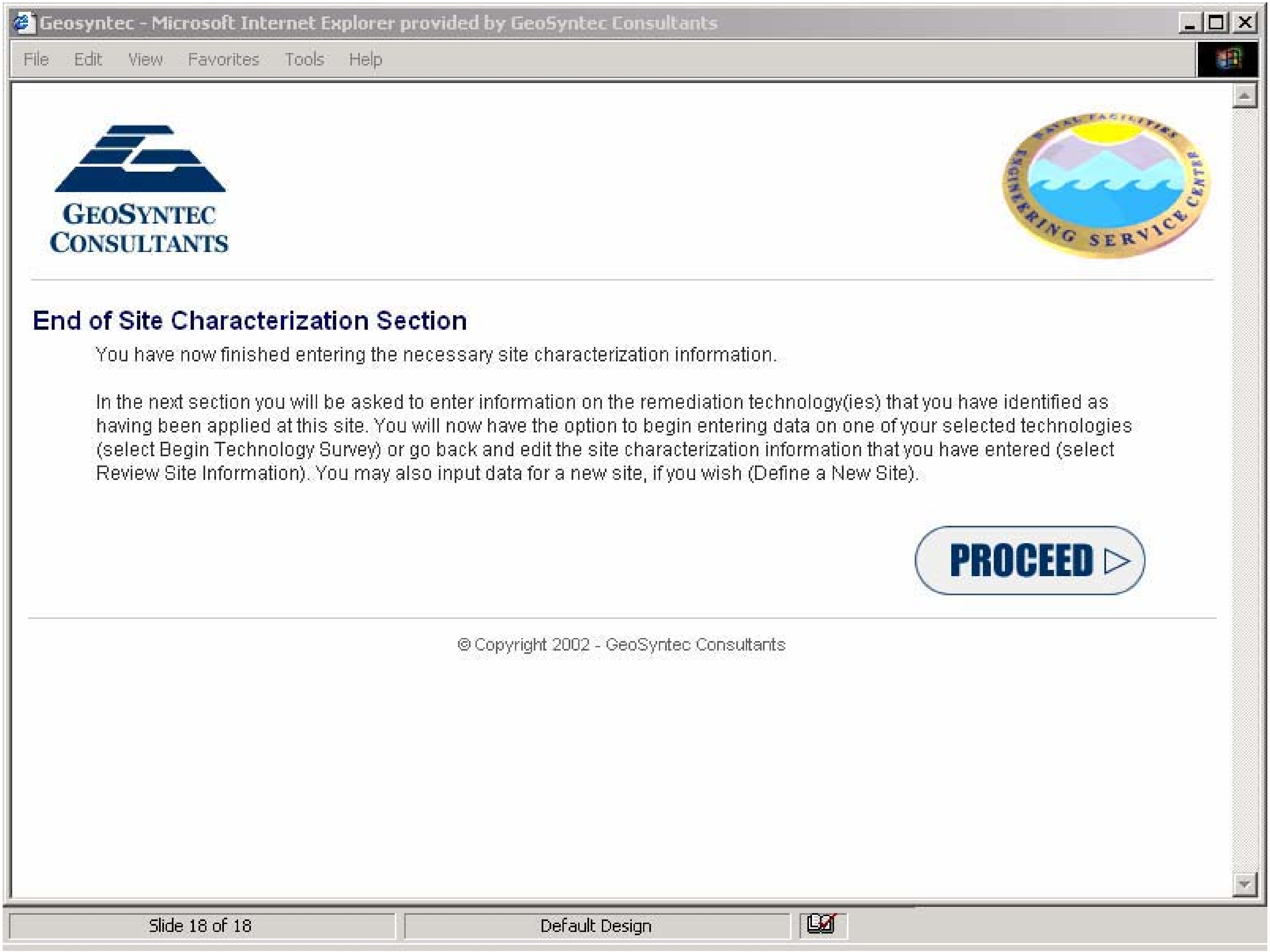
ZVI/nano-scale iron

☐ Zero-valent iron
☐ Nano-scale iron

Other

☐

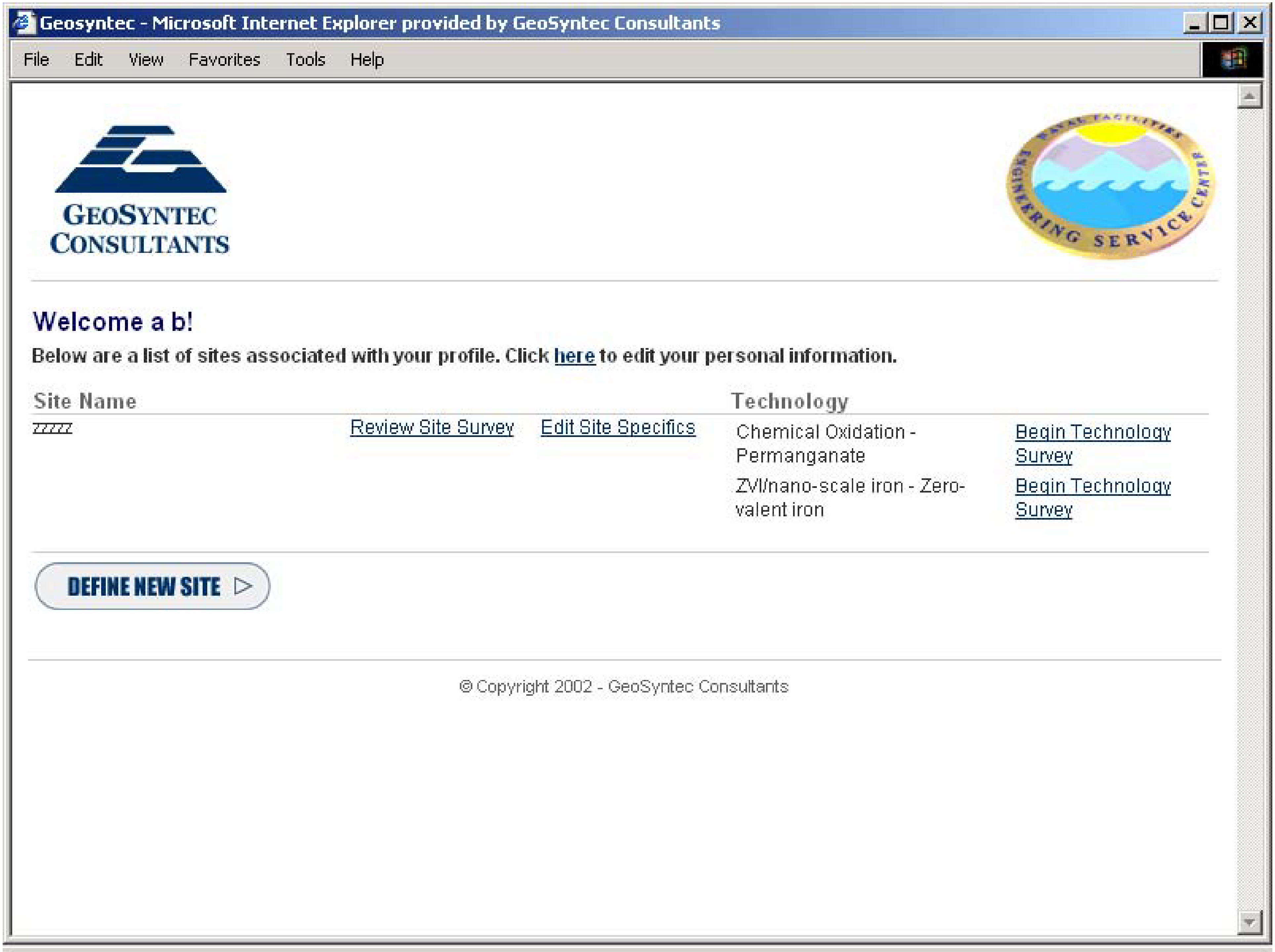
Please identify and briefly describe



End of Site Characterization Section

You have now finished entering the necessary site characterization information.

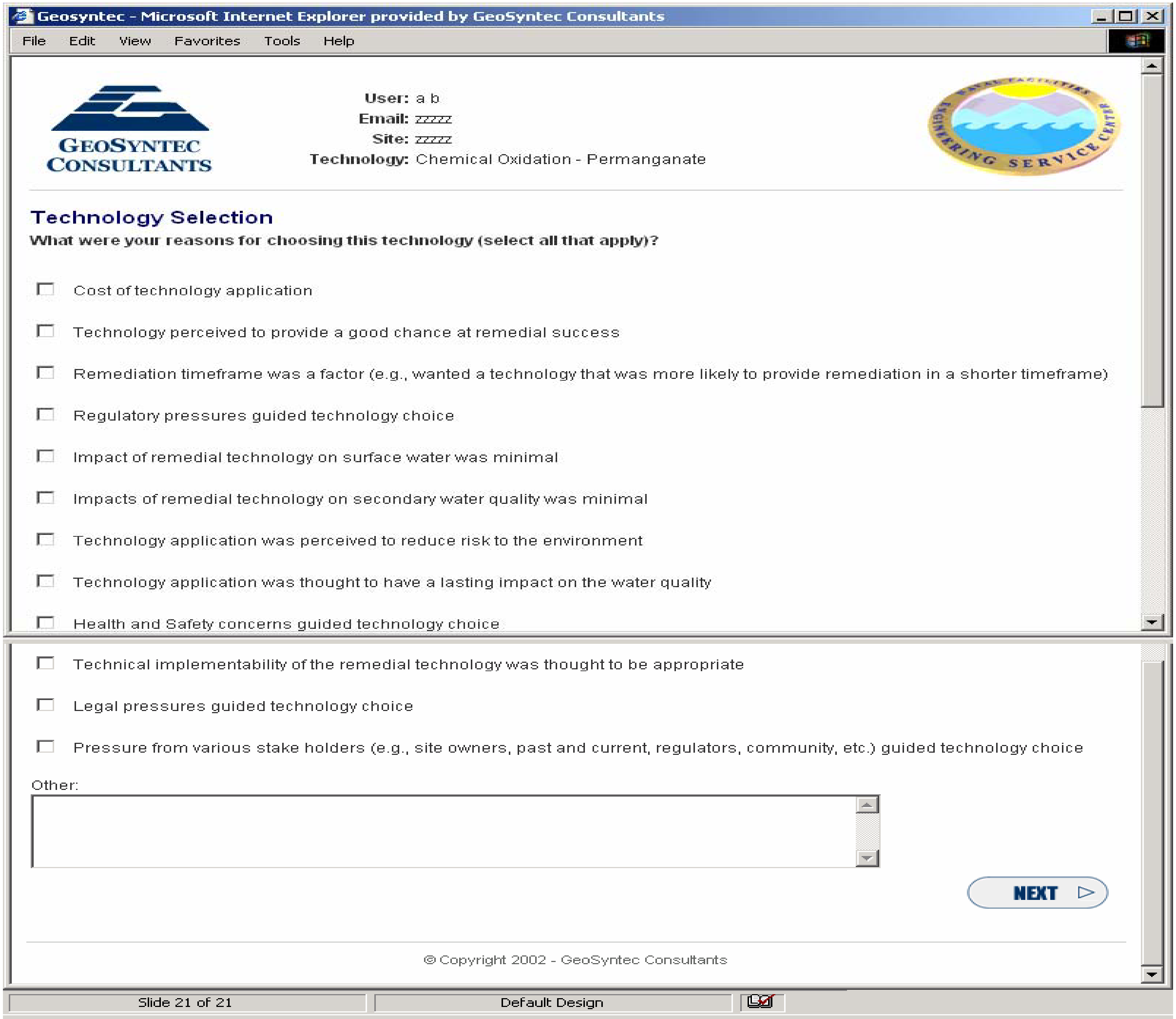
In the next section you will be asked to enter information on the remediation technology(ies) that you have identified as having been applied at this site. You will now have the option to begin entering data on one of your selected technologies (select Begin Technology Survey) or go back and edit the site characterization information that you have entered (select Review Site Information). You may also input data for a new site, if you wish (Define a New Site).



Welcome a b!

Below are a list of sites associated with your profile. Click here to edit your personal information.

Site Name			Technology	
zzzzz	Review Site Survey	Edit Site Specifics	Chemical Oxidation - Permanganate	Begin Technology Survey
			ZVI/nano-scale iron - Zero-valent iron	Begin Technology Survey



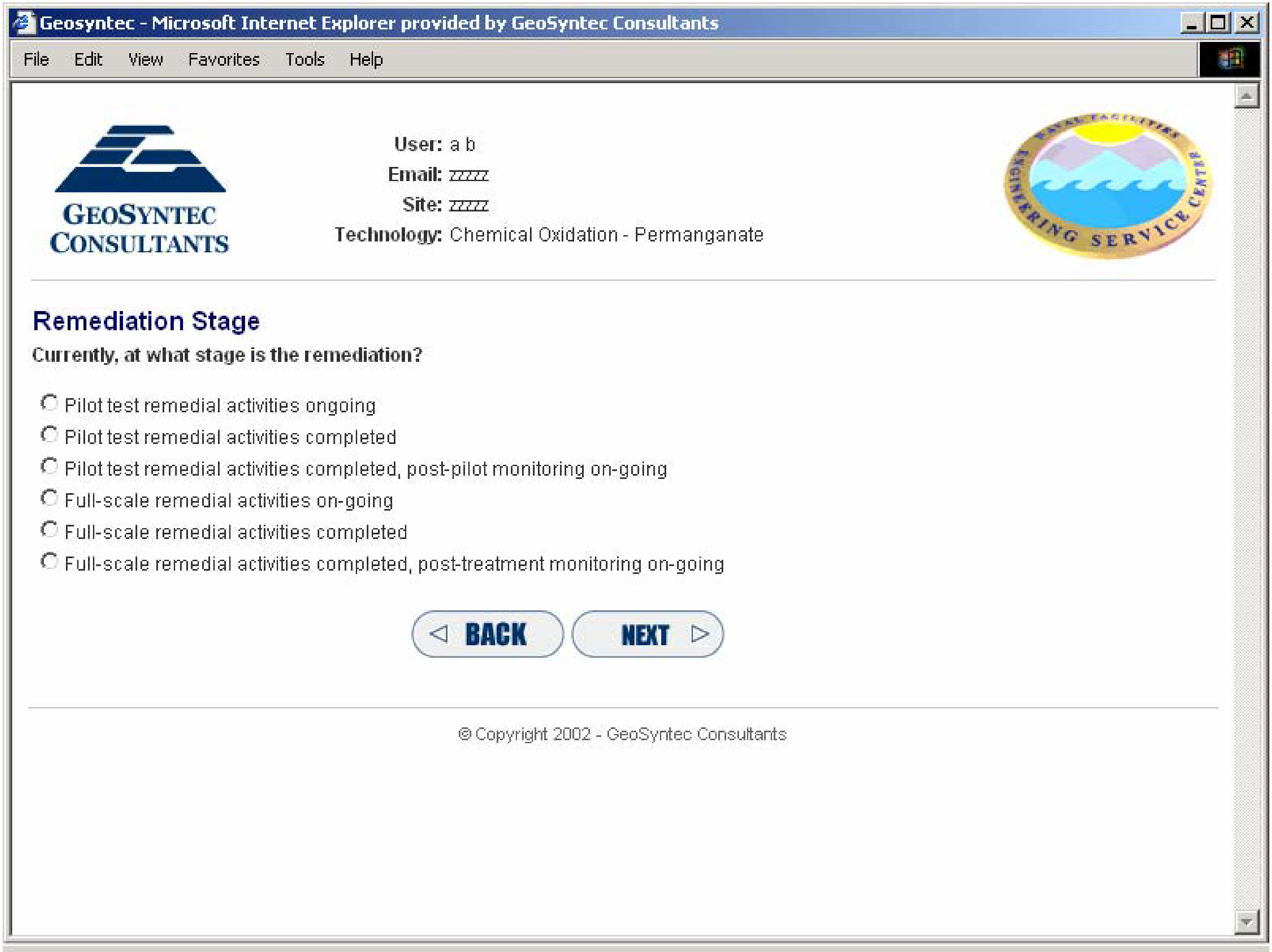
User: a b
Email: zzzzz
Site: zzzzz
Technology: Chemical Oxidation - Permanganate

Technology Selection

What were your reasons for choosing this technology (select all that apply)?

☐ Cost of technology application
☐ Technology perceived to provide a good chance at remedial success
☐ Remediation timeframe was a factor (e.g., wanted a technology that was more likely to provide remediation in a shorter timeframe)
☐ Regulatory pressures guided technology choice
☐ Impact of remedial technology on surface water was minimal
☐ Impacts of remedial technology on secondary water quality was minimal
☐ Technology application was perceived to reduce risk to the environment
☐ Technology application was thought to have a lasting impact on the water quality
☐ Health and Safety concerns guided technology choice
☐ Technical implementability of the remedial technology was thought to be appropriate
☐ Legal pressures guided technology choice
☐ Pressure from various stake holders (e.g., site owners, past and current, regulators, community, etc.) guided technology choice

Other:

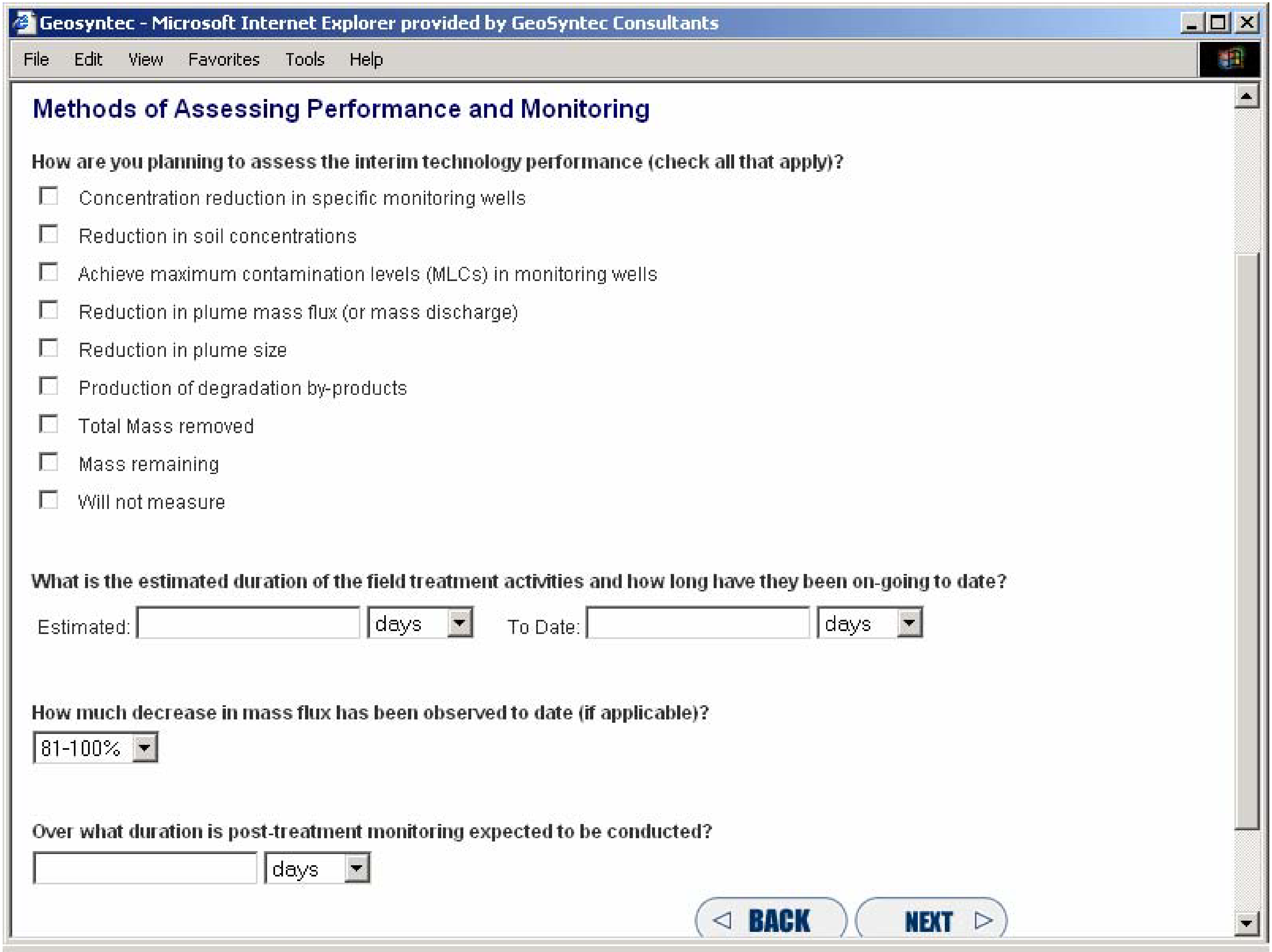


User: a b
Email: zzzzz
Site: zzzzz
Technology: Chemical Oxidation - Permanganate

Remediation Stage

Currently, at what stage is the remediation?

- ○ Pilot test remedial activities ongoing
- ○ Pilot test remedial activities completed
- ○ Pilot test remedial activities completed, post-pilot monitoring on-going
- ○ Full-scale remedial activities on-going
- ○ Full-scale remedial activities completed
- ○ Full-scale remedial activities completed, post-treatment monitoring on-going



Methods of Assessing Performance and Monitoring

How are you planning to assess the interim technology performance (check all that apply)?

- ☐ Concentration reduction in specific monitoring wells
- ☐ Reduction in soil concentrations
- ☐ Achieve maximum contamination levels (MLCs) in monitoring wells
- ☐ Reduction in plume mass flux (or mass discharge)
- ☐ Reduction in plume size
- ☐ Production of degradation by-products
- ☐ Total Mass removed
- ☐ Mass remaining
- ☐ Will not measure

What is the estimated duration of the field treatment activities and how long have they been on-going to date?

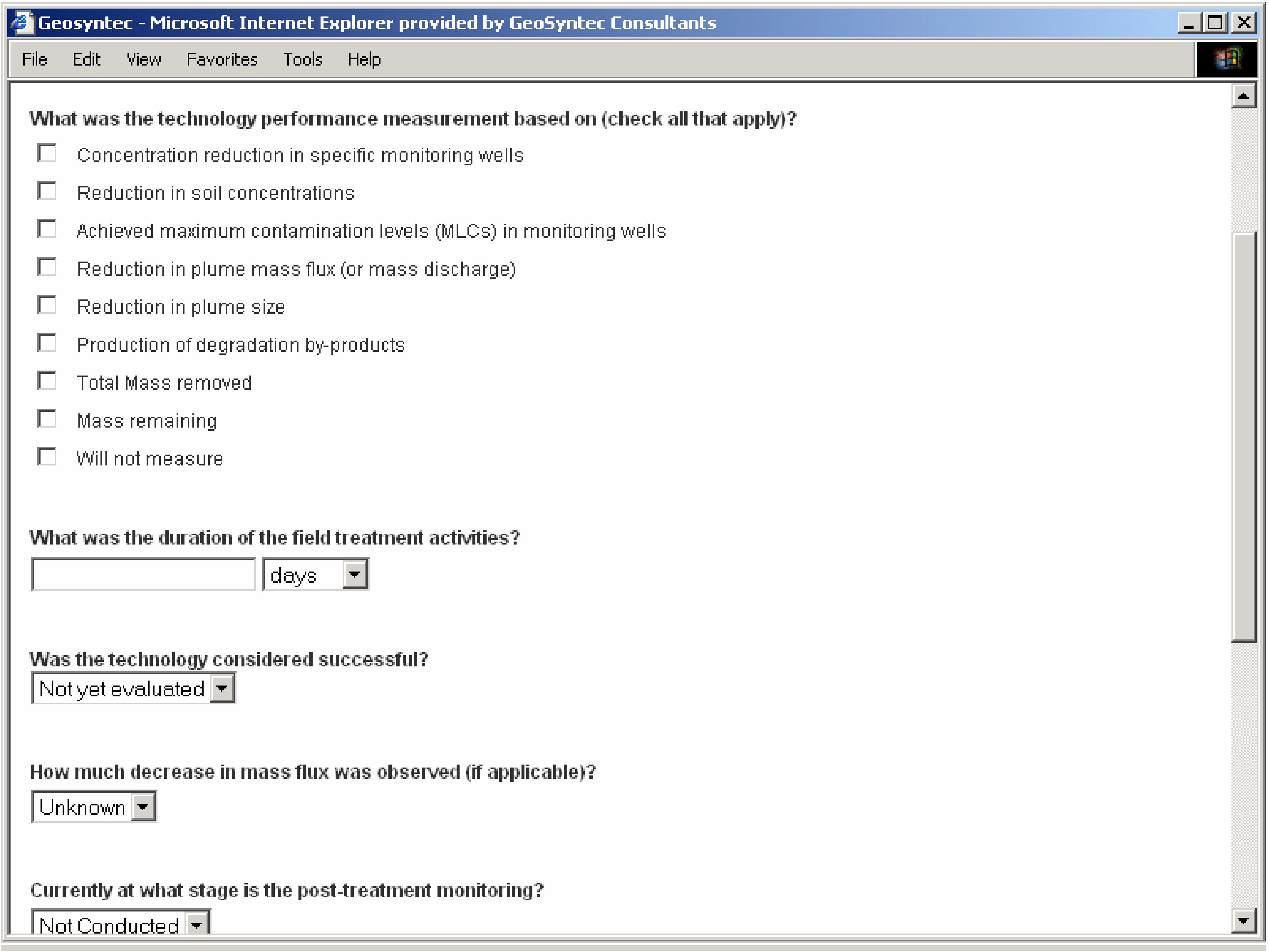
Estimated: days To Date: days

How much decrease in mass flux has been observed to date (if applicable)?

81-100%

Over what duration is post-treatment monitoring expected to be conducted?

days



What was the technology performance measurement based on (check all that apply)?

☐ Concentration reduction in specific monitoring wells

☐ Reduction in soil concentrations

☐ Achieved maximum contamination levels (MLCs) in monitoring wells

☐ Reduction in plume mass flux (or mass discharge)

☐ Reduction in plume size

☐ Production of degradation by-products

☐ Total Mass removed

☐ Mass remaining

☐ Will not measure

What was the duration of the field treatment activities?

days

Was the technology considered successful?

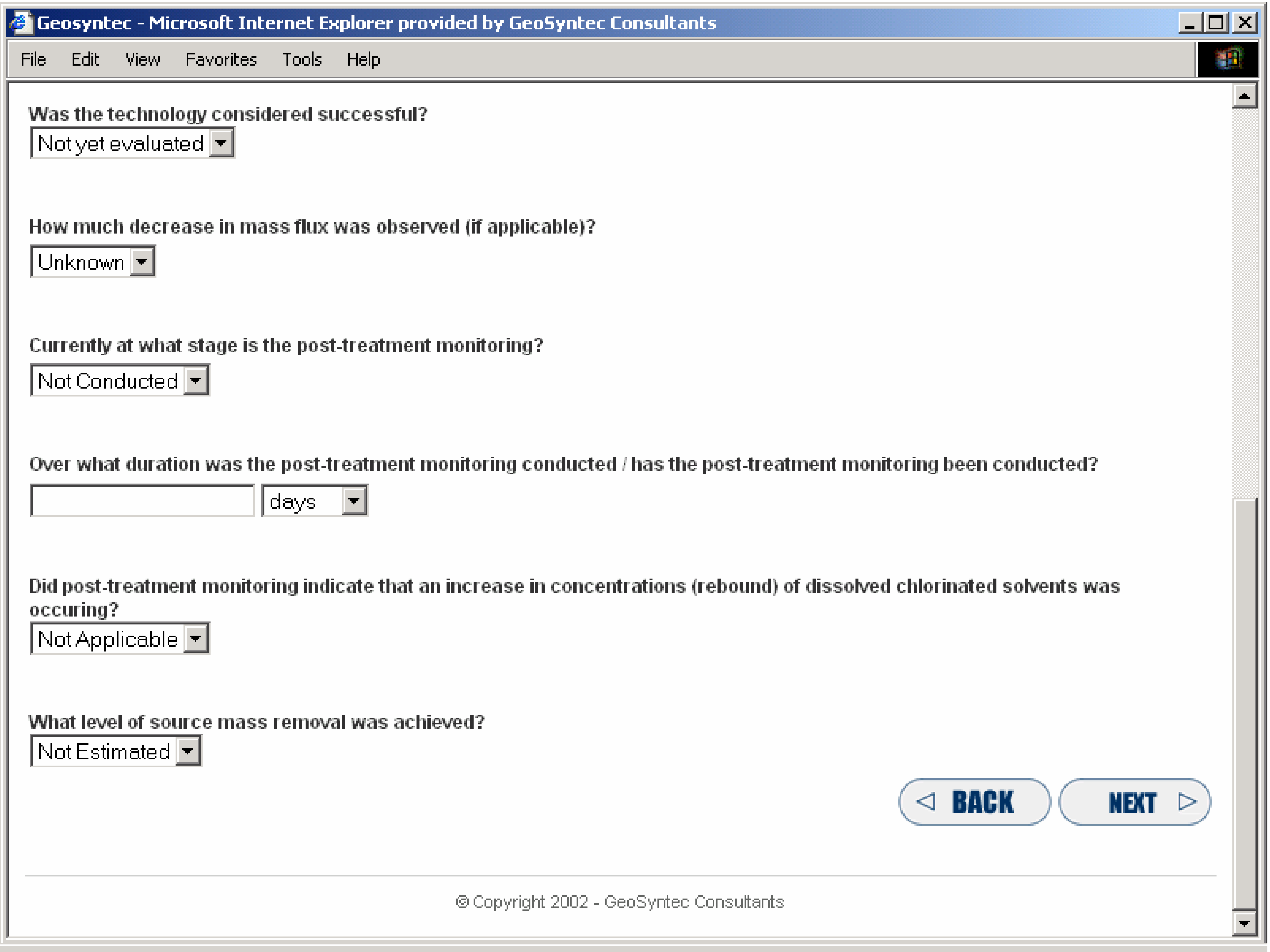
Not yet evaluated

How much decrease in mass flux was observed (if applicable)?

Unknown

Currently at what stage is the post-treatment monitoring?

Not Conducted



Was the technology considered successful?
Not yet evaluated

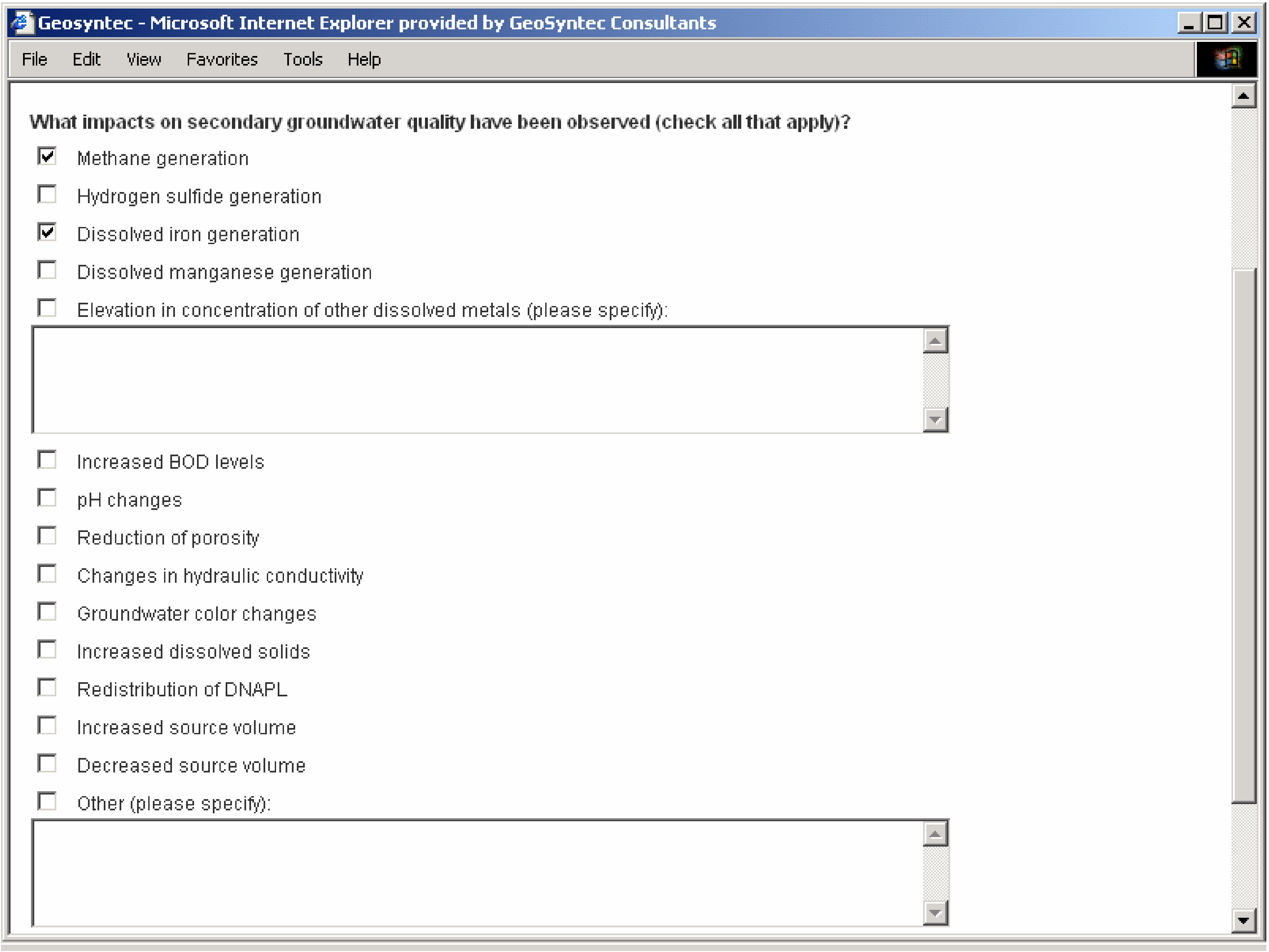
How much decrease in mass flux was observed (if applicable)?
Unknown

Currently at what stage is the post-treatment monitoring?
Not Conducted

Over what duration was the post-treatment monitoring conducted / has the post-treatment monitoring been conducted?
days

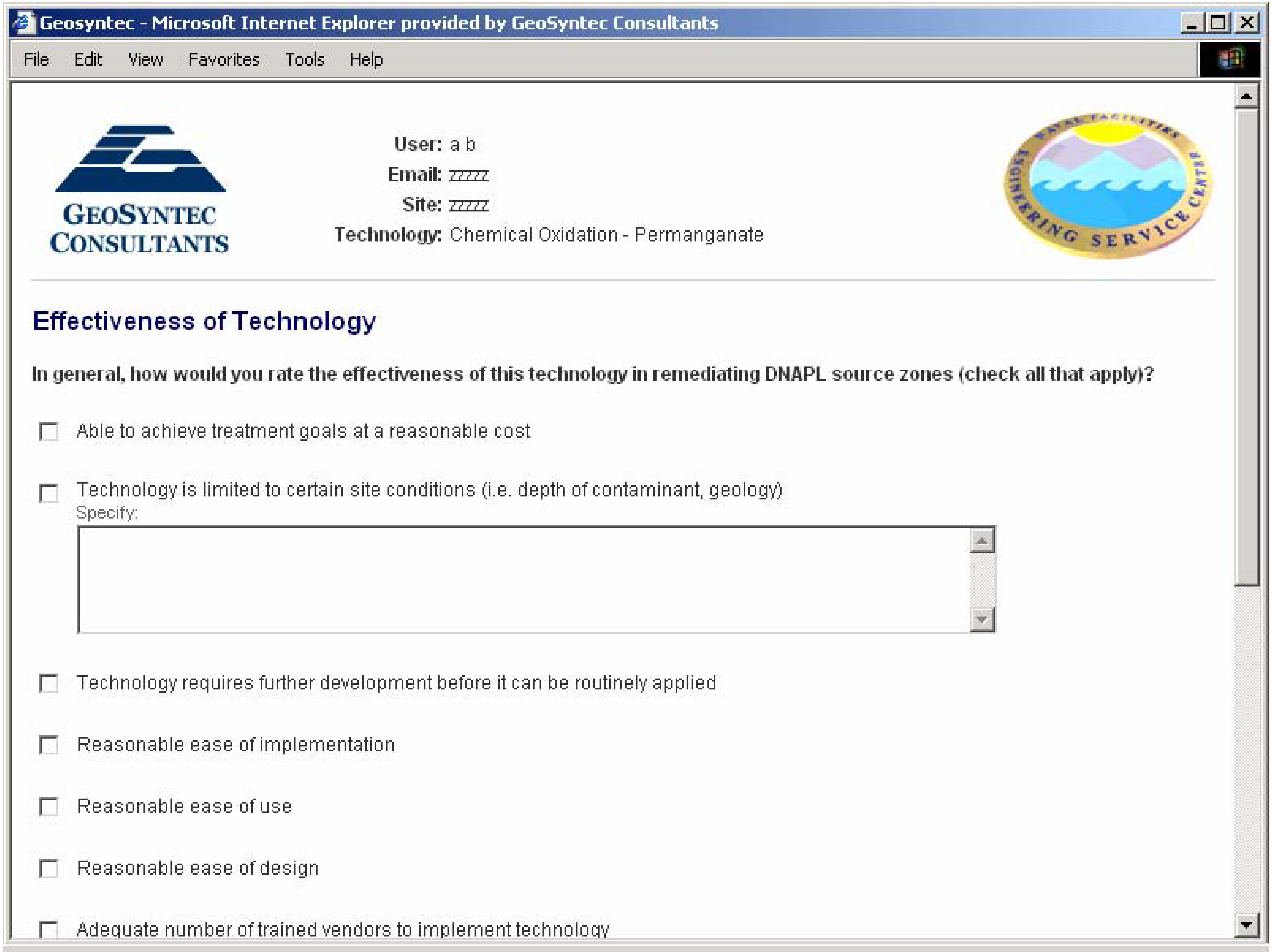
Did post-treatment monitoring indicate that an increase in concentrations (rebound) of dissolved chlorinated solvents was occuring?
Not Applicable

What level of source mass removal was achieved?
Not Estimated



What impacts on secondary groundwater quality have been observed (check all that apply)?

☑ Methane generation
☐ Hydrogen sulfide generation
☑ Dissolved iron generation
☐ Dissolved manganese generation
☐ Elevation in concentration of other dissolved metals (please specify):
☐ Increased BOD levels
☐ pH changes
☐ Reduction of porosity
☐ Changes in hydraulic conductivity
☐ Groundwater color changes
☐ Increased dissolved solids
☐ Redistribution of DNAPL
☐ Increased source volume
☐ Decreased source volume
☐ Other (please specify):



User: a b

Email: zzzzz

Site: zzzzz

Technology: Chemical Oxidation - Permanganate

Effectiveness of Technology

In general, how would you rate the effectiveness of this technology in remediating DNAPL source zones (check all that apply)?

☐ Able to achieve treatment goals at a reasonable cost

☐ Technology is limited to certain site conditions (i.e. depth of contaminant, geology)
Specify:

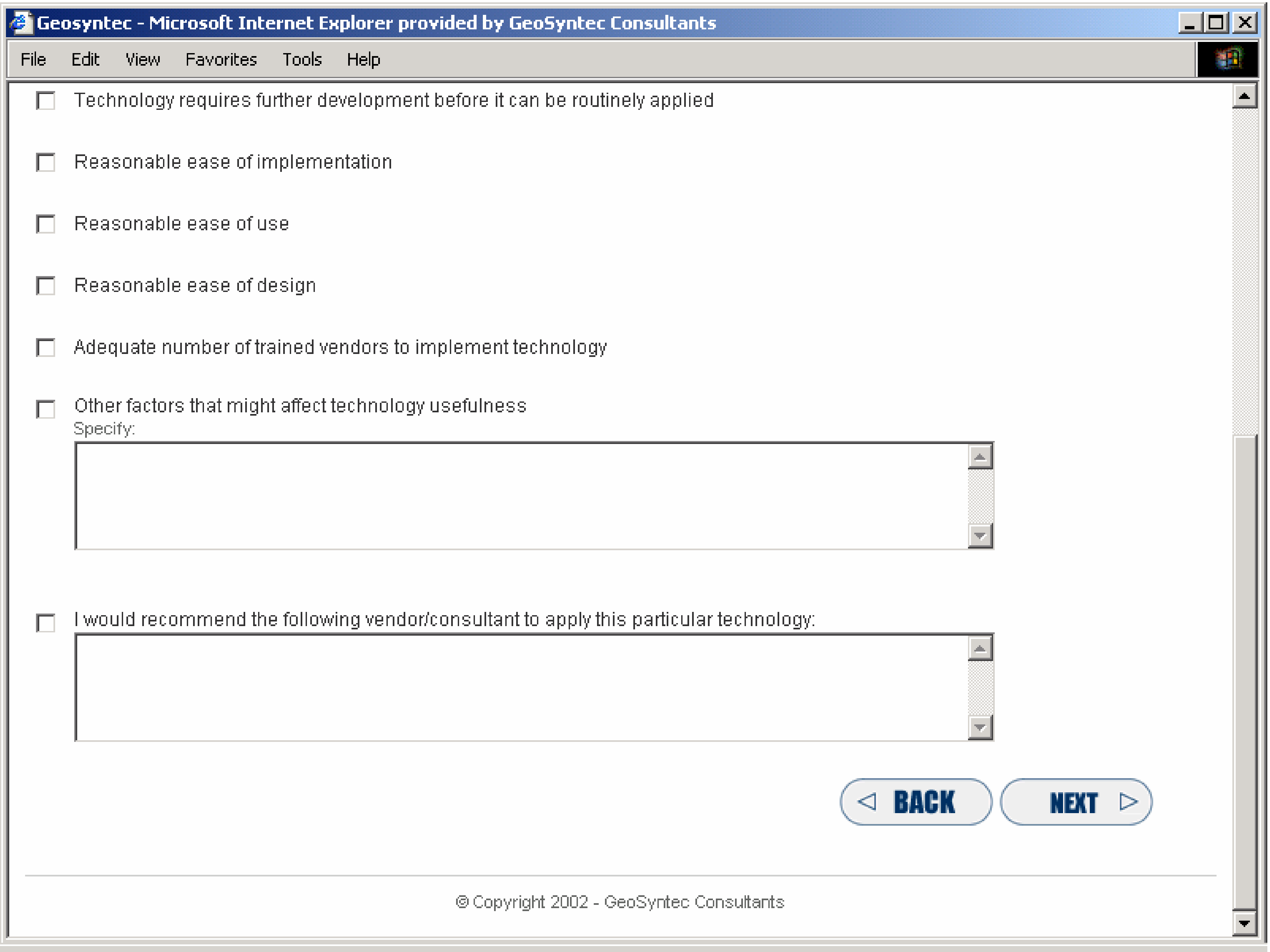
☐ Technology requires further development before it can be routinely applied

☐ Reasonable ease of implementation

☐ Reasonable ease of use

☐ Reasonable ease of design

☐ Adequate number of trained vendors to implement technology



☐ Technology requires further development before it can be routinely applied

☐ Reasonable ease of implementation

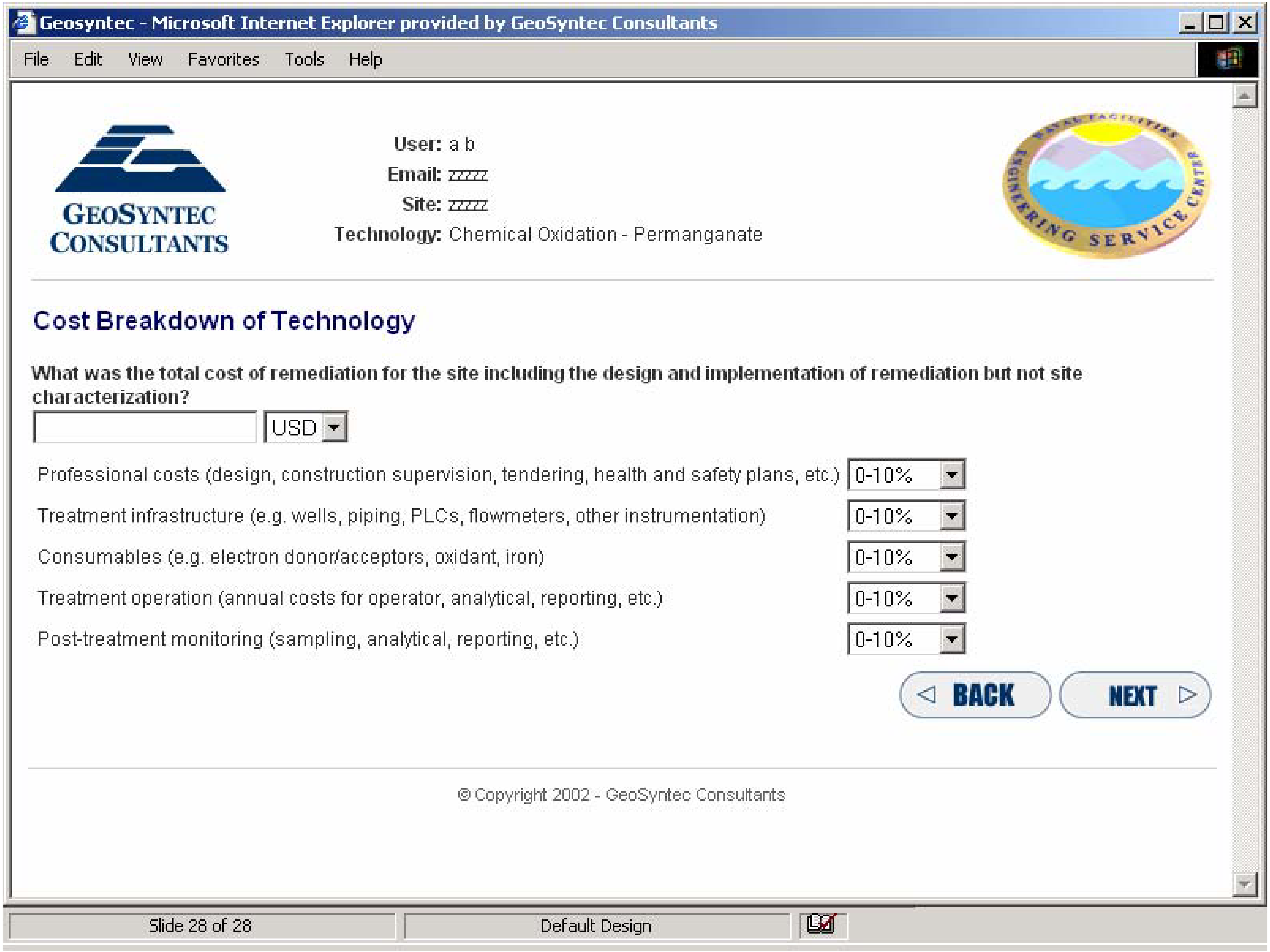
☐ Reasonable ease of use

☐ Reasonable ease of design

☐ Adequate number of trained vendors to implement technology

☐ Other factors that might affect technology usefulness
Specify:

☐ I would recommend the following vendor/consultant to apply this particular technology:



