A NOVEL AMENDMENT DELIVERY SYSTEM

A NOVEL AMENDMENT DELIVERY SYSTEM FOR GROUNDWATER IMPACTED BY VINYL CHLORIDE

By

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Abstract

Although successful in laboratory studies, field applications of in situ remediation of chlorinated solvents in groundwater have met with limited success. This is most often attributed to the inability to deliver the amendment evenly throughout the target zone, especially in low permeability and heterogeneous materials. The goal of this research was to employ a prototype of a novel delivery system to evenly deliver amendment across the depth and breadth of the subsurface in a cost-effective method. The research was conducted at 42 Voyager Court, Toronto, ON where concentrations of vinyl chloride in groundwater were in excess of Ontario Ministry of the Environment guidelines (O.Reg.153/04). The subsurface consisted of sandy and clayey silt fill underlain by sandy silt till.

The delivery system comprised 29, ¼" diameter, delivery points with small perforations along the length, installed in a fence perpendicular to groundwater flow, approximately 0.5 m upgradient of the area of concern. The delivery system used low flow rates (approximately 13 to 23% of total groundwater flow) and discrete delivery holes to deliver a potassium permanganate solution (approximately 40 g/L) amended with sodium bromide (approximately 0.8 g/L) across the depth of the subsurface. Fourteen multi-level monitoring wells, each with five sampling ports were installed to monitor the effectiveness.

After six months of delivery, sample results indicated that oxidant demand hindered the ability of potassium permanganate to reach and degrade the vinyl chloride. However, elevated bromide concentrations were detected at all downgradient sampling ports within a 1.5 m distance. Thus, the delivery system was successful at delivering the amendment across the depth and breadth of the target area and achieving even delivery.

Problems, typically leaks, were encountered with the delivery system design. Additional engineering would be required to improve the header system prior to commercializing this process. This would be a beneficial endeavor, as results of this work indicate that this passive delivery fence technique meets a real need in the remediation industry, which is the even distribution of amendment to target zones in the saturated subsurface, including zones of low permeability.

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List of Abbreviations

BM	benchmark
CDN	Canadian
DCE	dichloroethylene
DNAPL	dense non-aqueous phase liquid
EPA	United States Environmental Protection Agency
ESA	Environmental Site Assessment
EZVI	emulsified zero valent iron
GC	gas chromatography
H_2O_2/Fe^{2+}	Fenton's Reagent
ID	inner diameter
ISCO	in situ chemical oxidation
$KMnO_4$	potassium permanganate
LNAPL	light non-aqueous phase liquid
LOQ	limit of quantitation
LPM	low permeability media
mbg	metres below grade
mbTOC	metres below top of casing
MCL	maximum contaminant level
MDL	method detection limit
MLMW	multi-level monitor well
MNA	monitored natural attenuation
MOE	Ontario Ministry of the Environment
MnO_4^-	permanganate ion
$MnO_{2(s)}$	manganese dioxide solids
NaBr	sodium bromide
NOD	natural oxidant demand
NOM	naturally occurring organic matter
OD	outer diameter
PCE	tetrachloroethylene
PRB	permeable reactive barrier
PPT	pressure pulse technology
PVC	poly vinyl chloride
SCRD	state coalition for remediation of drycleaners
SPME	solid phase micro-extraction
TCE	trichloroethylene
TOC	top of casing
USD	United States Dollars
VC	vinyl chloride
VOC	volatile organic compound

Chapter 1: Introduction

1.1 Introduction

Groundwater is an important natural resource. It accounts for approximately 26% of the freshwater used in the United States – with about 68% going to irrigation and about 19% to the public water supply (USGS, 2006) . In Ontario, groundwater provides three million people, including 90% of the rural population, with potable, irrigation and industrial water supplies (MOE, 2004). In addition to potable and irrigation supplies, groundwater also recharges lakes, streams and wetlands. From both human health and ecosystem perspectives it is important to strive to maintain a protected and clean groundwater system. However, groundwater continues to be contaminated with heavy metals, hydrocarbons, chlorinated solvents, human and agricultural wastes and other compounds as a result of spills, careless disposal and management practices, and sometimes naturally occurring phenomena.

Historically it was thought that since groundwater was below the ground surface, it was naturally protected from contamination (Schwille, 1988). By the 1950s and 1960s the technical community became aware of the risks of groundwater contamination posed by waste disposal practices (Harris, 1990; McCarty, 1990). However, it was not until the discovery of toxic waste disposal sites and the associated health concerns, such as the Love Canal, in the early 1970s that the problem of groundwater contamination received widespread public and media attention (Harris, 1990; McCarty, 1990). Following this, public demand and government support brought money and research dollars to the problem.

The US Environmental Protection Agency (EPA) has estimated that there are over 200,000 sites in the United States contaminated with toxic substances, of which volatile organic compounds (VOCs) are often the contaminants of concern (Siegrist et al., 2001). Of the known hazardous waste sites in the United States, it is estimated that perhaps 80% of them have contaminated groundwater (EPA, 1998). It was these initial large-scale discoveries that lead to the creation of the EPA Superfund program – a program to fund remediation efforts at contaminated sites across the United States (WSTB, 1990).

Following the widespread recognition of groundwater contamination large amounts of money, time and resources have been dedicated to the development of solutions to restore contaminated sites. Common groundwater contaminants encountered include heavy metals, hydrocarbons and chlorinated solvents. Dense non-aqueous phase liquids (DNAPLs) are an important class of groundwater contaminants, which includes chlorinated solvents (e.g., tetrachloroethylene (PCE), trichloroethylene (TCE), and vinyl chloride (VC)). Chlorinated solvents are typically characterized by their low aqueous solubilities and their high specific densities, which (with the exception of VC whose specific density is 0.9) typically range from 1.3 to 1.6 (Siegrist et al., 2001). Hydrocarbons such as gasoline with densities less than that of water are referred to as light non-aqueous phase liquids (LNAPLs) and in free-phase form tend to pool on the surface of the water table. This sometimes makes LNAPL source zones easier to remove, and as well there are often natural microbiological processes present that are capable of destroying the plume and the source zone over time (Cherry et al., 1996). Whereas with LNAPL contamination it may be possible to excavate the contaminated area, or remove the pooled source from the water table surface, these methods are usually not cost-effective or practical when dealing with DNAPLs (Mackay and Cherry, 1989). Additionally, the natural microbes typically present do not result in complete biodegradation of chlorinated solvents (Cherry et al., 1996). Thus, the treatment approach for contaminated sites varies depending on the contaminant(s) of concern as well as the hydrogeological site conditions.

For shallow vadose zone and shallow water table sites, a 'dig and dump' approach is often used, where the contaminated soil is excavated and either treated on-site or removed for disposal. However, for more extensive and/or deeper contaminated areas, excavation and disposal costs quickly escalate as the volume of excavated aquifer material increases. This, coupled with legislation regarding off-site disposal and the high cost of on-site treatment, causes the dig and dump alternative to quickly become an expensive undertaking (Cherry et al., 1996). In these situations, the conventional approach has been to employ the 'pump and treat' technique, where groundwater is pumped from the subsurface, treated above ground, and either disposed or returned to the aquifer (McCarty, 1990). However, depending on the type of contaminant and the size of the plume, this approach can also be costly and lengthy, especially when dealing with chlorinated solvents. The pump and treat approach for chlorinated solvent sites can reach upwards of 30 years or longer (EPA, 1998) due to the presence of source mass combined with slow mass transfer rates (Mackay and Cherry, 1989). As a result, pump and treat typically suffices only as a means of plume containment (Cherry et al., 1996) with associated capital and operating costs.

The solubility of chlorinated solvents can range from 100s to 1000s of mg/L (i.e. VC has a solubility of 1100 mg/L, TCE has a solubility of 1400 mg/L and PCE has a solubility of 240 mg/L) (Pankow and Cherry, 1996). However, due to the toxicity and negative human health impacts of these compounds, the guidelines for acceptable levels in non-potable groundwater range from 0.5 to 100 μg/L (MOE, 1997, 2004a), which is orders of magnitude lower than the solubility limits. This low solubility, combined with the even lower guideline levels means that minute quantities of residual chlorinated solvents in the subsurface can continue to contaminate a groundwater plume to levels above guidelines for long periods of time (Mackay and Cherry, 1989; Mackay et al., 2000). The low solubility also hinders the ability of natural attenuation and pump and treat methods to remove the compounds (Mackay and Cherry, 1989; Mackay et al., 2000). Source mass transfer rates can not be achieved by these traditional methods at rates high enough to significantly degrade the source over reasonable time periods (Mackay and Cherry, 1989).

The goal in groundwater remediation then, especially when dealing with chlorinated solvents and their inherent difficulties, is to increase the mass transfer and removal rate over a shorter time period, and ideally destroy or remove the contaminants. Since the early 1990s, research has been directed towards developing efficient methods of remediating groundwater contamination in situ (Watts and Teel, 2006). One method that has received a lot of attention has been in situ chemical oxidation (ISCO). In a laboratory setting, there are many chemicals and materials capable of oxidizing and thus remediating groundwater contaminants, and many successful feasibility and bench scale studies have been conducted. Following these successes, pilot scale studies and full-scale field applications have been carried out to varying degrees of success.

Subsurface heterogeneity often plays a role in hindering the success of the treatment applications. ISCO has been traditionally carried out under a forced gradient system. The treatment amendment is delivered to the subsurface under pressure and often coupled with a downgradient extraction well which is also removing the amendment under pressure. This creates a forced gradient and flow field encompassing the zone of interest (Amarante, 2000). However, what is sometimes seen in these types of applications is an initial drop in contaminant concentrations, followed by a rebound after treatment has stopped, or an inability to fully remove the contaminant indicating that the residual or source zone contamination has not been completely destroyed (Travis and Doty, 1990).

There are many reasons for lack of complete remediation in ISCO studies, but one cause is the effect of the forced gradient in situations with subsurface heterogeneity (Travis and Doty, 1990). As the flow of amendment is forced through the treatment zone it tends to follow the path of least resistance and therefore is channeled through the zones of high permeability, and bypasses the areas of the aquifer of lower permeability. However, contaminant may be present in these low permeability zones, due to diffusion (Cherry et al., 1996) or low groundwater flow rates. As a result, uniform delivery of the amendment to the groundwater throughout the source zone is not typically achieved and therefore contaminant destruction is not typically fully realized. The inability to achieve uniform amendment distribution has been noted in various field studies (e.g., Quinn et al., 2005). Another hypothesis is that higher flow rates can push untreated water into a monitoring zone (Chapelle et al., 2005, Parker et al., 2002). In addition to the above-mentioned concerns, large volumes of amendment are typically used along with high flow rates and pressures which results in increased costs. Along with the increased cost there is also the issue of effluent disposal or complications associated with recycling extracted groundwater/amendment. These reasons have been attributed to the failure, or lack of full success, of both pilot and full scale remediation projects.

The need exists for an affordable and feasible method of delivering amendments to the subsurface that is capable of achieving even delivery across the depth and breadth of the source zone or plume. If even delivery can be achieved in a heterogeneous setting, there are many compounds that if uniformly delivered could result in full in situ destruction of various contaminants.

1.2 Thesis Overview

The overall goal of this research is to design, install and test a delivery system that is both cost-effective and capable of achieving even delivery of amendment to the subsurface. The system will deliver an amendment, in this case potassium permanganate ($KMnO_4$) with sodium bromide (NaBr), to groundwater for the purpose of remediation. The project site is the rear parking lot of a small industrial/commercial property located at 42 Voyager Court, Toronto, Ontario, a map of this location is provided in Appendix A. The shallow groundwater at the site has levels of VC in excess of Ontario Ministry of the Environment (MOE) guidelines (Table 3 under O.Reg. 153/04). The prototype will be employed at the site in the remedial program, and the efficiency of the novel delivery technology will be assessed. It is hypothesized the delivery system design combined with the low delivery flow rates (15 - 20% of the existing groundwater flow rate), will achieve even delivery of the amendments to the heterogeneous subsurface of the site.

The following tasks were outlined in order to meet the above-mentioned goals:

- assess the existing groundwater conditions;
- install the delivery system along with a network of 14 multi-level monitoring wells (MLMWs);
- deliver a $KMnO_4$ solution, with sodium bromide (NaBr) added as a conservative tracer, through the installed delivery system;
- collect and analyze groundwater samples from the MLMWs for concentrations of bromide, chloride and vinyl chloride for the duration of the delivery process to monitor the progress and mixing of the amendment;

- assess the effectiveness of the delivery system from the concentrations measured in the groundwater samples; and
- should uniform subsurface mixing be achievable, the other inherent objective of the project is to remediate levels of VC present at the site to levels below the acceptable MOE guidelines (MOE, 2004a).

To present the methodology and results of this research, this thesis is comprised of seven additional chapters following this Introduction. Chapter 2 presents background material that describes scientific principles and a literature review of existing bodies of research relevant to this study. Chapter 3 summarizes the site history information obtained from available consultant reports. Chapter 4 outlines the materials and methods used. Chapter 5 presents and discusses the results of the hydrogeological site characterization and Chapter 6 presents and discusses the results of the delivery system and monitoring network. Finally, Chapter 7 presents conclusions and recommendations on the findings, while Chapter 8 includes the references used throughout this work.

Chapter 2: Background

2.1 Chlorinated Solvents

As discussed in Chapter 1, chlorinated solvents are an important class of groundwater contaminants. These compounds, such as tetrachloroethylene (PCE), trichloroethylene (TCE), and vinyl chloride (VC) are commonly used in electronics manufacturing, degreasing and cleaning activities (Mackay and Cherry, 1989). PCE is one of the more common chemicals used in drycleaning, and is often found at sites as a result of poor disposal practices. TCE is commonly used in the manufacturing of adhesives. Both PCE and TCE belong to a class of compounds referred to as dense non-aqueous phase liquids (DNAPLs), due to their physical properties. VC is a product of the degradation of PCE and TCE; it is not readily degraded by the naturally occurring soil microbes at most sites, and is therefore often a persistent contaminant after the parent products have been degraded (Siegrist et al., 2001). The degradation pathway from PCE to VC is shown in Figure 2-1. Table 2-1 gives a summary of the chlorinated solvents present at 42 Voyager Court, as well as their physical properties.

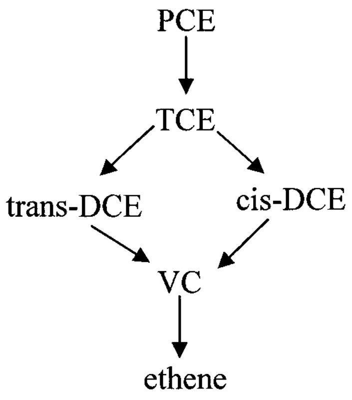
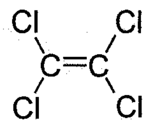
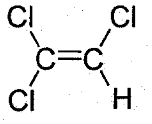
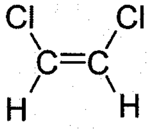
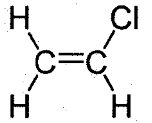


Figure 2-1: Degradation Pathway for PCE to VC

Table 2-1: Physical Properties of Select Chlorinated Solvents

Name	Formula	Diagram[+]	Density* (g/cm^3)	Solubility* (mg/L)
Tetrachloroethylene (PCE)	$Cl_2C=CCl_2$		1.63	237
Trichloroethylene (TCE)	$ClCH=CCl_2$		1.46	1385
Dichloroethylene (DCE) cis-1,2-DCE trans-DCE	$ClCH=ClCH$		1.28 1.26	7000 4390
Vinyl Chloride (VC, chloroethene, chloroethylene)	$CH_2=CHCl$		0.91	1100[a]

* Pankow and Cherry (1996) – Solubility value is calculated from vapor pressure p° and Henry's Law constant H: $S=p^{\circ}MW/(760H)$.
[+] USGS, 2006
[a] Schroth et al., (2001)

The physical properties of chlorinated solvents, (e.g., high densities, low solubilities and viscosities), make remediation difficult. The goal of many treatment technologies targeting chlorinated solvents is to increase the mass transfer rate in order to remove the mass over a shorter time period (e.g., ISCO, soil vapour extraction). The ideal result of remediation is to remove the mass present in the source zone, and destroy the contaminant(s).

2.1.1 Mechanisms of DNAPL Migration and Transport

Due to their physical properties, DNAPLs in the subsurface often have complex distributions influenced by subsurface heterogeneities (Feenstra et al., 1996), and can be present in several phases (i.e., liquid, dissolved, and gaseous). Figure 2-2 summarizes the various DNAPL distributions and phases present at contaminated sites. The following paragraphs summarize the DNAPL migration and transport mechanisms, and how these mechanisms result in the various distributions and phases present at most contaminated sites.

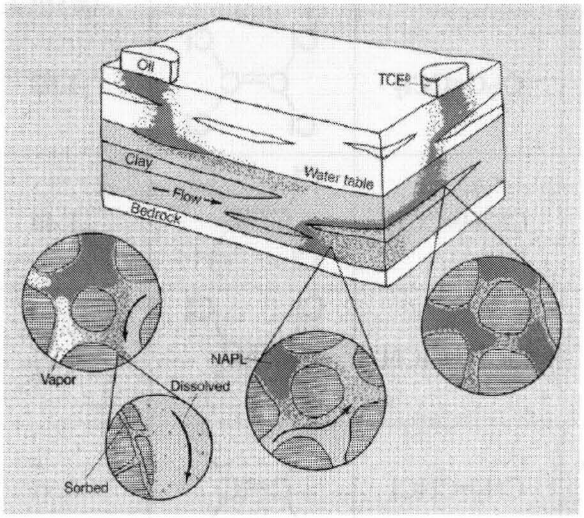


Figure 2-2: Transport Fate of DNAPL in Subsurface (McKay and Cherry, 1989)

DNAPLs can enter the subsurface in many ways (e.g., spill, accidental release, underground disposal) and can migrate downward through the water table due to their relatively high density and often low viscosities. Migration is halted when capillary forces exceed the gravitational and viscous forces. The capillary pressure is described by Equation 2-1:

$$\begin{aligned} P_c &= P_{nw} - P_w \\ &= \frac{2\sigma \cos\theta}{r} \end{aligned} \qquad \textbf{2-1}$$

where P_c [F/L^2] is the capillary pressure, P_{nw} [F/L^2] is the pressure of the non-wetting fluid (in this case DNAPL), P_w [F/L^2] is the pressure of the wetting fluid (in this case, water), σ [F/L] is the interfacial tension between the two fluids, θ [rad] represents the contact angle between the two fluids and the solid surface, and r [L] is the representative cylindrical radius of the pore space. As the pressure in the non-wetting phase increases with respect to the wetting phase, then the non-wetting fluid can invade increasingly smaller pores and displace the wetting fluid. If the water/DNAPL interfacial tension is decreased, then it is easier for the

DNAPL to enter the pore space. When the DNAPL encounters a finer layer, capillary pressures become large due to very small pore throats, and vertical migration may become arrested. DNAPL will spread laterally across the porous media surface, forming a region of high DNAPL saturation. These regions of high saturation are termed pooled or free-phase DNAPL. Once the driving forces diminish, DNAPL in the pore spaces can become disconnected (Pankow and Cherry, 1996).

As groundwater displaces the draining DNAPL, what remains is residual DNAPL. Residual DNAPL is defined as that which is retained in select pores due to snap-off and bypassing phenomena (Kamon et al., 2004). The typical residual DNAPL content (S_{nw}) in porous media ranges from 0.01 to 0.15 (Pankow and Cherry, 1996). As it is no longer continuous, the DNAPL becomes immobile, and therefore cannot be easily pumped out (Schroth et al., 2001). However, higher mass transfer rates occur from DNAPL present in residual formations than pooled formations due to the larger interfacial area to volume ratio available for mass transfer.

Although DNAPLs are immiscible, they will partially dissolve in water and it is this dissolved component that is transported in groundwater as the contaminant plume (Feenstra et al., 1996). This plume will move due to advection, and spread due to mechanical dispersion and molecular diffusion. At low velocities, diffusion is the larger contributor to spreading, whereas at higher velocities mechanical dispersion causes the majority of the spreading (Freeze and Cherry, 1979). This spreading can be slowed down or retarded by the sorption of DNAPL onto aquifer solids (Feenstra et al., 1996), particularly when large amounts of organic carbon are present.

DNAPL can also be present in the vadose zone. If the DNAPL is volatile, depending on the release mechanism, it may create a vapour plume in the soil air. The vapour phase DNAPL may also dissolve into groundwater, as surface water infiltrates through, or the water table fluctuates up into the zone of the vapour plume, (Pankow and Cherry, 1996).

Compounding the contamination problem is geological complexity. At many sites, aquifer materials are comprised of both higher permeability zones such as sand and gravel, and lower permeability zones such as silt and clay. As reported by McKay and Cherry (1989), dissolved contaminants can move relatively quickly through zones of higher permeability due to advection. However, over time contaminants will also invade zones of low permeability due to molecular diffusion and advection (see Figure 2-2). In order to achieve contaminant destruction and remediation at a site, it is also necessary to remediate these zones of low permeability. If they are overlooked or go untreated they will continue to contribute mass to the plume following remediation efforts.

2.2 Oxidation Reagents

Permanganate (MnO_4^-) was initially studied as an oxidant for use in water and wastewater treatment (Siegrist et al., 2001). MnO_4^- was first employed for its oxidation potential of reductants (e.g., reduced organics, naturally occurring organic matter (NOM)). Following this, research regarding MnO_4^- oxidation capacity turned to the examination of oxidants for treatment of target contaminants such as PCE, TCE and VC. MnO_4^- has also been used in the removal of iron and manganese, however, its ability to oxidize certain metals may be of some concern in certain field applications (see Section 2.2.3 for details) (Schnarr et al., 1998).

MnO_4^- along with hydrogen peroxide (H_2O_2)(or Fenton's reagent (H_2O_2/Fe^{+2})) and ozone (O_3) have all been proposed and studied for use in the oxidation of chlorinated solvents in groundwater applications. Early work involved the oxidation of VOCs with H_2O_2 or H_2O_2/Fe^{+2} and $KMnO_4$, and studies have shown that both are capable of achieving greater that 90% VOC removal in groundwater and soil and (Gates-Anderson et al., 2001).

Fenton's reagent requires a lower pH than typical groundwater conditions to operate effectively and therefore the pH of in-situ groundwater systems may need to be altered to implement this technique. Additionally, the Fenton's reagent oxidation reaction has been found to be strongly exothermic, with the production of heat and gas, which results in increased safety concerns. Fenton's reagent is also hindered by certain compounds found in groundwater such as carbonate, bicarbonate and organic matter due to competing reactions. Additionally, Fenton's reagent is toxic to soil microbes and therefore it is not compatible in combination with bioremediation, limiting its flexibility (Amarante, 2000; Siegrist et al., 2001).

Ozone also requires a pH lower than that typically present in subsurface systems to achieve effective reactions. As well, ozone is relatively unstable and in most cases must be produced on site with generators, increasing the complexity and operating costs (Watts and Teel, 2006). The half-life of ozone is quite short, and therefore application methods require multiple contact points in close succession to ensure the ozone reaches the contaminated area to effect the oxidation reaction, therefore decreasing its flexibility (Siegrist et al., 2001).

In contrast to Fenton's reagent and ozone, MnO_4^- can function as an oxidant under a pH range of about 3 to 12. This makes it suitable for a wide range of naturally occurring subsurface systems without the need to acidify or buffer

(Amarante, 2000; Siegrist et al., 2001). Additionally, MnO_4^- typically comes in a crystalline solid form, as $KMnO_4$, which is easily mixed on-site with groundwater or tap water to achieve desired application concentrations, and has a relatively high aqueous solubility at approximately 65.0 g/L in 20°C water (Carus, 2005). As a result of its ease of use, MnO_4^- has been widely studied in the last decade as an oxidant for chlorinated solvents in groundwater systems; however ozone and Fenton's reagent may have site-specific advantages.

2.2.1 Permanganate Reactions

Oxidation by MnO_4^- and the reaction process was thoroughly studied by Stewart (1965) who detailed the reactions of MnO_4^- with organic compounds. The reaction rate will depend somewhat on the pH of the system, with reaction kinetics increasing under both alkaline and acidic conditions as opposed to neutral conditions. Under acidic conditions, the MnO_4^- ion is converted to permanganic acid which is a stronger oxidant (Stewart, 1965). However, due to the natural pH range in most groundwater systems, MnO_4^- is typically the oxidant. In terms of the propensity for compounds to be oxidized by MnO_4^-, anions are more readily oxidized than neutral molecules, while neutral molecules are more readily oxidized than cations (Stewart, 1965).

Equations 2-2 and 2-3 outline the half-cell reactions for MnO_4^- under varying pH conditions (Siegrist et al., 2001):

$$MnO_4^- + 8H^+ + 5e^- \rightarrow Mn^{+2} + 4H_2O \qquad (pH<3.5) \qquad \textbf{2-2(a)}$$

where excess MnO_4^- oxidizes Mn^{+2} as follows:

$$3Mn^{+2} + 2MnO_4^- + 2H_2O \rightarrow 5MnO_{2(s)} + 4H^+ \qquad \textbf{2-2(b)}$$

$$MnO_4^- + 2H_2O + 3e^- \rightarrow MnO_{2(s)} + 4OH^- \qquad (3< pH<12) \qquad \textbf{2-3}$$

The oxidation reactions for PCE and its daughter products are given by equations 2-4(a) through 2-4(d) (Siegrist et al., 2001):

$$4KMnO_4 + 3C_2Cl_4 + 4H_2O \rightarrow 6CO_2 + 4MnO_{2(s)} + 4K^+ + 8H^+ + 12Cl^- \quad \textbf{2-4(a)}$$

(PCE)

$$2KMnO_4 + C_2HCl_3 \rightarrow 2CO_2 + 2MnO_{2(s)} + 2K^+ + 3Cl^- + H^+ \quad \textbf{2-4(b)}$$

(TCE)

$$8KMnO_4 + 3C_2H_2Cl_2 \rightarrow 6CO_2 + 8MnO_{2(s)} + 8K^+ + 6Cl^- + 2OH^- + 2H_2O \quad \textbf{2-4(c)}$$

(DCE)

$$10KMnO_4 3C_2H_3Cl \rightarrow 6CO_2 + 10MnO_{2(s)} + 10K^+ + 3Cl^- + 7OH^- + H_2O \quad \textbf{2-4(d)}$$

(VC)

$KMnO_4$ oxidizes the chlorinated solvents into relatively non-hazardous by-products including: carbon dioxide gas (CO_2), water (H_2O), potassium ions (K^+), chloride ions (Cl^-), hydrogen ions (H^+), hydroxyl (OH^-) and manganese dioxide particles ($MnO_{2(s)}$).

The amount of $KMnO_4$ required to treat a known mass of chlorinated solvent can be determined from the above reaction stoichiometry. Additionally, the production of Cl^- can be used to monitor the mass of chlorinated solvent destroyed. By monitoring increases in the effluent chloride ion concentration, the equivalent mass of solvent destroyed can often be calculated using a stoichiometric approach (Schnarr et al., 1998).

2.2.2 Mechanisms of $KMnO_4$ Transport in Groundwater

$KMnO_4$ is transported through the subsurface mainly due to advection under ambient groundwater flow conditions or under a forced hydraulic gradient (Siegrist et al., 2001). Additionally, though to a lesser extent, transport is influenced by mechanical dispersion (Siegrist et al., 2001). In cases of fine-grained soils and zones of low-permeability molecular diffusion may dictate the movement of $KMnO_4$ (Siegrist et al., 2001; Struse et al., 2002). Struse et al. (2002) studied the transport of $KMnO_4$ by diffusion in the treatment of a TCE impacted soil core and demonstrated that $KMnO_4$ could migrate via diffusion and degrade the TCE impacted material.

Transport may also be affected by density gradients, especially in the case of concentrated $KMnO_4$ solutions, as highly concentrated $KMnO_4$ solutions are more dense than water. The specific gravity of $KMnO_4$ crystals is approximately 2.7 g/cm^3 (Carus, 2005), and a 3% $KMnO_4$ solution prepared with $KMnO_4$ crystals has a specific gravity of 1.02 g/mL. As $KMnO_4$ is often applied at concentrations higher than 3%, sometimes even at concentrations upwards of 40%, the transport of the oxidant can be influenced by gravity resulting in an overall downward movement of oxidant, versus the predominantly lateral advective movement of groundwater. Density driven $KMnO_4$ movement has been reported to have affected monitoring results in field experiments and applications (e.g., Hood et al., 1997; Parker et al., 2002).

$KMnO_4$ is insoluble in hydrocarbon compounds (i.e., most chlorinated solvents) (Schnarr et al., 1998), but, as previously mentioned, is highly soluble in water. Therefore, the treatment mechanism in the case of a DNAPL source zone involves dissolution of DNAPL into aqueous solution, where it is oxidized upon contact with $KMnO_4$ (Siegrist et al., 2001). This oxidation process is thought to increase the mass transfer rate of DNAPL into groundwater by increasing the concentration gradient and therefore enhance the overall dissolution rate of the source zone. The stagnant film model (Nernst, 1904), as illustrated in Figure 2-3, is commonly applied to describe the mass transfer of DNAPL and subsequent destruction by $KMnO_4$.

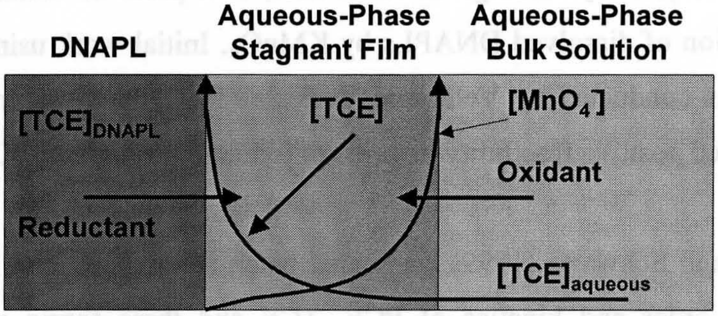


Figure 2-3: Stagnant film model of DNAPL mass transfer and destruction by MnO_4^- (adapted from Siegrist et al., 2001)

2.2.3 Application of Permanganate for ISCO in Laboratory Studies

To date, research regarding the oxidation of chlorinated solvents by MnO_4^- has been in the form of laboratory-scale studies consisting of batch tests to investigate the effectiveness of oxidants at destroying chlorinated solvents, and to determine the reaction mechanisms (e.g., Vella and Veronda, 1992; Yan and Schwartz, 1999). Additionally, bench-scale tests using one-dimensional (1-D) column flow studies and two-dimensional (2-D) tank flow studies have been employed to further evaluate the reaction and efficiencies under varying media and contaminant conditions (e.g., Schnarr et al., 1998; MacKinnon and Thomson, 2002). Further to laboratory-scale studies, pilot-scale field studies have been conducted as well as limited full-scale field applications (e.g., Hood et al., 1997; Parker et al., 2002). Following both the success and limited success of implementation, recent research has been focused on addressing issues such as natural oxidant demand and delivery problems.

Laboratory Experimentation

Generally, early findings of batch tests, as a proof of concept, indicated quick oxidation of dissolved DNAPLs by $KMnO_4$. Initial work using batch tests and TCE was conducted by Vella and Veronda (1992) in a soil medium. The study indicated positive feasibility in terms of oxidation of TCE by $KMnO_4$.

Yan and Schwartz (1999) conducted batch test experiments to determine the reaction order and kinetics of PCE, TCE and three forms of DCE in a permanganate solution. Additionally, the effects of pH and other organic compounds naturally occurring in the matrix were assessed. Findings indicated that the reactions were quick, with pseudo-first-order rate constants when the concentration of MnO_4^- was in excess (Yan and Schwartz, 1999). Pseudo-first order reactions can occur when one of the reactants is in large excess over the other and therefore its concentration is constant with respect to time (McIntosh, 2005). Additionally, as the number of chlorine atoms on the ethylene molecule decreased, the reaction rate was seen to increase as outlined in Table 2-2:

Table 2-2: Rate constants (K_{obs}: pseudo-first-order rate constant) and Half-Life

Chlorinated Ethylene	K_{obs} (10^{-4} s^{-1})	Half –Life (min)
PCE	0.45 ± 0.03	256.7
TCE	6.5 ± 0.1	17.8
cis-DCE	9.2 ± 0.5	12.6
trans-DCE	300 ± 20	0.4
1,1-DCE	23.8 ± 1.3	4.9
VC	NR	instantaneous*

(Yan and Schwartz, (1999); * Marvin et al., (2000)) The half-lives of the chlorinated ethylenes, were 18 minutes or less (with the exception of PCE whose half-life was over four hours) in the Yan and Schwartz (1999) experiments, and decreased with decreasing numbers of chlorine atoms, and the half-life of VC reported by Marvin et al. (2000) was instantaneous at $KMnO_4$ concentrations of 1 g/L. In a detailed study of the TCE reaction, the degradation appeared to be second order, however it did not appear to be significantly affected by the system pH (Yan and Schwartz, 1999). The pH was analysed within the range of 4 to 8, which is not considered to be an extreme pH range. Another interesting finding of the Yan and Schwartz (1999) work was with regards to degradation products, as it had been proposed that harmful products might be formed during the degradation process. However the study results suggested that complete dechlorination occurred and therefore the concern over harmful dechlorination by-products was not substantiated.

Li and Schwartz (2000) conducted batch tests to examine the reaction between natural aquifer material and MnO_4^-. Samples of various aquifer materials were used to evaluate the release of metals during the oxidation process. Results (with the exception of glass beads and silica sand) indicated that the aquifer materials were oxidized. Twelve elements were monitored in the experiments, and the aqueous concentrations of chromium (Cr), selenium (Se) and rubidium (Rb) were found to increase over the course of the experiments, with Cr showing the most significant increase (Li and Schwartz, 2000). Implications of these findings are that certain metals sorbed to the aquifer organic material may be oxidized and come into solution; Cr could possibly be oxidized to its hexavalent form (Cr(VI)), which may be of concern from a groundwater quality perspective.

In summary, the findings of these initial batch tests were that $KMnO_4$ could be used to successfully oxidize chlorinated solvents. Studies with respect to reactions rates indicated that theoretically the complete destruction of chlorinated solvents should occur quickly when exposed to the oxidant. These initial studies also confirmed that generally no harmless by-products were formed in the reactions, with the exception of the propensity of some metals present in the aquifer material to be oxidized and come into solution.

Laboratory Column and Tank Experiments

Column experiments are typically employed to observe and quantify oxidation reactions and components. For example, using a residual PCE source emplaced in a column, Schnarr et al. (1998) were able to achieve 91 to 96% removal with $KMnO_4$. Additionally, they confirmed the feasibility of using Cl^- as a tracer indicative of dechlorination with their results. In another example, Schroth et al. (2001) were also able to achieve the successful removal of a residual TCE source, and their results indicated that the use of oxidant flushing through the column resulted in an apparent increase in mass transfer rate from the TCE source when compared with water flushing alone.

MacKinnon and Thomson (2002), used an emplaced pool DNAPL source and flushed it with $KMnO_4$, however they were only able to achieve approximately 45% source destruction. These results, along with the above-mentioned column results among others (e.g., Lee et al., 2003) brought to light issues of $MnO_2(s)$ precipitation and CO_2 gas production. Both the production of MnO_2 solids and CO_2 gas were found to plug the cell, disrupt flow pathways, and prevent complete source destruction. MacKinnon and Thomson (2002) found that MnO_2 formed a precipitate rind around the source zone, preventing further destruction (see Section 2.2.4 for details on MnO_2).

Field Experimentation

Relatively early field experiments were conducted by Schnarr et al. (1998) in association with the column flow experiments discussed previously. The purpose of the field study was to evaluate the in situ oxidation of both a residual PCE source and a TCE/PCE point source. The studies were conducted within a relatively small (7.5m^3) sheet pile test cell, located in the well-characterized Borden aquifer. In the first experiment, a residual source zone was created by mixing PCE with soil and emplacing the mixture in the centre of the test pile cell. Six injection wells were then used to deliver a $KMnO_4$ solution, and six extraction wells were used to create the hydraulic gradient and flush the PCE source. Results indicated that complete removal from the residual source zone was obtained after 120 days (Schnarr et al., 1998).

Schnarr et al. (1998) constructed the point source to simulate a heterogeneously distributed pool in the subsurface formed via a slow leak. The point source was flushed with $KMnO_4$ solution similar to the residual source. The point source flushing resulted in a removal efficiency of 62%, a significant decrease in comparison with the residual source study under similar subsurface conditions. This highlighted the fact that the distribution of a DNAPL source is key to the effectiveness of the remediation system. The importance of the distribution of the source zone was reinforced by MacKinnon and Thomson (2002), who only achieved 45% destruction of their pooled source zone after flushing for 146 days at the laboratory scale.

Without the use of a sheet pile containment cell, Hood et al. (1997) evaluated the removal of an emplaced residual PCE/TCE source, also at Borden, via a $KMnO_4$ flush. Six injection and five extraction wells were used in combination with an 8 g/L $KMnO_4$ solution. After a flushing period of approximately 465 days, they had removed approximately 99% and 90% of the TCE and PCE respectively from the source zone. However, at least half the injected oxidant was lost from the treatment zone. This was suspected to be a result of the initially high delivery flow rates resulting in bypass and downward migration due to the increased density of the $KMnO_4$ solution relative to groundwater (Hood et al., 1997).

2.2.4 MnO_2 Precipitate Genesis

As discussed previously, the precipitation of MnO_2 has been found to reduce the permeability of porous media as well as form a rind of precipitate around a DNAPL pool (e.g., MacKinnon and Thomson, 2002), significantly reducing the rate of mass transfer from the DNAPL source zone to the aqueous phase $KMnO_4$ solution. In laboratory experiments, plugging, permeability decrease, preferential flow, and pump failure have all been attributed to the precipitation of MnO_2 (e.g., Li and Schwartz, 2000; Schroth et al., 2001). Study results indicate that the formation of MnO_2 precipitate forms the largest barrier in terms of remediating pooled versus residual or dissolved DNAPL with $KMnO_4$.

Studies conducted by Siegrist et al. (2002) addressed the production of particles in the oxidation of TCE. Under increasing concentrations of TCE, the production of filterable solids (i.e., the production of MnO_2 particles) increased. Siegrist et al. (2002) also found that filterable solids production increased when silt/clay sized particles were present in the groundwater, and that the system permeability decreased with the production of filterable solids.

Crimi and Siegrist (2004) investigated the effect of varying reaction conditions on the production of MnO_2 particles. They found faster and more extensive particle generation with the presence of higher $KMnO_4$ and TCE concentrations (Crimi and Siegrist, 2004). These results were consistent with the findings of Siegrist et al., (2002), and are expected based on stoichiometric considerations. As well, a lower pH (pH of 3) resulted in more of the MnO_2 particles remaining suspended in solution than at a higher pH (pH of 7). Over the long term, however, (in this study six months) settling was still observed. The presence of cations, in this case Ca^{+2}, also appeared to have some effect on increasing MnO_2 settling. Findings of this study indicate that consideration must be given to subsurface geochemical conditions prior to the implementation of ISCO. Based on these findings one may be able to manipulate design conditions to better achieve remediation goals and minimize the formation of troublesome MnO_2 particles (Crimi and Siegrist, 2004).

2.3 Natural Oxidant Demand

In addition to the amount of $KMnO_4$ stoichiometrically required to oxidize the chlorinated solvent, naturally occurring species and organic matter in the subsurface will also be oxidized by MnO_4^- (Haselow et al., 2003). For successful ISCO implementation, it is important to develop an estimate of not only the contaminant oxidant requirements but also the oxidant requirements of the aquifer solids so that the required oxidant load is not underestimated (Haselow et al., 2003). Early research into the oxidation and reduction capacity of aquifer solids was conducted by Barcelona and Holm (1991). Their results indicated that groundwater has little redox capacity compared to that of the aquifer solids. This increased redox capacity implies that aquifer solids represent a potential obstacle to the successful implementation of subsurface chemical oxidation (Barcelona and Holm, 1991).

Early studies, initially conducted in water treatment applications, identified the reaction of $KMnO_4$ with inorganic species such as reduced forms of iron, sulphur and manganese (Stewart, 1965). The reaction of $KMnO_4$ with both inorganic species (such as iron oxides, sulphur) as well as organic and humic matter in soil will compete with the contaminant for oxidation by $KMnO_4$ (Haselow et al., (2003); Crimi and Siegrist, (2005)).

In early MnO_4^- ISCO studies, researchers (e.g., Schnarr et al., (1998); Hood et al., (1997); Lowe et al., (2002)) noticed that the removal of contaminants from aquifer material, both in laboratory and field trials, required quantities of oxidant in excess of those predicted by the reaction stoichiometry. This excess demand, attributed to the consumption of oxidant by the soil material, was labeled as soil oxidant demand (SOD) or natural oxidant demand (NOD). Few studies have been conducted to specifically examine NOD, however, based on inferences from field/pilot studies, NOD values of 30, 11, and 1 g_{KMnO_4}/kg of dry aquifer material were estimated for various aquifer materials (Mumford et al., 2004). The exact mechanism and players in the NOD reaction are not fully understood. Studies have not focused on the correlation between certain reduced species, or organic matter and NOD due to the widely variable field conditions (Crimi and Siegrist, 2005).

Studies were conducted by Mumford et al. (2002, 2005) to specifically investigate the nature and reaction rate of NOD reactions with aquifer material. The initial conceptual model for NOD was that the full oxidant demand of the aquifer constituents must be met before the $KMnO_4$ could oxidize the contaminant of concern (Barcelona and Holm, 1991). Mumford et al. (2002) proposed that instead NOD could be thought of as a separate reaction, where depending on the reaction rate and transport mechanism, the $KMnO_4$ would either react with the aquifer material or with the contaminant of concern. In these studies both batch tests and flow through column tests were conducted on similar soil materials. An ultimate NOD in excess of 1.2 g/kg was estimated for batch tests, while NOD in column flow tests was on the order of 0.2 to 0.6 g/kg (17 to 50% of the batch test result). Findings indicated that it was possible for the $KMnO_4$ to be transported through the aquifer material prior to complete oxidation due to the competing reaction rates. It was therefore proposed that certain NOD reactions occur more slowly than previous models indicated (Mumford et al., 2005). The results of this study indicate that the $KMnO_4$ requirements of the aquifer material may be less than previous conceptual models indicated, however, in repeated application situations it may be necessary to continue to provide $KMnO_4$ in order to address the aquifer demand in repeated application situations (Mumford et al., 2005).

Detailed studies were also conducted by Crimi and Siegrist (2005) in a factorial experimental design to investigate, among other things, the effect of changing soil, groundwater, and DNAPL conditions on the media oxidant demand. Using concentrations ranging from 0.025 to 5% $KMnO_4$, and various soil materials, it was found that oxidant demands ranged from 0.08 to 13.2 g/kg after a 24 hour period. It was also found that increasing the oxidant load resulted in an increase in oxidant demand by the soil media, which was consistent with findings from Siegrist et al. (2002). This conclusion was also reached by Mumford et al. (2005), who suggest that it is due to the fact that there is an increased amount of $KMnO_4$ available for contact in each pore space.

2.4 In Situ Contaminant Destruction

There are two typical approaches for treating chlorinated solvent impacted sites; containment and source/plume mass destruction. Pump and treat systems, cut-off walls and permeable reactive barriers (PRBs) are three types of containment methodologies commonly employed in field applications (EPA, 2003). Although these methods have proven successful at containing contamination from migrating either off-site or towards sensitive receptors, few studies have documented the long-term effects of such containment methods

(EPA, 2003). In addition to the uncertainty over long-term operation, the biggest drawback to using containment as a solution is that the contamination still exists (Quinn et al., 2005). When the contamination is not actively remediated, the site requires long-term management and monitoring and therefore incurs the costs associated with these tasks (EPA, 2003).

An alternative to containment is active source/plume mass destruction. According to a report released by the EPA (2003), there are three proven source mass destruction technologies: thermal destruction, in situ surfactant/cosolvent flushing, and ISCO, with in situ bioremediation also receiving more research and application in recent years. All of these technologies rely on the delivery of various amendments to the subsurface with the goal of contacting and destroying/removing the source zone/plume, and all are subject to the same issue. The technologies rely on the even delivery of amendment through the target zone to function successfully. However, these techniques are rarely able to distribute the amendment throughout the target zone.

Commonly with in situ technologies, it is possible to achieve large mass reductions of the DNAPL source zone. There are several technologies proven in research that result in what the 2003 EPA research panel deemed "partial source depletion". What most applications lack, however, is the ability to deplete the dissolved and sorbed phase mass that is present in the low-permeability media (LPM) (EPA, 2003). Common in situ technologies have been limited in their ability to deliver amendment to, and therefore destroy the contaminant mass that is present in, the LPM. Travis and Doty (1990) noted that when contaminants are trapped in LPM, pumping and forced gradient techniques result in preferential flow through higher permeability zones. This results in bypass of the LPM and its associated contaminants. Unless the contaminants remaining in the LPM are addressed somehow, they will continue to contribute mass to the groundwater, and typically will contribute to rebound concentrations once the pumps have been turned off. Although it has been proposed that once the majority of the source mass is removed, concentrations released from the LPM may be significantly lower than the original contaminant concentration, if the end result is to achieve the applicable maximum contaminant level (MCL) for the site, the contaminant present in the LPM contaminant must often be addressed (EPA, 2003).

Various delivery methods have been employed for ISCO, including lance permeation (direct push injection), soil fracturing, soil mixing, air sparging with ozone, and well to well flushing (injection and extraction wells) (Siegrist et al., 2001). The two most common methods for applying in situ oxidation are high pressure injection wells and direct-push probes (Watts and Teel, 2006). In highly permeable formations, gravity fed wells and infiltration galleries have also been employed (Watts and Teel, 2006). For less permeable formations hydraulic or pneumatic fracturing has been the delivery method of choice.

2.4.1 Pneumatic Fracturing

Pneumatic fracturing involves fracturing either soil or rock formations with compressed air. The goal of this method is to increase the permeability of the formation through inducing fractures or increasing existing aperture widths (Ding et al., 1999). This increases the permeability of the media and therefore, the method of amendment transport is driven by advection/dispersion rather than original diffusion as it would have been in the low-permeability formation (Ding et al., 1999).

Siegrist et al. (1999) emplaced MnO_4^- solids in the subsurface via hydraulic fracturing to treat a TCE source at a location with silty clay soils. The MnO_4^- mixture was observed to create a diffusive zone which extended about 0.4 m from the fracture over a 10-month treatment period. In the zone of contact adjacent to the fractures, greater than 99% removal of the TCE was observed. The movement of MnO_4^- ions from the fractures was thought to occur mainly by diffusion in the low permeability soils, but possibly also by advection due to capillary forces (Siegrist et al., 1999).

Applications for this method would be as a reactive barrier to prevent further migration. A method for determining or ensuring that MnO_4^- diffuses sufficiently over the matrix distance between fractures would be required to achieve full containment and treatment of the source. To actively treat a plume, due to low transport rates in LPM, it might be necessary to create a fairly large fracture network which would result in increased costs. As the method of fracturing and oxidant emplacement often relies on passive DNAPL transport and dissolution through the zone of the hydraulic fracture, similar to a PRB, there may be little reduction in the time and associated monitoring costs as compared with natural attenuation, unless the fractures are applied in conjunction with a more active source destruction approach, or in large numbers.

2.4.2 Injection/Extraction Wells

Injection/extraction wells use a forced hydraulic gradient supplied via pumped extraction wells to distribute the oxidant to the desired location. This method is associated with relatively higher capital costs due to the installation of extraction wells and pumping mechanisms. Well installation itself can be costly, especially when large numbers of wells are required to treat an area (e.g. the 7.5 m^3 test cell treated by Schnarr et al. (1998) which required six injection and six extraction wells in addition to a monitoring network). Injection wells can either be horizontal or vertical.