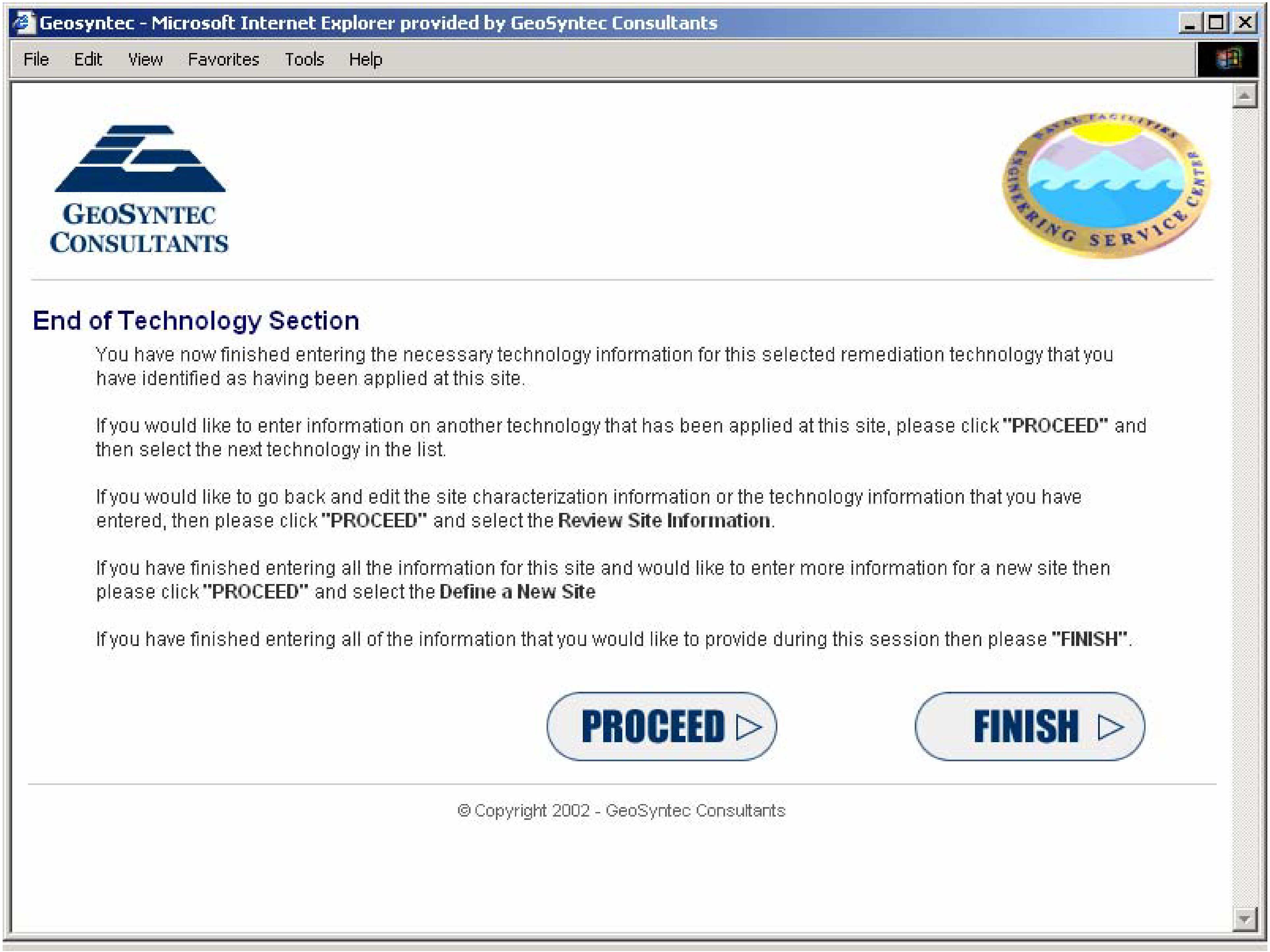
User: a b
Email: zzzzz
Site: zzzzz
Technology: Chemical Oxidation - Permanganate

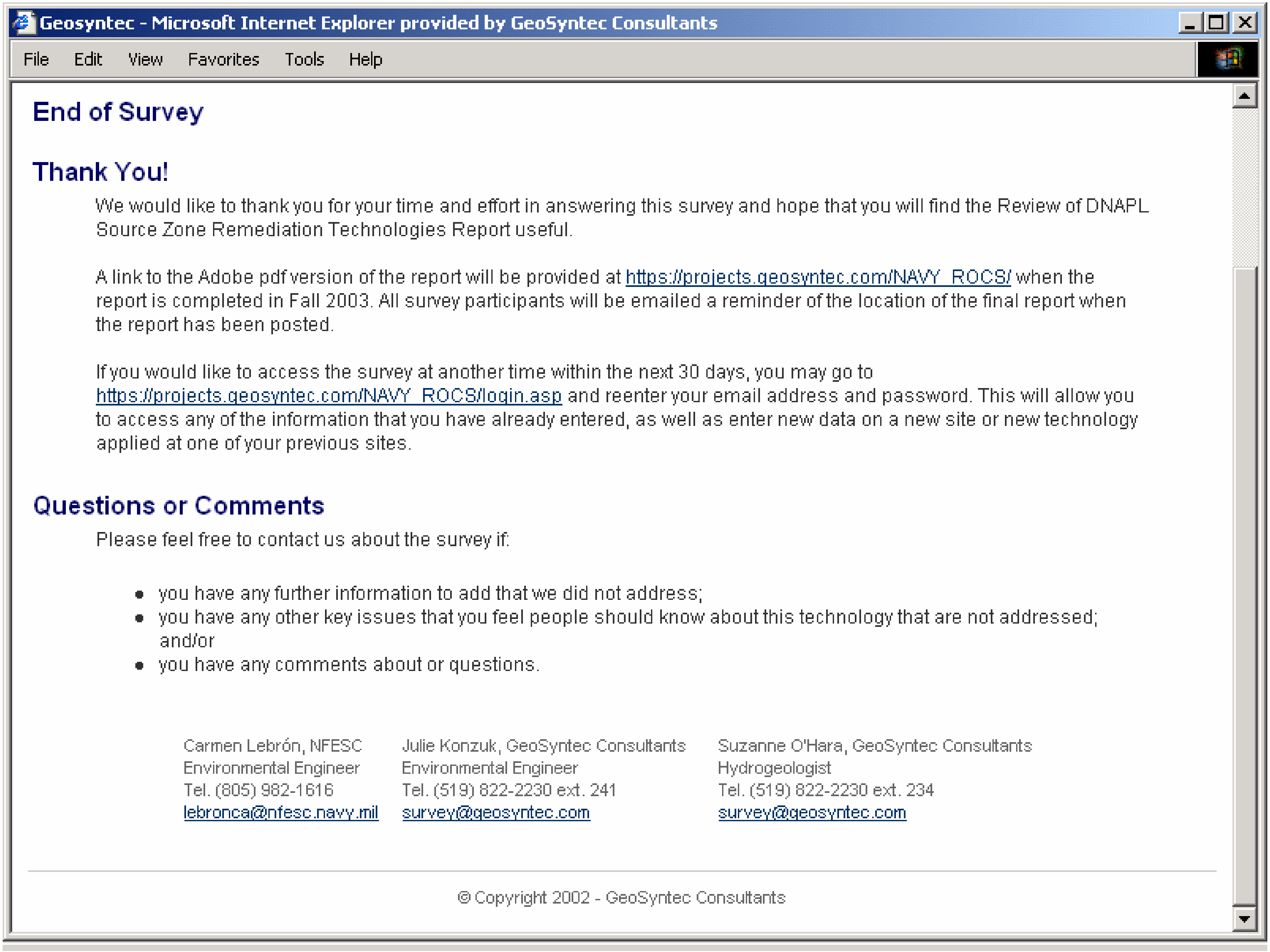
Cost Breakdown of Technology

What was the total cost of remediation for the site including the design and implementation of remediation but not site characterization?

USD

Professional costs (design, construction supervision, tendering, health and safety plans, etc.)	0-10%
Treatment infrastructure (e.g. wells, piping, PLCs, flowmeters, other instrumentation)	0-10%
Consumables (e.g. electron donor/acceptors, oxidant, iron)	0-10%
Treatment operation (annual costs for operator, analytical, reporting, etc.)	0-10%
Post-treatment monitoring (sampling, analytical, reporting, etc.)	0-10%





End of Survey

Thank You!

We would like to thank you for your time and effort in answering this survey and hope that you will find the Review of DNAPL Source Zone Remediation Technologies Report useful.

A link to the Adobe pdf version of the report will be provided at https://projects.geosyntec.com/NAVY_ROCS/ when the report is completed in Fall 2003. All survey participants will be emailed a reminder of the location of the final report when the report has been posted.

If you would like to access the survey at another time within the next 30 days, you may go to https://projects.geosyntec.com/NAVY_ROCS/login.asp and reenter your email address and password. This will allow you to access any of the information that you have already entered, as well as enter new data on a new site or new technology applied at one of your previous sites.

Questions or Comments

Please feel free to contact us about the survey if:

- you have any further information to add that we did not address;
- you have any other key issues that you feel people should know about this technology that are not addressed; and/or
- you have any comments about or questions.

Carmen Lebrón, NFESC
Environmental Engineer
Tel. (805) 982-1616
lebronca@nfesc.navy.mil

Julie Konzuk, GeoSyntec Consultants
Environmental Engineer
Tel. (519) 822-2230 ext. 241
survey@geosyntec.com

Suzanne O'Hara, GeoSyntec Consultants
Hydrogeologist
Tel. (519) 822-2230 ext. 234
survey@geosyntec.com

APPENDIX C

Detailed Survey Data Summary

APPENDIX C TABLE OF CONTENTS

Page

APPENDIX C: DETAILED SURVEY DATA SUMMARY

This Appendix presents a detailed summary of the survey questions and the data collected. Appendix D presents the interpretation of the data in terms of the impact of various site factors and technology choice on the remedial cost, duration and success. Tables are embedded within the text below. Figures may be found at the end of the appendix.

The following caveats are implicit in the data summary provided below:

i) The data is summarized separately for sites where the remedial technology was specified *versus* sites with unspecified technologies. The data for sites with unspecified technologies are presented separately because it is unclear whether these surveys were incomplete due to a lack of respondent interest, or to inappropriateness of data (*e.g.,* remedial activities targeted dissolved phase, as opposed to DNAPL).

ii) Variations in the number of total data available for each survey question arise due to the following:

- one survey respondent can enter data for multiple sites;
- one individual site location can have data for multiple technology applications; and
- few survey questions required answers before allowing the respondent to proceed forward through the survey, resulting in variable totals per question.

iii) For ease of discussion, the term "site" is used here to refer to a unique combination of site location and technology application. One site location may have multiple technology applications, either used sequentially or targeting different portions of the DNAPL source area(s); however, each technology application is treated as a separate site.

iv) Given the limited amount of available data on field applications of DNAPL remediation, the data collected may not be a statistically significant representation of all field applications.

1 Aquifer Geology/Lithology

Survey respondents were asked to specify the following:

i) Type of geologic material present in the DNAPL source area (*i.e.,* unconsolidated versus consolidated media);

ii) Classify the geological material by degree of fracturing and rock matrix permeability (consolidated material only) or degree of heterogeneity (unconsolidated material only); and

iii) Predominant lithology of the aquifer media within the DNAPL source zone.

See below for a summary of the data collected.

Q: Enter the relative percentage of aquifer media type.

Survey respondents were asked to provide information on all types of geologic media present at their site (*i.e*., consolidated versus unconsolidated), and to categorize the geologic media by the degree of fracturing and rock matrix permeability (consolidated media only) or degree of heterogeneity (unconsolidated media only). The respondent was asked to specify what relative portion (*i.e.,* percentage) of their site contained media with that description; more than one media type/description could be chosen for each site. Table C.1 provides a summary of the data that was entered into the survey database, broken down by sites with a remedial technology specified by the survey respondent and those without where the survey respondent did not complete the survey. Table D.17 in Appendix D provides a more detailed breakdown of the data, including the range of percentages and subdivided by technology (see Appendix D). In total, data was entered for 152 sites, of which 54 sites had both consolidated and unconsolidated media, 8 sites had only consolidated media, and 90 sites had only unconsolidated media.

Table C.1: Summary of the breakdown of the aquifer type.

Aquifer Media Type	Media Description	Descriptive Parameter	Sites with Technology Specified	Sites with Unspecified Technology	Total Sites*
Consolidated	Degree of Fracturing	Discretely Fractured	24	5	29 (46.8%)
		Highly Fractured	20	4	24 (38.7%)
		Unfractured	22	9	31 (50.0%)
		TOTAL SITES	**48**	**14**	**62**
	Rock Matrix Permeability	Low	28	5	33 (53.2%)
		High	25	11	36 (58.1%)
		Unknown	4	2	6 (9.7%)
		TOTAL SITES	**48**	**14**	**62**
Unconsolidated	Heterogeneity	Low	47	18	65 (45.1%)
		High	92	24	116 (80.6%)
		Unknown	14	0	14 (9.7%)
		TOTAL SITES	**127**	**17**	**144**

* - respondents were asked to provide information on all types of geologic media at the site;for sites with multiple geologic media present, it is possible to have answers that add to up to > 100%.

From Table C.1, it is evident that for the sites with consolidated material, there were approximately equal numbers of sites with discretely fractured and highly fractured bedrock, with equally distributed low and high rock matrix permeabilities. For the majority of the sites with unconsolidated material, the soil was highly heterogeneous.

Q: Choose one rock/soil type that best describes the predominant geologic material in the source area.

The lithology choices that were available are listed in Table C.2 below, along with a summary of the number of sites with each lithology where DNAPL remediation was attempted. In total, lithology was specified for 144 sites, of which 117 of these sites had a technology associated with them and the remaining 27 sites were from incomplete survey entries where no technology was specified. Of the 144 total sites, only 16 (11.1%) of the sites had predominantly consolidated media in the source area. The majority (128 or 88.9%) of the sites were located in unconsolidated media. Figure C.1 illustrates the breakdown of the sites that had a technology specified into consolidated (13 of the 117 sites) and unconsolidated (104 of the 117 sites) media, as well as the distribution of the subcategories within each. Table C.2 below and Table D.18 in Appendix D provide more detailed breakdowns of the data, with Table D.18 including the range of percentages and subdivided by technology (see Appendix D).

Of the 16 total consolidated media sites, the majority of the DNAPL remediation was attempted at sites having sedimentary rock (mostly shale, some karstic and non-karstic limestone) as the most prevalent geologic material in the source area (Table C.2). Conversely, DNAPL remediation was attempted at only one site with igneous (granitic) bedrock.

Of the 128 sites where remediation was undertaken in unconsolidated material, the majority of the sites had sand as the most prevalent geologic material in the source area, silt and clay being the next most prevalent (Table C.2). Only a few sites had gravel, till or unknown predominant soil types.

Table C.2: Summary of the breakdown of the predominant geologic material in the source area.

Aquifer Media Type	Lithology		Sites with Unspecified Technology	Sites with Specified Technology	Total Sites
Consolidated	Metamorphic	Metabasalt	0	1	1 (50.0%)
		Metashale	0	0	0 (0.0%)
		Other	0	1	1 (50.0%)
		TOTAL	**0**	**2**	**2 (12.5%)**
	Sedimentary	Shale	1	5	6 (54.5%)
		Sandstone	0	0	0 (0.0%)
		Limestone (non-karstic)	1	0	1 (9.1%)
		Limestone (karstic)	0	3	3 (27.3%)
		Other	0	1	1 (9.1%)
		TOTAL	**2**	**9**	**11 (68.8%)**
	Igneous	Granitic	0	1	1 (100%)
		Basaltic	0	0	0 (0.0%)
		Intermediate	0	0	0 (0.0%)
		Other	0	0	0 (0.0%)
		TOTAL	**0**	**1**	**1 (6.3%)**
	Unknown	**TOTAL**	**1**	**1**	**2 (12.5%)**
	TOTAL		**3**	**13**	**16 (11.1%)**
Unconsolidated	Gravel		0	8	8 (6.3%)
	Sand		12	45	57 (44.5%)
	Till		1	7	8 (6.3%)
	Silt		7	22	29 (22.7%)
	Clay		4	18	22 (17.2%)
	Unknown		0	4	4 (3.1%)
	TOTAL		**24**	**104**	**128 (88.9%)**

2 Hydrogeology

Survey respondents were asked to enter data describing the following hydrogeological parameters:

i) Hydraulic conductivity;

ii) Groundwater velocity;

iii) Sustainable well yield;

iv) Depth to groundwater; and

v) Horizontal and vertical hydraulic gradients.

Information for 137 sites was entered into the survey database; of these, 118 sites had a remedial technology specified while 19 did not.

Q: Choose the hydrogeological parameters that best describe the BULK conditions within the DNAPL source area.

Table C.3 summarizes the hydraulic conductivity data entered into the survey database. Survey respondents were asked to enter hydraulic conductivity data as order of magnitude ranges; the data have been grouped into three categories representing low, medium and high hydraulic conductivities for ease of discussion and analysis. Overall, of the 137 sites in the survey database with hydraulic conductivity data, 8 (5.8%) sites have hydraulic conductivities of less than 10^{-5} ft/day, 49 (35.8%) sites have hydraulic conductivities between 10^{-5} ft/day and 10 ft/day, and 23 (16.7%) sites have high hydraulic conductivities (greater than 10 ft/day). It is interesting to note that of the 137 responses to this question, 57 (41.6%) of the sites had an unknown hydraulic conductivity, a key parameter when evaluating site data.

Table C.3: Summary of the breakdown of hydraulic conductivity data.

Hydraulic Conductivity	Total Sites With Unspecified Technology	Total Sites With Technology Specified	Total Sites
< 10^{-5} ft/day	0	8	8 (5.8%)
10^{-5} to 10 ft/day	9	40	49 (35.8%)
> 10 ft/day	2	21	23 (16.7%)
Unknown	8	49	57 (41.6%)
TOTAL	**19**	**118**	**137**

Table C.4 provides a summary of the groundwater velocity data entered into the survey database. Survey respondents were asked to choose from order of magnitude ranges; the data have been grouped into three ranges representing low, medium and high groundwater velocities for ease of analysis and discussion. Overall, of the 137 sites in the survey database with groundwater velocity data, 3 (2.2%) sites have low groundwater velocities (< 10^{-3} ft/day), 40 (29.2%) sites have groundwater velocities between 10^{-3} and 1 ft/day, and 15 (10.9%) sites have high groundwater velocities (> 1 ft/day). Again, of the 118 responses, 79 (57.7%) of the sites had unknown groundwater velocities.

Table C.4: Summary of the breakdown of groundwater velocity data.

Groundwater Velocity	Total Sites With Unspecified Technology	Total Sites With Technology Specified	Total Sites
< 0.001 ft/day	0	3	3 (2.2%)
0.001 to 1 ft/day	7	33	40 (29.2%)
> 1 ft/day	1	14	15 (10.9%)
Unknown	11	68	79 (57.7%)
TOTAL	**19**	**118**	**137**

Table C.5 presents a summary of the sustainable well yield data collected from the survey. The survey respondents were asked to enter a numerical value for this site characteristic; the data in Table C.5 has been grouped into order of magnitude ranges for ease of presentation. Overall, 49 sites had well yield data entered into the survey, while 88 sites did not have well yield data specified (*i.e.,* answer was left blank if unknown or unanswered). Of the 49 sites in the survey database with sustainable well yield data, DNAPL remediation has been attempted at only a few (4 or 8.2%) sites with low (≤ 1 gallon per minute) sustainable well yields. The majority of the sites where DNAPL remediation has been attempted have sustainable well yields between 1 and 250 gpm. There was one site where the sustainable well yield was greater than 1,000 gpm.

Table C.5: Summary of the breakdown of sustainable well yield data.

Sustainable Well Yield	Total Sites With Unspecified Technology	Total Sites With Technology Specified	Total Sites
< 1 gpm	0	4	4 (2.9%)
1 to 10 gpm	3	12	15 (10.9%)
10 to 100 gpm	2	17	19 (13.9%)
100 to 1,000 gpm	0	10	10 (7.3%)
> 1,000 gpm	0	1	1 (0.8%)
Unspecified	14	74	88 (64.2%)
TOTAL	**19**	**118**	**137**

Table C.6 presents a summary of the depth to groundwater data collected from the survey. The survey respondents were asked to enter a numerical value for this site characteristic; the data in Table C.5 has been grouped into ranges for ease of presentation. Overall, 106 sites had depth to groundwater data entered into the survey, while 31 sites did not have groundwater depth specified (*i.e.,* answer was left blank if unknown or unanswered). Of the 106 sites in the survey database with depth to groundwater data, the majority of the sites where DNAPL remediation has been attempted have watertable depths less than 50 ft below ground surface (bgs). There was one site where the depth to groundwater was greater than 200 ft bgs.

Table C.6: Summary of the breakdown of depth to groundwater data.

Depth to Groundwater	Total Sites With Unspecified Technology	Total Sites With Technology Specified	Total Sites
< 10 ft bgs	8	42	50 (36.5%)
10 to 20 ft bgs	1	28	29 (21.2%)
20 to 50 ft bgs	2	16	18 (13.1%)
50 to 100 ft bgs	2	3	5 (3.6%)
100 to 200 ft bgs	1	2	3 (2.2%)
> 200 ft bgs	0	1	1 (0.7%)
Unspecified	5	26	31 (22.6%)
TOTAL	**19**	**118**	**137**

Table C.7 provides a summary of the horizontal and vertical hydraulic gradient data entered into the survey database. Survey respondents were asked to choose from order of magnitude ranges, which are listed in Table C.7. Overall, of the 137 sites in the survey database with hydraulic gradient data, the majority (37 or 27%) had horizontal gradients within the range of 0.001 to 0.1 ft/ft. A significant number (19 or 14.8%) had flatter gradients (*i.e.*, < 0.001 ft/ft). The majority of the vertical gradients were small, indicating a predominance of horizontal groundwater flow at most DNAPL impacted sites surveyed. Of the 137 sites, a large proportion had unknown hydraulic gradients, with slightly more sites having known horizontal rather than vertical hydraulic gradients.

Table C.7: Summary of the breakdown of hydraulic gradient data.

Direction of Gradient	Hydraulic Gradient	Total Sites With Unspecified Technology	Total Sites With Technology Specified	Total Sites
Horizontal	< 0.0001	1	3	4 (2.9%)
	0.0001 to 0.001	4	11	15 (10.9%)
	0.001 to 0.01	2	20	22 (16.1%)
	0.01 to 0.1	1	14	15 (10.9%)
	0.1 to 1	0	3	3 (2.2%)
	Unknown	11	67	78 (56.9%)
	TOTAL	**19**	**118**	**137**
Vertical	< 0.0001	0	7	7 (5.1%)
	0.0001 to 0.001	1	18	19 (13.9%)
	0.001 to 0.01	0	0	0 (0.0%)
	0.01 to 0.1	1	1	2 (1.5%)
	0.1 to 1	0	0	0 (0.0%)
	Unknown	17	92	109 (79.6%)
	TOTAL	**19**	**118**	**137**

3 DNAPL Source Zone Characteristics

A series of questions were asked in the survey pertaining directly to the DNAPL source zone. These included the following:

i) Source area chemistry (*i.e.,* DNAPL and dissolved phase contaminant profiles, other groundwater geochemistry);

ii) Size parameters of the DNAPL impacted zone (*i.e.,* areal extent, volume, maximum depth of the DNAPL, DNAPL distribution and shape); and

iii) DNAPL mass estimation (*i.e.,* methods of determining presence and mass, and an estimation of pre-remediation DNAPL mass).

See below for a summary of the data.

Q: Estimate the percentage of each type of chlorinated solvents that best describes the contaminant at your site if a sample of DNAPL has been analyzed.

Table C.8 provides a summary of the breakdown of the DNAPL composition data entered into the survey. Figure C.2 illustrates the breakdown of the DNAPL composition for sites that had an associated technology. Since some of the sites have multicomponent groundwater contaminants, the total percentage can be greater than 100%. The majority (68%) of the sites were impacted with primarily chlorinated ethenes; a smaller percentage had mixed DNAPL compositions (29%). Four sites did not have chlorinated ethenes, of which three of the sites had DNAPL consisting solely of chloroethanes and one site had both chloromethanes and chlorobenzenes.

Table C.8: Summary of DNAPL Composition

DNAPL Component	Total Sites With Unspecified Technology	Total Sites With Technology Specified	Total Sites
Chloroethenes (*e.g.*, PCE, TCE)	6 (100.0%)	71 (94.7%)	77 (95.1%)
Chloroethanes (*e.g.,* 1,2-DCA, 1,1,2,2-PCA)	2 (33.3%)	23 (30.7%)	26 (32.1%)
Chloromethanes (*e.g.,* DCM)	2 (33.3%)	12 (16.0%)	14 (17.3%)
Chlorobenzenes (*e.g.,* TCB)	1 (16.7%)	7 (9.3%)	8 (9.9%)
Total Sites with DNAPL Composition Data	**6**	**75**	**81**

Q: Estimate the MAXIMUM dissolved phase concentration of each chlorinated solvent that occurs within the defined source.

The maximum dissolved phase data was used to determine the overall distribution of groundwater contaminants grouped in terms of chloroethenes, chloroethanes, chloromethanes, and chlorobenzenes, as well as the maximum, median and average concentration of the dissolved contaminants. Table C.9 and Figure C.3 provide a summary of the distribution of groundwater chemistry data. Since some of the sites have multicomponent groundwater contaminants, the total percentage can be greater than 100%. As expected, the groundwater contaminant data is similar to the breakdown of the DNAPL composition data. Based on these numbers it can be seen that the majority (96%) of the sites were impacted with chlorinated ethenes and that a smaller percentage had mixed groundwater contaminant plumes.

Table C.9: Summary of Dissolved Phase Composition

Dissolved Phase Component	**Total Sites With Unspecified Technology**	**Total Sites With Technology Specified**	**Total Sites**
Chloroethenes (*e.g.*, PCE, TCE)	10 (90.9%)	66 (97.0%)	76 (96.2%)
Chloroethanes (*e.g.,* 1,2-DCA, 1,1,2,2-PCA)	4 (36.4%)	19 (28.0%)	23 (29.1%)
Chloromethanes (*e.g.,* DCM)	2 (18.2%)	10 (15.0%)	12 (15.2%)
Chlorobenzenes (*e.g.,* TCB)	1 (9.1%)	6 (9.0%)	7 (8.9%)
Total Sites with Groundwater Contamination Data	**11**	**68**	**79**

Table C.10 lists the main groundwater contaminant concentrations entered into the survey. Contaminant concentrations range from parts per billion (ppb) to the single-component solubility (S) of the majority of the contaminants. The single-component solubility represents the maximum theoretical achievable dissolved concentration of the contaminant. The following conclusions can be drawn from this data:

i) The higher chlorinated solvents (*e.g*., PCE, TCE, 1,1,1,2-PCA, 1,1,1-TCA, DCM) were present at a larger proportion to their theoretical concentrations. The average concentration of these contaminants was >14% of the solubility, with the maximum concentration of each >15%S.

ii) The lower chlorinated solvents (*e.g.*, cis-1,2-DCE, 1,1-DCE, CA, CM), with the exception of 1,2-DCA, were present at a much lower percentage of the theoretical maximum., with average concentrations <12%S, and maximum concentrations <13%S.

Table C.10: Summary of Maximum Groundwater Contaminant Concentrations

Contaminant		Minimum (mg/L)	Maximum (mg/L)	Median (mg/L)	Average (mg/L)	Solubility (mg/L)
Chloroethenes	PCE	0.1 (<0.1%)*	220 (93%)	44 (19%)	63 (27%)	237^a
	TCE	1 (<0.1%)	1400 (101%)	100 (7%)	268 (29%)	1385^a
	1,1-DCE	0.03 (<0.1%)	50 (2%)	25 (1%)	25 (1%)	2250^b
	cis-1,2-DCE	0.10 (<0.1%)	940 (13%)	9 (0.1%)	126 (2%)	6996^a
Chloroethanes	1,1,1,2-PCA	150 (14%)	160 (15%)	155 (14%)	155 (14%)	1100^e
	1,1,1-TCA	2.1 (0.2%)	2000 (154%)	59 (5%)	529 (41%)	1300^a
	1,1,2-TCA	0.054 (<0.1%)	50 (1%)	25 (0.6%)	25 (0.6%)	4400^a
	1,2-DCA	10 (0.1%)	3140 (37%)	10 (0.1%)	1053 (12%)	8500^a
	CA	0.01 (<0.1%)	18 (0.3%)	18 (0.3%)	12 (0.2%)	5710^c
Chloromethanes	DCM	10 (<0.1%)	12000 (60%)	1000 (5%)	5027 (25%)	20000^a
	CM	1.8 (<0.1%)	130 (0.2%)	100 (0.2%)	83 (0.2%)	53000^f
Chlorobenzenes	1,2,3-TCB	0.2 (<0.1%)	0.2 (<0.1%)	0.2 (<0.1%)	0.2 (<0.1%)	18^d
	1,2,4-TCB	4.78 (15%)	50 (160%)	27 (86%)	27 (86%)	31.3^d
	1,2-DCB	3.33 (2%)	1000 (640%)	502 (322%)	502 (322%)	156^b
	1,3-DCB	1 (0.8%)	100 (75%)	51 (38%)	51 (38%)	133^d
	CB	200 (40%)	200 (40%)	200 (40%)	200 (40%)	500^a

Single-Component Solubility values from:
a Pankow and Cherry (1996)
b Environmental Quality Management, 1998
c Mackay and Shiu (1977)
d Banerjee (1984)
e Howard (1990)
f http://chemfinder.cambridgesoft.com/ (visited on Feb 19, 2004)
* Percentages shown are the percentage of the single-component solubility, which represents the maximum theoretical achievable dissolved-phase concentration.

Q: Choose applicable concentration ranges from the following list of groundwater geochemistry parameters that may be relevant in terms of technology effectiveness.

Table D.26 (in Appendix D) summarizes the groundwater geochemistry data collected with the survey, ranging from inorganic parameters (*e.g.,* nitrate, sulfate); metals (*e.g.,* total and dissolved iron); field parameters (*e.g.,* pH, ORP, DO); organic parameters (*e.g.,* f_{oc}, BOD, DOC); and dissolved hydrocarbon gases (methane, ethene, and ethane).

Q: Provide the following information on the DNAPL distribution and mass prior to the onset of remedial activities. For sites with multiple DNAPL source zones, please provide the TOTAL value for all source zones (e.g., areal extent, volume, mass etc.) as appropriate.

Survey respondents were asked to specify the following information:

i) Total areal extent of DNAPL distribution;

ii) Total volume of impacted soil (pre-remediation) containing DNAPL;

iii) Maximum depth of the DNAPL;

iv) Distribution of DNAPL throughout the subsurface (*e.g.,* pools, residual, *etc.*); and

v) Estimated shape of the DNAPL distribution used in determining treatment geometry.

Table C.11 summarizes the distribution of responses to the areal extent of DNAPL. Of the 123 sites with responses to this question, 48 (39%) said that the areal extent was unknown. Although the responses ranged from 0.001 ft^2 to over 1,000,000 ft^2, the majority (31%) of the sites had a DNAPL areal extent of 10,000 to 100,000 ft^2. The accuracy of the two sites with areas less than 1 ft^2 could not be independently verified. Sites with areal extents less than 100 ft^2 were generally technology demonstrations.

Table C.11: Summary of Areal Extent of DNAPL Impacted Zone

Areal Extent of DNAPL Impacted Zone	Number of Sites With Unspecified Technology	Number of Sites With Technology Specified	Total Sites
0.001 to 0.01 ft^2	0 (0.0%)	1 (0.8%)[a]	1 (0.8%)
0.01 to 0.1 ft^2	0 (0.0%)	1 (0.8%)[a]	1 (0.8%)
1 to 10 ft^2	0 (0.0%)	4 (3.4%)	4 (3.3%)
10 to 100 ft^2	0 (0.0%)	5 (4.2%)	5 (4.1%)
100 to 1,000 ft^2	0 (0.0%)	11 (9.3%)	11 (8.9%)
1,000 to 10,000 ft^2	0 (0.0%)	10 (8.5%)	10 (8.1%)
10,000 to 100,000 ft^2	0 (0.0%)	23 (19.5%)	23 (18.7%)
100,000 to 1,000,000 ft^2	0 (0.0%)	11 (9.3%)	11 (8.9%)
> 1,000,000 ft^2	1 (20.0%)	8 (6.8%)	9 (7.3%)
Unknown	4 (80.0%)	44 (37.3%)	48 (39.0%)
Total Number of Sites	**5**	**118**	**123**

[a] These values were inputted into the survey; their accuracy is unknown.

Table C.12 summarizes the distribution of responses to the volume of the DNAPL impacted zone. Of the 123 sites with responses to this question, 55 (46.6%) said that the volume was unknown. Although the responses ranged from 1 ft^3 to over 1,000,000 ft^3, the majority of the sites had a DNAPL impacted volume of greater than 100,000 ft^3.

Table C.12: Summary of Volume of DNAPL Impacted Zone

Volume of DNAPL Impacted Zone	Number of Sites With Unspecified Technology	Number of Sites With Specified Technology	Total Sites
1 to 10 ft^3	0 (0.0%)	3 (2.5%)	3 (2.4%)
10 to 100 ft^3	0 (0.0%)	5 (4.2%)	5 (4.1%)
100 to 1,000 ft^3	0 (0.0%)	2 (1.7%)	2 (1.6%)
1,000 to 10,000 ft^3	0 (0.0%)	5 (4.2%)	5 (4.1%)
10,000 to 100,000 ft^3	0 (0.0%)	6 (5.1%)	6 (5.0%)
100,000 to 1,000,000 ft^3	0 (0.0%)	24 (20.3%)	24 (20.2%)
> 1,000,000 ft^3	0 (0.0%)	18 (15.3%)	18 (15.2%)
Unknown	5 (100.0%)	55 (46.6%)	60 (48.8%)
Total Number of Sites	**5**	**118**	**123**

Table C.13 summarizes the distribution of responses to the maximum depth of DNAPL. Of the 118 sites with responses to this question, 43 (36%) said that the maximum depth was unknown. Although the responses ranged from 1 ft to 10,000 ft below ground surface (bgs), the majority of the sites had a DNAPL depth between 10 and 100 ft bgs.

Table C.13: Summary of Maximum DNAPL Depth

Maximum Depth of DNAPL (bgs)	Number of Sites With Unspecified Technology	Number of Sites With Specified Technology	Total Sites
1 to 10 ft	0 (0.0%)	9 (7.6%)	9 (7.3%)
10 to 100 ft	2 (40.0%)	57 (48.3%)	59 (48.0%)
100 to 1,000 ft	0 (0.0%)	8 (6.8%)	8 (6.5%)
1,000 to 10,000 ft	0 (0.0%)	1 (0.8%)	1 (0.8%)
Unknown	3 (60.0%)	43 (36.4%)	46 (37.4%)
Total Number of Sites	**5**	**118**	**123**

One of the questions in the survey asked how the DNAPL was distributed in the subsurface, with the option of specifying DNAPL present in pools, as residual, sorbed to the soil particles, diffused into low K layers (rock matrix or clay) or in dead-end fractures. The respondents were asked to choose all of the parameters that applied to their site, resulting in greater than 100% totals. Table C.14 summarizes the DNAPL distribution results. Of the 179 responses to this question, from a total of 75 sites, the majority of the sites had residual (83%) or sorbed (61%) DNAPL. Of the remainder of the responses, 44% of the sites had pooled DNAPL, 40% had DNAPL diffused into low K layers and only 11% had DNAPL trapped in dead-end fractures.

Table C.14: Summary of DNAPL Distribution in Subsurface

Distribution of DNAPL in Subsurface	**Number of Sites With Unspecified Technology**	**Number of Sites With Specified Technology**	**Total Sites**
Dead-end fractures	0 (0.0%)	8 (10.7%)	8 (9.3%)
Diffused into low permeability layers/rock matrix	1 (9.1%)	30 (40.0%)	31 (36.0%)
Pools	2 (18.2%)	33 (44.0%)	35 (40.7%)
Residual	5 (45.5%)	62 (82.7%)	67 (77.9%)
Sorbed	3 (27.3%)	46 (61.3%)	49 (57.0%)
Total Number of Sites	**11**	**75**	**86**

Table C.15 summarizes the survey responses to the shape of the DNAPL distribution in the subsurface. Of the 118 responses, 53 (45%) said that the shape of the DNAPL was unknown. Of the sites where an estimate of the shape of the DNAPL distribution was available, the majority of the sites (36 or 31%) were believed to be irregular in shape.

Table C.15: Summary of the Shape of DNAPL Distribution in the Subsurface

Shape of DNAPL Distribution in Subsurface	Number of Sites With Unspecified Technology	Number of Sites With Technology Specified	Total Sites
Cylindrical	0 (0.0%)	15 (12.7%)	15 (12.2%)
Irregular	0 (0.0%)	36 (30.5%)	36 (29.3%)
Rectangular	0 (0.0%)	13 (11.0%)	13 (10.6%)
Triangular	0 (0.0%)	1 (0.8%)	1 (0.8%)
Unknown	5 (100.0%)	53 (44.9%)	58 (47.2%)
Total Number of Sites	**5**	**118**	**123**

Q: Enter the total number of sampling locations used to locate the DNAPL source area(s).

Table C.16 provides a summary of the number of DNAPL sampling locations and the type of methods used to sample for DNAPL. Of a total of 123 sites with sampling location data in the database, 52 of these sites (4 had unspecified technologies) did not specify any sampling method. Fully-screened monitoring well and soil samples were the most frequently used methods (employed at 41% and 37% of sites respectively). However, depth-discrete sampling and nested monitoring wells were used at nearly as many sites (28% and 32% of sites respectively).

Not included in Table C.16 is a count of the sites where other methods were used, since not all users specified the number of sampling locations where the other method was used. Specified other methods for DNAPL source location included the following:

i) Subsampling of soil cores;

ii) Multilevel wells with discrete sampling points;

iii) Cone penetrometer (CPT) with discrete sampling and CPT-ROST(rapid optical screening tool);

iv) hydropunch, simulprobe, multi-level sampler, instrumented membranes, mud rotary, ribbon samplers;

v) open borehole wells; and

vi) downstream spring outflow.

TableC.16: Number of Sampling Methods Used to Locate DNAPL Source Area(s)

Sampling Method	Number of Sampling Locations	Number of Sites With Unspecified Technology	Number of Sites With Technology Specified	Total Sites
Fully Screened Monitoring Wells	0[a]	4	69	73 (59.3%)
	0 to 10	0	21	21 (17.1%)
	10 to 50	0	20	20 (16.3%)
	50 to 100	1	5	6 (4.9%)
	>100	0	3	3 (2.4%)
Nested Monitoring Wells	0[a]	5	79	84 (68.3%)
	0 to 10	0	11	11 (8.9%)
	10 to 50	0	25	25 (20.3%)
	50 to 100	0	3	3 (2.4%)
	>100	0	0	0 (0.0%)
Depth-Discrete Sampling	0[a]	4	85	89 (72.4%)
	0 to 10	0	5	5 (4.1%)
	10 to 50	0	18	18 (14.6%)
	50 to 100	1	4	5 (4.1%)
	>100	0	6	6 (4.9%)
Soil Sampling	0[a]	4	73	77 (62.6%)
	0 to 10	0	2	2 (1.6%)
	10 to 50	0	25	25 (20.3%)
	50 to 100	1	12	13 (10.6%)
	>100	0	6	6 (4.9%)
Total Number of Sites		**5**	**118**	**123**

[a] ”0” was the default answer so if a respondent did not answer this question the value displayed will be “0”.

Q: How was the presence of DNAPL determined?

Table C.17 provides a summary of the methods used to identify DNAPL presence. Of a total of 122 sites with sampling location data in the database, 2 of these sites (5 had unspecified technologies) did not estimate the presence of DNAPL. DNAPL presence was most frequently inferred from groundwater chemistry and site history (employed at 57% and 52% of sites respectively). However, known spills and direct observation of DNAPL in wells and soil samples were used at a large number of sites as well (26%, 25% and 30% of sites respectively).

Not included in Table C.17 is a list of other methods used to determine DNAPL presence. Specified other methods for determining DNAPL presence included the following (presented below as stated by survey respondents):

i) degradation, odor, and staining of dedicated sampling;

ii) Research project with a controlled release, thus the exact volume of DNAPL was known;

iii) Combination of geoprobe-based dissolved phase groundwater sampling and soil sampling with source area limits inferred from observed TCE distribution;

iv) Originally inferred from soil sample results (partitioning calculations);

v) Detected in groundwater samples from temporary screened (but not sandpacked) well points;

vi) 20 membrane interface probe locations;

vii) Understanding of the nature of Hazardous Waste migration. If more than 72 barrels of NAPL are disposed of into a site (one truck load) the amount above 72 barrels must be present as NAPL. The flow of GW is slow and the concentrations of NAPLs in GW are small in the time since the large scale production of substituted hydrocarbons very little dissolution can occur. The rest has to be undissolved NAPL.

viii) Soil concentrations converted to equilibrium porewater and compared to solubility limits; and,

ix) A number of surface soil removal actions for VOCs + PCBs.

Table C.17: Number of Methods Used to Determine DNAPL Presence

Method	Number of Sites With Unspecified Technology	Number of Sites With Technology Specified	Total Sites
Site history	1	62	63 (51.6%)
Known spill(s)	0	32	32 (26.2%)
Inferred from dissolved contaminant concentrations	1	68	69 (56.6%)
Direct observation of DNAPL in soil sample	0	37	37 (30.3%)
Extracted from monitoring wells	1	30	31 (25.4%)
Membrane Interface Probe	0	10	10 (8.2%)
Ribbon NAPL Samplers/FLuTEs	0	2	2 (1.6%)
Partitioning tracers	0	5	5 (4.1%)
Presence not estimated	0	2	2 (1.6%)
Total Number of Sites	**5**	**117**	**122**

[a] ”0” was the default answer so if a respondent did not answer this question the value displayed will be “0”.

Q: How was the total (pre-remediation) DNAPL mass present in the subsurface estimated?

Table C.18 provides a summary of the methods used to identify DNAPL presence. Of a total of 122 sites with sampling location data in the database, 24% of these sites did not estimate the pre-remediation DNAPL mass. DNAPL mass was most frequently estimated from groundwater or soil contaminant concentrations (34% sites).

Not included in Table C.18 is a list of other methods used to estimate DNAPL mass. Specified other methods for DNAPL mass estimates included the following (presented as stated by survey respondents):

i) Interpolation of CPT/ROST response;

ii) Distribution is too heterogeneous to achieve any degree of confidence. The estimate is considered highly unreliable;

iii) Area and depth of the two migrating DNAPL plumes (not pools but moving highly saturated NAPL masses) were measured by wells (NAPL mass constituted 99.97% of characterized mass). records of wastes placed into the site. also the area and thickness and average concentration of the dilute solute plumes were measured and along with the partitioning to the aquifer solids was used to assess the mass in the APL partition (0.03% of the characterized mass);

iv) Groundwater modeling (MODFLOW) was used to back-calculate the amount of source present. Current VOC concentrations present in down-gradient monitoring wells were used to 'calibrate' the model and estimate the amount of source present;

Table C.18: Number of Methods Used to Estimate DNAPL Mass

Method	Number of Sites With Unspecified Technology	Number of Sites With Technology Specified	Total Sites
Site History	1	29	30 (24.6%)
Known Spill(s)	0	17	17 (13.9%)
Calculated from Groundwater or Soil Contaminant Concentrations	0	41	41 (33.6%)
Calculated from Mass Flux Measurements	0	4	4 (3.3%)
Partitioning Tracers	0	2	2 (1.6%)
Not Estimated	1	28	29 (23.8%)
Total Number of Sites	**5**	**117**	**122**

[a]"0" was the default answer so if a respondent did not answer this question the value displayed will be "0".

4 Remedial Technologies

Survey respondents were asked to specify the technology that was applied at their site and the stage of remediation, and provide reasons for their choice. The data collected are described below.

Q: Choose the remedial technology applied at this site.

Remedial technologies were specified for 118 of the sites entered into the survey. For purposes of analysis, remedial technologies that employed similar principles for DNAPL removal were combined under one "primary technology" (*e.g.,* chemical oxidation using permanganate or Fenton's reagent were defined under the same primary technology of chemical oxidation). Table C.19 summarizes the primary technologies that were specified by respondents to the survey (listed in order of most frequently used to least), and provides the breakdown of the number of sites where each primary technology was applied. Figure C.4 illustrates the distribution of technologies.

Bioremediation, thermal and chemical oxidation were the most often applied technologies (total 77%). Surfactant flushing and ZVI technologies were the least applied technologies (total 8.5%). Information was also provided for dual-phase extraction, excavation, pump and treat, and 6 undefined other technologies. No information was collected in the survey on sites where co-solvent flushing was applied.

Table C.19: Summary of Technologies Selected in the Survey

Technology	Number of Sites Where Technology was Applied
Thermal	27 (22.9%)
Bioremediation	25 (21.2%)
Chemical Oxidation	25 (21.2%)
Dual-Phase Extraction	13 (11.0%)
Excavation	11 (9.3%)
Other	7 (5.9%)
Zero-Valent Iron	6 (5.1%)
Surfactant Flushing	4 (3.4%)
Co-Solvent Flushing	0 (0.0%)
TOTAL	**118**

Table C.20 provides a summary of the breakdown of the primary technologies thermal, chemical oxidation, dual-phase extraction, other, and zero-valent iron into "secondary" technology descriptions that represent variations of the primary technology. Of the thermal technologies, resistive heating (six- and three-phase) and steam flushing were the most frequently applied, whereas data was input into the survey for only one site each of conductive heating and low-temperature six-phase heating. Of the chemical oxidation technologies, permanganate appears to be the most frequently chosen oxidant, while data on only one ozone site was entered into the survey. There does not appear to be a preferred method in what medium the DNAPL is extracted with the dual-phase extraction approaches. Of the zero-valent iron variations, non-specified use of ZVI was the most frequently applied alternative. EZVI using nano-scale iron is still in the development stage with only one pilot test completed to date.

The survey respondents were given the option of choosing “other” for a technology selection and providing a description of that technology. Unfortunately, due to an error in the posting of our web site, the link to the descriptions of the "other" technology was broken. All of the users who selected an “other” technology were contacted and asked to provide a description of the technology. However, six users did not reply to the request for additional information; these technology descriptions are listed in the database as “other – undefined”. For those “other” technologies that were defined, if the technology description could be combined with one of the other “primary” technology descriptions, then the technology was grouped under that primary technology description (*e.g.,* other – conductive heating becomes thermal – conductive heating).

Table C.20: Breakdown of Primary Technologies

Primary Technology	Secondary Technology	Number of Sites Where Technology was Applied
Thermal	Six-Phase Heating	10
	Steam	8
	Three-Phase Heating	5
	Resistive Heating	2
	Conductive Heating	1
	Low-Temp Six-Phase	1
Chemical Oxidation	Permanganate	15
	Fenton's Reagent	9
	Ozone	1
Dual-Phase Extraction	Water/DNAPL	5
	Water/air	5
	DNAPL/air	3
Other	Undefined	6
	Pump and Treat	1
Zero-Valent Iron	Zero-Valent Iron	4
	EZVI/Nano-Scale Iron	1
	ZVI/Clay Source Treatment	1

Q: State your reasons for choosing this technology.

Survey respondents were given a list of criteria to choose from that outlined their reasons for selecting a particular technology. Table C.21 contains a listing of these criteria, along with a summary of the number of times the criteria were chosen. The most frequently chosen criteria were: (*i*) remedial cost (62%); (*ii*) the perception of a good chance at remedial success (80%); (*iii*) appropriate technical implementability (41%); (*iv*) a lasting impact on the water quality (37%); and (*v*) remedial timeframe was a factor (35%).

Table C.21: Summary of Criteria for Technology Selection

Criteria	Frequency of Choice
Cost of technology application	52 (61.9%)
Technology perceived to provide a good chance at remedial success	67 (79.8%)
Remediation timeframe was a factor	29 (34.5%)
Regulatory pressures guided technology choice	7 (8.3%)
Impact of remedial technology on surface water is minimal	7 (8.3%)
Impact of remedial technology on secondary groundwater quality is minimal	9 (10.7%)
Technology application was perceived to reduce overall risk to environment	17 (20.2%)
Technology application was thought to have a lasting impact on the water quality	31 (36.9%)
Health and safety concerns guided technology choice	11 (13.1%)
Technical implementability of the remedial technology was thought to be appropriate	34 (40.5%)
Legal pressures guided technology choice	4 (4.8%)
Pressure from various stakeholders guided technology choice	11 (13.1%)
Other	12 (14.3%)
TOTAL SITES WITH DATA	**84**

Specified "other" reasons included the following:

i) Six sites were technology demonstrations (two were bioremediation applications, three were chemical oxidation using permanganate, and one was emulsified nano-scale ZVI);

ii) One ZVI project was a field research project of soil mixing with an iron and bentonite slurry conducted at the University of Waterloo (Waterloo, Ontario, Canada);

iii) Bioremediation was chosen at two sites where the remediation occurred inside of drycleaners;

iv) Excavation was chosen at one site with low permeability soil (silt), which rendered any *in situ* approach infeasible. The respondent adds, "We needed to get to MCLs in the sand and gravel immediately below the silt layer containing the DNAPL.

v) Low temperature six-phase heating was chosen at one site over six phase heating due to the proximity to underground utilities.

vi) For one site where the technology was undefined, the respondent states, "Ideal site to try innovative technology"; and

vii) At one site, steam flushing was chosen because steam was readily available at the site, and there was no cost to tap into the steam source.

Q: Specify the current stage of remediation.

Survey respondents were asked to specify the stage of remediation for each site (*i.e.,* pilot *versus* full-scale, and completed *versus* ongoing). Table C.22 lists the distribution of treatment stage. Of 80 total DNAPL treatment attempts, 31 were full-scale applications and 49 were pilot tests. Data was collected for only 2 full-scale systems and 33 pilot tests where the remediation was considered to be complete and post-treatment monitoring was not on-going.

Table C.22: Breakdown of Sites by Stage of Remediation and Scale of Treatment

Stage of Remediation	**Scale of Treatment**	
	Full-Scale Application	**Pilot Test**
Remediation completed	2	33
Remediation completed, post-treatment monitoring ongoing	12	6
Remedial activities on-going	17	10
TOTAL	**31 (38.8%)**	**49 (61.3%)**

5 Cost and Treatment Duration Data

Q: What was the duration of field treatment activities to date? For on-going treatment, what is the estimated duration of future field treatment activities?

Table C.23 lists the actual and estimated duration of field treatment activities for both full and pilot scale treatment stages. These durations do not include any post-treatment monitoring. All pilot tests appeared to be completed within 5 years, with the majority (28 of 29 sites) of field treatment activities completed within 2 years. In comparison, only 16 of 22 full-scale applications were completed (or estimated to be completed) within 2 years. Six sites (27%) had longer durations of 5, 10, 15, 30, 50 and 150 years. Section 1.2.2 of Appendix D provides a detailed breakdown and analysis of the data by technology.

Table C.23: Breakdown of Duration of Field Treatment Activities

Monitoring	Duration in Months	Full-Scale Application	Pilot Test
Actual Duration	< 4	5	13
	4 to 8	4	5
	8 to 16	0	6
	16 to 24	2	1
	24 to 34	0	1
	60	1	1
	120	1	0
	180	1	0
Estimated Duration	1 to 10	3	1
	10 to 20	2	1
	360	1	0
	600	1	0
	1800	1	0
TOTAL SITES		**22**	**29**

Q: Over what duration was post-treatment monitoring conducted/what is the estimated duration (for on-going monitoring)?

Table C.24 lists the duration of post treatment monitoring activities (actual if completed and predicted if ongoing) for both full and pilot scale treatment stages. Post-treatment monitoring was generally terminated within 4 years (29 of 31 sites). One site had monitoring on-going for 10 years.

Table C.24: Breakdown of Post-Treatment Monitoring Duration

Monitoring	Duration in Months	Full-Scale Application	Pilot Test
Post Treatment Duration	0	0	2
	0.5 to 5	2	6
	5 to 15	5	5
	15 to 25	1	3
	25 to 35	0	0
	35 to 50	3	0
	50 to 75	1	0
	120	1	0

Q: What was the total cost of remediation for the site including the design and implementation of remediation but not site characterization?

Table C.25 provides a summary of the DNAPL treatment cost data entered into the survey database. All costs are quoted in US dollars. Figure C.5 is a histogram showing the actual costs entered by the survey respondents for each site. These costs represent the design and implementation of the remediation, but omit the costs required for the initial site characterization. The costs are broken down into the scale of treatment (*i.e.,* full-scale *versus* pilot test) as well as the size of the DNAPL impacted zone. The breakdown by size is less informative for the pilot test applications as the size of the DNAPL impacted zone is that of the entire site, not just the targeted treatment zone of the pilot test.

Cost data was provided for 16 sites at which full-scale treatment was either completed (1), treatment complete but post-treatment monitoring on-going (6), or on-going (9). Data was also collected for a total of 31 pilot test, of which the majority of the tests were completed (all but 3 sites). Of the large, full-scale applications, remedial treatment costs were generally in the millions of dollars, with the largest cost being a \$15M water/DNAPL dual-phase treatment (on-going) at a site with a DNAPL impacted zone that was in the range of 100,000 to 1,000,000 ft^2. The smallest cost was reported as being \$75K at two sites where full-scale treatment was completed and post-treatment monitoring was ongoing. The sites were a ZVI treatment for a site with a DNAPL impacted zone that was in the range of 100 to 1,000 ft^2 and a bioremediation treatment with an unknown size. None of the pilot tests had costs greater than \$2M, with the majority being less than \$0.5M. It should be noted that a significant portion of the pilot tests under \$0.5M were small-scale (<1,000 ft^2) technology demonstrations/field research projects. If the technology demonstrations are removed from the count, the pilot test costs were generally within the range of \$150,000 to \$2M.

Table C.25: Summary of Remedial Cost Data

Treatment Scale	**Total Cost (USD)**	**Size of DNAPL Zone**[a]			**TOTAL SITES**
		Small	**Large**	**Unknown**	
Full-Scale	<\$0.5M	3	2	2	7
	\$0.5M to \$1M	0	1	0	1
	\$1M to \$2M	0	2	0	2
	\$2M to \$4M	0	2	0	2
	\$4M to \$10M	0	2	1	3
	>\$10M	0	1	0	1
	Total	**3**	**10**	**3**	**16**
Pilot Test	<\$0.5M	10	3	3	16
	\$0.5M to \$1M	1	8	2	11
	\$1M to \$2M	1	2	1	4
	\$2M to \$4M	0	0	0	0
	\$4M to \$10M	0	0	0	0
	>\$10M	0	0	0	0
	Total	**12**	**13**	**6**	**31**

[a] DNAPL zone size classifications were:
small = area < 10,000 ft^2 and volume < 100,000 ft^3
large = area > 10,000 ft^2 and volume > 100,000 ft^3.

Q: Provide a breakdown of the remedial cost components (Table C.26 provides the criteria presented in the survey).

Survey respondents were asked to provide an approximate breakdown of each significant component (*i.e.,* professional costs, consumables, treatment operation and infrastructure and post-treatment monitoring) of the remedial project relative to the total cost (not including site characterization). Table C.26 provides a summary of the breakdown of the DNAPL treatment cost data entered into the survey database. All data is presented as a percentage of the total actual cost. Figure C.6 is a histogram showing the cost breakdown of the technology applications as a percent of the total costs. The total cost percent varies from 100% because the cost breakdown data was inputted into the survey as a range and the mid point of the ranges were used to calculate the percentages.

Table C.26: Breakdown of Remedial Cost Data

Breakdown of Remedial Costs	% of Total Costs	Number of Sites
Professional Costs	0 to 10%	53
	11 to 20%	11
	21 to 30%	8
	31 to 40%	2
	41 to 50%	2
	51 to 60%	1
Post Treatment Monitoring Costs	0 to 10%	63
	11 to 20%	7
	21 to 30%	6
	31 to 40%	1
Consumable Costs	0 to 10%	64
	11 to 20%	4
	21 to 30%	3
	31 to 40%	4
	51 to 60%	1
	61 to 70%	1

Breakdown of Remedial Costs	% of Total Costs	Number of Sites
Treatment Operation Costs	0 to 10%	43
	11 to 20%	8
	21 to 30%	13
	31 to 40%	4
	41 to 50%	6
	51 to 60%	1
	61 to 70%	1
	81 to 90%	1
Treatment Infrastructure Cost	0 to 10%	50
	11 to 20%	7
	21 to 30%	8
	31 to 40%	11
	51 to 60%	1

6 Methods of Assessing Performance and Monitoring

Survey respondents were asked to specify how they were planning on evaluating, or had evaluated, the performance of the technology. The data collected are described below.

Q: How are you planning to assess the interim technology performance – or – What was the technology performance measurement based on (check all that apply)?

Depending on the stage of remediation (ongoing *versus* completed), the above question varied; however the list of options was the same for both sets of remedial stages. Table C.27 list the responses and number of sites with responses selected. The most frequently chosen performance metric was the monitoring of concentration reductions in specific monitoring wells (79% of sites). Other frequently chosen metrics include: (*i*) total DNAPL mass removed (36% of sites); and (*ii*) reduction in soil concentrations (36%).

Table C.27: Summary of Methods for Assessing Performance

Method of Assessing Performance	Number of Sites
Concentration reduction in specific monitoring wells	63 (79%)
Reduction in soil concentrations	29 (36%)
Achieve MCLs in monitoring wells	11 (14%)
Reduction in plume mass flux (or mass discharge)	18 (23%)
Reduction in plume size	20 (25%)
Production of degradation by-products	22 (28%)
Total mass removed	29 (36%)
Mass remaining	14 (18%)
Will not measure	0 (0%)
TOTAL NUMBER OF SITES	**80**

Since asked to check all that apply it is possible to have answers that add to up to > 100%

7 Treatment Effectiveness

Remedial effectiveness can be evaluated using a number of different criteria, including the following:

i) Removal of DNAPL source mass;

ii) Decrease in dissolved phase mass flux from the source area;

iii) Rebound in mass flux; and

iv) Impacts to secondary groundwater quality.

Although survey respondents were asked which of a number of methods they were going to use to evaluate success (Section 6), they were only asked to provide information on each of the four success criteria listed above. Information on these parameters were collected to rate the overall perceived success of the technology in remediating the DNAPL, and to indicate which external factors might have impacted the remediation process. The responses are discussed below.

Q: What level of source mass removal was achieved?

There were a total of 53 sites with source mass removal data. Table C.28 summarizes the source mass removal data that were specified by respondents to the survey. Of the 53 sites, 62% have not estimated the degree of source mass removal. Responses ranged from 10% to 100% source mass removal, with 16 sites (30%) having greater than 50% mass removal.

Table C.28: Summary of Source Mass Removal

Percent Source Mass Removal	Number of Sites
100%	4 (8 %)
>90%	7 (13 %)
80 to 90%	3 (6 %)
50 to 80%	2 (4 %)
25 to 50%	2 (4 %)
10 to 25%	1 (2 %)
<10%	1 (2 %)
Not Estimated	33 (62 %)
Total	**53**

Q: How much decrease in mass flux was observed?

There were a total of 80 responses to the question of how much of a decrease in mass flux was observed after remediation. It should be noted that this question was asked whether the technology application was ongoing or completed (decrease observed to date *versus* decrease observed, respectively). In order to evaluate success, data was considered only from the completed technology applications (53 sites). Table C.29 summarizes the mass flux data that were specified by respondents to the survey. Of the 80 responses, 54% said that the mass flux decrease was unknown. Although 6 sites (7.5%) had 0% decrease in mass flux, 21 sites (26%) had 81 to 100% decreases.

Table C.29: Summary of Mass Flux Decrease

Percent Mass Flux Decrease	**Number of Sites Completed**	**Number of Sites Ongoing**
81 to 100%	13 (25 %)	8 (30 %)
61 to 80%	5 (9 %)	1 (3.7 %)
41 to 60 %	1 (26 %)	1 (3.7 %)
21 to 40 %	0 (0 %)	1 (3.7 %)
1 to 20 %	0 (0 %)	1 (3.7 %)
0 %	2 (4 %)	4 (15 %)
Not Estimated	32 (60 %)	11 (41 %)
Total	**53**	**27**

Q: Currently at what stage is the post-treatment?

For many of the parameters used to evaluate success, a certain level of post-treatment monitoring is necessary to determine whether the level of mass decrease or reduction in mass flux was a permanent change or a temporary change due to things such as dilution, seasonal changes in the groundwater flow direction, desorption or counter-diffusion of contaminants from low permeability layers, *etc*. Table C.30 summarizes the post-treatment monitoring stage data that were specified by respondents to the survey. The data indicates that post-treatment monitoring is being conducted at the majority of sites (72%).

Table C.30: Summary of Post –Treatment Monitoring Stage

Post –Treatment Monitoring Stage	**Number of Sites**
Completed	25 (47.2%)
Ongoing	13 (24.5%)
Not Conducted	15 (28.3%)
Total	**53**

Q: Did post-treatment monitoring indicate that an increase in concentrations (rebound) of dissolved chlorinated solvents was occurring?

A total of 53 respondents answered the question of observed rebound. Table C.31 summarizes the rebound data that were specified by respondents to the survey. Rebound was not evaluated at 60% of the sites. Of those sites where rebound was tracked, 67% of the sites had rebound of the dissolved phase concentrations.

Table C.31: Summary of Rebound Data

Occurrence of Rebound	Number of Sites
Yes	14 (26.4%)
No	7 (13.2%)
Not Evaluated	32 (60.4%)
Total	**53**

Q: What impacts on secondary groundwater quality have been observed?

Table C.32 provides a list of the secondary groundwater quality parameters that the survey respondents had to choose from, of which they were to check all that apply. A total of 35 sites had at least one secondary groundwater quality issue selected for a total of 81 responses. Of these, the most prevalent choice was a decrease in source area volume (34%). None of the sites experienced an increase in source area volume. Changes in groundwater color (23%), elevated concentration of dissolved metals (23%), and methane generation (23%) were also frequent impacts (*i.e.,* occurred at more than 20% of sites).

Table C.32: Summary of impacts to secondary groundwater quality data.

Secondary Groundwater Quality Indicator	Number of Sites With The Indicator Selected
Methane generation	8 (22.8%)
Hydrogen sulfide generation	1 (2.9%)
Dissolved iron generation	7 (20.0%)
Dissolved manganese generation	7 (20.0%)
Elevated concentration of other metals	8 (22.9%)
Increased Biochemical Oxygen Demand	4 (11.4%)
Change in pH	7 (20.0%)
Reduced soil porosity	6 (17.1%)
Change in hydraulic conductivity	5 (14.3%)
Change in groundwater color	8 (22.9%)
Increased dissolved solids	3 (8.6%)
Redistribution of DNAPL	4 (11.4%)
Increase in source area volume	0 (0.0%)
Decrease in source area volume	12 (34.3%)
Other	5 (14.3%)
TOTAL SITES WITH SECONDARY GROUNDWATER IMPACTS	**35**

Q: Was this technology considered successful?

One of the questions in the DNAPL survey that was asked of the user was whether the technology application was considered a poor success, a fair success, successful, or not yet evaluated. Table C.33 summarizes the perceived success of the technology applications. Of the sites where remedial success was evaluated, 64% of the remedies were successful, 34% were fairly successful, and 2% performed poorly.

Table C.33: Summary of Perceived Success

Perceived Success	Number of Sites
Success	28 (52.8%)
Fair Success	15 (28.3%)
Poor Success	1 (1.9%)
Not Yet Evaluated	9 (17.0%)
Total	**53**

Q: Indicate which factors impacted remediation.

Table C.34 provides the list of external factors impacting the remedial process that the survey respondents were asked to choose from. Data from a total of 118 sites was collected (*i.e.,* all sites with specified technologies). The remedial budget and cost was the most frequently chosen factor (61% of sites). The remaining four factors were all chosen with approximately the same frequency (23 to 31% of all sites).

Table C.34: Summary of Breakdown of External Factors that Impacted the Remedial Process

Factors that Impacted the Remedial Process	Number of Sites With The Factor Selected
Facility operations constrained site access	27 (22.9%)
Presence of surface infrastructure impacted ability to estimate DNAPL mass or effectively conduct remediation	28 (23.7%)
Proximity to surface water impacted technology choice, design or effectiveness	35 (29.7%)
Regulatory pressures impacted clean-up criteria/time-frame	37 (31.4%)
Budget / remediation cost	72 (61.0%)
TOTAL SITES WITH FACTORS SELECTED	**118**

8 Data Gaps

Optimally, a study such as this would include data collected from sites with a wide variety of site characteristics and technologies, enabling statistical analyses of the data to confirm the presence of trends and to determine where correlation exists between factors. However, a minimum amount of data is required to achieve statistically significant conclusions. This minimum was not achieved for a number of reasons for the majority of the parameters analyzed for here.

Although attempts were made to compile a comprehensive database of information pertaining to DNAPL remediation, the data necessary to draw quantitative conclusion is very complex and difficult to collect. The difficulties in collecting this type of information arise from many factors including:

- people do not have a driver to collect or compile the data needed for this type of analysis;
- there are the complications of confidentiality;
- biased views toward a specific technology may exist and without data verification this may not be obvious; and
- it is difficult for people to make the time to respond to this type of survey.

Data deficiencies arise due to a number of factors, including the following:

i) **Limited number of survey respondents:** The survey was posted on the web page for a total of 6 months. Three rounds of email requests for respondents were sent out to over 700 people, coupled with mailings of marketing materials to over 3,000 people and posting of requests for survey participants on several widely accessed newsletters/webpages. However, only a total of 61 people (plus the 21 published case studies) provided information on technology applications.

ii) **Incomplete survey responses:** Of the 164 DNAPL impacted sites specified in the survey database, only a portion of these provided site characterization data (*i,e.,* geology, hydrogeology, DNAPL source zone parameters), and only 118 of these had a remedial technology specified. Of these 118 sites, 38 sites had little more than site characterization data provided (*i.e.,* no information pertaining to remedial technologies was collected), leaving only 80 sites for which the survey respondent fully completed the survey. Three email reminders were sent to respondents with incomplete survey data in an attempt to increase the number of completed surveys.

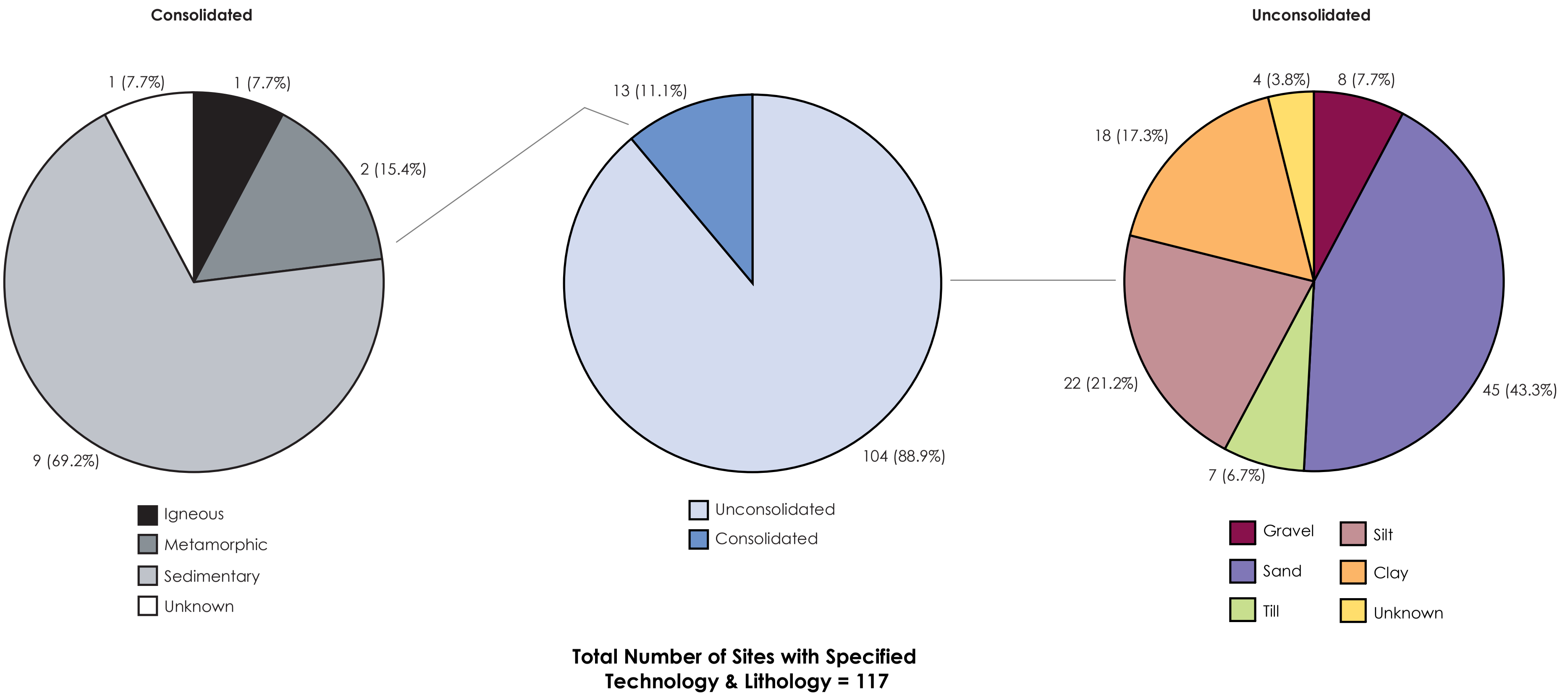
iii) **Insufficient field testing:** There is limited information available on the impact of some factors and technologies, due to a lack of field testing. For example, the use of emulsified nano-scale zero-valent iron is still in the technology development stage, with only one field test completed to date.

9 Survey Participant List

Table C.35 is a list of the 21 published case studies that were entered into the survey by GeoSyntec personnel identifying the site name, location, and technology application. Survey participants were asked if their names and contact information could be included on a list of respondents in the final report as a resource for Navy RPMs, site owners, regulators, etc. considering this technology. Table C.36 is a list of contact information for survey participants, along with the technology that they entered information about, who said that their contact information could be included in the report.

TABLE C.35
LIST OF PUBLISHED CASE STUDIES IN SURVEY
Navy Review of Case Studies

State,Province	Location_Name	Technology
Florida	Pinellas Northeast Site	Bioremediation
Idaho	Idaho National Engineering and Environmental Labor	Bioremediation
New Jersey	Active Industrial Facility	Chemical Oxidation-Fenton's Reagent
Massachusetts	Former News Publisher Facility	Chemical Oxidation-Fenton's Reagent
Maryland	Graces Quarter, APG	Chemical Oxidation-Fenton's Reagent
Ohio	Portsmouth Gaseous Diffusion Plant, X-701B Facilit	Chemical Oxidation-Permanganate
New Hampshire	US Army Cold Regions Research and Engineering Labo	Chemical Oxidation-Permanganate
Florida	Former Dry Cleaning Facility	Chemical Oxidation-Permanganate
California	328 Site, Santa Clara, CA	Dual Phase-Water/air extraction
Virginia	US Defense Supply Center Richmond Acid Neutralizat	Dual Phase-Water/air extraction
North Carolina	Union Chemical Company Superfund Site	Surfactant Flushing
Utah	Operable Unit 2, Hill AFB	Surfactant Flushing
Kentucky	SWMU 91 Treatability Study	Thermal-Resistive heating
Texas	Air Force Plant 4	Thermal-Six phase heating
Oregon	Former Pharmaceutical Manufacturer (ICN)	Thermal-Six phase heating
Florida	Launch Complex 34	Thermal-Six phase heating
Illinois	Former Electronics Manufacturing Facility	Thermal-Six phase heating
Alaska	Poleline Road Disposal Area (PRDA), Operable Unit	Thermal-Six phase heating
South Carolina	Savannah River Site, Area M	Thermal-Six phase heating
Illinois	AG Communication Systems	Thermal-Steam
Ohio	DOE Portsmouth	Thermal-Steam

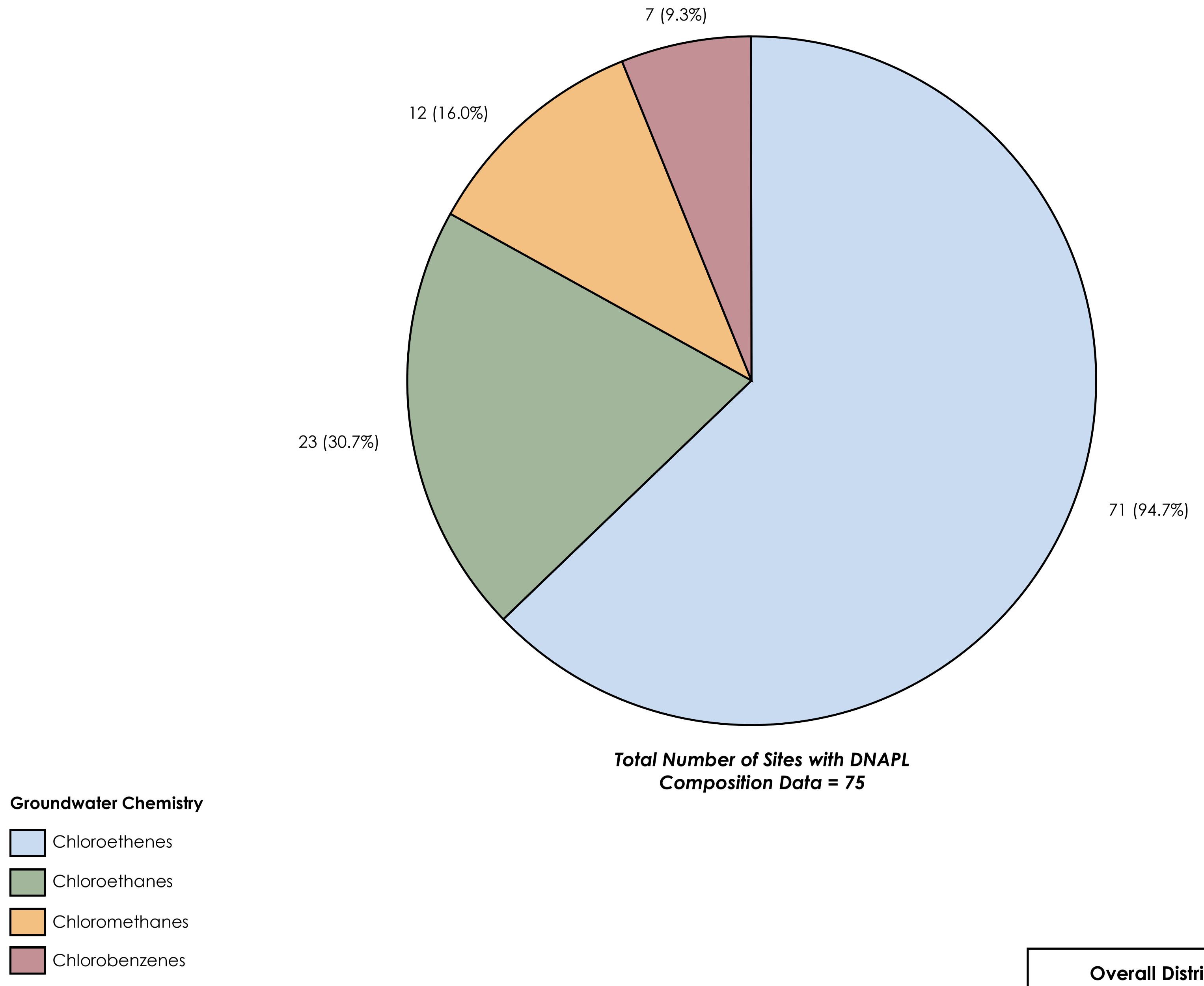


13 (11.1%) = Number of Sites (% of Total)

pie graphs_groups.ai

Number of Sites With Lithology
Data Entered Into Survey
Navy ROCS

Feb. 2004 | Figure: **C.1** | GeoSyntec Consultants



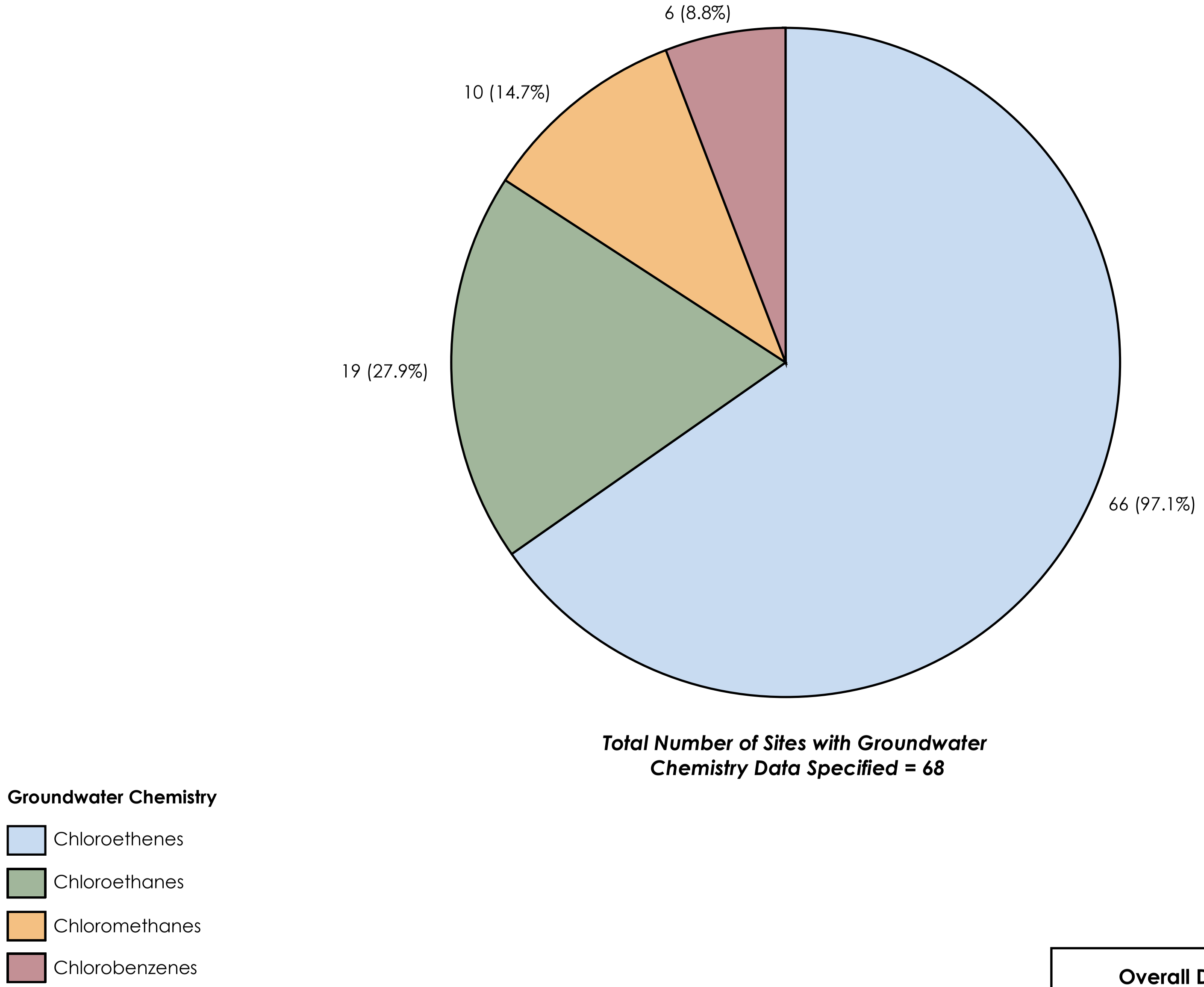
Note: Some sites had multicomponent DNAPL resulting in >100% total

12 (16.0%) = Number of Sites (% of Total)

Overall Distribution of DNAPL Composition
Navy ROCS

Feb. 2004 | Figure: **C.2** | GEOSYNTEC CONSULTANTS

pie graphs_groups.ai



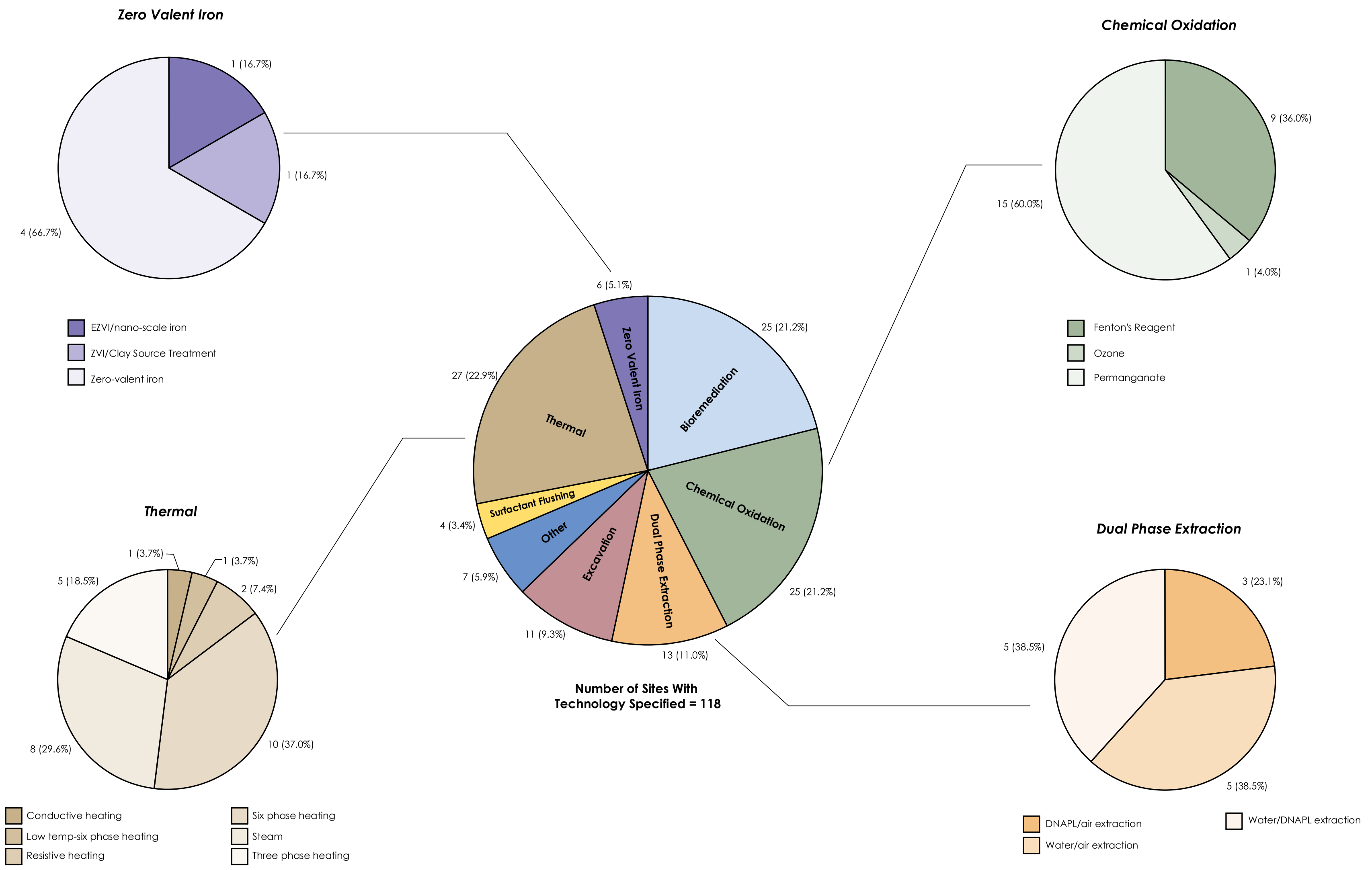
Total Number of Sites with Groundwater Chemistry Data Specified = 68

Note:
Some sites had multicomponent groundwater chemistry resulting in >100% total
19 (27.9%) = Number of sites (% of total)

pie graphs_groups.ai

Overall Distribution of Groundwater Chemistry
Navy ROCS

Feb. 2004 | Figure: **C.3** | GeoSyntec Consultants



Notes: The "other" category consists of 6 undefined technologies, and one site where pump and treat was applied.

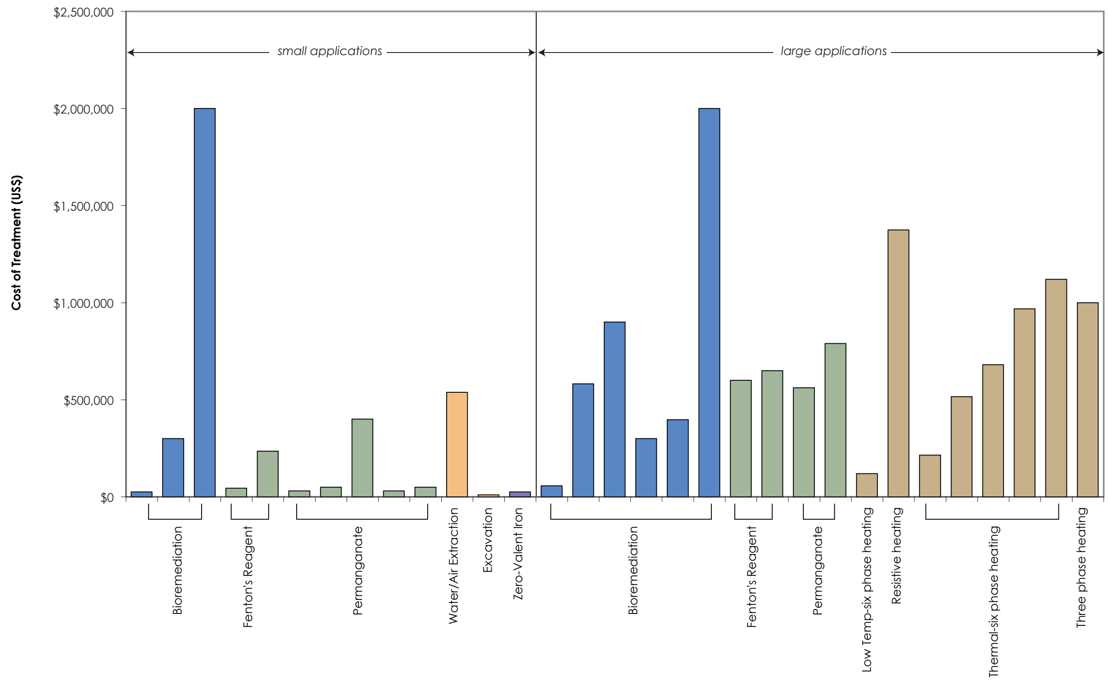
11 (9.0%) = Number of Sites (% of total sites with technology specified)

Number of Sites with Technology
Data Entered in the Survey
Navy ROCS

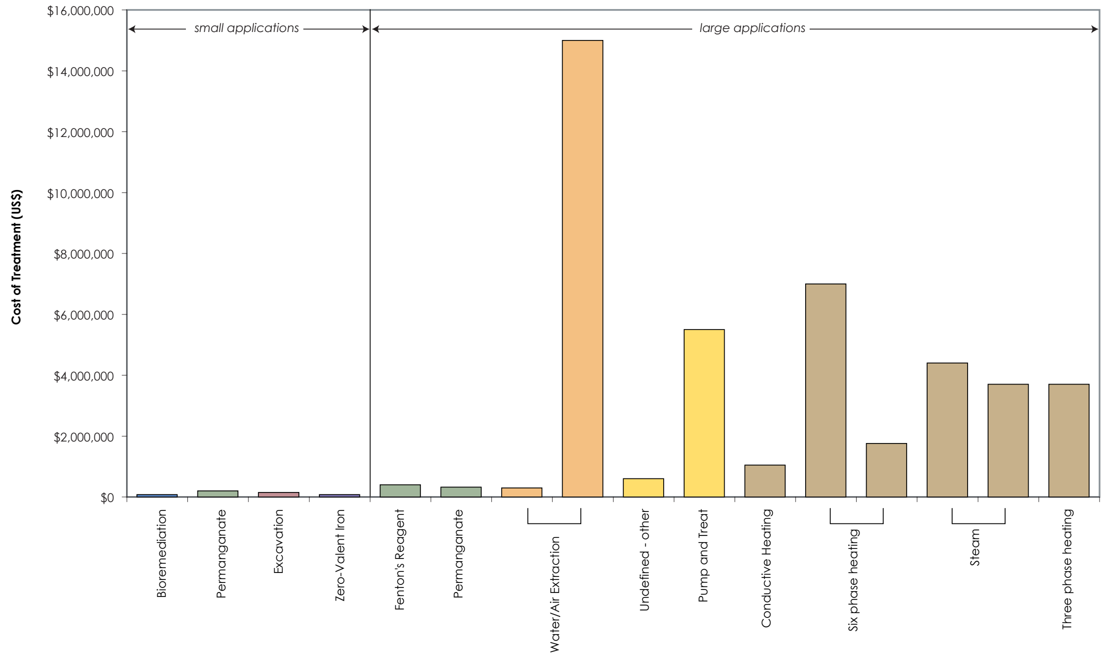
Feb. 2004 | Figure: **C.4** | GEOSYNTEC CONSULTANTS

pie graphs_groups.ai

Pilot-Test Applications



Full-Scale Applications



Technology Legend

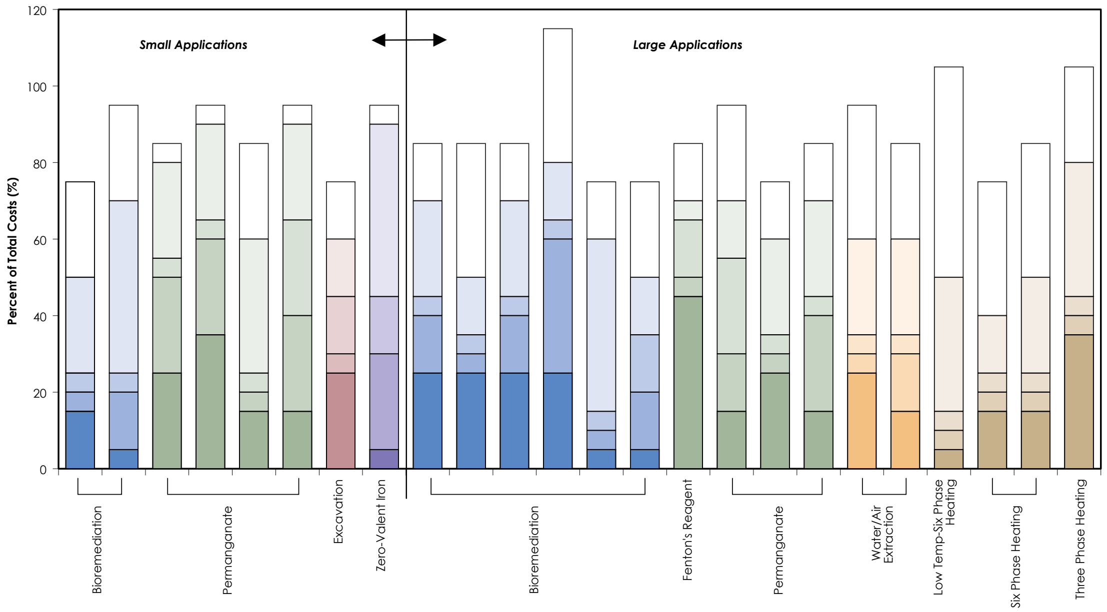
- 🟦 Bioremediation
- 🟩 Chemical Oxidation
- 🟪 Zero Valent Iron
- 🟧 Dual Phase Extraction
- 🟫 Thermal
- 🟥 Excavation
- 🟨 Pump and Treat

bar graphs_groups.ai

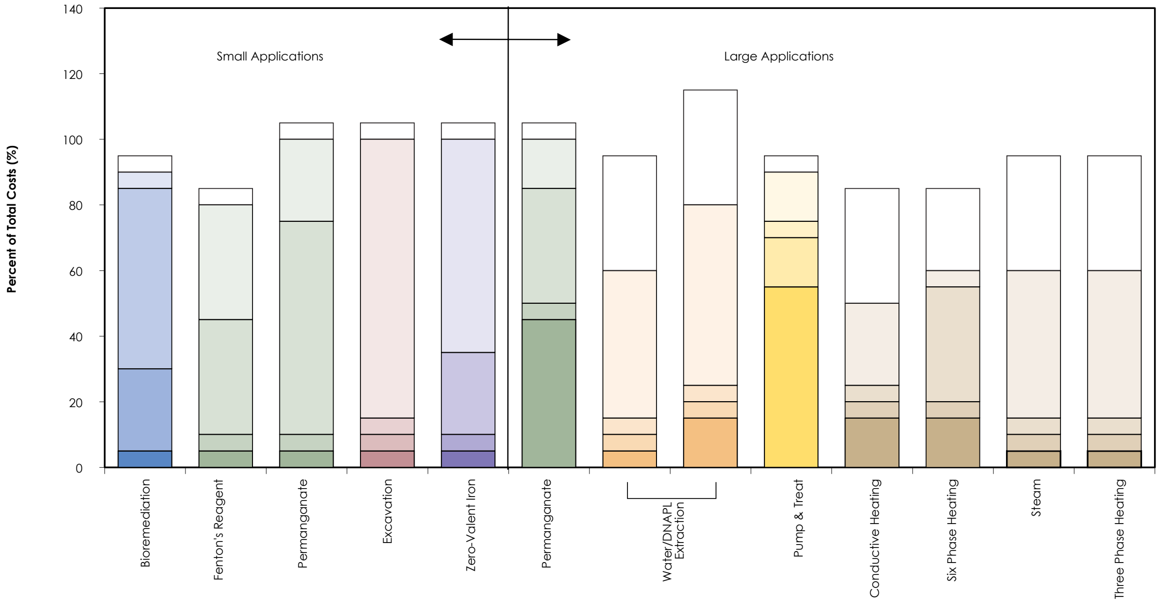
Actual Cost of Technology Applications
Navy ROCS

Feb. 2004
Figure: **C.5**
GeoSyntec Consultants

Pilot Scale Applications



Full Scale Applications



Technology Legend

- 🟦 Bioremediation
- 🟩 Chemical Oxidation
- 🟪 Zero Valent Iron
- 🟧 Dual Phase Extraction
- 🟫 Thermal
- 🟥 Excavation
- 🟨 Pump and Treat

Cost Breakdown

- ⬜ Treatment Infrastructure
- ░ Treatment Operation
- ▒ Consumables
- ▓ Post-Treatment Monitoring
- ⬛ Professional Costs

Notes:
1. Color shading (dark to light) is consistent for all technologies.
2. Total cost percent varies from 100% because cost breakdown data was inputted into survey as ranges and midpoints of ranges were chosen for illustration

Cost Breakdowns of Technology Applications
Percent of Total Costs
Navy ROCS

Feb. 2004
Figure: **C.6**
GeoSyntec Consultants

bar graphs_groups.ai

APPENDIX D

Survey Data Comparison and Interpretation

APPENDIX D TABLE OF CONTENTS

Page

APPENDIX D: SURVEY DATA COMPARISON AND INTERPRETATION

The DNAPL remediation case study data collected with the web-based survey was presented in Section 4 and Appendix C. An interpretation of the data is discussed in the following sections:

i) General overview of technology performance and effectiveness (Section 1); and

ii) Impact of site characteristics on technology application and performance (Section 2).

Smaller tables are embedded directly into the text. The remaining tables and all figures may be found at the end of the appendix.