Field studies recently conducted by Quinn et al. (2005) used pressure pulse technology (PPT) as a means of injecting emulsified zero valent iron

(EZVI) in situ. PPT uses high flow rates in combination with high pressure pulses to deliver the amendment via an injection well. Results indicated approximately a 68% decrease of the TCE concentration in groundwater; however they observed poor distribution of the EZVI in the subsurface. The researchers attributed the poor distribution to problems with the delivery system, as the PPT injection wells did not evenly distribute EZVI to the subsurface. Better success was met in subsequent applications with the trial use of pneumatic fracturing and direct injection (Quinn et al., 2005). Pneumatic fracturing and direct injection (i.e., lance permeation) both employ much lower flow rates and pressures for amendment delivery than PPT.

Injection/extraction wells were also used by Salvetti et al. (2001) to address a PCE source area at a location in Florida. In this study, an approximately 20-foot wide, 65-foot long recirculation cell, which comprised three injection and three extraction wells, was used to deliver $KMnO_4$ to the subsurface (both a shallow and deep zone, separated by a cemented sand layer). The delivery method met with good results in the shallow subsurface zone, however they observed preferential flow patterns and poor oxidant distribution in the more heterogeneous, less permeable deeper zone.

In heterogeneous settings, the forced hydraulic gradient can result in bypass of zones of LPM as discussed previously, which can result in incomplete source destruction, or the rebound of aqueous contaminant concentrations as gradients reverse and the contaminant present in LPM diffuses towards the faster-moving groundwater. McGuire et al. (2006) conducted a review of 59 DNAPL source depletion treatment sites (reported in literature or to regulatory agencies) and found that extended monitoring data were only available for a few sites. However, the available data indicated that contaminant rebound was often exhibited. Of the 23 sites that employed ISCO, seven had long term data. Of those, 81% of the wells experienced rebound, and 31% of the wells that did experience rebound exhibited concentrations higher than the pre-treatment levels. The displacement of contaminants from untreated areas, and diffusion from LPM following treatment were cited as possible reasons for the high rebound concentrations. The author noted however that reverse diffusion from LPM zones was not an issue with other treatment technologies (i.e., bioremediation), and therefore this was unlikely to be the sole cause. Although some sites met closure requirements, none achieved long-term MCLs at all wells.

2.4.3 Direct Injection/Lance Permeation

Direct injection, also referred to as direct push or lance permeation, typically involves the use of direct push probes to distribute amendment to specific locations in the subsurface and can be employed under a variety of flow rates. Moes et al. (2000) evaluated $KMnO_4$ injection with lance permeation to treat a TCE and VC contaminated source zone with contaminant concentrations reaching 260 mg/L. The site mainly consisted of clay and silt in the saturated zone, and these low permeability deposits created problems with oxidant delivery that hindered success. The $KMnO_4$ solution was completely rejected by the LPM in some areas, and as a result, the desired oxidant loading could not be achieved. Additionally, increased dissolution of hazardous metals, as seen from the increased effluent metal concentrations, was observed (hexavalent chromium and selenium) (Moes et al., 2000). Overall the oxidation process was not effective over the treatment area due to both the site conditions and the delivery technique, however it was effective in pockets.

Mott-Smith et al. (2000) met greater success with their ISCO application in which direct injection was employed. In this application TCE was initially present in very high concentrations, approximately 1500 mg/L. The subsurface of the treatment area was stratified in three layers: an upper fine sand unit, a middle layer of silty fine sand and sandy clay lenses, and a lower layer of shell hash, fine sand, silty fine sand, and sandy clay – a heterogeneous mixture, with lenses of varying hydraulic conductivities (Mott-Smith et al., 2000). Low-flow direct push injection was used to deliver MnO_4^- over 0.6 m intervals to address both horizontal and vertical subsurface variations. Tracer tests were initially performed at one of the injection sites and determined that the injection method of lance permeation would be sufficient to transport the MnO_4^- without pumping to reach the desired treatment area (Mott-Smith et al., 2000). Following initial treatment, before significant $KMnO_4$ was injected to treat the suspected mass of contaminant, visual evidence of $KMnO_4$ had been observed at all the multi-level sampling points in all three subsurface zones, indicating successful delivery through the fine-grained layer. At the time of publication, only two of the three treatment phases had been completed.

Parker et al. (2002), utilized low flow direct push injection to deliver a concentrated $KMnO_4$ solution to a fine and medium-grain sand aquifer where previous remediation attempts with Fenton's reagent delivered through injection/extraction wells had been ineffective. The low flow delivery was expected to decrease the risk of contaminant displacement away from the treatment zone, which can occur with high pressure/high flow delivery systems (Parker et al., 2002). As well, by supplying the amendment at a low flow rate in a concentrated form, fingering and diffusion could enable the amendment to migrate into the lower permeability formation (Parker et al., 2002). Researchers achieved even distribution of the $KMnO_4$ in the subsurface and long-term monitoring, six months following the injection episode, indicated that rebound had not occurred.

One serious disadvantage of direct push injection is that it involves the use of a direct push drill rig to deliver each amendment dose. Multiple doses may often be required at a site and this makes it necessary to hire a direct push drill rig for each application, as there is no infrastructure in place to enable multiple applications. This can seriously escalate remediation costs.

2.5 Summary

There have been many field applications involving the delivery of amendments for the destruction/removal of contaminants of concern and the target goals have been met at some sites (Siegrist et al., 2001). In many cases there has been poor performance and goals have not been achieved, which is often attributed to the inability to uniformly deliver the oxidant to the subsurface. This non-uniform delivery can be the result of many factors such as heterogeneities, low permeability, and natural oxidant demand among others (Siegrist et al., 2001). If the remediation goal is to achieve groundwater contaminant concentrations near or below the applicable guidelines over the long term, then it is necessary to ensure that the amendments are able to fully reach and react with the contaminant of concern.

Using discrete delivery and low flow rates provide the most promise at achieving uniform amendment distribution, even in heterogeneous and lower permeability media. However, methods described above do not easily lend themselves to repeat applications and are associated with high costs, in terms of both monitoring and time, for hiring a drill rig for every application. Therefore, there exists a need for an economical delivery system that can achieve an even distribution of amendments with repeat applications.

Chapter 3: Site History

This chapter provides a summary of the findings from the review of the historical site documentation. When activities were carried out by S&P and AMEC between 2002 and 2004, the applicable guidelines for soil and groundwater contaminant concentrations were included in Table B from the Ontario Ministry of the Environment (MOE) *Guidelines for Use at Contaminated Sites in Ontario* (1997) (MOE, 1997). Effective spring 2004, the Ontario regulations changed, and the guidelines are now included in Table 3 of the Soil, Ground Water and Sediment Standards for Use Under Part XV.1 of the *Environmental Protection Act*, laid out by Ontario Regulation 153/04 (O.Reg. 153/04), the new MOE Brownsfield legislation (MOE, 2004a). The Table 3 guideline concentrations for PCE and VC in soil and for VC, cis-1,2-DCE, TCE and PCE in groundwater are the same as those found under the previous Table B guidelines for industrial land use, non-potable groundwater, and coarse textured soils. While groundwater concentrations are low enough to meet the guidelines for fine and medium textured soils in some areas of the site, grain size analysis has not been performed and therefore these less stringent criteria can not yet be applied. However, in the following sections, when a sample would be below the guideline level for fine and medium textured soils, it is indicated with a note. In this chapter, the guideline in place at the time of sample collection is the guideline that is referenced; it should be emphasized that this is not necessarily the current guideline.

3.1 Compilation of Historical Reports

3.1.1 Site Overview

The study site is a commercial/industrial property located at 42 Voyager Court in Toronto, Ontario. The site is currently occupied by an office/warehouse building with an automotive repair shop operating in the eastern portion of the building. Figure 3-1 shows the layout of the site and building location. In Figure 3-1, both Map North and the designated Project North are shown. For all further discussion in this and subsequent sections, when direction is stated, it will refer to the Project North as shown in Figure 3-1.

A list of the reports reviewed and referenced for this research is provided in Table B-1 in Appendix B. Previous environmental investigations carried out at the site by others identified PCE concentrations in the soil and VC concentrations in the groundwater in excess of MOE Table B guidelines for industrial land use. Reports listed in Table B-1 identified historical site activities which included the storage of flammable liquids in the northwest corner of the building, handling of flammable solvents and film cleaners by a previous tenant (O'Connor, 1997), and storing fill from an unknown origin near the north property line (S & P, 2002). However, following the identification of exceedances of chlorinated solvents in the soil and groundwater, no source for the elevated VC levels was provided (AMEC, 2004).

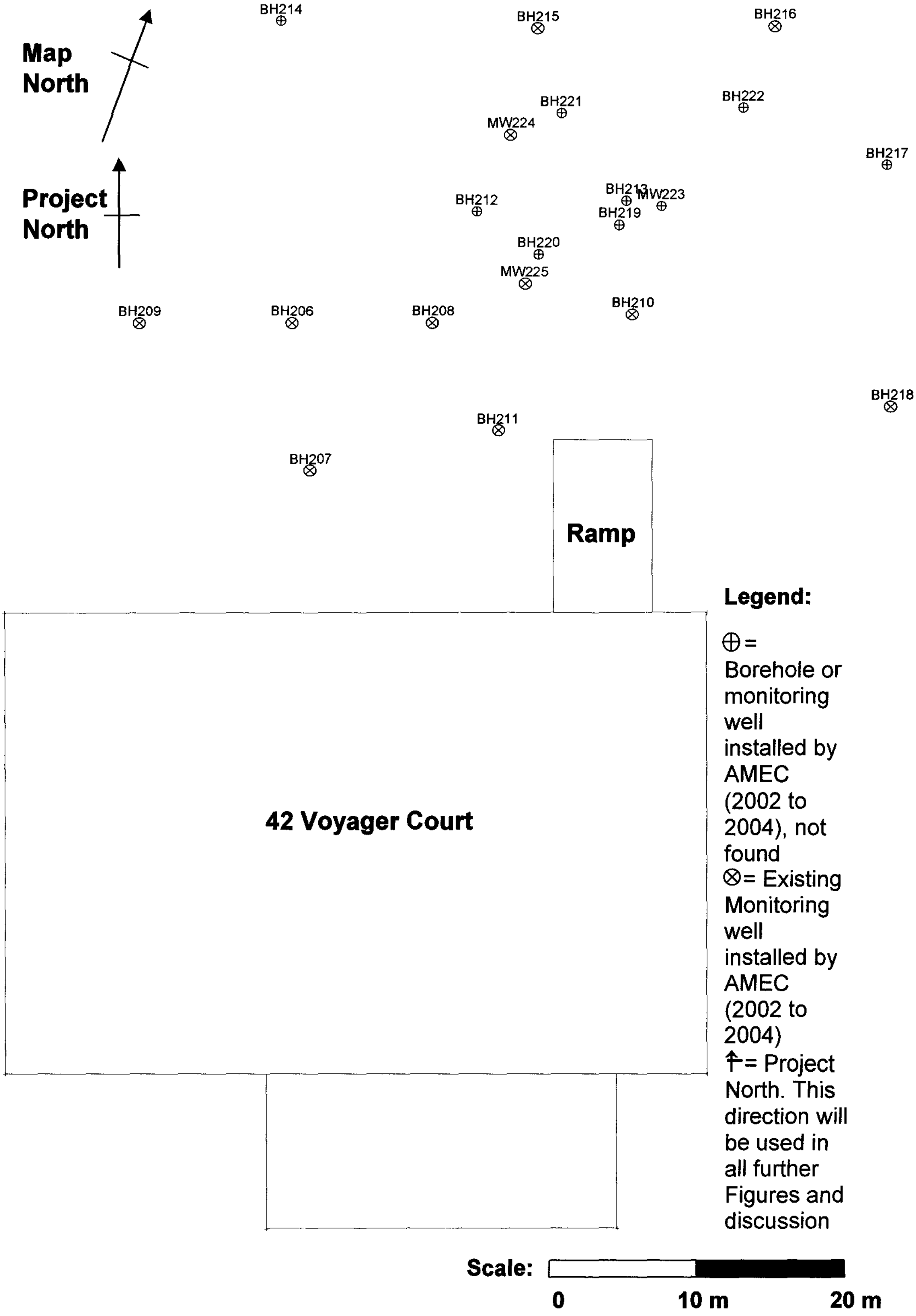


Figure 3-1: Building and Existing and Former Well Locations

3.1.2 Site History

The property is approximately 0.62 hectares (S&P, 2002). Based on topography, Shaheen and Peaker (2002) estimated the groundwater flow direction was to the northeast across the site, in the direction of a tributary of Etobicoke Creek. Figure 3-2 provides a general overview of the subsurface composition, based on a review of borehole records. Records completed by Shaheen and Peaker (2002) indicated that the exposed groundcover on the site was asphalt or topsoil, underlain by approximately 0.3 to 2.5 m of sandy silt and clayey silt fill, which was then underlain by sandy silt till and clayey silt till. Borehole records completed by AMEC (2002 to 2004) indicated that the subsurface of the northeastern portion of the site consists mainly of approximately 1.5 to 2.5 m of sandy silt and clayey silt fill underlain by sandy silt to approximately 6 to 8 mbg, which is then underlain by grey, weathered shale bedrock.

The Phase I and Phase II ESA carried out by Shaheen & Peaker (2002) identified nickel impacted soil along the southwestern side of the site, mainly between the side of the building and 40 Voyager Court. During the delineation activities of the Phase II ESA, Shaheen & Peaker drilled boreholes and installed monitoring wells along the south and west of the site: BH1, BH2, BH6, BH101, BH102, BH103, BH104, and BH105. Groundwater samples were collected from these wells in February 2002 and analysed for VOC compounds. With the exception of BH1, the wells had non-detectable levels of VOCs. In BH1, 1,1-DCE was detected at 0.3 μg/L, which was below the applicable MOE guidelines (Table B) of 0.66 μg/L (S & P, 2002).

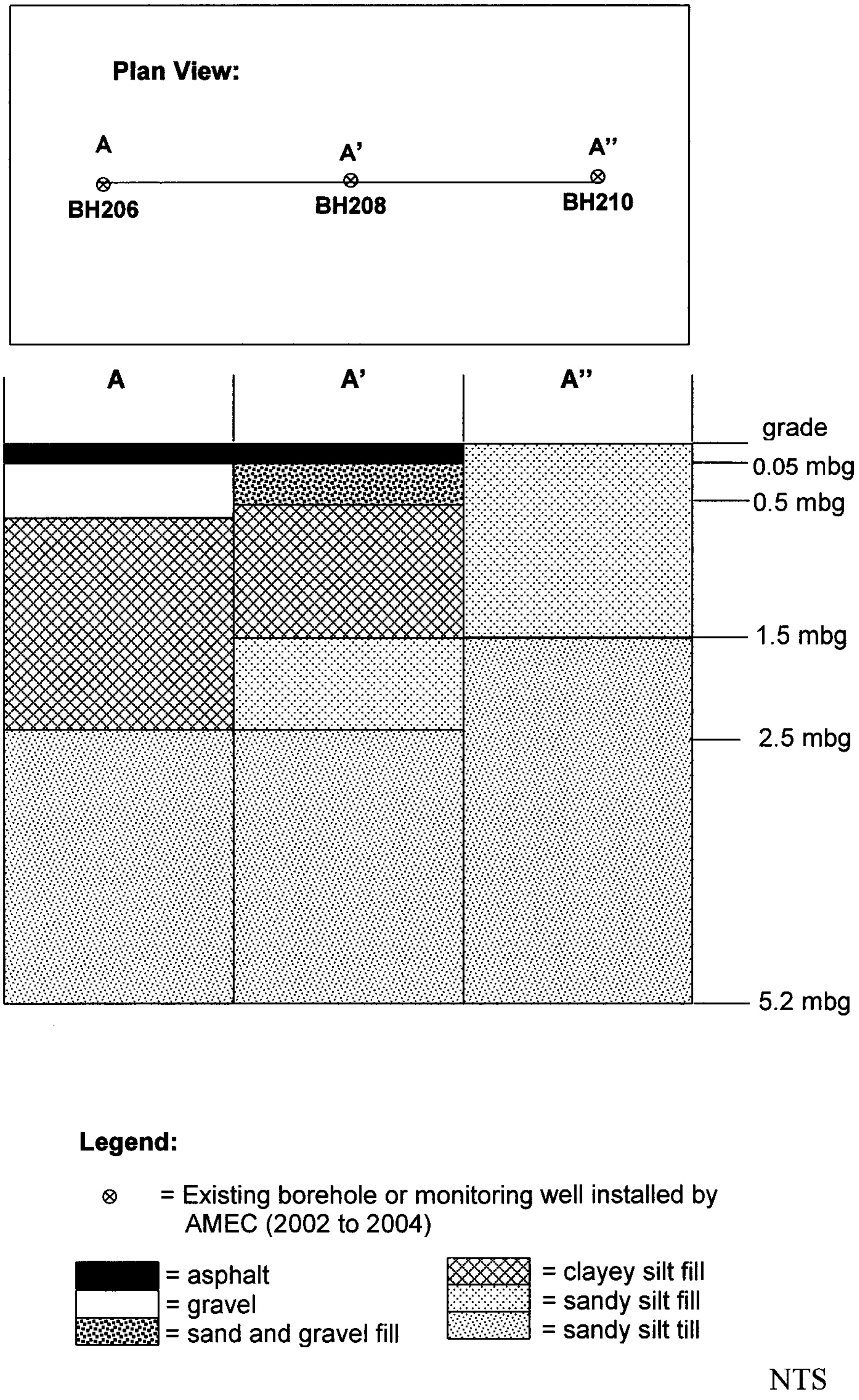


Figure 3-2: General Overview of Subsurface Composition

AMEC then conducted nickel excavation activities on the southwest side of the site. During their site activities, carried out over the period of 2002 to 2004, AMEC identified chlorinated solvent impacted soil. Initially, soil contaminated with PCE was identified on the northeastern corner of the property. To investigate these impacts, AMEC drilled 21 boreholes over the period of 2002 to 2004 in the northeastern portion of the site and completed them as monitoring wells (see Table 3-1 for well details and Figure 3-1 for monitoring well locations).

Table 3-1: Monitoring Well Details for wells installed by AMEC

Well ID	Date Installed	Depth (mbg)	Screen Interval (mbg)
BH206 to BH209	June 8, 2002	0 to 4.5 – 5.5	1.5 – 4.5
BH210 to BH212	July 6, 200	0 to 4.5 - 5.5	1.5 – 4.6
BH213At o BH218	July 20, 2002	0 to 4.5 – 5.5	1.5 – 4.6
BH213D	July 20, 2002	5 to 8	6.7 – 7.6
BH219 (bedrock) BH220 to BH222	March 13, 2003	0 to 10.7 0 to 7.5	9.2 – 10.6 Borehole only – no MW
MW223 to MW227 (bedrock wells)	January 20 & 21, 2004	7.5 to 11	12.2 – 15.2(MW223A) 9.8 – 11.4 (MW223 B through MW227)

PCE concentrations in soil ranged from non-detect to 2250 μg/g, which was above MOE guidelines of 0.45 μg/g (AMEC, May 23, 2003). Soil contaminant concentration results reported by AMEC from these well borings are outlined in Table 3-2. No other lab or concentration data were provided for these soil samples.

Prior to the excavation of the PCE impacted soil on the northeastern portion of the site, groundwater samples were collected and analysed by AMEC through June and July 2002 (although detailed dates and lab reports were not available). Table 3-3 is a summary of the chlorinated solvent impacts as reported in a May 23, 2003 letter report.

Table 3-2: Soil Sample Results

Well ID	Sample Interval	PCE (μg/g)	VC (μg/g)
BH208	NR	dbg	0.003
BH210	NR	dbg	NR
BH211	NR	dbg	NR
BH212	NR	dbg	NR
BH213A	1.52 – 2.12 mbg	**2250**	NR
BH213D	6.11 – 6.71 mbg	**4.4**	NR
BH214	NR	dbg	NR
BH219	NR	dbg	NR

(AMEC - May 23, 2003)
NR = not reported in available AMEC reports
dbg = detected below applicable MOE Table B guidelines
bold = concentration exceeds Table B guidelines

Table 3-3: Groundwater Sample Results

Well ID	Date Collected	Compound	Result (μg/L)
BH206	June or July 2002	VC	dbg
BH208	June or July 2002	VC	**27.7**
BH210	June or July 2002	VC	**0.9**
BH212	July 2002	VC cis-1,2-DCE	dbg **141**
BH213A	July 23, 2002	cis-1,2-DCE TCE PCE	**4320** **184** **9160**
BH213D	July 23, 2002	PCE	**390**
BH219	March 18, 2003	PCE	**8**

(AMEC, May 23, 2003)
NR = not reported in available AMEC reports
dbg = detected below applicable MOE Table B guidelines
bold = concentration exceeds Table B guidelines

Generally, the well screens were three metres long, and installed from 1.5 to 4.6 mbg; BH213D is the exception, with a screen 0.8 m in length, installed from 6.7 to 7.6 mbg. BH219 and MW223 to MW227 were screened in the bedrock which is beyond the scope of this work. From the sample results outlined in Tables 3-2 and 3-3, the chlorinated solvent impacts were highest in the vicinity of BH212 and BH213, with decreasing concentrations in the direction of BH208, BH210 and BH219. The reported chlorinated solvent concentrations in groundwater were higher in the shallow groundwater rather than the deeper groundwater samples (Table 3-3), which corresponds with the soil sample results from BH213 (Table 3-2). However, sample depth was not reported for the soil samples taken from the other boreholes (i.e., not BH213), and therefore little can be inferred from the soil results beyond the presence or absence of contamination.

As a result of the soil sample and groundwater analysis results, approximately 1100 tonnes of soil were reportedly excavated in the fall of 2003 from the northeast corner of the site. The excavation extended from the ground surface to a depth ranging from 2.5 to 4.5 mbg, and the soil was disposed of off-site (see Figure B-1 for the extent of the excavation (AMEC, 2003)). BH212, BH213 and BH219 were reportedly destroyed during the excavation work. Following the excavation activities, groundwater samples were collected from some of the completed monitoring wells, and chlorinated solvent levels, specifically VC, continued to be detected above the MOE guidelines (Table B). A summary of the groundwater sampling results from June 2003 through July 2004 is presented in Table 3-4.

Tables 3-3 and 3-4 indicate that over the course of the four sampling events, the VC concentration in BH208 ranged from 16.9 to 27.7 μg/L, with one non-detect sample in January 2004. As VC concentrations in BH208 continued to exceed the MOE guidelines, the new site owners were required by their financial institution to take remedial action, to reduce the VC concentration in BH208 below the applicable MOE guidelines, as a condition of the mortgage.

Table 3-4: Summary of Groundwater Sample Results

			BH208			**BH210**			**MW223A**		**MW223B**		**MW224**	**MW225**		**MW226**		**MW227**	
VOC (µg/L)	**MDL** (µg/L)	Table B* Guide-lines (µg/L)	18-Jun-03	29-Jan-04	9-Jul-04	18-Jun-03	29-Jan-04	9-Jul-04	23-Jan-04	9-Jul-04	23-Jan-04	9-Jul-04	23-Jan-04	23-Jan-04	9-Jul-04	23-Jan-04	9-Jul-04	23-Jan-04	9-Jul-04
VC	0.4	0.5	**16.9**	nd	**21.9**	**0.9**	nd	**4.2**	nd	nd	nd	nd	nd	**6.4**	**3.7/3.2**	nd	nd	nd	nd
1,1 - DCE	0.3	0.66	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
cis-1,2-DCE	0.7	70	15.6	7	18.3	3.5	6.6	10.1	1.1	1.1	nd	nd	3.2	1.6	nd	27	20.7	nd	nd
trans-1,2-DCE	0.2	100	nd	nd	nd	0.1	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
TCE	0.4	50	nd	nd	nd	0.4	4.9	6.4	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
PCE	0.3	5	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	1.9	nd	nd	nd	nd	nd	nd

AMEC, 2003 & 2004
MDL = Method detection limit provided in available samples reports
nd = non-detect
bold = sample exceeds MOE Table B guideline

Chapter 4: Materials and Experimental Methodology

This chapter provides an outline of the materials used and methodology followed throughout the course of this research. Section 4.1 describes the methodology applied for the site characterization. Section 4.2 through 4.4 details the experimental design, including the construction and installation of the injection points, the layout and preparation of the amendment delivery system and solution, and the design, construction, installation and sampling of the multi-level monitoring wells (MLMWs). Finally, Section 4.5 describes the sampling and analytical techniques.

4.1 Site Background/Profile Development

The site history was summarized and the existing groundwater conditions were characterized prior to conducting the experimental work. This information is necessary to develop an appropriate design of the delivery system. This section describes the compilation of site data, site reconnaissance, and activities carried out to develop an estimate of the groundwater flow rate.

4.1.1 Compilation of Site Data

Twelve reports prepared by engineering consultants (AMEC Earth and Environmental Limited (AMEC), Shaheen and Peaker Limited (S & P) and O'Connor and Associates Limited (O'Connor)) for the site were reviewed. The reports consisted of two Phase I Environmental Site Assessments (ESA) and one Phase I ESA update, a Phase II ESA, and summaries of the remediation and monitoring efforts. The data from these reports were compiled to aid in developing a good understanding of historical site uses and therefore potential environmental issues, as well as a hydrogeological conceptual model.

4.1.2 Initial Site Reconnaissance

On March 22 and March 30, 2005 an attempt was made to locate existing groundwater monitoring wells suspected to be remaining on-site using the historical site documentation as a guide. The condition of the existing wells was assessed on April 6, 2006. The static water level was measured in each well and a weighted tape (Solinst Model 101, Georgetown, ON) was used to measure the depth to the bottom of each well. This well depth was compared to available borehole records. If the measured well depth was shallower than the borehole record indicated, it was possible that surface debris may have entered the well and was interfering with the well screen. These wells were deemed incompetent, and were not used in further characterization, monitoring or remedial efforts.

4.1.3 Surveying of Well Elevations

Existing wells were surveyed by JRS on June 7, 2005. All wells were surveyed to a benchmark (BM) on the site, the centre of the eastern curb on the garage ramp. The wells were surveyed to the top of the PVC casing. As the casing was sometimes unevenly cut, the well casing was marked to indicate the side that had been surveyed. The elevations were surveyed to the nearest 0.5 cm (S_{el} [L]). For wells on the south side of the site, where the BM could not be seen from the sights of the survey equipment, BH102, which was in sight of both the wells on the south side of the site, as well as the BM, was taken as the reference from the new tripod position and these wells were then tied back to the initial benchmark to determine elevations.

4.1.4 Water Levels

Water Level Collection

On April 6, 2005 water levels were collected using a water level meter (Solinst Model 101), equipped with a P2 probe and 50 ft tape. During this initial assessment, bailers were found to be present in the majority of the wells, or strings indicating that bailers had been present at some point. These bailers were subsequently removed and water levels collected.

From April 22, 2005 onwards water levels were collected using a water level tape (Solinst Model 101) equipped with a P2 probe and a 25 m tape with 0.001 m gradations. Prior to June 7, 2005 the water level was measured from the highest point of the casing. After the wells were surveyed on June 7, 2005 subsequent water level readings were measured from the survey mark on the PVC well casing. Water levels collected prior to June 7, 2005 were then corrected to the proper elevation using survey data.

Water levels were collected by slowly lowering the probe into the well casing until an audible beep was heard, indicating water contact. Each measurement was repeated two to three times until a consistent measurement was recorded as the depth (m) below the top of the well casing (mbTOC) [L]. Using the survey elevations (S_{el}) [L], water table elevations (WT_{el}) [L] were calculated as follows:

$$WT_{el} = S_{el} - \mathrm{mbTOC} \qquad \textbf{4-1}$$

In addition to water levels, precipitation data were collected from the online historical precipitation and temperature data maintained by the Weather

Network, which is based on data collected by Environment Canada at the weather station located at Pearson International Airport (Weather Network, 2006). The weather station is located approximately one to six kilometers east of the site (depending on the location of the weather station on the airport property).

Flow Nets

Equipotential lines represent a boundary of constant hydraulic head (h) [L] defined as:

$$h = \psi + z \qquad \textbf{4-2}$$

where (ψ) [L] represents the pressure head and z [L] represents the elevation head. At the water table, ψ is zero and therefore the head relationship becomes (Freeze and Cherry, 1979):

$$h = z \qquad \textbf{4-3}$$

Therefore, equipotential lines can be developed from water table elevation data. Flow lines then, run orthogonal to the equipotential lines (Freeze & Cherry, 1979). Flow and equipotential lines drawn through a two dimensional cross-section of the system are known as a flow net and can be employed to estimate the groundwater flow direction. Water table elevations and constant head contours were plotted using Surfer (Version 8.02, Golden Software, Inc., Golden, CO); kriging was selected to interpolate the water table elevation data between actual data points.

Gradient and Flow Direction

The groundwater flow direction was calculated using a spreadsheet described by Devlin (2003) which conducted matrix algebra based on water table elevation and well location data from multiple wells. Implicit in the spreadsheet is the assumption that the water table plane is linear (i.e., not applicable to pumping wells, which have a curved surface geometry). This assumption was applicable at this site.

The spreadsheet provides a solution to the equation of a plane:

$$Ax + By + Cz - D = 0 \qquad \textbf{4-4}$$

where x [L] and y [L] represent the graphical coordinates of the well locations, and z [L] represents the hydraulic head, or water table elevation at each of the wells. The solution provides a regional, or site-scale solution to the equation of the plane, and provides a numerical solution to what might otherwise be interpreted from the plot of water table contours (Devlin, 2003). A copy of the spreadsheet was provided on a website described in the article by Devlin (2003) and this spreadsheet was used to calculate the gradient and direction of groundwater flow. Water level data from several water level collection events were used, and several of the matrix calculations were checked by hand prior to using the results provided by the spreadsheet.

The x and y well coordinates for the existing on-site wells used in these calculations were obtained from site plans provided by AMEC and measured using the map scale provided. For reference purposes, the southwest corner of the site was assumed to be 0,0 and then all locations were measured using a ruler from the scaled map. It was assumed that the map scale and representation were accurate, and the data collected were then converted from the map scale to metres.

4.1.5 Sample Collection

The existing wells were prepared for sampling on April 21, 2005. Low density polyethylene (LDPE) Waterra tubing (1/2" ID x 5/8" OD) (Waterra Pumps Limited, Mississauga, ON) was installed in each of the wells to be sampled. The Waterra tubing was fitted with a footvalve (D-25, Waterra Pumps Limited) and a length of tubing was cut so that the tubing would reach the bottom of the well screen and extend above the casing.

On April 22, 2005 an initial round of groundwater samples was collected from the existing wells. Prior to sample collection, three well volumes were purged from each of the well casings with the Waterra tubing and footvalves (or until the well was dry). Samples were collected by lifting a volume of groundwater through the Waterra tubing into three 40 mL EPA glass VOC bottles, with hole-top caps lined with Teflon septa supplied by Maxxam Analytics Inc. (Mississauga, ON). Samples were filled to the top and a meniscus created before they were sealed to ensure no air bubbles were present. In addition to samples from the above-mentioned wells, a field blank was created (labeled as MW100) by filling three 40 mL EPA glass VOC bottles in the field with distilled water. A blind duplicate sample (labeled as MW308) was also collected from BH208. All samples were immediately placed on ice in a cooler and stored until they were transported to the Maxxam laboratory at the end of the day. Samples were submitted for the analysis of VOCs in accordance with MOE Table B guidelines (MOE, 1997).

4.1.6 Hydraulic Conductivity

Slug tests were conducted in triplicate on wells BH206, BH207, BH208, BH209, BH210, BH215, and in duplicate on BH218. The slug tests were conducted by injecting a 'slug' of a known volume of distilled water into the wells and monitoring the recovery of the water level. This was done to develop an estimate of the subsurface hydraulic conductivity in the immediate vicinity of the well.

Immediately upon pouring the slug into a well, the water level recovery was monitored, initially every 15 to 30 seconds, and then less frequently as time progressed. The data were then collected and interpreted using Hvorslev's method (Freeze and Cherry, 1979) to develop an estimate of hydraulic conductivity at each well. Hvorslev's method was appropriate as the measurements were made through a point piezometer, and the assumptions of a homogeneous, isotropic, infinite medium with incompressible soil and water is reasonable (Freeze and Cherry, 1979). In this method, the rate (q) [L^3/T] of inflow at time (t) [T] is proportional to the hydraulic conductivity (K) [L/T] as follows:

$$q(t)=\pi r^2 \, {}^{dh}\!/_{dt} = FK(H-h) \qquad \textbf{4-5}$$

where (H-h) [L] is the unrecovered head difference and F [L] is a shape factor that depends on the intake of the piezometer, and in the case of a long-screened monitor well where L/R >8, (i.e. the existing wells on the site) is represented by Equation 4-6:

$$F=\frac{2\pi L}{\ln\left(2L/D\right)} \qquad \textbf{4-6}$$

When the piezometer is of length (L) [L] and diameter (D) [L], if (H-h)/(H-H_o) is plotted logarithmically versus time in hours, the time lag T_o can be determined as the value when (H-h)/(H-H_o) = 0.37 (Freeze and Cherry, 1979). The hydraulic conductivity can then be determined as follows:

$$K=\frac{r^2\ln\left(L/R\right)}{2LT_o} \qquad \textbf{4-7}$$

4.1.7 Groundwater Flow Rate

Using the estimate for hydraulic conductivity, and the gradients obtained from the plots of water table elevations, the groundwater flow rate was estimated by:

$$Q=-K\,i\,A \qquad \textbf{4-8}$$

where Q [L^3/T] is the groundwater flow rate, K [L/T] is the hydraulic conductivity, i [-] is the hydraulic gradient obtained from the slope of the water table, and A [L^2] is the cross-sectional area perpendicular to the direction of flow. To design the amendment flow rate and concentration it was necessary to define an area to obtain a value for A. For this project, the study area was initially considered to be a cross-section perpendicular to groundwater flow 6 m deep (depth from the water table to bedrock) and 1 m wide.

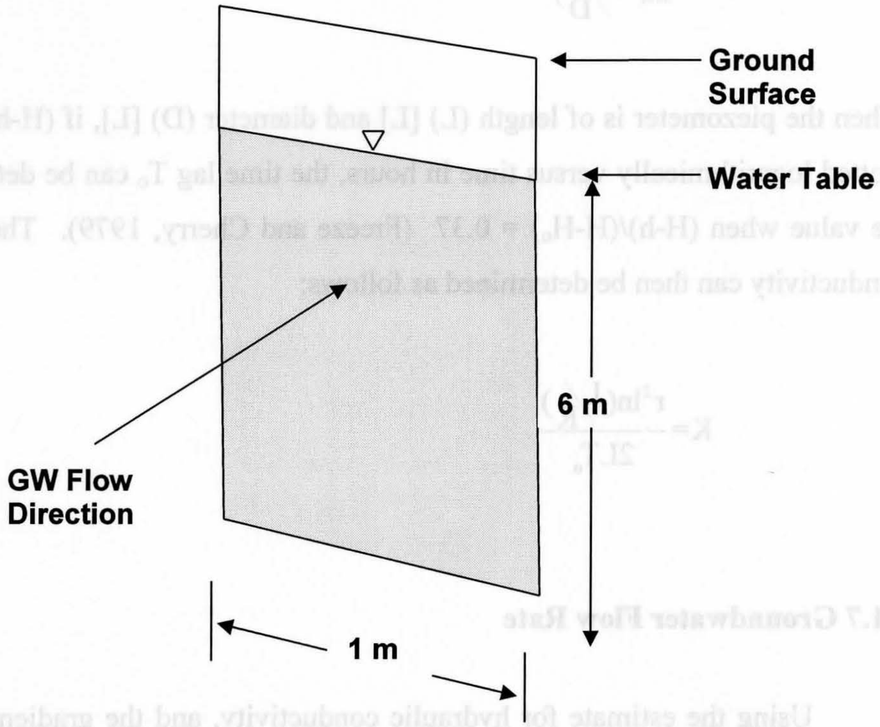


Figure 4-1: Cross-Sectional Flow Area

4.1.8 Natural Oxidant Demand (NOD) Testing

Prior to delivering the $KMnO_4$ solution, it was necessary to develop an estimate of the NOD of the aquifer solids. The NOD was estimated from a series of experiments that were conducted using soil samples collected during the installation of the amendment delivery system and the monitoring network. The soil samples were either air or oven dried, and homogenized to break up any conglomerated material. The vials were cleaned, dried and weighed (AB204-S, Mettler Toledo, Mississauga, ON) empty (M_{empty}) [M]. The samples were then split between three to nine 20 mL borosilicate glass vials with hole-top caps and Teflon-lined septa and a known mass of soil was added to each vial (see Figure 4-

2). The vials were then re-weighed ($M_{w/soil}$) [M]. The mass of soil in each vial was determined as follows:

$$M_{soil} = M_{w/soil} - M_{empty} \tag{4-9}$$

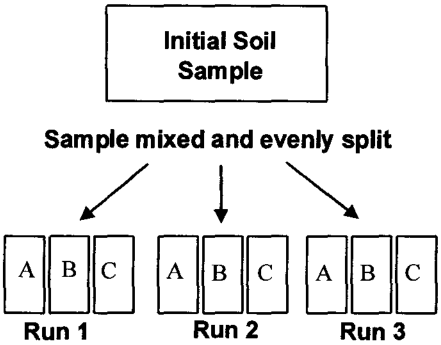


Figure 4-2: Soil Sample Preparation

$KMnO_4$ solutions were prepared at two different concentrations (8 g/L and 25 g/L). The concentration of the $KMnO_4$ in these solutions was measured analytically (see Section 4.5.3). With the concentration of $KMnO_4$ known (C_{KMnO4}) [M/L^3], a known volume ($\forall_{KMnO4}$) [L^3] was added to each vial using a volumetric pipette (Reference Series, Eppendorf, Mississauga, ON). The mass of $KMnO_4$ (M_{KMnO4}) [M] in each reactor was then calculated as follows:

$$M_{KMnO4} = C_{KMnO4} \times \forall_{KMnO4} \tag{4-10}$$

For each run, soil-free controls were also prepared to monitor any changes in the concentration of the $KMnO_4$ solution over time that were not due to the NOD of the soil. Once filled, the vials were capped and stored in the dark.

Samples were collected from each vial periodically from the start of the experiment. Samples were generally collected from each of the triplicate reactors and controls at each time period. Five to 10 μL of sample were removed, depending on the concentration of the solution, and then diluted with 1400 μL of distilled water in a plastic cuvette for analysis by spectrophotometer (see Section 4.5.3). The concentration of each sample (C_{sample}) [M/L^3] was calculated from the measured concentration of the diluted sample ($C_{dilution}$) [M/L^3] as follows:

$$C_{sample} = \frac{C_{dilution} \times \forall_{total}}{\forall_{sample}} \tag{4-11}$$

where $\forall_{total}$ [L^3] is a sum of the volume removed from the original undiluted sample, $\forall_{sample}$, and the volume of water added (1400 μL) to the cuvette, and $\forall_{sample}$ [L^3] is the volume removed from the original undiluted sample (i.e. 5μL or 10 μL). From this concentration, and the concentration of the control measured at the same time period, the NOD [M/M] was calculated as follows:

$$NOD = \frac{(C_{sample} - C_{control})\forall_{KMnO_4}}{M_{soil}} \tag{4-12}$$

Two $KMnO_4$ concentrations and temperatures were used for the various experiments, as well as soil samples from various locations in the study area. A fractional factorial design was employed and is summarized in Table 4-1.

Table 4-1: NOD Experimental Design Layout

Run	Soil Type	Location	Drying Method	Temperature (° C)	$[KMnO_4]$ (g/L)
4	Reddish till with silt and sand	MW302	Air	5	8
5				25	25
7	Reddish grey till with silt and sand	MW311	Air	5	8
8					25
9	Light brown till with silt and sand	MW303/304	Air	5	8
10					25
11	Light brown till with silt and sand	MW305	Air	5	8
12					25
13	See above	MW307/308	Air	5	25
14	See above	MW311	Air	5	25

4.2 Amendment Delivery System Design and Installation

The amendment delivery system was designed, constructed and installed upon the completion of the review of historical reports and site characterization. The following section outlines the design and construction of the delivery points. Details on installation and connections are also provided.

4.2.1 Delivery Point Construction

The delivery points were constructed from 20 ft lengths of Schedule 80 (1/4" ID x 1/2" OD) PVC tubing (Canadian Pipe Supply, Toronto, ON). Holes (1/32" diameter) were drilled straight through the tubing every 0.2 m along the entire length. 50 μm stainless steel screen (approximately 0.02 x 0.06 m pieces) (Gerard Daniel Worldwide, Mississauga, ON) was wrapped around the drilled holes and secured with foil tape (Nashua general purpose, Tyco Adhesives, Franklin, MA). The stainless steel screen was used to prevent subsurface soils from clogging the drilled holes when the delivery points were installed; the 50 μm mesh size was chosen due to the presence of silt and clay in the aquifer material.

The bottom end of the tubing was sealed with either a PVC slip cap or a Teflon tape-wrapped bolt (see Figures 4-3 and 4-4 for details). If necessary, a PVC coupling was used to join lengths of tubing.

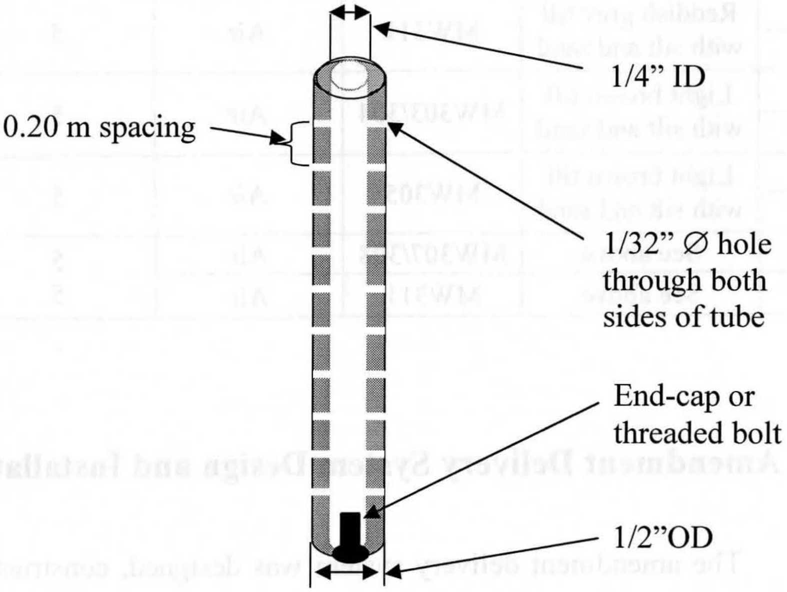


Figure 4-3: Delivery Point Cross- Section

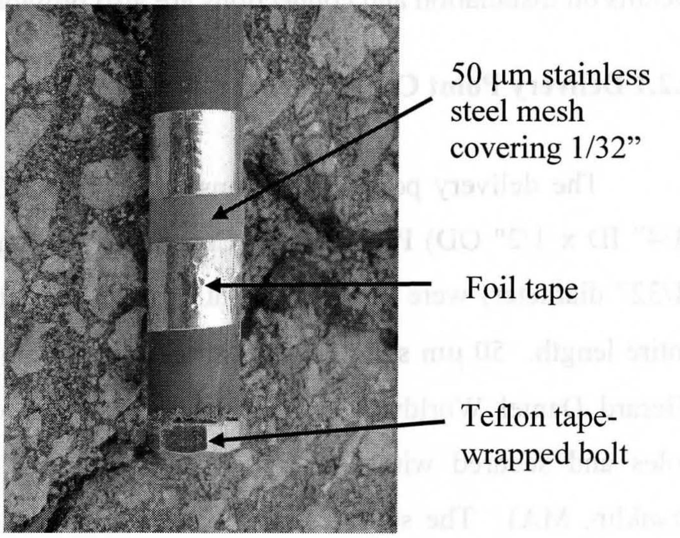


Figure 4-4: Bottom of Constructed Delivery Point

4.2.2 Delivery Point Installation

The delivery points were installed between October 11 and 13, 2005. Points were installed with a Geoprobe direct push drill rig (Powerprobe 9630 PRO, Profile Drilling, Toronto, ON). The drill rig was fitted with a 1.5" drive point and rod. Refusal was generally met between 3.4 and 4.3 metres below grade (mbg). Once the hole was completed (i.e., refusal was met), a delivery point, prepared as described in Section 4.2.1, was inserted into the hole and capped with a PVC slip cap.

4.2.3 Delivery Point Header

Once the delivery points were installed, the PVC slip caps were drilled and tapped. A ¼" threaded brass all-tube T connector with compression fittings (Watts, North Andover, MA) was wrapped with Teflon tape and threaded into the top of each slip cap (see Figures 4-5 and 4-6 for details). A slip cap was then friction fit to the top of each delivery point and sealed with a thin layer of PVC cement.

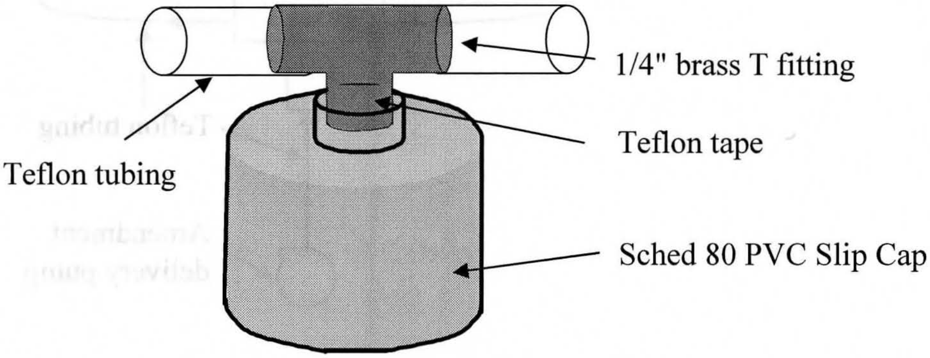


Figure 4-5: Slip Cap and Brass T Details

Figure 4-6: Slip Cap and Brass T Assembly

Once the caps were secured to the delivery points, a length of Teflon tubing (3/8" ID, Saint Gobain Performace Plastics, Akron, Ohio) was sealed to the two remaining ends of each brass T using the supplied compression fittings. As a limited number of pumps and drives were available, the headers typically attached the delivery points in pairs, to form a closed loop between each pair of delivery points via a brass T fitting (see Figure 4-7 for layout).

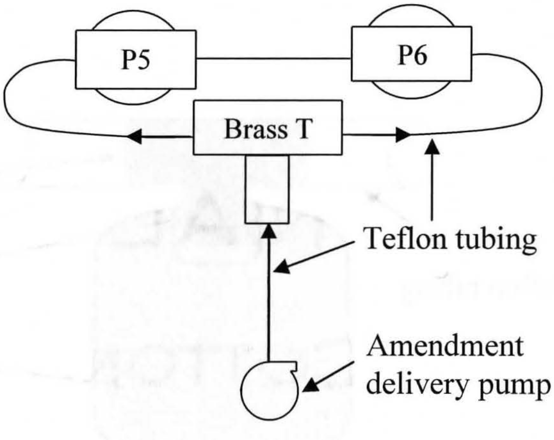


Figure 4-7: Layout of Paired Delivery points

Each closed loop was then connected to a pump header on an amendment delivery pump. Four peristaltic pumps (L/S Variable Speed, Modular Drive 1-100 rpm, Masterflex, Anjou, QC), each equipped with four pump heads (Standard Pump Head, L/S 14, Masterflex), and norprene pump tubing (Norprene L/S 14, Masterflex) were used to deliver the amendment. This pump and drive combination was capable of delivering amendment at flow rates ranging from 0.21 to 130 mL/min. The pump tubing was connected to the Teflon supply lines with a small length of flexible tygon tubing and nylon cable ties (see Figure 4-8 for details).

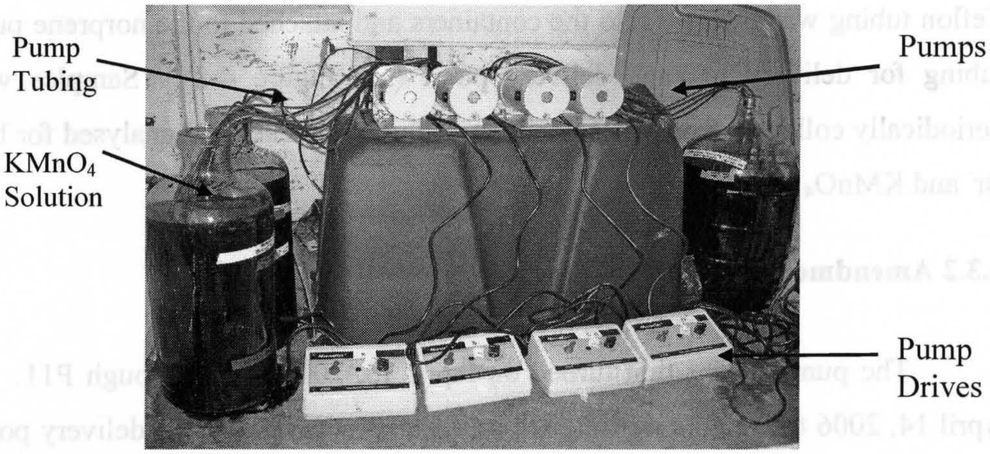


Figure 4-8: Pump and Drive Layout for Amendment Delivery

4.3 Amendment Preparation and Delivery

Once the delivery points, lines, and pumps were connected, it was possible to begin delivering the amendment solution. This task involved preparing the amendment solution, switching the pumps on, and then continually leak testing and repairing the system. Once the initial leaks were repaired, the system was run continuously. This process is described in the following sections.

4.3.1 Amendment Solution Preparation

$KMnO_4$ solution, amended with sodium bromide (NaBr) as a conservative tracer, was prepared on-site prior to injection. The solution was prepared by dissolving approximately 600 to 840 g of $KMnO_4$ (Technical Grade – Lot # 9592, Carus Chemicals, LaSalle, IL) and 20 g of NaBr (Reagent Grade Sodium Bromide Crystal, JT Baker, France) in 20 L of tap water. The solution was stirred for approximately five to 10 minutes to dissolve the $KMnO_4$ crystals, and then filtered using a 0.45 µm FHT-45 groundwater filter (Waterra, Mississauga, ON) into glass storage containers ranging in size from 10 L to 40 L. A length of Teflon tubing was inserted into the containers and attached to the norprene pump tubing for delivery to each delivery point (see Figure 4-8). Samples were periodically collected from the amendment solution batches and analysed for both Br^- and $KMnO_4$ concentrations.

4.3.2 Amendment Delivery

The pumps were first turned on April 13, 2006 to P1 through P11. On April 14, 2006 the pumps were turned on for the remainder of the delivery points (P12 through P30). When possible, leaks were repaired to the system as they were encountered. Pumps and prepared permanganate solutions were stored in a locked service van adjacent to the delivery site.

Pumps ran continuously from April 18 to October 4, 2006 (with exceptions noted in Chapter 5 due to problems (i.e., power failures, errors etc.), and periodically from October 15 to November 15, 2006. For various reasons to be discussed in Chapter 5, flow was not continued to all the delivery points for the duration of the experiment. The flow rates from each pump head was measured periodically.

4.4 Groundwater Monitoring

Following the installation of the delivery points, MLMWs were constructed and installed on site to monitor the effectiveness of the delivery system. The details of the construction, installation and sampling methodology for the MLMWs are described in this section.

4.4.1 Multi-Level Monitor Well Construction

MLMWs were constructed similar to those described by Cherry et al. (1983) and consisted of a ½" centre-stalk of PVC as a support (Canadian Pipe Supply, Toronto, ON), surrounded by five varying lengths of Teflon tubing (0.250" OD x 0.187" ID, Saint-Gobain Performance Plastics, Akron, OH), each with a 0.05 m discrete slotted screen at the end. To create the well screen, the bottom 0.05 m of the cut Teflon tube was scored, creating holes approximately every 0.01 to 0.015 m on both sides of the tubing. 50 μm stainless steel mesh (Gerard Daniel Worldwide, Mississauga, ON) was then cut into 0.04 x 0.08 m pieces, folded and secured to the end of each slotted screen. 0.04 m was folded over the tip of the Teflon tubing and wrapped like a package. The Teflon screens were wrapped in the 50 μm stainless steel mesh to minimize subsurface particles from entering the well screen during installation and sampling. Three to four nylon cable ties were used to secure the screen to the tubing; one at the tip, one at the end of the 0.05 m length and two in the middle (see Figure 4-9 for details). Once the borehole was drilled, and the depth was known, the Teflon tubing was attached in the field to the support PVC at the desired depths, with the excess tubing cut off the top.

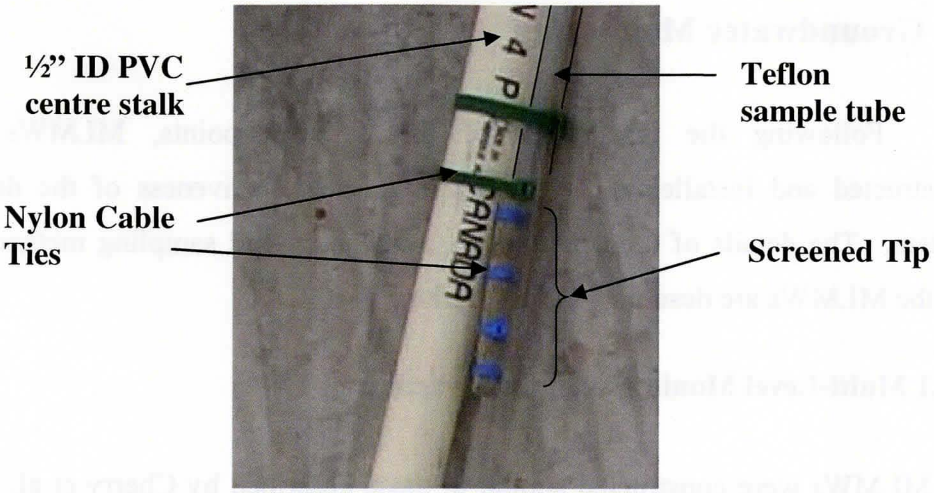


Figure 4-9: MLMW Well Screen

The centre stalk piece of ½" PVC was cut to a length slightly greater than the approximate depth of the borehole. Port 5 was then attached with the screened tip at the bottom end of the centre-stalk ½" PVC and affixed with nylon cable ties. Port 4 was attached with the screened tip 0.6 m up from the bottom of Port 5. This process was repeated, measuring 0.6 m between each screen until the uppermost sampling port, Port 1, was attached (with the exception of MW311, which had approximately 1.2 m between ports). The sampling ports were then marked as follows:

- Port 1 – marked with blue PVC tape, shallowest sampling port
- Port 2 – marked with white PVC tape
- Port 3 – marked with green PVC tape
- Port 4 – marked with yellow PVC tape
- Port 5 – marked with red PVC tape, deepest sampling port

4.4.2 Multi-Level Monitor Well Installation

The MLMWs were installed on October 13, 14 and 17, 2005 using equipment and personnel supplied by Profile Drilling (see Section 4.2.2 for equipment details). During the initial well installation, MW301, it was not possible to install the monitor wells using the direct push technique. The subsurface soil would not collapse around the installed well, and the maximum diameter available with the direct push technique was approximately 2”. While this borehole was of sufficient size to accommodate the assembled well, it did not provide enough space for the measurement of the sand pack and bentonite seal depths that were necessary, as the formation was not naturally collapsing. As a result, it was necessary to auger the holes for the MLMWs.

An 8” hollow stem auger was used, and with the exception of MW311 (which was augered to a depth of approximately 6 mbg) the boreholes were augered to between 3.6 and 4.2 mbg, at which point refusal was met (a very densely packed till layer, in which boulders/rock was sometimes encountered). To eliminate contamination between MLMW boreholes, the augers were rinsed between locations. Additionally, the wells were installed starting from a location suspected to be the least contaminated and finishing at the area suspected to be most contaminated based on historical soil and groundwater sample reports.

The well assembly was then lowered into the open auger hole and sand pack alternating with bentonite seal was added to hydraulically isolate each monitoring point. For Port 5, approximately 0.3 m of sand and 0.15 m of bentonite seal were added and for the remaining ports, approximately 0.6 m of sand pack topped by 0.15 m of bentonite seal was placed in the auger hole. The goal was to keep the well screen near the centre of the sand pack (see Figure 4-10 and 4-11 for details). The depth of each bentonite and sand layer was measured using a tape measure.

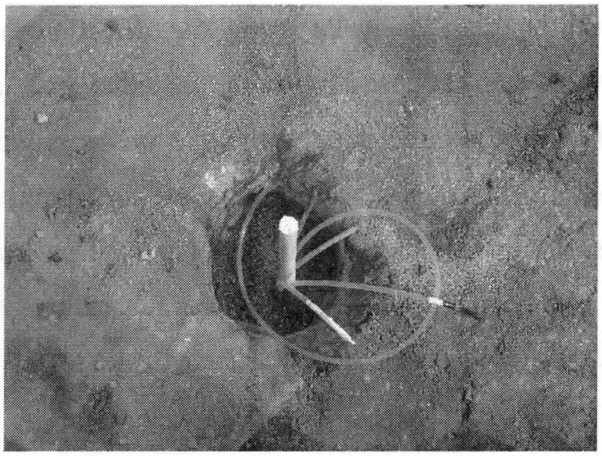


Figure 4-10: View of Installed MLMW

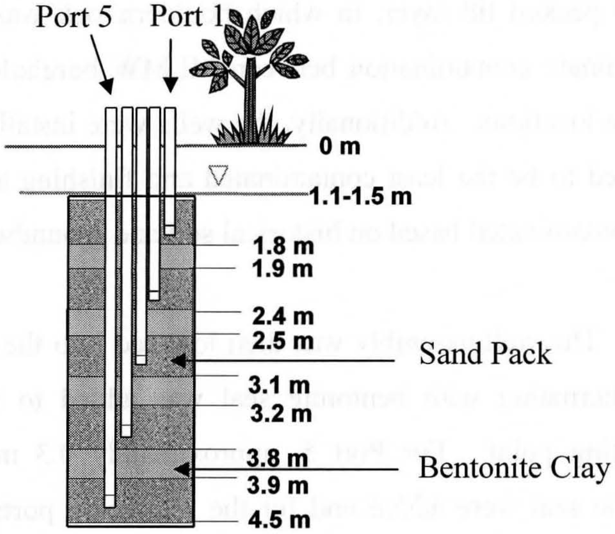


Figure 4-11: Layout of Ports 1 to 5 in Installed MLMW
(depths and water table are estimates)

Following installation, each well was covered with a protective cap consisting of a 4" OD PVC sleeve cut and installed over the well and driven approximately 0.15 m into the ground. The PVC sleeves were then capped with threaded PVC covers.

Several soil samples were collected from the direct push as well as MLMW auger borings, and one core sample was extracted from P10 using a dual tube liner. The core sample from P10 was assessed in the field, and discrete sections were removed from this core sample, as well as collected from the borings for grain size characterization and natural oxidant demand testing. A list of all soil samples collected is provided in Table A-1 in Appendix A.

4.4.3 Groundwater Sample Collection

The initial round of MLMW sampling was conducted from November 2, 2005 through November 10, 2005. Samples were collected in 20 mL borosilicate vials (VWR International, Mississauga, ON) with hole-top caps and fluoropolymer resin/silicone septa. For subsequent sampling events, generally borosilicate glass vials (11 mL, 15-425 hole top caps, Chromatographic Specialties Inc., Brockville, ON) with Teflon-lined silicone septa were used for sample collection.

Samples were collected with the use of a peristaltic pump (L/S Variable Speed, Modular Drive 6-600rpm, Masterflex) and a sampling assembly designed to minimize the loss of VOCs. Figure 4-12 provides a schematic of the sampling assembly. The assembly consisted of a small length (approximately 0.05 m) of flexible Tygon tubing (3/16" ID x 5/16" OD, Saint-Gobain Performance Plastics, Akron, OH) which was fitted over the MLMW Teflon sampling point. This piece of flexible tubing was then fitted with a stainless steel disposable needle (18 – 21 gauge, BD Precision Glide, Oakville, ON), which pierced the septa of the sample vial and inserted so that the tip was near the bottom of the vial. A shorter needle (BD Precision Glide, 1") was used on the outlet side, again connected via a small piece of flexible tubing (less than 0.1 m) connected to the norprene pump tubing (Masterflex, L/S 15) via a polyethylene fitting. The flexible tubing and syringe tips were replaced for each sample collection point.

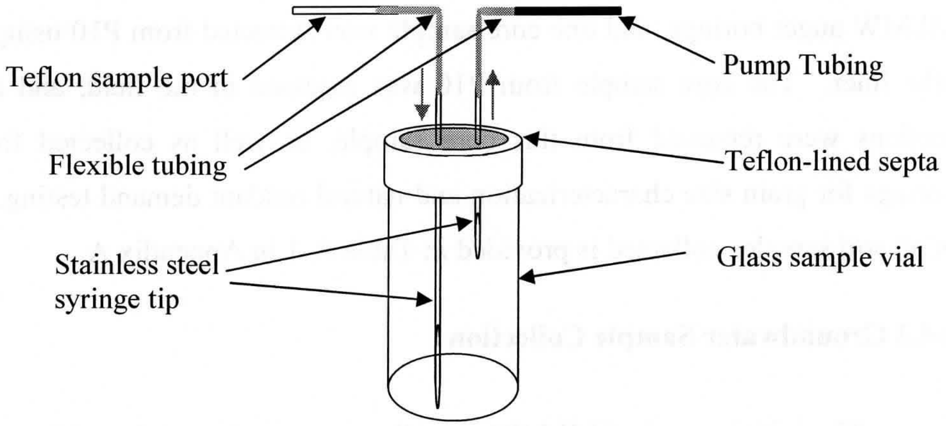


Figure 4-12: Sample Collection Manifold

Prior to sample collection, a small volume of water, equivalent to approximately three sample tubing volumes, was purged from the well at a low flow rate of approximately 100 mL/min or less. This was done to flush the tubing and ensure the sample collected was representative of the groundwater at the sampling tip. A low flow rate was employed to minimize disturbance at the well tip.

Once the well was purged, the sampling manifold was connected and the vials were filled, at a flow rate of approximately 10 mL/min. The samples collected were in contact only with Teflon, stainless steel, and a small section of flexible tubing, and were collected prior to contact with the pump tubing and pump head. For VOC analysis, samples required zero headspace. To obtain this, once the vial was filled, the cap was removed and the sample was quickly topped off with a small volume of sample present in the flexible tubing attached to the Teflon sampling port. This was immediately capped with a new Teflon septa and hole-top cap, to minimize exposure to the atmosphere. Samples were then placed on ice, and stored in a cooler and/or refrigerated until analysis. Duplicates and field blanks were collected in accordance with the procedures outlined in Section 4.1.5.

BH208 was sampled for ions (Br^- and Cl^-) and VC. When samples were collected for VC analysis, the well was purged (typically with Waterra tubing as outlined in Section 4.1.5, or with the peristaltic pump) and then the samples were collected using the sampling procedures described for the MLMWs, except that a length of Teflon tubing was inserted down well to collect the actual sample instead of using the existing Waterra tubing. Analyses were conducted as described in 4.5.1 through 4.5.4.

4.5 Analytical Methods

This section describes the analytical methods used in this research. Analytical methods were used to quantify concentrations of ions (Br^- and Cl^-), VC, $KMn0_4$, conductivity and total dissolved solids from the samples collected as described in the previous sections.

4.5.1 Ion Chromatography

Both Br^- and Cl^- were quantified with liquid ion chromatography. A Varian ProStar Model 410 autosampler, and Varian ProStar Model 230 solvent delivery module (Varian Inc., Oakville, ON) were used in combination with a Dionex CD25 conductivity detector (Dionex, Sunnyvale, CA). For the analysis, a 0.3 mM $NaHCO_3$/2.7 mM Na_2CO_3 eluent solution was run through an IonPac AS12A 4 x 200 mm analytical column (Dionex, Sunnyvale, CA), at a flow rate of 1.5 mL/min. The system was run in conjunction with a Dionex AMMS III 4 mm cation suppressor with a 25 mN H_2SO_4 regenerant. Eluent and regenerant solutions were prepared in accordance with Standard Methods Method 4110 (AWWA, 1998).

Samples were prepared by transferring 1.5 mL of sample into 2 mL glass autosampler vials with polypropylene hole-top screw caps and Teflon lined septa (Chromatographic Specialties Inc., Brockville, ON). Groundwater samples containing particulate or sediment were first centrifuged at 12,000 rpm for 15 minutes in 1.5 mL micro-centrifuge tubes (DiaMed Lab Supplies Inc., Mississauga, ON) using a Beckman Coulter Allegra 25R centrifuge to remove settleable solids. Following centrifuging, 1.35 mL of the sample was transferred to an autosampler vial for analysis.

In addition to groundwater samples, both Br^- and Cl^- standards were analysed to prepare standard curves. Standards were prepared in accordance with procedures outlined in Standard Methods Method 4110 (AWWA, 1998), and several different batches of standards were prepared over the duration of the research Three ranges of standard curves were developed for Br^- due to the wide range of concentrations encountered in the field samples; however one standard curve was developed for Cl^- analysis. Figures A-1 and A-2, Appendix A provide a sample of a standard curve for both Br^- and Cl^-. Once the standard curves were developed, Br^- and Cl^- standards were run with each batch of groundwater samples to ensure that the standard curves had not drifted. There were minor fluctuations over the duration of the research however the standard curves remained relatively stable throughout. The method detection limit (MDL) was determined in accordance with Standard Methods Method 1030C, (AWWA, 1998) and was 0.3 mg/L for Br^- and 4.9 mg/L for Cl^-.

4.5.2 Gas Chromatography

VC was quantified using gas chromatography (GC). A Varian CP-3800 gas chromatograph equipped with a Combi-Pal autosampler and a flame ionization detector (FID) was employed for these analyses. The sample was extracted by solid-phase micro-extraction (SPME) with a Supelco 100 μm polydimethylsiloxane SPME fibre. The carrier gas, helium, was run through a Varian CP-Wax (52CB 25 m x 0.53 mm ID) column at 10 mL/min. The fibre was injected to the column through a 0.75 mm ID SPME injection sleeve (SUPELCO, Bellefonte, PA) using splitless injection flow.

Samples were prepared by transferring 0.5 mL of sample with a gastight syringe into chilled and salted 2 mL glass auto sampler vials with polypropylene screw hole-top caps and Teflon lined septa (Chromatographic Specialties, Inc., Brockville, ON). The original samples were refrigerated prior to extraction and once prepared in the auto sampler vials, were stored in the freezer until several hours before analysis. Samples were brought to room temperature and agitated prior to GC analysis.

VC calibration standards were prepared in accordance with Standard Methods Method 6200, (AWWA, 1998) using a 100 μg/mL VC in methanol stock solution (HC-290, Ultra Scientific, North Kingstown, RI). Standards were prepared in 11 and 20 mL glass vials as described in Section 4.4.4 with Teflon-lined septa and stored the freezer until use. Three standard curves were prepared due to the wide range of concentrations encountered; a sample of the standard curve for VC is included in Figure A-3 in Appendix A. Standards of varying concentrations were run with the groundwater samples to ensure that the standard curves had not drifted since the last GC use. The GC did drift over the duration of the experiment, however check samples were generally within one standard deviation of the standard curve. In cases where there was greater drift, a temporary standard curve was generated for that run. The MDL was determined in accordance with Standard Methods Method 1030C, (AWWA, 1998) and was found to be 2.5 μg/L and the limit of quantitation (LOQ) was 10 μg/L for VC.

4.5.3 Spectrophotometry

Concentrations of $KMnO_4$ were measured in the laboratory using a LKB Biochrom Ultraspec Plus UV/Visible Spectrophotometer at 525 nm. Concentrations of $KMnO_4$ were measured in the field using a Hach DR/2000 Spectrophotometer. The spectrophotometer readings were not consistent at absorbances above about 2.1, and therefore samples with absorbances above these readings were diluted prior to analysis and the concentration was subsequently determined by Equation 4-13:

$$C_{sample} = \frac{C_{dilution} \forall_{total}}{\forall_{sample}} \qquad \textbf{4-13}$$

where C_{sample} (g/L) is the concentration of the permanganate in the reactor, $C_{dilution}$ (g/L) is the concentration of the diluted sample as measured by the spectrophotometer, $\forall_{total}$ is the volume of the diluted sample (μL) and $\forall_{sample}$ (μL) is the volume of original sample (typically 5 or 10 μL). An example of a standard curve for $KMnO_4$ analysis is included in Figure A-4 in Appendix A.

4.5.4 Conductivity and Total Dissolved Solids

For samples collected in September and October 2006, conductivity, temperature and total dissolved solids were occasionally measured in the field using a Hach Model 44600 Conductivity/TDS Meter. The measurements were collected from the purged groundwater, and the wells were purged until the readings stabilized, which was approximately three well volumes or less.

Chapter 5: Site Characterization Results and Discussion

The first part of this chapter, Section 5.1, provides the results of the hydrogeological investigation obtained from existing site infrastructure (i.e., existing monitor wells). This information is then used to develop parameter estimates (i.e., hydraulic conductivity, groundwater flow rate) required for the design and installation of the delivery and monitoring system. Section 5.2 provides the results of the NOD testing.

5.1 Reconnaissance and Site Characterization Activities

5.1.1 Existing Well Conditions

Following the document review described in Chapter 3, a list of wells still expected to be present on the site was compiled. A search was conducted for the wells in March 2005, and the condition of each existing well was assessed through visual observation and a water level tape in April 2005. The groundcover in the area of the former excavation, at the NE corner of the site, was fill that had recently been moved, which hindered the well locates. A summary of the existing well conditions is provided Table 5-1. Wells that were missing covers, caps and plugs were considered to be in poor condition. These protective seals and covers are intended to prevent surface debris and water from entering the well casing (e.g., rocks, silt, etc.) and interfering with the well screen. Bailers found in two of the wells (BH211, BH216) were filled with silty material upon removal of the bailers. Wells that were found in good condition were deemed to be competent and were used in further characterization/monitoring work.

Table 5-1: Summary of Well Conditions

Well ID	Date Installed	Installed By	Notes
BH1	30-Jan-02	S & P	Present – poor condition (protruding casing).
BH2	30-Jan-02	S & P	Located in area of nickel impacted excavated soils (AMEC, July 2002). Assumed destroyed, but no mention of decommissioning in July 2002 report
BH6	30-Jan-02	S & P	Present
BH101	11-Feb-02	S & P	Not found
BH102	11-Feb-02	S & P	Missing cover and cap
BH103	11-Feb-02	S & P	Present
BH104	11-Feb-02	S & P	See BH2 notes
BH105	11-Feb-02	S & P	See BH2 notes
BH206	8-Jun-02	AMEC	Present
BH207	8-Jun-02	AMEC	No cap or cover, loose J-plug, mud in casing
BH208	8-Jun-02	AMEC	Present
BH209	8-Jun-02	AMEC	No cap, but J-plug
BH210	6-Jul-02	AMEC	Present
BH211	6-Jul-02	AMEC	No cover, cap or plug. Rocks in casing
BH212	6-Jul-02	AMEC	Located within Fall 2003 excavation limits. Reportedly decommissioned as part of remedial excavation by AMEC, no details of decommissioning procedure were given
BH213	20-Jul-02	AMEC	See BH212 notes
BH214	20-Jul-02	AMEC	Not found
BH215	20-Jul-02	AMEC	Present, no plug.
BH216	20-Jul-02	AMEC	No cover, cap, or plug. Found submerged in a puddle
BH217	20-Jul-02	AMEC	Not found, possibly buried under fill
BH218	20-Jul-02	AMEC	No cover, cap, or plug.
BH219	13-Mar-03	AMEC	Located within Fall 2003 excavation limits and decommissioned as part of remedial excavation work program by AMEC. Decommissioning procedure outlined in December 2003 report.
MW223A	20-Jan-04	AMEC	Not found, possibly buried under fill
MW223B	20-Jan-04	AMEC	Not found, possibly buried under fill
MW224	20-Jan-04	AMEC	Not found. Could not be found by AMEC w/metal detector during July 2004, suspected to be located under recently paved area. AMEC assumed to be destroyed during other activities on-site.
MW225	20-Jan-04	AMEC	Present
MW226	20-Jan-04	AMEC	Present
MW227	20-Jan-04	AMEC	Not found, possibly buried under fill

highlighted = wells deemed to be competent and used for further characterization/monitoring

5.1.2 Well Elevation Surveys

The surveyed elevations for the existing wells are presented in Table B-2 in Appendix B. The benchmark used for the elevation survey was the centre bottom edge of the curb on the east side of the garage ramp. The benchmark elevation was then assumed to be 100.00 m for reference purposes. The well casing for BH1 was in poor condition and protruding from the ground and therefore was not surveyed. MW225 was buried under fill at the time of the survey and could not be found, therefore elevation measurements were not collected for this well. These elevations were then used for comparison of water level data.

5.1.3 Water Levels and Groundwater Flow Direction

Water levels were collected from existing wells on several occasions at the site, and were measured as depth to water below the top of the well casing (mbTOC), and based on survey elevations, this measurement was then converted and recorded as a water table elevation (m). A summary of the water table elevations collected at the site from spring/summer 2005 is available in Table B-3.

Figure 5-1 shows the trend in the water table elevation at select wells during the spring and summer of 2005. Concurrent with the changes in water table elevations, precipitation data were also collected and are presented in Figure 5-2. Constant head contours were plotted and are shown in Figures 5-3 through 5-5. The direction of groundwater flow is perpendicular to the constant head contours, and is indicated on Figures 5-3 through 5-5 with an arrow. The groundwater flow direction ranged from N26°E to N52°E over the course of the spring and summer of 2005.

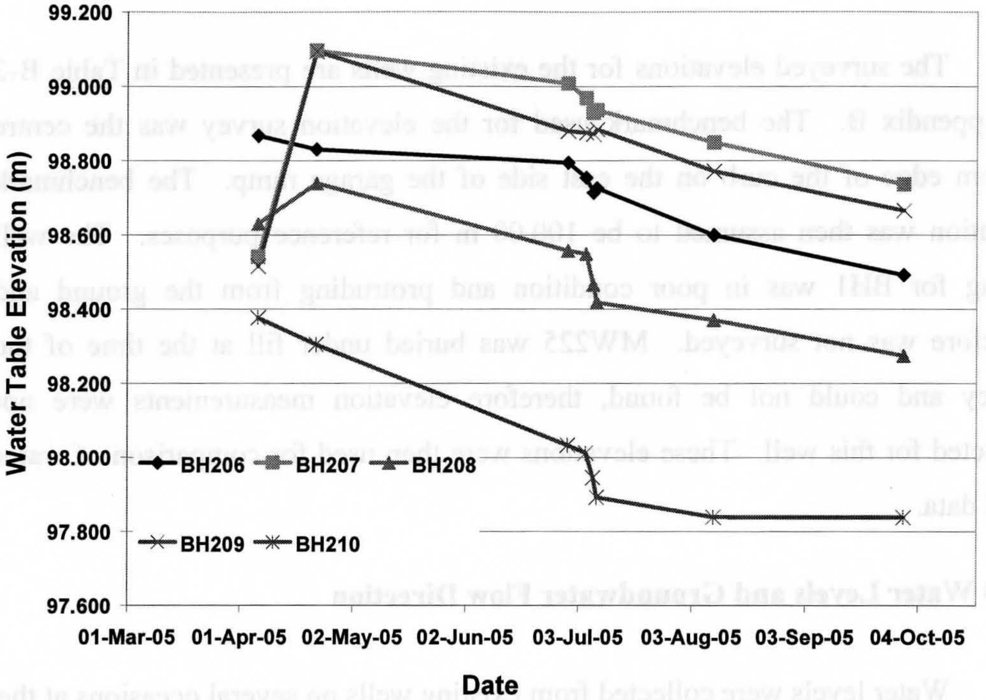


Figure 5-1: Water Table Elevation – Spring/Summer 2005

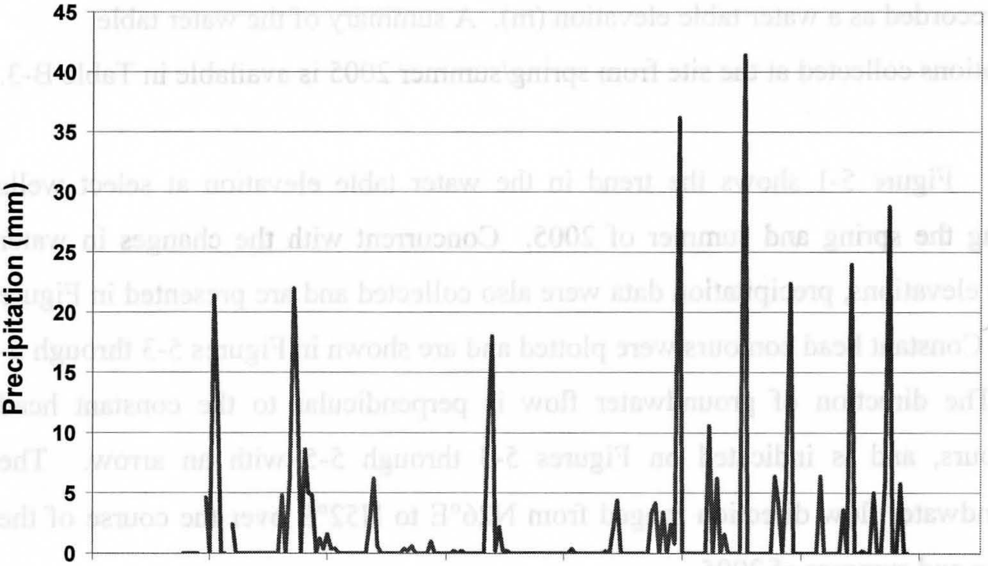


Figure 5-2: Precipitation Data – Spring/Summer 2005

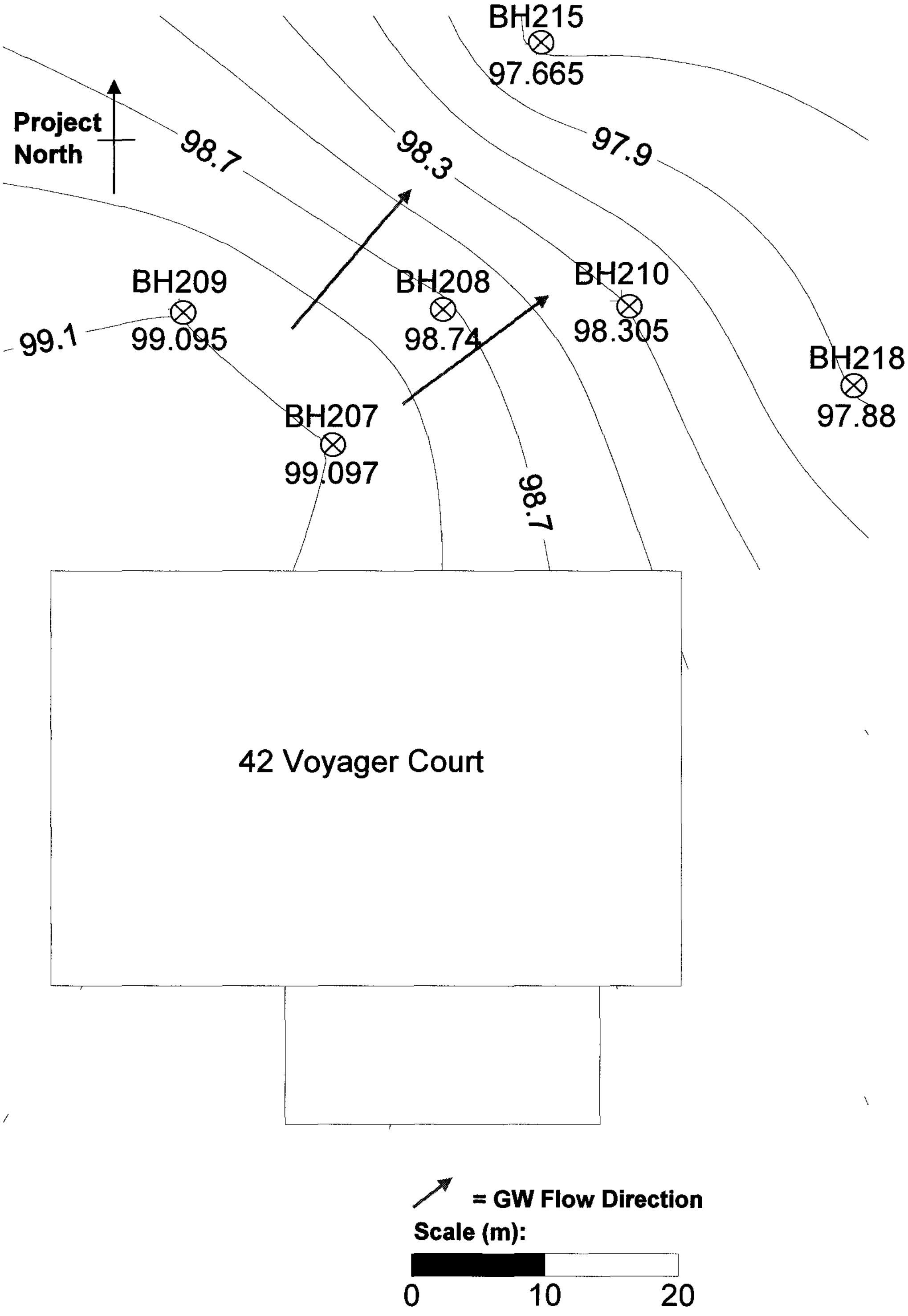


Figure 5-3: Water Table Elevations – April 22, 2005

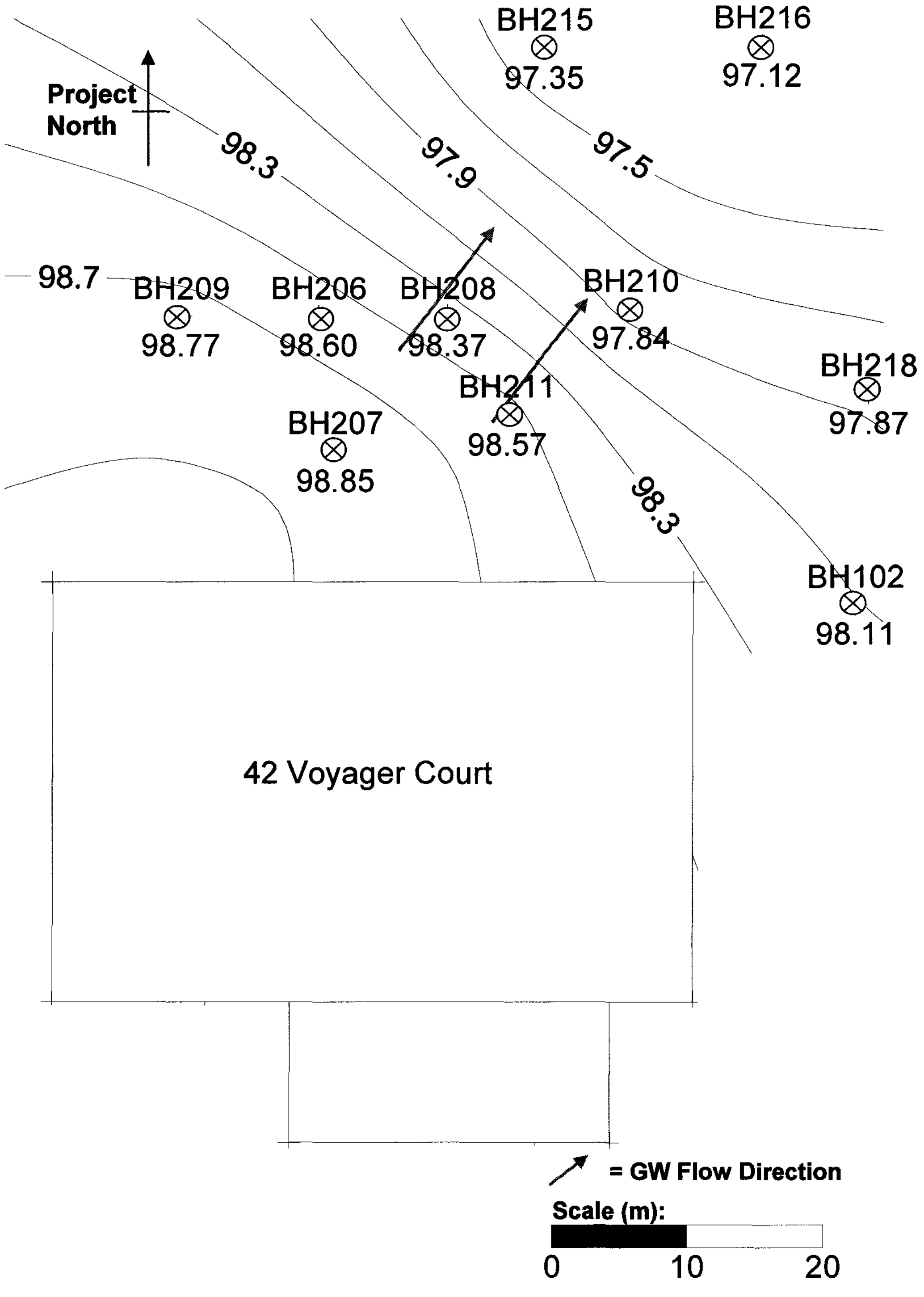


Figure 5-4: Water Table Elevations – August 8, 2005

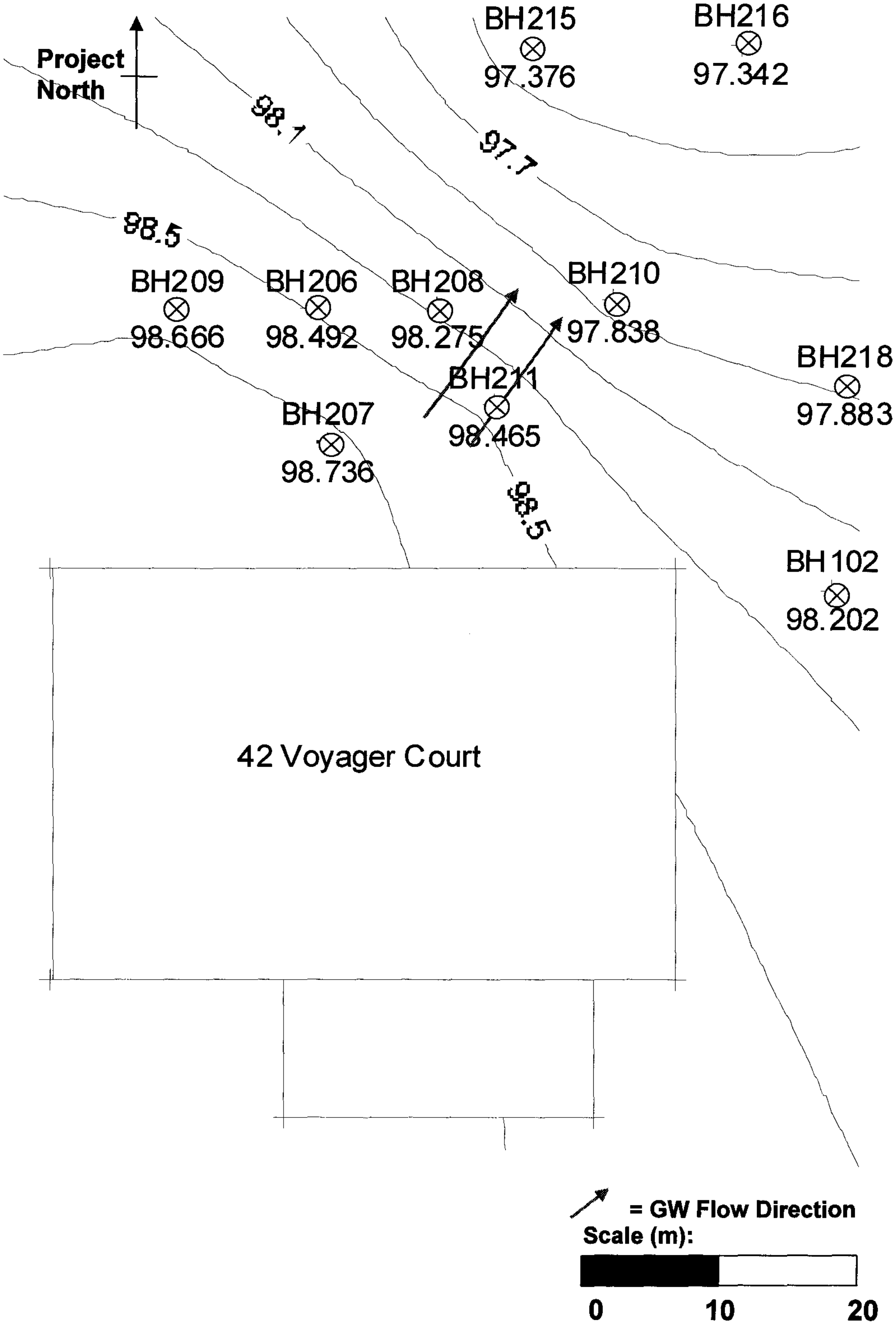


Figure 5-5: Water Level Elevations – September 30, 2005

From Figures 5-1 and 5-2, it appears that water levels in BH207 and BH208 and increased between April 6 and April 22, 2005; however all wells showed a general decline in water levels over the summer months, likely due to the dry conditions. However, since the water levels measured in BH207, BH208 and BH209 on April 6, 2005 were collected shortly after the removal of the bailers, the hydraulic head data may have been affected in these wells, as the water levels had likely not fully recovered. Also interesting to note is the decline in water table elevations in BH206, BH207, BH208, and BH210 in early July, as this coincides with the period over which the slug tests were conducted; the implications of this finding will be discussed in Section 5.1.4.

Hydraulic Gradient and Groundwater Flow Direction

The target area of concern to be remediated was in the vicinity of BH208, as determined by the background chemistry data (see Chapter 3). The wells deemed competent on the north side of the site were used to estimate the hydraulic gradient (i). Using the spreadsheet described and provided by Devlin (2003), and water level data collected from BH206 to BH210 the gradient and direction of groundwater flow were calculated for several dates as given in Table 5-2.

Table 5-2: Hydraulic Gradient and Groundwater Flow Direction

Date	Wells Used	Gradient, i (m/m)	Direction
June 23, 2005	BH206 to BH208	0.034	N54°E
	BH206 to BH210	0.037	N45°E
August 9, 2005	BH206 to BH208	0.037	N41°E
	BH206 to BH210	0.043	N40°E
September 30, 2005	BH206 to BH208	0.035	N40°E
	BH206 to BH210	0.038	N47°E

Table 5-2 indicates that the hydraulic gradient ranged from 0.034 m/m to 0.043 m/m over spring and summer of 2005. As these estimates are based on water levels in the wells, some of which may not be truly representative of the formation conditions due to plugging etc., both the low and high extremes of the estimates were used in the groundwater flow rate calculations.

5.1.4 Hydraulic Conductivity

The date and details of the slug tests are summarized in Table B-4 in Appendix B. The results of the slug tests, analysed using the Hvorslev method, for each well (BH206 to BH210 and BH215) are given in Table 5-3 and an example of the slug test data is provided in Appendix B. Table 5-3 indicates that the hydraulic conductivity estimates ranged from 0.4 to 2.8 cm/d. The results were fairly repeatable, with an increasing conductivity trend through progressive tests in some wells (i.e., BH209, BH215).

Table 5-3: Summary of Hydraulic Conductivity Estimates

Well	Date	K estimate (cm/d)	Average K (cm/d)	Standard Deviation
BH206	30-Jun-05	0.8	0.8	0
	7-Jul-05	0.8		
	8-Jul-05	0.8		
BH207	30-Jun-05	1.3	1.4	0.1
	7-Jul-05	1.4		
	8-Jul-05	1.4		
BH208	30-Jun-05	2.1	2.5	0.4
	5-Jul-05	2.8		
	7-Jul-05	2.7		
BH209	30-Jun-05	0.4	0.8	0.4
	7-Jul-05	1.0		
	8-Jul-05	1.1		
BH210	30-Jun-05	0.3	0.4	0.1
	5-Jul-05	0.4		
	7-Jul-05	0.4		
BH215	30-Jun-05	0.6	0.9	0.2
	5-Jul-05	0.9		
	8-Jul-05	1.1		

The values obtained from these estimates (approximately 4.6 x 10^{-8} - 3.2 x 10^{-7} m/s) are within the lower range of those typically reported in literature for silt (1 x 10^{-9} - 2 x 10^{-5} m/s, (Domenico and Schwartz (1990)), and in the middle of those typically reported for tills (1 x 10^{-12} - 2 x 10^{-6} m/s (Domenico and Schwartz, (1990)). These estimates may provide an accurate reflection of subsurface conditions, or they may be affected by the condition of the wells. As the wells had not been fully sealed and protected prior to the start of this project, it is possible that the casings and well screens may have become plugged with surface debris and other material.

Falling head slug tests rely on forcing fluid out through the well bore, and depend on having a well developed monitoring well (Weight and Sonderegger, 2004). In the case of the wells at this site, many were found in poor condition, and had not been sampled recently. Therefore it is possible that some were in poor condition, and may have been plugged with silt or surface debris. As these wells would not be considered well developed, the results from the slug tests may not accurately represent the subsurface conditions. BH208 was found to be in fairly good condition, and had been regularly sampled according to available reports. Therefore it was considered to provide more reliable data than the other wells. Although BH210 was sampled as regularly as BH208, it yielded a much lower hydraulic conductivity reading, and it is unclear whether this conductivity is representative of the formation, or a result of plugging in the well bore. The hydraulic conductivity values obtained for BH208 and BH210 were used in subsequent calculations as the high and low estimates for this parameter.

The trend of increasing conductivity values over time as increasing numbers of slug tests were performed may be due to forcing flow out of the well screen. It is possible that the falling head slug test could aid in the well development and improve performance (i.e., by forcing silt and other clogging materials out). This unclogging of the well screen could also explain the trend of decreasing water levels over the period during which the slug tests were conducted, as previously mentioned in Section 5.1.3.

5.1.5 Groundwater Flow Rate Estimate

Once the estimates of hydraulic gradient (i) and hydraulic conductivity (K) were obtained, the groundwater flux (q) was estimated and is given in Table 5-4. Using the high and low estimates for q, estimates of travel times over the duration of the project were calculated, and are summarized in the Table 5-5.

Table 5-4: Groundwater Flux

Scenario 1: Low Estimate			**Scenario 2: High Estimate**		
K=	0.4	cm/d	K=	2.5	cm/d
i=	0.034	m/m	i=	0.043	m/m
q=	**0.01**	**cm/d**	**q=**	**0.11**	**cm/d**

Table 5-5: Groundwater Travel Times

Scenario 1: Low Estimate		**Scenario 2: High Estimate**	
Time (days)	Travel Distance (cm)	Time (days)	Travel Distance (cm)
30	0.4	30	3.2
60	0.8	60	6.5
90	1.2	90	9.7
180	2.4	180	19.4
270	3.7	270	29.0
365	5.0	365	39.2

Table 5-5 indicates that the groundwater is expected to travel relatively slowly. In the direction of flow, using low estimates of parameters, groundwater is estimated to move only 5 cm over a one year time period, while using the higher estimates, groundwater is expected to travel approximately 40 cm during a one year time period. It appears that the northeast area of the site is underlain by a slow-moving formation, which is typical of a silty till.