1 General Overview of Technology Performance and Effectiveness

The technology performance data was analyzed for trends by technology and for other factors that impacted treatment cost, duration and remedial success. The results of the analysis are presented in the following sections:

i) remedial technology selection (Section 1.1);

ii) treatment cost and duration (Section 1.2); and

iii) remedial performance (Section 1.3).

1.1 Remedial Technology Selection

Table D.1 provides a summary of the technology selection criteria broken down by secondary technology. The technology selection criteria that were chosen by survey respondents as one reason for selecting each technology by more than 50% of the survey respondents were as follows (note: no information was provided for ozone oxidation, co-solvent flushing, or ZVI/clay):

i) **Cost of technology application:** all technologies except pump and treat, steam flushing and EZVI.

ii) **Technology perceived to provide a good chance at remedial success:** all technologies except DNAPL/air dual-phase extraction, and pump and treat.

iii) **Remediation timeframe was a factor:** water/DNAPL dual-phase extraction, excavation, conductive and low-temp six-phase heating, and EZVI.

iv) **Regulatory pressures guided technology choice:** pump and treat only.

v) **Impact of remedial technology on surface water was minimal:** This criteria was not chosen more than 50% of the time for any one technology, but was chosen for at least one site for bioremediation, chemical oxidation and water/DNAPL dual-phase extraction.

vi) **Impacts of remedial technology on secondary groundwater quality was minimal:** Low-temp six phase heating only.

vii) **Technology application was perceived to reduce risk to the environment:** water/DNAPL dual-phase extraction, excavation, and conductive and low-temp six-phase heating.

viii) **Technology application was thought to have a lasting impact on the water quality:** bioremediation, DNAPL/air extraction, surfactant flushing, and resistive and three-phase heating.

ix) **Health and safety concerns guided technology choice:** This criteria was not chosen more than 50% of the time for any one technology, but was chosen for at least one site for bioremediation, chemical oxidation, and water/air and DNAPL/air dual-phase extraction.

x) **Technical implementability of the remedial technology was thought to be appropriate:** Fenton's reagent, water/air and DNAPL/air dual-phase extraction, surfactant flushing and three-phase heating.

xi) **Legal pressures guided technology choice:** Pump and treat only.

xii) **Pressure from various stakeholders guided technology choice:** pump and treat and resistive heating only.

Other reasons for technology selection included (stated as entered into the survey):

i) Bioremediation, Chemical Oxidation, EZVI - The site was ideal/or chosen for technology demonstrations;

ii) Excavation - Low permeability of soil (silt) rendered any *in situ* approach infeasible. We needed to get to MCLs in the sand and gravel immediately below the silt layer containing the DNAPL; and *iii)* Low-temp six-phase heating was chosen at one site over higher-temp six-phase thermal methods due to proximity to underground utilities – are considering chemical oxidation or other technology instead.

1.2 Cost and Treatment Duration

1.2.1 Treatment Cost

The treatment cost data was analyzed for the following:

i) Trends in the treatment costs, by comparing total costs, the cost breakdown, and approximate unit cost comparisons; and

ii) The impact of size of the DNAPL impacted zone and scale of treatment on the costs.

Optimally, the trends in the treatment costs and calculation of unit costs should be performed using the size of the targeted treatment zone. However, this data was not collected with the survey; the assumption was made, for purposes of analysis and categorization, that the targeted treatment zone and the DNAPL impacted zone were of similar orders of magnitude. Unit costs for full-scale applications were thus calculated using the size of the DNAPL impacted zone. Unit costs for pilot tests, however, were not calculated as it is likely that the targeted treatment area of the pilot test is significantly smaller than the DNAPL impacted zone of the entire site. To determine the impact of the size of the DNAPL impacted zone on the costs, the data (pilot- and full-scale) was sorted into small applications, which corresponded to areas < 10,000 ft^2 and volumes < 100,000 ft^3, and large applications with areas > 10,000 ft^2 and volumes > 100,000 ft^3.

The treatment cost data is summarized or illustrated in tables and figures as follows:

i) Table D.2 provides a breakdown of the total treatment cost data by secondary technology, the size of the DNAPL impacted zone, and the scale of treatment (*e.g.*, full-scale *versus* pilot test);

ii) Table D.3 summarizes the cost breakdown data, categorized by secondary technology and the scale of treatment;

iii) Figure D.1 illustrates the distribution of the actual costs across all sites (by the scale of treatment and size of the DNAPL impacted zone);

iv) Figure D.2 shows the cost breakdown by percent of costs, again sorted by the scale of treatment and the size of the DNAPL impacted zone;

v) Figure D.3 is similar to Figure D.2, but with the cost breakdown as actual costs;

vi) Figure D.4 shows unit costs by areal extent of the DNAPL impacted zone for the full-scale applications only; and

vii) Figure D.5 shows a similar figure to Figure D.4, but with unit costs by volume of the DNAPL impacted zone. Figure D.6 shows the unit cost comparison by DNAPL mass removed.

As discussed in Appendix C, the smaller applications were generally less than US$0.5M, with the exception of one bioremediation pilot test. The costs of the pilot tests were similar within size categories, and did not seem to be impacted by technology. However, at full-scale, the cost of the dual-phase extraction, pump and treat and thermal applications were generally significantly more than that of the sites where bioremediation and chemical oxidation were applied (Figure D.1 and Table D.2).

In terms of the breakdown of costs, the following trends appear to be present (Table D.3 and Figures D.2 and D.3):

i) Treatment infrastructure appears to represent a larger proportion of the costs of larger treatment applications than smaller ones for both pilot- and full-scale applications.

ii) Consumables (*e.g.,* electron donor, iron, oxidant, surfactant, *etc.*) tend to represent a larger proportion of the cost of full-scale applications in comparison to pilot tests;

iii) Professional costs appear to comprise a larger portion of pilot test applications than full-scale; and

iv) Treatment operation represents a significant portion of costs for all technologies.

Unit costs were calculated by volume and area of the DNAPL-impacted zone for full-scale applications only. Again, unit costs are only calculated for the full-scale applications since the targeted treatment size of the pilot tests were likely to be less than the size of the DNAPL impacted zone, thus affecting the accuracy of the calculation. The unit costs are shown as ranges as the survey respondents were asked to specify the volume, area and DNAPL mass data from a list of order of magnitude ranges. Order of magnitude ranges were specified since, due to the difficulty in obtaining accurate volume, area and DNAPL mass data, any data provided were not likely to be more accurate than that.

Figures D.4 and D.5 show the unit cost variation for the full-scale sites with both cost and area, and cost and volume data provided. The unit costs are affected by the size of the DNAPL impacted zone, with smaller sites having much larger unit costs. It is difficult to draw any meaningful conclusions between technologies, given the lack of data. Very little data was available where both DNAPL mass removal and cost data were provided, as a result, no trends by mass removed are discernible (see Figure D.6).

1.2.2 Treatment Duration

Figures D.7 and D.8 illustrate the range in treatment duration for pilot test and full-scale applications respectively. The data shown in the histograms are data from individual sites. The treatment durations shown on Figures D.7 and D.8 are broken down by the field activity duration (actual to date and estimated future activity) and the estimated/actual duration of the post-treatment monitoring program. Therefore, these durations represent the time required until no further remedial action with that particular technology is required on site.

Of the limited amount of pilot-test data available, the bioremediation sites appeared to require the longest pilot tests, although the range in duration was large (2 months to 4 years; Figure D.7). There did not appear to be any trends in the relative duration of the post-treatment monitoring *versus* the treatment activities. There was also limited full-scale data collected (see Figure D.8). Note the change in scale on the vertical axis (duration in months). The one conclusion that can be drawn from this comparison is the significant difference between the duration of the remedial technologies that employ *in situ* destruction or enhancement of the DNAPL mobilization/flushing mechanisms (*e.g.,* bioremediation, chemical oxidation, excavation, thermal and ZVI technologies) versus that of the technologies that rely on flushing as the principal DNAPL removal mechanism (*i.e.,* pump and treat and dual-phase extraction). The expected treatment durations of the three sites using water/DNAPL dual-phase extraction and pump and treat were 45 and 75 years (dual-phase) to 158 years (pump and treat). The remainder of the technologies had expected durations of less than 4 years. It should be noted that pump and treat has been used on that site for five years to date, while the two dual-phase extraction sites have been in operation for 10 and 15 years, and are still operating. No trends in the relative proportion of post-treatment monitoring *versus* treatment activity duration are apparent, except perhaps for a longer duration of post-treatment monitoring for full-scale *versus* pilot test applications.

Optimally, treatment duration should be analyzed for correlations to the following:

i) the size of the targeted treatment area, as the size of the application will impact the treatment implementation and operation;

ii) DNAPL distribution (*e.g.,* pools, residual, *etc.*);

iii) the cost of the treatment; and

iv) remedial success.

However, insufficient data was collected in order to do so (see Appendix C - Section 8 and Section 6 of the report).

1.3 Technology Performance Evaluation

Several remedial effectiveness criteria were evaluated to determine what impact technology choice and site characteristics may have on the degree of success of remediation. General technology performance criteria included the following:

i) the perception of technology effectiveness and performance (Section 1.3.1) ; and

ii) factors impacting remedial performance (Section 1.3.2).

More specific technology performance criteria were also evaluated, including the following:

i) extent of DNAPL mass removal (Section 1.3.3);

ii) decrease of mass flux (Section 1.3.4);

iii) occurrence of rebound of dissolved phase concentrations (Section 1.3.5);

iv) achievement of remedial goals and/or site closure (Section 1.3.6); and

v) impacts to secondary groundwater quality (section 1.3.7).

DNAPL remediation technologies may be effective in terms of only one or more of the above criteria; however, the most effective technology would meet all criteria. Therefore, each technology was also evaluated in how well it met all criteria (Section 1.3.8).

1.3.1 Perception of Technology Effectiveness

Survey respondents were asked to rate the technology performance at their site. Figure D.9 provides a summary of the perceived success sorted by primary technology. Table D.4 provides a breakdown of the perceived success data by secondary technology as well as the role of the survey respondent in the groundwater community. The following conclusions can be drawn:

i) Of the sites where success was evaluated, more than 50% of the sites were rated successful for bioremediation (78% of 9 sites), chemical oxidation using Fenton's reagent (63% of 8 sites), excavation (75% of 4 sites), ZVI (67% of 3 sites), and thermal (100% of 4 sites of six-phase heating, 50% of 2 sites of steam flushing, and 100% of 1 site each of conductive and low-temperature six-phase heating) technologies.

ii) Only bioremediation, excavation and thermal technologies (six-phase, conductive and low-temperature six-phase heating) were rated successful for more than 75% of the sites.

iii) Technologies that were predominantly rated as having a fair success were chemical oxidation using permanganate (57% of 7 sites), surfactant flushing (100% of 2 sites), the thermal technology resistive heating (1 site), and EZVI (1 site).

iv) The three sites using dual-phase water/air extraction had ratings of good, fair and poor successes.

There was not enough data to discern any correlation between role in the environmental community and perception of success.

Survey respondents were also asked to rate their technology according to a list of effectiveness criteria, which are listed in Table D.5. Table D.5 also summarizes the responses according to the respondent's role in the environmental community. The following can be concluded from the distribution of responses (effectiveness criteria is listed in bold print, with the results after):

i) **Able to achieve treatment goals at a reasonable cost:** Regulators (100% of 2) and vendors (83% of 6) agreed most strongly with this statement. Site owners (25% of 4) agreed the least with this statement. Consultants (52% of 33) and DoD RPMs (54% of 13) were fairly neutral.

ii) **Technology is limited to certain site conditions:** Site owners agreed most strongly with this statement (75% of 4). Vendors agreed the least strongly (17% of 6). Consultants (36% of 33), regulators (50% of 2) and DoD RPMs (46% of 13)_were fairly neutral.

iii) **Technology requires further development before it can be routinely applied:** In general, few respondents agreed with this statement. Vendors agreed the most frequently at 33% of 6 respondents.

iv) **Reasonable ease of implementation:** Regulators and site owners all (100% of 6) agreed with this statement. Vendors, consultants, and DoD RPMs were neutral (50%, 49% and 46% respectively).

v) **Reasonable ease of use:** Again, regulators and site owners agreed 100% with this statement. Vendors, consultants, and DoD RPMs were neutral (50%, 55%, and 69% respectively).

vi) **Reasonable ease of design:** The responses were similar to the previous two, with the exception of fewer vendors agreeing with this statement (33% of 6).

vii) **Adequate number of trained vendors to implement technology:** No vendors agreed with this statement, but 100% of the regulators agreed. A large proportion of site owners also agreed.

Table D.6 provides a breakdown of the responses by secondary technology. Table D.7 contains a listing of all technologies that had greater than 50% agreement with each statement. The following conclusions can be drawn from this data:

i) Technologies that were generally considered reasonable to implement and use and were able to achieve the remedial goals at a reasonable cost were bioremediation, chemical oxidation using permanganate, excavation, conductive and low-temp six-phase heating and ZVI.

ii) Pump and treat and EZVI were not generally rated as able to achieve remedial goals at reasonable costs, but were frequently chosen for their ease of use and design.

iii) The ZVI technologies were the only technologies that were thought to need further development prior to routine use.

iv) Technologies that were generally thought to be more limited by particular site conditions included chemical oxidation using permanganate, DNAPL/air dual-phase extraction, excavation, surfactant flushing, ZVI, and resistive and low-temperature six-phase heating. Section 1.3.2 provides more detail on the specific limitations.

Table D.7: Summary of Technologies for Which >50% of Survey Respondents Chose the Technology Performance Criteria

Technology		Able to achieve treatment goals at a reasonable cost	Technology is limited to certain site conditions	Technology requires further development before routine application	Reasonable ease of implementation	Reasonable ease of use	Reasonable ease of design	Adequate number of trained vendors	**TOTAL SITES**
Bioremediation		✓			✓	✓	✓		17
Chemical Oxidation	Fenton's Reagent	✓							9
	Permanganate	✓	✓		✓	✓	✓		13
Dual-Phase Extraction	Water/air				✓	✓	✓	✓	6
	Water/DNAPL				✓	✓	✓	✓	3
	DNAPL/air		✓						1
Excavation		✓	✓		✓				5
Pump and Treat					✓	✓			1
Surfactant Flushing		✓	✓						2
Thermal	Conductive	✓				✓	✓		1
	Low-Temp six-Phase	✓	✓		✓	✓	✓		1
	Resistive	✓	✓						1
	Six-Phase	✓							9
	Three-Phase								3
	Steam Flushing	✓							5
ZVI	EZVI			✓		✓	✓		1
	ZVI/Clay	✓	✓		✓	✓	✓		1
	ZVI	✓	✓	✓	✓	✓		✓	2

1.3.2 Factors Impacting Remedial Effectiveness

Table D.6 provides a listing of specific limitations provided by survey respondents for each technology. These limitations can be summarized as follows:

i) heterogeneity impacts the effective delivery of amendments used for bioremediation, chemical oxidation (both Fenton's reagent and permanganate), and surfactant flushing;

ii) bioremediation requires a particular microbial community; however, bioaugmentation with the appropriate microbial community can be done to compensate;

iii) high carbonate content causes a more rigorous reaction and higher reagent consumption for Fenton's reagent;

iv) permanganate degrades only a limited range of DNAPLs degradable, the presence of DNAPL pools can impact remedial effectiveness, and the precipitation of manganese dioxide can cause pore plugging and reduction of soil permeability when using permanganate;

v) the aquifer must be dewatered adequately for DNAPL/air extraction;

vi) water/air extraction is applicable to sites with low transmissivity and permeability, with no possibility for short-circuiting; extreme heterogeneity requires careful engineering;

vii) extraction limited to shallow overburden only;

viii) pump and treat systems must be compatible with other on-site systems, and containment must be achieved;

ix) low-temperature six-phase heating is applicable only for DNAPL pools and for depths that can be economically serviced by hand bailing;

x) resistive and six-phase heating are impacted by soil conductivity;

xi) cost is significant for the thermal technologies six- and three-phase heating, and there is a shortage of qualified vendors;

xii) proximity of underground utilities/infrastructure are problematic, and DNAPL present in narrow "chimney" configurations at depths beyond 50 ft bgs may present significant application and cost challenges for six-phase heating; and *xiii)* testing of steam flushing in fractures has been inconclusive; and

xiv) ZVI with clay is applicable only in unconsolidated materials that are accessible to soil mixing or jet grouting equipment. The construction contractor must know how to undertake soil mixing.

Table D.8 provides a breakdown of external factors that may impact remedial effectiveness. Table D.9 summarizes the data by presenting the technologies that had each external factor chosen by survey respondents at least 50% of the time. No trends are apparent, other than that most technologies were impacted by budget/remediation costs.

Table D.9: Summary of Technologies that had >50% of Survey Respondents Selecting Each External Factor That Impacted Remedial Effectiveness

Technology		Facility operations constrained site access	Presence of surface infrastructure impacted ability to estimate or remediate DNAPL mass	Proximity to surface water impacted technology choice, design or effectiveness	Regulatory pressures impacted clean-up criteria/time-frame	Budget/remediation cost	**TOTAL SITES**
Bioremediation		✓				✓	25
Chemical Oxidation	Fenton's Reagent					✓	9
	Permanganate					✓	15
Dual-Phase Extraction	Water/air					✓	5
	Water/DNAPL					✓	5
	DNAPL/air	✓		✓			3
Excavation				✓	✓	✓	11
Pump and Treat					✓		1
Surfactant Flushing							4
Thermal	Conductive					✓	1
	Low-Temp six-Phase				✓		1
	Resistive	✓	✓	✓			2
	Six-Phase					✓	10
	Three-Phase			✓			5
	Steam Flushing				✓	✓	8
ZVI	EZVI		✓			✓	1
	ZVI/Clay		✓				1
	ZVI	✓	✓				4

1.3.3 DNAPL Mass Removal

Figure D.10 and Table D.10 summarize the DNAPL mass removal by primary and secondary technologies respectively. There were a total of 20 sites with source mass removal data. Table D.11 summarizes the distribution of mass removal effectiveness by technology. The majority (70%) of sites had >80% mass removal. Only four sites achieved 100% mass removal (one excavation pilot test, one six-phase and one conductive heating [both full-scale], and one chemical oxidation pilot test using permanganate). DNAPL/air dual-phase extraction performed poorly with less than 10% mass removal. The low-temperature six-phase heating pilot test also performed poorly in terms of mass removal; however, it should be noted that this pilot test was terminated prematurely in order to focus on another remedial technology. Therefore, the extent of DNAPL mass removal does not necessarily reflect what may have been achieved if the pilot test had continued.

Table D.10 also contains a listing of other relevant site characteristics. Of the four sites where 100% source mass removal was believed to be achieved, rebound was not evaluated at two (50%) of the sites; the DNAPL was present only as residual in three (75%) of the sites and had an unknown distribution at the fourth. Two (50%) of the sites were full-scale treatments (one with post-treatment monitoring ongoing) and two (50%) of the sites were pilot-scale treatments.

Table D.11: Summary of DNAPL Mass Removal Effectiveness

Technology		**> 80% Mass Removal**	**25 to 80% Mass Removal**	**< 25% Mass Removal**	**TOTAL SITES**
Bioremediation		1 (100%)			1
Chemical Oxidation	Fenton’s Reagent	4 (100%)			4
	Permanganate	2 (50%)	2 (50%)		4
Dual-Phase Extraction	DNAPL/air			1 (100%)	1
Excavation		3 (100%)			3
Surfactant Flushing		1 (100%)			1
Thermal	Conductive	1 (100%)			1
	Low-Temp six-Phase			1 (100%)	1
	Six-Phase	1 (100%)			1
	Steam Flushing		1 (100%)		1
ZVI	EZVI		1 (100%)		1
TOTAL SITES		**14 (70%)**	**4 (20%)**	**2 (10%)**	**20**

1.3.4 Mass Flux Decrease

Figure D.11 and Table D.12 summarize the mass flux decrease by primary and secondary technologies respectively; Table D.12 also contains a listing of other site characteristics. Table D.13 summarizes the distribution of mass flux decrease by technology. There were a total of 21 sites with mass flux decrease data (Table D.13). The majority (62%) of sites had a mass flux decrease greater than 80%. In comparison, 86% of sites had a mass flux decrease greater than 50%. The only technologies that did not achieve >80% mass flux decrease in at least half of the sites were excavation and EZVI. Two sites had no mass flux decreases (chemical oxidation using permanganate was applied at one, excavation the other). Both of these technologies were targeting DNAPL in a predominantly fractured bedrock environment. The excavation was on-going. Of these 13 sites with >80% decrease, rebound was evaluated at only three (23%) sites (two with no rebound, one with rebound), the DNAPL distribution was unknown for 8 (62%) sites and present as residual at 4 (31%) sites and residual and sorbed at 1 (8%) site.

Table D.13: Summary of Observed Mass Flux Decrease

Technology		**Observed Mass Flux Decrease**				**TOTAL SITES**
		0%	**41 to 60%**	**61 to 80%**	**81 to 100%**	
Bioremediation				2 (50%)	2 (50%)	4
Chemical Oxidation	Fenton's Reagent				2 (100%)	2
	Permanganate	1 (25%)		1 (25%)	2 (50%)	4
Excavation		1 (50%)		1 (50%)		2
Surfactant Flushing				1 (50%)	1 (50%)	2
Thermal	Six-Phase				5 (100%)	5
	Steam Flushing				1 (100%)	1
ZVI	EZVI		1 (100%)			1
TOTAL SITES		**2**	**1**	**5**	**13**	**21**

1.3.5 Occurrence of Rebound of Dissolved Phase Concentrations

Figure D.12 and Table D.14 summarize the rebound occurrence by primary and secondary technologies respectively. Table D.15 summarizes the distribution of rebound occurrence by secondary technology. There were a total of 21 sites with rebound data (Table D.15). The majority (67%) of sites did not have rebound occur. The technologies where rebound did occur were permanganate (83% of 6 sites), excavation (50% of 2 sites), and low-temperature six-phase heating (100% of 1 sites). Again, it should be emphasized that the low-temperature six-phase heating site was a pilot test that was terminated prematurely; therefore, the occurrence of rebound does not necessarily reflect the result of a completed application

Table D.14 contains a listing of other related site characteristics along with the rebound and technology data. Of the seven sites with rebound, four had DNAPL present in pools and two had DNAPL diffused into low K layers. However, of the 14 sites with no observed rebound, three sites had DNAPL in pools and four had DNAPL diffused into low K layers so DNAPL distribution may not be a good indicator on its own for evaluating the difficulty of achieving success.

Table D.15: Summary of Occurrence of Rebound of Dissolved Phase Concentrations

Technology		**Rebound Occurred**		**TOTAL SITES**
		yes	**no**	
Bioremediation			3 (100%)	3
Chemical Oxidation	Fenton's Reagent		4 (100%)	4
	Permanganate	5 (83%)	1 (17%)	6
Excavation		1 (50%)	1 (50%)	2
Thermal	Conductive		1 (100%)	1
	Low-Temp six-Phase	1 (100%)		1
	Resistive			
	Six-Phase		1 (100%)	1
	Three-Phase			
	Steam Flushing		1 (100%)	1
ZVI	EZVI		1 (100%)	1
	ZVI		1 (100%)	1
TOTAL SITES		**7**	**14**	**21**

1.3.6 Achievement of Remedial Goals and Site Closure

Survey respondents were only asked to evaluate success based on source mass removal, mass flux decrease, rebound and perceived success. Subsequent to the closure of the survey, an email request was sent out to the 53 participants who provided success data asking them the following questions:

i) State whether they achieved dissolved phase concentrations reduced to less than maximum concentration levels (MCLs) upon completion of the remediation scheme.

ii) If MCLs were achieved, state the stage of treatment (*i.e.,* pilot test versus full-scale) and the length of post treatment monitoring.

iii) If MCLs were not achieved, were remedial goals met?

iv) If MCLs were not achieved, but regulatory closure was, state how regulatory closure of the site was achieved.

In total, 8 sites had responses to these questions. Although out of the 53 sites, 4 sites were believed to have had 100% source mass removal and 13 sites had greater than 81% mass flux reduction, only one site claimed to have achieved MCLs after remediation. The site where MCLs were achieved was an excavation application with silt as the dominant lithology; however, the site did not achieve regulatory goals with respect to cis 1,2-DCE which has an MCL of 70 ppb and a site clean up goal of 5 ppb. The post remediation monitoring is ongoing, several years after the completion of remediation.

As a number of the sites were pilot scale demonstrations, achieving MCLs and site closure would not be expected at that stage of remediation. Of the 8 responses to the questions about MCLs, five stated that the pilot scale remediation attempts did meet the project goals, which were set above MCLs. Of these, two were bioremediation applications, one was a dual phase application, one was a permanganate application that is now going to full scale and one is an application of six phase heating that is now going to full scale. Of the remaining two sites, one was a Fenton's application which did not achieve remedial goals or MCLs and one was a full scale application of bioremediation were MCLs and regulatory closure are expected to be achieved within three years.

1.3.7 Impacts to Secondary Groundwater Quality

Figure D.13 summarizes the responses to observed secondary groundwater quality impacts sorted on a per primary technology basis. Table D.16 summarizes secondary groundwater quality impacts by secondary technology. If we consider only the criteria that were selected for at least 50% of sites per technology, the following conclusions can be drawn:

i) **Generation/mobilization of undesirable compounds** (*e.g.,* methane, hydrogen sulfide, dissolved iron, manganese and other metals mobilization): Primarily impacted bioremediation, chemical oxidation using permanganate (manganese generation, dissolved metals, permanganate, chloride) and Fenton's reagent (metals mobilization, with hexavalent chromium observed at one site), EZVI (methane generation due to stimulated bioactivity), and dual-phase extraction.

ii) **Changes in groundwater aesthetic parameters** (*e.g.*, increased biochemical oxygen demand, pH change, increased dissolved solids and change in groundwater color): Primarily impacted bioremediation, and chemical oxidation using permanganate (change in groundwater color only).

iii) **Changes in soil hydraulic properties** (*e.g.*, changes in hydraulic conductivity and reduced soil porosity): Primarily occurred during chemical oxidation using Fenton's reagent, conductive heating, and ZVI.

iv) **Changes in DNAPL distribution** (*i.e.,* decrease/increase in source area volume and redistribution of DNAPL): Redistribution of DNAPL occurred with Fenton's reagent, water/DNAPL dual-phase extraction, and excavation. No technology application caused an increase in the source area. Decreases in source area volume were primarily observed for all dual-phase extraction methods, excavation, ZVI, three-phase heating, and steam flushing.

In general, bioremediation, chemical oxidation (particularly permanganate) and dual phase extraction had the most secondary groundwater issues identified, although some of them were noted to be temporary (*i.e.*, groundwater color changes with the application of permanganate).

1.3.8 Overall Technology Performance

It is possible for remediation at a site to meet one or more of the success criteria, yet fail to meet other criteria. For example, a large amount of DNAPL mass may be removed from the subsurface, but rebound may occur, coupled with insignificant mass flux decrease. The optimal result from remedial activities would be a large amount of DNAPL mass removed, significant mass flux reduction, and no post-treatment rebound of dissolved phase concentrations. To evaluate the level of success that was achieved for various combinations of site conditions and technologies, the sites were sorted according to varying degrees of each success criteria. Sites with "unknown" responses to any of the success criteria eliminated the site from consideration. The following results were found:

i) **Greater than 80% mass removal AND a greater than 61% reduction in mass flux AND no observed rebound AND a perceived success:** Only two sites met the most stringent of the success criteria. Bioremediation and chemical oxidation (permanganate) were applied at these sites. Both sites had sandy aquifers and were pilot-scale applications.

ii) **80% mass removal AND a greater than 61% reduction in flux AND perceived a success:** Four sites met this criteria, with the technologies being chemical oxidation (permanganate – two sites), bioremediation (one site) and excavation (one site). All four sites had sandy aquifers. All but the site with excavation were pilot-scale applications.

iii) **80% mass removal AND a greater than 61% reduction:** Six sites in total met this criteria, with the technologies applied being chemical oxidation (permanganate – two sites), bioremediation (one site), excavation (one site), surfactant flushing (one site) and thermal six-phase heating (one site). All sites except for the surfactant flush had sandy aquifers; the surfactant flush was conducted in a clay aquifer. Only the excavation and the thermal six phase heating were full-scale applications, the remaining were pilot-scale.

iv) **80% mass removal AND no observed rebound AND a perceived success:** Seven sites met this criteria. These sites include the three chemical oxidation sites (one permanganate, two Fenton's reagent), one bioremediation, two thermal applications (steam and conductive heating) and one excavation. If the perceived success criteria is removed from this evaluation, another chemical oxidation application (Fenton's reagent) is included. The sites were all unconsolidated, and the lithologies comprised three sand, three clay and one silt sites. Five of the sites were completed full scale applications and two were pilot scale applications.

v) **Greater than 61% reduction in flux AND no observed rebound AND a perceived success:** Two bioremediation, one chemical oxidation (permanganate), and one thermal (six phase heating) sites met this criteria (four in total). Two of the sites had sandy aquifers, the other two had clay. Two of the applications were full scale and two were pilot scale.

The two predominant trends that appear to be consistent throughout all sites that met all degrees of success criteria were:

i) Not one of the "successful" sites had remediation applied in unconsolidated media. The prevalent lithology was sand, with some sites with predominantly clay.

ii) The majority of the "successful" sites were applied at the pilot-scale. Only excavation and thermal technologies met even the least stringent of the criteria for full-scale applications.

2 Impact of Site Characteristics on Technology Application and Performance

The data was also analyzed to determine the impact of the following site characteristics on the technology application and performance:

i) aquifer geology and lithology (Section 2.1);

ii) hydrogeology (Section 2.2);

iii) DNAPL source zone characteristics (Section 2.3); and *iv)* DNAPL detection, sampling and mass estimation (Section 2.4).

Optimally, a full analysis would also include looking at the impact of these site characteristics on remedial costs and treatment duration. Unfortunately, insufficient cost and treatment duration data was collected to come to any meaningful conclusions (see Section 1.2); therefore, remedial costs and treatment duration are not discussed here.

2.1 Aquifer Geology and Lithology

Figure D.14 provides a breakdown of predominant lithology distribution in the DNAPL source zone by technology. Table D.17 provides a more detailed breakdown of the data by lithology sub-category (*e.g.,* metashale, limestone, sand, *etc.*) and secondary technology. In general, data was entered into the survey for only unconsolidated geologic media sites for the technologies dual phase extraction, pump and treat, and surfactant flushing. Similarly, data was collected for only unconsolidated sites for the technologies excavation, ZVI and thermal, with the exception of 1 site each where they were applied at a site with sedimentary rock. Both bioremediation and chemical oxidation were applied at the largest range of geologic media types, including both consolidated and unconsolidated media.

Table D.18 provides a detailed breakdown of the geology data (*i.e.,* degree of fracturing and rock matrix permeability for consolidated media, and degree of heterogeneity for unconsolidated media). Based on this data, all technologies except for pump and treat, some of the thermal technologies (*i.e.,* conductive heating, low-temp six-phase and six-phase heating), and the EZVI and ZVI/clay combination were performed at sites with at least some bedrock. It should be noted, however, that data was collected for only one site for each of these technologies except for six-phase heating. Again, bioremediation and chemical oxidation using permanganate have been applied over the widest variation in geological conditions.

Tables D.19 through to D.22 outline the breakdown of the various remedial success parameters by the predominant lithology in the source area. A number of interesting trends arise from these tables. For example, sites with consolidated media were generally described as follows:

i) no successful fractured bedrock sites are reported (Table D.19);

ii) no one entered data of estimates of the DNAPL source mass removal at a fractured bedrock site (Table D.20);

iii) neither of the fractured bedrock sites had any reduction in mass flux (Table D.21); and *iv)* the occurrence of post-treatment rebound was unknown (Table D.22).

In comparison, sites with predominantly unconsolidated media could be described as follows:

i) two-thirds of 43 sites with unconsolidated media were perceived to be successfully remediated, with the remaining almost one-third perceived to be fairly successful (one poor success as well; Table D.19);

ii) 55% of 20 sites had a >90% reduction in the DNAPL source mass, with the majority of the remainder experiencing at least a 50% reduction (Table D.20);

iii) the majority (68% of 19 sites) of the sites had a mass flux reduction of 80 to 100%, with only one site experiencing less than a 40% decrease (Table D.21); and

iv) two-thirds of 20 sites did not experience post-treatment rebound (Table D.23).

As mentioned in Section 8 of Appendix C, these conclusions are based on a limited data set. Although attempts were made to compile a comprehensive database of information pertaining to DNAPL remediation, the data necessary to draw quantitative conclusion is very complex and difficult to collect.

Table D.19: Trends in Perceived Success With Lithology in Source Area

Geologic Media	Predominant Lithology in Source Area		Number of Sites With Perceived Success			
			Poor	**Fair**	**Success**	**Not Yet Evaluated**
Consolidated	Metamorphic	Metabasalt				
		Other Metamorphic				1
	Sedimentary	Shale				
		Limestone (karstic)		1		
		Other Sedimentary				1
	Igneous	Granitic				
	Unknown					
Unconsolidated	Gravel			2	1	2
	Sand			6	13	1
	Till				1	1
	Silt		1	2	4	2
	Clay			2	8	1
	Unknown			2	1	

Table D.20: Trends in Source Mass Removal With Lithology in Source Area

Geologic Media	Predominant Lithology in Source Area		Number of Sites With Level of Source Mass Removal							
			Unknown	< 10%	10 to 25%	25 to 50%	50 to 80%	80 to 90%	> 90%	100%
Consolidated	Metamorphic	Metabasalt								
		Other Metamorphic	1							
	Sedimentary	Shale								
		Limestone (karstic)	1							
		Other Sedimentary								
	Igneous	Granitic								
	Unknown									
Unconsolidated	Gravel		4							
	Sand		9			2	2	1	3	3
	Till		2							
	Silt		2	1	1			2	1	
	Clay		5						3	1
	Unknown		3							

Table D.21: Trends in Mass Flux Reduction With Lithology in Source Area

Geologic Media	Predominant Lithology in Source Area		Number of Sites With Level of Mass Flux Reduction					
			Unknown	**0%**	**0 to 40%**	**40 to 60%**	**60 to 80%**	**80 to 100%**
Consolidated	Metamorphic	Metabasalt						
		Other Metamorphic		1				
	Sedimentary	Shale						
		Limestone (karstic)		1				
		Other Sedimentary						
	Igneous	Granitic						
	Unknown							
Unconsolidated	Gravel		3					1
	Sand		11			1	3	5
	Till		1					1
	Silt		5				1	
	Clay		5				1	3
	Unknown							3

Table D.22: Trends in Rebound With Lithology in Source Area

Geologic Media	Predominant Lithology in Source Area		Number of Sites With Rebound		
			Unknown	Yes	No
Consolidated	Metamorphic	Metabasalt			
		Other Metamorphic	1		
	Sedimentary	Shale			
		Limestone (karstic)	1		
		Other Sedimentary			
	Igneous	Granitic			
	Unknown				
Unconsolidated	Gravel		2	1	1
	Sand		10	4	6
	Till		2		
	Silt		3	1	2
	Clay		4		5
	Unknown		3		

2.2 Hydrogeology

The breakdown of hydrogeological parameters by primary technology is illustrated in several figures as follows:

i) Figure D.15 summarizes the hydraulic conductivity;

ii) Figure D.16 summarizes the groundwater velocity; and

iii) Figure D.17 summarizes the sustainable well yield.

Table D.23 provides a more detailed breakdown of the hydraulic conductivity, depth to groundwater, groundwater velocity, hydraulic gradient and sustainable well yield data by secondary technology.

The most prevalent hydrogeological characteristics of the sites at which DNAPL remediation has been attempted can be described as follows (Section 2, Appendix C):

i) hydraulic conductivity (*K*) between 10^{-5} ft/day and 10 ft/day (49 of 80 sites, 61%);

ii) groundwater velocity (*v*) between 10^{-3} and 1 ft/day (40 of 58 sites, 69%);

iii) sustainable well yield between 1 and 100 gpm (29 of 49 sites, 59%);

iv) depth to groundwater less than 50 ft below ground surface (bgs; 97 of 106 sites, 92%); and

v) horizontal gradients within the range of 0.001 to 0.1 ft/ft. (37 of 59 sites, 63%), and small (<0.001 ft/ft) vertical gradients, indicating a predominance of horizontal groundwater flow at most DNAPL impacted sites surveyed.

Each remedial technology was applied at sites that generally fit into the above categories, with the following notable exceptions (Table D.23):

i) **Bioremediation:** Also applied at a number of sites with highly conductive and permeable aquifers (*e.g.,* 4 of 7 sites had sustainable well yields greater than 100 gpm, with one site above 1,000 gpm; and 4 of 14 sites had *v*>1 ft/day).

ii) **Chemical oxidation using Fenton's reagent and permanganate:** The *Fenton's reagent* sites could all be categorized as above. Notable exceptions for the *permanganate* sites include the application at: (*i*) larger depths (*e.g.*, 2 of 13 sites with groundwater depths between 50 to 200 ft bgs); and (*ii*) sites with permeable and conductive aquifers (*e.g.,* 1 of 6 sites with *v*>1 ft/day; 3 of 10 sites with *K*>10 ft/day; 2 of 7 sites with a horizontal hydraulic gradient between 0.1 and 1 ft/ft; and 1 of 6 sites with a sustainable well yield between 100 to 1,000 gpm).

iii) **Dual-phase extraction:** *Water/air* and *water/DNAPL* extraction were also employed at lower conductivity sites (*e.g.,* both *water/air* and *water/DNAPL* had one site with a sustainable well yield <1 gpm; *water/DNAPL* had one site with a horizontal gradient between 0.0001 to 0.001 ft/ft). *DNAPL/air*, in comparison, was applied at more conductive sites (*e.g.,*one site with *K*>10 ft/day, and one site with a sustainable well yield between 100 to 1,000 gpm).

iv) **Excavation:** Excavation was also applied at 1 (of 9) sites with a deeper groundwater table (50 to 100 ft bgs), and both low permeability (*e.g.,* one site each with $K<10^{-5}$ ft/day and sustainable well yield<1 gpm) and high permeability aquifers (*e.g.,* two [of 6] sites with $K>10$ ft/day and 1 [of 6] sites with a sustainable well yield between 100 to 1,000 gpm).

v) **Surfactant flushing:** Also applied at sites with higher conductivity aquifers (*e.g.,* one [of 3] sites had $K>10$ ft/day, and one [of 2] sites with sustainable well yields between 100 and 1,000 gpm).

vi) **Thermal technologies:** *Resistive, six-phase,* and *three-phase heating*, as well as *steam flushing* have all been applied at sites with more permeable aquifers (e.g., sustainable well yields as high as 100 to 1,000 gpm, and $v>1$ ft/day at 1 site each for *three-phase heating* and *steam flushing*, $K>10$ ft /day at one to two sites each for all four technologies).

vii) **ZVI:** EZVI was applied at a high conductivity site (K>10 ft/day), while ZVI was applied at one low conductivity site (K<10-5 ft/day).

Table D.24 outlines the breakdown of the perceived remedial success by the hydrogeology parameter. No trends in the data are discernible, likely due more to a lack of data than a lack of impact of the hydrogeology on the remedial success. The breakdown of the remainder of the success parameters is not shown, since the data available for these factors are even fewer in number.

Table D.24: Trends in Perceived Success With Hydrogeology Parameters

Hydrogeology Parameters		**Number of Sites With Perceived Success**			
		Poor	**Fair**	**Success**	**Not Yet Evaluated**
Depth to Groundwater	< 50 ft		8	21	3
	50 to 200 ft		1	1	
	> 200 ft				
Groundwater Velocity	< 0.001 ft/day		1	2	
	0.001 to 1 ft/day		4	8	
	> 1 ft/day			1	
Hydraulic Conductivity	< 10^{-5} ft/day			4	
	10^{-5} to 10 ft/day		4	9	2
	> 10 ft/day		1	2	
Horizontal Hydraulic Gradient	< 0.001		1	3	
	0.001 to 0.1		1	5	1
	> 0.1		1	1	
Sustainable Well Yield	< 10 gpm		2	2	
	10 to 100 gpm		1		1
	> 100 gpm				

2.3 DNAPL Source Zone Characteristics

The DNAPL source zone characteristics, which included DNAPL composition, size of the source zone (areal extent, volume and depth), shape of the source zone, and the DNAPL distribution in the subsurface, were evaluated on a technology specific basis.

2.3.1 Source Zone Geochemistry

The distribution of DNAPL composition was evaluated for each of the technologies. Data was collected from a total of 91 sites. Figure D.18 summarizes the DNAPL composition distribution by technology. Bioremediation, thermal, excavation and dual phase extraction were applied at sites contaminated with all four groups of DNAPLs. ZVI and surfactant flushing were applied at sites with only chloroethene contamination.

Chemical oxidation was applied at sites with chloroethenes, chloroethanes, and chloromethanes as components of the DNAPL.

The distribution of groundwater chemistry was also evaluated for each of the technologies. The breakdown by technology varies slightly from the groundwater chemistry breakdown. This could be due to different components in the dissolved phase then in the DNAPL phase or it could also be due to the respondents answering "unknown" to one of the questions and providing an answer to the other, changing the percentages when broken down by technology. There are a total of 80 sites with groundwater chemistry data. Figure D.19 summarizes the groundwater chemistry distribution by technology. Bioremediation, chemical oxidation and dual phase extraction were applied at sites contaminated with all four groups of contaminants. ZVI and surfactant flushing (only one application with groundwater chemistry data) were applied at sites with only chloroethene contamination. Thermal and excavation were applied at sites with chloroethenes, chloroethanes, and chloromethanes. The two sites without chloroethenes were sites impacted by chloroethanes and at each of these sites remediation was undertaken by chemical oxidation using Fenton's Reagent.

There are no obvious trends in the success data in terms of the DNAPL or groundwater chemistry data (Table D.25).

Table D.26contains a detailed breakdown of the groundwater geochemistry (non-VOC data) by secondary technology. Little geochemistry data was provided; therefore, no discernible trends can be seen.

2.3.2 DNAPL Source Zone Areal Extent

Figure D.20 summarizes the distribution in DNAPL areal extent by technology. On a per technology basis, bioremediation and chemical oxidation have been applied at the largest range in areal extent. Of the 7 sites with areal extents of source zones greater than 1,000,000 ft^2, three of the sites were remediated using excavation, two with dual phase extraction and one each with bioremediation and thermal.

There are no obvious trends in the success data in terms of the areal extent. Of the four sites with an areal extent of 1 to 10 ft, all were considered successful. Of those with data, there was >90% mass removal and 81 to 100% mass flux decrease. However, at all the other areal extent ranges, remediation was considered either successful or a fair success. For the site with the largest area that had success data (100,000 to <1,000,000 ft^2), the application was considered successful although there was only >10 to 25% mass removal and rebound did occur (Table D.27). It should be noted; however, that at this site the low-temperature six-phase heating demonstration was terminated before completion in order to focus on another remediation technology application at the site.

2.3.3 DNAPL Source Zone Volume

Figure D.21 summarizes the distribution in DNAPL volume data by technology. On a per technology basis, chemical oxidation and excavation have been applied at sites with the largest range in volumes of DNAPL impacted soil, followed by bioremediation and dual phase extraction. Based on the data provided from the survey, thermal treatments have been mainly applied at sites with greater than 100,000 ft^3 volume of DNAPL impacted soils. In contrast, of the two surfactant flushing sites with a known volume of DNAPL impacted soil, both were at sites with between 10 and 100 ft^3.

There were no trends in the success data with respect to DNAPL volume.

2.3.4 Maximum DNAPL Depth

Figure D.22 summarizes the distribution in maximum DNAPL depth data by technology. On a per technology basis, bioremediation has been applied at sites with the greatest depths of DNAPL distribution with three sites having depths between 100 and 1000 ft bgs and one site having a DNAPL depth greater than 1,000 ft bgs. Chemical oxidation, thermal, and excavation have been applied at sites with DNAPL depths between 1 and 1,000 ft bgs.

There are no trends in the success data with respect to maximum DNAPL depth (Table D.28) with the exception that for all but three sites with success data, the maximum DNAPL depth is <100 ft. Of those three sites one site had DNAPL between 100 and 1000 ft and was considered a success with >90% mass removal using a thermal (steam) application, one was considered a fair success with 81 to100% mass flux reduction using bioremediation, and at the third site, a chemical oxidation using permanganate site with DNAPL at a depth of 100 to 1000 ft, success has not yet been evaluated; however, to date there has been 0% mass flux reduction.

2.3.5 DNAPL Distribution in Subsurface

Figure D.23 summarizes the range in DNAPL distribution in the subsurface by technology. On a per technology basis, surfactant flushing was applied at sites with DNAPL present as either pools or at residual saturation, where as bioremediation, chemical oxidation, dual phase extraction and excavation were attempted at sites with DNAPL distributed in all of the classifications.

Table D.29 summarizes the remediation success factors for the various DNAPL distribution parameters. There are no obvious trends with respect to the DNAPL distribution data.

2.3.6 DNAPL Shape in Subsurface

Figure D.24 summarizes the range in DNAPL source zone shape in the subsurface by technology. This question was asked to get an idea of the level of characterization that had been conducted on the source zones. On a per technology basis, surfactant flushing was applied at sites with DNAPL present as either pools or at residual saturation, where as bioremediation, chemical oxidation, dual phase extraction and excavation were attempted at sites with DNAPL distributed in all of the classifications.

2.3.7 DNAPL Detection, Sampling and Mass Estimation

Table D.30 provides a summary of the relative frequency that each sampling method is used at a site, for only the sites where at least one method was specified. The relative percentage is described by the maximum, minimum, average and median usage percentages. No one method was used at all sites. Only 14 of 123 sites used only one sampling method, of which 8 sites used only fully-screened monitoring wells; 3 sites used only nested monitoring wells; 3 sites used only soil sampling; and 0 sites used only depth-discrete sampling. The median and average relative frequencies indicate that soil sampling is the most frequently chosen sampling method.

Also included in Table D.30 is a description of the number of sampling locations used at each site, also described by the maximum, minimum, average and median number of sampling locations. As can be seen by these numbers, large numbers of sampling locations have been used at some sites; however, the average numbers are generally much smaller.

Table D.30: Number of Sampling Locations Used to Locate the DNAPL Source Area(s)

Frequency Metric	**Sampling Method**	**Frequency of Use of Sampling Methods**			
		Minimum	**Maximum**	**Median**	**Average**
Relative Percentage of Use on Each Site	Fully-Screened Monitoring Wells	0.0%	100.0%	22.7%	29.5%
	Nested Monitoring Wells	0.0%	100.0%	2.8%	15.0%
	Depth-Discrete Samples	0.0%	98.5%	0.0%	19.6%
	Soil Samples	0.0%	100.0%	44.4%	35.8%
Overall Usage	Fully-Screened Monitoring Wells	0	700	6	36
	Nested Monitoring Wells	0	50	3	10
	Depth-Discrete Samples	0	1300	0	73
	Soil Samples	0	1500	20	71

Table D.31 outlines the correlation between the various remedial success parameters and the sampling method used to detect and locate the DNAPL source area. While it should be noted that there was minimal data available to analyze, there are some interesting trends that are illustrated in this table, including:

i) at the sites where the treatment was perceived to be successful, the average method for locating the DNAPL source area consisted of an approximately even mixture of fully-screened monitoring wells, nested monitoring wells, depth-discrete samples and soil samples. Conversely, the less successful sites predominantly used fully-screened monitoring wells on average;

ii) the sites most successful at removing DNAPL mass from the source area tended to have soil samples being the predominant method for DNAPL detection. In comparison, the sites where less DNAPL mass was removed tended to rely more heavily on fully-screened monitoring wells; and

iii) There does not appear to be any trend in the mass flux reduction or rebound occurrence with DNAPL sampling method.