5.1.6 Sample Results from Initial Sampling Round

Table 5-6 presents the analytical results of the samples collected from the existing on-site wells on April 22, 2005; analysis by Maxxam Analytics. MW100 is the field blank that was collected and submitted for analysis along with the other samples. Table 5-6 indicates the concentration of VC in BH208 continued to exceed the applicable MOE guidelines, although concentrations are generally lower than those reported by AMEC on previous dates (with the exception of the nd in January 2004). Concentrations of VC in BH210, BH215 and MW226 exceed the Table 3 guideline of 0.5 μg/L for coarse-grained soils, however if the guideline for fine- to medium-textured soils (1.3 μg/L) was applied, MW226 would be below the guideline, and BH210 and BH215 would be close.

Based on the available VOC chemistry data (Chapter 3) and the results outlined in Table 5-6, it is apparent that the VC impacts are greatest in the vicinity of BH208. BH210, BH215 and MW225 also had VC concentrations that slightly exceeded guidelines. Figure B-1 in Appendix B, shows that these wells are generally located around the periphery of the PCE soil excavation conducted by AMEC in 2003. VC may be present as one of the daughter products of the degradation of PCE, and even a very small quantity of residual contaminated soil could be contributing to the elevated VC concentrations. It was proposed by AMEC that the elevated VC concentrations in the groundwater could be the result of a dissolved phase groundwater plume that extended from the area of the excavated PCE impacted soil (AMEC, 2003). Since the well screens are long (approximately 3 m in length) it is not possible to tell from these data whether it is a very small lense of highly contaminated groundwater becoming diluted over the screened depth of the well, or a larger lense of a lower concentration. As it is not possible to discern the interval from which the contamination is originating, it will be necessary to target the entire depth with amendment for remedial purposes.

Table 5-6: Groundwater Sample Results - April 22, 2005

Compound	**MDL (µg/L)**	O.Reg 153/04 Table 3 Guidelines (µg/L)	MW100 – Field Blank	BH207	BH208	BH208-Blind Dup	BH209	BH210	BH215	BH218	MW225	MW226
VC	0.2	0.5	nd	nd	**9.3**	**8.5**	nd	**1.5**	**1.5**	nd	**0.6**	nd
1,1 - DCE	0.1	0.66	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
cis-1,2-DCE	0.1	70	nd	nd	8.4	9.1	nd	5.5	**71.6**	nd	1.9	23.3
trans-1,2-DCE	0.1	100	nd	nd	0.1	0.2	nd	nd	0.5	nd	nd	nd
TCE	0.1	50	nd	nd	nd	nd	nd	2.3	nd	nd	nd	0.1
PCE	0.1	5	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

bold = exceeds Table 3 guidelines for coarse-grained formation
Table 3 guidelines for VC in fine to medium-grained soils is 1.3 µg/L
nd = concentration not detected above Maxxam detection limits

5.2 Natural Oxidant Demand

Before delivering the $KMnO_4$ solution, it was necessary to estimate the NOD of the aquifer solids. There were several objectives in the NOD experimentation. Overall, the goal was to determine an estimate of the NOD for the site for use in design calculations. In addition, a secondary goal was to determine whether varying the $KMnO_4$ concentration affected the NOD, as this finding would be useful in deciding on the target $KMnO_4$ delivery concentration. Thirdly, the goal was to determine whether NOD varied spatially, as soil samples had been collected from several different locations in the treatment area. The experiments described in this section were conducted on soil samples collected during delivery system and MLMW installation at the site (see Chapter 6 for installation details).

The solubility of $KMnO_4$ is approximately 65 g/L at 20°C (Carus, 2005). Groundwater temperature was expected to be in the range of 10°C or lower and during delivery the air temperature could be below 10°C. As a result, a target concentration of 40 g/L was chosen for the amendment delivery, as $KMnO_4$ solubility decreases with decreasing temperature (Carus, 2005). This concentration was similar to the higher end concentrations employed in other studies reported in the literature (e.g., Parker et al., 2002). The amendment delivery rate would be approximately 13 to 23% of the groundwater flow rate (for details see Section 6.2.2). At 40 g/L, once diluted with groundwater, the concentration of $KMnO_4$ would be approximately 5 to 10 g/L. However immediately upon leaving the delivery points (before complete mixing with the groundwater) the concentration of $KMnO_4$ in the groundwater was anticipated to be higher. As a result, to approximate expected subsurface concentrations, $KMnO_4$ concentrations of 8 g/L and 25 g/L were chosen for use in the NOD experiments.

Soil samples analysed in the NOD experiments were collected during the installation of MW302, MW303/304, MW305, MW307/308 and MW311. Figure 5-6 shows the locations from which the soil samples were taken. Generally, two types of soil were encountered in the samples; a reddish till with silt, sand and some gravels and a beige till with silt, sand and some gravels. Details of the reactor preparation (i.e,. location, mass of soil, type of soil, and mass of $KMnO_4$ added) are included in Table B-5 in Appendix B. To investigate the effects sample location and concentration changes on NOD, the samples were run in pairs so that generally for each location one set of reactors was run with the 8 g/L $KMnO_4$ solution, and the second set of reactors was run with the 25 g/L $KMnO_4$ solution.

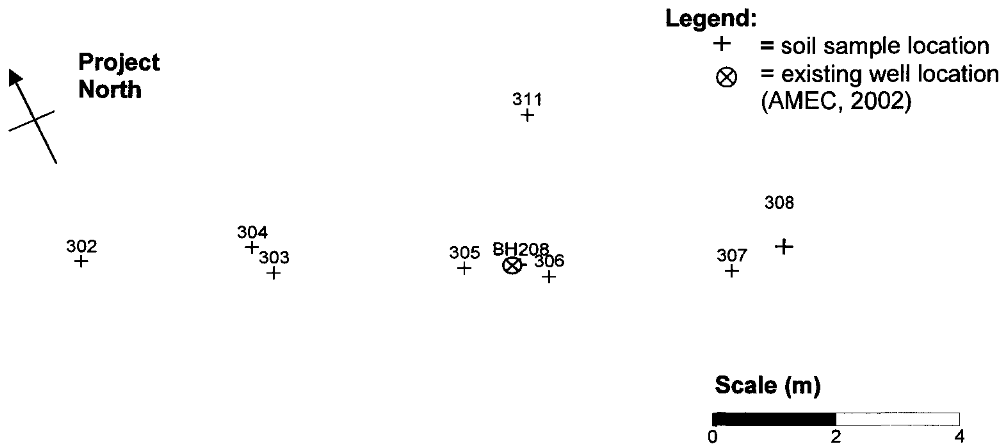


Figure 5-6: NOD Soil Sample Locations

In total, four pairs of reactors were analysed (runs 4 through 12). Runs 4 and 5 (MW302) examined the effect of temperature on NOD, and to do this, both used the 8 g/L solution. Runs 7 and 8 (MW311), runs 9 and 10 (MW303/304) and runs 11 and 12 (MW305) examined the effect of changing $KMnO_4$ concentration and thus one run used the 8 g/L solution and the other used the 25 g/L solution in each pair. Runs 13 (MW307) and 14 (MW311) were both run at 25 g/L to provide additional data on spatial variation.

A detailed summary of the sample results from the experiments is provided in Table B-6 in Appendix B. Plots of the NOD measured over time for each of the experimental comparisons (i.e., runs 4 and 5, runs 7 and 8) are also included in Figures B-2 through B-6 in Appendix B. To analyze the results, an estimate of the ultimate NOD (NOD_{ult}) was determined from the plot data. The experiments were typically run for 140 to 160 hours, with the exception of runs 4 and 5 which were run for 350 hours, and runs 7 and 8 which were run for 250 hours. From the plots in Appendix B, generally, the runs appeared to reach a fairly steady NOD value, with the exception of runs 11 through 14. This estimated steady NOD value was assumed to be representative of the anticipated NOD_{ult} for the batch reaction. For runs 11 through 14, as a steady NOD value was not as apparent, the final 3 values were averaged to estimate the NOD_{ult}. Actual soil mass measurements were not available for run 14 and therefore the results may not be as representative. The estimated NOD values are summarized in Table 5-7:

Table 5-7: Summary of Ultimate NOD Estimates

Run	Sample Location	$KMnO_4$ Concentration (g/L)	Ultimate NOD Estimate (g/kg)
4	MW302	8	3
5	MW302	8	4
7	MW311	8	4
8	MW311	25	6
9	MW303/304	8	7
10	MW303/304	25	8
11	MW305	8	9
12	MW305	25	14
13	MW307/308	25	20
14	MW311	25	6

To evaluate the effect of temperature and concentration on the NOD estimates, confidence intervals (CI) were constructed on the mean NOD_{ult} for each run and are summarized in Table 5-8, with $\bar{x}$, s_x and CI values in g/kg. If there is no overlap in the calculated confidence intervals it indicates significance at a given level. For runs 4 and 5, temperature had a statistically significant effect on the NOD_{ult}. As a result, the subsequent runs were conducted at 5°C, which is more representative of groundwater temperatures than 25°C.

Table 5-8: Confidence Intervals NODult

	Run 4 8g/L 5°C	**Run 5 8 g/L 25°C**	**Run 7 8 g/L 5°C**	**Run 8 25g/L 5°C**	**Run 9 8 g/L 5°C**	**Run 10 25g/L 5°C**	**Run 11 8 g/L 5°C**	**Run 12 25g/L 25°C**
n =	7	4	3	3	3	3	3	3
$t_{v,\alpha}$ =	2.447	3.182	1.886	1.886	1.886	1.886	4.30	4.30
$\bar{x}$=	3.0	3.8	4.2	5.7	6.7	7.8	8.8	13.3
s_x =	0.341	0.245	0.17	0.82	0.67	1.6	0.12	1.03
Level	95%		80%		80%		95%	
CI:	[2.7,3.3]	[3.5,4.4]	[4.0,4.4]	[4.8,6.6]	[5.9,7.4]	[5.6,9.9]	[8.5,9.1]	[10.7,15.8]

Looking at effects of concentration change, at an 80% confidence level, the $KMnO_4$ concentration has a significant effect on the mean NOD_{ult} for two of the run pairs (locations MW311 and MW305), with an increase in mean NOD_{ult} with increasing $KMnO_4$ concentration. The variation in the data was too great, however, to detect any significant effect of $KMnO_4$ concentration on NOD_{ult} in runs 9 and 10. An increase in NOD_{ult} with increasing $KMnO_4$ concentration coincides with findings in literature (e.g., Crimi et al., 2005). Therefore, for design considerations, the NOD estimate corresponding to the higher $KMnO_4$ concentrations will be used as a more conservative figure.

Figure 5-7 shows the location of soil samples analysed in these experiments and the corresponding NODult values obtained from the 25 g/L run. Runs 5 (MW302) and 7 (MW311) were both run at a concentration of 8 g/L and a temperature of 5°C, and both produced an NODult estimate of 4 g/kg. Therefore for the purpose of spatial analysis it is assumed that at 25 g/L NODult for MW302 soil samples would be similar to those of the MW311 soil samples, and therefore the value of 6 g/kg is used from MW302 as well.

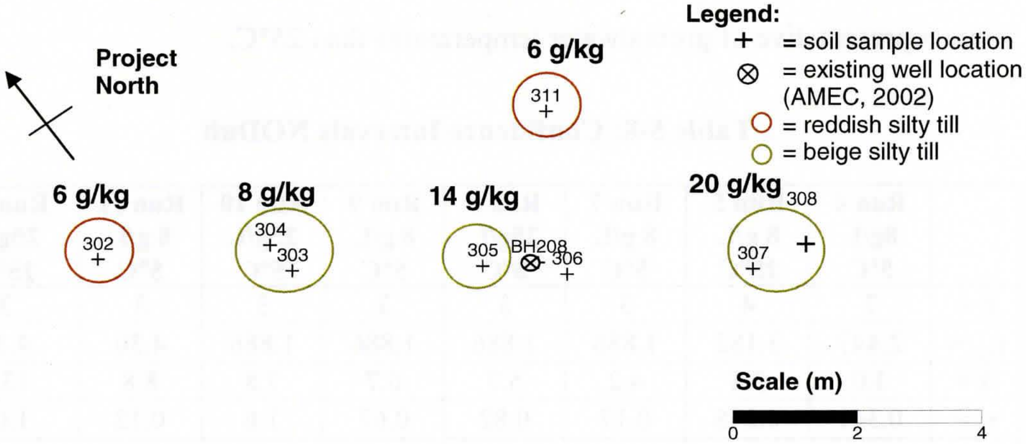


Figure 5-7 Spatial Variation of Average NOD values for [$KMnO_4$] = 25g/L

Generally it appears that the NOD estimates range from approximately 6 to 20 g/kg under batch test conditions, with an average NOD estimate at 25 g/L of 10 g/kg. The NOD estimates are lower at the north end of the study area than at the southern end. Approximately 24 kg of $KMnO_4$ would be required to satisfy the NOD of the subsurface in order to travel 0.5 m to reach BH208, based on a 1m^2 cross-section and a NOD$_{ult}$ of 10 g/kg. This amount required to satisfy the NOD greatly exceeds the $KMnO_4$ requirement of 0.7 g for the estimated mass of VC present in the vicinity of BH208 (see Table B-7 in Appendix B).

In the literature, (e.g., Mumford et al., 2002), experiments using flow-through reactors have reported lower NOD estimates than batch tests. Based on those findings, it could be expected that under flow-through conditions at the site, the actual NOD observed in the field may be lower than the average 10 g/kg predicted. However, based on the estimate of groundwater flux for the site described in Section 5.1.5, travel times are predicted to be relatively long. As a result, it is anticipated that the subsurface conditions may be more representative of batch test conditions than flow-through conditions. If both travel time and NOD estimates provided in this Chapter are reasonable, then $KMnO_4$ may not reach BH208 over the time frame of the project, as it may not be possible to deliver sufficient $KMnO_4$ to cover a 0.5 m distance to BH208 at the low design flow rates.

5.3 Summary of Findings and Implications for Design

Estimates of hydraulic conductivity in the study area at the site are low, and as a result groundwater flow rates and anticipated travel times are fairly slow. The estimated groundwater flux is 0.01 to 0.11 cm/day, which translates into travel time estimates of 0.05 to 0.5 m/year. Due to the conditions of the on-site wells, these travel time estimates may not be truly representative. The NOD estimates ranged from 6 to 20 g/kg, and these, coupled with the slow travel times, may indicate increased difficulty in delivering sufficient $KMnO_4$ to overcome NOD and reach BH208.

According to these estimates of groundwater flux and travel times, it would be necessary to place the delivery system as close to BH208 as possible, to expect a delivered amendment to reach BH208 within the duration of this project (i.e., approximately one year), or shortly thereafter. It would also be necessary to leave a sufficient distance to allow for dispersion and even mixing across the formation prior to arrival at BH208. The line of delivery points was therefore installed approximately 0.5 m upgradient of BH208 in a line perpendicular to the direction of groundwater flow. The driller indicated that it would be difficult to get closer than approximately 0.5 m without risking destroying BH208, as the installation was unknown and it was possible the borehole is installed on a slight angle. As it was expected that amendment travel times would be slow, the

MLMWs needed to be placed as close to the delivery points as possible, without disturbing them, in order to collect meaningful sample information over the duration of the project.

The calculated travel times (Table 5-5) are based on estimates of hydraulic conductivity and hydraulic gradient, which are calculated from data collected in the field from the existing long-screen (~ 3 m) monitoring wells. These data can only provide an estimate of subsurface conditions, and are limited by both the condition of the wells, and the assumption that long-screen wells are representative of the subsurface conditions. With a long-screen well, the data provide an averaged value across the depth of the well screen. However, it is possible that were the calculations conducted over more discrete intervals, such as the case with MLMWs, that the hydraulic conditions would actually vary over the depth depending on the subsurface heterogeneity (i.e. if a lense of more permeable material is present, such as sand, the travel time through this medium would be greater than the average obtained from the long-screen well calculations). As MLMWs are used for the monitoring system, some wells were placed further down gradient (up to 5m) than anticipated by the travel times to account for the possibility that groundwater, and therefore the delivered amendment, might actually move faster than expected.

Chapter 6: Amendment Delivery and Monitoring Results

After the existing reports for the site were reviewed and the site was characterized, the amendment delivery system and monitoring network were designed and installed. During the amendment delivery, samples were collected to evaluate the effectiveness of the system. This chapter summarizes the design and installation of both the amendment delivery system and the monitoring network, presents the details of the amendment delivery, and finally analyzes the results obtained through sampling the monitoring network.

6.1 Delivery System Design and Installation

Profile Drilling installed the delivery system between October 11 and October 12, 2005 with a direct push drill rig. A total of 29 delivery points, labeled P1 through P30 (P9 was not installed) were installed in a line, or fence, perpendicular to the direction of groundwater flow. The delivery fence was installed approximately 0.5 m upgradient of BH208, and the distance between the delivery points ranged from 0.44 to 0.85 m (see Figures 6-1 and 6-2 for detailed layouts).

The direct push drive point met refusal at approximately 3.8 mbg during the installation of P1. After P1 was installed, Profile Drilling attempted to auger a deeper borehole, and P10 was installed with an 8" auger to 5 mbg. Augering is a much more costly technique, as it takes more time to reach similar depths. Additionally, augering is more disruptive to the subsurface. Since little additional benefit in terms of depth was attained through augering, the remaining delivery points were installed with the direct push technique, and thus were installed to depths of approximately 4 mbg. Table C-1 in Appendix C provides details on the depth of boreholes and the delivery points (including the number of screened delivery holes).

Figure 6-3 shows the initial configuration of the pumps and the passive delivery fence. The delivery system was reconfigured on several occasions as a result of both leaks and uneven flow through the delivery point headers, which will be discussed in further detail in Section 6.2.2. Figure 6-4 shows the final system configuration; the dates shown on this figure indicate the date each change was made.

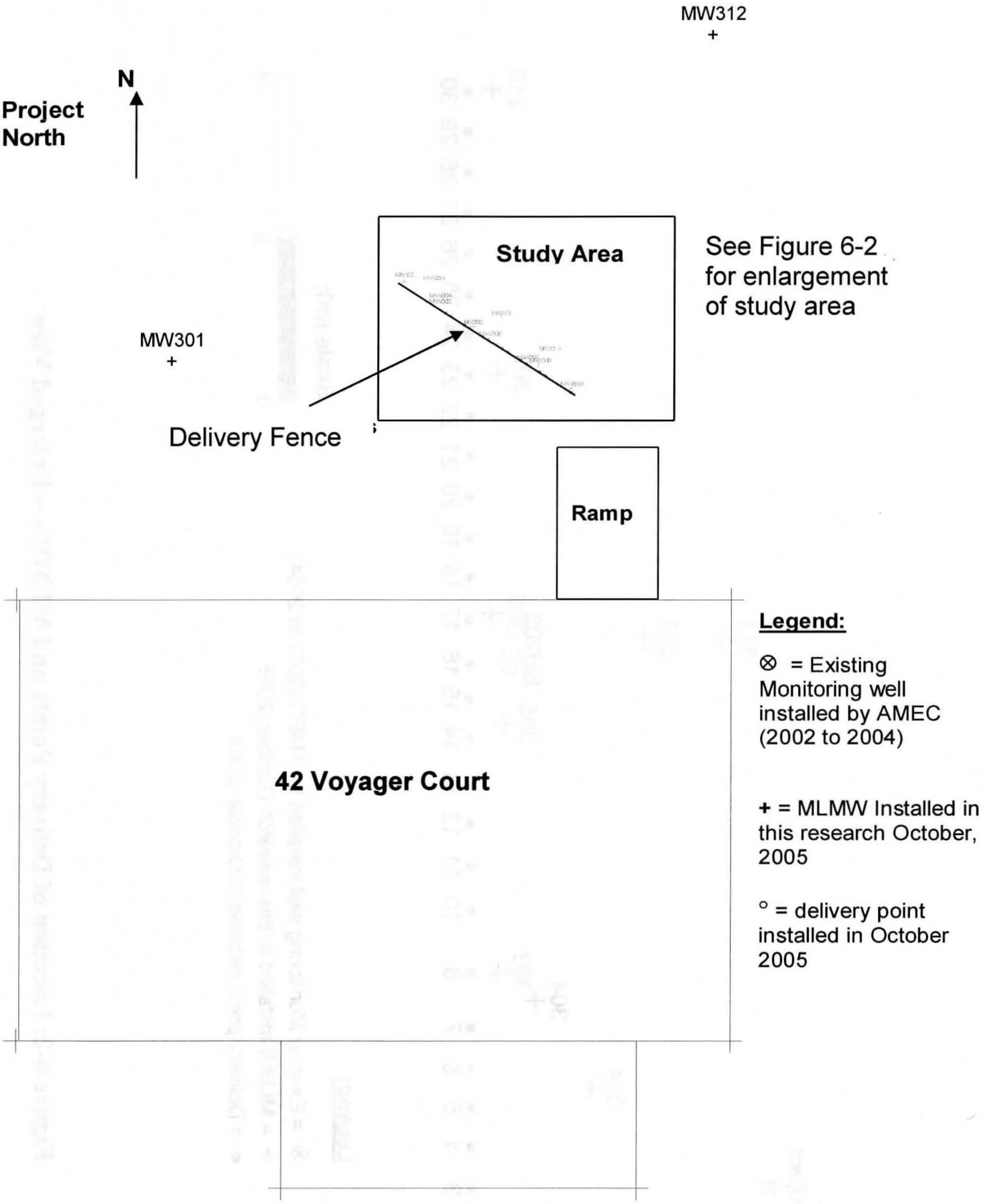


Figure 6-1: Location of Delivery Points and MLMWs installed in October 2005

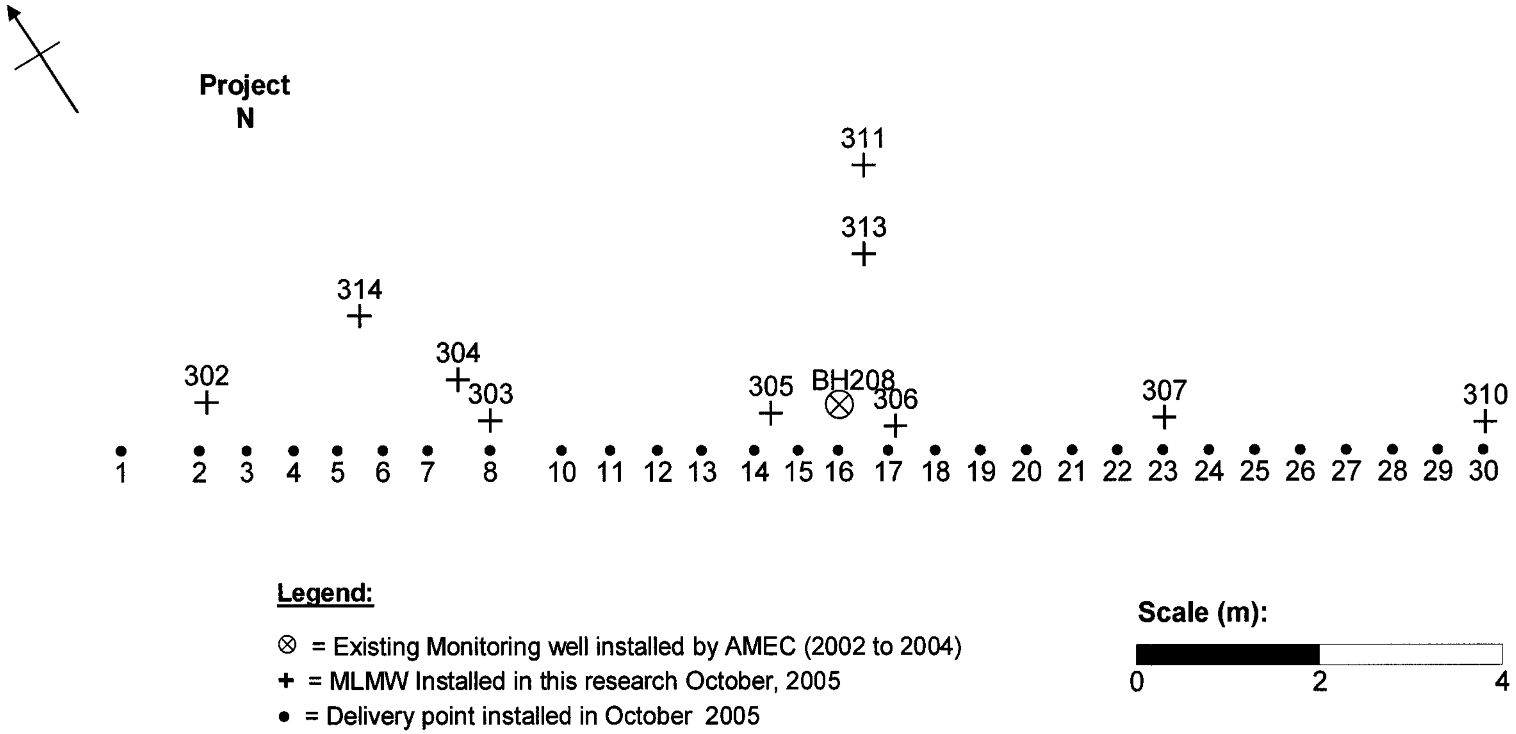


Figure 6-2: Location of Delivery Points and MLMWs – Enlarged View

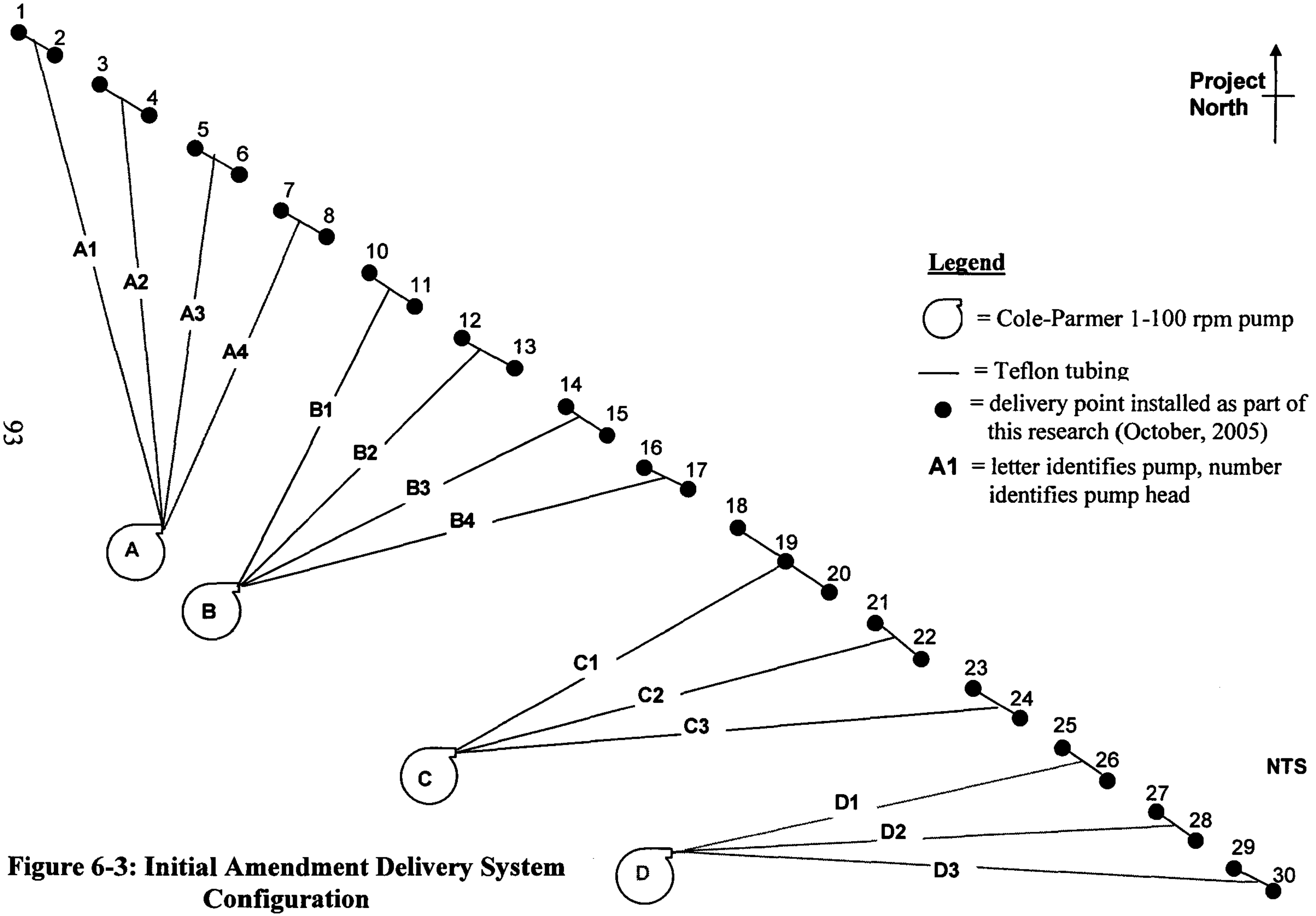


Figure 6-3: Initial Amendment Delivery System Configuration

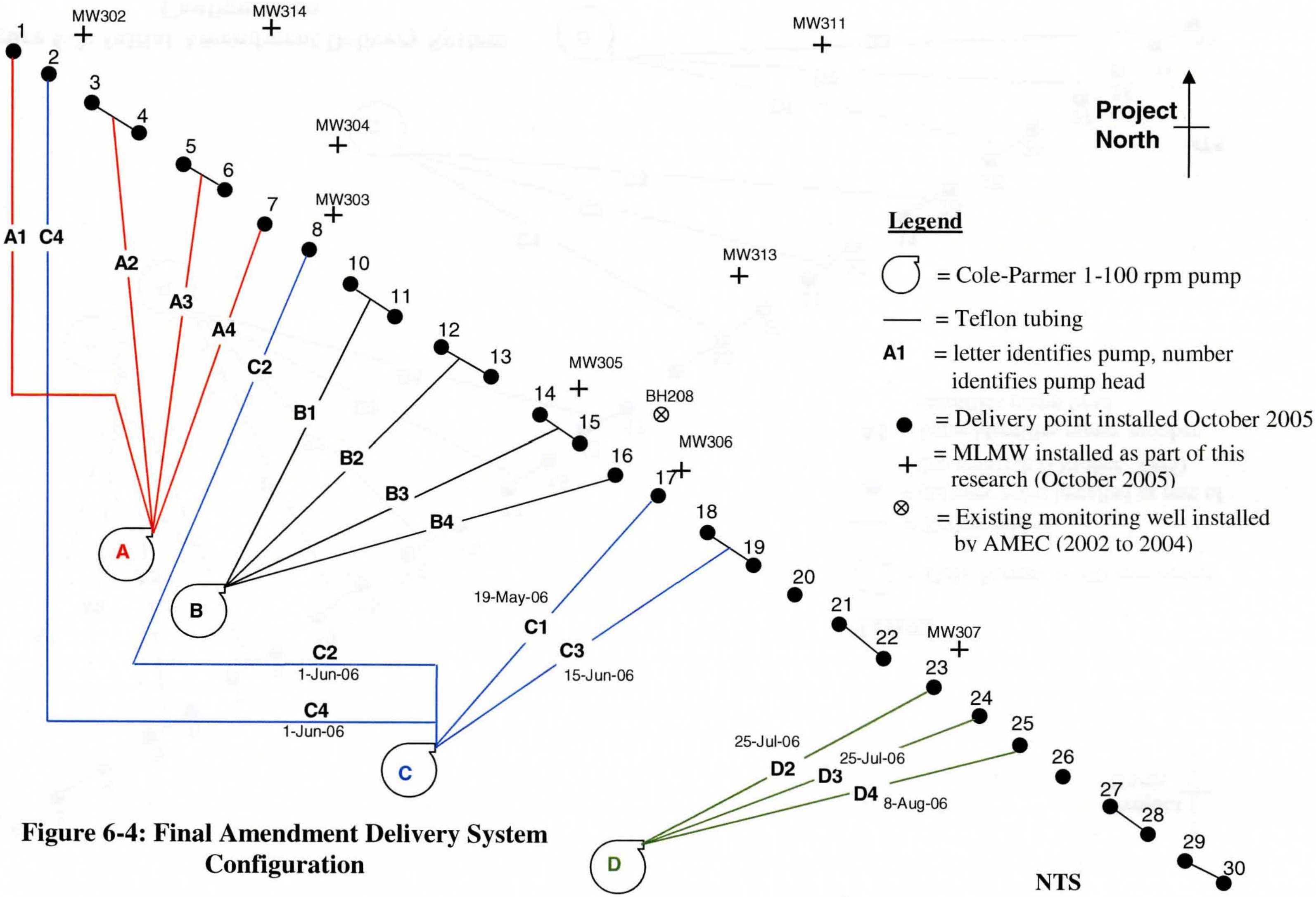


Figure 6-4: Final Amendment Delivery System Configuration

6.2 Amendment Preparation and Delivery

6.2.1 Amendment Preparation

The average $KMnO_4$ concentration in the amendment ranged from 36 to 42 g/L. As the amendment solution was delivered at a low flow rate, a high concentration of $KMnO_4$ was used to maximize the mass of $KMnO_4$ delivered to the target area. As discussed in Section 5.3, based on the solubility limits of $KMnO_4$, the target concentration for the amendment solution was 40 g/L. The target concentration for Br^- was approximately 0.8 g/L. This concentration is sufficient to achieve a detectable Br^- concentration increase in the subsurface while minimizing the quantity of NaBr required. With a delivery rate that was 13 to 23% of the groundwater flow rate, the concentration of Br^- in the subsurface should reach approximately 100 to 186 mg/L, which is well above the background Br^- levels (which ranged from below the MDL to 1.3 mg/L). Br^- was initially added to the amendment solution on April 17, 2006, but it was not continually added until May 4, 2006. The average Br^- concentration in the amendment solution was approximately 0.8 g/L.

6.2.2 Amendment Delivery

In total, the system delivered 1300 L of amendment solution from April 13, 2006 to November 10, 2006. Over this time, the amendment used a total of 50 kg of $KMnO_4$ and approximately 1.2 kg of NaBr. P1 through P17 received the majority of this solution, which is a total of 16 delivery points since P9 does not exist. Table C-2 in Appendix C provides a summary of the amendment delivery solutions, including the Br^- and $KMnO_4$ concentration present in each batch, and the delivery point that received each batch.

Table 6-1 summarizes the average amendment delivery rate to each pump head. This delivery rate was calculated based on the decrease observed in the pump reservoir over time divided by the number of pumpheads the reservoir was serving. Generally, the rate of amendment delivery to the pumpheads (which would serve one or two delivery points depending on the configuration, see Figure 6-4) was on the order of 0.5 to 0.7 L/pumphead/day.

Table 6-1: Average Flow Rate per Pump Head

Pump ID	Number of Pump Heads	Pump Head ID	Average Flow Rate (L/d per pump head)
A	4	(A1, A2, A3, A4)	0.6
B	4	(B1, B2, B3, B4)	0.5
C	4	(C1, C2, C3, C4)	0.5
D	3	(D1, D2, D3)	0.7

This delivery rate is in accordance with the initial desired delivery rate of 10 L/day for the system of 30 delivery points (which would be 0.3 L/day for each delivery point, or 0.6 L/pumphead/day). The target delivery rate was chosen to be approximately 15 % of the groundwater flow rate, so that the delivery system would not significantly disrupt the groundwater flow, and therefore the remediation system would, in effect, be passive. The flow rate was calculated based on the delivery area (15 m wide, by 3 m deep, as the delivery points were installed to depths of approximately 4 m, and the water table fluctuated between 0.8 to 1.3 mbg), and the groundwater flux ($q = 0.11$ cm/d). The groundwater flow rate crossing the entire delivery fence (P1 through P30) is approximately 50 L/d, and therefore an amendment delivery rate of 10 L/d is approximately 17% of the total flow rate through the delivery area.

Flow measurements at each pump head were collected by periodically measuring the rate of flow from each of the pump head effluent tubes, and were typically 0.5 L/d. This flow data indicates that the flow was fairly evenly distributed among the pump heads at each pump. Although each pump distributed the flow relatively evenly between each pump head, the pump heads did not distribute the flow evenly between the delivery points (recall each pump head initially served two delivery points). Observation of the passive delivery fence suggested that flow generally entered only one delivery point per pairing for the duration of the project. The flow would occasionally switch delivery points if the assembly was tightened or replaced (i.e., changing a brass T due to leaks would occasionally result in a diversion of flow from one delivery point to another). Since the delivery points sharing pump heads did not receive an even distribution of amendment flow, the delivery lines were reconfigured (see Figure 6-4). This was done to ensure successful delivery of amendment to the delivery points located directly upgradient of the MLMWs (P2, P8, P16, and P17). This was necessary as the MLMWs were the only tool available for assessing the effectiveness of the delivery system. Pumps C and D were turned off on May 18, 2006 as it was not possible to stop the delivery points that were connected to these pumps from leaking. Line C1 was connected to P17 on May 19, 2006, and on June 1, 2006 C2 was connected to P8 and C4 was connected to P2.

If one pump head serves two delivery points, as originally intended, the effective cross-sectional target area encompassed by the two points is 3 m^2, and at $q = 0.0011$ m/d, the volume of groundwater crossing that area is 3.3 L/d. For the average amendment delivery rate of 0.5 L/d per pumphead, the amendment constituted approximately 13% of the total flow rate (i.e., amendment solution (0.5 L/d) plus groundwater (3.3 L/d)). After reconfiguration, where one pump head fed only one delivery point (i.e., P1, P2, P7, P8, P16, P17), the amendment constituted approximately 23% of the total flow rate.

In addition to the pairing distribution problems, leaking fittings and caps also negatively affected the delivery of amendment to the passive delivery fence.

Leaks were a regular occurrence at nearly all delivery points, with the exception of P1 through P8 which only had minor leaks at several of the fittings. Nearly all the leaks occurred at the connections between the brass T fittings and the PVC slip caps. Caps and Ts were replaced on several occasions, and silicon caulking was applied to the assembly as well, but it was apparent that the assembly did not completely seal and the leaks continued. Leaks were responsible for the shutdown of P18 through P30 which occurred relatively early in the project, and P10 through P17 were regularly found to be leaking over the duration of the project. Table C-3 in Appendix C provides details of the leaks and shutdowns. As a result of these problems it is not possible to determine the exact amount of solution successfully delivered to the subsurface at these points (P10 through P17). For delivery points P1 through P8, where there was little visible evidence of leaks, it is assumed that all of the amendment delivered reached the subsurface.

The entire delivery system was shut off for extended periods (i.e., more than one or two days) over the period of August 1 to August 8, 2006, September 1 to September 10, 2006, and October 5 to October 16, 2006 (the first two due to accidental cut-off of power, the third due to leaks). Additionally, from October through November 2006, flow was no longer steady, as the system was frequently shut down when it was expected to fall below freezing overnight, to prevent flow lines from freezing/rupturing.

6.3 Groundwater Monitoring

Following the installation of the delivery points, MLMWs were constructed and installed at the site to monitor the effectiveness of the passive delivery fence. Fourteen MLMWs were installed and labeled as MW301 through MW314; MW301 was installed as a background well, MW312 was located near the property boundary, and the other MLMWs were installed between 0.26 and

5.1 m downgradient of the delivery fence. Figure 6-2 shows the location of the 14 MLMWs installed at the site and Table C-4 in Appendix C provides a summary of the well installation details (i.e., borehole depth, sampling port labels, and sampling port depths). Borehole records for the MLMWs are not included, as the boreholes were not cored and logged due to cost constraints. Generally, the subsurface composition observed from the auger cuttings was silty till, with evidence of sand and gravel. At depths of approximately 4 mbg, Profile Drilling encountered large rock. However, according to the historical borehole logs, AMEC did not encounter bedrock until approximately 6 mbg in the deeper well installations at the site. AMEC only cored and logged BH208 to 4.6 mbg, but at that depth they had not yet encountered bedrock. Therefore it was assumed that the rocks encountered by Profile Drilling in this work were large gravel or boulders.

Water levels were collected periodically from several of the existing wells on the site over the course of amendment delivery. Figures 6-5 through 6-8 provide contour plots of water level elevations measured on several dates. The groundwater flow direction ranged from N40°E to N65°E over the duration of the amendment delivery, and is indicated by an arrow on the figures, and summarized in Table 6-2.

Table 6-2: Groundwater Flow Direction Spring/Summer 2006

Date	Flow Direction
April 28, 2006	N40°E
June 16, 2006	N65°E
July 14, 2006	N41°E
September 30, 2006	N57°E

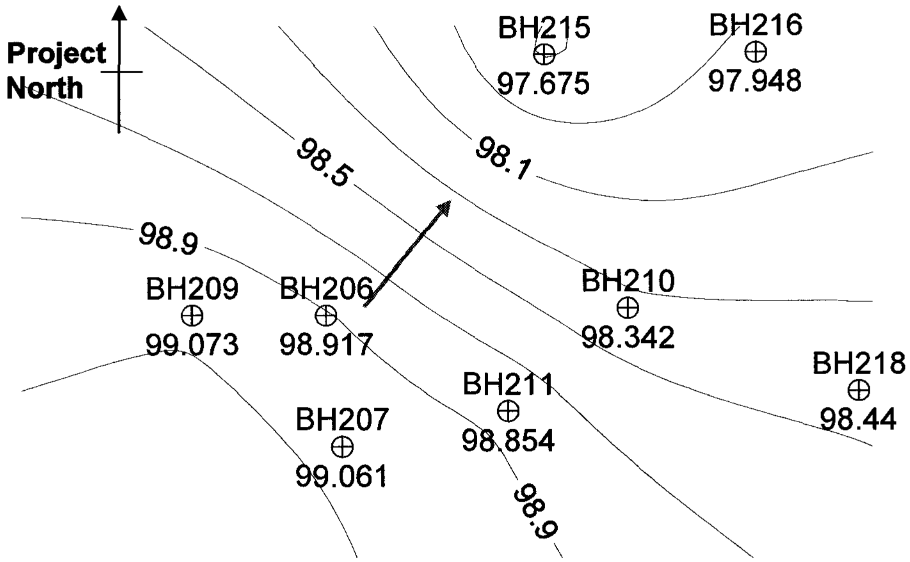


Figure 6-5: Water Table Elevations – April 28, 2006

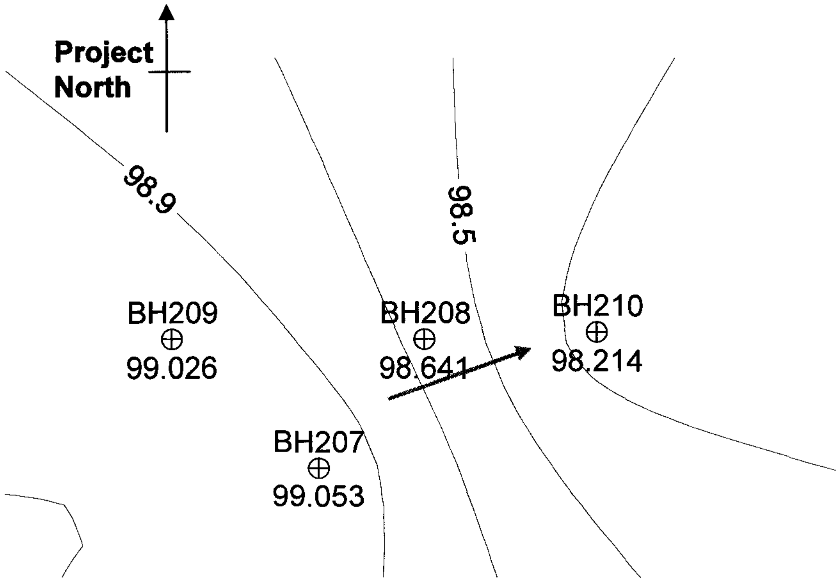


Figure 6-6 Water Table Elevations – June 16, 2006

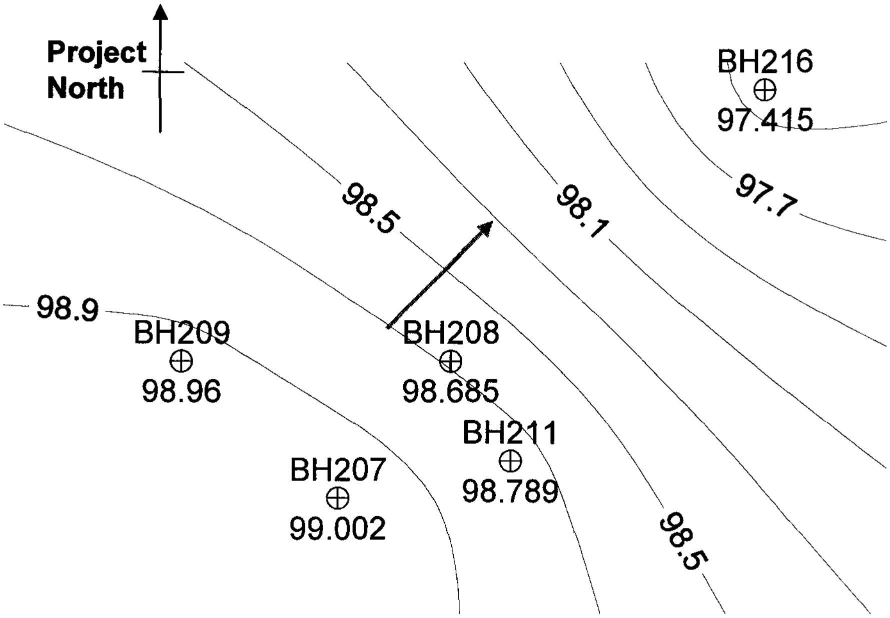


Figure 6-7: Water Table Elevations – July 14, 2006

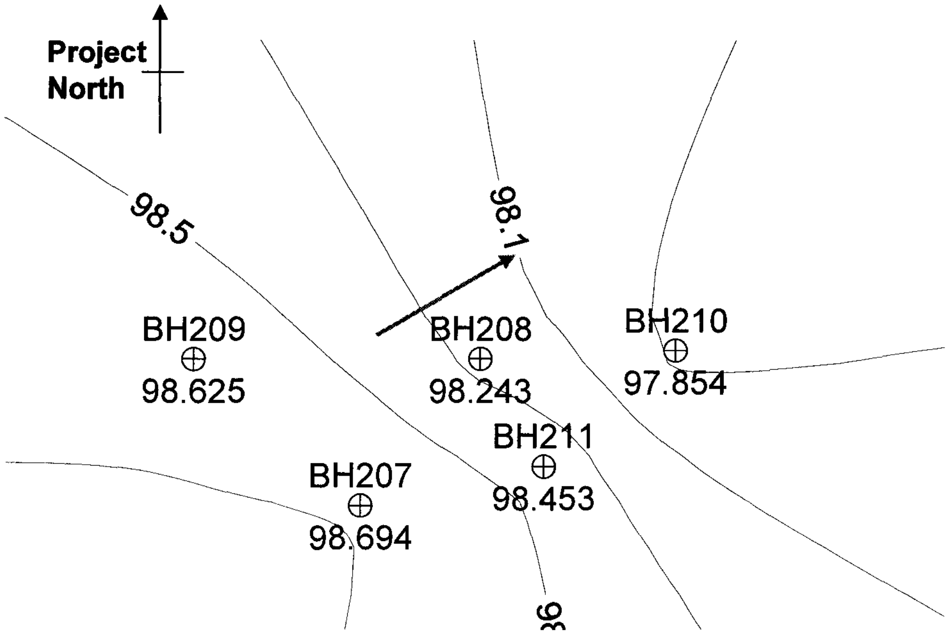


Figure 6-8: Water Table Elevations – September 30, 2006

6.3.1 Background MLMW Sampling

Prior to the delivery of the $KMnO_4$/NaBr solution, two rounds of background groundwater samples were collected from the MLMW network and analysed for VC concentrations. The first sampling event took place over November 2, 3 & 11, 2005. Following a heavy rainfall of approximately 28.4 mm on November 15, 2005 (Weather Network, 2006) a second round of groundwater samples was collected on November 16, 17 & 18, 2005 (with the exception of MW312 the property boundary well). Additionally, most samples were later analysed for background concentrations of Br^- and Cl^-. Table C-5 in Appendix C provides detailed sample results. Figure 6-9 provides a summary of VC concentration profiles for each MLMW where VC concentrations exceeded of 100 μg/L.

Elevated VC concentrations detected in the MLMWs were in the vicinity of BH208 and extended to the north/northwest. VC concentrations in the MLMWs adjacent to BH208 ranged from non-detect (MDL = 2.5 μg/L) to <LOQ (LOQ = 10 μg/L) in MW306 to the south and between <LOQ and 90 μg/L in MW305 to the north. Moving further northwest of BH208, MW302 had VC concentrations between 120 and 650 μg/L, MW303 had VC concentrations between 30 and 430 μg/L and the highest VC concentrations were observed in MW304-4 (nearly 1900 μg/L) and MW314-4 (1300 μg/L). Concentrations of VC were non-detect in both the background well (MW301) and the property boundary well (MW312) during the first round of analysis. A low level (~40 μg/L) VC concentration was detected in one of the duplicate samples of MW301-4 during the second round of analysis, however the second of the duplicate samples was non-detect. Therefore it is suspected that the sample with 40 μg/L may have been subjected to contamination.

One reason for the discrepancy between the historical VC concentrations in BH208 (which had a maximum reported VC concentration of 27.7 μg/L) and those found in the nearby MLMWs is the difference in screen lengths, which results in a 'borehole averaging effect'. The wells installed during previous site activities (BH20X series) are typically screened over a 3 m depth, and therefore average the stratigraphic concentration variations over the column of groundwater present at this depth. The MLMW samples on the other hand, are collected from hydraulically isolated intervals that are each screened over approximately 0.6 m. Therefore, a much more discretized view of the contaminant zone is observed with a MLMW than with a monitoring well screened over a larger depth.

From Figure 6-9, it is apparent that the highest VC concentrations occur in MW304 and MW314, and in these two wells the highest concentration was in the 3 to 3.5 mbg range (port 4) on both dates. MW303 and MW311 show a similar trend, with the highest VC concentrations between 3 and 3.5 mbg, in port 4. In MW305, which is not depicted in Figure 6-9, the highest VC concentration also occurred in port 4. One interpretation from Figure 6-9 is that there is a lense of VC contamination located between approximately 3 and 4 mbg, concentrated in the vicinity of MW314 and MW304 and extending slightly southeast towards BH208 and MW313. From the sample results, VC contamination does not appear to extend much south or east of BH208.

Recall that borehole records from the existing wells indicated approximately 1.5 to 2.5 m of sandy silt and clayey silt fill underlain by sandy silt till. During installation of the delivery points, Profile Drilling indicated that there was a harder layer, which was more difficult to push through occurring somewhere between 3.6 and 4 mbg (where refusal was typically met). Therefore, a less permeable till layer exists below approximately 3 or 4 mbg. This postulation of a less permeable zone combined with the initial sample results constitutes a conceptual VC contamination model for the site. Had a small PCE spill occurred previously, its vertical migration would have been arrested just above the low permeability zone. Therefore, the largest PCE, TCE and daughter product concentrations would also occur just above this low permeability zone. This is consistent with the VC depth profiles shown in Figure 6-9.

There do appear to be residual concentrations of VC at fairly high levels in the shallow groundwater as well. These concentrations span approximately 1 to 2.5 mbg in the vicinity of MW302, MW311 and MW303. This is likely due to fluctuations in the water table elevations after rainfall events (i.e., the difference from early November to late November sample results in MW311). When the water table rose, so did the VC concentrations. This is likely due to the dissolution of residual contamination present in the vadose zone.

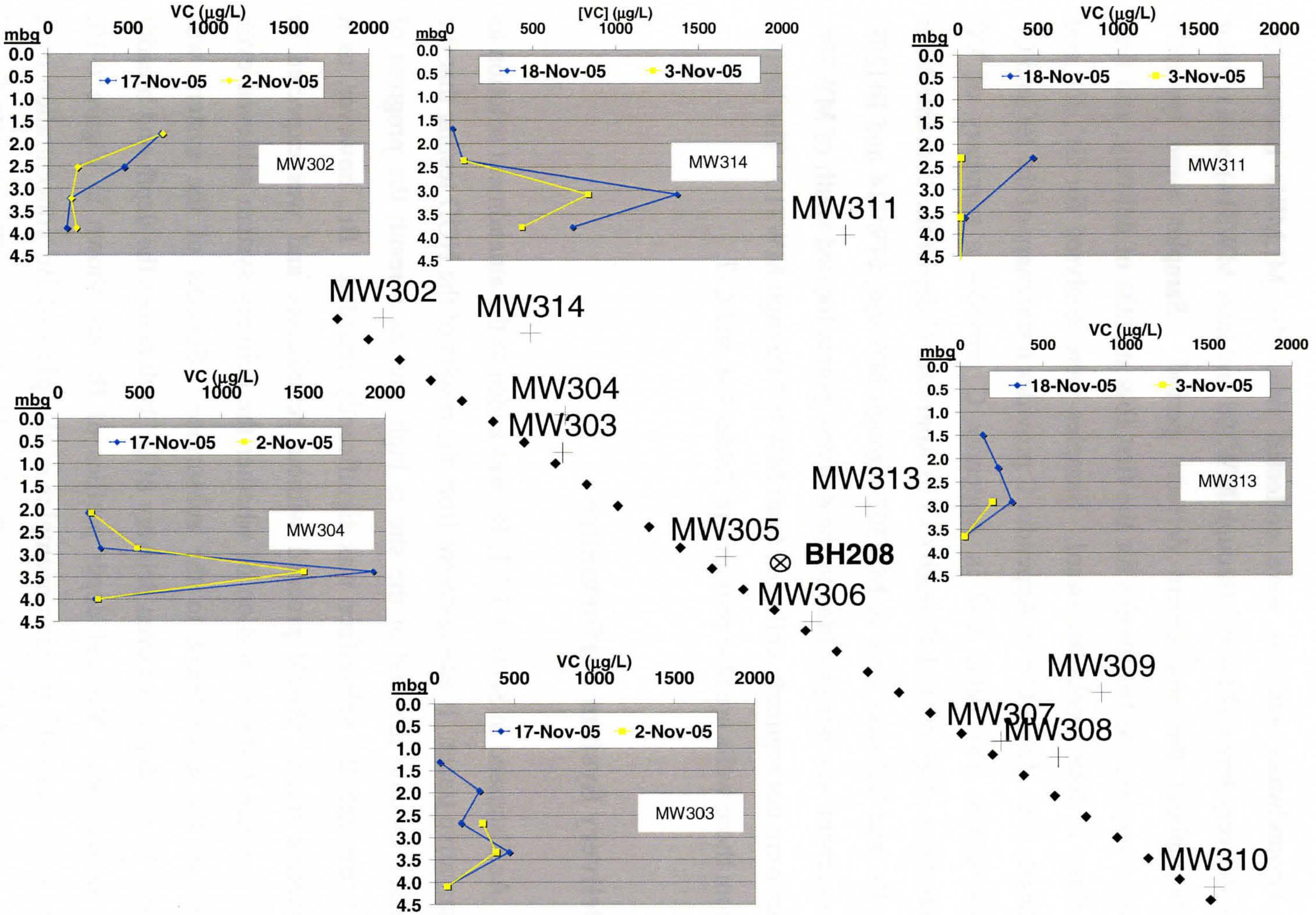


Figure 6-9: Pre – Remediation VC Sample Results by depth

6.3.2 Ongoing MLMW Sampling

Groundwater samples were collected from the MLMWs nearest the passive delivery fence (MW302 through MW306 and later MW314) on a regular basis throughout the amendment delivery period. Samples were typically collected every one to two weeks for the first four months of delivery, and then every three to four weeks afterward. Samples were analysed for Br^-, Cl^- and periodically VC. Table C-6 in Appendix C provides a summary of the Br^- and Cl^- analysis results, and Table C-7 in Appendix C provides a summary of VC concentrations. Figures C-1 through C-7 in Appendix C depict the concentrations of Cl^-, Br^- and VC over time in MW302 through MW306, MW314 and BH208. As amendment was not provided to the delivery points located south of MW306, samples were not regularly collected from MW307 through MW310. The limited data from these wells are also provided in Tables C-6 and C-7.

6.4 Delivery System Performance

As discussed in Section 4.3.1, Br^- was added to the amendment solution as a conservative tracer. It was apparent from the results of the NOD testing that the subsurface oxidant demand at the site is high, and as a result the progress of $KMnO_4$ through the subsurface was significantly retarded. Br^-, however, as a conservative tracer, should proceed without retardation, and was expected to provide a much faster indication of whether the delivery system achieved even delivery of the amendment to the subsurface. Success of the system was measured by the degree of even delivery of Br^- both across the depth and breadth of the target area. Vertical depth profiles of Br^- are shown in Figure 6-10. Figures 6-11 and 6-12 provide examples of the plots of Br^- concentration over time for MW303 and MW306 respectively. The Br- concentration data for all wells are provided in Appendix C (Figures C1 through C7).

From the plots outlined in Figure 6-10, it is apparent that increased concentrations of Br^- were detected in all ports of MW302 to MW306 and MW314 by October 10, 2006. Concentrations of Br^- varied with depth and position relative to the nearest upgradient delivery point. MW303 and MW306 are located closest to upgradient delivery points, at approximately 0.32 and 0.26 m respectively. It took approximately two to three weeks to detect elevated Br^- concentrations in ports 1 through 4 in MW303 but approximately four months to reach the lowest port (5). Similarly, it took approximately one week to detect elevated Br^- concentrations in MW306, once P17 was reconnected on May 19, 2006, but approximately one month to reach port 4. Table 6-3 provides a summary of Br^- arrival times for MW302 through MW306 and MW314. The arrival of the dispersive front is considered to be when two or more sample ports had elevated Br^- concentrations.

Table 6-3: Estimates of Br^- Arrival Times

MLMW	Distance Downgradient of nearest P (m)	Actual arrival of Dispersive Front (d)+	Theoretical arrival of Advective front (d)*	Notes
MW302	0.52	60	473	Directly downgradient of P2
MW303	0.32	30	291	Directly downgradient of P8
MW304	0.76	60	691	Out from the middle of P7&P8
MW305	0.40	30	364	Offset 0.16 m south of P14
MW306	0.26	10	236	Directly downgradient of P17
MW311	5.15	?	4681	Out from the middle of P16 & P17
MW313	2.1	?	1910	Out from the middle of P16 & P17
MW314	1.44	150	1310	Out from the middle of P5 & P6
BH208	0.46	60	418	Offset 0.15 m south of P16

+ measured data
*theoretical calculation based on Table 5-5 data; (downgradient distance)/(q=0.0011m/d)

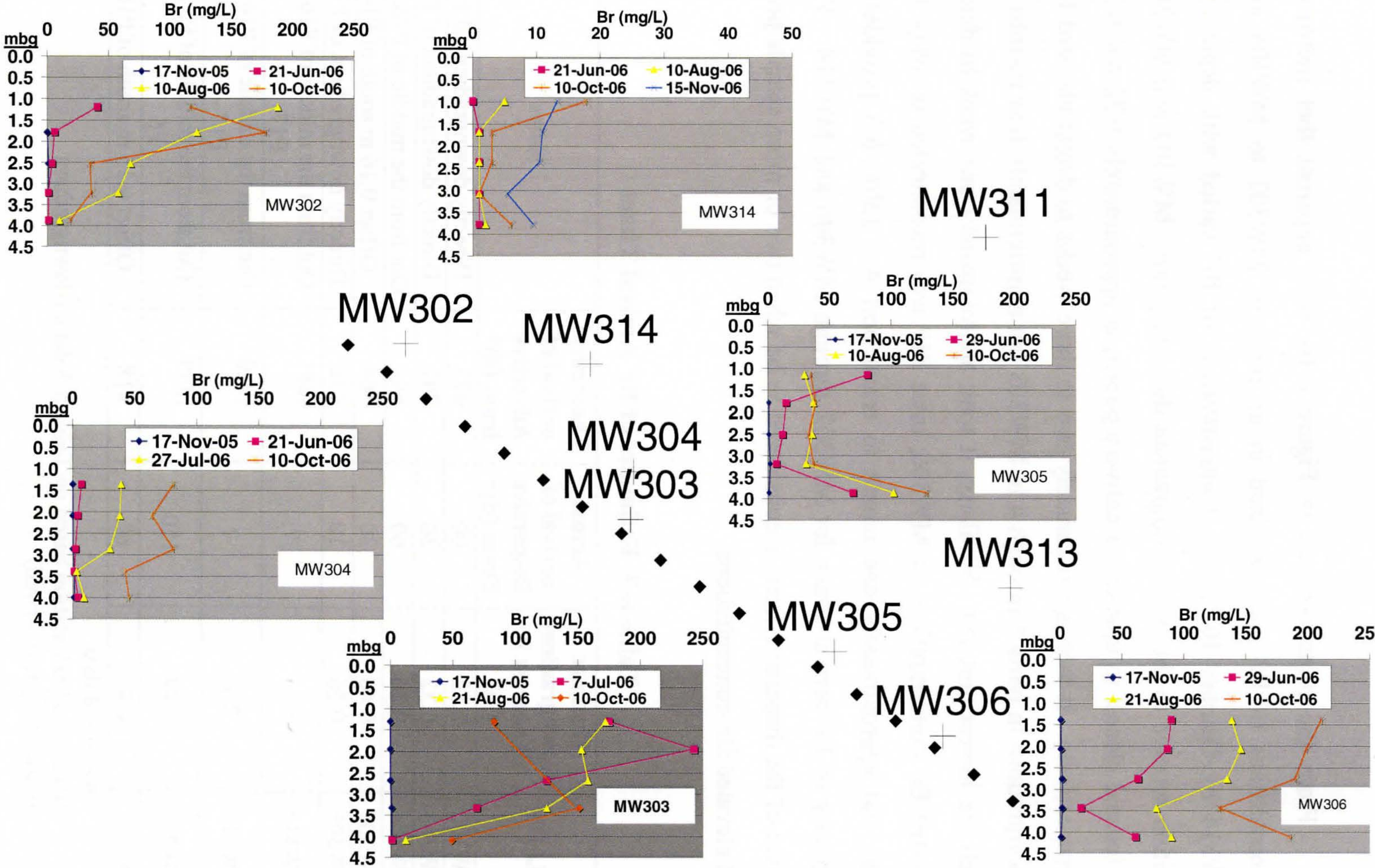


Figure 6-10: Bromide Concentration with Depth

Note: MW314 has smaller scale to show resolution

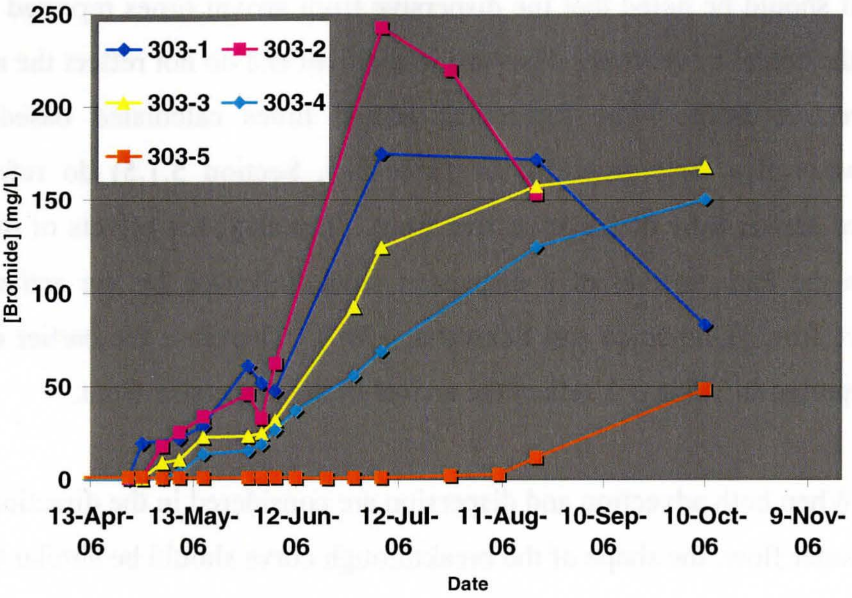


Figure 6-11: Br$^-$ Concentration over Time – MW303

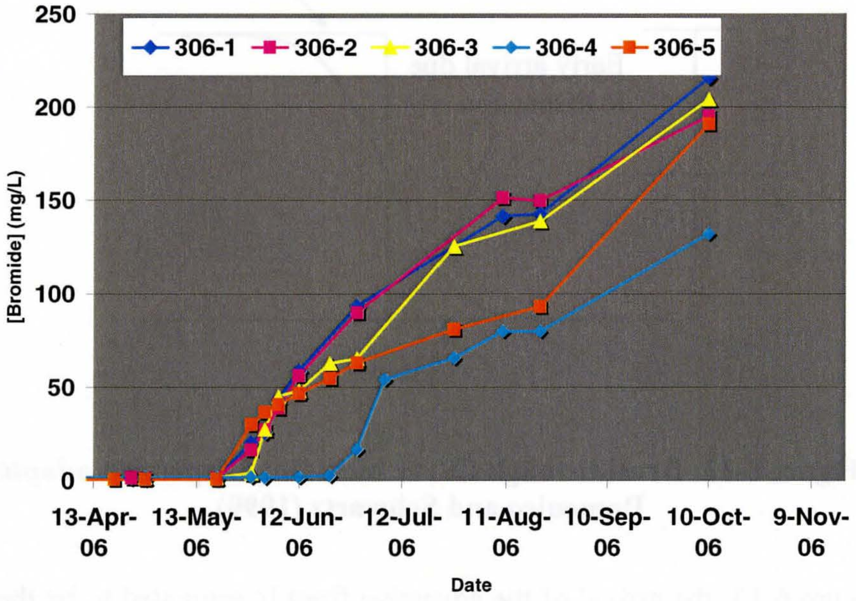


Figure 6-12: Br$^-$ Concentration over Time – MW306

It should be noted that the dispersive front arrival times reported in Table 6-3 are the actual travel times observed in the field and do not reflect the arrival of the advective front. The theoretical arrival times calculated based on the groundwater flow rate (reported in Table 5-5, Section 5.1.5) do refer to the estimated arrival time of the advective front. In reality, the effects of dispersion result in the early arrival of a dispersive front, followed by the arrival of the advective front (Domenico and Schwartz, 1990). Therefore the earlier detection times reported in Table 6-3 reflect the arrival of the dispersive front.

When both advection and dispersion are considered in the direction of groundwater flow, the shape of the breakthrough curve should be similar to that shown in Figure 6-13.

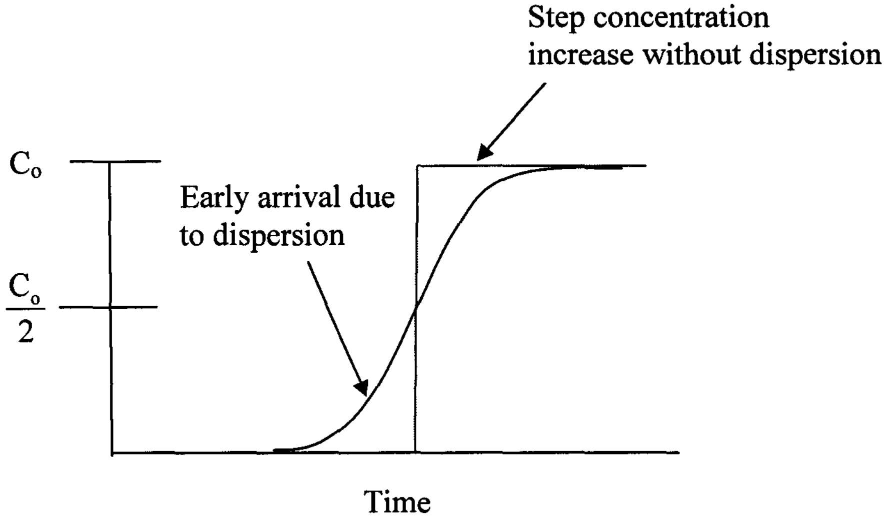


Figure 6-13: Breakthrough Curve including Dispersion adapted from Domenico and Schwartz (1990)

From Figure 6-13, the arrival of the advective front is estimated to be the time at which the observed concentration is $C_o/2$. The Ogata-Banks equation can be used to describe the above situation, and provides a solution for the one-dimensional case of the advection dispersion equation with initial condition C(x, 0) = 0, and boundary conditions C(0,t) = C_o (continuous source) and C(∞,t) = 0 (Domenico and Schwartz, 1990). The Ogata-Banks solution is as follows (Domenico and Schwartz, 1990):

$$C(x,t)=\left(\frac{C_o}{2}\right)erfc\left[\frac{(x-vt)}{2(Dt)^{1/2}}\right]+\exp(vx/D)erfc\left[\frac{(x+vt)}{2(Dt)^{1/2}}\right] \qquad \textbf{6-1}$$

where D [L^2/T] is the coefficient of hydrodynamic dispersion (comprised of molecular diffusion and mechanical dispersion), v [L/T] is the linear groundwater velocity, and x [L] is the downgradient position at time t [T] (Domenico and Schwartz, 1990). Often, the second term of Equation 6-1 can be ignored as its value is small when the groundwater velocity is not. However, in these calculations, the second term is not ignored as its value is significant given the low estimate for v at this site (were v to increase by an order of magnitude, the second term of Equation 6-1 would be negligible). As the free solution diffusion coefficient for salts in porous media typically ranges from approximate 10^{-6} to 10^{-8} m^2/s (Domenico and Schwartz, 1990), it is appropriate to simplify D by eliminating the diffusive component such that D= αv, where α [L] is the longitudinal dispersivity.

In the case of one pump head serving one delivery point the amendment solution comprises approximately 23% of the total flow rate (i.e., amendment solution (0.5 L/d) plus groundwater (1.7 L/d per area served by one delivery point)). Therefore, the Br^- concentration of 0.8 g/L in the amendment solution should be diluted to 186 mg/L as it mixes with the groundwater in the delivery zone. These calculations, however, assume that the amendment fully mixes with the groundwater 0.25 m on either side of the delivery point. Concentrations of Br^- slightly exceeded the expected 186 mg/L at MW302-1 and MW303-2 on one occasion, and at MW306 (with the exception of port 4). These high concentrations indicate that at close proximity, the amendment was not yet fully diluted with the anticipated volume of groundwater, however the concentrations were generally within 15% of the maximum expected. At the upper sample ports of these wells, the concentrations observed are within range of those that would be expected, given the proximity to the delivery points (i.e., less than 0.5 m).

MW304 is located 0.76 m downgradient and between two delivery points (each directly fed). Br^- was detected at all five monitoring depths served by this well. Therefore, the data from this well indicate that mechanical dispersion succeeded in mixing the Br^- laterally over the 0.5 m width served by the two delivery points within 0.76 m of the delivery fence. When the advective front arrives at MW304, the expected Br^- concentration is $C_o/2$, or 93 mg/L. The maximum concentration observed at the upper three sample ports was an average of 78 mg/L on October 10, 2006.

Figure 6-10 shows that Br^- concentrations were 84% of those that would be expected upon arrival of the advective front at the upper three ports of MW304 (1,2,3) by October 10, 2006, however the Br^- concentrations were only about 50% of $C_o/2$ at the lower two ports (4,5). Therefore, it appears that the delivery points P7 and P8 were successful at fully mixing the amendment with the groundwater across the depth and breadth of the area they served, however the advancement of the advective front was much slower at the lower two sampling ports. This slower movement is likely due to a less conductive layer at those depths (between approximately 3.4 and 4.1 mbg, which agrees with the findings presented in Section 6.3.1). Assuming that the advective front had arrived at the upper three ports of MW304 by the end of the monitoring period, it would correspond to a groundwater flux of q = (0.76 m/210 days), which would be 0.0035 m/d. This is slightly higher, but within the same range of the q calculated in Section 5.1.5. As to date, the full $C_o/2$, has not yet been observed at this well, q = 0.0011 m/d will be used in the subsequent calculations. However, based on the delayed arrival times at the lower ports, the calculations that follow will be representative of the conductivity of the more permeable layer (i.e., the upper three sampling ports) and will not necessarily represent the conductivity of the lower less permeable layer.

As it appears that the groundwater and amendment have fully mixed upon reaching MW304, the Ogata-Banks equation given by (6-1) can be used to calculate an estimate of longitudinal dispersion (D) for the site, where:

$v = 0.0011$ m/d
$x = 0.76$ m
$t = 180$ days
$C_o = 186$ mg/L
$C(x,t) = 78$ mg/L

$D = 0.0018\ m^2/d$

Dividing by the velocity estimate, this value of dispersion represents a longitudinal dispersivity (α) of approximately 1.8 m. This value is within the range of longitudinal dispersivities typically reported for experimental scales of approximately 10 m (Domenico and Schwartz, 1990). Figure 6-14 shows the Br^- concentration over time, predicted by the Ogata-Banks solution for MW304, as well as the actual Br^- concentrations observed in the field at MW304. Although the field observations show a delayed Br^- arrival, the shape of the curve is very similar for both the predicted and observed Br^- concentrations in the upper three ports of MW304, while the lower two ports are also a similar shape, however the arrival time is slower, as they are present in the lower conductivity layer. Figure 6-14 indicates good agreement between the predicted and observed Br^- concentrations and confirms that even delivery and mixing was achieved in the vicinity of MW304.

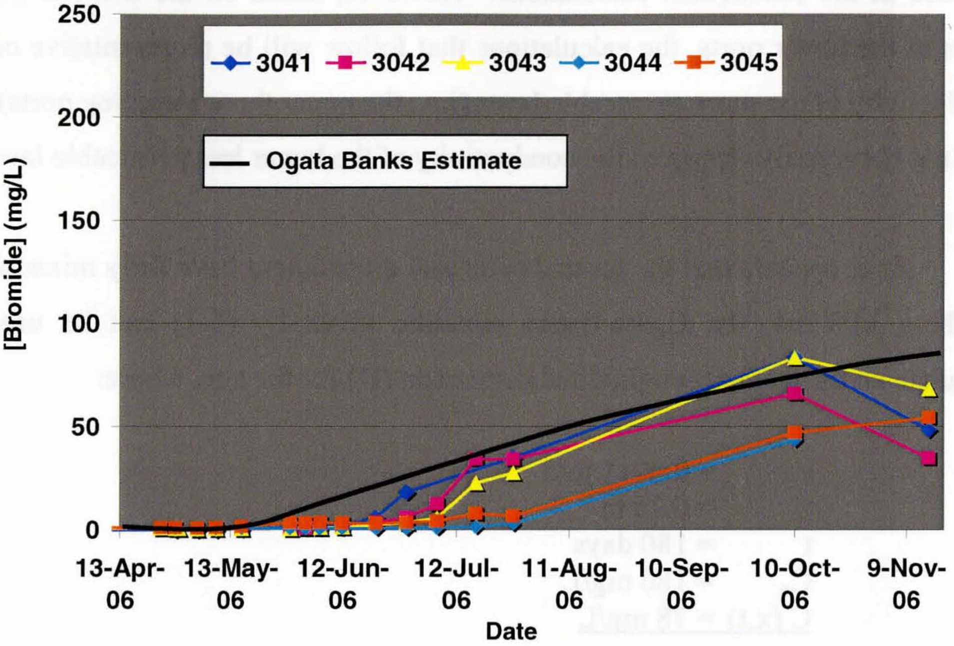


Figure 6-14: Observed and Predicted Bromide Concentrations – MW304

As this dispersivity estimate and prediction appears to fit the field data reasonably well, the Ogata-Banks equation was then applied to the other monitoring wells to estimate the concentration expected at time t = 180 days (roughly October 10, 2006). As additional sample data were available for MW314, the concentration was calculated for time t = 210 days (roughly November 15, 2006). Table 6-4 provides a summary of these calculations. C_o for MW302 through MW306 is the same as described for MW304, as these wells are all served by delivery points that received direct flow. However MW314 is served by two delivery points that shared the flow from one pumphead (P5 & P6), and MW311 and MW313 are served by four delivery points sharing the flow from three pumpheads (P14&P15, P16, P17). The value for C_o used in the calculations for these MLMWs reflects a change in the mass of amendment delivered.

Table 6-4: Concentration (C*) Estimated by the Ogata Banks Solution

MLMW	Upgradient Delivery Points	Distance Downgradient (m)	Elapsed Time (d)	C_0 (mg/L)	C* Estimate (mg/L)	Measured $[Br^-]^+$ (mg/L)
MW302	P2	0.52	180	186	112	103
MW303	P8	0.32	180	186	141	135
MW304	P7, P8	0.76	180	186	79	78
MW305	P14	0.40	180	186	129	38
MW306	P17	0.26	180	186	149	177
MW311	P14&P15, P16, P17	5.15	180	148	0	-
MW313	P14&P15, P16, P17	2.1	180	148	2.5	2.5
MW314	P5&P6	1.44	210	104	15	10
BH208	P16	0.46	180	186	120	22

& = delivery points are splitting flow from one pump head
\+ = average $[Br^-]$ of upper three sample ports

According to these calculations it should take approximately two years for a detectable increase in Br^- at MW311. The above calculations provide an estimate of what is expected, however they assume a constant C_0 source, and in the case of some wells (i.e., MW305) at which the upgradient delivery point (P14) was subject to many leaks, this was not achieved. However, an assessment can be made as to the effectiveness of the delivery system by comparing the Ogata Banks estimates with the measured concentrations presented in Table 6-4 and Figure 6-10. If the predicted concentration is near concentrations observed in the field for an MLMW in the more conductive layer, then the amendment has been evenly delivered. Taking into account the lower conductivity layer, and using MW304 as an example, if the observed concentration is within 50% of the predicted concentration in the lower sample ports, than it is assumed that even delivery has been achieved in the less permeable layer, but that is has been delayed by the decreased conductivity.

In summary, MW302, MW303, and MW306, which are the closest MLMWs, all showed marked Br^- increases across all depths. The decline in Br^-

concentration in some ports of MW302 and MW303 in October may be due to system plugging or leaks, or delivery system shutdowns; however earlier sample results indicated higher concentrations across the depths. All of these wells (MW302, MW303, MW306) experienced a slower advancement of Br^- at the lower sampling ports (MW302-3,-4,-5; MW303-4,-5; MW306-4). Moving further downgradient, observed Br^- concentrations were also in agreement with predicted concentrations across the depth and breadth of the study area (i.e., MW314). The slower rate of Br^- advancement with depth (i.e., MW304, MW313, MW314) was also observed downgradient. For example, at a downgradient distance of 1.4 m, MW314 had Br^- concentrations similar to those predicted in Table 6-4 at sample port 1, and concentrations were close at ports 2,3 and 5 however, again port 4 is slower, at approximately 40% of the predicted concentration at a depth of 3 mbg.

These findings add weight to the theory that a less permeable layer is present in the subsurface. However, even though the Br^-concentrations are lower at some depths, they are still elevated, and are just advancing at a slower rate. This is indicative of the success of the delivery system. If the hypothesis of a less permeable layer is correct, with a higher flow rate, and a more traditional delivery system, this zone may have been bypassed by the amendment all together, and it would not have been possible to deliver amendment to this location.

6.5 Remediation of Vinyl Chloride

This section discusses the effectiveness of the delivery system in terms of remediating the VC. This assessment is made based on the analyses of samples for Cl^-, $KMnO_4$ and VC. The following sections describe these analyses.

6.5.1 Chloride

As discussed in Chapter 2, Cl^- can often be an indicator of successful dechlorination at chlorinated solvent-impacted sites. When initial concentrations of chlorinated solvents are high, and dechlorination through remediation is successful, a corresponding increase in Cl^- is often detected. This increase can be used to calculate the mass of chlorinated solvent destroyed stoichiometrically if the chlorinated solvent is known. For example, in a laboratory experiment where only TCE is present, all detectable Cl^- increase must have come from the dechlorination of TCE. If there is more than one type of chlorinated compound present then it becomes difficult to determine the mass of solvent destroyed, as different compounds have different numbers of Cl atoms. If the background Cl^- concentration in a groundwater is high, the mass of chlorinated solvent destroyed must be sufficient to cause a detectable change in Cl^- concentration above background levels.

Cl^- concentrations were monitored over time at the MLMWs and the results are provided in Table C-6, and are plotted in Figures C-6 through C-12 in Appendix C. An example of the Cl^- concentration versus time plots for MW302 and MW303 are shown in Figures 6-15 and 6-16 respectively. While there do appear to be discernible increases in Cl^- concentrations measured at several points in time in Figure 6-16 (MW303) it was difficult to discern changes in Cl^- concentrations at the other wells, including MW302.

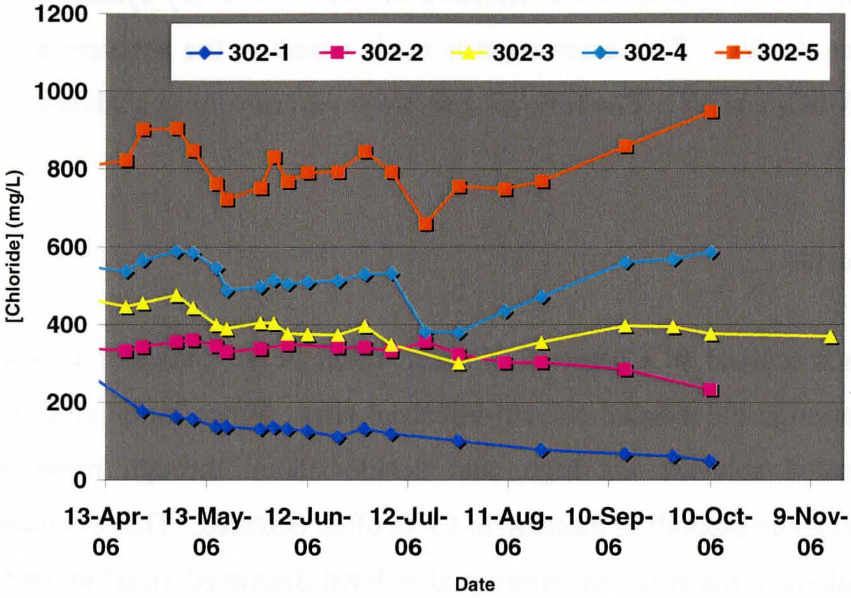


Figure 6-15: Chloride Concentrations over Time – MW302

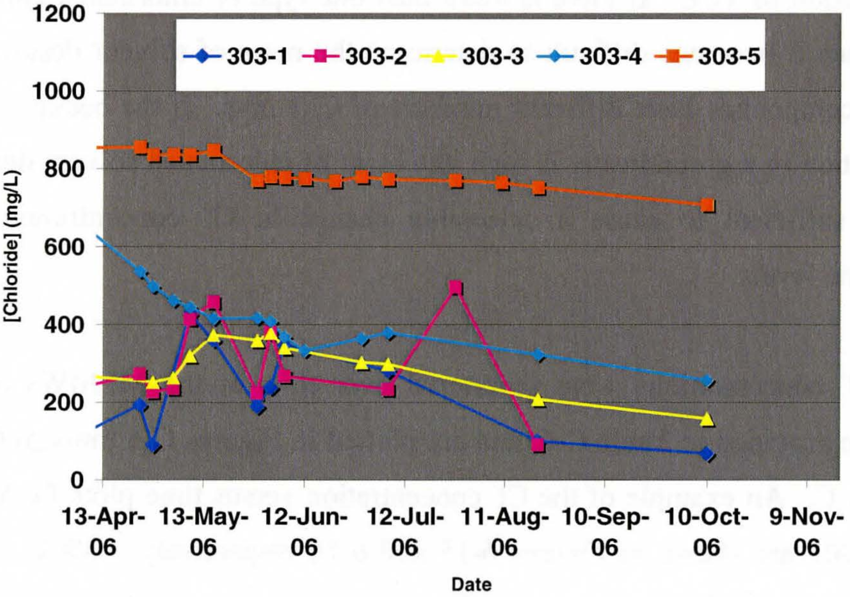


Figure 6-16: Chloride Concentrations over Time – MW303

Cl^- concentrations were quite high prior to amendment delivery (several hundred mg/L), and fluctuated greatly over the duration of the experiment, possibly due to changes in water levels, parking lot salt runoff, subsurface microbial activities and sample preparation methodologies. When samples were prepared for VC analysis, they were transferred into salted GC vials. This transfer was completed prior to sample preparation for Cl^- analysis and it is possible that the sample may have been contaminated with Cl^- from the GC vials during this transfer. This may have been responsible for some fluctuations detected in the samples analysed in Fall 2005. In later sample preparation, the VC transfer syringe was properly cleaned to eliminate the possibility of Cl^- contamination. Additionally, not all samples were prepared for VC analysis after Fall 2005.

If all the VC present in the groundwater was destroyed (assuming 1000 μg/L VC), the Cl^- concentration in the groundwater would rise by 560 μg/L. This small increase in Cl^- concentration would be difficult to detect given the high background concentration of Cl^-, as well as the MDL of 4.9 mg/L. As a result, Cl^- was not used as an indicator of VC remediation in this research.

6.5.2 $KMnO_4$

Over the duration of the experiment, $KMnO_4$ was detected at MW302-2, MW303, MW306, MW307-5 and BH208. Table 6-5 provides a summary of the date that $KMnO_4$ and Br^- were first detected in each well. The difference in arrival times between the non-reactive Br^- and the reactive $KMnO_4$ provides an indication of the subsurface oxidant demand, which is comprised of both the NOD and the chlorinated solvent oxidant demand (which is much lower than the NOD based on the calculations presented in Section 5-3). Table 6-5 also includes the maximum $KMnO_4$ concentration measured in the sample. Complete $KMnO_4$ analytical and visual observation details are provided in Table C-6 in Appendix C.

Not every sample with visual indication of $KMnO_4$ presence was analysed for $KMnO_4$ concentrations. When samples were analysed, concentrations of $KMnO_4$ were measured in the field for the samples collected in August 2006, and were measured in the lab on the day they were collected in October and November of 2006. The previous $KMnO_4$ analyses were typically performed one to several days following sample collection, and may have been subject to degradation due to possible reactions with oxidizable material in the sample vials (i.e. chlorinated solvent, aquifer materials). The potential for degradation is suspected, as some samples that were initially light pink turned peach or brown after several days had passed, indicating that the $KMnO_4$ reacted to form MnO_2. Samples that were pink or darker (MW303-1 through MW303-4, MW302-2, BH208), still had visual indication of $KMnO_4$ after they were refrigerated for longer periods of time, indicating an excess $KMnO_4$; however visual degradation was not as evident in these darker coloured samples as the colour change was not as pronounced (it was difficult to visually determine concentration differences in the darker coloured samples prior to dilution).

Table 6-5: $KMnO_4$ Results

Well ID	Date of Initial Br- Detection	Date of initial $KMnO_4$ Visual Detection	Lag Time (days)	Darkest colour observed	Maximum [$KMnO_4$] (g/L)
MW302-2	21-Jun-06	15-Nov-06	150	Dark pink	0.12
MW303-1	28-Apr-06	6-Jun-06	38	Dark purple	7.5
MW303-2	4-May-06	4-May-06	0	Dark purple	5.1
MW303-3	4-May-06	4-May-06	0	Purple	1.3
MW303-4	9-May-06	16-May-06	7	Purple	0.6
MW303-5	27-Jul-06	10-Oct-06	45	Light pink	0.02
MW306-1	29-May-06	6-Jun-06	7	Dark purple	1.8
MW306-2	29-May-06	12-Jun-06	14	Dark purple	1.6
MW306-3	29-May-06	12-Jun-06	14	Dark pink	0.4
MW306-4	21-Jun-06	29-Sep-06	98	Light pink	0.07
MW306-5	29-May-06	21-Jun-06	22	Purple	1.5
BH208	12-Jun-06	29-Sep-06	107	Pink	0.02

The lag time estimates in Table 6-5 indicate that, with the exception of MW303-2 and MW303-3, the subsurface demand for $KMnO_4$ resulted in the retardation of $KMnO_4$. Based on the variations in lag times, it appears that different subsurface locations have varying degrees of $KMnO_4$ demand. The variations may be due to aquifer material heterogeneities and/or the presence of contaminants. Based on the NOD results outlined in Figure 4-9, NOD was highest, and therefore the lag time should be greatest, in the vicinity of MW306 and BH208. The NOD estimate for MW303 was lower than MW306, and MW302 had the lowest NOD estimate of all, and therefore should have had the shortest lag time. Overall, the spatial NOD findings, are not in agreement with the lag times presented in Table 6-5. As the NOD estimates are based on small sample volumes (i.e., 20 mL reactors) they may not provide a representative sample of the actual soil mass encountered in the vicinity of the MLMWs.

Figures 6-11 and 6-12 provide visual representation of the Br^- breakthrough for both MW303 and MW306. These figures show that MW306-4 and MW303-5 both show a delayed arrival of Br^-; Table 6-5 indicates that both of these ports also have an increased lag time compared to the other sample ports in the well. In MW306-4, the initial detection of Br^- was approximately one month later than the initial detection of Br^-at the other sample ports in that well. However, the initial detection of $KMnO_4$ in MW306-4 was approximately 2.5 months later than the initial detection $KMnO_4$ the other sample ports in the same well, even though generally all locations in MW306 had similar background VC concentrations. From this comparison it appears that with a slower arrival of amendment at the well, as indicated by the Br^- arrival time, there is also an increased $KMnO_4$ consumption, resulting in an even slower $KMnO_4$ arrival. This corresponds to findings in literature which indicate that NOD increases with increasing retention times (i.e., greater NOD in batch tests compared to flow-through tests (Mumford et al., 2002)).

The retarded $KMnO_4$ movement confirms the finding from Chapter 4 that oxidant demand will greatly increase the delivery time required to achieve successful remediation at the site. As of November 10, 2006, approximately 50 kg of $KMnO_4$ has been delivered to the subsurface and $KMnO_4$ was detected no further than approximately 0.5 m downgradient, and even then it was not detected in all of the lower permeability layers. However, assuming that the subsurface demand was satisfied to a distance 0.5 m downgradient with 50 kg of $KMnO_4$, at least 500 kg of $KMnO_4$ would be required to reach MW311. At a concentration of 40 g/L, an additional 12,500 L of amendment is needed. At a flow rate of 8 L/d (0.5 L/d per delivery point over 16 delivery points) this would take approximately 1560 days, or roughly 4.3 years to deliver. This is twice as long as the time that would be required to transport a non-reactive amendment the same distance (approximately two years as per the calculations in Table 6-4).

By reconfiguring the system to better target the known VC contamination (within the lateral extent of P1 through P17 only) it may be possible to decrease the duration of the delivery. One possible configuration is to reinstall P18 through P30, which are not required in their current location due to the lack of VC, in a second line further downgradient from P1 through P17 to better target VC concentrations. Using the delivery flow rate of 0.5 L/d per delivery point (purchasing additional pumps to provide better delivery) it would be possible to deliver up to approximately 20 L/d to the target area, which based on these estimates would reduce the delivery time to approximately 600 days.

6.5.3 Vinyl Chloride

A summary of VC sample results is provided in Table C-7 in Appendix C. Figures C-1 through C-7 provide plots of VC concentration over time for MLMWs that were regularly sampled and contained VC concentrations in excess of 100 μg/L. Figure 6-17 illustrates both the pre- and post-remediation VC concentration profiles, for each of the MLMWs with VC concentrations in excess of 100 μg/L.

In wells where $KMnO_4$ was detected (MW302-2, MW303, MW306, and BH208), concentrations of VC typically decreased to below the LOQ and were often near or below the MDL. This is most notable in MW303, where concentrations of VC initially ranged from approximately 30 to several hundred μg/L, and with the exception MW303-5, have been below the LOQ since May 2006. $KMnO_4$ was first detected in MW303-5 during the October 10, 2006 sampling event, and VC concentrations were below the LOQ on November 15, 2006. As $KMnO_4$ was first detected at MW303-5 on October 10, 2006 it is anticipated that the VC concentration at this sample port would have been below the LOQ at this point as well, although these samples were not analysed for VC on this date.

The continued detection of low levels of VC, often below the LOQ but above the MDL, in some of the samples with persistent visual indication of $KMnO_4$ (i.e., still pink or purple even after analysis) is puzzling. Several of the samples collected from MW303 and BH208 had visual evidence of $KMnO_4$ for several weeks after collection, yet analysis indicated the presence of VC concentrations above the MDL. Based on the reaction rates described in Chapter 2, if $KMnO_4$ continues to be in excess (as is inferred by the continued visual presence), then it should have destroyed all the VC present in these samples. One explanation for this discrepancy is that the presence of $KMnO_4$ interferes with the VC analysis.

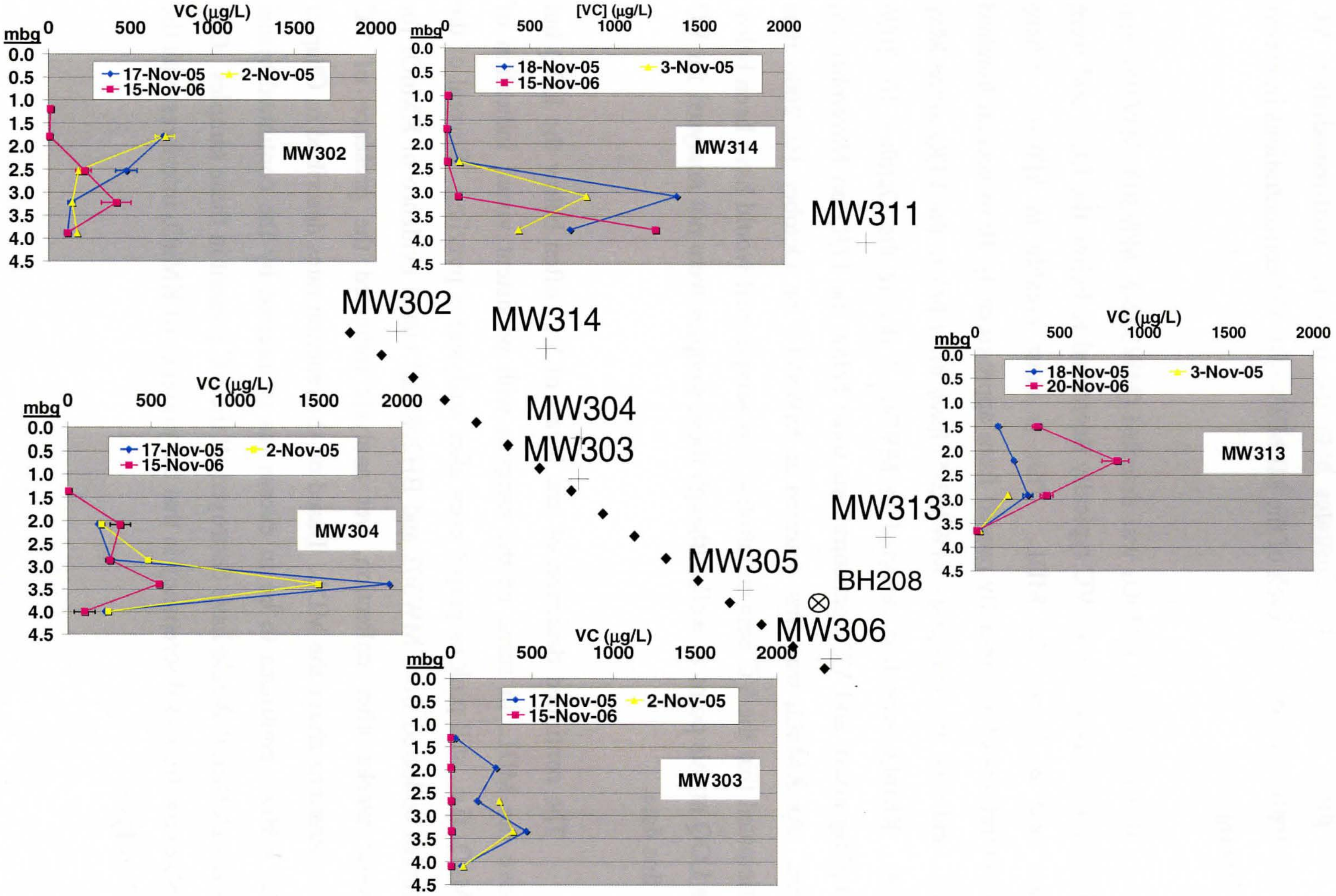


Figure 6-17: Post-Remediation VC Concentration Depth Profiles

In wells where $KMnO_4$ was not detected, VC concentrations fluctuated over time. Table 6-6 presents a summary of the mean VC concentrations detected both pre- and post-amendment and provides a 90% confidence interval (CI) comparison between them. The CIs were calculated as follows:

$$\mathrm{CI} = \bar{x} \pm t_{v,\alpha}\frac{s_x}{\sqrt{n}} \qquad \textbf{6-2}$$

where $\bar{x}$ (μg/L) is the mean VC concentration for each date. Cochran's procedure was then used to determine if there was a statistical difference between the mean concentrations for the two sampling events. To do this, the CIs constructed on the mean VC concentrations were compared; any overlap between the pre- and post-amendment delivery CIs indicated that there was no significant decrease in VC concentration (Montgomery and Runger, 2003).