Table D.31: Correlation Between Treatment Success and DNAPL Sampling Method

Success Metric	**Criteria**	**Average Percent of Sampling Locations per Site**				**Total Sites**
		Fully-Screened Monitoring Wells	**Nested Monitoring Wells**	**Depth-Discrete Sampling**	**Soil Samples**	
Perceived Success	Poor					0
	Fair	61.9%	8.6%	6.9%	22.6%	5
	Success	26.8%	22.4%	23.9%	26.9%	19
DNAPL Mass Reduction	<10%					0
	10 to 25%	1.1%	0.0%	93.3%	5.6%	1
	25 to 50%	64.4%	4.8%	1.9%	28.8%	2
	50 to 80%	64.7%	33.3%	0.0%	0.0%	1
	80 to 90%	6.9%	5.0%	30.3%	57.8%	2
	>90%	3.7%	17.0%	31.5%	47.8%	3
	100%	33.7%	12.5%	12.5%	41.3%	2
Mass Flux Reduction	0%					0
	0 to 40%					0
	40 to 60%	28.8%	9.6%	3.8%	57.7%	1
	60 to 80%	50.0%	5.0%	15.0%	30.0%	2
	80 to 100%	54.5%	0.0%	3.7%	41.8%	3
Rebound Occurrence	Yes	35.8%	8.7%	26.9%	28.7%	5
	No	32.5%	7.6%	14.7%	45.2%	8

Note: Blank spaces denote a lack of data

TABLE D.1: SUMMARY OF TECHNOLOGY SELECTION CRITERIA DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY
Navy ROCS

TECHNOLOGY SELECTION CRITERIA	NUMBER OF SITES THAT MATCH THE TECHNOLOGY SELECTION CRITERIA PER TECHNOLOGY																					TOTAL SITES
	BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			
		Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only	
Cost of technology application	16 (88.9%)	5 (62.5%)	8 (57.1%)			4 (66.7%)	2 (66.7%)	1 (100.0%)	5 (83.3%)	1 (50.0%)		1 (50.0%)	1 (100.0%)	1 (100.0%)	1 (100.0%)	5 (55.6%)	1 (33.3%)				1 (50.0%)	**52 (61.9%)**
Technology perceived to provide a good chance at remedial success	15 (83.3%)	8 (100.0%)	9 (64.3%)			4 (66.7%)	3 (100.0%)		4 (66.7%)	1 (50.0%)		2 (100.0%)	1 (100.0%)	1 (100.0%)	1 (100.0%)	8 (88.9%)	3 (100.0%)	4 (80.0%)	1 (100.0%)		2 (100.0%)	**67 (79.8%)**
Remediation timeframe was a factor	6 (33.3%)	3 (37.5%)	6 (42.9%)			2 (33.3%)	2 (66.7%)		3 (50.0%)				1 (100.0%)	1 (100.0%)		2 (22.2%)		2 (40.0%)	1 (100.0%)			**29 (34.5%)**
Regulatory pressures guided technology choice	1 (5.6%)		3 (21.4%)			1 (16.7%)	1 (33.3%)				1 (100.0%)											**7 (8.3%)**
Impact of remedial technology on surface water was minimal	3 (16.7%)	1 (12.5%)	2 (14.3%)				1 (33.3%)															**7 (8.3%)**
Impacts of remedial technology on secondary groundwater quality was minimal	3 (16.7%)		2 (14.3%)			1 (16.7%)	1 (33.3%)		1 (16.7%)					1 (100.0%)								**9 (10.7%)**
Technology application was perceived to reduce risk to the environment	4 (22.2%)	1 (12.5%)	5 (35.7%)			2 (33.3%)	3 (100.0%)	1 (100.0%)	3 (50.0%)				1 (100.0%)	1 (100.0%)		1 (11.1%)	1 (33.3%)					**17 (20.2%)**
Technology application was thought to have a lasting impact on the water quality	9 (50.0%)	3 (37.5%)	3 (21.4%)			2 (33.3%)		3 (300.0%)	1 (16.7%)	1 (50.0%)		1 (50.0%)			1 (100.0%)	1 (11.1%)	2 (66.7%)	1 (20.0%)				**31 (36.9%)**
Health and safety concerns guided technology choice	6 (33.3%)	1 (12.5%)	2 (14.3%)			1 (16.7%)		1 (100.0%)														**11 (13.1%)**
Technical implementability of the remedial technology was thought to be appropriate	8 (44.4%)	5 (62.5%)	5 (35.7%)			3 (50.0%)	1 (33.3%)	2 (200.0%)	1 (16.7%)	1 (50.0%)		1 (50.0%)					2 (66.7%)	2 (40.0%)				**34 (40.5%)**
Legal pressures guided technology choice			2 (14.3%)					1 (100.0%)			1 (100.0%)											**4 (4.8%)**
Pressure from various stakeholders guided technology choice	3 (16.7%)		3 (21.4%)			1 (16.7%)	1 (33.3%)	1 (100.0%)			1 (100.0%)				1 (100.0%)							**11 (13.1%)**
Other[a]	4 (22.2%)		3 (21.4%)						1 (16.7%)	1 (50.0%)								1 (20.0%)	1 (100.0%)		1 (50.0%)	**12 (14.3%)**
TOTAL SITES WITH DATA	**18**	**8**	**14**	**0**	**0**	**6**	**3**	**1**	**6**	**2**	**1**	**2**	**1**	**1**	**1**	**9**	**3**	**5**	**1**	**0**	**2**	**84**

Notes

Blank spaces indicate no survey respondent selected the corresponding factors for that technology application.

[a] "Other" reasons for technology selection included the following:

Bioremediation - two were technology demonstration projects, and two were performed inside drycleaners
Chemical oxidation using permanganate - three were technology demonstrations
Excavation - "Low permeability of soil (silt) rendered any in-situ approach infeasible. We needed to get to MCLs in the sand and gravel immediately below the silt layer containing the DNAPL."
Undefined other - "Ideal site to try innovative technology"
Steam flushing - "Steam is easily available at the site. No cost to tap into steam source."
EZVI/nanoscale iron - first technology demonstration
ZVI - "University of Waterloo Masters of Science Thesis. Soil mixing with iron and bentonite slurry. Referenced work by Sharon Wadley UW Masters Thesis, 2002. Other references also available."

TABLE D.2: SUMMARY OF REMEDIAL COST DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY, SCALE OF REMEDIATION AND TREATMENT SIZE
Navy ROCS

SCALE OF TREATMENT	SIZE OF DNAPL ZONE[a]	RANGE IN TOTAL COSTS (USD)	NUMBER OF SITES THAT COULD BE DESCRIBED BY REMEDIAL COST PER TECHNOLOGY																					TOTAL SITES WITH COST DATA
			BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			
				Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only	
Full-Scale	Small	< $0.5M			1						1												1	3
		$0.5 to $1M																						0
		$1M to $2M																						0
		$2M to $4M																						0
		$4M to $10M																						0
		> $10M																						0
		Total	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**3**
	Large	< $0.5M			1				1															2
		$0.5 to $1M										1												1
		$1M to $2M													1			1						2
		$2M to $4M																	1	1				2
		$4M to $10M																1		1				2
		> $10M							1															1
		Total	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**2**	**1**	**2**	**0**	**0**	**0**	**10**
	Unknown	< $0.5M	1	1																				2
		$0.5 to $1M																						0
		$1M to $2M																						0
		$2M to $4M																						0
		$4M to $10M											1											1
		> $10M																						0
		Total	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3**
	TOTAL		**1**	**1**	**2**	**0**	**0**	**0**	**1**	**0**	**1**	**1**	**1**	**0**	**1**	**0**	**0**	**2**	**1**	**2**	**0**	**0**	**1**	**16**
Pilot-Scale	Small	< $0.5M	2	1	5						1												1	10
		$0.5 to $1M						1																1
		$1M to $2M	1																					1
		$2M to $4M																						0
		$4M to $10M																						0
		> $10M																						0
		Total	**3**	**1**	**5**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**12**
	Large	< $0.5M	1													1		1						3
		$0.5 to $1M	1	2	1													3	1					8
		$1M to $2M															1	1						2
		$2M to $4M																						0
		$4M to $10M																						0
		> $10M																						0
		Total	**2**	**2**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**5**	**1**	**0**	**0**	**0**	**0**	**13**
	Unknown	< $0.5M	2	1																				3
		$0.5 to $1M	1		1																			2
		$1M to $2M	1																					1
		$2M to $4M																						0
		$4M to $10M																						0
		> $10M																						0
		Total	**4**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**6**
	TOTAL		**9**	**4**	**7**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**1**	**5**	**1**	**0**	**0**	**0**	**1**	**31**

Notes

[a] DNAPL zone sizes are classified as follows:

Small: area < 10,000 ft^2, volume < 100,000 ft^3

Large: area > 10,000 ft^2, volume > 100,000 ft^3

Blank spaces denote no data entered for that parameter.

TABLE D.3: SUMMARY OF REMEDIAL COST DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY, SCALE OF REMEDIATION AND TREATMENT SIZE
Navy ROCS

COST CATEGORY	COST BREAKDOWN	SCALE OF TREATMENT	NUMBER OF SITES THAT COULD BE DESCRIBED BY COST BREAKDOWN PARAMETER PER TECHNOLOGY																					TOTAL SITES WITH COST BREAKDOWN DATA
			BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			
				Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only	
Professional Costs	**0 to 10%**	Full-Scale	3	4	3			1	2		3	1						1	1	4			1	24
		Pilot Test	9	3	2			1		1	1			2		1	1	5	1	1			1	29
		Total	**12**	**7**	**5**	**0**	**0**	**2**	**2**	**1**	**4**	**1**	**0**	**2**	**0**	**1**	**1**	**6**	**2**	**5**	**0**	**0**	**2**	**53**
	10 to 20%	Full-Scale	0		0				1		0				1			1		0				3
		Pilot Test	1	0	4			1		0	0			0			0	2	0	0				8
		Total	**1**	**0**	**4**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**11**
	20 to 30%	Full-Scale																						0
		Pilot Test	4	0	2			1		0	1			0			0	0	0	0				8
		Total	**4**	**0**	**2**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**8**
	30 to 40%	Full-Scale																						0
		Pilot Test			1														1					2
		Total	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**2**
	40 to 50%	Full-Scale			1																			1
		Pilot Test		1																				1
		Total	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**
	50 to 60%	Full-Scale											1											1
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
	60 to 70%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	70 to 80%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	80 to 90%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Post-Treatment Monitoring	**0 to 10%**	Full-Scale	2	4	4			1	3		3	1			1			2	1	4			1	27
		Pilot Test	9	4	4			2		1	2			2		1	1	7	2	1				36
		Total	**11**	**8**	**8**	**0**	**0**	**3**	**3**	**1**	**5**	**1**	**0**	**2**	**1**	**1**	**1**	**9**	**3**	**5**	**0**	**0**	**1**	**63**
	10 to 20%	Full-Scale											1											1
		Pilot Test	4		1			1																6
		Total	**4**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**7**
	20 to 30%	Full-Scale	1																					1
		Pilot Test			4																		1	5
		Total	**1**	**0**	**4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**6**
	30 to 40%	Full-Scale																						0
		Pilot Test	1																					1
		Total	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
	40 to 50%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	50 to 60%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	60 to 70%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	70 to 80%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	80 to 90%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

TABLE D.3: SUMMARY OF REMEDIAL COST DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY, SCALE OF REMEDIATION AND TREATMENT SIZE
Navy ROCS

COST CATEGORY	COST BREAKDOWN	SCALE OF TREATMENT	NUMBER OF SITES THAT COULD BE DESCRIBED BY COST BREAKDOWN PARAMETER PER TECHNOLOGY																					TOTAL SITES WITH COST BREAKDOWN DATA
			BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			
				Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only	
Consumables	**0 to 10%**	Full-Scale	2	3	2			1	3		3		1		1			1	1	4				22
		Pilot Test	13	3	7			3		1	1			2		1	1	7	2	1				42
		Total	**15**	**6**	**9**	**0**	**0**	**4**	**3**	**1**	**4**	**0**	**1**	**2**	**1**	**1**	**1**	**8**	**3**	**5**	**0**	**0**	**0**	**64**
	10 to 20%	Full-Scale																						0
		Pilot Test	1	1							1												1	4
		Total	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**4**
	20 to 30%	Full-Scale																					1	1
		Pilot Test			2																			2
		Total	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**3**
	30 to 40%	Full-Scale		1	1							1						1						4
		Pilot Test																						0
		Total	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**4**
	40 to 50%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	50 to 60%	Full-Scale	1																					1
		Pilot Test																						0
		Total	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
	60 to 70%	Full-Scale			1																			1
		Pilot Test																						0
		Total	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
	70 to 80%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	80 to 90%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Treatment Operating Costs	**0 to 10%**	Full-Scale	3	3	2			1	1		2	1						2		3				18
		Pilot Test	6	4	2			1		1	1			2			1	5	1	1				25
		Total	**9**	**7**	**4**	**0**	**0**	**2**	**1**	**1**	**3**	**1**	**0**	**2**	**0**	**0**	**1**	**7**	**1**	**4**	**0**	**0**	**0**	**43**
	10 to 20%	Full-Scale			1								1											2
		Pilot Test	3		1						1							1						6
		Total	**3**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**8**
	20 to 30%	Full-Scale			1										1									2
		Pilot Test	3		5			2										1						11
		Total	**3**	**0**	**6**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**13**
	30 to 40%	Full-Scale		1																				1
		Pilot Test			1											1			1					3
		Total	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**4**
	40 to 50%	Full-Scale							1										1	1				3
		Pilot Test	2																				1	3
		Total	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**1**	**6**
	50 to 60%	Full-Scale							1															1
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
	60 to 70%	Full-Scale																					1	1
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**
	70 to 80%	Full-Scale																						0
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	80 to 90%	Full-Scale									1													1
		Pilot Test																						0
		Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**

TABLE D.3: SUMMARY OF REMEDIAL COST DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY, SCALE OF REMEDIATION AND TREATMENT SIZE
Navy ROCS

COST CATEGORY	COST BREAKDOWN	SCALE OF TREATMENT	NUMBER OF SITES THAT COULD BE DESCRIBED BY COST BREAKDOWN PARAMETER PER TECHNOLOGY																					TOTAL SITES WITH COST BREAKDOWN DATA
			BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			
				Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only	
Treatment Infrastructure	0 to 10%	Full-Scale	3	4	4			1	1		3		1					1		3			1	22
		Pilot Test	6	3	5			1		1	1			2			1	5	1	1			1	28
		Total	9	7	9	0	0	2	1	1	4	0	1	2	0	0	1	6	1	4	0	0	2	50
	10 to 20%	Full-Scale																						0
		Pilot Test	3	1	2						1													7
		Total	3	1	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	7
	20 to 30%	Full-Scale																						0
		Pilot Test	3		2			1											1					7
		Total	3	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	7
	30 to 40%	Full-Scale							2			1			1				1	1				6
		Pilot Test	2					1										2						5
		Total	2	0	0	0	0	1	2	0	0	1	0	0	1	0	0	2	1	1	0	0	0	11
	40 to 50%	Full-Scale																						0
		Pilot Test																						0
		Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	50 to 60%	Full-Scale																						0
		Pilot Test														1								1
		Total	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
	60 to 70%	Full-Scale																						0
		Pilot Test																						0
		Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	70 to 80%	Full-Scale																						0
		Pilot Test																						0
		Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	80 to 90%	Full-Scale																						0
		Pilot Test																						0
		Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Notes

[a] DNAPL zone sizes are classified as follows:

Small: area < 10,000 ft^2, volume < 100,000 ft^3

Large: area > 10,000 ft^2, volume > 100,000 ft^3

Blank spaces denote no data entered for that parameter.

TABLE D.4: SUMMARY OF PERCEIVED SUCCESS SORTED BY TECHNOLOGY
Navy ROCS

Technology	Role in Groundwater Community	Perceived Success
Bioremediation	Consultant	Success
	Consultant	Success
	Consultant	Success
	Consultant	Success
	Consultant	Success
	DOD RPM	Success
	DOD RPM	Success
	Published Case Studies	Fair Success
	Published Case Studies	Fair Success
Chemical Oxidation-Fenton's Reagent	Consultant	Fair Success
	DOD RPM	Success
	Published Case Studies	Fair Success
	Published Case Studies	Success
	Vendor	Success
	Vendor	Success
	Vendor	Success
Chemical Oxidation-Permanganate	Consultant	Fair Success
	Consultant	Success
	Consultant	Success
	Consultant	Success
	DOD RPM	Fair Success
	Published Case Studies	Fair Success
	Published Case Studies	Fair Success
Dual Phase-Water/air extraction	DOD RPM	Success
	Published Case Studies	Fair Success
	DOD RPM	Poor success
Excavation	Consultant	Success
	Consultant	Success
	Consultant	Success
		Fair Success
Surfactant Flushing	Published Case Studies	Fair Success
	Published Case Studies	Fair Success
Thermal-Resistive heating	Published Case Studies	Fair Success
Thermal-Six phase heating	DOD RPM	Success
	Published Case Studies	Success
	Published Case Studies	Success
	Published Case Studies	Success
Thermal-Steam	Consultant	Success
	Published Case Studies	Fair Success
Thermal - Conductive Heating	DOD RPM	Success
Thermal - Low temp-six phase heating	Consultant	Success
ZVI - EZVI/nano-scale iron	Consultant	Fair Success
ZVI -Zero-valent iron	Site Owner/RPM	Success
	Vendor	Success

TABLE D.5: SUMMARY OF TECHNOLOGY PERFORMANCE CRITERIA COLLECTED WITH THE SURVEY SORTED BY SURVEY RESPONDENT ROLE IN ENVIRONMENTAL COMMUNITY
Navy ROCS

TECHNOLOGY EFFECTIVENESS CRITERIA	**ROLE IN ENVIRONMENTAL REMEDIATION COMMUNITY**							**TOTAL**
	CONSULTANT	**REGULATOR**	**VENDOR**	**DOD RPM**[a]	**SITE OWNER**	**ACADEMIC**	**PUBLISHED CASE STUDIES**	
Able to achieve treatment goals at a reasonable cost	17 (51.5%)	2 (100.0%)	5 (83.3%)	7 (53.8%)	1 (25.0%)		16 (72.7%)	**48 (60.0%)**
Technology is limited to certain site conditions	12 (36.4%)	1 (50.0%)	1 (16.7%)	6 (46.2%)	3 (75.0%)		5 (22.7%)	**28 (35.0%)**
Technology requires further development before it can be routinely applied	4 (12.1%)	0 (0.0%)	2 (33.3%)	1 (7.7%)	0 (0.0%)		1 (4.5%)	**8 (10.0%)**
Reasonable ease of implementation	16 (48.5%)	2 (100.0%)	3 (50.0%)	6 (46.2%)	4 (100.0%)		2 (9.1%)	**33 (41.3%)**
Reasonable ease of use	18 (54.5%)	2 (100.0%)	3 (50.0%)	9 (69.2%)	4 (100.0%)		1 (4.5%)	**37 (46.3%)**
Reasonable ease of design	19 (57.6%)	2 (100.0%)	2 (33.3%)	8 (61.5%)	4 (100.0%)		2 (9.1%)	**37 (46.3%)**
Adequate number of trained vendors to implement technology	10 (30.3%)	2 (100.0%)	0 (0.0%)	4 (30.8%)	3 (75.0%)		0 (0.0%)	**19 (23.8%)**
Other factors that might affect technology usefulness	2 (6.1%)	1 (50.0%)	1 (16.7%)	5 (38.5%)	0 (0.0%)		0 (0.0%)	**9 (11.3%)**
TOTAL RESPONDENTS PER CATEGORY	**33**	**2**	**6**	**13**	**4**	**0**	**22**	**80**

Notes
Blank spaces indicate no sites were impacted by the corresponding criteria.

TABLE D.6: SUMMARY OF TECHNOLOGY PERFORMANCE CRITERIA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY
Navy ROCS

TECHNOLOGY		ROLE IN ENVIRONMENTAL COMMUNITY	Able to achieve treatment goals at a reasonable cost	Technology is limited to certain site conditions[b]	Technology requires further development before it can be routinely applied	Reasonable ease of implementation	Reasonable ease of use	Reasonable ease of design	Adequate number of trained vendors to implement technology	Other factors that might affect technology usefulness[d,e]	TOTAL SITES WITH TECHNOLOGY DATA
BIOREMEDIATION		Consultant	6	2	3	5	6	7	3		**17**
		DOD RPM[a]	3	3		3	3	1	3		
		Regulator									
		Site Owner									
		Vendor	1		1	1	1				
		Published Case Studies	2			1	1	1			
		Total	**12 (70.6%)**	**5 (29.4%)**	**4 (23.5%)**	**10 (58.8%)**	**11 (64.7%)**	**9 (52.9%)**	**6 (35.3%)**	**0 (0.0%)**	
CHEMICAL OXIDATION	**Fenton's Reagent[c]**	Consultant		1					1		**9**
		DOD RPM[a]	1				1	1			
		Regulator									
		Site Owner									
		Vendor	4	1		1	1	1			
		Published Case Studies	3								
		Total	**8 (88.9%)**	**2 (22.2%)**	**0 (0.0%)**	**1 (11.1%)**	**2 (22.2%)**	**2 (22.2%)**	**1 (11.1%)**	**0 (0.0%)**	
	Permanganate	Consultant	4	5		7	7	7	4		**13**
		DOD RPM[a]	1		1	1	1	1			
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies	2	1							
		Total	**7 (53.8%)**	**6 (46.2%)**	**1 (7.7%)**	**8 (61.5%)**	**8 (61.5%)**	**8 (61.5%)**	**4 (30.8%)**	**0 (0.0%)**	
	Ozone	Consultant									**0**
		DOD RPM[a]									
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies									
		Total	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	
CO-SOLVENT FLUSHING		Consultant									**0**
		DOD RPM[a]									
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies									
		Total	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	
DUAL-PHASE EXTRACTION	**Water/Air**	Consultant									**6**
		DOD RPM[a]		1		1	1	1	1	1	
		Regulator									
		Site Owner		1		2	2	2	2		
		Vendor									
		Published Case Studies	1								
		Total	**1 (16.7%)**	**2 (33.3%)**	**0 (0.0%)**	**3 (50.0%)**	**3 (50.0%)**	**3 (50.0%)**	**3 (50.0%)**	**1 (16.7%)**	
	Water/DNAPL	Consultant									**3**
		DOD RPM[a]									
		Regulator	1			1	1	1	1	1	
		Site Owner		1		1	1	1	1		
		Vendor									
		Published Case Studies									
		Total	**1 (33.3%)**	**1 (33.3%)**	**0 (0.0%)**	**2 (66.7%)**	**2 (66.7%)**	**2 (66.7%)**	**2 (66.7%)**	**1 (33.3%)**	
	DNAPL/Air	Consultant									**1**
		DOD RPM[a]		1							
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies									
		Total	**0 (0.0%)**	**1 (100.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	
EXCAVATION		Consultant	2	2		1	1	1	1		**5**
		DOD RPM[a]									
		Regulator	1	1		1	1	1	1		
		Site Owner				1					
		Vendor									
		Published Case Studies									
		Total	**3 (60.0%)**	**3 (60.0%)**	**0 (0.0%)**	**3 (60.0%)**	**2 (40.0%)**	**2 (40.0%)**	**2 (40.0%)**	**0 (0.0%)**	

TABLE D.6: SUMMARY OF TECHNOLOGY PERFORMANCE CRITERIA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY
Navy ROCS

TECHNOLOGY		ROLE IN ENVIRONMENTAL COMMUNITY	Able to achieve treatment goals at a reasonable cost	Technology is limited to certain site conditions[b]	Technology requires further development before it can be routinely applied	Reasonable ease of implementation	Reasonable ease of use	Reasonable ease of design	Adequate number of trained vendors to implement technology	Other factors that might affect technology usefulness[d,e]	TOTAL SITES WITH TECHNOLOGY DATA
OTHER	Undefined	Consultant									1
		DOD RPM[a]									
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies									
		Total	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	
	Pump and Treat	Consultant									1
		DOD RPM[a]				1	1			1	
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies									
		Total	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**1 (100.0%)**	**1 (100.0%)**	**0 (0.0%)**	**0 (0.0%)**	**1 (100.0%)**	
SURFACTANT FLUSHING		Consultant									2
		DOD RPM[a]									
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies	1	1							
		Total	**1 (50.0%)**	**1 (50.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	
THERMAL	Conductive Heating	Consultant									1
		DOD RPM[a]	1				1	1		1	
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies									
		Total	**1 (100.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**1 (100.0%)**	**1 (100.0%)**	**0 (0.0%)**	**1 (100.0%)**	
	Low-Temp Six-Phase	Consultant	1	1		1	1	1		1	1
		DOD RPM[a]									
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies									
		Total	**1 (100.0%)**	**1 (100.0%)**	**0 (0.0%)**	**1 (100.0%)**	**1 (100.0%)**	**1 (100.0%)**	**0 (0.0%)**	**1 (100.0%)**	
	Resistive Heating	Consultant									1
		DOD RPM[a]									
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies	1	1							
		Total	**1 (100.0%)**	**1 (100.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	
	Six-Phase Heating	Consultant	1	1		1	1	1		1	9
		DOD RPM[a]	1	1						1	
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies	4	2	1						
		Total	**6 (66.7%)**	**4 (44.4%)**	**1 (11.1%)**	**1 (11.1%)**	**1 (11.1%)**	**1 (11.1%)**	**0 (0.0%)**	**2 (22.2%)**	
	Three-Phase Heating	Consultant	1								3
		DOD RPM[a]						1		1	
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies									
		Total	**1 (33.3%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**0 (0.0%)**	**1 (33.3%)**	**0 (0.0%)**	**1 (33.3%)**	
	Steam Flushing	Consultant	2			1	1	1	1	1	5
		DOD RPM[a]									
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies	2			1		1			
		Total	**4 (80.0%)**	**0 (0.0%)**	**0 (0.0%)**	**2 (40.0%)**	**1 (20.0%)**	**2 (40.0%)**	**1 (20.0%)**	**1 (20.0%)**	

TABLE D.6: SUMMARY OF TECHNOLOGY PERFORMANCE CRITERIA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY
Navy ROCS

TECHNOLOGY		ROLE IN ENVIRONMENTAL COMMUNITY	Able to achieve treatment goals at a reasonable cost	Technology is limited to certain site conditions[b]	Technology requires further development before it can be routinely applied	Reasonable ease of implementation	Reasonable ease of use	Reasonable ease of design	Adequate number of trained vendors to implement technology	Other factors that might affect technology usefulness[d,e]	TOTAL SITES WITH TECHNOLOGY DATA
ZERO-VALENT IRON	Emulsified	Consultant			1		1	1		1	1
		DOD RPM[a]									
		Regulator									
		Site Owner									
		Vendor									
		Published Case Studies									
		Total	**0 (0.0%)**	**0 (0.0%)**	**1 (100.0%)**	**0 (0.0%)**	**1 (100.0%)**	**1 (100.0%)**	**0 (0.0%)**	**1 (100.0%)**	
	With Clay	Consultant									1
		DOD RPM[a]									
		Regulator									
		Site Owner	1	1		1	1	1		1	
		Vendor									
		Published Case Studies									
		Total	**1 (100.0%)**	**1 (100.0%)**	**0 (0.0%)**	**1 (100.0%)**	**1 (100.0%)**	**1 (100.0%)**	**0 (0.0%)**	**1 (100.0%)**	
	ZVI only	Consultant									2
		DOD RPM[a]									
		Regulator									
		Site Owner	1	1		1	1	1			
		Vendor	1		1	1	1	1		1	
		Published Case Studies									
		Total	**2 (100.0%)**	**1 (50.0%)**	**1 (50.0%)**	**2 (100.0%)**	**2 (100.0%)**	**2 (100.0%)**	**0 (0.0%)**	**1 (50.0%)**	

Notes

[a] DOD RPM refers to Department of Defense remedial project manager.

[b] Specified site conditions for which technology may be limited included the following:

Bioremediation: "Technology is limited by low permeability of till material that is the source area. We are hoping it will prove effective in the overlying fill aquifer."

"Presence of DHE organisms or bioaugmentation required."

"The effectiveness of In-Situ Reactive Zone (IRZ) technology using soluble carbohydrates on pooled DNAPL has not been proven, although it has been shown to be applicable to sorbed or residual DNAPL. Optimal ranges for site characteristics are discussed in "Technical Protocol for Using Soluble Carbohydrates to Enhance Reductive Dechlorination of Chlorinated"

"primarily limited to source areas where the appropriate redox conditions can be promoted"

Chemical oxidation, Fenton's reagent: "high carbonate content causes more vigorous reaction and higher reagent consumption"

"permeabilities < 1 x 10-6 cm/sec"

Chemical oxidation, permanganate: "Highly sensitive to ability to deliver reagent to subsurface and achieve good mixing"

"In situ chemical oxidation using permanganate is more effective for remediation of dissolved contaminant and residual DNAPL. The remediation of pooled DNAPL has also been achieved in test facilited with technology we recently developed to treat the Mn oxide precipitates."

"ability to deliver oxidant"

"The distribution of the DNAPL within the site geology plays a key role in the application of this technology. In addition, permanganate is only applicable to some types of DNAPL

"primarily limited to smaller source areas where DNAPL is present at residual non-wetting phase saturation; readily applied in more permeable geology; fractured environments

DNAPL/air dual-phase extraction: "site soils could not be dewatered adequately to get air into soil"

Water/air dual-phase extraction: "Vacuum-enhanced recovery (VER) is applicable to sites with generally low transmissivity (<500 gpd/ft), permeability of 1e-3 to 1e-6, and no potential for short-circuiting. Extreme heterogeneity requires careful engineering design."

Water/DNAPL dual-phase extraction: "20 dollar/gal cost of NAPL pumping with incineration on site is profoundly cheaper than the average ground water pump and treat cost of 50000 dollar/gal . Risk reduction is many orders of magnitude better as well."

Excavation: "Limestone made hand digging difficult"

"shallow overburdenplume only. less practical with depth"

Surfactant flushing: "permeability contrasts lead to difficulty in surfactant distribution"

Low-temp six-phase heating: "Applicable only when DNAPL is found pooled."

Resistive heating: "electrical conductivity of soil"

Six-phase heating: "Low heat 6 phase was tried (max of 70 degrees C) because of the close proximity of underground utilities. May have to try chemical oxidation or some other technology at the pilot study site."

"soil conductivity"

"High treatment costs per unit volume. Justified when difficult geology and/or restricted timelines are encountered. DNAPL in narrow "chimney" configuration at depths beyond 50 feet may present significant application and cost challenges."

Zero-valent iron: "Unconsolidated materials accessible to soil mixing equipment or jet grouting equipment."

[c] One duplicate site is included in the Fenton's reagent data, where a vendor and DOD RPM both entered data. The only differences between their replies to this question were the vendor did not select "ease of use" or "ease of design" as applying to this technology.

[d] Specified "other" factors that may impact technology usefulness included the following:

Chemical oxidation, permanganate: "Precipitation of oxidation by-product Mn oxide can cause pore plugging and reduction of permeability. Technology in treating the Mn oxide precipitates has been developed."

Low-temp six-phase heating: "Limited to depths that can economically be serviced by hand bailing"

Pump and treat: "containment, compatibility with adjacent PRPs' systems"

Six-phase heating: "Technology is expensive"

"shortage of qualified vendors"

Three-phase heating: "Cost is significant"

Steam flushing: "Testing in fractures has been inconclusive at other sites."

Emulsified nano-scale ZVI: "further work needs to be conducted on refining the injection of the EZVI into the treatment zone"

Zero-valent iron: "Chlorinated compounds amenable to treatment with ZVI"

"Construction contractor must know how to undertake soil mixing adequately."

[e] Other comments not specific to impact on technology usefulness included the following:

Water/air dual-phase extraction: "VER has been used successfully at low-permeability sites that are not amenable to conventional P&T/vapor extraction techniques. To overcome air and groundwater flow restrictions of low-permeability formations, high vacuums are created at a well by liquid-ring or other specialty pumps. The high vacuum creates a much greater driving force for airflow in the unsaturated zone. Combined with gravity, this increases the rate of groundwater and/or NAPL recovery, and the size of the capture zone. In addition, in highly adsorptive silt and clay formations, subsurface oxygen levels are increased, enhancing naturally-occurring biodegradation.

Water/DNAPL dual-phase extraction: "It is currently used at over 40000 sites. It is the first step of Triple Train. It is the cheapest removal unit operation of the three in Triple Train (20 dollar/gal). It only works with the NAPL saturations above residual. Second unit operation of Tri [comment was too long and remainder is missing]

Conductive heating: "Even an area where treatment temperatures never exceeded 212 F was treated. This suggests that the remedial goals could have been achieved at lower cost."

TABLE D.8: SUMMARY OF EXTERNAL FACTORS IMPACTING REMEDIAL EFFECTIVENESS / TECHNOLOGY CHOICE DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOG
Navy ROCS

EXTERNAL FACTORS THAT IMPACTED REMEDIAL CHOICE / EFFECTIVENESS	NUMBER OF SITES THAT COULD BE DESCRIBED BY EXTERNAL FACTORS PER TECHNOLOGY																				UNSPECIFIED TECHNOLOGY	TOTAL WITH TECHNOLOGY SPECIFIED
	BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON				
		Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only		
Facility operations constrained site access	11 (44.0%)		5 (33.3%)				1 (20.0%)	2 (66.7%)	3 (27.3%)	1 (16.7%)							1 (20.0%)	1 (12.5%)			2 (50.0%)		**27 (22.9%)**
Presence of surface infrastructure impacted ability to estimate DNAPL mass or effectively conduct remediatio	9 (36.0%)	2 (22.2%)	5 (33.3%)	1 (100.0%)			1 (20.0%)	1 (33.3%)	2 (18.2%)							1 (10.0%)	1 (20.0%)	1 (12.5%)	1 (100.0%)	1 (100.0%)	2 (50.0%)		**28 (23.7%)**
Proximity to surface water impacted technology choice, design or effectiveness	9 (36.0%)		3 (20.0%)				1 (20.0%)	2 (66.7%)	6 (54.5%)	3 (50.0%)		1 (25.0%)			1 (50.0%)	2 (20.0%)	3 (60.0%)	2 (25.0%)				2 (40.0%)	**35 (29.7%)**
Regulatory pressures impacted clean-up criteria/time-frame	7 (28.0%)		5 (33.3%)	1 (100.0%)		1 (20.0%)	1 (20.0%)		9 (81.8%)	3 (50.0%)	1 (100.0%)			1 (100.0%)	1 (50.0%)	2 (20.0%)	2 (40.0%)	4 (50.0%)					**37 (31.4%)**
Budget / remediation cost	17 (68.0%)	5 (55.6%)	9 (60.0%)	1 (100.0%)		3 (60.0%)	4 (80.0%)	1 (33.3%)	8 (72.7%)	3 (50.0%)		1 (25.0%)	1 (100.0%)		2 (100.0%)	7 (70.0%)	2 (40.0%)	5 (62.5%)	1 (100.0%)		1 (25.0%)	1 (20.0%)	**72 (61.0%)**
TOTAL SITES WITH DATA	**25**	**9**	**15**	**1**	**0**	**5**	**5**	**3**	**11**	**6**	**1**	**4**	**1**	**1**	**2**	**10**	**5**	**8**	**1**	**1**	**4**	**5**	**118**

Notes
Blank spaces indicate no survey respondent selected the corresponding factors for that technology applicatio

TABLE D.10: SUMMARY OF SOURCE MASS REMOVAL SORTED BY TECHNOLOGY

Navy ROCS

Source mass removal	Site_ID	Technology	Mass Flux Decrease	Rebound	Perceived Success	Lithology	DNAPL Distribution					Stage	Post Treatment Monitoring
							Dead-end fractures	Diffused Into Low K Layers	In pools	Residual	Sorbed		
100%	248	Chemical Oxidation-Permanganate	81-100%	No	Success	Sand				X		Pilot test completed	
	218	Thermal-Six phase heating	81-100%	Unknown	Not yet evaluated	Sand						Full-scale completed	On going
	144	Thermal- Conductive Heating	Unknown	No	Success	Clay				X		Full-scale completed	
	46	Excavation	Unknown	Unknown	Success	Sand				X		Pilot test completed	
>90%	235	Surfactant Flushing	81-100%	Unknown	Fair Success	Clay				X		Pilot test completed	
	250	Chemical Oxidation-Permanganate	81-100%	Yes	Success	Sand				X	X	Pilot test completed	
	197	Bioremediation	61-80%	No	Success	Sand						Pilot test completed	On-going
	100	Excavation	Unknown	No	Success	Silt		X	X	X	X	Full-scale completed	On-going
	245	Chemical Oxidation-Fenton's Reagent	Unknown	No	Success	Clay		X		X	X	Full-scale completed	On-going
	153	Thermal-Steam	Unknown	No	Success	Clay		X				Full-scale completed	On-going
	117	Chemical Oxidation-Fenton's Reagent	Unknown	No	Success	Sand						Full-scale completed	On-going
>80 <90%	155	Excavation	61-80%	Yes	Success	Sand		X		X	X	Full-scale completed	On-going
	45	Chemical Oxidation-Fenton's Reagent	Unknown	No	Fair Success	Silt				X		Pilot test completed	
	186	Chemical Oxidation-Fenton's Reagent	Unknown	Unknown	Success	Silt						Full-scale completed	
>50 <80%	237	Thermal-Steam	81-100%	Unknown	Fair Success	Sand				X		Pilot test completed	
	249	Chemical Oxidation-Permanganate	Unknown	Yes	Fair Success	Sand			X	X	X	Pilot test completed	
>25<50	181	Chemical Oxidation-Permanganate	61-80%	Yes	Fair Success	Sand			X	X	X	Pilot test completed	
	253	ZVI - EZVI/nano-scale iron	41-60%	No	Fair Success	Sand			X	X		Pilot test completed	
>10<25	241	Thermal - Low temp-six phase heating	Unknown	Yes	Success	Silt			X	X	X	Pilot test completed	
<10	244	Dual Phase-DNAPL/air extraction	Unknown	Unknown	Poor Success	Silt		X	X	X	X	Pilot test completed	On going

TABLE D.12: SUMMARY OF MASS FLUX DECREASE SORTED BY TECHNOLOGY
Navy ROCS

Mass Flux Decrease	Technology	Source Mass Removal	Rebound	Perceived Success	Lithology	DNAPL Distribution					Stage	Post Treatment Monitoring
						Dead-end Fractures	Diffused Into Low K Llayers	In pools	Residual	Sorbed		
81-100%	Chemical Oxidation-Permanganate	100%	No	Success	Sand				X		Pilot test completed	
	Thermal-Six phase heating	100%	Unknown	Not yet evaluated	Sand						Full-scale completed	On going
	Surfactant Flushing	>90%	Unknown	Fair Success	Clay				X		Pilot test completed	
	Chemical Oxidation-Permanganate	>90%	Yes	Success	Sand				X	X	Pilot test completed	
	Thermal-Steam	>50 <80%	Unknown	Fair Success	Sand				X		Pilot test completed	
	Thermal-Six phase heating	Unknown	No	Success	Clay						Pilot test completed	
	Chemical Oxidation-Fenton's Reagent	Unknown	Unknown	Fair Success	Unknown						Pilot test completed	
	Bioremediation	Unknown	Unknown	Fair Success	Unknown						Pilot test completed	
	Bioremediation	Unknown	Unknown	Fair Success	Sand						Pilot test completed	
	Chemical Oxidation-Fenton's Reagent	Unknown	Unknown	Not yet evaluated	Gravel						Pilot test completed	
	Thermal-Six phase heating	Unknown	Unknown	Success	Unknown						Pilot test completed	
	Thermal-Six phase heating	Unknown	Unknown	Not yet evaluated	Till						Pilot test completed	
	Thermal-Six phase heating	Unknown	Unknown	Success	Clay				X		Pilot test completed	
61-80%	Bioremediation	>90%	No	Success	Sand						Pilot test completed	On going
	Excavation	>80 <90%	Yes	Success	Sand		X		X	X	Full-scale completed	On going
	Chemical Oxidation-Permanganate	>25 <50%	Yes	Fair Success	Sand			X	X	X	Pilot test completed	
	Bioremediation	Unknown	No	Success	Clay						Full-scale completed	On going
	Surfactant Flushing	Unknown	Unknown	Fair Success	Silt			X			Pilot test completed	
41-60%	ZVI - EZVI/nano-scale iron	>25 <50%	No	Fair Success	Sand			X	X		Pilot test completed	
0%	Chemical Oxidation-Permanganate	Unknown	Unknown	Not yet evaluated	Metamorphic						Pilot test completed	
	Excavation	Unknown	Unknown	Fair Success	Limestone	X	X		X	X	Full-scale completed	On going

TABLE D.14: SUMMARY OF REBOUND SORTED BY TECHNOLOGY
Navy ROCS

						DNAPL Distribution						
Rebound	**Technology**	**Source Mass Removal**	**Mass Flux Decrease**	**Perceived Success**	**Lithology**	**Dead-end fractures**	**Diffused into Low K Layers**	**In pools**	**Residual**	**Sorbed**	**Stage**	**Post Treatment Monitoring**
Yes	Chemical Oxidation-Permanganate	>90%	81-100%	Success	Sand				X	X	Pilot test completed	
	Chemical Oxidation-Permanganate	Unknown	Unknown	Success	Shale	X	X	X	X	X	Pilot test completed	
	Excavation	>80 <90%	61-80%	Success	Sand		X		X	X	Full-scale completed	On going
	Chemical Oxidation-Permanganate	>50 <80%	Unknown	Fair Success	Sand			X	X	X	Pilot test completed	
	Chemical Oxidation-Permanganate	>25 <50%	61-80%	Fair Success	Sand			X	X	X	Pilot test completed	
	Thermal - Low temp-six phase heating	>10 <25%	Unknown	Success	Silt			X	X	X	Pilot test completed	
	Chemical Oxidation-Permanganate	Unknown	Unknown	Fair Success	Gravel						Pilot test completed	
No	Chemical Oxidation-Permanganate	100%	81-100%	Success	Sand				X		Pilot test completed	
	Other - Conductive Heating	100%	Unknown	Success	Clay				X		Full-scale completed	
	Bioremediation	>90%	61-80%	Success	Sand						Pilot test completed	On going
	Excavation	>90%	Unknown	Success	Silt		X	X	X	X	Full-scale completed	On going
	Chemical Oxidation-Fenton's Reagent	>90%	Unknown	Success	Clay		X		X	X	Full-scale completed	On going
	Thermal-Steam	>90%	Unknown	Success	Clay		X				Full-scale completed	On going
	Chemical Oxidation-Fenton's Reagent	>90%	Unknown	Success	Sand						Full-scale completed	On going
	Chemical Oxidation-Fenton's Reagent	>80 <90%	Unknown	Fair Success	Silt				X		Pilot test completed	
	ZVI - EZVI/nano-scale iron	>25 <50%	41-60%	Fair Success	Sand			X	X		Pilot test completed	
	Thermal-Six phase heating	Unknown	81-100%	Success	Clay						Pilot test completed	
	Bioremediation	Unknown	61-80%	Success	Clay						Full-scale completed	On going
	Bioremediation	Unknown	Unknown	Success	Sand		X	X	X	X	Pilot test completed	On going
	Chemical Oxidation-Fenton's Reagent	Unknown	Unknown	Success	Gravel						Pilot test completed	
	ZVI -Zero-valent iron	Unknown	Unknown	Success	Sand				X	X	Pilot test completed	

TABLE D.16: SUMMARY OF IMPACTS TO SECONDARY GROUNDWATER QUALITY DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY

Navy ROCS

IMPACTS TO SECONDARY GROUNDWATER QUALITY	NUMBER OF SITES THAT COULD BE DESCRIBED BY SECONDARY GROUNDWATER QUALITY PARAMETER PER TECHNOLOGY																				TOTAL
	BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			
		Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only	
Methane generation	7 (63.6%)																		1 (100.0%)			**8 (21.6%)**
Hydrogen sulfide generation	1 (9.1%)																					**1 (2.7%)**
Dissolved iron generation	5 (45.5%)					1 (33.3%)	1 (50.0%)															**7 (18.9%)**
Dissolved manganese generation			5 (55.6%)			1 (33.3%)	1 (50.0%)															**7 (18.9%)**
Elevated concentration of other metals[c]		1 (100%)	7 (77.8%)																			**8 (21.6%)**
Increased BOD[a]	4 (36.4%)																					**0 (0.0%)**
Change in pH	6 (54.5%)		1 (11.1%)																			**7 (18.9%)**
Reduced soil porosity	2 (18.2%)		1 (11.1%)																1 (100.0%)		2 (100.0%)	**6 (16.2%)**
Change in hydraulic conductivity		1 (100.0%)	1 (11.1%)										1 (100.0%)								2 (100.0%)	**5 (13.5%)**
Change in groundwater color			7 (77.8%)				1 (50.0%)															**8 (21.6%)**
Increased dissolved solids	2 (18.2%)		1 (11.1%)																			**3 (8.1%)**
Redistribution of DNAPL		1 (100.0%)	1 (11.1%)				1 (50.0%)		1 (50.0%)													**4 (10.8%)**
Increase in source area volume																						**0 (0.0%)**
Decrease in source area volume	2 (18.2%)		1 (11.1%)			2 (66.7%)	1 (50.0%)	1 (100.0%)	2 (100.0%)								1 (100.0%)	1 (100.0%)			1 (50.0%)	**12 (32.4%)**
Other[b]	1 (9.1%)		2 (22.2%)				1 (50%)							1 (100%)		1 (100%)			1 (100%)			**7 (18.9%)**
TOTAL SITES WITH DATA	**11**	**1**	**9**	**0**	**0**	**3**	**2**	**1**	**2**	**0**	**0**	**0**	**1**	**1**	**0**	**1**	**1**	**1**	**1**	**0**	**2**	**37**

Notes

Blank spaces indicate no sites were impacted by the corresponding criteria.

[a] Biochemical oxygen demand (BOD).

[b] Specified "other" responses included the following:
- Bioremediation - One survey respondent specified the following other change: "increase in Dehalococcoides ethenogenes".
- Chemical oxidation using permanganate - Responses included increases in oxidation-reduction potential (ORP) and temporary impact to color.
- Dual-phase extraction of water and DNAPL - Response included "More contaminant mass has been removed from this one site by NAPL pumping than by ground water pump and treat at all other sites on the planet for all years combined".
- Low temp six-phase heating - Response included "[no impact]: effort was implemented on an opportunistic basis, and was discontinued in order to focus efforts on a larger application of a different technology."
- Six-phase heating - Response included "drop in groundwater concentrations of DNAPL components."
- Emulsified nano-scale ZVI - Response included "porosity reduction assumed to be temporary."

[c] Specified elevated concentrations in metals included the following:
- Chemical oxidation using Fenton's Reagent - One survey respondent specified an increase in hexavalent chromium.
- Chemical oxidation using permanganate - Responses included chloride (4 sites), potassium permanganate (3), and transient increases of some metals (unspecified, 1 site).