The 90% CIs indicate that statistically significant VC decreases occurred in MW302-2 and MW302-3, MW303, MW304-4 and MW304-5, MW313-5, and MW314-3 and MW314-4. The reductions in VC concentrations in MW303 and MW302-2 are suspected to be due to the destruction of VC by $KMnO_4$. In the other wells where $KMnO_4$ was detected (i.e., BH208, MW306) the variation in the sample data was too great to discern a statistically significant decrease in VC concentration, although theoretically a decrease is expected based on the presence of $KMnO_4$. At the 90% confidence level, VC concentrations increased in MW313-2, MW313-3 and MW302-4. As evident from plots provided in Appendix C, increases were also noted in some of the other wells over the course of the amendment delivery. These increases in VC concentration could either be due to the movement of groundwater from areas of higher VC concentration into the vicinity of the well screen, or the fluctuations in the water table, as was seen in pre-delivery VC concentrations.

Table 6-6: CI for Pre- and Post-Remediation Mean VC Concentrations

Well ID	Pre Delivery Sample Date	90% CI on x_{bar} (μg/L)	Post Delivery Sample Date	90% CI on x_{bar} (μg/L)	Excess $KMnO_4$
BH208	22-Apr-05	[-11 , 37]	15-Sep-06	[2, 24]	No
	-	-	10-Nov-06	[3, 5]	Yes
	-	-	20-Nov-06	**[-2, 5]**	Yes
302-1	-	-	21-Jun-06	[0,8]	No
	-	-	15-Nov-06	**[-11, 35]**	No
302-2	2-Nov-05	[613 , 816]	15-Nov-06	**[-11, 25]**	Yes
302-3	17-Nov-05	[363, 587]	15-Nov-06	[139, 302]	No
302-4	17-Nov-05	[98, 173]	15-Nov-06	[264, 569]	No
302-5	17-Nov-05	[0, 239]	15-Nov-06	[88, 144]	No
303-1	17-Nov-05	[16, 47]	15-Nov-06	**[-3, 5]**	Yes
303-2	17-Nov-05	[187, 372]	15-Nov-06	**[0, 7]**	Yes
303-3	17-Nov-05	[142, 187]	15-Nov-06	[3, 5]	Yes
303-4	17-Nov-05	[266, 663]	15-Nov-06	[5, 6]	Yes
303-5	17-Nov-05	[61, 74]	15-Nov-06	**[0, 6]**	Yes
304-1	-	-	21-Jun-06	[1,2]	No
	-	-	15-Nov-06	[1, 7]	No
304-2	17-Nov-05	[95, 367]	15-Nov-06	[0, 698]	No
304-3	17-Nov-05	[188, 328]	15-Nov-06	[96, 409]	No
304-4	17-Nov-05	[1818, 2030]	15-Nov-06	[471, 623]	No
304-5	17-Nov-05	[206, 237]	15-Nov-06	**[-4, 205]**	No
306-1	17-Nov-05	[2, 13]	15-Nov-06	**[-1, 7]**	No
306-2	-	-	15-Nov-06	**[-2, 9]**	Yes
306-3	17-Nov-05	[3, 4]	15-Nov-06	**[-9, 23]**	Yes
306-5	-	-	15-Nov-06	[2, 3]	Yes
313-2	18-Nov-05	[61, 213]	20-Nov-06	[188, 548]	No
313-3	18-Nov-05	[172, 286]	20-Nov-06	[705, 977]	No
313-4	18-Nov-05	[129, 495]	20-Nov-06	[186, 660]	No
313-5	18-Nov-05	[19,28]	20-Nov-06	[11, 14]	No
314-1	-	-	15-Nov-06	[11,26]	No
314-2	18-Nov-05	[0, 37]	15-Nov-06	[4, 19]	No
314-3	3-Nov-05	[49, 118]	15-Nov-06	[11, 19]	No
314-4	18-Nov-05	[892, 1845]	15-Nov-06	[63, 93]	No
314-5	18-Nov-05	[455, 1023]	15-Nov-06	[852, 1633]	No

Notes: From VC analysis, MDL = 2.5 μg/L, LOQ = 10 μg/L
Highlighted = decrease in VC concentration from pre-delivery levels
Highlighted = increase in VC concentration from pre-delivery levels
Bold = 90% CI includes VC concentration below MOE guidelines (1.5 μg/L)

These results, coupled with the discussion in the previous section on $KMnO_4$, indicate that where the subsurface oxidant demand was met and $KMnO_4$ reached the MLMW, VC concentrations decreased significantly (below the MDL at many locations). However, until $KMnO_4$ reaches the entire extent of the area of concern, VC concentrations still exist in excess of guidelines. The Br^- analysis indicates that the amendment was delivered across both the depth and breadth of the subsurface, regardless of the permeability. As a result, provided that enough $KMnO_4$ is supplied to travel the required distance, the entire depth and breadth of the contamination downgradient of the delivery points should be remediated. In this case, then rebound is not expected, as even the VC present in the LPM will be destroyed.

6.6 Cost Considerations

Recalling the goals outlined in Chapter 1, in addition to evenly delivering the amendment to the subsurface and remediating VC concentrations in groundwater, the other objective of this design was to accomplish the aforementioned goals in a cost-effective manner. Compared to other available remediation technologies, the method described and tested in this research was expected to be more cost-effective. Although costs are often site-specific, this objective was evaluated by comparing costs involved with remediation projects at several sites of similar size and similar subsurface compositions.

The State Coalition for the Remediation of Drycleaners (SCRD) with supports from the EPA Superfund program provides a database of dry cleaning sites where site investigation and remediation work has been undertaken. This database provides details on the project location, the estimated size of the contaminant plume, the subsurface location of the plume, site hydrogeology, the remedial approach followed, and the associated costs (SCRD, 2006). Several sites were selected from this database for cost comparison. The comparison was made between the reported cost of the technology employed at the SCRD site, and the cost estimate if the site employed the delivery system designed and described in this research. The three SCRD sites evaluated in this comparison are within a similar size range (approximately one to two times the areal extent of 42 Voyager Court), and of a similar depth and subsurface composition as the site studied in this research.

For cost calculations, it was necessary to determine the number of delivery points required. For the US sites, the number of delivery points required was estimated assuming that the delivery point placement density would be similar to that used in this research. For these calculations, several improvements were made to the design. Firstly, the connectors used were changed to Swagelock fittings (Niagara, ON), which were more expensive than the fittings used in the current research (from approximately \$2 for the Watts brass T's, to approximately \$28 for the Swagelock fittings). This was done in attempt to remedy the leak issue. Secondly, in the cost estimate for 42 Voyager Court, it was assumed that the delivery fence would be installed in two rows to improve delivery – one row being the existing row (P1 through P17), with a second row installed several metres downgradient in front of the existing row to decrease the time required to target the extent of the VC plume (which was estimated to be within the lateral extent of P1 through P17). Thirdly, the number of pumps and pumpheads was increased in the cost estimate to provide one pump head for every delivery point to ensure delivery to all points. Finally, the amount of $KMnO_4$ estimated to be required at the site was 500 kg for 42 Voyager Court, and then scaled according to treatment volume for the other sites in the comparison. The design changes described in this paragraph were included in the cost estimate for both 42 Voyager Court as well as the three example US EPA sites. Cost estimates were based on the pricing obtained from contractors over the duration of this research.

The estimate of $KMnO_4$ is subject to change based on site-specific NOD and contaminant profiles, however as $KMnO_4$ makes up a small fraction of the estimated capital costs (~ 10%), it is not expected to largely influence the results of the cost comparison. Drilling costs are estimated based on the costs incurred in this project, and are site-specific. Costs provided by the SCRD are assumed to be in US dollars (USD), while costs estimates calculated for the passive delivery fence were based on Canadian dollar figures, and were converted for the sake of comparison to USD assuming an exchange rate of $1.12 CDN per $1 USD (TD Canada Trust, rate effective November 19, 2006). Also, the SCRD lists several different cost categories in their cost summary. For this comparison, the cost for 'Design and Implementation' is assumed to be representative of the capital costs involved in the installation of the treatment system and only this value is used in the comparison (**bold** in Table 6-7).

Table 6-7 presents a summary of the site characteristics, the reported capital costs, and the cost estimated using the delivery system described in this research. A detailed summary outlining the cost calculations is provided in Table C-8 in Appendix C. From these data, it is apparent that for locations C and D, the passive delivery fence appears to presents significant cost savings over the traditional methods actually employed (in situ bioremediation/SVE and monitored natural attenuation/SVE).

Table 6-7: Cost Considerations and Estimates (Estimates in $USD)

Location	Contaminants	Details	Technology	Actual Costs Reported	Cost w/DP
42 VoyagerCourt, Toronto, ON	VC: up to 2000 µg/L	Depth: 0 – 4.5 mbg Plume Size: 10 m x 10 m Glacial sandy silt till: 0 - 6 mbg	ISCO – Passive Delivery Fence System Assumes all 29 IPs installed in two lines in vicinity of VC	Cost for Assessment: $ - Capital Costs: **$15,415** (Includes materials and installation of IPs including $KMnO_4$) Cost for Operation and Maintenance: $ - Total Costs for Cleanup: $ -	**$15,820**
A Stannard Dry Cleaners and Launderers Oshkosh, WI	Stoddard's Solvent: 1,500 µg/L Naphthalene: 74 µg/L TCE: 3.4 µg/L VC: 2.3 µg/L	Depth: 2 mbg Plume Size:21m x11m Glacial till clay, 0 - 6 mbg. Occasional fine sand layers	Excavated 594 tons of soil and landfilled Continue with MNA	Cost for Assessment: $47,800 Cost to Design and Implement: **$38,969** Cost for Operation and Maintenance: $7,335 Total Costs for Cleanup: $94,104	**$42,870**
B Sta Brite Cleaners II Sarasota, FL	cis1,2-DCE: 469 µg/L PCE: 164 µg/L trans-1,2-DCE: 16 µg/L TCE: 405 µg/L	Depth: 4.5 mbg Plume Size:21m x11m Clayey sand: 0 - 4 mbg; Fine to coarse-grained sand with limestone lenses: 4–7 mbg	In Situ Bioremediation , Soil Vapor Extraction	Cost for Assessment: $87,200 Cost to Design and Implement: **$102,400** Cost for Operation and Maintenance: $69,500 (includes monitoring) Site Restoration :$ 5,000 Total Costs for Cleanup: $264,100	**$42,900**
C Sable French Cleaners Lake Worth, FL	cis1,2-DCE: 14.6 µg/L PCE: 9.7 µg/L trans1,2-DCE: 0.9 µg/L	Depth: 4.6 mbg Plume Size: 12 mx9 m Silty, fine-grained sand: 0-4.3 mbg Silty, fine to medium sand: 4.3 – 17.7 mbg	In Situ: MNA, Soil Vapor Extraction Located beneath mall floor slab	Cost for Assessment: $67,800 Cost to Design and Implement: **$84,400** Cost for Operation and Maintenance: $57,800 (includes monitoring) Site Restoration: $5,000 Total Costs for Cleanup: $215,000	**$22,320**

For location A, which employed mainly excavation and monitored natural attenuation (MNA), the capital costs are quite similar. However, by employing the passive delivery fence described in this research, the user would anticipate remediation of contaminants to levels below guidelines in a timeline shorter than would be experienced with MNA. As a result, although operating and maintenance costs associated with the passive delivery fence would likely be higher than the assessment and monitoring costs associated with MNA on a yearly basis, once the site is remediated, the costs associated with the passive delivery fence would cease, as concentrations at the site would hopefully meet guideline criteria. Therefore on-going costs associated with site assessment/remediation would also cease, possibly making the passive delivery fence more affordable than MNA over the long-term.

Although this comparison has been based on estimates and a limited number of data, it does appear that compared to traditional methods the passive delivery fence can provide a very cost-effective alternative. The application of this system is limited to relatively shallow contamination (<50 ft) due to the limitations of direct-push drilling. However, in cases with shallow subsurface groundwater contamination, especially in heterogeneous settings, this delivery system is cost effective and flexible. Moreover, it will achieve delivery of amendment across the depth and breadth of the subsurface thereby eliminating one of the largest contributors to failure of in-situ remediation technologies: the even distribution of amendment throughout the target zone.

Chapter 7: Conclusions and Recommendations

The first section of this chapter, Section 7.1, provides conclusions from the work conducted to meet the objectives of this research. Section 7.2 provides the resulting recommendations. The recommendations address further design improvements as well as future operation at the study site to remediate the VC impacts.

7.1 Conclusions

7.1.1 Site Characterization

Based on review of existing site documentation and the results of testing carried out at the site as part of this research, the target area for remediation was determined to be the immediate vicinity of BH208, an existing monitoring well screened over 3 m from approximately 1.5 to 4.5 mbg. In this well, levels of vinyl chloride were detected in excess of MOE guidelines (O.Reg. 153/04) and historically ranged from non-detect (MDL= 0.3 μg/L) to 27.7 μg/L. This existing monitoring well was installed in an area consisting of sandy and clayey silt fill underlain by sandy silt till. Hydraulic testing conducted as part of this research indicated that the groundwater flux through the target area was approximately $q = 0.0011$ m/d, with hydraulic conductivity estimated to be between 4.6×10^{-8} and 3.2×10^{-7} m/s, which is in agreement with low end conductivity values reported in literature for silty till. The groundwater flow direction in this area typically ranged between N40°E and N65°E over the duration of the research.

7.1.2 Delivery System Performance

Based on the findings of the site characterization, the delivery system was designed and installed in a 15 m long fence, perpendicular to the direction of groundwater flow and approximately 0.5 m upgradient of BH208. The system comprised 29 (1/4" ID x ½" OD x 4 m long) PVC delivery points, with 1/32" holes drilled every 0.2 m along the length, connected with a header comprised of a PVC slip cap, brass T and Teflon tubing. The delivery points were initially connected in pairs with a circulation loop of Teflon tubing, so that one pump head fed two delivery points. Four peristaltic pumps delivered a potassium permanganate solution amended with sodium bromide to the delivery points over a period of approximately six months. A total of 50 kg $KMnO_4$, and 1.2 kg NaBr was delivered in 1300 L of water. 14 multi-level monitoring wells (MLMWs), installed with five sample ports each, monitored the effectiveness of the delivery system.

Problems encountered with the system generally consisted of excessive leaks at the slip caps and fittings, and an inability to ensure the even delivery of flow to the delivery points unless the system was reconfigured so that each delivery point was fed directly by one pump header. It was not possible to stop the leaks at many of the delivery points, and as a result the south half of the delivery system (P18 through P30) was disconnected for the duration of the research.

In the northern half of the delivery system (P1 through P17) where amendment was near continuously delivered, elevated Br^- concentrations at downgradient MLMW sampling ports indicated that the delivery system was successful. At the end of the six month delivery period, elevated Br^- levels were detected at all ports of the MLMWs located up to 1.5 m downgradient of the delivery system, and at several of the sampling ports at the MLMW located 2.1 m downgradient of the delivery system. Elevated Br^- concentrations were also detected in BH208. The Br^- travel times varied across the depth of the subsurface and this was suspected to be due to subsurface heterogeneities. The elevated Br^- levels indicate that the delivery system was successful at meeting the main objective of this research. The delivery system successfully delivered the amendment, in this case the conservative Br^-, across the depth and breadth of the subsurface and thus achieved even delivery. The limited cost comparison conducted indicates that the delivery system described in this research also provides a cost-effective alternative to traditional remediation technologies.

7.1.3 Remediation of Vinyl Chloride

The installation and sampling of the MLMW network indicated that VC concentrations in the northern part of the study area ranged from non-detect (MDL = 2.5 μg/L, LOQ = 10 μg/L) up to 1900 μg/L. The higher subsurface resolution afforded by the numerous MLMW sampling ports provided a much more detailed picture of the VC concentrations than was initially available with the existing on-site monitoring network. Once $KMnO_4$ reached and was detected in a sampling port, the VC present should be remediated. Literature indicated that the reaction rate between $KMnO_4$ and VC was near instantaneous and complete.

Initial laboratory testing indicated that the subsurface oxidant demand at the site ranged from 6 to 20 g/kg, which would significantly retard the advancement of the $KMnO_4$ front. As a result, $KMnO_4$ was only detected in three of the seven MLMWs that had elevated Br^- concentrations, and no further than 0.5 m downgradient. $KMnO_4$ was also detected in BH208. Once $KMnO_4$ was detected in wells with initially high VC concentrations (i.e., MW303, MW302-2), the VC concentration dropped significantly (i.e., from initial concentrations of 465 μg/L at MW303-4 to below the LOQ). However, in wells where $KMnO_4$ was detected, VC analysis indicated the continued presence of low level VC concentrations in the groundwater samples. Even when visual evidence of $KMnO_4$ persisted, the 90% CI on the mean VC ranged from non-detect to over 11 μg/L. It is suspected that this is due to analytical interference, as theoretically when $KMnO_4$ is in excess, all VC should be destroyed.

Delivery has ceased at the site for the winter, however VC concentrations still exist at up to 1200 μg/L as of the last sample event (November 15 and 20, 2006). Based on the advancement of $KMnO_4$ seen to date, it is anticipated that under the current system configuration, up to 500 kg of additional $KMnO_4$ would be required to satisfy the oxidant demand and reach the furthest downgradient areas of known contamination (a distance of approximately 5 m). Based on the even delivery indicated by the Br^- analysis, it is expected that given enough time, $KMnO_4$ will thoroughly contact and remediate all downgradient VC contamination, and thus rebound will not be expected.

7.2 Recommendations

7.2.1 Delivery System Design Improvements

Prior to further use of the system, improved fittings and cap assemblies are recommended to eliminate the problems of leaks and ensure the delivered amendment reaches the subsurface. It is recommended that a mechanical engineer be consulted to design and improve the header configuration for the delivery system.

By reconfiguring the system to better target the known VC contamination at the site (within the lateral extent of P1 through P17 only) it may be possible to decrease the required delivery duration. One possible configuration would be to reinstall P18 through P30, which are not required in their current location due to the lack of VC, in a second line further downgradient from P1 through P17 to better target VC concentrations. Using the tested delivery flow rate of 0.5 L/d per delivery point (purchasing additional pumps to provide better delivery) it would then be possible to deliver up to 20 L/d to the target area, which based on the estimates would reduce the delivery time required by half in order to provide sufficient amendment to remediate the remaining VC.

7.2.2 Remediation of Vinyl Chloride

To verify the postulation that $KMnO_4$ interferes with the GC analysis, VC-free $KMnO_4$ standards should be run at $KMnO_4$ concentrations similar to those present in MW303 and BH208 to determine if a peak at the elution time of VC is detected.

An accredited laboratory should analyze several of the samples showing visual evidence of $KMnO_4$ with low level VC concentrations (e.g., Maxxam Analytical) with a MDL of 0.5 µg/L or lower. This is recommended to confirm the presence of low level VC in these samples as theoretically VC should not be present.

Amendment delivery should be continued until $KMnO_4$ reaches the extent of the contamination. Following arrival of $KMnO_4$ and completion of delivery, on-going monitoring would be required to determine whether or not VC rebound is experienced in the target area.

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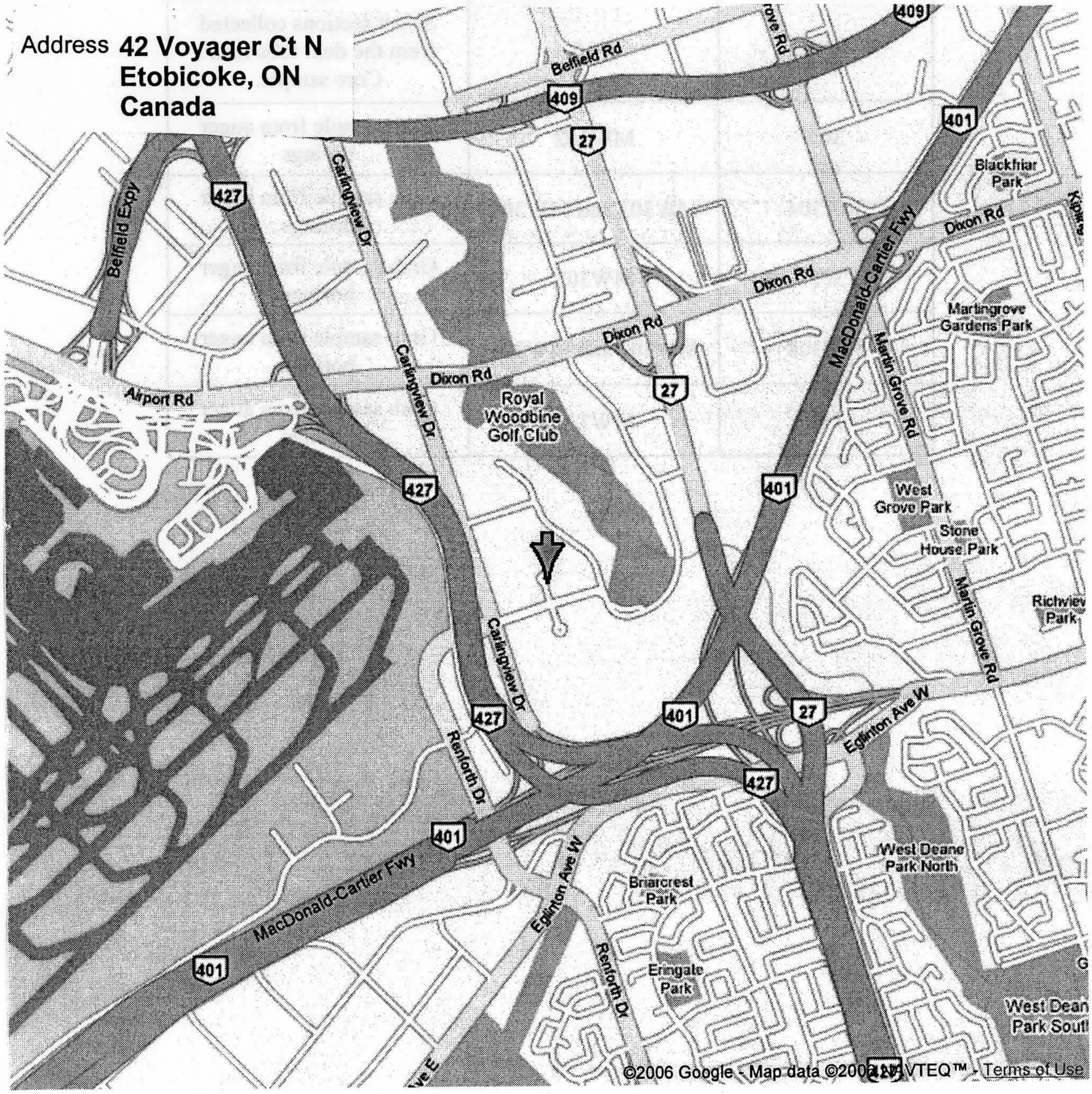
Appendix A: Materials and Methodology Additional Information



Address 42 Voyager Ct N
Etobicoke, ON
Canada

Source: Google Maps
http://maps.google.com
Accessed 21-Dec-06

Table A-1: Soil Sample Type and Location

Soil Sample ID	Location	Type
IP10	IP10	Select sections collected from the dual tube liner. Core sample.
302	MW302	Grab sample from auger borings
303/304	MW303 and MW304	Grab sample from auger borings
305	MW305	Grab sample from auger borings
307/308	MW307 and MW308	Grab sample from auger borings
311	MW311	Grab sample from auger borings

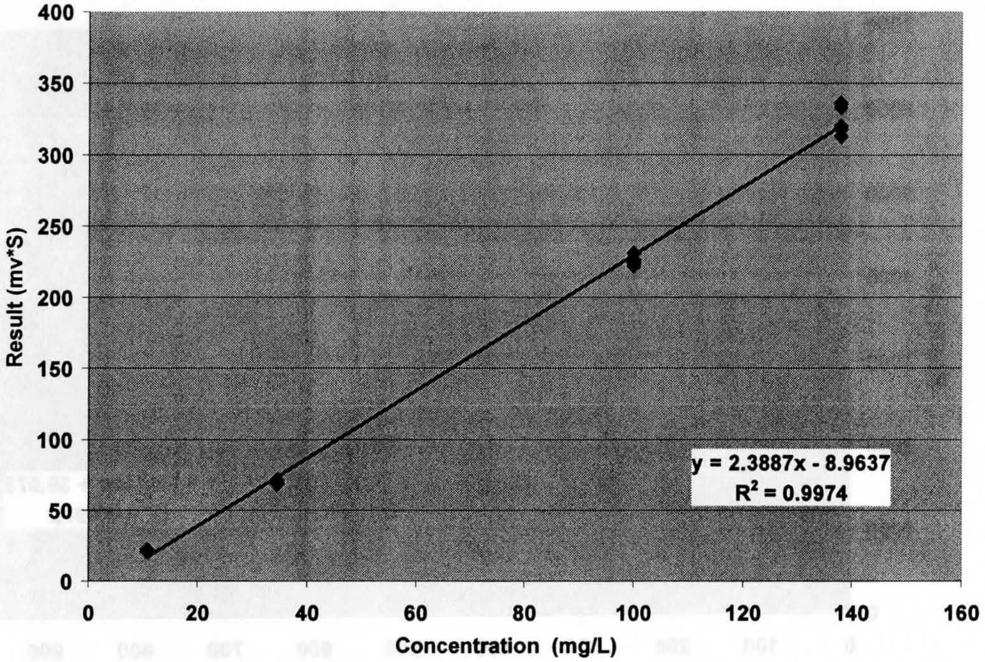


Figure A-1: Bromide Standard Curve

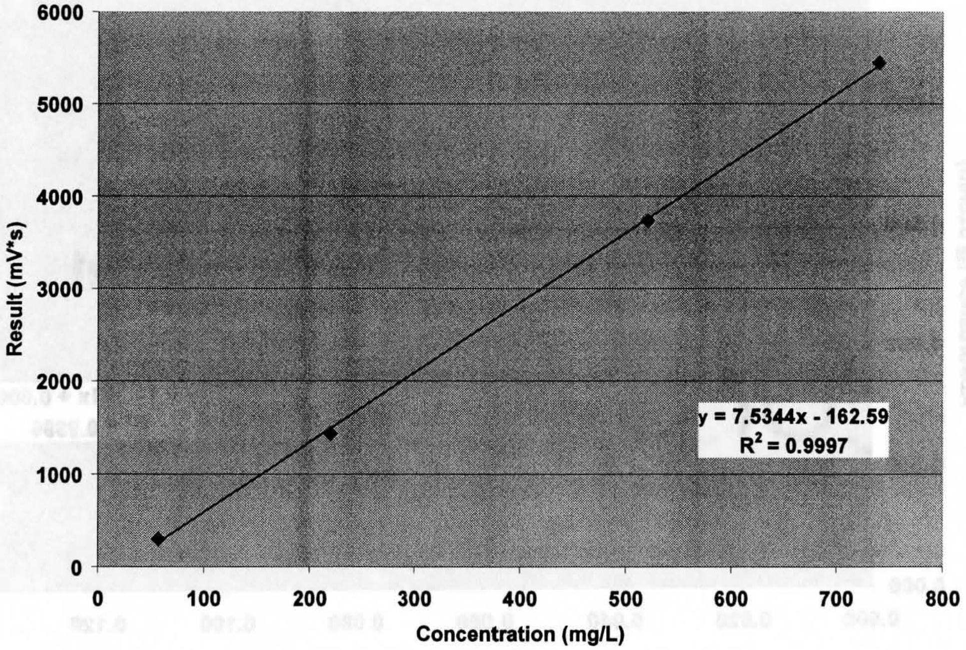


Figure A-2: Chloride Standard Curve

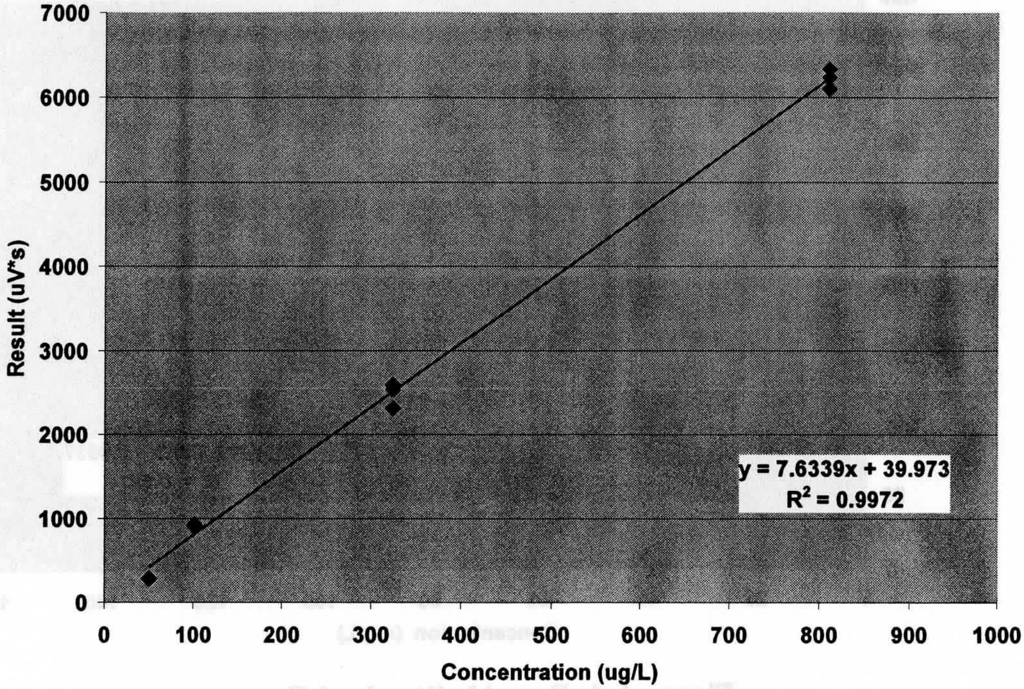


Figure A-3: VC Standard Curve

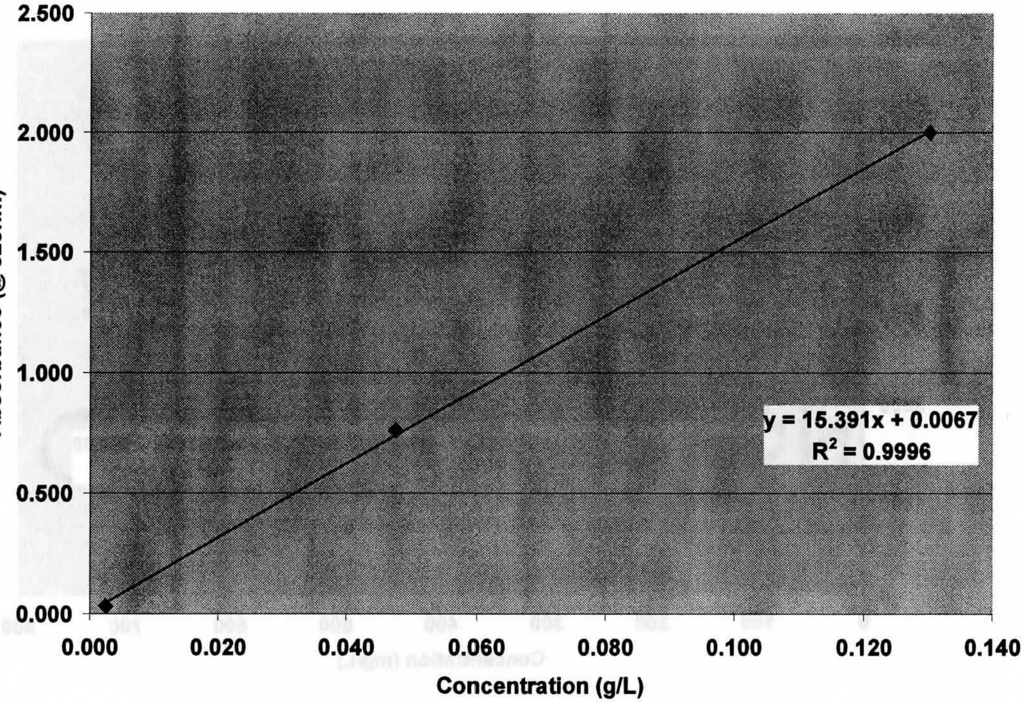


Figure A-4: $KMnO_4$ Standard Curve

Appendix B: Site Characterization Additional Information

Table B-1: List of Available Site Investigation Reports

Date	Report/Letter Title	Prepared By
25-Sep-97	Phase I-C Environmental Site Assessment R.E. #14,001 - 42 Voyager Court North, Etobicoke, Ontario	O'Connor
29-Sep-00	2000 Pavement Evaluation - 42 Voyageur Court, Etobicoke, Ontario	S & P
22-Feb-02	Summary of Findings: Phase 1 & 2 Environmental Site Assessment - 42 Voyageur Court North, Toronto, Ontario	S & P
Jul-02	Remedial Excavation Report - Nickel Impacted Soils	AMEC
28-Mar-03	Status Update – Supplemental Investigation of Chlorinated Solvent Soil Impacts – 42 Voyageur Court, Toronto	AMEC
23-May-03	Summary of Chlorinated Solvent Impacts Investigation and proposed Remediation – 42 Voyageur Court, Toronto, Ontario	AMEC
Dec-03	Remedial Excavation Report - Chlorinated Solvent Impacted Soils	AMEC
10-Feb-04	Post-Remedial Excavation Groundwater Investigation - 42 Voyageur Court, Toronto, Ontario	AMEC
25-Mar-04	Phase I Environmental Site Assessment Update - 42 Voyageur Court North, Toronto, Ontario	AMEC
08-Jul-04	Work Plan and Budget - Groundwater Monitoring and Sampling, 42 Voyageur Court, Toronto, Ontario	AMEC
13-Jul-04	Summer 2004 Groundwater Sampling and Monitoring Event, 42 Voyager Court, Toronto, Ontario	AMEC
16-Aug-04	Remediation of Residual Vinyl Chloride Groundwater Impacts, 42 Voyageur Court, Toronto, Ontario	AMEC

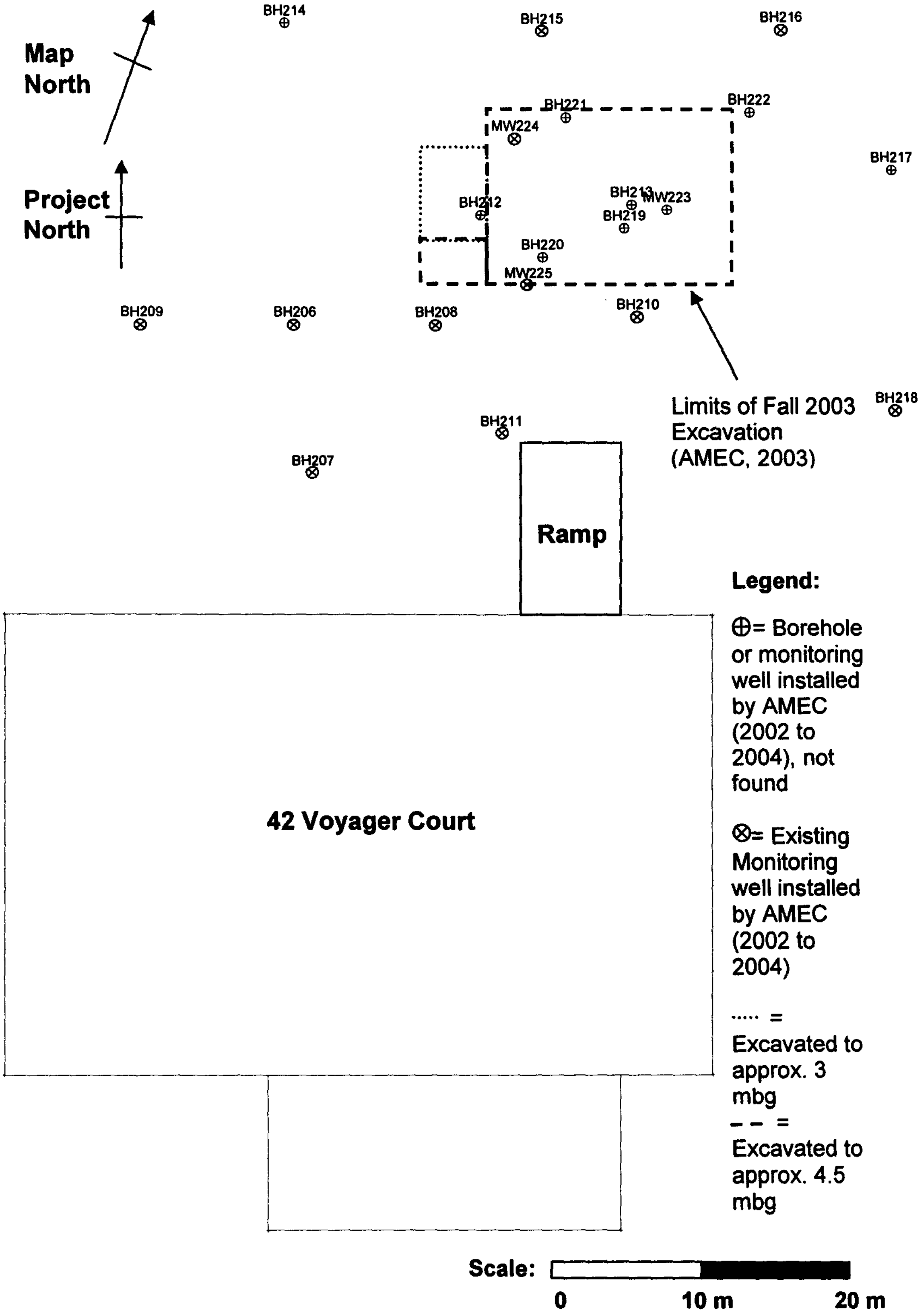


Figure B-1: Approximate PCE Impacted Soil Excavation Limits (AMEC 2003)

Table B-2: Summary of Surveyed Well Elevations

Well ID	Measured Elevation (m)	Referenced Elevation (m)
BM	1.470	100.000
BH1	-	-
BH6	1.485*	100.915
BH102	1.460, 2.390*	100.010
BH103	1.500*	100.900
BH206	1.532	99.938
BH207	1.615	99.855
BH208	1.605	99.865
BH209	1.500	99.970
BH210	1.560	99.910
BH211	1.690	99.780
BH215	2.050	99.420
BH216	2.190	99.280
BH218	1.530	99.940
MW226	1.888	99.582

BM = Benchmark

* = well was measured from a secondary survey location, and BH102 was used to tie the location back to the original survey location – see Section 3.1.3

Table B-3: Water Table Elevations– Spring/Summer 2005

	Water Table Elevation (m)								
Well ID	**6-Apr-05**	**22-Apr-05**	**23-Jun-05**	**30-Jun-05**	**5-Jul-05**	**7-Jul-05**	**8-Jul-05**	**9-Aug-05**	**30-Sep-05**
BH6	99.159	-	99.532	-	-	-	-	-	-
BH102	98.433	-	98.327	-	-	-	-	98.106	98.202
BH103	98.891	-	-	-	-	-	-	-	-
BH206	98.868	-	98.733	98.795	-	98.714	98.726	98.600	98.492
BH207	98.541	99.097	-	-	-	-	-	-	98.736
BH208	98.631	98.740	98.471	98.558	98.549	98.466	-	98.371	98.275
BH209	98.516	99.095	98.880	98.880	-	98.872	98.884	98.772	98.666
BH210	98.377	98.305	97.996	98.033	98.012	97.945	-	97.839	97.838
BH211	98.795	-	98.685	-	-	-	-	98.566	98.465
BH215	97.649	97.665	97.577	-	97.513	-	97.450	97.353	97.376
BH216	97.991	-	97.509	-	-	-	-	97.120	97.342
BH218	97.956	97.880	98.049	98.041	98.057	-	-	97.866	97.883

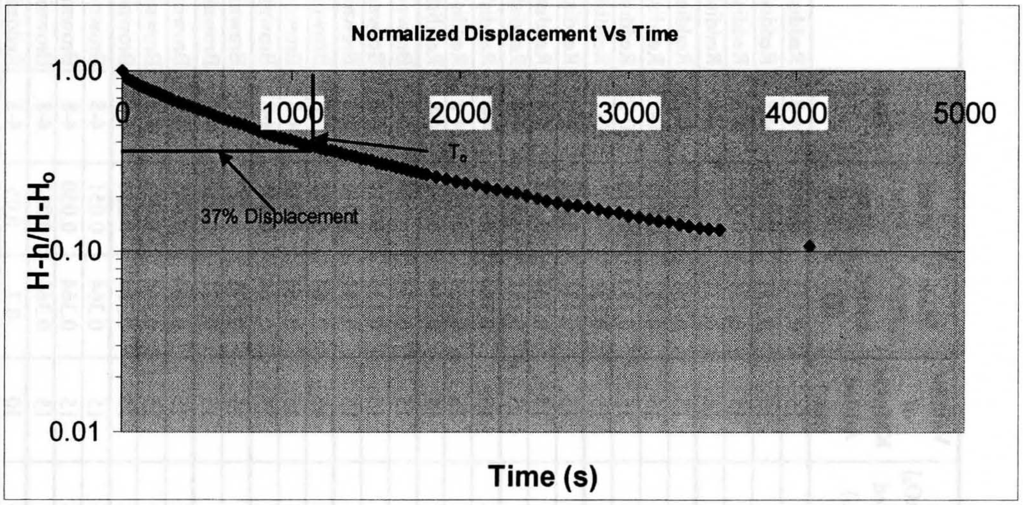
Table B-4: Summary of Slug Test Volumes

Well ID	Date	Volume Added (mL)	Date	Volume Added (mL)	Date	Volume Added (mL)	Date	Volume Added (mL)
BH206	30-Jun-05	500	-	-	7-Jul-05	1000	8-Jul-05	1000
BH207	30-Jun-05	500	-	-	7-Jul-05	1000	8-Jul-05	1000
BH208	30-Jun-05	500	5-Jul-05	1000	7-Jul-05	1000	-	-
BH209	30-Jun-05	500	-	-	7-Jul-05	1000	8-Jul-05	1000
BH210	30-Jun-05	500	5-Jul-05	1000	7-Jul-05	1000	-	-
BH215	30-Jun-05	500	5-Jul-05	1000	-	-	8-Jul-05	1000

Example of Slug Test Data - Analysis using Hvorslev Method

BH 208 - July 7, 2005

Initial WL:	**1.399**	
Volume Added:	**0.96**	**L**
Well X-Sectional Area:	**0.002027**	**m^2**
Expected Rise:	**47.36**	**cm**



Analysis Using Hvorslev Method

Total Initial Displacement:	0.474 m
37% of displacement:	0.175 m
Water Level with 37% Displacement:	1.224 mbTOC

r = 0.0254 radius of well casing (m)
R = 0.075 radius of well screen (m)
Le = 3.38 screen length (including sand pack) (m)
Le/R = 45.07
ho = 0.970
H = 1.399
To 1170
K= 3.11E-07 m/s
0.03 m/day
2.68 cm/day

Table B-5: Reactor Preparation Details

Sample ID	Date Prepared	MW Soil ID	Mass of Vial Empty (g)	Mass of Vial with Soil (g)	Mass Soil (g)	[$KMnO_4$] Added (g/L)	Volume of KMnO4 Added (mL)	Mass $KMnO_4$ Added (g)	Mass $KMnO_4$/ Mass Soil	Temp	Soil Description
4A	14-Mar-06	302Ai	13.897	24.700	10.803	8	15	0.131	0.012	4-8	Reddish till with gravels, sand and silt
4B	14-Mar-06	302Ai	13.898	24.184	10.286	8	15	0.131	0.013	4-8	Reddish till with gravels, sand and silt
4C	14-Mar-06	302Ai	13.875	25.116	11.242	8	15	0.131	0.012	4-8	Reddish till with gravels, sand and silt
4D	14-Mar-06	302Ai	control			8	15	0.131		4-8	Reddish till with gravels, sand and silt
5A	14-Mar-06	302Ai	13.840	24.037	10.197	8	15	0.131	0.013	20-25	Reddish till with gravels, sand and silt
5B	14-Mar-06	302Ai	13.903	24.389	10.486	8	15	0.131	0.012	20-25	Reddish till with gravels, sand and silt
5C	14-Mar-06	302Ai	13.895	24.007	10.111	8	15	0.131	0.013	20-25	Reddish till with gravels, sand and silt
5D	14-Mar-06	302Ai	control			8	15	0.131		20-25	Reddish till with gravels, sand and silt
7A	17-Mar-06	311Aii	13.989	25.411	11.422	8	15	0.131	0.011	4-8	Reddish grey till with silt, sand and gravels
7B	17-Mar-06	311Aii	14.196	25.260	11.064	8	15	0.131	0.012	4-8	Reddish grey till with silt, sand and gravels
7C	17-Mar-06	311Aii	14.032	24.629	10.598	8	15	0.131	0.012	4-8	Reddish grey till with silt, sand and gravels
8A	17-Mar-06	311Aii	14.349	25.326	10.977	25	15	0.364	0.033	4-8	Reddish grey till with silt, sand and gravels
8B	17-Mar-06	311Aii	14.094	24.413	10.319	25	15	0.364	0.035	4-8	Reddish grey till with silt, sand and gravels
8C	17-Mar-06	311Aii	13.650	25.517	11.867	25	15	0.364	0.031	4-8	Reddish grey till with silt, sand and gravels
9A	21-Mar-06	303/304Ai	13.873	22.191	8.318	8	15	0.131	0.016	4-8	Brownish beige till with silt, sand and gravels
9B	21-Mar-06	303/304Ai	13.939	22.104	8.165	8	15	0.131	0.016	4-8	Brownish beige till with silt, sand and gravels
9C	21-Mar-06	303/304Ai	13.849	21.866	8.017	8	15	0.131	0.016	4-8	Brownish beige till with silt, sand and gravels
10A	21-Mar-06	303/304Ai	13.893	22.509	8.615	25	15	0.364	0.042	4-8	Brownish beige till with silt, sand and gravels
10B	21-Mar-06	303/304Ai	13.870	21.475	7.606	25	15	0.364	0.048	4-8	Brownish beige till with silt, sand and gravels
10C	21-Mar-06	303/304Ai	13.806	22.646	8.840	25	15	0.364	0.041	4-8	Brownish beige till with silt, sand and gravels
11B	21-Mar-06	305 A	14.049	21.869	7.820	8	15	0.131	0.017	4-8	Brownish beige till with silt, sand and gravels
11C	21-Mar-06	305 A	13.849	20.504	6.655	8	15	0.131	0.020	4-8	Brownish beige till with silt, sand and gravels
12A	21-Mar-06	305 A	13.965	22.029	8.064	25	15	0.364	0.045	4-8	Brownish beige till with silt, sand and gravels
12B	21-Mar-06	305 A	13.900	21.755	7.855	25	15	0.364	0.046	4-8	Brownish beige till with silt, sand and gravels
12C	21-Mar-06	305 A	13.837	20.541	6.705	25	15	0.364	0.054	4-8	Brownish beige till with silt, sand and gravels
13A	22-Mar-06	307/308 Ai	14.049	21.226	7.176	25	15	0.364	0.051	4-8	Brownish beige till with silt, sand and gravels
13B	22-Mar-06	307/308 Ai	14.022	21.246	7.223	25	15	0.364	0.050	4-8	Brownish beige till with silt, sand and gravels
13C	22-Mar-06	307/308 Ai	13.707	20.857	7.150	25	15	0.364	0.051	4-8	Brownish beige till with silt, sand and gravels
14A	23-Mar-06	311			16	25	30	0.7	0.05	4-8	Reddish grey till with silt, sand and gravels
14B	23-Mar-06	311			16	25	30	0.7	0.05	4-8	Reddish grey till with silt, sand and gravels
14C	23-Mar-06	311			8	25	15	0.4	0.05	4-8	Reddish grey till with silt, sand and gravels