TABLE D.18: SUMMARY OF GEOLOGY DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY
Navy ROCS

GEOLOGY PARAMETERS				NUMBER OF SITES THAT COULD BE DESCRIBED BY GEOLOGY PARAMETER PER TECHNOLOGY																						TOTAL SITES WITH TECHNOLOGY SPECIFIED
				BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			UNSPECIFIED TECHNOLOGY	
					Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only		
Consolidated Media	Degree of Fracturing	Discretely fractured	1 to 20%[a]	2		1			2		2	1								1				1	4	10
			21 to 40%	1						1		1														3
			41 to 60%	1			1					1														3
			61 to 80%	1		1					1				1					1	1					6
			81 to 100%	1									1												1	2
			Total	**6**	**0**	**2**	**1**	**0**	**2**	**1**	**3**	**3**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**2**	**1**	**0**	**0**	**1**	**5**	**24**
		Highly fractured	1 to 20%	1		2					2	1								1					3	7
			21 to 40%							1		1														2
			41 to 60%			1																				1
			61 to 80%	1			1					1													1	3
			81 to 100%	1		1				1			2								2					7
			Total	**3**	**0**	**4**	**1**	**0**	**0**	**2**	**2**	**3**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**2**	**0**	**0**	**0**	**4**	**20**
		Unfractured	1 to 20%	2			1			1	1	2			1					1	1					10
			21 to 40%						1																	1
			41 to 60%																							0
			61 to 80%																						2	0
			81 to 100%	2	2	1				1	1	3									1				7	11
			Total	**4**	**2**	**1**	**1**	**0**	**1**	**2**	**2**	**5**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**2**	**0**	**0**	**0**	**9**	**22**
		TOTAL		**13**	**2**	**7**	**3**	**0**	**3**	**5**	**7**	**11**	**3**	**0**	**2**	**0**	**0**	**0**	**0**	**4**	**5**	**0**	**0**	**1**	**18**	**66**
	Matrix Permeability	Low	1 to 20%	1					1		1									1	1					5
			21 to 40%	1			1			1		2														5
			41 to 60%	1		1					1	1			1										2	5
			61 to 80%	1	1	1			1				1												2	5
			81 to 100%	1		1			1	2								1			2				1	8
			Total	**5**	**1**	**3**	**1**	**0**	**3**	**3**	**2**	**3**	**1**	**0**	**1**	**0**	**0**	**1**	**0**	**1**	**3**	**0**	**0**	**0**	**5**	**28**
		High	1 to 20%							1			1												4	2
			21 to 40%																						2	0
			41 to 60%			1				1	1	2			1											6
			61 to 80%	1			1					1	1												2	4
			81 to 100%	4	1						1	1	1		1					1	2			1	3	13
			Total	**5**	**1**	**1**	**1**	**0**	**0**	**2**	**2**	**4**	**3**	**0**	**2**	**0**	**0**	**0**	**0**	**1**	**2**	**0**	**0**	**1**	**11**	**25**
		Unknown	1 to 20%																							0
			21 to 40%																							0
			41 to 60%																							0
			61 to 80%																							0
			81 to 100%	2								2													2	4
			Total	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**4**
		TOTAL		**12**	**2**	**4**	**2**	**0**	**3**	**5**	**4**	**9**	**4**	**0**	**3**	**0**	**0**	**1**	**0**	**2**	**5**	**0**	**0**	**1**	**18**	**57**
Unconsolidated Media	Heterogeneity	Low	1 to 20%	1		2				1	1	2	1		1			1			1				5	11
			21 to 40%	1	1																				3	2
			41 to 60%	4		1	1					2								1	1	1			3	11
			61 to 80%	2							1				1					1	3				3	8
			81 to 100%	4	1	5										1					1			3	4	15
			Total	**12**	**2**	**8**	**1**	**0**	**0**	**1**	**2**	**4**	**1**	**0**	**2**	**1**	**0**	**1**	**0**	**2**	**6**	**1**	**0**	**3**	**18**	**47**
		High	1 to 20%	2					1		1	1	1	0	1	1				1	1				5	10
			21 to 40%	4	1	1	1			1		2								1	1	1			4	13
			41 to 60%	3		2			1			1							1						1	8
			61 to 80%	2	2					1	1	1	1				1		3	1	1				8	14
			81 to 100%	6	4	2			3	3	1	5	4	1	3			2	6	2	2		1	2	6	47
			Total	**17**	**7**	**5**	**1**	**0**	**5**	**5**	**3**	**10**	**6**	**1**	**4**	**1**	**1**	**2**	**10**	**5**	**5**	**1**	**1**	**2**	**24**	**92**
		Unknown	1 to 20%	1			1			1		2														5
			21 to 40%																							0
			41 to 60%																							0
			61 to 80%																							0
			81 to 100%	3	1	2						2									1					9
			Total	**4**	**1**	**2**	**1**	**0**	**0**	**1**	**0**	**4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**14**
		TOTAL		**33**	**10**	**15**	**3**	**0**	**5**	**7**	**5**	**18**	**7**	**1**	**6**	**2**	**1**	**3**	**10**	**7**	**12**	**2**	**1**	**5**	**42**	**153**

Notes

[a] Ranges represent the portion of the site aquifer that can be described with the related parameter.
Blank spaces denote no data entered for that parameter.

TABLE D.23: SUMMARY OF HYDROGEOLOGY DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY
Navy ROCS

HYDROGEOLOGY PARAMETERS		NUMBER OF SITES THAT COULD BE DESCRIBED BY HYDROGEOLOGY PARAMETER PER TECHNOLOGY																						TOTAL SITES WITH TECHNOLOGY SPECIFIED
		BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			UNSPECIFIED TECHNOLOGY	
			Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only		
Depth to Groundwater	< 10 ft	9	2	5	1		3	4	1	4		1			1		2	3	1	1	1	3	8	42
	10 to 20 ft	7	2	5					1	3	4		1			1	2	1	1				1	28
	20 to 50 ft	5		1			1		1	1	1		1	1				1	2			1	2	16
	50 to 100 ft			1						1									1				2	3
	100 to 200 ft			1													1						1	2
	> 200 ft	1																						1
	Unspecified	3	5	2			1	1		2	1		2			1	5		3				5	26
	TOTAL	**25**	**9**	**15**	**1**	**0**	**5**	**5**	**3**	**11**	**6**	**1**	**4**	**1**	**1**	**2**	**10**	**5**	**8**	**1**	**1**	**4**	**19**	**118**
Groundwater Velocity	< 0.001 ft/day																		1	1		1		3
	0.001 to 1 ft/day	10	1	5				1	1	2	2		2				1	3	3		1	1	7	33
	> 1 ft/day	4		1				1		3	1					1	1	1	1				1	14
	Unknown	11	8	9	1		5	3	2	6	3	1	2	1	1	1	8	1	3			2	11	68
	TOTAL	**25**	**9**	**15**	**1**	**0**	**5**	**5**	**3**	**11**	**6**	**1**	**4**	**1**	**1**	**2**	**10**	**5**	**8**	**1**	**1**	**4**	**19**	**118**
Hydraulic Conductivity	< 10^{-5} ft/day	1								1	2			1			1		1			1		8
	10^{-5} to 10 ft/day	9	3	7			1	2	2	3	2	1	2			1		3	2		1	1	9	40
	> 10 ft/day	7		3					1	2			1			1	1	2	2	1			2	21
	Unknown	8	6	5	1		4	3		5	2		1		1		8		3			2	8	49
	TOTAL	**25**	**9**	**15**	**1**	**0**	**5**	**5**	**3**	**11**	**6**	**1**	**4**	**1**	**1**	**2**	**10**	**5**	**8**	**1**	**1**	**4**	**19**	**118**
Horizontal Hydraulic Gradient	< 0.0001	2																				1	1	3
	0.0001 to 0.001	2						1	1	1	1		1					2	1	1			4	11
	0.001 to 0.01	4	1	2						1	2	1				1	1	2	3		1	1	2	20
	0.01 to 0.1	5		3				1		2	1		1						1				1	14
	0.1 to 1			2						1														3
	Unknown	12	8	8	1		5	3	2	6	2		2	1	1	1	9	1	3			2	11	67
	TOTAL	**25**	**9**	**15**	**1**	**0**	**5**	**5**	**3**	**11**	**6**	**1**	**4**	**1**	**1**	**2**	**10**	**5**	**8**	**1**	**1**	**4**	**19**	**118**
Vertical Hydraulic Gradient	< 0.0001	2		1						2									1			1		7
	0.0001 to 0.001	3							1	3	2		1			1	1	3	3				1	18
	0.001 to 0.01																							0
	0.01 to 0.1		1																				1	1
	0.1 to 1																							0
	Unknown	20	8	14	1		5	5	2	6	4	1	3	1	1	1	9	2	4	1	1	3	17	92
	TOTAL	**25**	**9**	**15**	**1**	**0**	**5**	**5**	**3**	**11**	**6**	**1**	**4**	**1**	**1**	**2**	**10**	**5**	**8**	**1**	**1**	**4**	**19**	**118**
Sustainable Well Yield	< 1 gpm						1	1		1	1													4
	1 to 10 gpm	2	1	3				2		1			1					1	1				3	12
	10 to 100 gpm	1		2			1		1	3	1	1				1	1	2	2			1	2	17
	100 to 1000 gpm	3		1					1	1	1		1					1	1					10
	> 1000 gpm	1																						1
	Unspecified	18	8	9	1		3	2	1	5	3		2	1	1	1	9	1	4	1	1	3	14	74
	TOTAL	**25**	**9**	**15**	**1**	**0**	**5**	**5**	**3**	**11**	**6**	**1**	**4**	**1**	**1**	**2**	**10**	**5**	**8**	**1**	**1**	**4**	**19**	**118**

Notes
Blank spaces denote no data entered for that parameter.

TABLE D.25: SUMMARY OF SUCCESS DATA SORTED BY DNAPL COMPOSITION

Navy ROCS

					DNAPL Composition			
Perceived Success	**Source mass removal**	**Mass Flux Decrease**	**Rebound**	**Technology**	Chloroethenes	Chloroethanes	Chloromethanes	Chlorobenzenes
Success	>90%	61-80%	No	Bioremediation	100%	0%	0%	0%
	Unknown	61-80%	No	Bioremediation	100%	0%	0%	0%
	Unknown	Unknown	No	Bioremediation	100%	0%	0%	0%
	Unknown	Unknown	Unknown	Bioremediation	100%	0%	0%	0%
	Unknown	Unknown	Unknown	Bioremediation	100%	0%	0%	0%
	Unknown	Unknown	Unknown	Bioremediation	100%	0%	0%	0%
	Unknown	Unknown	Unknown	Bioremediation	100%	0%	0%	0%
	>90%	Unknown	No	Chemical Oxidation-Fenton's Reagent	>90 - <100%	0%	>0 - 10%	0%
	>90%	Unknown	No	Chemical Oxidation-Fenton's Reagent	100%	0%	0%	0%
	>80 <90%	Unknown	Unknown	Chemical Oxidation-Fenton's Reagent	0%	100%	0%	0%
	Unknown	Unknown	No	Chemical Oxidation-Fenton's Reagent	>20 - 30%	>70 - 80%	0%	0%
	Unknown	Unknown	Unknown	Chemical Oxidation-Fenton's Reagent	100%	0%	0%	0%
	100%	81-100%	No	Chemical Oxidation-Permanganate	100%	0%	0%	0%
	>90%	81-100%	Yes	Chemical Oxidation-Permanganate				
	Unknown	Unknown	Unknown	Dual Phase-Water/air extraction	>80 -90%	>10 - 20%	0%	0%
	100%	Unknown	Unknown	Excavation	100%	0%	0%	0%
	>90%	Unknown	No	Excavation	>70 - 80%	>0 - 10%	0%	>0 - 10%
	>80 <90%	61-80%	Yes	Excavation	100%	0%	0%	0%
	100%	Unknown	No	Other - Conductive Heating				
	>10 <25%	Unknown	Yes	Other - Low temp-six phase heating	>10 - 20%	>70 - 80%	0%	0%
	Unknown	81-100%	No	Thermal-Six phase heating	>70 - 80%	>20 - 30%	0%	0%
	Unknown	81-100%	Unknown	Thermal-Six phase heating				
	Unknown	81-100%	Unknown	Thermal-Six phase heating	100%	0%	0%	0%
	Unknown	Unknown	Unknown	Thermal-Six phase heating	>10 - 20%	>70 - 80%	0%	0%
	>90%	Unknown	No	Thermal-Steam	100%	0%	0%	0%
	Unknown	Unknown	No	ZVI/nano-scale iron-Zero-valent iron	100%	0%	0%	0%
	Unknown	Unknown	Unknown	ZVI/nano-scale iron-Zero-valent iron	100%	0%	0%	0%
Fair Success	Unknown	81-100%	Unknown	Bioremediation	100%	0%	0%	0%
	Unknown	81-100%	Unknown	Bioremediation	100%	0%	0%	0%
	>80 <90%	Unknown	No	Chemical Oxidation-Fenton's Reagent				
	Unknown	81-100%	Unknown	Chemical Oxidation-Fenton's Reagent	>70 - 80%	0%	>20 - 30%	0%
	>50 <80%	Unknown	Yes	Chemical Oxidation-Permanganate				
	>25 <50%	61-80%	Yes	Chemical Oxidation-Permanganate	100%	0%	0%	0%
	Unknown	Unknown	Unknown	Chemical Oxidation-Permanganate	100%	0%	0%	0%
	Unknown	Unknown	Yes	Chemical Oxidation-Permanganate	100%	0%	0%	0%
	Unknown	Unknown	Unknown	Dual Phase-Water/air extraction	100%	0%	0%	0%
	Unknown	0%	Unknown	Excavation	0%	>90 - <100%	0%	0%
	>25 <50%	41-60%	No	Other - EZVI/nano-scale iron	100%	0%	0%	0%
	>90%	81-100%	Unknown	Surfactant Flushing	100%	0%	0%	0%
	Unknown	61-80%	Unknown	Surfactant Flushing	100%	0%	0%	0%
	Unknown	Unknown	Unknown	Thermal-Resistive heating	100%	0%	0%	0%
	>50 <80%	81-100%	Unknown	Thermal-Steam	100%	0%	0%	0%
Poor Success	<10%	Unknown	Unknown	Dual Phase-DNAPL/air extraction				
Not yet evaluated	Unknown	81-100%	Unknown	Chemical Oxidation-Fenton's Reagent	0%	100%	0%	0%
	Unknown	0%	Unknown	Chemical Oxidation-Permanganate				
	Unknown	81-100%	Unknown	Thermal-Six phase heating	>40 - 50%	>40 - 50%	0%	0%
	100%	81-100%	Unknown	Thermal-Six phase heating	100%	0%	0%	0%

TABLE D.26: SUMMARY OF GROUNDWATER GEOCHEMISTRY DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY
Navy ROCS

GEOCHEMISTRY PARAMETERS		NUMBER OF SITES THAT COULD BE DESCRIBED BY GEOCHEMISTRY PARAMETER PER TECHNOLOGY																						TOTAL SITES WITH TECHNOLOGY SPECIFIED
		BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			UNSPECIFIED TECHNOLOGY	
			Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only		
Nitrate	< 1 mg/L	5	1					1		1								1	1	1		1	3	12
	1 to 10 mg/L	3																				1	1	4
	10 to 100 mg/L	3							1	1			1					1	2					9
	100 to 1,000 mg/L	1																						1
	>1,000 mg/L																							0
	Non-detect	1		1																				2
	Unknown	14	11	15	1	0	5	4	3	10	6	1	3	1	1	2	11	3	5	0	1	3	9	100
Nitrite	< 1 mg/L	4	1							1								1	1			1	2	9
	1 to 10 mg/L	1							1				1					1	1					5
	10 to 100 mg/L																							0
	100 to 1,000 mg/L																							0
	>1,000 mg/L																							0
	Non-detect	2		1																			1	3
	Unknown	20	11	15	1	0	5	5	3	11	6	1	3	1	1	2	11	3	6	1	1	4	10	111
Sulfate	< 1 mg/L																							0
	1 to 10 mg/L	5								1												1	2	7
	10 to 100 mg/L	4		1						1									1	1			1	8
	100 to 1,000 mg/L	3						1			1											1	2	6
	>1,000 mg/L	1	1																				1	2
	Non-detect																							0
	Unknown	14	11	15	1	0	5	4	4	10	5	1	4	1	1	2	11	5	7	0	1	3	7	105
Sulfide	< 1 mg/L	1									1											1	1	3
	1 to 10 mg/L	1								1													2	2
	10 to 100 mg/L																							0
	100 to 1,000 mg/L																							0
	>1,000 mg/L																							0
	Non-detect	1		1																				2
	Unknown	24	12	15	1	0	5	5	4	11	5	1	4	1	1	2	11	5	8	1	1	4	10	121
Phosphate	< 1 mg/L	1																				1	1	2
	1 to 10 mg/L																						1	0
	10 to 100 mg/L	2																						2
	100 to 1,000 mg/L																							0
	>1,000 mg/L																							0
	Non-detect																							0
	Unknown	24	12	16	1	0	5	5	4	12	6	1	4	1	1	2	11	5	8	1	1	4	11	124
Calcium	< 1 mg/L																							0
	1 to 10 mg/L			1																				1
	10 to 100 mg/L	2																				1	2	3
	100 to 1,000 mg/L	1	1	1				1		1		1						1	2				2	9
	>1,000 mg/L																							0
	Non-detect																							0
	Unknown	24	11	14	1	0	5	4	4	11	6	0	4	1	1	2	11	4	6	1	1	4	9	115
Magnesium	< 1 mg/L																							0
	1 to 10 mg/L	1																		1		1		3
	10 to 100 mg/L	1		2				1		1		1						1	2				2	9
	100 to 1,000 mg/L		1																				1	1
	>1,000 mg/L																							0
	Non-detect																							0
	Unknown	25	11	14	1	0	5	4	4	11	6	0	4	1	1	2	11	4	6	0	1	4	10	115
Carbonate	< 1 mg/L									1									1				1	2
	1 to 10 mg/L							1																1
	10 to 100 mg/L																					1	2	1
	100 to 1,000 mg/L	2	1																				1	3
	>1,000 mg/L																							0
	Non-detect																							0
	Unknown	25	11	16	1	0	5	4	4	11	6	1	4	1	1	2	11	5	7	1	1	4	9	121
Mercury	< 1 mg/L	1							1	1			1					1	2			1	1	8
	1 to 10 mg/L										1													1
	10 to 100 mg/L																							0
	100 to 1,000 mg/L																							0
	>1,000 mg/L																							0
	Non-detect	1										1												2
	Unknown	25	12	16	1	0	5	5	3	11	5	0	3	1	1	2	11	4	6	1	1	4	12	117

TABLE D.26: SUMMARY OF GROUNDWATER GEOCHEMISTRY DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY
Navy ROCS

GEOCHEMISTRY PARAMETERS		NUMBER OF SITES THAT COULD BE DESCRIBED BY GEOCHEMISTRY PARAMETER PER TECHNOLOGY																						TOTAL SITES WITH TECHNOLOGY SPECIFIED
		BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			UNSPECIFIED TECHNOLOGY	
			Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only		
Arsenic	< 1 mg/L	1	1					1		1		1							1			1	3	7
	1 to 10 mg/L	1							1		1		1					1	1					6
	10 to 100 mg/L																							0
	100 to 1,000 mg/L																							0
	>1,000 mg/L																							0
	Non-detect	1																					1	1
	Unknown	24	11	16	1	0	5	4	3	11	5	0	3	1	1	2	11	4	6	1	1	4	9	114
Hexavalent Chromium	< 1 mg/L	1	1						1	1			1					1	2			1	1	9
	1 to 10 mg/L																							0
	10 to 100 mg/L																							0
	100 to 1,000 mg/L																							0
	>1,000 mg/L																							0
	Non-detect	1		1																				2
	Unknown	25	11	15	1	0	5	5	3	11	6	1	3	1	1	2	11	4	6	1	1	4	12	117
Hydrogen	< 0.1 mg/L	3																				1	2	4
	0.1 to 0.5 mg/L																							0
	0.5 to 1 mg/L																							0
	1 to 1.5 mg/L																							0
	>1.5 mg/L																							0
	Non-detect																							0
	Unknown	24	12	16	1	0	5	5	4	12	6	1	4	1	1	2	11	5	8	1	1	4	11	124
Dissolved Iron	< 1 mg/L	4	1					1		1									1	1		1	1	10
	1 to 10 mg/L	1		1								1										1	1	4
	10 to 100 mg/L	2							1		1		1					1	1				2	7
	100 to 1,000 mg/L	1																						1
	>1,000 mg/L																							0
	Non-detect																							0
	Unknown	19	11	15	1	0	5	4	3	11	5	0	3	1	1	2	11	4	6	0	1	3	9	106
Total Iron	< 1 mg/L	3		1						1									1			1		7
	1 to 10 mg/L	3	1	2				1		1										1			1	9
	10 to 100 mg/L	1							1			1	1					2	2				1	8
	100 to 1,000 mg/L	1																				1		2
	>1,000 mg/L																							0
	Non-detect																							0
	Unknown	19	11	13	1	0	5	4	3	10	6	0	3	1	1	2	11	3	5	0	1	3	11	102
Dissolved Manganese	< 1 mg/L	2		1				1		1		1							1	1		1	3	9
	1 to 10 mg/L	1							1				1					2	2				1	7
	10 to 100 mg/L	1																				1		2
	100 to 1,000 mg/L																							0
	>1,000 mg/L			1																				1
	Non-detect																							0
	Unknown	23	12	14	1	0	5	4	3	11	6	0	3	1	1	2	11	3	5	0	1	3	9	109
Total Manganese	< 1 mg/L	3						1		1		1							1			1	2	8
	1 to 10 mg/L	1		1					1				1					1	1					6
	10 to 100 mg/L	1																				1		2
	100 to 1,000 mg/L																							0
	>1,000 mg/L																							0
	Non-detect																							0
	Unknown	22	12	15	1	0	5	4	3	11	6	0	3	1	1	2	11	4	6	1	1	3	11	112
Fraction Organic Carbon	< 10^{-4} kg/kg									1									1					2
	10^{-4} to 10^{-3} kg/kg																					1	2	1
	10^{-3} to 10^{-2} kg/kg	1	1									1						1	1					5
	10^{-2} to 10^{-1} kg/kg			1																				1
	>10^{-1} kg/kg	1							1				1					1	1					5
	Non-detect																							0
	Unknown	25	11	15	1	0	5	5	3	11	6	0	3	1	1	2	11	3	5	1	1	4	11	114
Biochemical Oxygen Demand (BOD)	< 1 mg/L	1																				1		2
	1 to 10 mg/L	1						1	1				1					1	1					6
	10 to 100 mg/L																						1	0
	100 to 1,000 mg/L																						1	0
	>1,000 mg/L																							0
	Non-detect	1																						1
	Unknown	24	12	16	1	0	5	4	3	12	6	1	3	1	1	2	11	4	7	1	1	4	11	119

TABLE D.26: SUMMARY OF GROUNDWATER GEOCHEMISTRY DATA COLLECTED WITH THE SURVEY SORTED BY TECHNOLOGY
Navy ROCS

GEOCHEMISTRY PARAMETERS		NUMBER OF SITES THAT COULD BE DESCRIBED BY GEOCHEMISTRY PARAMETER PER TECHNOLOGY																						TOTAL SITES WITH TECHNOLOGY SPECIFIED
		BIOREMEDIATION	CHEMICAL OXIDATION			CO-SOLVENT FLUSHING	DUAL-PHASE EXTRACTION			EXCAVATION	OTHER		SURFACTANT FLUSHING	THERMAL						ZERO-VALENT IRON			UNSPECIFIED TECHNOLOGY	
			Fenton's Reagent	Permanganate	Ozone		Water/Air	Water/DNAPL	DNAPL/Air		Undefined	Pump and Treat		Conductive Heating	Low-Temp Six-Phase	Resistive Heating	Six-Phase Heating	Three-Phase Heating	Steam Flushing	Emulsified	With Clay	ZVI only		
Dissolved Organic Carbon (DOC)	< 1 mg/L	1							1				1					1	1	1		1		7
	1 to 10 mg/L	2	1					1															1	4
	10 to 100 mg/L	1																				1	1	2
	100 to 1,000 mg/L	1																						1
	>1,000 mg/L																							0
	Non-detect																							0
	Unknown	22	11	16	1	0	5	4	3	12	6	1	3	1	1	2	11	4	7	0	1	3	11	114
Dissolved Oxygen	< 1 mg/L	3	1	1						1	1							1	2	1		1	1	13
	1 to 5 mg/L	7		1				1		2												1		12
	5 to 10 mg/L	1							1				1					1	1				3	5
	>10 mg/L																							0
	Non-detect																							0
	Unknown	16	11	14	1	0	5	4	3	9	5	1	3	1	1	2	11	3	5	0	1	3	9	99
pH	< 4																							0
	4 to 6	4								1											1	4	4	10
	6 to 7	7	2	2				1	1	1	1		1					2	2			1		21
	7 to 8	2		1				1		1									1	1			3	7
	8 to 9																							0
	> 9	1																						1
	Unknown	13	10	13	1	0	5	3	3	9	5	1	3	1	1	2	11	3	5	0	0	0	6	89
Oxidation-Reduction Potential (ORP)	< -150 mV	4									1											2	1	7
	-150 to -50 mV	4		1														1	1	1		1	1	9
	-50 to 0 mV	1	1							2														4
	0 to 50 mV			1				1															1	2
	>50 mV	3																				1	1	4
	Unknown	15	11	14	1	0	5	4	4	10	5	1	4	1	1	2	11	4	7	0	1	1	9	102
Methane	< 1 mg/L	7	1						1	1			1					1	1	1			1	14
	1 to 10 mg/L	2																						2
	10 to 100 mg/L	1																					1	1
	100 to 200 mg/L																							0
	> 200 mg/L																							0
	Non-detect			1																			1	1
	Unknown	17	11	15	1	0	5	5	3	11	6	1	3	1	1	2	11	4	7	0	1	5	10	110
Ethane	< 1 mg/L	4	1							1														6
	1 to 10 mg/L																						1	0
	10 to 20 mg/L																							0
	20 to 30 mg/L																							0
	30 to 40 mg/L																							0
	> 40 mg/L	1																						1
	Non-detect	3		1																			1	4
	Unknown	19	11	15	1	0	5	5	4	11	6	1	4	1	1	2	11	5	8	1	1	5	11	117
Ethene	< 1 mg/L	4								1										1				6
	1 to 10 mg/L	2																						2
	10 to 100 mg/L	1																						1
	100 to 1,000 mg/L		1																					1
	1,000 to 2,000 mg/L																							0
	> 2,000 mg/L																							0
	Non-detect	2	1	1							1												2	5
	Unknown	18	10	15	1	0	5	5	4	11	5	1	4	1	1	2	11	5	8	0	1	5	11	113
TOTAL SITES WITH GEOCHEMISTRY DATA		**27**	**12**	**16**	**1**	**0**	**5**	**5**	**4**	**12**	**6**	**1**	**4**	**1**	**1**	**2**	**11**	**5**	**8**	**1**	**1**	**5**	**13**	**128**

Notes
Blank spaces denote no data entered for that parameter.

TABLE D.27: SUMMARY OF SUCCESS DATA COLLECTED WITH THE SURVEY SORTED BY AREAL EXTENT
Navy ROCS

Areal Extent (ft^2)	Technology	Lithology	Source mass removal	Mass Flux Decrease	Rebound	Perceived Success
1 to <10	Chemical Oxidation-Permanganate	Sand	100%	81-100%	No	Success
	Excavation	Sand	100%	Unknown	Unknown	Success
	Chemical Oxidation-Permanganate	Sand	>90%	81-100%	Yes	Success
	Bioremediation	Sand	Unknown	Unknown	Unknown	Success
10 to <100	Chemical Oxidation-Permanganate	Sand	>50 <80%	Unknown	Yes	Fair Success
	Chemical Oxidation-Permanganate	Sand	>25 <50%	61-80%	Yes	Fair Success
	ZVI/nano-scale iron-Zero-valent iron	Sand	Unknown	Unknown	No	Success
100 to <1,000	Excavation	Sand	>80 <90%	61-80%	Yes	Success
	ZVI - EZVI/nano-scale iron	Sand	>25 <50%	41-60%	No	Fair Success
	ZVI/nano-scale iron-Zero-valent iron	Sand	Unknown	Unknown	Unknown	Success
	Thermal-Resistive heating	Clay	Unknown	Unknown	Unknown	Fair Success
1,000 to <10,000	Thermal - Conductive Heating	Clay	100%	Unknown	No	Success
	Chemical Oxidation-Fenton's Reagent	Gravel	Unknown	Unknown	No	Success
	Bioremediation	Sand	Unknown	Unknown	Unknown	Success
	Dual Phase-Water/air extraction	Gravel	Unknown	Unknown	Unknown	Fair Success
10,000 to <100,000	Excavation	Silt	>90%	Unknown	No	Success
	Chemical Oxidation-Fenton's Reagent	Clay	>90%	Unknown	No	Success
	Thermal-Steam	Clay	>90%	Unknown	No	Success
	Chemical Oxidation-Fenton's Reagent	Silt	>80 <90%	Unknown	No	Fair Success
	Thermal-Steam	Sand	>50 <80%	81-100%	Unknown	Fair Success
	Chemical Oxidation-Fenton's Reagent	Unknown	Unknown	81-100%	Unknown	Fair Success
	Bioremediation	Unknown	Unknown	81-100%	Unknown	Fair Success
	Bioremediation	Sand	Unknown	Unknown	No	Success
	Dual Phase-Water/air extraction	Till	Unknown	Unknown	Unknown	Success
	Bioremediation	Clay	Unknown	Unknown	Unknown	Success
	Thermal-Six phase heating	Silt	Unknown	Unknown	Unknown	Success
	Chemical Oxidation-Permanganate	Gravel	Unknown	Unknown	Yes	Fair Success
	Dual Phase-DNAPL/air extraction	Silt	<10%	Unknown	Unknown	Poor Success
100,000 to <1,000,000	Thermal - Low temp-six phase heating	Silt	>10 <25%	Unknown	Yes	Success

TABLE D.28: SUMMARY OF SUCCESS DATA COLLECTED WITH THE SURVEY SORTED BY DNAPL DEPTH
Navy ROCS

DNAPL Depth (ft)	Technology	Lithology	Source mass removal	Mass Flux Decrease	Rebound	Perceived Success
1 to <10	Chemical Oxidation-Permanganate	Gravel	Unknown	Unknown	Yes	Fair Success
	Chemical Oxidation-Permanganate	Sand	100%	81-100%	No	Success
	Thermal-Steam	Sand	>50 <80%	81-100%	Unknown	Fair Success
10 to <100	Bioremediation	Sand	Unknown	Unknown	Unknown	Success
	Bioremediation	Sand	Unknown	Unknown	Unknown	Success
	Bioremediation	Sand	Unknown	Unknown	No	Success
	Chemical Oxidation-Fenton's Reagent	Silt	>80 <90%	Unknown	No	Fair Success
	Chemical Oxidation-Fenton's Reagent	Unknown	Unknown	81-100%	Unknown	Fair Success
	Chemical Oxidation-Fenton's Reagent	Clay	>90%	Unknown	No	Success
	Chemical Oxidation-Permanganate	Sand	>50 <80%	Unknown	Yes	Fair Success
	Chemical Oxidation-Permanganate	Sand	>25 <50%	61-80%	Yes	Fair Success
	Chemical Oxidation-Permanganate	Sand	>90%	81-100%	Yes	Success
	Dual Phase-Water/air extraction	Gravel	Unknown	Unknown	Unknown	Fair Success
	Excavation	Sand	100%	Unknown	Unknown	Success
	Excavation	Silt	>90%	Unknown	No	Success
	Thermal - Conductive Heating	Clay	100%	Unknown	No	Success
	Thermal - Low temp-six phase heating	Silt	>10 <25%	Unknown	Yes	Success
	Thermal-Resistive heating	Clay	Unknown	Unknown	Unknown	Fair Success
	Thermal-Six phase heating	Silt	Unknown	Unknown	Unknown	Success
	ZVI - EZVI/nano-scale iron	Sand	>25 <50%	41-60%	No	Fair Success
	ZVI/nano-scale iron-Zero-valent iron	Sand	Unknown	Unknown	No	Success
	ZVI/nano-scale iron-Zero-valent iron	Sand	Unknown	Unknown	Unknown	Success
100 to <1,000	Thermal-Steam	Clay	>90%	Unknown	No	Success
1,000 to <10,000	Bioremediation	Unknown	Unknown	81-100%	Unknown	Fair Success
Unknown	Bioremediation	Clay	Unknown	Unknown	Unknown	Success
	Chemical Oxidation-Fenton's Reagent	Gravel	Unknown	Unknown	No	Success
	Dual Phase-Water/air extraction	Till	Unknown	Unknown	Unknown	Success
	Excavation	Sand	>80 <90%	61-80%	Yes	Success

TABLE D.29: SUMMARY OF SUCCESS DATA COLLECTED WITH THE SURVEY SORTED BY DNAPL DISTRIBUTION
Navy ROCS

10 Sites with DNAPL in Pools

					DNAPL Distribution in Subsurface						
Technology	**Source Mass Removal**	**Mass Flux Decrease**	**Rebound**	**Perceived Success**	**Dead-end Fractures**	**Diffused Into Low K Layers**	**In pools**	**Residual**	**Sorbed**	**Treatment Stage**	**Post Treatment Monitoring**
Excavation	>90%	Unknown	No	Success		X	X	X	X	Full-scale completed	On going
Chemical Oxidation-Permanganate	>50 <80%	Unknown	Yes	Fair Success			X	X	X	Pilot test completed	
Chemical Oxidation-Permanganate	>25 <50%	61-80%	Yes	Fair Success			X	X	X	Pilot test completed	
ZVI - EZVI/nano-scale iron	>25 <50%	41-60%	No	Fair Success			X	X		Pilot test completed	
Thermal - Low temp-six phase heating	>10 <25%	Unknown	Yes	Success			X	X	X	Pilot test completed	
Dual Phase-DNAPL/air extraction	<10%	Unknown	Unknown	Poor Success		X	X	X	X	Pilot test completed	On going
Surfactant Flushing	Unknown	61-80%	Unknown	Fair Success			X			Pilot test completed	
Bioremediation	Unknown	Unknown	No	Success		X	X	X	X	Pilot test completed	On going
Thermal-Three phase heating	Unknown	Unknown	Unknown	Not Yet Evaluated		X	X	X	X	Pilot test completed	
Thermal-Six phase heating	Unknown	Unknown	Unknown	Success			X	X		Pilot test completed	On going

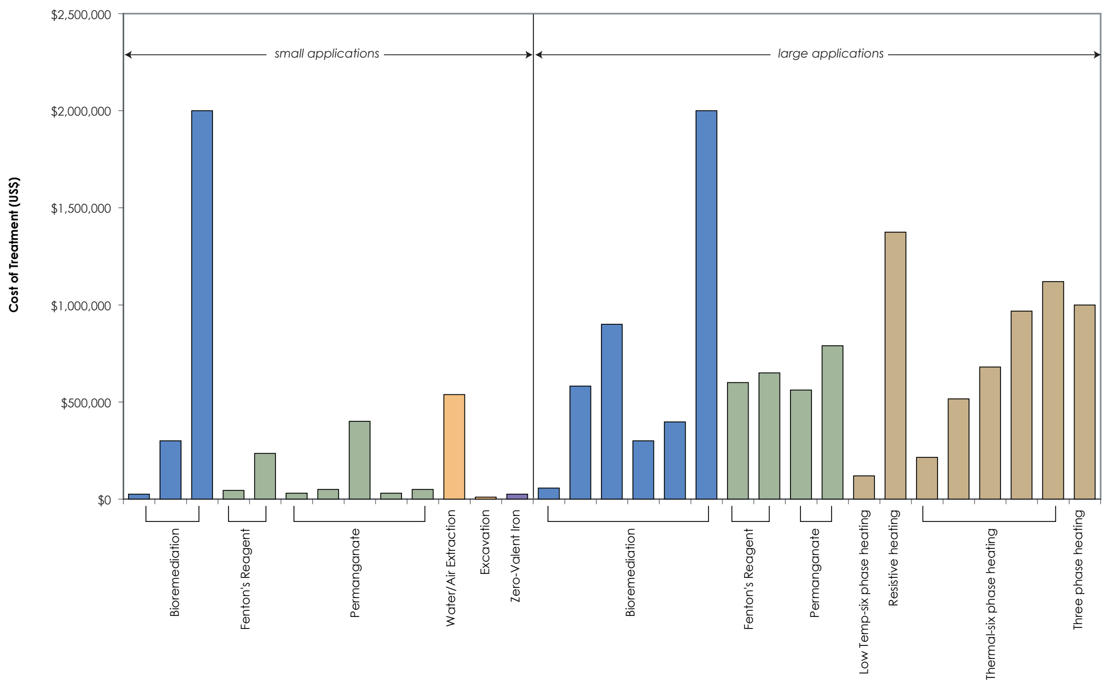
One site with DNAPL trapped in dead-end fractures

					DNAPL Distribution in Subsurface						
Technology	**Source Mass Removal**	**Mass Flux Decrease**	**Rebound**	**Perceived Success**	**Dead-end Fractures**	**Diffused Into Low K Layers**	**In pools**	**Residual**	**Sorbed**	**Treatment Stage**	**Post Treatment Monitoring**
Excavation	Unknown	0%	Unknown	Fair Success	X	X		X	X	Full-scale completed	On going

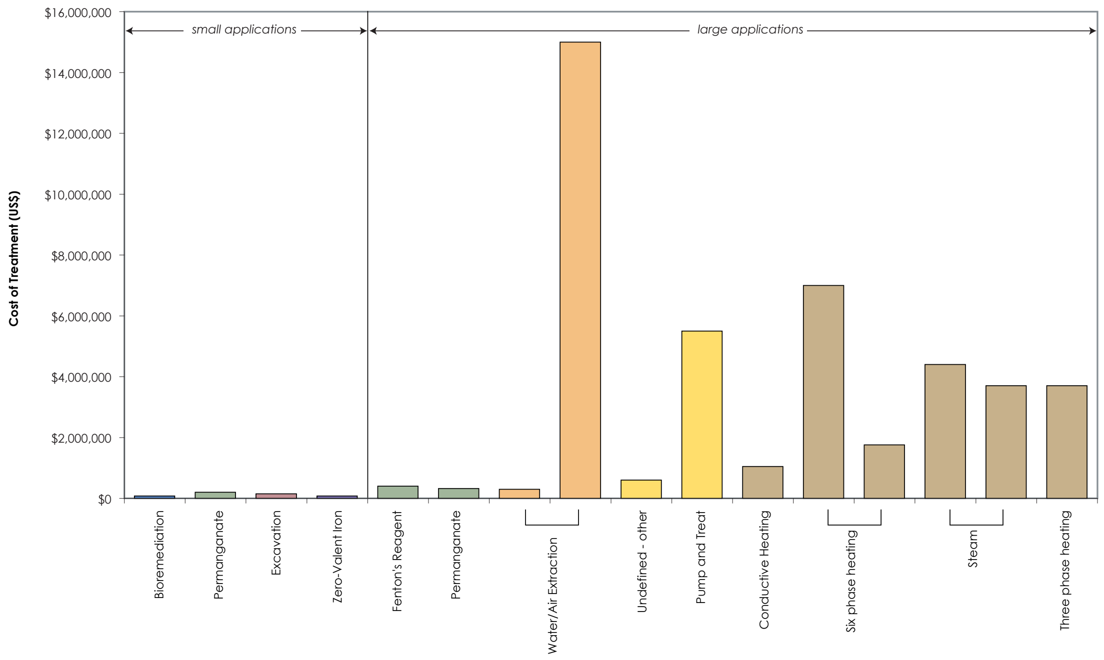
11 Sites with DNAPL Diffused into Low K Layers

					DNAPL Distribution in Subsurface						
Technology	**Source Mass Removal**	**Mass Flux Decrease**	**Rebound**	**Perceived Success**	**Dead-end Fractures**	**Diffused Into Low K Layers**	**In pools**	**Residual**	**Sorbed**	**Treatment Stage**	**Post Treatment Monitoring**
Excavation	>90%	Unknown	No	Success		X	X	X	X	Full-scale completed	On going
Chemical Oxidation-Fenton's Reagent	>90%	Unknown	No	Success		X		X	X	Full-scale completed	On going
Thermal-Steam	>90%	Unknown	No	Success		X				Full-scale completed	On going
Excavation	>80 <90%	61-80%	Yes	Success		X		X	X	Full-scale completed	On going
Bioremediation	Unknown	Unknown	No	Success		X	X	X	X	Pilot test completed	On going
Dual Phase-Water/air extraction	Unknown	Unknown	Unknown	Success		X		X	X	Pilot test completed	
Bioremediation	Unknown	Unknown	Unknown	Success		X		X	X	Pilot test completed	
Bioremediation	Unknown	Unknown	Unknown	Success		X		X	X	Pilot test completed	On going
Excavation	Unknown	0%	Unknown	Fair Success	X	X		X	X	Full-scale completed	On going
Dual Phase-DNAPL/air extraction	<10%	Unknown	Unknown	Poor Success		X	X	X	X	Pilot test completed	On going
Thermal-Three phase heating	Unknown	Unknown	Unknown	Not Yet Evaluated		X	X	X	X	Pilot test completed	

Pilot-Test Applications



Full-Scale Applications



Technology Legend

🟦 Bioremediation
🟩 Chemical Oxidation
🟪 Zero Valent Iron
🟧 Dual Phase Extraction

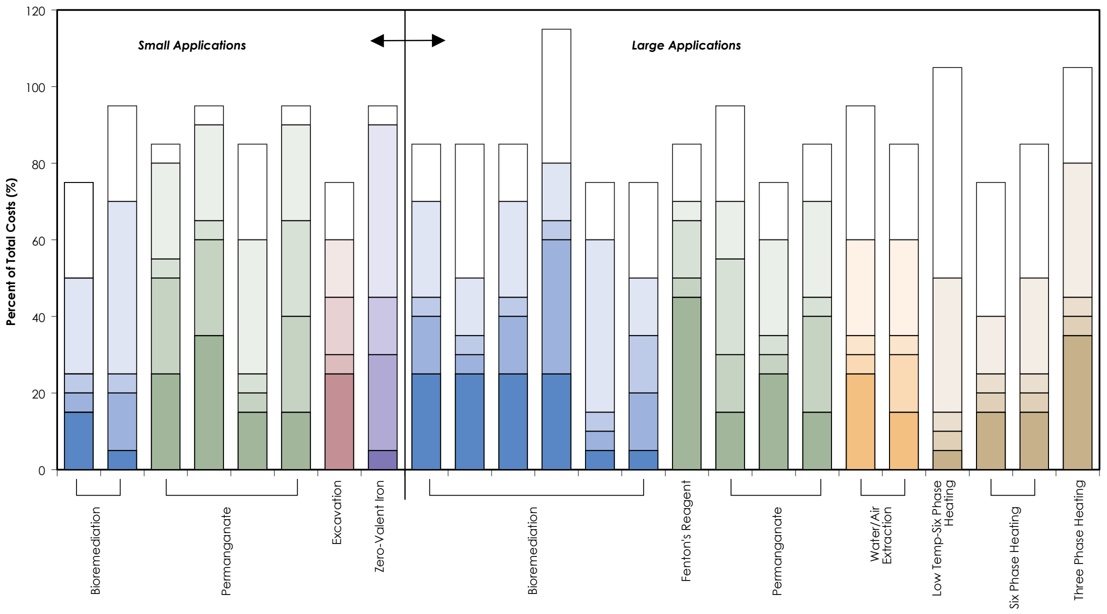
🟫 Thermal
🟥 Excavation
🟨 Pump and Treat

bar graphs_groups.ai

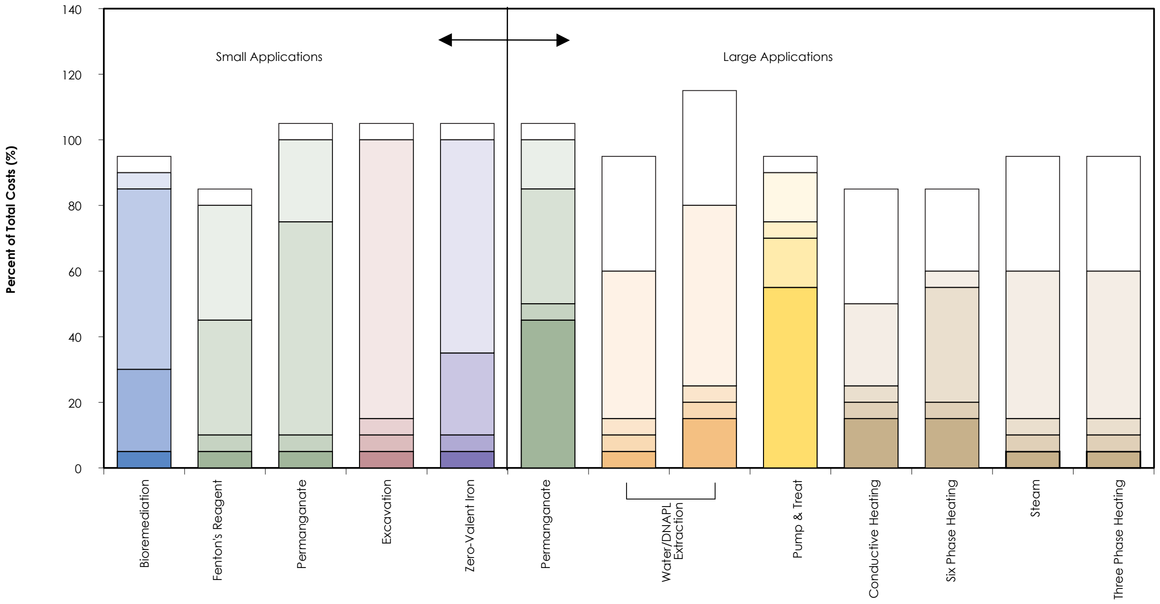
Actual Cost of Technology Applications
Navy ROCS

Feb. 2004
Figure: **D.1**
GEOSYNTEC CONSULTANTS

Pilot Scale Applications



Full Scale Applications



Technology Legend

- 🟦 Bioremediation
- 🟩 Chemical Oxidation
- 🟪 Zero Valent Iron
- 🟧 Dual Phase Extraction
- 🟫 Thermal
- 🟥 Excavation
- 🟨 Pump and Treat

Cost Breakdown

- ☐ Treatment Infrastructure
- ▨ Treatment Operation
- ▨ Consumables
- ▨ Post-Treatment Monitoring
- ■ Professional Costs

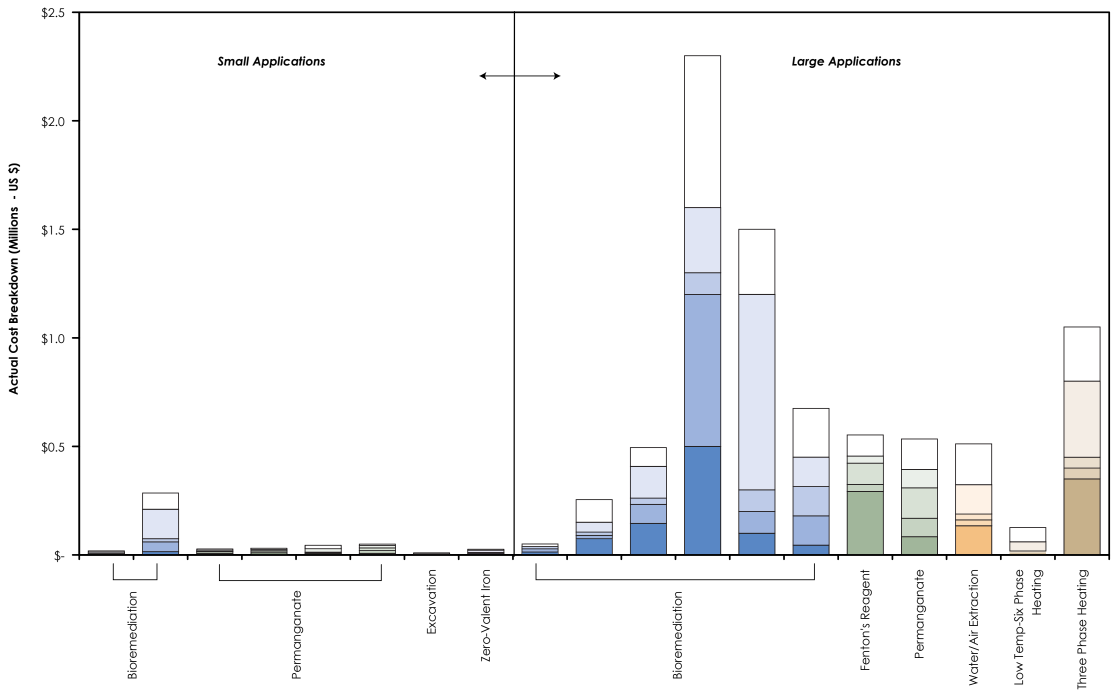
Notes:
1. Color shading (dark to light) is consistent for all technologies.
2. Total cost percent varies from 100% because cost breakdown data was inputted into survey as ranges and midpoints of ranges were chosen for illustration