Table B-6: Summary of NOD Sample Results

Sample ID	Elapsed Time (h)	Corrected Absorbance	Sample Concentration (g/L)	Concentration Change (g/L) vs Control	Mass Soil (g)	NOD (g/kg)	Avg NOD
4A1	1	0.897	8.16	0.06	10.80	0.08	-0.04
4B1	1	0.904	8.22	0.00	10.29	0.00	
4C1	1	0.920	8.36	-0.15	11.24	-0.20	
4D1	1	0.904	8.22				
4A2	2	0.916	8.33	0.28	10.80	0.39	0.55
4B2	2	0.907	8.25	0.37	10.29	0.53	
4C2	2	0.889	8.08	0.53	11.24	0.71	
4D2	2	0.947	8.61				
4A3	3	0.876	7.96	0.15	10.80	0.20	0.20
4D3	3	0.892	8.11				
4A4	5	0.850	7.72	1.05	10.80	1.46	1.51
4B4	5	0.847	7.70	1.07	10.29	1.57	
4D4	5	0.965	8.77				
4A5	7	0.888	8.07	0.66	10.80	0.92	1.00
4B5	7	0.863	7.85	0.89	10.29	1.29	
4C5	7	0.896	8.15	0.59	11.24	0.78	
4D5	7	0.960	8.73				
4A6	24	0.905	8.23	0.70	10.80	0.97	1.01
4C6	24	0.894	8.13	0.79	11.24	1.06	
4D6	24	0.981	8.92				
4A7	49	0.844	7.67	0.77	10.80	1.07	1.34
4B7	49	0.808	7.34	1.10	10.29	1.61	
4C7	49	0.819	7.44	1.00	11.24	1.33	
4D7	49	0.928	8.44				
4A8	73	0.852	7.74	0.73	10.80	1.02	1.55
4A8-dup	73	0.824	7.49	0.98	10.80	1.37	
4C8	73	0.746	6.77	1.70	11.24	2.27	
4B8	73	0.816	7.41	1.06	10.29	1.55	
4D8	73	0.932	8.47				
4C9	83	0.737	6.69	2.31	11.24	3.09	2.69
4B9	83	0.818	7.43	1.57	10.29	2.29	
4D9	83	0.989	9.00				
4A9	83	0.778	7.07	1.93	10.80	2.68	
4A10	125	0.807	7.33	1.91	10.80	2.65	3.22
4B10	125	0.757	6.88	2.36	10.29	3.44	
4B10-dup	125	0.761	6.91	2.32	10.29	3.39	
4C10	125	0.735	6.67	2.56	11.24	3.42	
4D10	125	1.015	9.23				
4B11	169	0.687	6.23	2.30	10.29	3.35	3.09
4C11	169	0.707	6.41	2.12	11.24	2.83	
4D11	169	0.938	8.53				
4A12	194	0.814	7.40	1.66	10.80	2.31	3.11
4B12	194	0.701	6.36	2.70	10.29	3.94	
4C12	194	0.743	6.75	2.31	11.24	3.09	
4D12	194	0.996	9.06				
4A13	239	0.747	6.79	1.69	10.80	2.35	2.35
4D13	239	0.932	8.48				
4C14	269	0.665	6.03	2.36	11.24	3.15	3.15
4D14	269	0.923	8.39				

Table B-6 continued: Summary of NOD Sample Results

Sample ID	Elapsed Time (h)	Corrected Absorbance	Sample Concentration (g/L)	Concentration Change (g/L) vs Control	Mass Soil (g)	NOD (g/kg)	Avg NOD
4A15	291	0.779	7.08	1.92	10.80	2.66	3.31
4B15	291	0.728	6.61	2.39	10.29	3.48	
4C15	291	0.679	6.16	2.84	11.24	3.79	
4D15	291	0.989	9.00				
4A16	311	0.750	6.81	1.51	10.80	2.09	2.70
4B16	311	0.680	6.17	2.15	10.29	3.14	
4C16	311	0.679	6.16	2.16	11.24	2.88	
4D16	311	0.915	8.32				
5A1	1	0.878	7.98	0.59	10.20	0.87	0.84
5B1	1	0.871	7.92	0.65	10.49	0.93	
5C1	1	0.890	8.09	0.48	10.11	0.71	
5D1	1	0.942	8.57				
5A2	2	0.860	7.82	0.38	10.20	0.56	0.47
5B2	2	0.875	7.95	0.24	10.49	0.35	
5C2	2	0.864	7.86	0.34	10.11	0.51	
5D2	2	0.902	8.20				
5A3	3	0.877	7.97	0.38	10.20	0.57	0.83
5C3	3	0.839	7.62	0.73	10.11	1.09	
5D3	3	0.919	8.35				
5A4	5	0.841	7.64	1.00	10.20	1.46	1.46
5B4	5	0.829	7.54	1.10	10.49	1.58	
5C4	5	0.851	7.73	0.91	10.11	1.35	
5D4	5	0.950	8.64				
5B5	7	0.810	7.36	1.12	10.49	1.60	1.60
5C5	7	0.814	7.40	1.08	10.11	1.60	
5D5	7	0.932	8.48				
5A6	24	0.798	7.25	1.26	10.20	1.85	1.99
5B6	24	0.769	6.98	1.52	10.49	2.17	
5C6	24	0.791	7.19	1.31	10.11	1.95	
5D6	24	0.935	8.50				
5A7	49	0.746	6.77	1.58	10.20	2.32	2.60
5B7	49	0.703	6.38	1.97	10.49	2.82	
5C7	49	0.721	6.55	1.80	10.11	2.67	
5D7	49	0.918	8.35				
5A8	73	0.720	6.53	1.62	10.20	2.38	2.55
5B8	73	0.693	6.28	1.86	10.49	2.66	
5C8	73	0.704	6.39	1.76	10.11	2.61	
5D8	73	0.896	8.15				
5A9	83	0.708	6.42	2.27	10.20	3.33	3.33
5A9-dup	83	0.723	6.56	2.13	10.20	3.13	
5D9	83	0.955	8.69				
5B9	83	0.628	5.69	3.00	10.49	4.29	
5C9	83	0.697	6.32	2.36	10.11	3.51	
5A10	125	0.681	6.17	2.44	10.20	3.59	4.03
5B10	125	0.625	5.66	2.95	10.49	4.22	
5C10	125	0.643	5.83	2.79	10.11	4.14	
5C10-dup	125	0.640	5.80	2.82	10.11	4.18	
5D10	125	0.947	8.62				

Table B-6 continued: Summary of NOD Sample Results

Sample ID	Elapsed Time (h)	Corrected Absorbance	Sample Concentration (g/L)	Concentration Change (g/L) vs Control	Mass Soil (g)	NOD (g/kg)	Avg NOD
5A11	169	0.663	6.01	2.41	10.20	3.54	3.72
5A11-dup	169	0.685	6.21	2.20	10.20	3.24	
5B11	169	0.615	5.57	2.84	10.49	4.07	
5C11	169	0.629	5.70	2.71	10.11	4.02	
5D11	169	0.925	8.42				
5D12	194	0.448	8.06				
5A13	240	0.663	6.01	2.43	10.20	3.58	3.58
5D13	240	0.929	8.45				
5D14	267	0.903	8.21				
5B14	267	0.619	5.61	2.60	10.49	3.73	4.09
5C14	267	0.576	5.22	3.00	10.11	4.44	
7A1	2	0.855	7.771	0.244	11.422	0.32	0.43
7B1	2	0.835	7.588	0.428	11.064	0.58	
7C1	2	0.852	7.741	0.275	10.598	0.39	
7D1	2	0.882	8.016				
7A2	4	0.858	7.802	0.646	11.422	0.85	1.19
7B2	4	0.826	7.509	0.939	11.064	1.27	
7C2	4	0.816	7.414	1.034	10.598	1.46	
7D2	4	0.952	8.657				
7D2-dup	4	0.906	8.239				
7A3	8	0.817	7.426	0.913	11.422	1.20	1.77
7B3	8	0.815	7.408	0.931	11.064	1.26	
7C3	8	0.697	6.321	2.019	10.598	2.86	
7D3	8	0.888	8.074				
7D3-dup	8	0.946	8.605				
7A4	75	0.638	5.780	2.299	11.422	3.02	2.65
7C4	75	0.713	6.468	1.612	10.598	2.28	
7D4	75	0.889	8.080				
7A5	95	0.645	5.848	2.568	11.422	3.37	3.34
7B5	95	0.683	6.193	2.223	11.064	3.01	
7C5	95	0.646	5.857	2.559	10.598	3.62	
7D5	95	0.925	8.416				
7A6	119	0.652	5.912	2.434	11.422	3.20	3.34
7B6	119	0.617	5.588	2.758	11.064	3.74	
7C6	119	0.679	6.162	2.183	10.598	3.09	
7D6	119	0.918	8.346				
7D6-dup	119	0.975	8.868				
7A7	168	0.601	5.448	2.516	11.422	3.30	3.33
7B7	168	0.619	5.612	2.351	11.064	3.19	
7C7	168	0.607	5.495	2.469	10.598	3.49	
7D7	168	0.870	7.909				
7D7-dup	168	0.882	8.019				
7A8	194	0.606	5.493	2.944	11.422	3.87	4.01
7B8	194	0.611	5.533	2.904	11.064	3.94	
7C8	194	0.602	5.457	2.980	10.598	4.22	
7D8	194	0.928	8.437				
7A9	216	0.609	5.521	3.390	11.422	4.45	4.35
7B9	216	0.619	5.606	3.304	11.064	4.48	
7C9	216	0.662	6.000	2.910	10.598	4.12	
7D9	216	0.960	8.730				
7D9-dup	216	0.999	9.091				

Table B-6 continued: Summary of NOD Sample Results

Sample ID	Elapsed Time (h)	Corrected Absorbance	Sample Concentration (g/L)	Concentration Change (g/L) vs Control	Mass Soil (g)	NOD (g/kg)	Avg NOD
7A10	237	0.577	5.228	3.231	11.422	4.24	4.18
7B10	237	0.584	5.292	3.167	11.064	4.29	
7C10	237	0.620	5.622	2.837	10.598	4.02	
7D10	237	0.930	8.459				
8B1	2	1.195	21.701	3.998	10.319	5.81	3.68
8C1	2	1.347	24.477	1.223	11.867	1.55	
8D1	2	1.414	25.700				
8A2	4	1.260	22.888	2.939	10.977	4.02	2.14
8B2	4	1.372	24.933	0.895	10.319	1.30	
8C2	4	1.374	24.957	0.870	11.867	1.10	
8D2	4	1.421	25.828				
8A3	8	1.304	23.691	1.260	10.977	1.72	2.85
8B3	8	1.279	23.235	1.716	10.319	2.49	
8C3	8	1.186	21.531	3.420	11.867	4.32	
8D3	8	1.373	24.951				
8B4	75	1.046	18.969	3.785	10.319	5.50	2.49
8C4	75	1.276	23.168	-0.414	11.867	-0.52	
8D4-dup	75	1.253	22.754				
8A5	95	1.201	21.805	2.313	10.977	3.16	5.82
8B5	95	0.966	17.508	6.609	10.319	9.61	
8C5	95	1.125	20.411	3.706	11.867	4.68	
8D5	95	1.328	24.117				
8D5-dup	95	1.339	24.318				
8A6	119	1.167	21.190	2.550	10.977	3.48	3.79
8B6	119	1.140	20.697	3.043	10.319	4.42	
8C6	119	1.156	20.989	2.751	11.867	3.48	
8D6	119	1.341	24.355				
8D6-dup	119	1.273	23.125				
8A7	168	0.976	17.703	6.013	10.977	8.22	5.56
8B7	168	1.196	21.720	1.996	10.319	2.90	
8D7	168	1.359	24.690				
8D7-dup	168	1.252	22.742				
8A8	194	1.164	21.135	4.400	10.977	6.01	6.57
8B8	194	1.151	20.898	4.637	10.319	6.74	
8C8	194	1.103	20.022	5.514	11.867	6.97	
8D8-dup	194	1.405	25.535				
8A9	217	1.317	23.914	2.328	10.977	3.18	4.95
8B9	217	1.225	22.249	3.992	10.319	5.80	
8C9	217	1.190	21.604	4.637	11.867	5.86	
8D9	217	1.444	26.241				
9A1	3	0.805	7.316	0.754	8.318	1.36	1.38
9B1	3	0.791	7.188	0.883	8.165	1.62	
9C1	3	0.819	7.445	0.626	8.017	1.17	
9D1	3	0.888	8.071				
9A2	6	0.767	6.965	1.835	8.318	3.31	3.18
9B2	6	0.768	6.971	1.829	8.165	3.36	
9C2	6	0.801	7.274	1.527	8.017	2.86	
9D2	6	0.967	8.801				
9A3	24	0.669	6.067				
9B3	24	0.681	6.177				
9B3-repea	24	0.690	6.263				

Table B-6 continued: Summary of NOD Sample Results

Sample ID	Elapsed Time (h)	Corrected Absorbance	Sample Concentration (g/L)	Concentration Change (g/L) vs Control	Mass Soil (g)	NOD (g/kg)	Avg NOD
9A4	30	0.610	5.527	3.182	8.318	5.74	5.33
9B4	30	0.633	5.741	2.968	8.165	5.45	
9C4	30	0.677	6.144	2.565	8.017	4.80	
9D4	30	0.957	8.709				
9A5	74	0.506	4.571	2.666	8.318	4.81	3.96
9B5	74	0.582	5.267	1.970	8.165	3.62	
9C5	74	0.595	5.386	1.851	8.017	3.46	
9D5	74	0.797	7.237				
9A6	100	0.538	4.867	3.475	8.318	6.27	5.90
9B6	100	0.556	5.032	3.310	8.165	6.08	
9C6	100	0.605	5.478	2.864	8.017	5.36	
9D6	100	0.917	8.342				
9A7	123	0.472	4.266	4.278	8.318	7.72	6.97
9B7	123	0.528	4.776	3.768	8.165	6.92	
9C7	123	0.574	5.197	3.347	8.017	6.26	
9D7	123	0.939	8.544				
9A8	143	0.483	4.363	4.226	8.318	7.62	7.14
9B8	143	0.538	4.867	3.723	8.165	6.84	
9C8	143	0.538	4.870	3.719	8.017	6.96	
9D8	143	0.944	8.590				
10A1	3	0.899	16.285	0.572	8.615	1.00	1.00
10D1	3	0.930	16.857				
10A2	6	1.338	24.300	0.000	8.615	0.00	0.00
10B2	6	1.240	22.523	0.000	7.606	0.00	
10C2	6	1.251	22.712	0.000	8.840	0.00	
10D2	6	1.064	19.304				
10A3	23	2.142	19.559	1.344	8.615	2.34	1.91
10B3	23	2.156	19.687	1.215	7.606	2.40	
10C3	23	2.225	20.322	0.580	8.840	0.98	
10D3	23	2.288	20.902				
10A4	29	1.307	23.746	1.102	8.615	1.92	4.58
10B4	29	1.174	21.318	3.530	7.606	6.96	
10C4	29	1.211	21.981	2.866	8.840	4.86	
10D4	29	1.368	24.848				
10A5	73	1.170	21.245	3.432	8.615	5.98	9.54
10B5	73	1.061	19.255	5.422	7.606	10.69	
10C5	73	0.972	17.630	7.047	8.840	11.96	
10D5	73	1.358	24.677				
10A6	96	1.098	19.918	2.380	8.615	4.14	6.51
10B6	96	1.112	20.180	2.118	7.606	4.18	
10C6	96	0.866	15.683	6.615	8.840	11.22	
10D6	96	1.228	22.298				
10A7	119	1.137	20.636	5.240	8.615	9.12	7.21
10B7	119	1.233	22.383	3.493	7.606	6.89	
10C7	119	1.243	22.572	3.305	8.840	5.61	
10D7	119	1.424	25.876				
11B1	3	0.837	7.610	1.090	7.820	2.09	2.52
11C1	3	0.818	7.429	1.270	6.655	2.86	
11C1-dup	3	0.830	7.542	1.157	6.655	2.61	
11D1	3	0.956	8.700				

Table B-6 continued: Summary of NOD Sample Results

Sample ID	Elapsed Time (h)	Corrected Absorbance	Sample Concentration (g/L)	Concentration Change (g/L) vs Control	Mass Soil (g)	NOD (g/kg)	Avg NOD
11B2	6	0.804	7.301	0.919	7.820	1.76	1.53
11C2-dup	6	0.841	7.646	0.574	6.655	1.29	
11C2	6	0.829	7.536	0.684	6.655	1.54	
11D2	6	0.904	8.220				
11B3	24	0.703	6.376	1.444	7.820	2.77	2.65
11C3	24	0.738	6.697	1.124	6.655	2.53	
11D3	24	0.860	7.820				
11B4	30	0.684	6.208	2.339	7.820	4.49	4.29
11B4-dup	30	0.706	6.409	2.138	7.820	4.10	
11D4	30	0.940	8.547				
11B5	74	0.525	4.745	3.475	7.820	6.67	7.41
11B5-dup	74	0.564	5.102	3.118	7.820	5.98	
11C5	74	0.440	3.966	4.254	6.655	9.59	
11D5	74	0.904	8.220				
11B6	100	0.508	4.596	4.077	7.820	7.82	7.96
11B6-dup	100	0.553	5.005	3.668	7.820	7.04	
11C6	100	0.516	4.663	4.010	6.655	9.04	
11D6	100	0.953	8.672				
11B7	123	0.521	4.709	3.982	7.820	7.64	9.00
11C7-dup	123	0.487	4.400	4.290	6.655	9.67	
11C7-dup	123	0.487	4.397	4.294	6.655	9.68	
11D7	123	0.955	8.691				
11B8	143	0.460	4.153	4.578	7.820	8.78	9.43
11B8-dup	143	0.467	4.217	4.513	7.820	8.66	
11C8	143	0.434	3.918	4.813	6.655	10.85	
11D8	143	0.960	8.730				
12A1	3	1.259	22.870	1.095	8.064	2.04	3.19
12B1	3	1.179	21.403	2.562	7.855	4.89	
12C1	3	1.255	22.791	1.175	6.705	2.63	
12D1	3	1.319	23.965				
12A2	6	1.197	21.726	-0.676	8.064	-1.26	1.04
12B2	6	1.078	19.565	1.485	7.855	2.84	
12C2	6	1.122	20.356	0.694	6.705	1.55	
12D2	6	1.160	21.050				
12A3	24	1.148	20.843	3.189	8.064	5.93	6.52
12B3	24	1.140	20.685	3.347	7.855	6.39	
12C3	24	1.146	20.795	3.238	6.705	7.24	
12D3	24	1.323	24.032				
12A4	30	1.260	22.888	1.668	8.064	3.10	8.94
12B4	30	0.928	16.821	7.735	7.855	14.77	
12D4	30	1.352	24.556				
12B5	77	1.068	19.377		7.855	0.00	
12C5	77	1.027	18.634		6.705	0.00	
12A6	100	1.100	19.961	4.674	8.064	8.69	11.29
12B6	100	0.995	18.038	6.597	7.855	12.60	
12C6	100	1.048	19.011	5.623	6.705	12.58	
12D6	100	1.356	24.635				
12A7	123	1.021	18.525	8.325	8.064	15.49	15.17
12B7	123	1.047	18.984	7.866	7.855	15.02	
12C7	123	1.110	20.143	6.707	6.705	15.00	
12D7	123	1.477	26.850				

Table B-6 continued: Summary of NOD Sample Results

Sample ID	Elapsed Time (h)	Corrected Absorbance	Sample Concentration (g/L)	Concentration Change (g/L) vs Control	Mass Soil (g)	NOD (g/kg)	Avg NOD
12A8	145	1.004	18.214	7.370	8.064	13.71	13.40
12B8	145	1.048	19.005	6.579	7.855	12.56	
12C8	145	1.067	19.364	6.220	6.705	13.92	
12D8	145	1.408	25.584				
13B1	7	1.399	25.414	-3.195	7.223	0.00	0.41
13C1	7	1.202	21.829	0.389	7.150	0.82	
13D1	7	1.224	22.219				
13A2	55	1.141	20.703	4.394	7.176	9.18	12.55
13B2	55	1.022	18.531	6.567	7.223	13.64	
13C2	55	0.994	18.026	7.072	7.150	14.83	
13D2	55	1.381	25.097				
13A3	78	1.079	19.584	1.461	7.176	3.05	6.09
13A3-dup	78	1.007	18.257	2.787	7.176	5.83	
13C3	78	0.914	16.565	4.479	7.150	9.40	
13D3	78	1.159	21.044				
13A4	101	1.018	18.470	6.421	7.176	13.42	14.80
13B4	101	0.983	17.825	7.066	7.223	14.67	
13c4	101	0.944	17.113	7.778	7.150	16.32	
13D4	101	1.370	24.890				
13A5	121	0.821	14.873	10.017	7.176	20.94	19.93
13B5	121	0.961	17.429	7.461	7.223	15.49	
13C5	121	0.760	13.759	11.131	7.150	23.35	
13D5	121	1.370	24.890				
14A1	29	1.345	24.428	-6.932	*16.000*	0.00	0.00
14B1	29	1.303	23.673	-6.177	*16.000*	0.00	
14C1	29	1.250	22.706	-5.209	*8.000*	0.00	
14D1	29	0.965	17.496				
14A2	52	1.325	24.075	-1.923	*16.000*	0.00	0.95
14B2	52	1.339	24.318	-2.167	*16.000*	0.00	
14C2	52	1.137	20.636	1.515	*8.000*	2.84	
14D2	52	1.220	22.152				
14A3	75	1.263	22.937	3.956	*16.000*	7.42	7.63
14B3	75	1.263	22.931	3.962	*16.000*	7.43	
14C3	75	1.245	22.608	4.284	*8.000*	8.03	
14D3	75	1.480	26.893				
14A4	95	1.454	26.430	-0.043	*16.000*	-0.08	4.94
14B4	95	1.165	21.154	5.234	*16.000*	9.81	
14C4	95	1.304	23.679	2.708	*8.000*	5.08	
14D4	95	1.452	26.387				

16.000 = estimated mas
values were mis

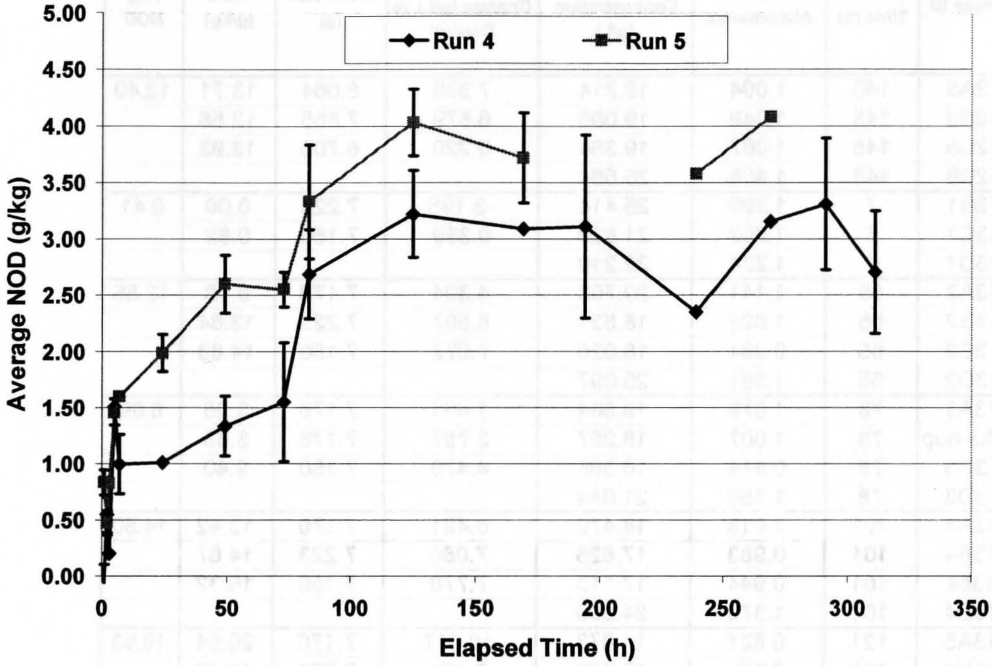
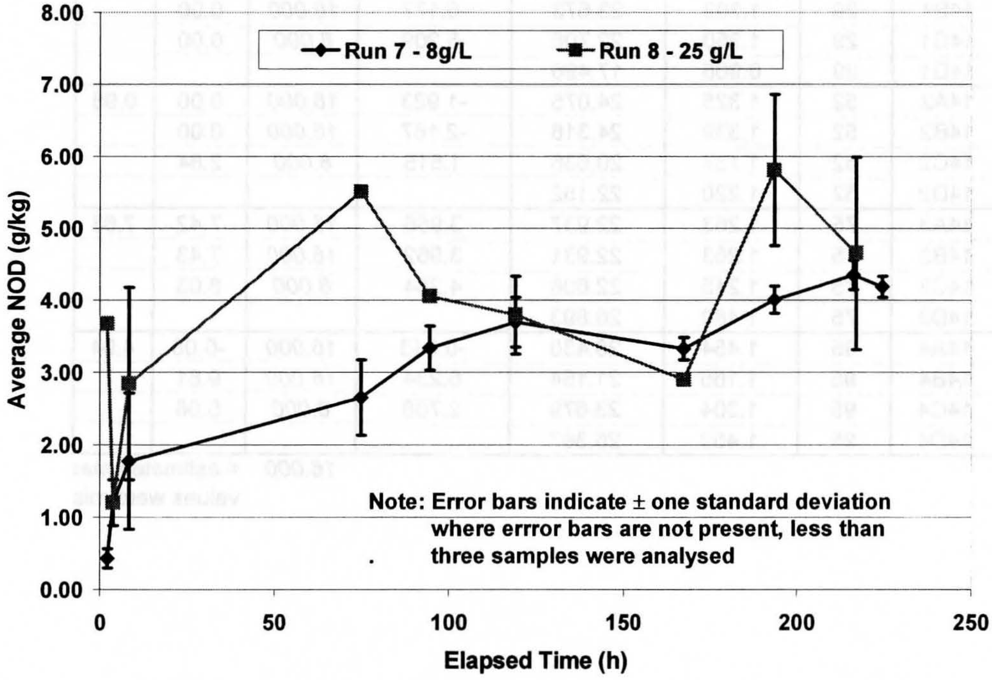


Figure B-2: Run 4 & 5 – MW302



Note: Error bars indicate ± one standard deviation where errror bars are not present, less than three samples were analysed

Figure B-3: Run 7 & 8 – MW311

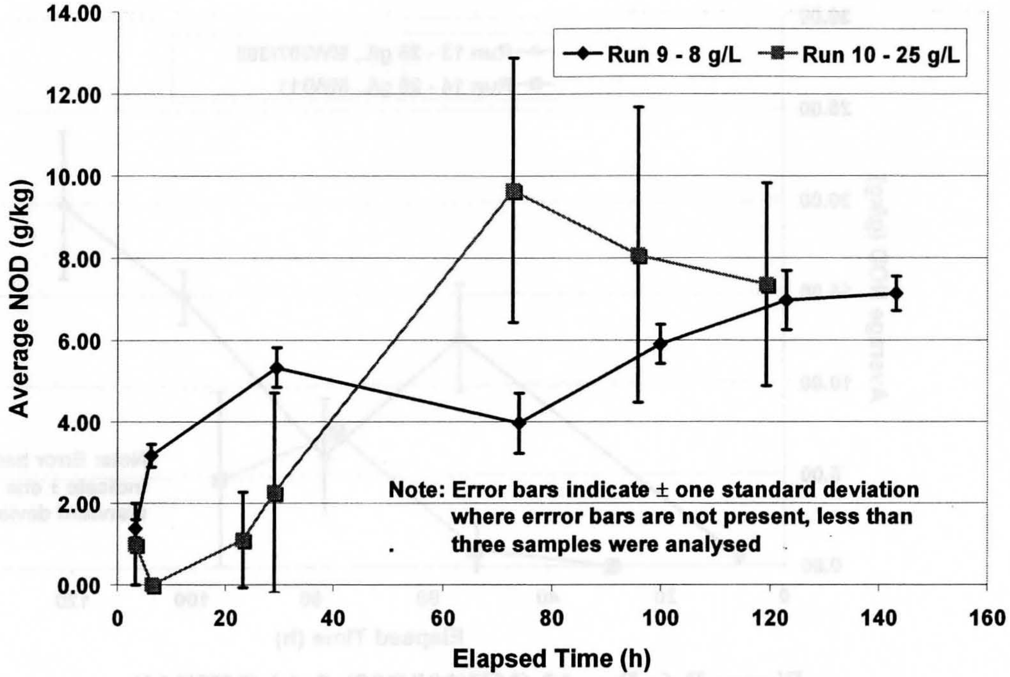


Figure B-4: Run 9 & 10 – MW303/304

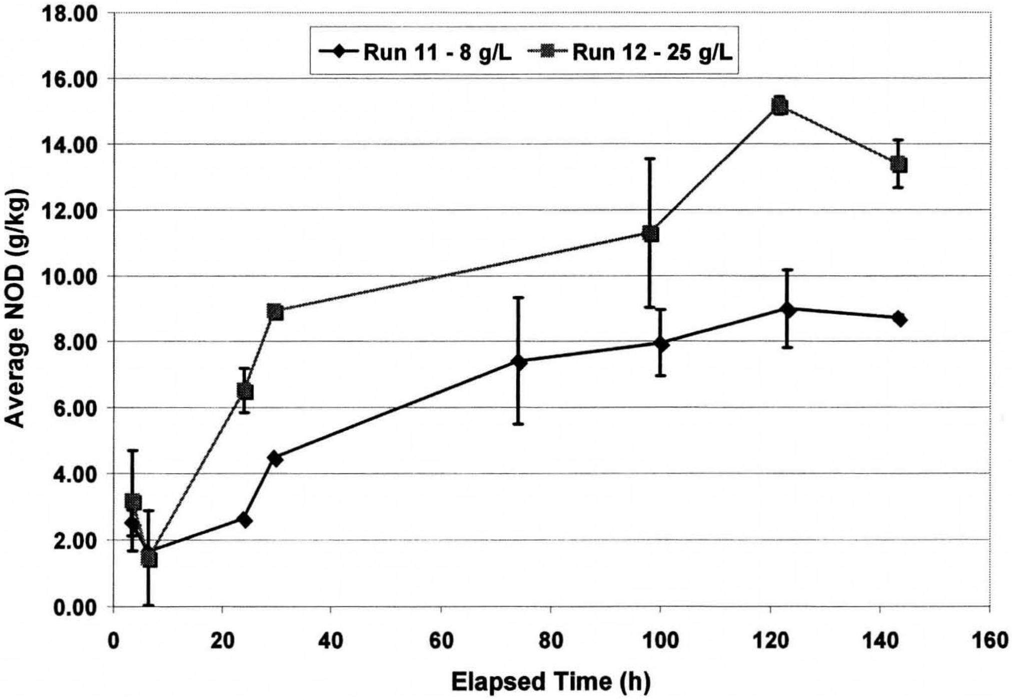


Figure B-5: Run 11 & 12 - MW305

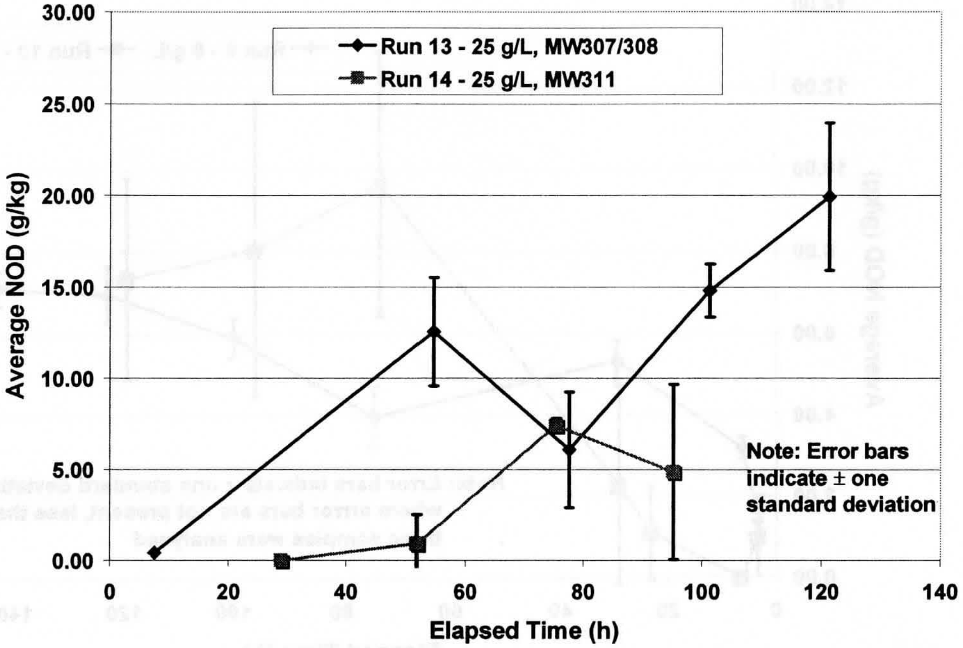


Figure B-6: Run 13 (MW307/308) & 14 (MW311)

Table B-7- Permanganate Mass Requirements for a 0.5 m^2 Cross-Section

Contaminant Mass	**Value & Units**	**Notes**
Estimated average Concentration of VC =	100 μg/L	
Unit Length of Injection Fence=	1 m	
Average Depth of Injection Points =	3.96 m	
Distance Perpendicular to Injection Fence =	0.5 m	
Estimated Porosity of Subsurface =	0.4	
Estimated Volume of Water =	0.79 m^3	
Estimated Mass of VC	0.08 g	
Stoichiometry		
Molar Mass of VC	62.50 g/mol	
Molar Mass of $KMnO_4$	158.01 g/mol	
Stoichiometric Relation between $KMnO_4$:VC	3.33 mol $KMnO_4$: mol VC	
Mol VC present	0.00 mol	
Mol $KMnO_4$ Required	0.00 mol	
Mass $KMnO_4$ Required to treat VC	0.67 g	
Aquifer Solids		
Estimated Bulk Density	1380 kg/m^3	Estimated from mass of soil sample per volume of reactor
Estimated Soil Volume	1.75 m^3	
Estimated Soil Mass	2415 kg	
Average NOD at 25 g/L	10 g/kg	
Mass $KMnO_4$ Required	24 kg	
Mass $KMnO_4$ Anticipated	5 kg	Based on approximately 25% of ultimate demand in flow through vs batch experiments as seen in literature column experiments

Appendix C: Delivery and Monitoring System Data

Table C-1 - Delivery Point Details

Delivery Point ID	Depth of Borehole (mbg)	Depth to Top Delivery Hole (mbg)	Depth of Bentonite Seal (mbg)	Number of Active Screens	Installation Notes
IP1	3.8	0.6		-	Wet from 1.2 to 2.4mbg; Hard packed layer from 2.7 to 3.7 mbg
IP2	4.0	0.4	0.2	-	
IP3	4.0	0.4	0.1	-	
IP4	3.8	0.2		18	
IP5	4.0	0.3	0.2	17	Bentonite seal collapsed to 0.66mbg; hole is sealed down to 0.84mbg
IP6	3.9	0.5	0.2	18	
IP7	4.0	0.2		17	
IP8	4.1	0.3		19	
IP10	5.2	0.4	0.2	-	Installed with 8" Auger. Direct push core collected
IP11	4.0	0.3	0.2	-	
IP12	4.0	0.5	0.2	-	
IP13	4.1	0.5		-	
IP14	4.2	0.3		19	
IP15	4.1	0.3		19	
IP16	4.0	0.4		19	
IP17	4.0	0.3		19	
IP18	3.9	0.3		19	
IP19	4.0	0.5		18	
IP20	4.0	0.3		19	
IP21	4.0	0.5		18	
IP22	4.0	0.3		19	
IP23	3.9	0.5		18	
IP24	4.0	0.5		18	
IP25	4.0	0.5		18	
IP26	4.0	0.5		18	
IP27	4.0	0.5		18	
IP28	4.0	0.3		19	Has coupling 1.8m above bottom
IP29	4.0	0.3		19	Has coupling 1.9m above bottom
IP30	4.0	0.5		-	Has coupling 0.2mbg

TableC-2 - Amendment Preparation Summary

Batch ID	Date Prepared	Volume	KMnO4 Added (g)	NaBr Added (g)	[KMnO4] g/L	[NaBr] g/L	Pump Reservoir
1	11-Apr-06	20		0			
2	13-Apr-06	20	Residue	0			A, B
3	17-Apr-06	20					
4	17-Apr-06	20	500	10	25	0.2	A, CD
5	21-Apr-06	20	750.2	15	38	0.6	A, B, CD
6	26-Apr-06	20	720	18	36	0.7	A, B
7	26-Apr-06	20	720	0	36	0.1	CD
8	01-May-06	20	720	10	36	1.0	A, B
9	04-May-06	20	720	20	36	0.8	CD
10	09-May-06	20	720	13	36	0.5	A, B
11	09-May-06	20	720	13	36	0.5	CD
12	12-May-06	20	720	19	36	0.7	A, B
13	12-May-06	20	600	20	30	0.7	A, B, C
14	18-May-06	20	720	20	36	0.7	A, B, C
15	23-May-06	20	720	20	36	0.8	A, B
16	29-May-06	20	720	20	36	0.8	A, B
17	01-Jun-06	20	720	20	36	0.8	A, B
18	02-Jun-06	20	720	20	36	0.8	C
19	02-Jun-06	20	720	20	36	0.8	A,B
20	06-Jun-06	20	720	20	36	0.7	A,B, C
21	09-Jun-06	20	720	20	36	0.8	A,B, C
22	12-Jun-06	20	720	20	36	0.8	A,B
23	12-Jun-06	20	720	20	36	0.8	C
24	15-Jun-06	20	720	20	36	0.8	A, B, C
25	20-Jun-06	20	840	20	42	0.7	A,B
26	20-Jun-06	20	840	20	42	0.8	C
27	23-Jun-06	20	840	20	42	0.8	A,B
28	27-Jun-06	20	840	20	42	0.8	A
29	27-Jun-06	20	840	20	42	0.8	B
30	29-Jun-06	20	840	20	42	0.8	C
31	-	-	-	-	-	0.8	
32	07-Jul-06	20	840	5	42	0.2	A, B, C
33	11-Jul-06	20	840	20	42	0.8	A
34	11-Jul-06	20	840	20	42	0.8	B
35	11-Jul-06	20	840	20	42	0.8	C
36	17-Jul-06	20	840	20	42	0.8	B
37	21-Jul-06	20	840	20	42	0.8	C, A
38	21-Jul-06	20	840	20	42	0.8	A
39	31-Jul-06	20	840	20	42	0.8	A
40	31-Jul-06	20	840	20	42	0.8	B, C
41	31-Jul-06	20	840	20	42	0.8	A, C
42	10-Aug-06	20	840	20	42	0.8	A, C
43	14-Aug-06	20	840	20	42	0.8	C, A
44	14-Aug-06	20	840	20	42	0.8	A, B, C
45	14-Aug-06	20	840	20	42	0.8	B, D
46	18-Aug-06	20	840	20	42	0.8	B, D
47	23-Aug-06	20	840	20	42	0.8	A, D
48	23-Aug-06	20	840	20	42	0.7	C
49	23-Aug-06	20	840	20	42	0.8	B
50	29-Aug-06	20	840	20	42	0.8	A, B, C
51	29-Aug-06	20	840	20	42	0.8	A, B, D
52	31-Aug-06	20	840	20	42	0.8	A, C
53	31-Aug-06	20	720	20	36	0.8	A, C, D
54	31-Aug-06	20	840	20	42	0.8	B, D
55	31-Aug-06	20	720	20	36	0.8	C
56	14-Sep-06	20	840	20	42	0.8	C
57	14-Sep-06	20	840	20	42	0.8	C
58	14-Sep-06	20	840	20	42	0.7	B
59	14-Sep-06	20	840	20	42	0.7	A
60	15-Sep-06	20	840	20	42	0.7	B, D
61	21-Sep-06	20	840	20	42	0.7	C
62	21-Sep-06	20	840	20	42	0.7	B, C
63	21-Sep-06	20	840	20	42	0.8	B, C
64	26-Sep-06	20	720	20	36	0.8	A, B
65	26-Sep-06	20	600	20	30	0.8	B, C
66	26-Sep-06	20	720	20	36	0.8	B, C
67		20	720	20	36	-	-
68		20	540	20	27	-	-
69		20	540	20	27	-	-
70		20	720	-	36	-	-

Total Used: 51 1223

Table C-3 Delivery Point Delivery Issues

IP	Date	Problem
IP1	01-Jun-06	Direct delivery commenced
	11-Jul-06	Leaks
	25-Jul-06	New T installed
IP2	23-May-06	leak
	1-Jun-06	No flow (to IP1 instead); leak; direct line installed
IP3 & IP4	23-May-06	No flow to IP4 (to IP3); typically flow to IP3 not IP4
IP5 & IP6	23-May-06	No flow to IP6 (to IP5); typically flow to IP5 not IP6
IP7	01-Jun-06	Direct delivery commenced
IP8	29-May-06	No flow to IP8 (to IP7 instead) from May 23 to May 29
	01-Jun-06	Direct line installed
	11-Jul-06	Small leak
IP10 & IP11	05-May-06	No flow to IP11; to IP10 instead
	23-May-06	No flow
IP12 & IP13	05-May-06	No flow to IP12 (to IP13 instead); typically flow to IP13 not IP12
	23-May-06	Leak at IP13
IP14	23-May-06	Leak (regularly leaking through the Fall)
	16-Jun-06	Added teflon straw
	25-Jul-06	New T installed
IP15	14-Apr-06	No flow to IP15 (to IP14 instead)
		Typically through June, July and August flow was to IP14
IP16	23-May-06	Leak
	11-Jul-06	Leak
	25-Jul-06	Leak
IP17	13-Apr-06	Disconnected due to leaks
	19-May-06	Reconnected
	01-Jun-06	Leaking
	15-Jun-06	Disconnected due to leaks; reconnected 16-Jun-06
	11-Jul-06	Leaking
	25-Jul-06	New T installed; regularly leaking through the fall
IP18&IP19	16-May-06	Flow stopped when Pump C turned off due to leaks
	15-Jun-06	T replaced and tightened; IPs reconnected
	19-Jun-06	Disconnected due to leaks
	25-Jul-06	Caps caulked, tightened; Flow returned
	27-Jul-06	Leaks continued; flow stopped
IP20	16-May-06	Flow stopped when Pump C turned off due to leaks
IP21- IP28	05-May-06	Most IPs leaking; tightened, replaced T's
	16-May-06	Leaks continued; Pumps C & D turned off
	25-Jul-06	Caps caulked, tightened; Flow returned to IP 21-25
	27-Jul-06	Leaks continued; Flow stopped, MLMW downgradient were generally nd for VC therefore no further attempt made to stop leaks and deliver amendment; will focus on IP1 through IP17
IP29 & IP30	13-Apr-06	Disconnected due to leaks

Note: **25-Jul-06 All caps caulked**

Table C-4 - MLMW Installation Details

Well ID	Depth of Borehole (mbg)	Screen Location (mbg)	Sand Pack Bottom (mbg)	Sand Pack Top (mbg)	Effective Screen Length (m)
301-1	3.58	1.13	1.30	0.91	0.38
301-2		1.72	1.98	1.42	0.56
301-3		2.35	2.51	2.13	0.38
301-4		2.89	3.10	2.69	0.41
301-5		3.56	3.58	3.25	0.33
302-1	3.76	1.20	1.42	0.91	0.51
302-2		1.79	2.06	1.60	0.46
302-3		2.53	2.67	2.24	0.43
302-4		3.22	3.28	2.84	0.43
302-5		3.78	3.76	3.43	0.33
303-1	3.86	1.31	1.40	0.89	0.51
303-2		1.96	2.01	1.55	0.46
303-3		2.68	2.72	2.26	0.46
303-4		3.33	3.43	2.87	0.56
303-5		4.09	3.86	3.61	0.25
304-1	3.94	1.36	1.50	0.94	0.56
304-2		2.08	2.16	1.65	0.51
304-3		2.86	2.72	2.31	0.41
304-4		3.39	3.40	2.82	0.58
304-5		4.00	3.94	3.58	0.36
305-1	3.73	1.15	1.27	0.91	0.36
305-2		1.79	1.93	1.42	0.51
305-3		2.51	2.54	2.08	0.46
305-4		3.19	3.25	2.64	0.61
305-5		3.86	3.73	3.40	0.33
306-1	4.06	1.40	1.70	1.19	0.51
306-2		2.07	2.26	1.85	0.41
306-3		2.76	2.88	2.44	0.44
306-4		3.44	3.56	3.05	0.51
306-5		4.12	4.06	3.76	0.30
307-1	3.81	1.23	1.42	0.91	0.51
307-2		1.93	2.03	1.57	0.46
307-3		2.55	2.57	2.18	0.38
307-4		3.20	3.30	2.84	0.46
307-5		3.93	3.81	3.45	0.36
308-1	3.96	1.37	1.52	1.04	0.48
308-2		1.96	2.21	1.75	0.46
308-3		2.74	2.90	2.41	0.48
308-4		3.44	3.51	3.05	0.46
308-5		3.75	3.96	3.66	0.30
309-1	3.76	1.00	1.40	0.91	0.48
309-2		1.65	1.98	1.55	0.43
309-3		2.30	2.59	2.13	0.46
309-4		2.97	3.23	2.77	0.46
309-5		3.67	3.76	3.38	0.38
310-1	3.96	1.39	1.55	1.07	0.48
310-2		2.07	2.29	1.70	0.58
310-3		2.74	2.87	2.44	0.43
310-4		3.40	3.51	3.02	0.48
310-5		4.10	3.96	3.66	0.30
311-1	6.10	1.29	1.80	1.07	0.74
311-2		2.30	3.00	1.96	1.04
311-3		3.62	4.22	3.20	1.02
311-4		4.84	5.26	4.42	0.84
311-5		5.68	6.10	5.49	0.61
312-1	3.96	-	1.35	0.81	0.53
312-2		-	2.01	1.56	0.44
312-3		-	2.69	2.16	0.53
312-4		-	3.38	2.84	0.53
312-5		-	3.84	3.53	0.30
313-1	3.66	0.93	1.07	0.61	0.46
313-2		1.49	1.65	1.22	0.43
313-3		2.19	2.29	1.85	0.43
313-4		2.91	3.10	2.44	0.66
313-5		3.65	3.58	3.25	0.33
314-1	3.81	0.99	1.14	0.71	0.43
314-2		1.68	1.83	1.27	0.56
314-3		2.36	2.44	1.98	0.46
314-4		3.08	3.07	2.59	0.48
314-5		3.78	3.61	3.25	0.36