Cost Breakdowns of Technology Applications
Percent of Total Costs
Navy ROCS

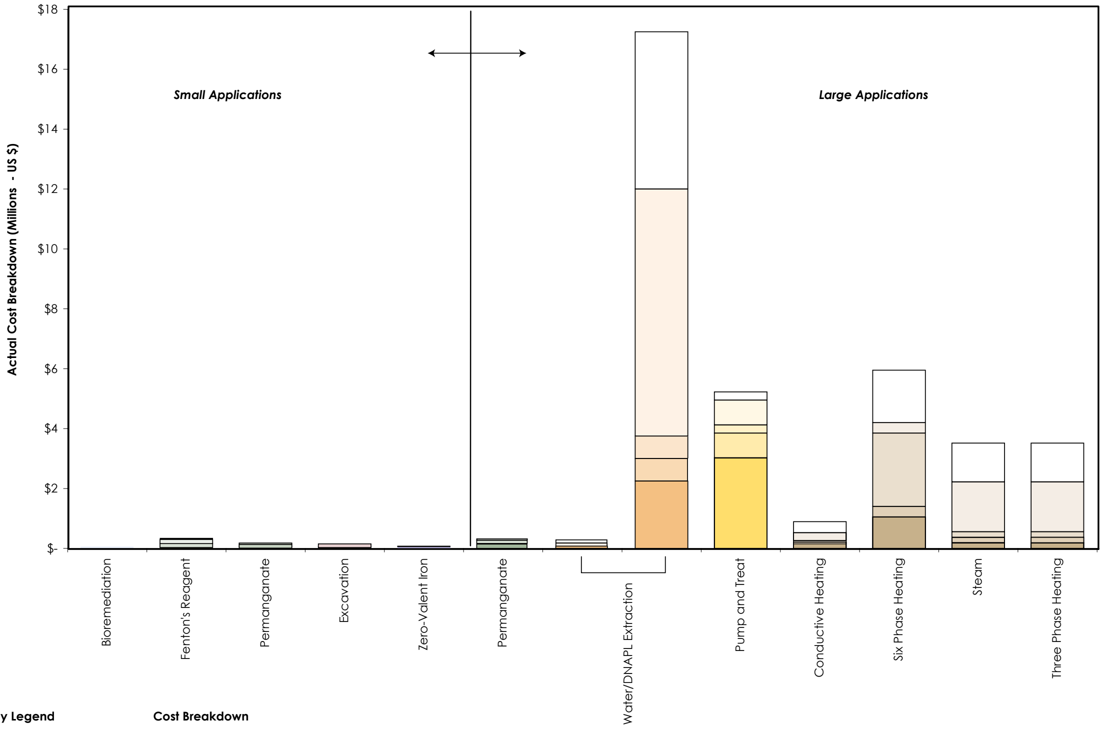
Feb. 2004 | Figure: **D.2** | GeoSyntec Consultants

bar graphs_groups.ai

Pilot Scale Application



Full Scale Applications



Technology Legend

- 🟦 Bioremediation
- 🟩 Chemical Oxidation
- 🟪 Zero Valent Iron
- 🟧 Dual Phase Extraction
- 🟫 Thermal
- 🟥 Excavation
- 🟨 Pump and Treat

Cost Breakdown

- ☐ Treatment Infrastructure
- ░ Treatment Operation
- ▒ Consumables
- ▓ Post-Treatment Monitoring
- ■ Professional Costs

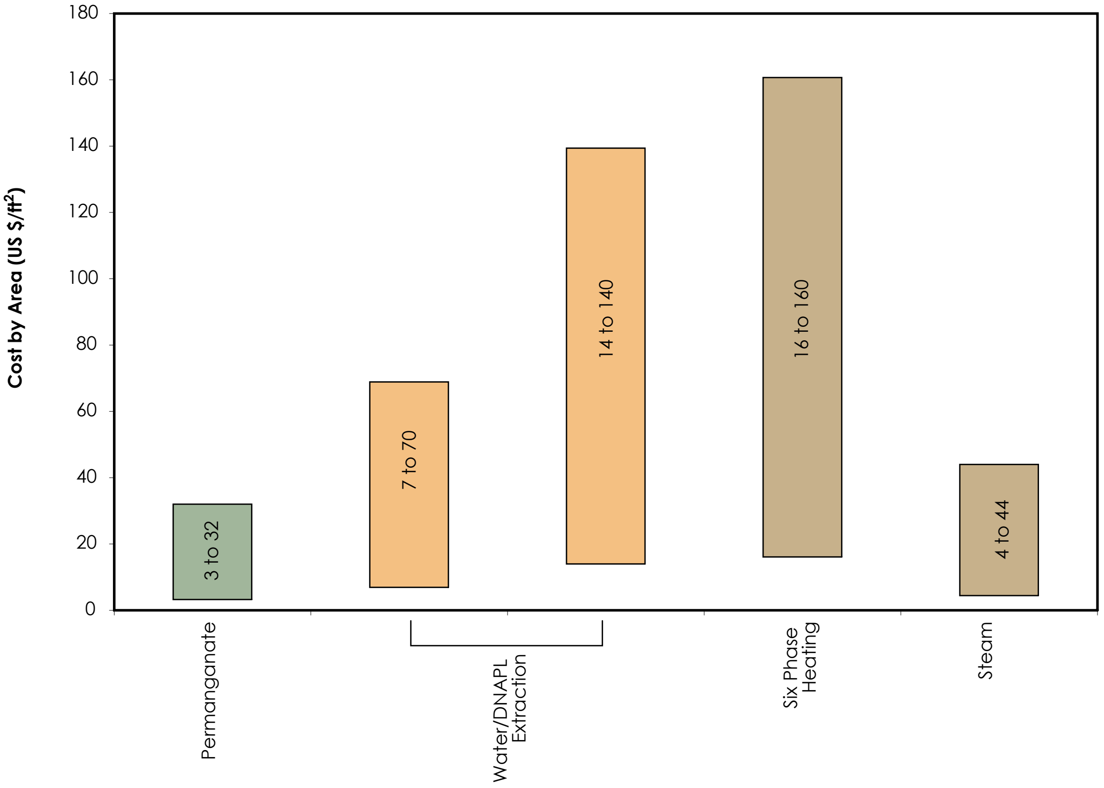
Note: Color shading (dark to light) is consistent for all technologies.

Cost Breakdowns of Technology Applications
Range of Total Costs
Navy ROCS

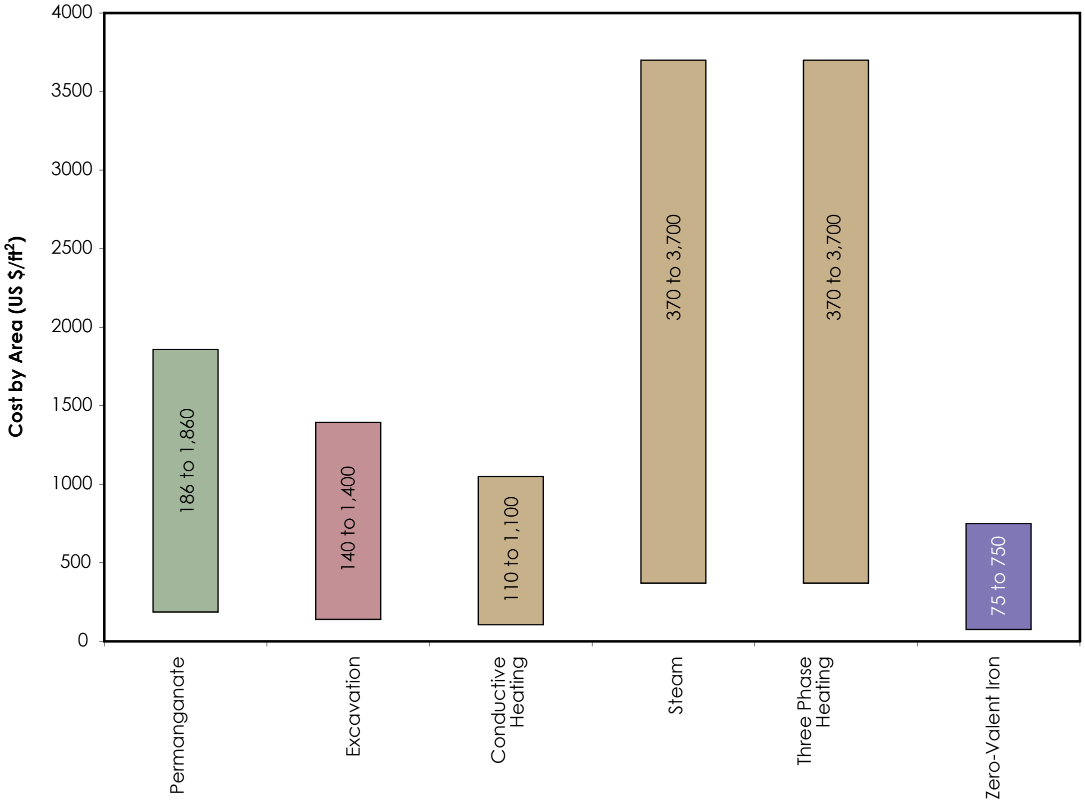
Feb. 2004 | Figure: **D.3** | GeoSyntec Consultants

bar graphs_groups.ai

Large Full Scale Applications



Small Full Scale Applications



- 🟦 Bioremediation
- 🟩 Chemical Oxidation
- 🟪 Zero Valent Iron
- 🟧 Dual Phase Extraction
- 🟫 Thermal
- 🟥 Excavation
- 🟨 Pump and Treat

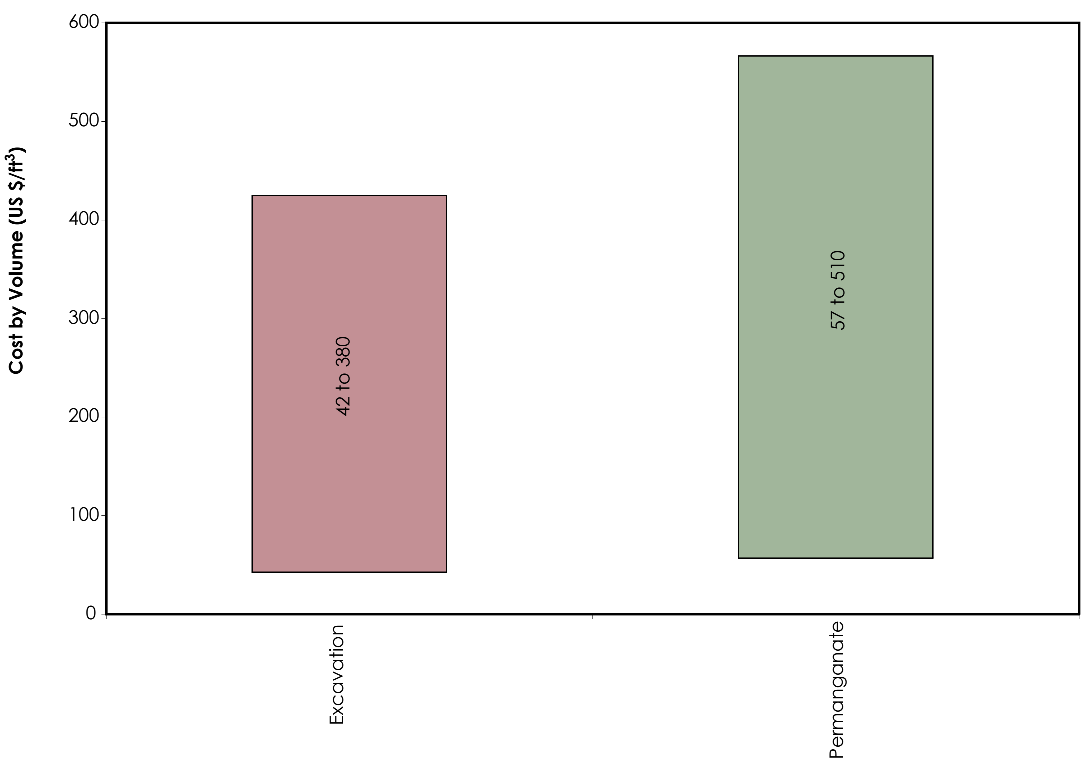
Note:

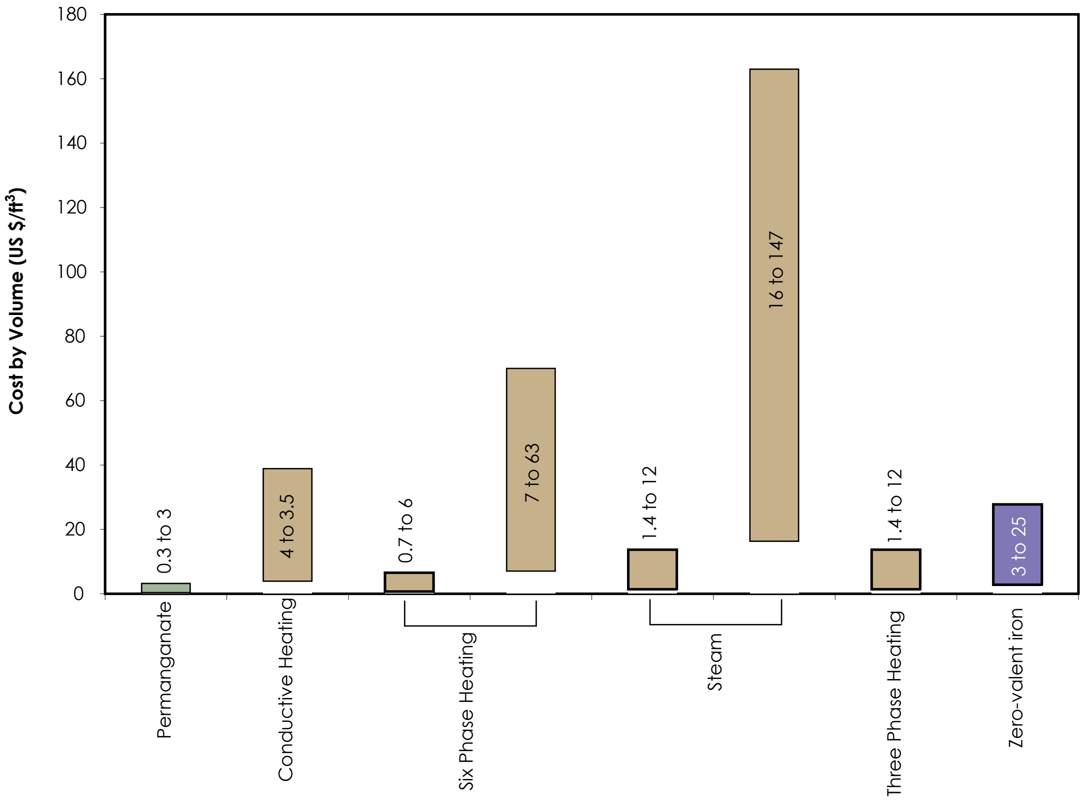
Ranges in unit costs are reported since treatment area was entered into the survey as order of magnitude ranges

Unit Treatment Cost by Total DNAPL Impacted Area
Navy ROCS

Feb. 2004 | Figure: **D.4** | GEOSYNTEC CONSULTANTS

bar graphs_groups.ai


Small Full Scale Applications


Large Full Scale Applications

🟦 Bioremediation

🟩 Chemical Oxidation

🟪 Zero Valent Iron

🟧 Dual Phase Extraction

🟫 Thermal

🟥 Excavation

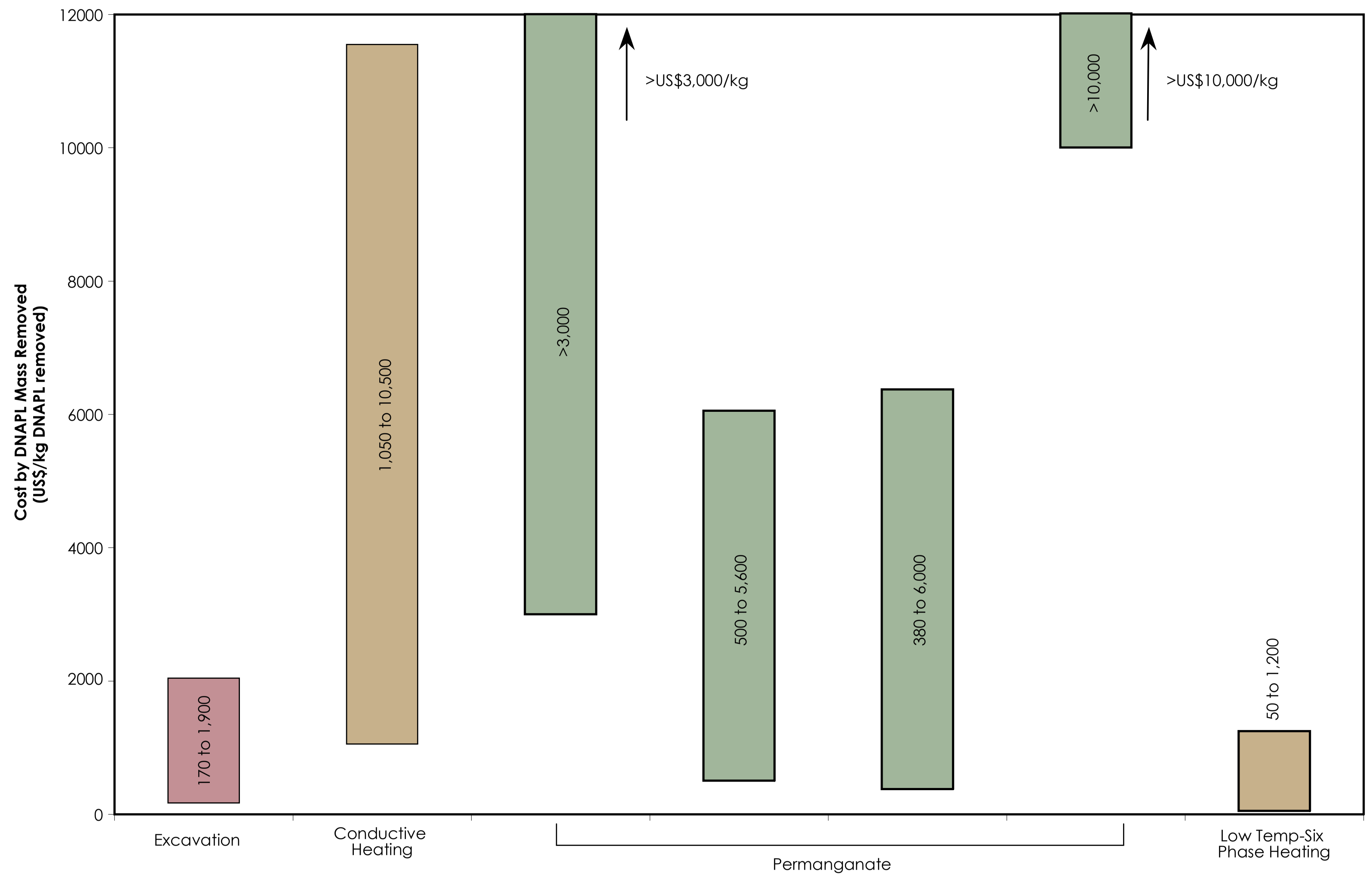
🟨 Pump and Treat

Note:
Ranges in unit costs are reported since treatment area was entered into the survey as order of magnitude ranges

Unit Treatment Cost by Total DNAPL Impacted Volume
Navy ROCS

Feb. 2004	Figure: **D.5**	GeoSyntec Consultants

bar graphs_groups.ai



Technology

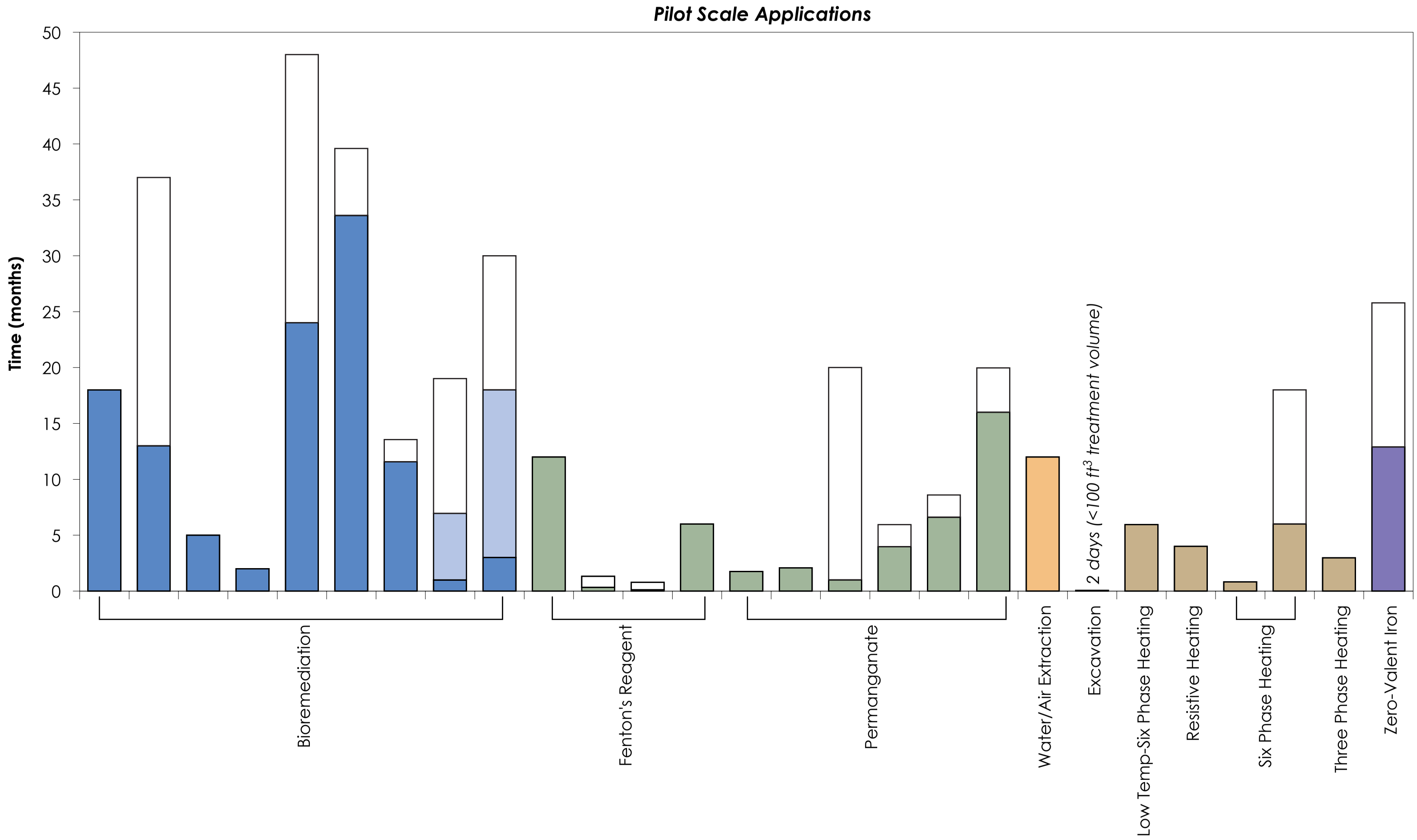
Note:

Range in unit costs are reported since DNAPL mass removed was calculated using the percentage mass removal and the pre-treatment DNAPL mass estimates, which were both entered into the survey as order of magnitude ranges

Cost by DNAPL Mass Removal
Navy ROCS

Feb. 2004 | Figure: **D.6** | GEOSYNTEC CONSULTANTS

bar graphs_groups.ai



Technology Legend

- 🟦 Bioremediation
- 🟩 Chemical Oxidation
- 🟪 Zero Valent Iron
- 🟧 Dual Phase Extraction
- 🟫 Thermal
- 🟥 Excavation
- 🟨 Pump and Treat

Treatment Stage Legend

- ☐ Post Treatment Monitoring Duration
- ▨ Estimate Future Treatment Duration
- ■ Actual Field Activity Duration

Note: Color shading (dark to light) is consistent for all technologies.

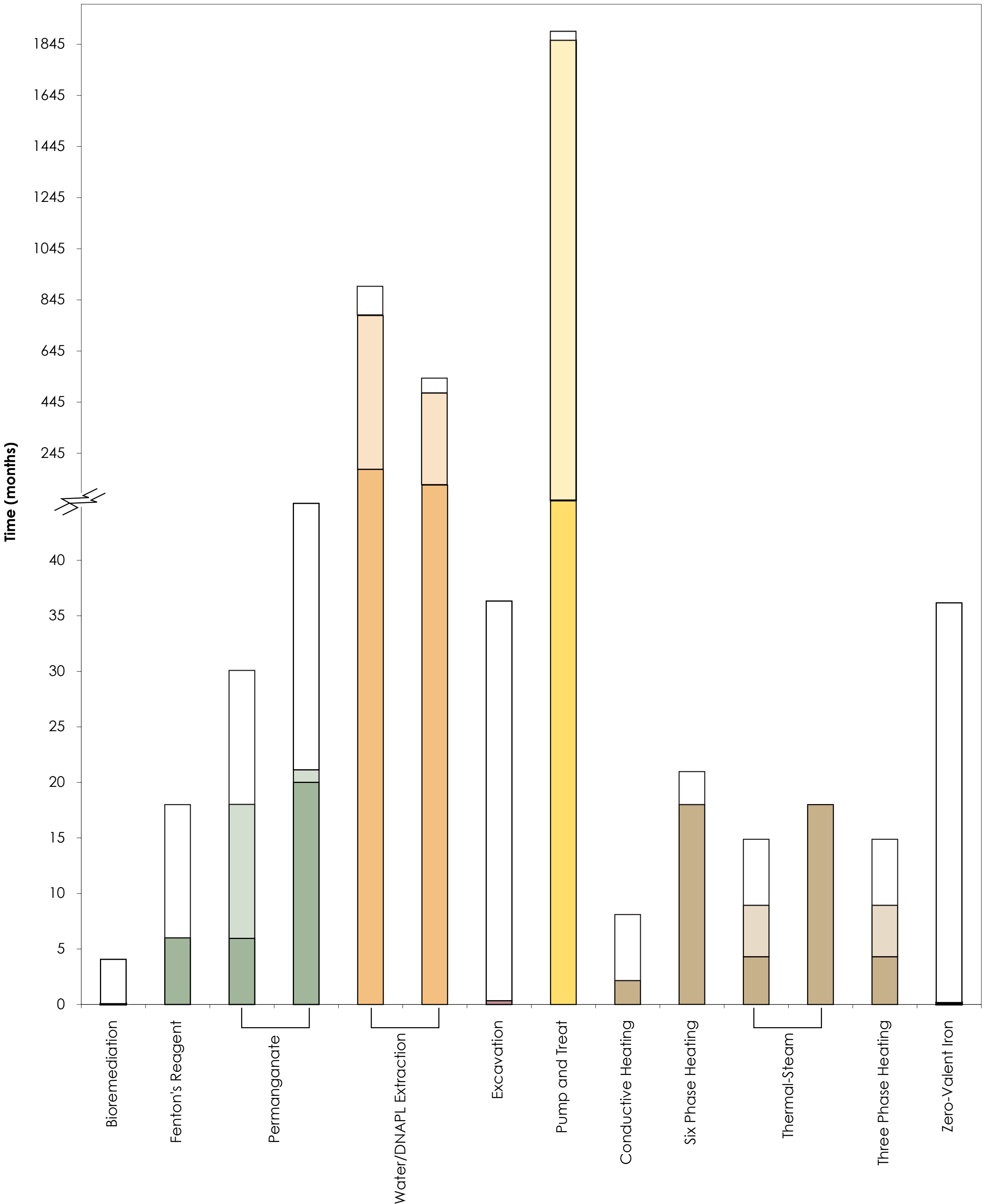
DNAPL Treatment Duration for Pilot Scale Applications
Navy ROCS

Feb. 2004

Figure: **D.7**

GeoSyntec Consultants

bar graphs_groups.ai



Technology Legend

- 🟦 Bioremediation
- 🟩 Chemical Oxidation
- 🟪 Zero Valent Iron
- 🟧 Dual Phase Extraction
- 🟫 Thermal
- 🟥 Excavation
- 🟨 Pump and Treat

Treatment Stage Legend

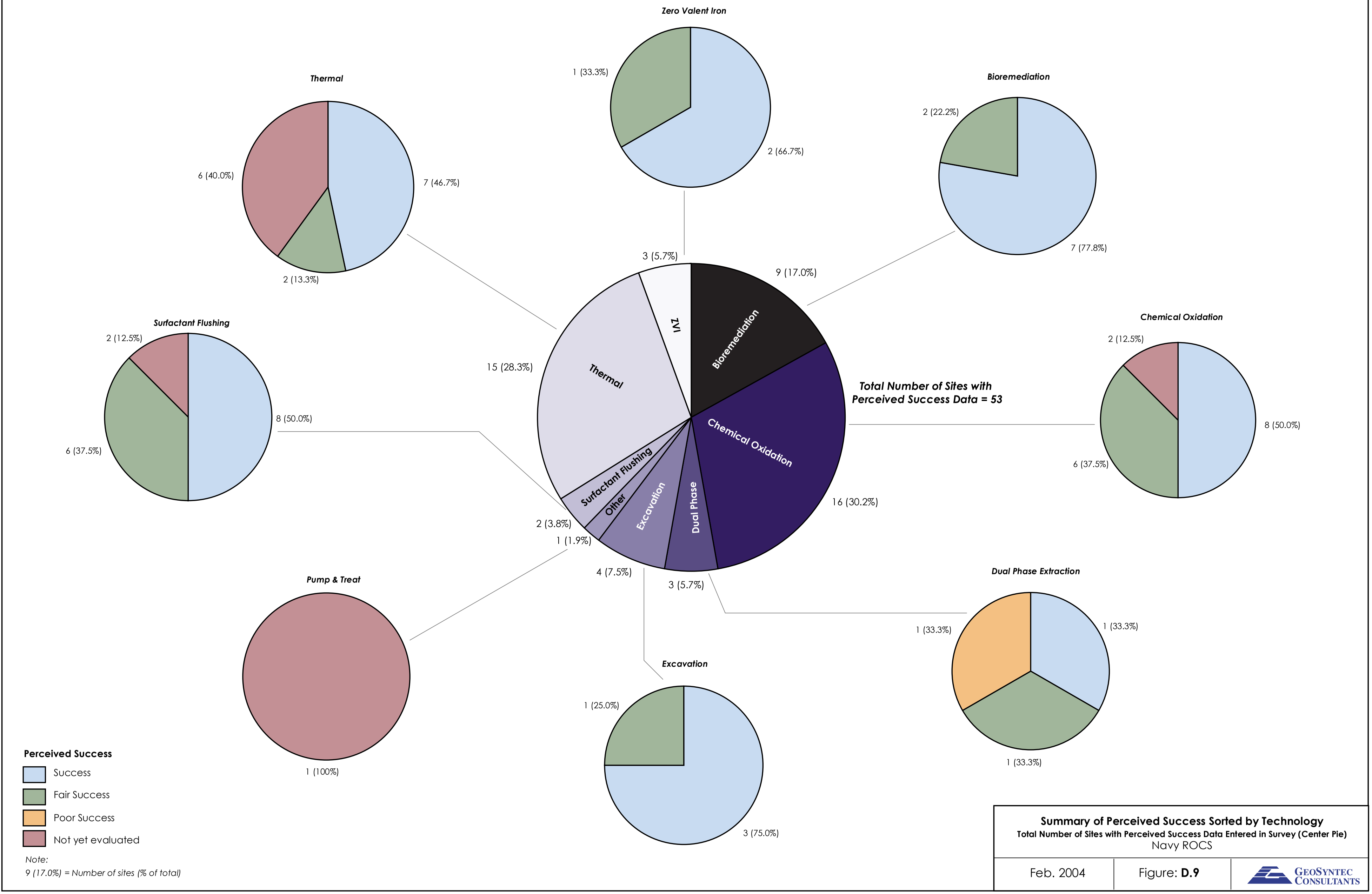
- ☐ Post Treatment Monitoring Duration
- ▨ Estimate Future Treatment Duration
- ■ Actual Field Activity Duration

Note: Color shading (dark to light) is consistent for all technologies.

DNAPL Treatment Duration for Full-Scale Applications
Navy ROCS

Feb. 2004 | Figure: **D.8** | GeoSyntec Consultants

bar graphs_groups.ai

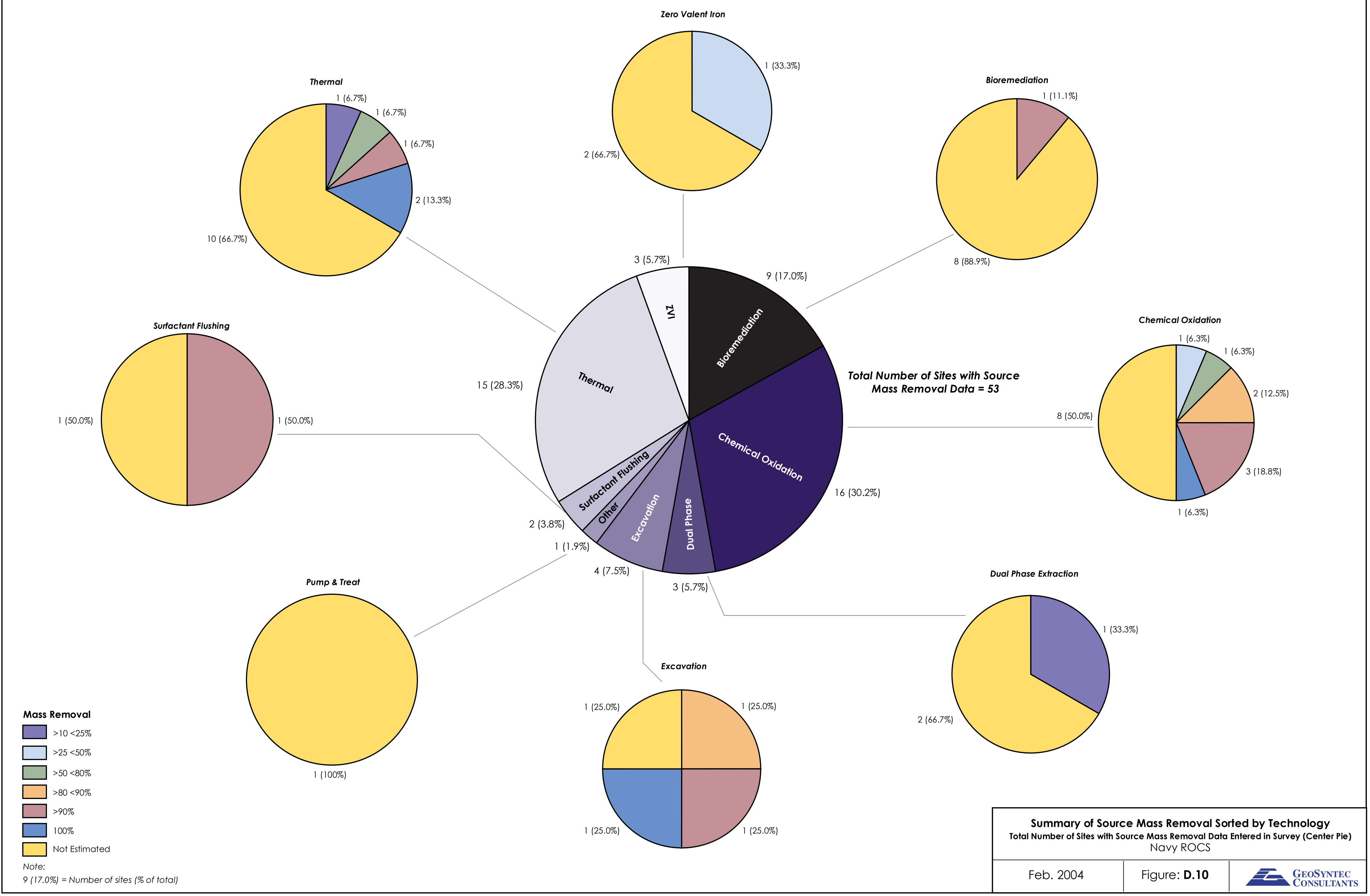


Summary of Perceived Success Sorted by Technology

Total Number of Sites with Perceived Success Data Entered in Survey (Center Pie)

Navy ROCS

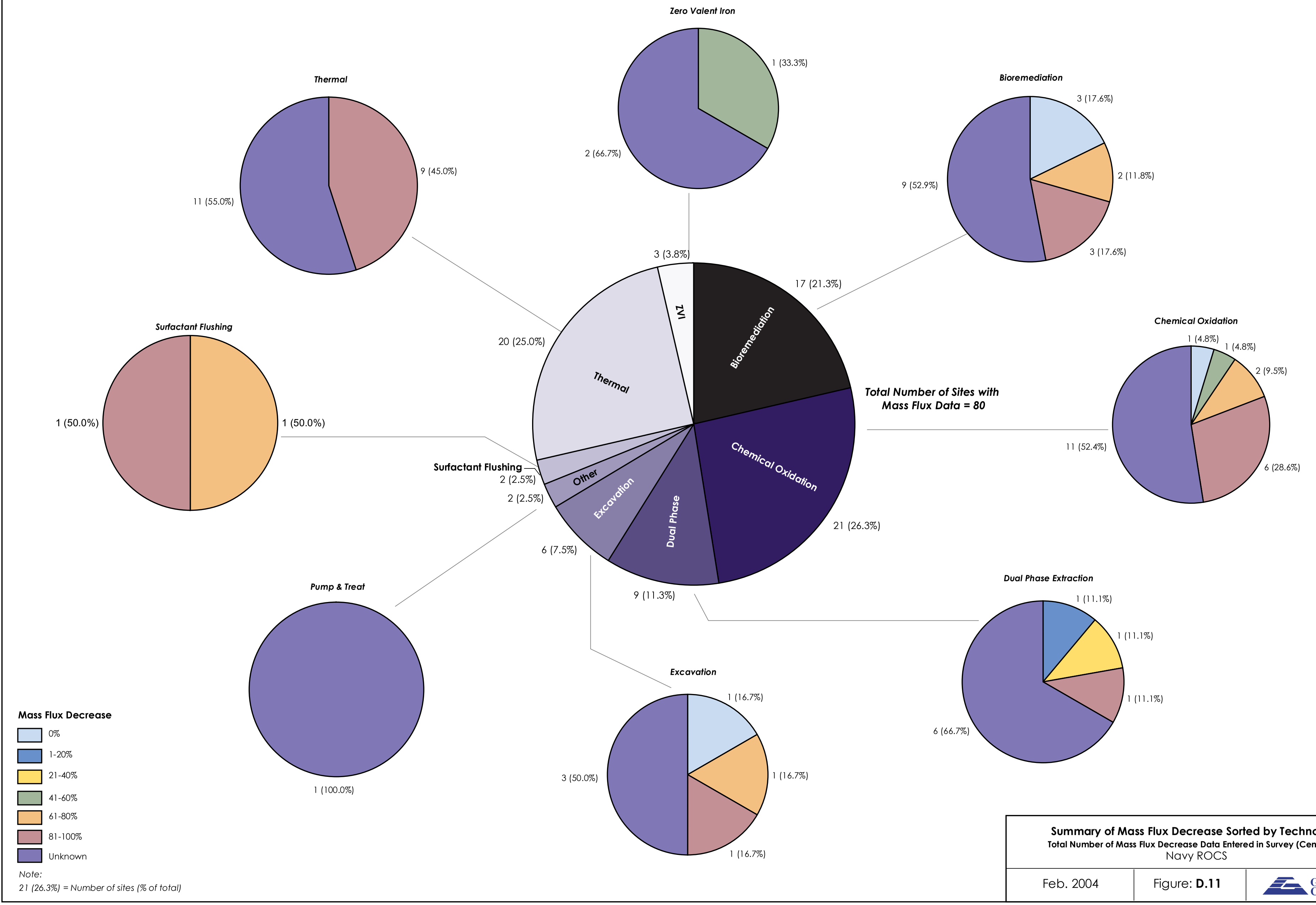
Feb. 2004 | Figure: **D.9** | GeoSyntec Consultants



Summary of Source Mass Removal Sorted by Technology
Total Number of Sites with Source Mass Removal Data Entered in Survey (Center Pie)
Navy ROCS

Feb. 2004	Figure: **D.10**	GeoSyntec Consultants

pie graphs_groups.ai

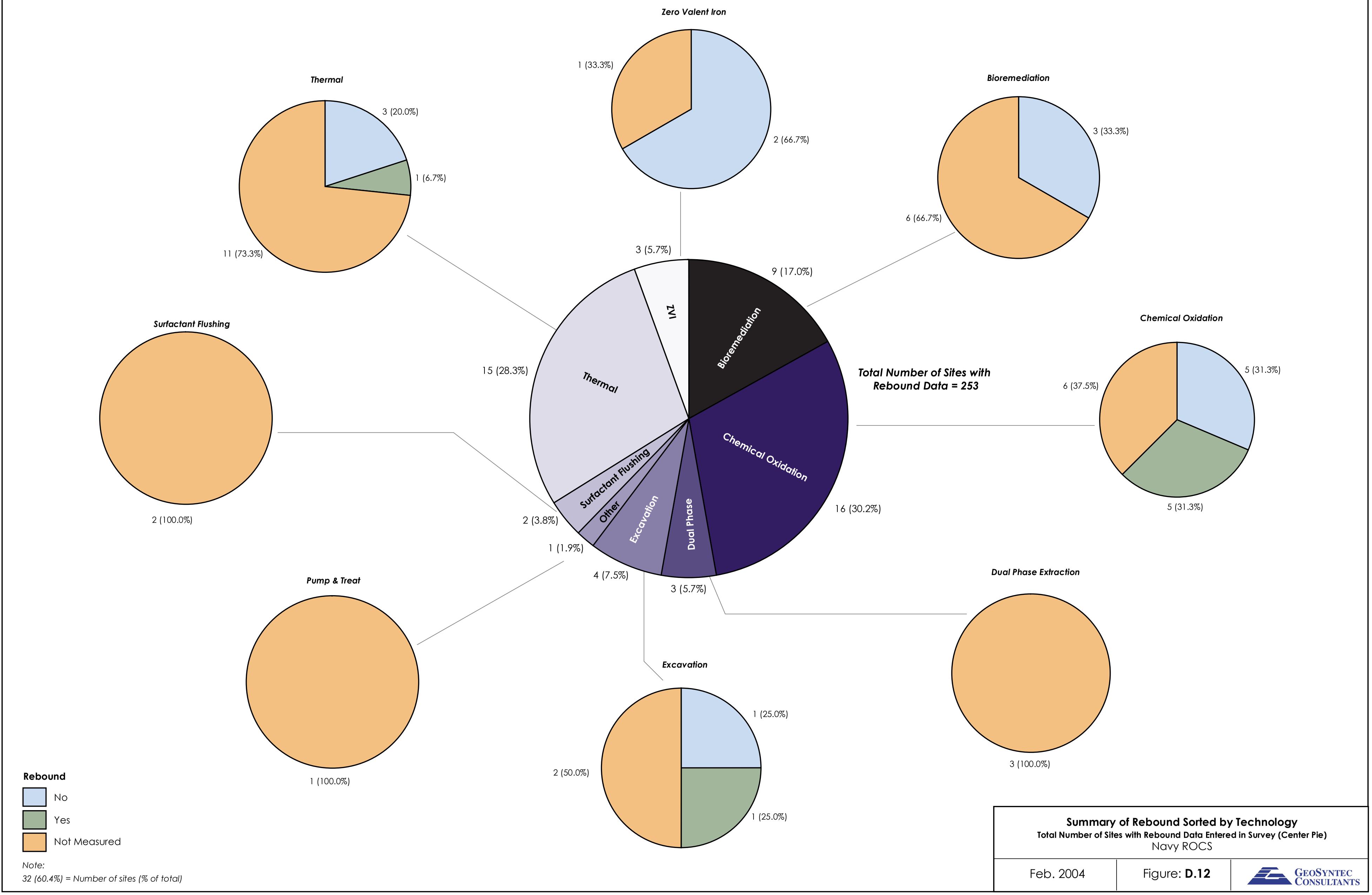


Note:
21 (26.3%) = Number of sites (% of total)

pie graphs_groups.ai

Summary of Mass Flux Decrease Sorted by Technology
Total Number of Mass Flux Decrease Data Entered in Survey (Center Pie)
Navy ROCS

Feb. 2004	Figure: **D.11**	GEOSYNTEC CONSULTANTS

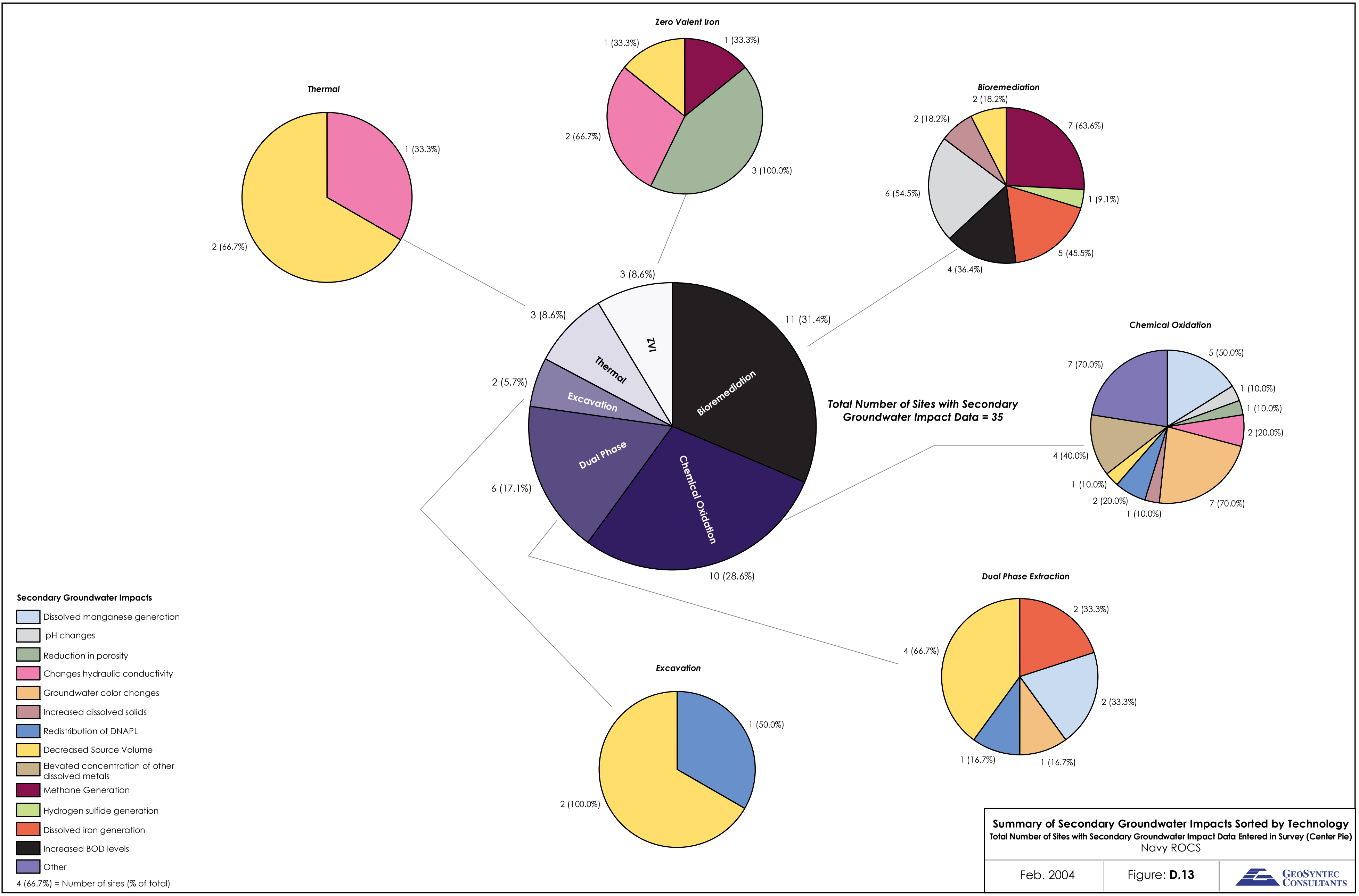


Note:
32 (60.4%) = Number of sites (% of total)

Summary of Rebound Sorted by Technology
Total Number of Sites with Rebound Data Entered in Survey (Center Pie)
Navy ROCS

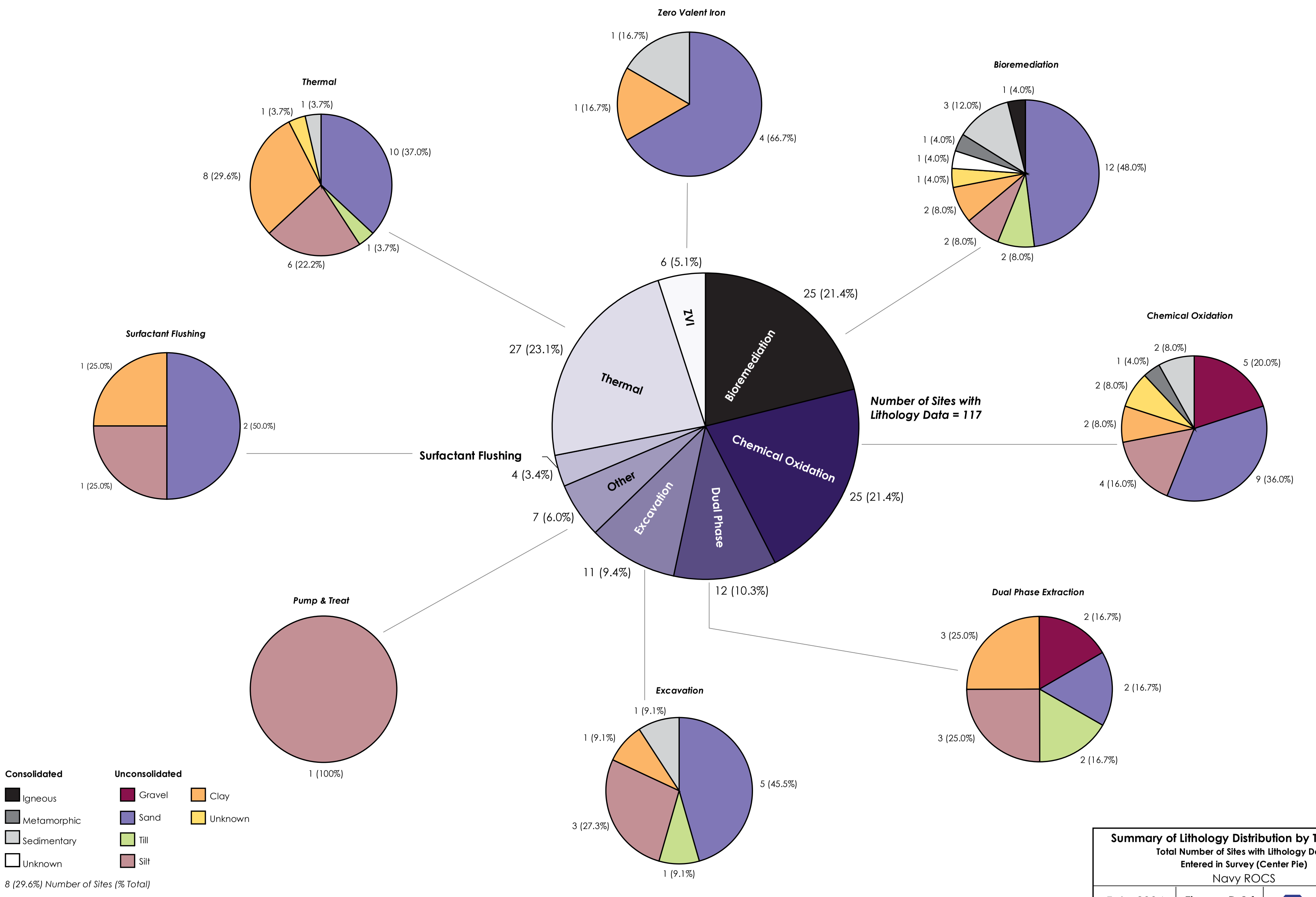
Feb. 2004	Figure: **D.12**	GeoSyntec Consultants

pie graphs_groups.ai



Summary of Secondary Groundwater Impacts Sorted by Technology
Total Number of Sites with Secondary Groundwater Impact Data Entered in Survey (Center Pie)
Navy ROCS

Feb. 2004
Figure: **D.13**
GeoSyntec Consultants



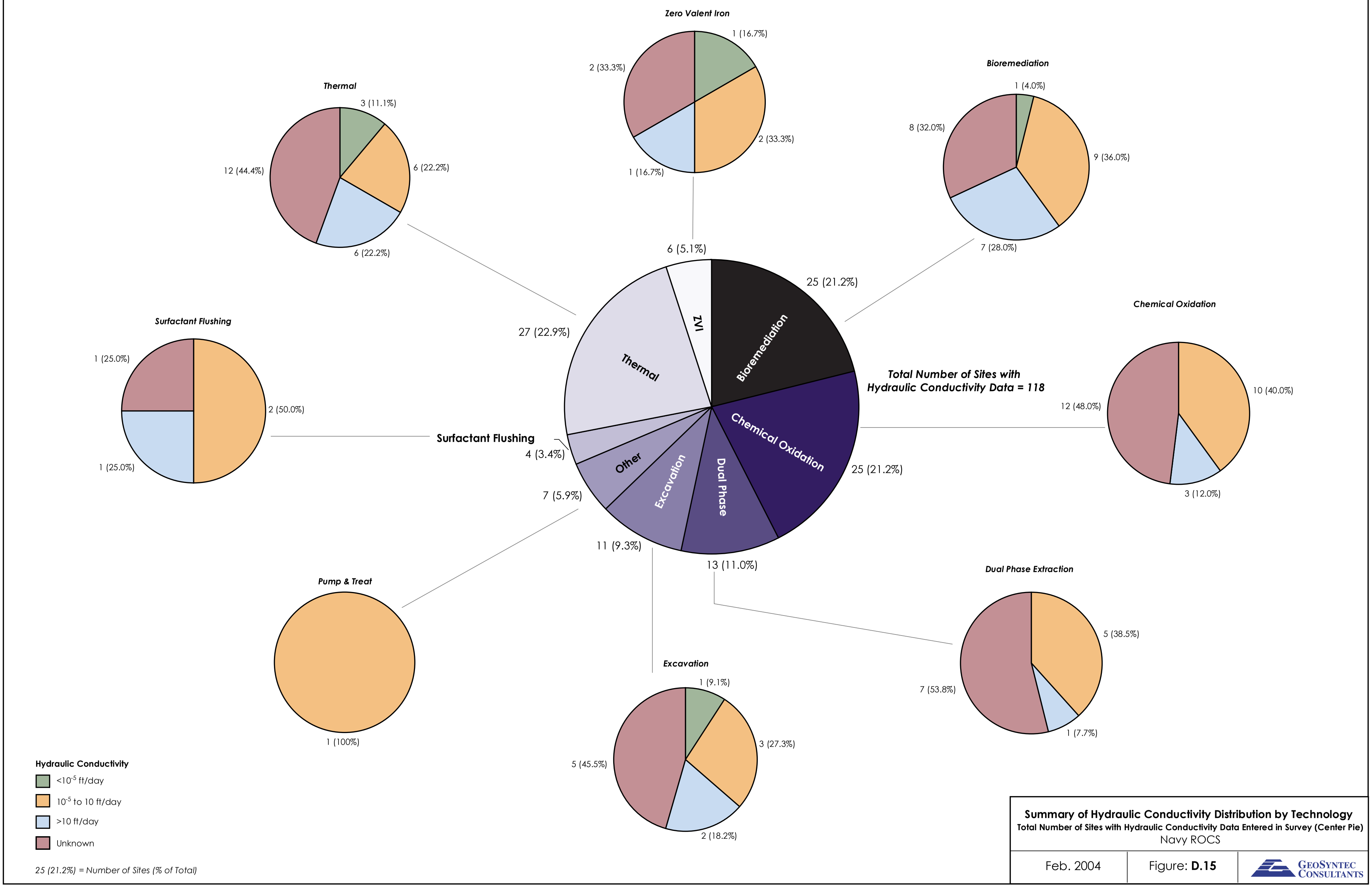
8 (29.6%) Number of Sites (% Total)

Note: Data for undefined other technologies was not included in the technology-specific breakdown.

Summary of Lithology Distribution by Technology
Total Number of Sites with Lithology Data
Entered in Survey (Center Pie)
Navy ROCS

Feb. 2004 | Figure: **D.14** | GeoSyntec Consultants

pie graphs_groups.ai

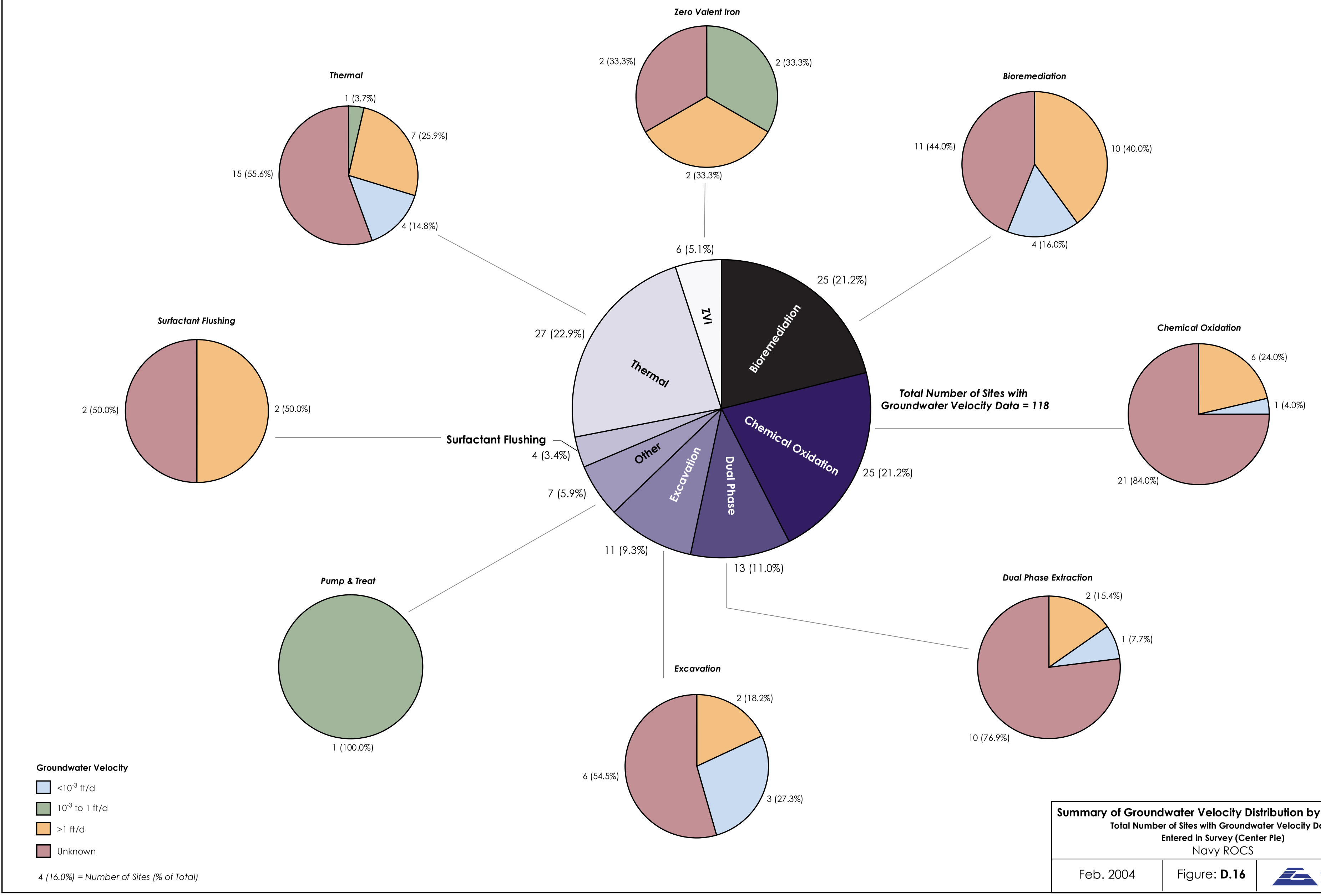


Summary of Hydraulic Conductivity Distribution by Technology

Total Number of Sites with Hydraulic Conductivity Data Entered in Survey (Center Pie)

Navy ROCS

Feb. 2004	Figure: **D.15**	GEOSYNTEC CONSULTANTS



pie graphs_groups.ai

Summary of Groundwater Velocity Distribution by Technology

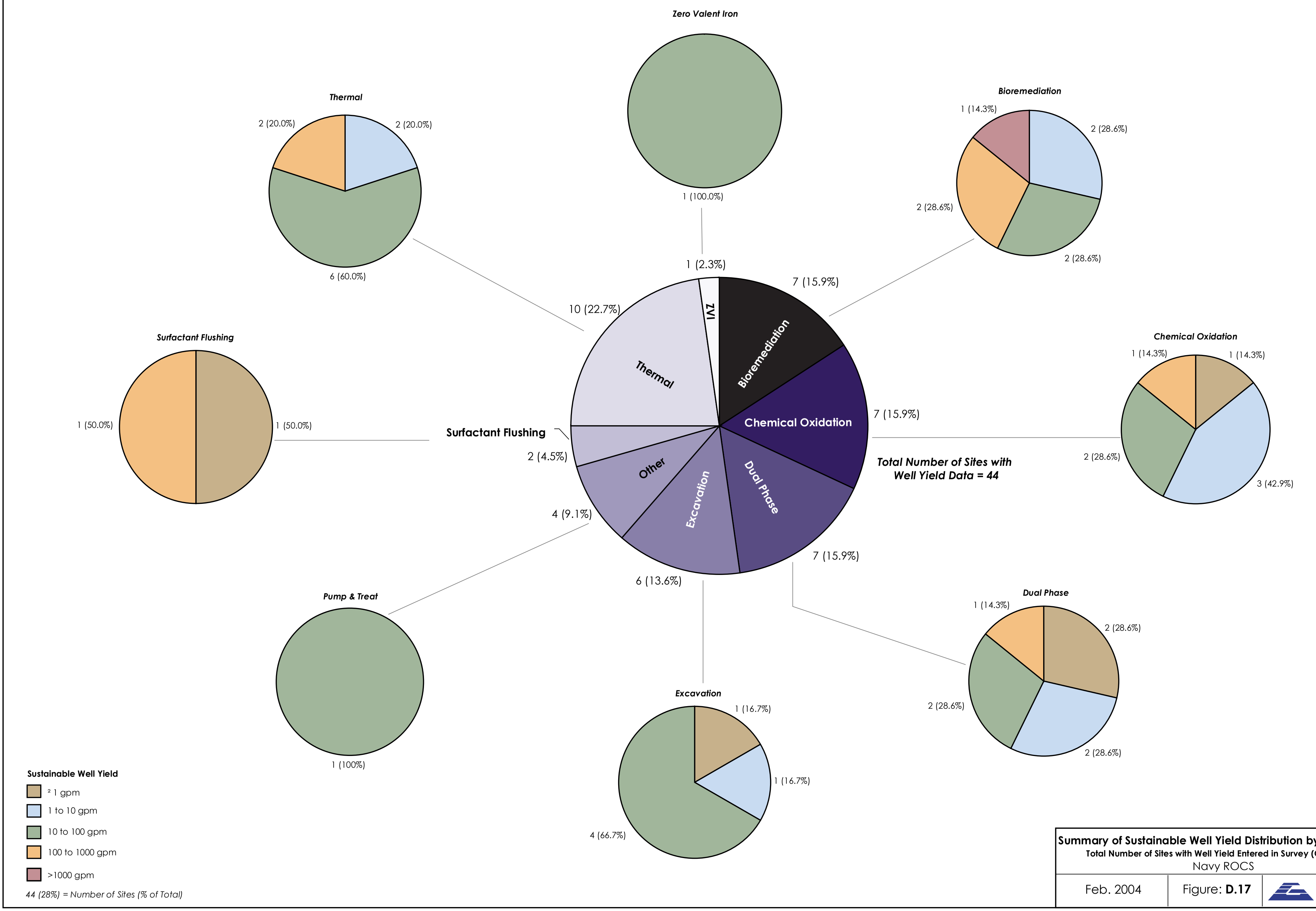
Total Number of Sites with Groundwater Velocity Data Entered in Survey (Center Pie)

Navy ROCS

Feb. 2004

Figure: **D.16**

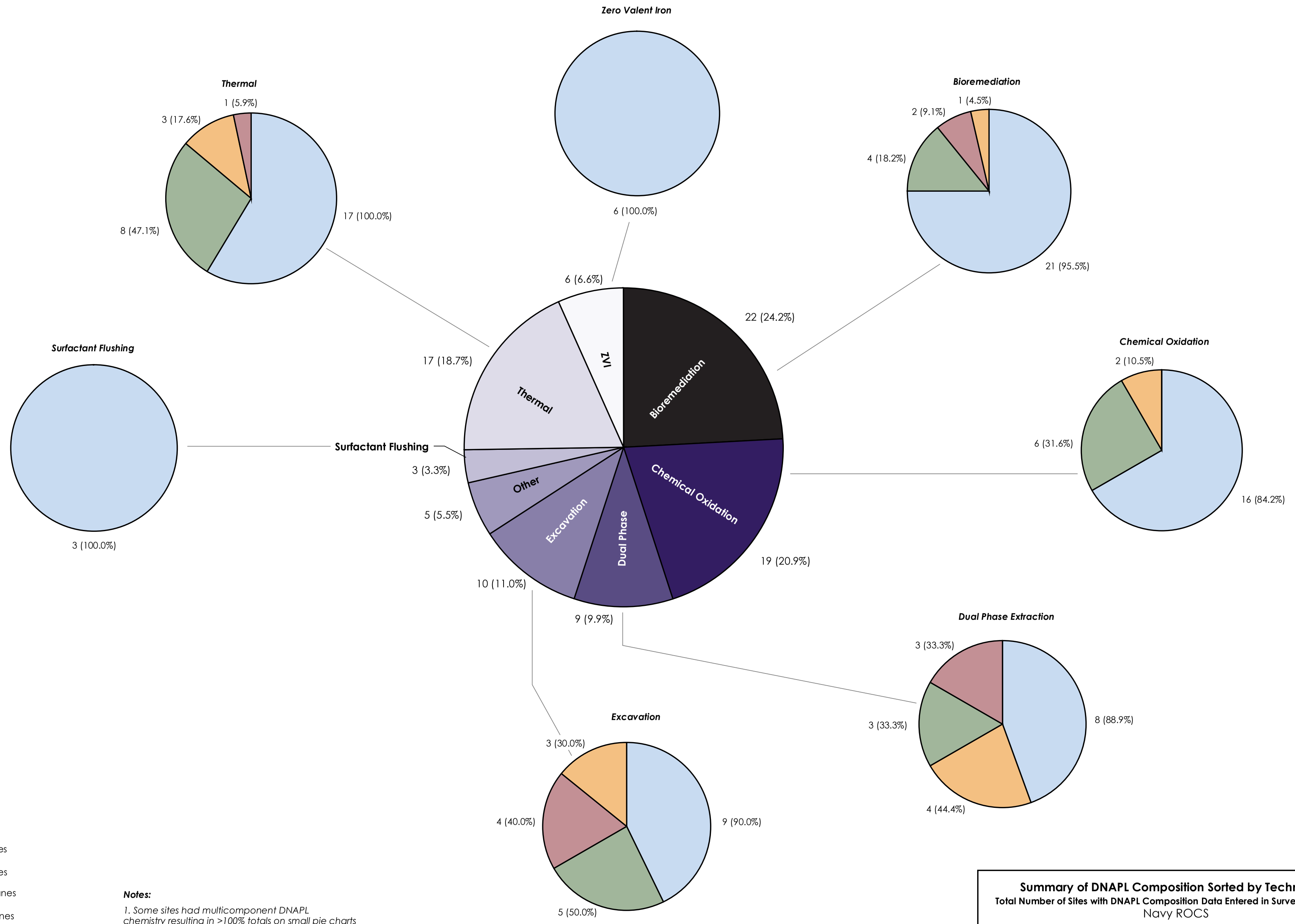
GEOSYNTEC CONSULTANTS



pie graphs_groups.ai

Summary of Sustainable Well Yield Distribution by Technology
Total Number of Sites with Well Yield Entered in Survey (Center Pie)
Navy ROCS

Feb. 2004 | Figure: **D.17** | GeoSyntec Consultants



- ▨ Chloroethenes
- ▨ Chloroethanes
- ▨ Chloromethanes
- ▨ Chlorobenzenes

20 (100%) = Number of Sites (% of Total)

Notes:

1. Some sites had multicomponent DNAPL chemistry resulting in >100% totals on small pie charts

2. Pump & treat site had no DNAPL composition specified

Summary of DNAPL Composition Sorted by Technology

Total Number of Sites with DNAPL Composition Data Entered in Survey (Center Pie)

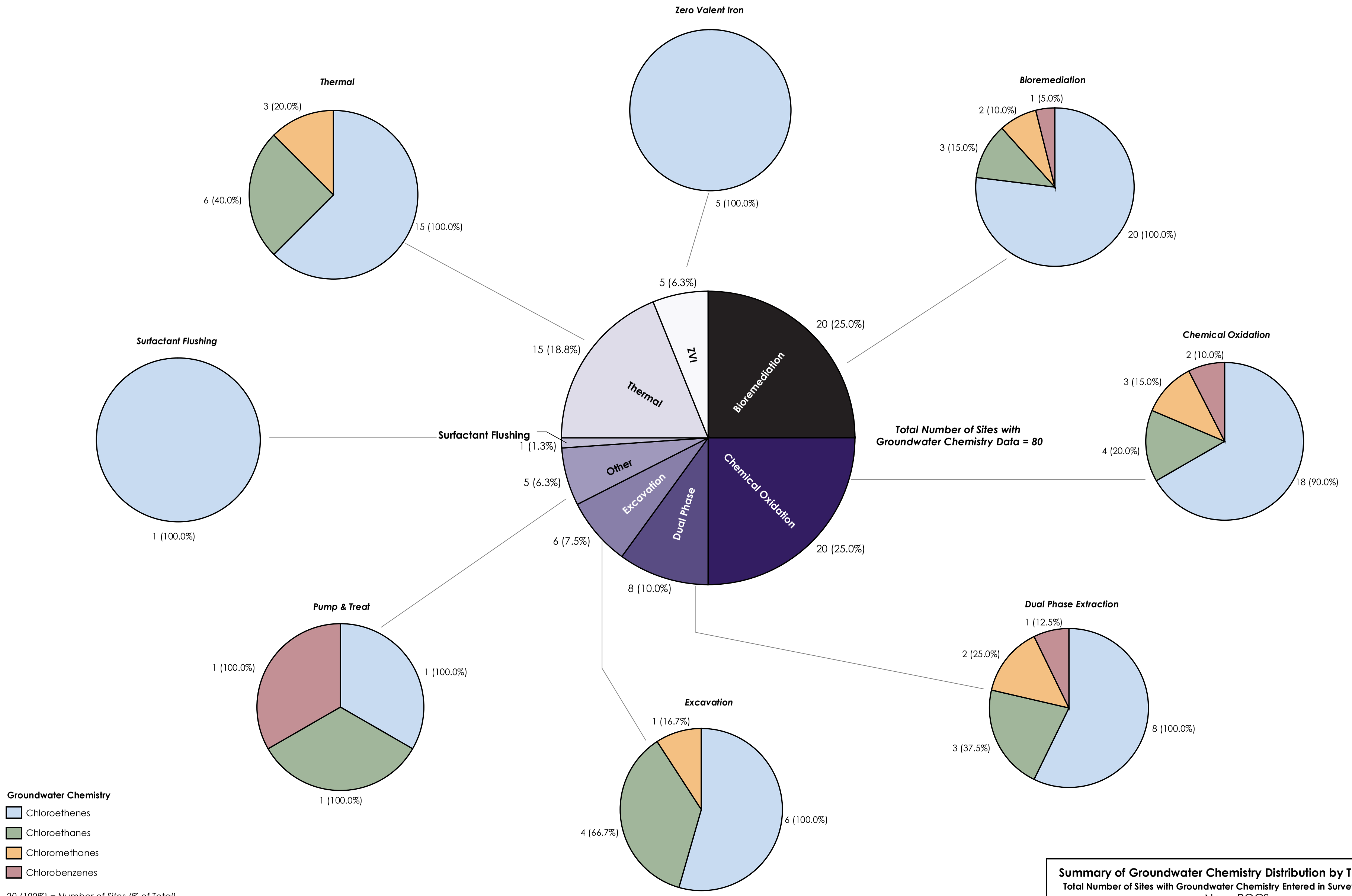
Navy ROCS

Feb. 2004

Figure: **D.18**

GEOSYNTEC CONSULTANTS

pie graphs_groups.ai



20 (100%) = Number of Sites (% of Total)

Note: Some sites had multicomponent groundwater chemistry resulting in >100% totals on small pie charts

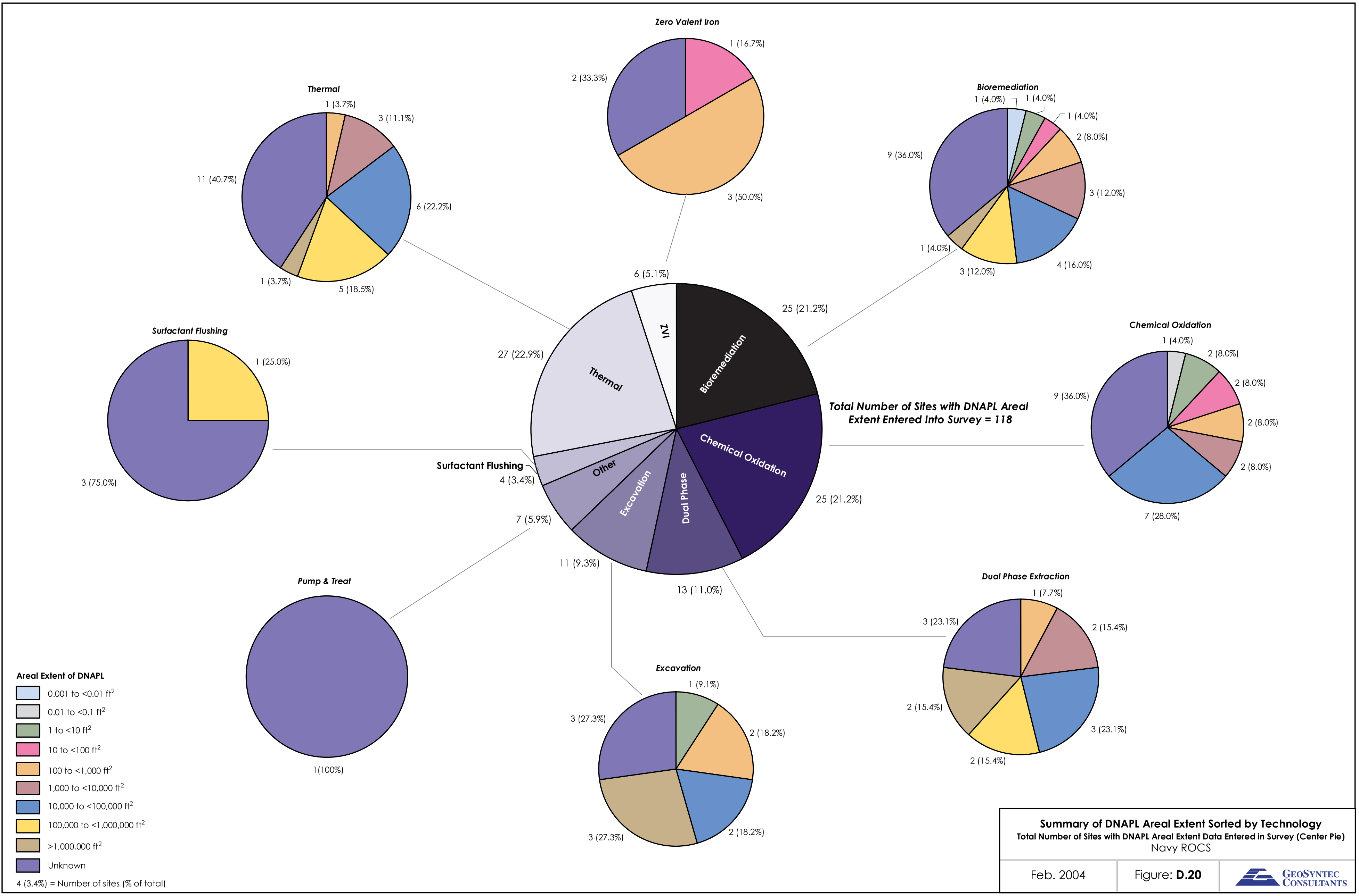
pie graphs_groups.ai

Summary of Groundwater Chemistry Distribution by Technology

Total Number of Sites with Groundwater Chemistry Entered in Survey (Center Pie)

Navy ROCS

Feb. 2004	Figure: **D.19**	GeoSyntec Consultants

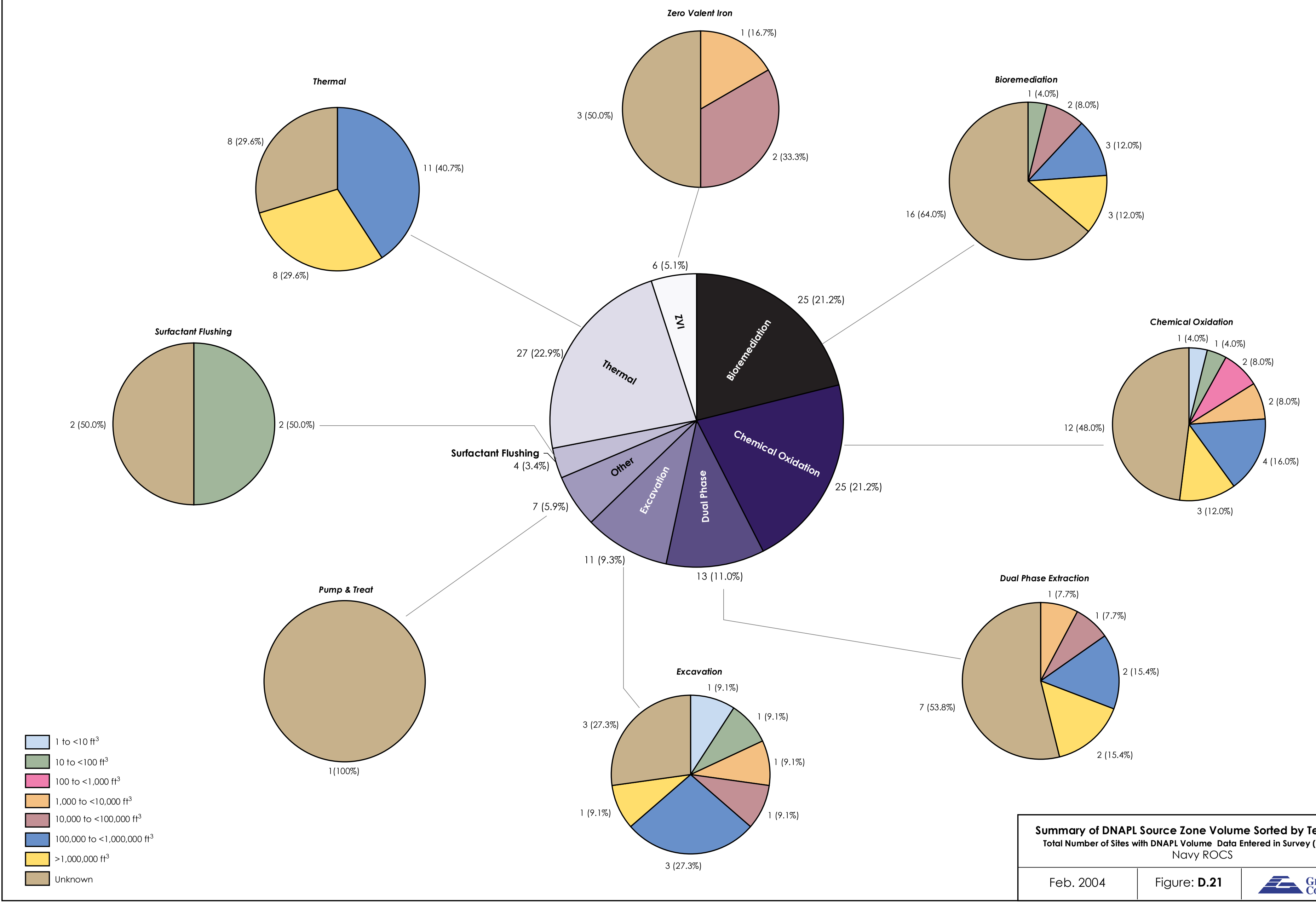


Summary of DNAPL Areal Extent Sorted by Technology

Total Number of Sites with DNAPL Areal Extent Data Entered in Survey (Center Pie)

Navy ROCS

Feb. 2004	Figure: **D.20**	GEOSYNTEC CONSULTANTS



▭	1 to <10 ft^3
▭	10 to <100 ft^3
▭	100 to <1,000 ft^3
▭	1,000 to <10,000 ft^3
▭	10,000 to <100,000 ft^3
▭	100,000 to <1,000,000 ft^3
▭	>1,000,000 ft^3
▭	Unknown

Summary of DNAPL Source Zone Volume Sorted by Technology
Total Number of Sites with DNAPL Volume Data Entered in Survey (Center Pie)
Navy ROCS

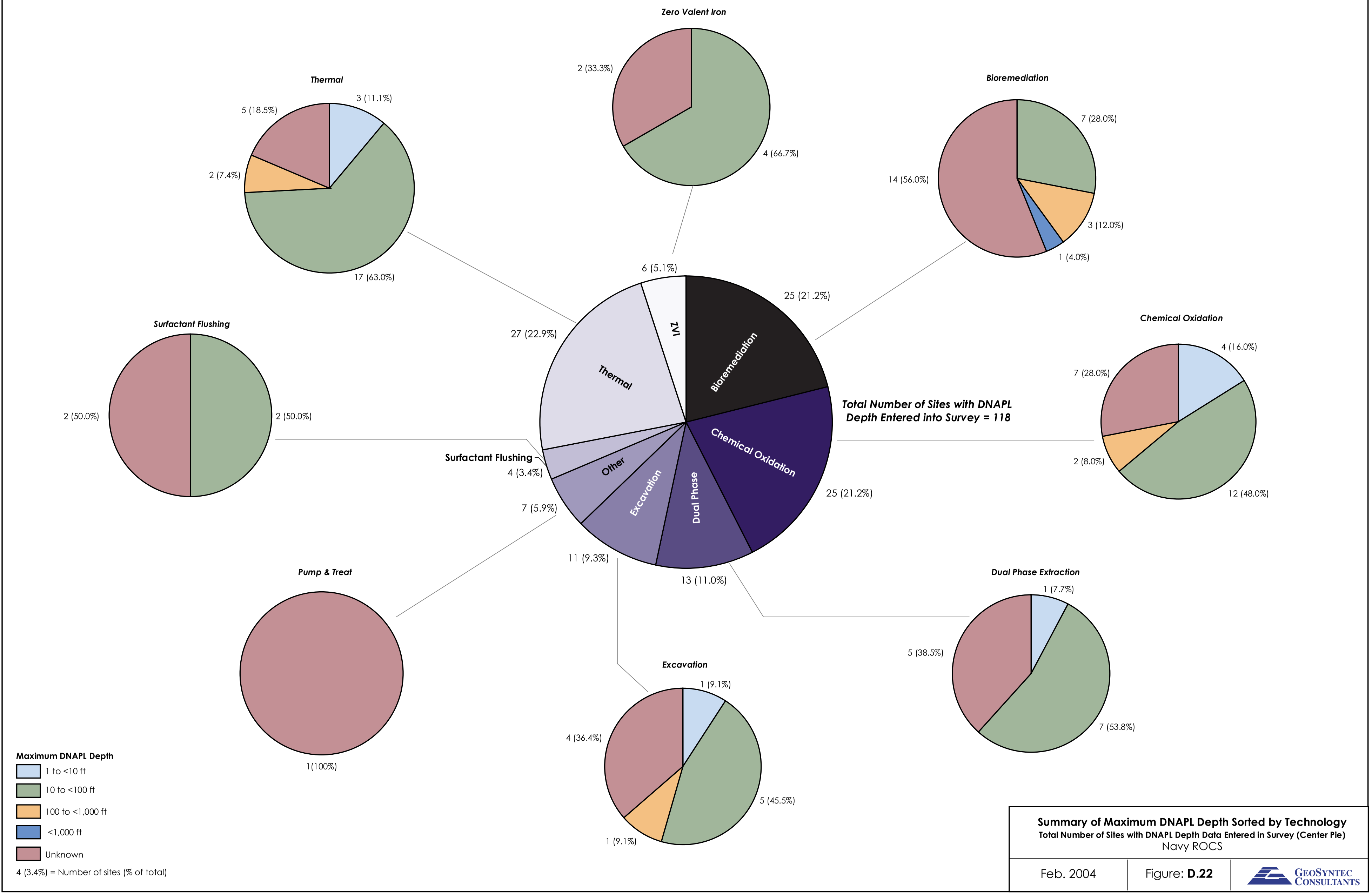
Feb. 2004
Figure: **D.21**
GEOSYNTEC CONSULTANTS

pie graphs_groups.ai

Summary of Maximum DNAPL Depth Sorted by Technology

Total Number of Sites with DNAPL Depth Data Entered in Survey (Center Pie)

Navy ROCS

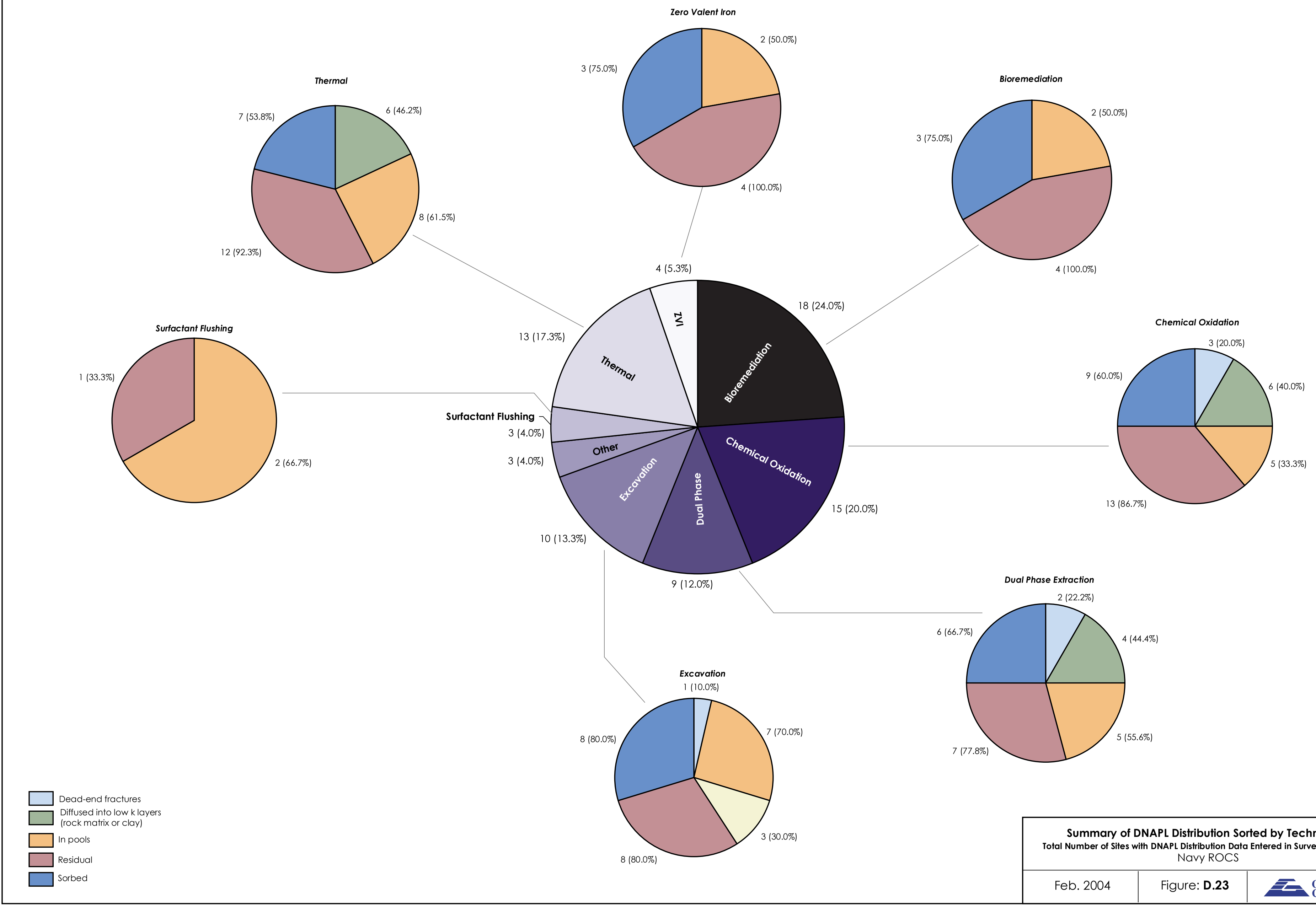


Feb. 2004

Figure: **D.22**

GeoSyntec Consultants

pie graphs_groups.ai



Summary of DNAPL Distribution Sorted by Technology

Total Number of Sites with DNAPL Distribution Data Entered in Survey (Center Pie)

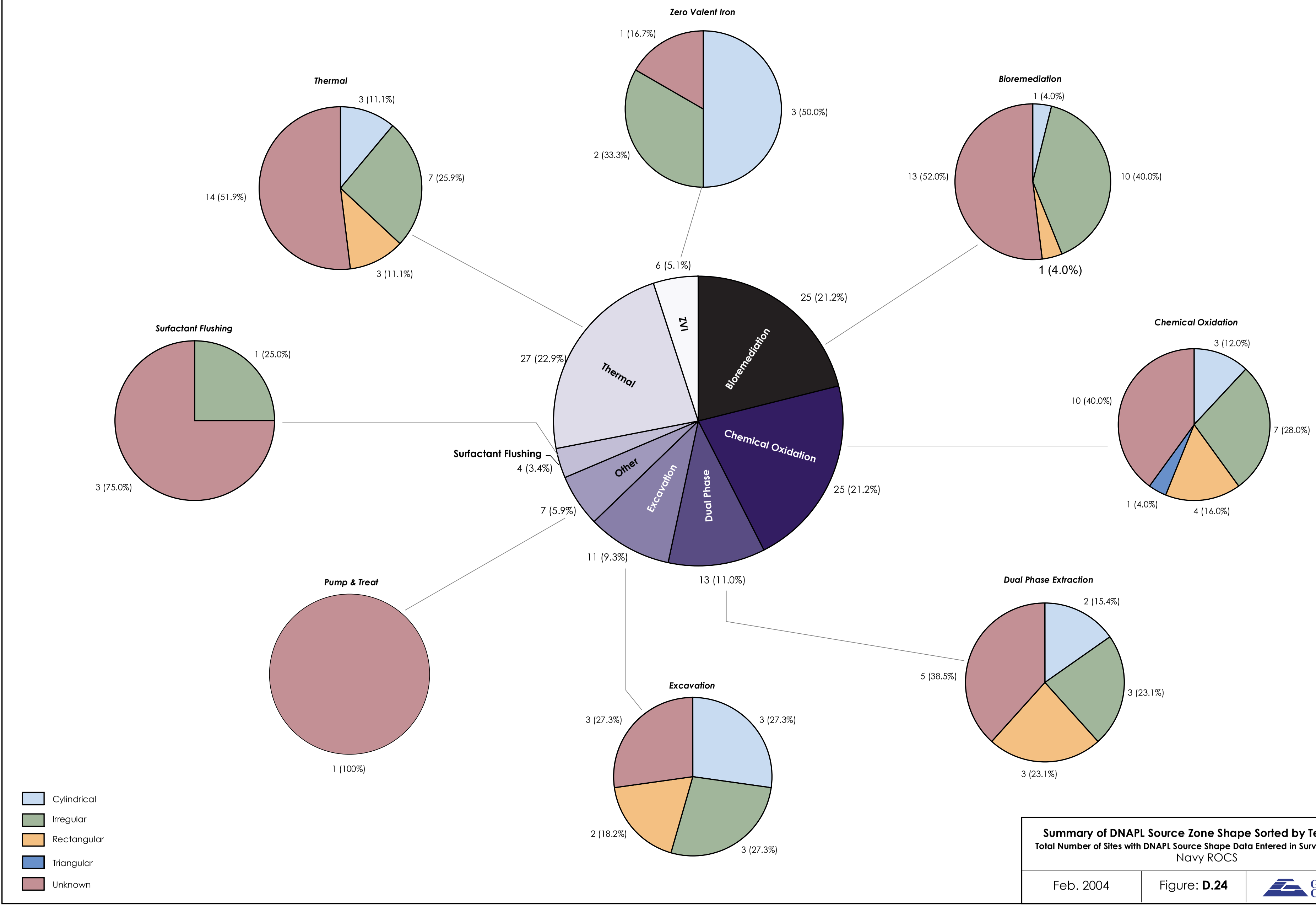
Navy ROCS

Feb. 2004

Figure: **D.23**

GeoSyntec Consultants

pie graphs_groups.ai



Summary of DNAPL Source Zone Shape Sorted by Technology

Total Number of Sites with DNAPL Source Shape Data Entered in Survey (Center Pie)

Navy ROCS

Feb. 2004

Figure: **D.24**

GeoSyntec Consultants

pie graphs_groups.ai