Table C-5 - Preliminary MLMW Sample Results

Well ID	Sample Port	Date Collected	Min (ug/L)	Max (ug/L)	Average (ug/L)	# Samples
MW301						
301	4	02-Nov-05	nd	nd	nd	3
301	4	16-Nov-05	nd	39	39/nd	2
301	5	02-Nov-05	nd	nd	nd	3
301	5	16-Nov-05	<LOQ	24	<LOQ	2
MW302						
302	2	02-Nov-05	650	769	715	3
302	2	17-Nov-05	691	716	704	2
302	3	02-Nov-05	169	196	182	2
302	3	17-Nov-05	408	540	475	3
302	4	02-Nov-05	139	147	143	2
302	4	17-Nov-05	117	160	136	3
302	5	02-Nov-05	174	174	174	1
302	5	17-Nov-05	96	135	116	2
MW303						
303	1	17-Nov-05	29	34	31	2
303	2	17-Nov-05	219	327	280	3
303	3	02-Nov-05	299	299	299	1
303	3	17-Nov-05	161	168	164	2
303	4	02-Nov-05	307	458	382	2
303	4	17-Nov-05	433	496	465	2
303	5	02-Nov-05	76	76	76	1
303	5	17-Nov-05	67	69	68	2
MW304						
304	2	02-Nov-05	202	202	202	1
304	2	17-Nov-05	124	222	181	3
304	3	02-Nov-05	481	481	481	1
304	3	17-Nov-05	247	269	258	2
304	4	02-Nov-05	1408	1590	1499	2
304	4	17-Nov-05	1871	1994	1924	3
304	5	02-Nov-05	242	242	242	1
304	5	17-Nov-05	219	224	222	2
MW305						
305	1	17-Nov-05	13	14	14	2
305	2	17-Nov-05	32	36	34	2
305	3	02-Nov-05	<LOQ	<LOQ	<LOQ	1
305	3	17-Nov-05	31	40	36	3
305	4	02-Nov-05	90	90	90	1
305	4	17-Nov-05	82	82	82	1
305	5	02-Nov-05	50	50	50	1
305	5	17-Nov-05	nd	nd	nd	0
MW306						
306	1	17-Nov-05	<LOQ	<LOQ	<LOQ	2
306	3	17-Nov-05	<LOQ	<LOQ	<LOQ	2
306	4	02-Nov-05	<LOQ	<LOQ	<LOQ	2
306	4	17-Nov-05	<LOQ	<LOQ	<LOQ	2
306	5	02-Nov-05	<LOQ	<LOQ	<LOQ	1
306	5	17-Nov-05	nd	nd	nd	2
MW307						
307	1	17-Nov-05	nd	nd	nd	2
307	2	17-Nov-05	nd	nd	nd	2
307	3	03-Nov-05	nd	nd	nd	1
307	3	17-Nov-05	nd	nd	nd	2
307	4	03-Nov-05	<LOQ	<LOQ	<LOQ	1
307	4	16-Nov-05	nd	nd	nd	2
307	5	03-Nov-05	nd	nd	nd	1
307	5	16-Nov-05	nd	nd	nd	2

nd = not detected above MDL (2.5 µg/L)

<LOQ = detected above MDL but below LOQ of 10 µg/L

Table C-5 continued - Preliminary MLMW Sample Results

MW308						
308	1	16-Nov-05	nd	nd	nd	2
308	2	03-Nov-05	<LOQ	<LOQ	<LOQ	1
308	2	16-Nov-05	<LOQ	<LOQ	<LOQ	2
308	3	16-Nov-05	<LOQ	<LOQ	<LOQ	2
308	4	03-Nov-05	<LOQ	<LOQ	<LOQ	1
308	5	03-Nov-05	<LOQ	<LOQ	<LOQ	1
308	5	16-Nov-05	nd	<LOQ	<LOQ	2
MW309						
309	1	16-Nov-05	nd	nd	nd	2
309	2	16-Nov-05	nd	nd	nd	2
309	3	16-Nov-05	<LOQ	<LOQ	<LOQ	2
309	4	03-Nov-05	nd	nd	nd	1
309	4	16-Nov-05	nd	<LOQ	nd	2
309	5	03-Nov-05	nd	nd	nd	2
309	5	16-Nov-05	nd	nd	nd	2
MW310						
310	3	03-Nov-05	nd	nd	nd	1
310	3	16-Nov-05	nd	nd	nd	2
310	4	03-Nov-05	nd	nd	nd	1
310	4	16-Nov-05	nd	<LOQ	nd	2
310	5	03-Nov-05	nd	nd	nd	1
310	5	16-Nov-05	nd	<LOQ	nd	2
MW311						
311	2	03-Nov-05	20	20	20	1
311	2	18-Nov-05	455	481	468	2
311	3	03-Nov-05	16	16	16	1
311	3	18-Nov-05	14	61	41	3
311	4	03-Nov-05	16	16	16	1
311	4	18-Nov-05	<LOQ	12	11	2
MW312						
312	2	11-Nov-05	nd	nd	nd	1
312	3	11-Nov-05	nd	nd	nd	1
312	4	11-Nov-05	nd	nd	nd	1
312	5	11-Nov-05	nd	nd	nd	1
MW313						
313	2	18-Nov-05	125	149	137	2
313	3	18-Nov-05	220	238	229	2
313	4	03-Nov-05	194	194	194	1
313	4	18-Nov-05	283	341	312	2
313	5	03-Nov-05	25	25	25	1
313	5	18-Nov-05	23	24	24	2
MW314						
314	2	11-Nov-05	na	na	na	1
314	2	18-Nov-05	12	19	15	2
314	3	03-Nov-05	76	91	84	2
314	3	18-Nov-05	75	81	78	2
314	4	03-Nov-05	801	865	833	2
314	4	18-Nov-05	1293	1444	1369	2
314	5	03-Nov-05	433	433	433	1
314	5	18-Nov-05	675	802	739	2

nd = not detected above MDL (2.5 μg/L)
<LOQ = detected above MDL but below LOQ of 10 μg/L

Table C-6: Chloride, Bromide, and $KMnO_4$ Sample Results

Sample Details			Chloride			Bromide				$KMnO_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
BH208												
208		24-Apr-06	489	489	489	1.1	1.1	1.1	1	No	-	-
208		4-May-06	488	484	490	1.0	0.9	1.0	4	No	-	-
208		16-May-06	483	482	485	1.0	1.0	1.0	3	No	-	-
208		19-May-06	464	463	466	1.2	1.2	1.2	2	No	-	-
208		6-Jun-06	484	476	491	2.3	2.3	2.4	3	No	-	-
208		12-Jun-06	505	500	512	3.0	2.9	3.1	3	No	-	-
208		16-Jun-06	526	520	536	3.6	3.4	3.9	3	No	-	-
208		21-Jun-06	495	492	497	4.8	4.5	4.9	3	No	-	-
208		7-Jul-06	505	505	505	6.2	6.2	6.2	1	No	-	-
208		17-Jul-06	512	499	516	7.2	7.1	7.3	6	No	-	-
208		10-Aug-06	511	510	513	11	11	11	3	No	-	-
208		21-Aug-06	529	528	529	12	12	12	2	No	-	-
208		15-Sep-06	541	529	547	15	14	16	5	No	-	-
208		29-Sep-06	516	507	525	26	23	31	5	Yes	light pink	0.02
208		10-Oct-06	532	532	532	22	22	22	1	Yes	pink	0.02
208		10-Nov-06								Yes	pink	-
208		20-Nov-06								Yes	pink	-
MW301												
301	4	16-Nov-05	976	972	977	-	-	-	3	No	-	-
301	4	20-Nov-06										
301	5	2-Nov-05	318	315	322	-	-	-	2	No	-	-
301	5	16-Nov-05	303	303	303	-	-	-	1	No	-	-
301	5	20-Nov-06								No	-	-
MW302												
302	1	19-Jan-06	735	728	748	0.4	nd	0.6	3	No	-	-
302	1	24-Apr-06	177	176	178	0.4	0.4	0.5	2	No	-	-
302	1	4-May-06	163	163	163	nd	nd	nd	1	No	-	-
302	1	9-May-06	157	157	157	1.3	1.3	1.3	1	No	-	-
302	1	16-May-06	137	137	137	4.0	4.0	4.1	2	No	-	-
302	1	19-May-06	137	136	138	6.3	6.2	6.3	2	No	-	-
302	1	29-May-06	132	132	132	13	13	13	1	No	-	-
302	1	2-Jun-06	136	136	136	16	16	16	1	No	-	-
302	1	6-Jun-06	131	131	131	19	19	19	1	No	-	-
302	1	12-Jun-06	126	126	126	24	24	24	1	No	-	-
302	1	21-Jun-06	112	112	112	43	43	42	1	No	-	-
302	1	29-Jun-06	133	132	134	68	68	68	3	No	-	-
302	1	7-Jul-06	120	120	120	132	132	133	2	No	-	-
302	1	27-Jul-06	102	100	104	191	188	195	3	No	-	-
302	1	21-Aug-06	78	77	79	193	191	195	2	No	-	-
302	1	15-Sep-06	68	68	68	166	165	168	2	No	-	-
302	1	29-Sep-06	61	60	61	147	146	149	2	No	-	-
302	1	10-Oct-06	49	49	49	120	120	120	1	No	-	-
302	1	15-Nov-06								No	-	-
302	2	2-Nov-05	754	748	758	0.4	nd	0.6	6	No	-	-
302	2	17-Nov-05	797	794	799	0.4	0.4	0.5	2	No	-	-
302	2	19-Jan-06	948	948	948	0.8	0.8	0.8	1	No	-	-
302	2	2-Feb-06	377	377	377	-	-	-	1	No	-	-
302	2	19-Apr-06	333	333	333	0.7	0.6	0.7	3	No	-	-
302	2	24-Apr-06	342	341	344	0.6	0.5	0.6	2	No	-	-
302	2	4-May-06	356	356	356	nd	nd	nd	1	No	-	-
302	2	9-May-06	360	360	360	nd	nd	nd	1	No	-	-
302	2	16-May-06	345	345	345	0.4	0.4	0.4	1	No	-	-
302	2	19-May-06	329	329	330	nd	nd	0.4	2	No	-	-
302	2	29-May-06	337	337	337	0.7	0.7	0.7	1	No	-	-
302	2	6-Jun-06	349	347	351	1.4	1.4	1.4	2	No	-	-
302	2	21-Jun-06	341	341	341	4.8	4.8	4.8	1	No	-	-
302	2	29-Jun-06	341	340	342	6.6	6.6	6.7	2	No	-	-
302	2	7-Jul-06	331	331	331	11	11	12	2	No	-	-
302	2	17-Jul-06	356	353	358	25	25	25	2	No	-	-
302	2	27-Jul-06	323	323	323	54	54	54	1	No	-	-
302	2	10-Aug-06	302	302	302	91	91	91	1	No	-	-
302	2	21-Aug-06	303	303	303	101	101	101	1	No	-	-
302	2	15-Sep-06	285	282	289	117	116	118	2	No	-	-
302	2	29-Sep-06								No	orange ppt	-
302	2	10-Oct-06	232	231	233	147	144	149	2	No	yellow	-

Table C-6 continued: Chloride, Bromide, and $KMnO_4$ Sample Results

Sample Details			Chloride			Bromide				$KMnO_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
302	2	15-Nov-06							1	Yes	dark pink	0.12
302	3	2-Nov-05	867	864	871	0.7	0.7	0.7	4	No	-	-
302	3	17-Nov-05	856	856	856	0.6	0.6	0.6	1	No	-	-
302	3	2-Feb-06	576	576	576	0.0	0.0	0.0	1	No	-	-
302	3	19-Apr-06	445	445	446	0.5	0.5	0.5	2	No	-	-
302	3	24-Apr-06	455	450	460	0.5	0.4	0.5	2	No	-	-
302	3	4-May-06	476	476	476	0.4	0.4	0.4	1	No	-	-
302	3	9-May-06	444	444	444	0.5	0.5	0.5	1	No	-	-
302	3	16-May-06	399	399	399	0.6	0.6	0.6	1	No	-	-
302	3	19-May-06	389	380	399	0.9	0.8	1.1	2	No	-	-
302	3	29-May-06	404	404	404	1.3	1.3	1.3	1	No	-	-
302	3	2-Jun-06	403	402	405	1.4	1.3	1.4	2	No	-	-
302	3	6-Jun-06	376	376	376	2.2	2.2	2.2	1	No	-	-
302	3	12-Jun-06	375	375	375	3.0	3.0	3.0	1	No	-	-
302	3	21-Jun-06	374	368	380	4.0	3.8	4.1	2	No	-	-
302	3	29-Jun-06	396	393	402	4.4	4.2	4.5	3	No	-	-
302	3	7-Jul-06	349	349	349	15	15	15	1	No	-	-
302	3	27-Jul-06	301	301	301	82	82	82	1	No	-	-
302	3	21-Aug-06	355	355	355	58	58	58	1	No	-	-
302	3	15-Sep-06	397	395	399	39	39	39	2	No	-	-
302	3	29-Sep-06	394	394	394	34	34	34	1	No	-	-
302	3	10-Oct-06	376	375	377	40	40	40	3	No	-	-
302	3	15-Nov-06	370	370	370	43	43	43	1	No	-	-
302	4	2-Nov-05	900	899	900	1.0	1.0	1.1	4	No	-	-
302	4	17-Nov-05	900	899	901	0.9	0.9	1.0	2	No	-	-
302	4	19-Jan-06	938	938	938	1.1	1.1	1.1	1	No	-	-
302	4	2-Feb-06	621	621	621	nd	nd	nd	1	No	-	-
302	4	19-Apr-06	537	532	541	0.7	0.7	0.8	2	No	-	-
302	4	24-Apr-06	566	564	568	0.8	0.8	0.8	2	No	-	-
302	4	4-May-06	589	589	589	0.6	0.6	0.6	1	No	-	-
302	4	9-May-06	585	585	585	0.6	0.6	0.6	1	No	-	-
302	4	16-May-06	546	546	546	0.7	0.7	0.7	1	No	-	-
302	4	19-May-06	488	486	489	0.6	0.5	0.6	3	No	-	-
302	4	29-May-06	497	496	499	0.6	0.6	0.6	2	No	-	-
302	4	2-Jun-06	514	514	514	0.7	0.7	0.7	1	No	-	-
302	4	6-Jun-06	504	504	504	0.7	0.7	0.7	1	No	-	-
302	4	12-Jun-06	509	509	509	0.7	0.7	0.7	1	No	-	-
302	4	21-Jun-06	512	510	514	1.1	1.1	1.1	2	No	-	-
302	4	29-Jun-06	530	528	531	1.3	1.3	1.3	2	No	-	-
302	4	7-Jul-06	532	532	532	2.0	2.0	2.0	1	No	-	-
302	4	17-Jul-06	381	381	382	38	37	38	2	No	-	-
302	4	27-Jul-06	380	380	380	61	61	61	1	No	-	-
302	4	10-Aug-06	434	434	434	46	46	46	1	No	-	-
302	4	21-Aug-06	472	472	473	40	40	40	2	No	-	-
302	4	15-Sep-06	560	551	570	32	30	34	2	No	-	-
302	4	29-Sep-06	568	565	571	27	27	27	2	No	-	-
302	4	10-Oct-06	588	588	588	26	26	26	1	No	-	-
302	5	2-Nov-05	1025	1020	1030	0.8	0.7	0.9	4	No	-	-
302	5	17-Nov-05	997	996	999	0.7	0.7	0.7	3	No	-	-
302	5	2-Feb-06	723	723	723	0.4	0.4	0.4	1	No	-	-
302	5	19-Apr-06	823	822	825	1.0	0.9	1.1	2	No	-	-
302	5	24-Apr-06	903	902	904	1.2	1.2	1.2	2	No	-	-
302	5	4-May-06	906	906	906	0.9	0.9	0.9	1	No	-	-
302	5	9-May-06	848	848	848	0.9	0.9	0.9	1	No	-	-
302	5	16-May-06	763	760	765	0.9	0.8	1.0	2	No	-	-
302	5	19-May-06	723	723	724	0.9	0.9	0.9	2	No	-	-
302	5	29-May-06	752	752	752	1.1	1.1	1.1	1	No	-	-
302	5	2-Jun-06	831	831	831	1.0	1.0	1.0	1	No	-	-
302	5	6-Jun-06	768	768	768	1.0	1.0	1.0	1	No	-	-
302	5	12-Jun-06	791	787	796	1.3	1.3	1.4	2	No	-	-
302	5	21-Jun-06	793	793	793	1.3	1.3	1.3	1	No	-	-
302	5	29-Jun-06	846	842	849	2.0	1.9	2.0	2	No	-	-
302	5	7-Jul-06	793	792	793	2.2	2.1	2.2	3	No	-	-
302	5	17-Jul-06	659	659	659	2.2	2.2	2.3	2	No	-	-
302	5	27-Jul-06	755	755	755	7.9	7.9	7.9	1	No	-	-
302	5	10-Aug-06	749	749	749	8.7	8.7	8.7	1	No	-	-

Table C-6 continued: Chloride, Bromide, and KMnO$_4$ Sample Results

Sample Details			Chloride			Bromide				KMnO$_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
302	5	21-Aug-06	769	769	769	7.9	7.9	7.9	1	No	-	-
302	5	15-Sep-06	859	851	867	8.3	8.0	8.5	2	No	-	-
302	5	10-Oct-06	948	948	948	14	14	14	1	No	-	-
MW303												
303	1	17-Nov-05	166	166	167	nd	nd	nd	2	No	-	-
303	1	2-Feb-06	58	58	58	nd	nd	nd	1	No	-	-
303	1	31-Mar-06	88	88	88	nd	nd	nd	2	No	-	-
303	1	24-Apr-06	192	191	193	0.4	0.4	0.4	2	No	-	-
303	1	28-Apr-06	90	90	91	20	19	20	3	No	-	-
303	1	9-May-06	427	427	427	22	22	22	1	No	-	-
303	1	16-May-06	359	359	359	29	29	29	1	No	-	-
303	1	29-May-06	189	189	189	61	61	61	1	No	-	-
303	1	2-Jun-06	237	236	238	52	51	52	2	No	-	-
303	1	6-Jun-06	346	346	346	48	48	48	1	Yes	med pink	0.08
303	1	12-Jun-06								Yes	purple	1.92
303	1	21-Jun-06								Yes	dark purple	-
303	1	29-Jun-06								Yes	dark purple	4.09
303	1	7-Jul-06	281	281	281	175	175	175	1	Yes	purple	7.52
303	1	27-Jul-06								Yes	purple	-
303	1	10-Aug-06								Yes	dark pink	-
303	1	21-Aug-06	100	100	101	172	171	173	2	Yes	dark pink	1.23
303	1	10-Oct-06	67	67	67	83	83	83	1	Yes	dark pink	0.78
303	1	15-Nov-06								Yes	light purple	0.79
303	2	17-Nov-05	388	386	390	nd	nd	nd	2	No	-	-
303	2	19-Jan-06	252	252	252	nd	nd	nd	2	No	-	-
303	2	2-Feb-06	118	118	118	nd	nd	nd	1	No	-	-
303	2	24-Apr-06	272	270	274	0.5	0.4	0.6	3	No	-	-
303	2	28-Apr-06	227	223	230	1.3	1.2	1.4	2	No	-	-
303	2	4-May-06	235	235	235	18	18	18	1	Yes	dark pink	-
303	2	9-May-06	414	414	414	26	26	26	1	Yes	dark pink	-
303	2	16-May-06	457	457	457	34	34	34	1	Yes	dark pink	-
303	2	29-May-06	222	222	222	46	46	46	1	No	yellow	-
303	2	2-Jun-06	380	376	384	33	32	33	2	No	-	-
303	2	6-Jun-06	266	266	266	62	62	62	1	Yes	purple	0.63
303	2	12-Jun-06								Yes	purple	1.66
303	2	21-Jun-06								Yes	dark purple	-
303	2	29-Jun-06								Yes	dark purple	3.03
303	2	7-Jul-06	233	233	233	243	243	243	1	Yes	purple	-
303	2	12-Jul-06								Yes	purple	5.11
303	2	27-Jul-06	496	496	496	220	220	220	1	Yes	purple	-
303	2	10-Aug-06								Yes	purple	-
303	2	21-Aug-06	90	90	90	153	153	153	1	Yes	dark purple	2.19
303	2	10-Oct-06								Yes	dark purple	1.85
303	2	15-Nov-06								Yes	dark purple	1.10
303	3	2-Nov-05	852	847	855	nd	nd	nd	3	No	-	-
303	3	17-Nov-05	717	713	726				3	No	-	-
303	3	2-Feb-06	315	315	315	nd	nd	nd	1	No	-	-
303	3	28-Apr-06	251	249	252	0.4	nd	0.6	2	No	-	-
303	3	4-May-06	262	262	262	9.0	9.0	9.0	1	Yes	med pink	-
303	3	9-May-06	319	319	319	11	11	11	1	Yes	dark pink	-
303	3	16-May-06	372	372	372	23	23	23	1	Yes	dark pink	-
303	3	29-May-06	359	359	359	23	23	23	1	No	clear	-
303	3	2-Jun-06	377	377	377	25	25	25	1	No	-	-
303	3	6-Jun-06	340	340	340	32	32	32	1	Yes	light purple	0.15
303	3	12-Jun-06								Yes	dark pink	0.20
303	3	21-Jun-06								Yes	purple	-
303	3	29-Jun-06	302	302	302	93	92	94	2	Yes	purple	0.72
303	3	7-Jul-06	297	297	297	125	125	125	1	Yes	light purple	1.15
303	3	27-Jul-06								Yes	purple	-
303	3	10-Aug-06								Yes	purple	-
303	3	21-Aug-06	207	206	209	158	157	159	2	Yes	purple	1.28
303	3	10-Oct-06								Yes	purple	0.95
303	3	15-Nov-06								Yes	dark pink	0.17
303	4	2-Nov-05	854	722	990				4	No	-	-
303	4	17-Nov-05	1076	1076	1076	0.9	0.9	0.9	1	No	-	-
303	4	19-Jan-06								No	-	-

Table C-6 continued: Chloride, Bromide, and KMnO$_4$ Sample Results

Sample Details			Chloride			Bromide				KMnO$_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
303	4	31-Mar-06	704	703	704	0.7	0.6	0.8	2	No	-	-
303	4	24-Apr-06	535	534	537	0.7	0.6	0.8	3	No	-	-
303	4	28-Apr-06	497	497	497	0.8	0.8	0.8	1	No	-	-
303	4	4-May-06	461	461	461	0.4	0.4	0.4	1	No	-	-
303	4	9-May-06	444	442	445	3.7	3.4	3.9	2	No	-	-
303	4	16-May-06	415	415	415	14	14	14	1	Yes	light pink	-
303	4	29-May-06	416	416	416	16	16	16	1	No	orange	-
303	4	2-Jun-06	407	407	407	19	19	19	1	No	clear	-
303	4	6-Jun-06	367	367	367	27	27	27	1	Yes	dark pink	0.09
303	4	12-Jun-06	332	332	332	37	37	37	1	Yes	dark pink	0.18
303	4	21-Jun-06								Yes	purple	-
303	4	29-Jun-06	363	362	364	56	55	56	2	Yes	dark pink	0.26
303	4	7-Jul-06	378	378	378	69	69	69	1	Yes	dark pink	0.30
303	4	27-Jul-06								Yes	dark pink	-
303	4	10-Aug-06								Yes	light purple	-
303	4	21-Aug-06	323	323	323	125	125	125	1	Yes	pink	0.13
303	4	10-Oct-06	255	255	256	151	150	152	2	Yes	purple	0.61
303	4	15-Nov-06								Yes	dark pink	0.17
303	5	2-Nov-05	657	651	664	0.7	0.7	0.7	1	No	-	-
303	5	17-Nov-05	695	695	695	0.9	0.9	0.9	1	No	-	-
303	5	2-Feb-06	849	849	849	0.7	0.7	0.7	1	No	-	-
303	5	24-Apr-06	855	855	855	1.2	1.2	1.3	2	No	-	-
303	5	28-Apr-06	836	835	837	1.2	1.1	1.3	2	No	-	-
303	5	4-May-06	837	837	837	0.8	0.8	0.8	1	No	-	-
303	5	9-May-06	835	835	835	1.0	1.0	1.0	1	No	-	-
303	5	16-May-06	847	832	875	1.0	0.9	1.2	3	No	-	-
303	5	29-May-06	769	769	769	1.2	1.2	1.2	1	No	-	-
303	5	2-Jun-06	779	779	779	1.1	1.1	1.1	1	No	-	-
303	5	6-Jun-06	777	777	777	1.2	1.2	1.2	1	No	-	-
303	5	12-Jun-06	774	774	774	1.0	1.0	1.0	1	No	-	-
303	5	21-Jun-06	767	767	767	0.9	0.9	0.9	1	No	-	-
303	5	29-Jun-06	779	779	779	1.0	1.0	1.0	1	No	-	-
303	5	7-Jul-06	773	773	773	1.1	1.1	1.1	1	No	-	-
303	5	27-Jul-06	769	764	778	2.1	2.0	2.2	3	No	-	-
303	5	10-Aug-06	764	764	764	2.9	2.9	2.9	1	No	yellow	-
303	5	21-Aug-06	752	749	755	12	12	12	3	No	clear	-
303	5	10-Oct-06	707	706	708	49	49	49	2	Yes	faint pink	nd
303	5	15-Nov-06								Yes	light pink	0.02
MW304												
304	1	2-Feb-06	67	67	67	nd	nd	nd	1	No	-	-
304	1	28-Apr-06	52	52	52	nd	nd	nd	1	No	-	-
304	1	4-May-06	64	64	64	0.0	0.0	nd	1	No	-	-
304	1	9-May-06	69	69	69	0.0	nd	nd	1	No	-	-
304	1	16-May-06	57	57	57	0.5	0.5	0.5	1	No	-	-
304	1	29-May-06	44	44	44	1.2	1.2	1.2	1	No	-	-
304	1	2-Jun-06	47	47	47	1.1	1.1	1.1	1	No	-	-
304	1	6-Jun-06	44	44	44	1.7	1.7	1.7	1	No	-	-
304	1	12-Jun-06	46	46	46	1.9	1.8	2.0	3	No	-	-
304	1	21-Jun-06	55	55	55	6.0	6.0	6.0	1	No	-	-
304	1	29-Jun-06	56	56	56	18	18	18	1	No	-	-
304	1	27-Jul-06	59	59	59	35	35	35	1	No	-	-
304	1	10-Oct-06	90	89	91	84	82	85	3	No	-	-
304	1	15-Nov-06	46	46	46	49	49	49	1	No	-	-
304	2	2-Nov-05	788	787	789	0.6	0.5	0.6	2	No	-	-
304	2	17-Nov-05	724	723	726	0.4	0.4	0.4	1	No	-	-
304	2	2-Feb-06	107	107	107	0.0	0.0	0.0	1	No	-	-
304	2	24-Apr-06	193	191	194	0.4	0.3	0.5	4	No	-	-
304	2	28-Apr-06	187	187	187	0.2	0.2	0.3	2	No	-	-
304	2	4-May-06	223	223	223	0.3	0.3	0.3	1	No	-	-
304	2	9-May-06	236	236	236	0.4	0.4	0.4	1	No	-	-
304	2	16-May-06	198	198	198	0.3	0.3	0.3	1	No	-	-
304	2	29-May-06	185	185	186	0.4	0.4	0.4	2	No	-	-
304	2	2-Jun-06	172	172	172	0.5	0.5	0.5	1	No	-	-
304	2	6-Jun-06	148	148	149	0.9	0.8	1.0	2	No	-	-
304	2	12-Jun-06	184	184	184	1.3	1.3	1.3	1	No	-	-
304	2	21-Jun-06	202	202	202	3.8	3.8	3.8	2	No	-	-

Table C-6 continued: Chloride, Bromide, and $KMnO_4$ Sample Results

Sample Details			Chloride			Bromide				$KMnO_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
304	2	29-Jun-06	217	217	217	5.8	5.8	5.8	1	No	-	-
304	2	7-Jul-06	204	198	211	13	12	13	2	No	-	-
304	2	17-Jul-06	180	179	181	34	34	34	3	No	-	-
304	2	27-Jul-06	174	174	174	34	34	34	1	No	-	-
304	2	10-Oct-06	201	200	201	66	65	67	2	No	-	-
304	2	15-Nov-06	239	239	239	35	35	35	1	No	-	-
304	3	2-Nov-05	696	392	852				3	No	-	-
304	3	17-Nov-05	823	821	824	0.0	0.0	0.0	3	No	-	-
304	3	23-Mar-06	288	288	288	0.5	0.5	0.5	1	No	-	-
304	3	24-Apr-06	279	277	280	0.8	0.7	0.9	2	No	-	-
304	3	28-Apr-06	271	271	271	0.5	0.5	0.5	1	No	-	-
304	3	29-Apr-06	280	280	280	0.4	0.4	0.4	1	No	-	-
304	3	4-May-06	280	280	280	0.3	0.3	0.3	1	No	-	-
304	3	9-May-06	292	292	292	0.4	0.4	0.4	1	No	-	-
304	3	16-May-06	285	285	285	0.4	0.4	0.4	1	No	-	-
304	3	29-May-06	264	264	264	0.6	0.6	0.6	1	No	-	-
304	3	6-Jun-06	272	272	272	1.0	1.0	1.0	1	No	-	-
304	3	12-Jun-06	263	263	263	1.2	1.2	1.2	1	No	-	-
304	3	29-Jun-06	282	282	283	3.4	3.2	3.6	3	No	-	-
304	3	7-Jul-06	286	286	286	5.8	5.8	5.8	1	No	-	-
304	3	17-Jul-06	258	257	258	23	23	23	2	No	-	-
304	3	27-Jul-06	251	250	251	28	27	28	2	No	-	-
304	3	10-Oct-06	257	256	258	84	83	84	2	No	-	-
304	3	15-Nov-06	249	249	249	68	68	68	1	No	-	-
304	4	2-Nov-05	914	914	914	1.3	1.3	1.3	1	No	-	-
304	4	17-Nov-05	883	881	884	1.1	1.0	1.2	2	No	-	-
304	4	2-Feb-06	628	628	628	0.6	0.6	0.6	1	No	-	-
304	4	28-Apr-06	473	473	473	0.9	0.9	0.9	1	No	-	-
304	4	4-May-06	456	455	457	0.6	0.6	0.7	2	No	-	-
304	4	9-May-06	446	446	446	0.7	0.7	0.7	1	No	-	-
304	4	16-May-06	434	434	434	0.8	0.8	0.8	1	No	-	-
304	4	29-May-06	425	425	425	0.8	0.8	0.8	1	No	-	-
304	4	2-Jun-06	404	404	404	0.5	0.5	0.5	1	No	-	-
304	4	6-Jun-06	398	396	399	0.6	0.6	0.6	2	No	-	-
304	4	12-Jun-06	386	386	386	0.6	0.6	0.6	1	No	-	-
304	4	21-Jun-06	376	376	376	0.6	0.6	0.6	1	No	-	-
304	4	29-Jun-06	390	386	397	0.8	0.7	0.8	3	No	-	-
304	4	7-Jul-06	387	384	391	1.0	1.0	1.0	3	No	-	-
304	4	17-Jul-06	393	392	394	1.4	1.4	1.4	2	No	-	-
304	4	27-Jul-06	382	380	384	3.0	2.9	3.0	2	No	-	-
304	4	10-Oct-06	349	344	352	44	43	45	3	No	-	-
304	4									No	-	-
304	5	2-Nov-05	678	678	678	1.1	1.1	1.1	1	No	-	-
304	5	17-Nov-05	620	617	623	1.0	0.9	1.0	2	No	-	-
304	5	2-Feb-06	637	636	638	0.7	0.6	0.7	2	No	-	-
304	5	23-Mar-06	667	667	668	0.8	0.8	0.8	2	No	-	-
304	5	24-Apr-06	671	665	676	1.0	1.0	1.0	2	No	-	-
304	5	28-Apr-06	701	701	701	1.0	1.0	1.0	1	No	-	-
304	5	4-May-06	705	705	705	0.8	0.8	0.8	1	No	-	-
304	5	9-May-06	699	699	699	0.9	0.9	0.9	1	No	-	-
304	5	16-May-06	728	728	728	1.4	1.4	1.4	1	No	-	-
304	5	29-May-06	607	607	607	3.4	3.4	3.4	1	No	-	-
304	5	2-Jun-06	638	638	638	3.2	3.2	3.2	1	No	-	-
304	5	6-Jun-06	568	568	568	3.4	3.3	3.4	2	No	-	-
304	5	12-Jun-06	623	623	623	3.2	3.2	3.2	1	No	-	-
304	5	21-Jun-06	641	641	641	3.2	3.2	3.2	1	No	-	-
304	5	29-Jun-06	674	669	679	3.5	3.4	3.6	3	No	-	-
304	5	7-Jul-06	692	692	692	4.3	4.3	4.3	1	No	-	-
304	5	17-Jul-06	679	679	680	7.9	7.7	8.0	2	No	-	-
304	5	27-Jul-06	695	695	695	6.7	6.7	6.7	1	No	-	-
304	5	10-Oct-06	662	659	664	47	47	47	3	No	-	-
304	5	15-Nov-06	480	480	480	54	54	54	1	No	-	-
MW305												
305	1	17-Nov-05	66	66	66	nd	nd	nd	1	No	-	-
305	1	12-Jan-06	165	165	165	0.3	0.3	0.3	1	No	-	-
305	1	2-Feb-06	127	123	130	0.3	0.3	0.3	1	No	-	-

Table C-6 continued: Chloride, Bromide, and $KMnO_4$ Sample Results

Sample Details			Chloride			Bromide				$KMnO_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
305	1	19-Apr-06	147	147	147	0.4	0.4	0.5	3	No	-	-
305	1	28-Apr-06	140	140	140	0.2	0.2	0.2	1	No	-	-
305	1	4-May-06	162	162	162	0.5	0.5	0.5	1	No	-	-
305	1	19-May-06	70	69	70	4.0	3.8	4.2	3	No	-	-
305	1	29-May-06	122	122	123	4.8	4.8	4.8	2	No	-	-
305	1	2-Jun-06	101	101	101	28	28	28	1	No	-	-
305	1	6-Jun-06	106	106	106	31	31	31	1	No	-	-
305	1	12-Jun-06	159	159	159	21	21	21	1	No	-	-
305	1	21-Jun-06	202	202	202	15	15	15	1	No	-	-
305	1	29-Jun-06	87	87	87	84	84	84	1	No	yellow	
305	1	7-Jul-06	134	134	134	55	55	55	1	No	-	-
305	1	27-Jul-06	201	201	201	49	49	49	1	No	-	-
305	1	10-Aug-06	124	124	124	31	31	31	1	No	-	-
305	2	17-Nov-05	208	207	208	1.3	1.3	1.3	1	No	-	-
305	2	12-Jan-06	131	131	132	0.3	0.3	0.4	2	No	-	-
305	2	19-Jan-06	190	186	194	0.6	0.6	0.6	2	No	-	-
305	2	2-Feb-06	158	158	158	0.5	0.5	0.5	1	No	-	-
305	2	24-Apr-06	183	183	183	0.4	0.4	0.4	1	No	-	-
305	2	4-May-06	180	180	180	0.5	0.5	0.5	1	No	-	-
305	2	9-May-06	197	197	197	0.9	0.9	0.9	1	No	-	-
305	2	16-May-06	205	205	205	1.5	1.5	1.5	1	No	-	-
305	2	19-May-06	191	191	191	1.6	1.5	1.7	2	No	-	-
305	2	29-May-06	163	163	163	8.3	8.3	8.3	1	No	-	-
305	2	2-Jun-06	150	150	150	26	26	26	1	No	-	-
305	2	6-Jun-06	137	137	137	27	27	27	1	No	-	-
305	2	12-Jun-06	156	156	156	20	20	20	1	No	-	-
305	2	21-Jun-06	193	193	194	15	15	15	3	No	-	-
305	2	29-Jun-06	217	217	217	15	15	15	1	No	yellow	-
305	2	7-Jul-06	170	170	170	45	45	45	1	No	-	-
305	2	27-Jul-06	187	187	187	41	41	41	1	No	-	-
305	2	10-Aug-06	192	192	192	39	39	39	1	No	-	-
305	2	29-Sep-06	170	168	174	44	44	44	3	No	-	-
305	2	10-Oct-06	179	178	181	41	41	41	2	No	-	-
305	3	2-Nov-05	517	510	521	1.0	0.9	1.1	4	No	-	-
305	3	17-Nov-05	536	535	537	1.5	1.5	1.5	2	No	-	-
305	3	12-Jan-06	190	189	191	0.8	0.8	0.9	2	No	-	-
305	3	24-Apr-06	182	181	182	0.6	0.5	0.6	2	No	-	-
305	3	4-May-06	195	195	195	0.4	0.4	0.4	1	No	-	-
305	3	9-May-06	204	204	204	0.7	0.7	0.7	1	No	-	-
305	3	16-May-06	210	209	211	0.7	0.6	0.7	2	No	-	-
305	3	19-May-06	215	215	215	1.2	1.2	1.2	1	No	-	-
305	3	29-May-06	213	213	213	1.7	1.7	1.7	1	No	-	-
305	3	2-Jun-06	219	215	223	1.5	1.3	1.6	2	No	-	-
305	3	6-Jun-06	159	157	160	26	25	27	4	No	-	-
305	3	12-Jun-06	152	152	152	28	28	28	1	No	-	-
305	3	29-Jun-06	231	231	232	13	13	13	2	No	yellow	
305	3	7-Jul-06	187	185	190	33	33	34	2	No	-	-
305	3	17-Jul-06	204	204	204	34	34	34	1	No	-	-
305	3	27-Jul-06	214	214	214	35	35	35	1	No	-	-
305	3	10-Aug-06	219	219	219	37	37	37	1	No	-	-
305	3	21-Aug-06	216	215	217	34	34	34	2	No	-	-
305	3	29-Sep-06	231	228	236	35	34	38	5	No	orange ppt	
305	3	10-Oct-06	230	230	230	34	34	34	1	No	-	-
305	4	2-Nov-05	729	725	735	1.6	1.5	1.6	3	No	-	-
305	4	17-Nov-05	725	724	726	1.5	1.5	1.6	2	No	-	-
305	4	12-Jan-06	629	627	631	1.5	1.5	1.6	2	No	-	-
305	4	19-Jan-06	588	588	588	1.4	1.4	1.4	1	No	-	-
305	4	28-Apr-06	366	366	366	1.7	1.7	1.7	1	No	-	-
305	4	9-May-06	364	364	364	1.5	1.5	1.5	1	No	-	-
305	4	16-May-06	343	343	343	1.0	1.0	1.0	1	No	-	-
305	4	19-May-06	328	326	329	1.1	1.0	1.1	2	No	-	-
305	4	29-May-06	333	333	333	1.4	1.4	1.4	1	No	-	-
305	4	2-Jun-06	319	319	319	1.1	1.1	1.1	1	No	-	-
305	4	6-Jun-06	314	312	316	1.4	1.4	1.5	2	No	-	-
305	4	12-Jun-06	309	309	309	2.3	2.3	2.3	1	No	-	-
305	4	29-Jun-06	302	302	302	6.3	6.3	6.3	1	No	yellow	-

Table C-6 continued: Chloride, Bromide, and KMnO$_4$ Sample Results

Sample Details			Chloride			Bromide				KMnO$_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
305	4	7-Jul-06	304	304	304	7.9	7.9	7.9	1	No	-	-
305	4	17-Jul-06	299	299	299	9.2	9.2	9.2	1	No	-	-
305	4	27-Jul-06	271	271	271	21	21	21	1	No	-	-
305	4	10-Aug-06	254	254	254	28	28	28	1	No	-	-
305	4	21-Aug-06	271	269	272	26	25	26	2	No	-	-
305	4	29-Sep-06	300	295	303	31	30	32	3	No	yellow	-
305	4	10-Oct-06	295	294	296	33	33	34	2	No	-	-
305	5	2-Nov-05	614	609	619	1.2	1.1	1.4	5	No	-	-
305	5	12-Jan-06	551	550	552	1.1	1.0	1.2	2	No	-	-
305	5	2-Feb-06	524	524	524	1.5	1.5	1.5	1	No	-	-
305	5	24-Apr-06	451	451	451	2.0	2.0	2.0	1	No	-	-
305	5	4-May-06	442	442	442	2.9	2.9	2.9	1	No	-	-
305	5	9-May-06	440	440	440	4.9	4.9	4.9	1	No	-	-
305	5	16-May-06	425	424	426	10	10	10	3	No	-	-
305	5	19-May-06	411	411	411	26	26	26	1	No	-	-
305	5	29-May-06	404	404	404	29	29	29	1	No	-	-
305	5	2-Jun-06	383	383	383	45	45	45	1	No	-	-
305	5	6-Jun-06	351	351	351	77	77	77	1	No	-	-
305	5	12-Jun-06	352	350	353	73	73	74	2	No	-	-
305	5	21-Jun-06	359	359	359	69	69	69	1	No	-	-
305	5	29-Jun-06	353	353	353	71	71	71	1	No	-	-
305	5	7-Jul-06	358	358	358	81	81	81	1	No	-	-
305	5	27-Jul-06	344	344	344	100	100	100	1	No	-	-
305	5	10-Aug-06	353	353	353	105	105	105	1	No	-	-
305	5	29-Sep-06	372	372	372	123	123	123	1	No	yellow	
305	5	10-Oct-06	345	345	345	132	132	132	1	No	-	-
MW306												
306	1	17-Nov-05	334	332	335				4	No	-	-
306	1	23-Mar-06	256	256	257	0.6	0.6	0.7	2	No	-	-
306	1	24-Apr-06	278	278	279	1.2	1.0	1.4	2	No	-	-
306	1	28-Apr-06	252	252	252	0.9	0.9	0.9	1	No	-	-
306	1	19-May-06	270	270	270	1.1	1.1	1.1	1	No	-	-
306	1	29-May-06	280	280	280	20	20	20	1	No	-	-
306	1	2-Jun-06	297	297	297	26	26	26	1	No	-	-
306	1	6-Jun-06	294	294	294	43	43	43	1	Yes	light pink	
306	1	12-Jun-06	301	301	301	59	59	59	1	Yes	light pink	0.02
306	1	21-Jun-06								Yes	light pink	
306	1	29-Jun-06	309	306	311	93	93	93	2	No	orange	
306	1	7-Jul-06								Yes	light pink	0.00
306	1	27-Jul-06								Yes	dark pink	
306	1	10-Aug-06	286	286	286	141	141	141	1	Yes	peach	
306	1	21-Aug-06	308	308	308	143	143	143	1	No	clear	
306	1	29-Sep-06								Yes	dark purple	
306	1	10-Oct-06	178	178	178	216	216	216	1	Yes	dark purple	1.79
306	1	15-Nov-06								Yes	peach	nd
306	2	24-Apr-06	346	346	346	1.5	1.5	1.5	1	No	-	-
306	2	28-Apr-06	335	335	335	1.0	1.0	1.0	1	No	-	-
306	2	24-Apr-06	347	347	347	1.2	1.2	1.2	1	No	-	-
306	2	19-May-06	343	343	343	1.2	1.2	1.2	1	No	-	-
306	2	29-May-06	316	316	316	16	16	16	1	No	-	-
306	2	2-Jun-06	308	308	308	27	27	27	1	No	-	-
306	2	6-Jun-06	313	313	313	39	39	39	1	No	-	-
306	2	12-Jun-06	313	313	313	56	56	56	1	Yes	light pink	0.03
306	2	21-Jun-06								Yes	light pink	0.02
306	2	29-Jun-06	310	310	311	90	89	91	2	Yes	faint pink	
306	2	7-Jul-06								Yes	light pink	0.01
306	2	27-Jul-06								Yes	pink	
306	2	10-Aug-06	269	269	269	152	152	152	1	Yes	peach	
306	2	21-Aug-06	306	306	306	150	150	150	1	No	clear	
306	2	29-Sep-06								Yes	purple	
306	2	10-Oct-06	166	166	166	195	195	195	1	Yes	dark purple	1.59
306	2	15-Nov-06								Yes	light pink	0.02
306	3	17-Nov-05	790	788	792				5	No	-	-
306	3	23-Mar-06	556	554	557	1.7	1.7	1.7	2	No	-	-
306	3	28-Apr-06	503	503	503	1.6	1.6	1.6	1	No	-	-
306	3	19-May-06	503	503	503	1.7	1.7	1.7	1	No	-	-

Table C-6 continued: Chloride, Bromide, and KMnO$_4$ Sample Results

Sample Details			Chloride			Bromide				KMnO$_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
306	3	29-May-06	492	492	492	3.8	3.8	3.8	1	No	-	-
306	3	2-Jun-06	382	382	382	27	27	27	1	No	-	-
306	3	6-Jun-06	341	341	342	45	45	45	2	No	-	-
306	3	12-Jun-06	346	346	346	48	48	48	1	Yes	light pink	-
306	3	21-Jun-06	362	360	363	63	62	63	2	Yes	light pink	-
306	3	29-Jun-06	365	365	366	65	65	65	2	No	yellow	-
306	3	7-Jul-06								Yes	light pink	0.01
306	3	27-Jul-06	331	327	335	125	123	128	2	No	brown	-
306	3	10-Aug-06								Yes	faint pink	-
306	3	21-Aug-06	329	329	329	139	139	139	1	No	clear	-
306	3	29-Sep-06								Yes	dark pink	-
306	3	10-Oct-06	225	225	225	204	204	204	1	Yes	dark pink	0.42
306	3	15-Nov-06								Yes	light pink	0.01
306	4	3-Nov-05	697	697	697	1.4	1.3	1.5	2	No	-	-
306	4	17-Nov-05	627	627	627	1.6	1.6	1.6	1	No	-	-
306	4	28-Apr-06	564	564	564	1.7	1.7	1.7	2	No	-	-
306	4	19-May-06	564	564	564	1.7	1.7	1.7	1	No	-	-
306	4	29-May-06	570	570	570	1.8	1.8	1.8	1	No	-	-
306	4	2-Jun-06	567	567	567	1.6	1.6	1.6	1	No	-	-
306	4	12-Jun-06	557	557	557	1.9	1.9	1.9	1	No	-	-
306	4	21-Jun-06	555	555	555	2.6	2.6	2.6	1	No		
306	4	29-Jun-06	521	521	521	17	17	17	1	No	yellow	-
306	4	7-Jul-06	419	419	419	54	54	54	1	No	yellow	-
306	4	27-Jul-06	416	415	417	66	65	66	2	No	-	-
306	4	10-Aug-06	397	397	397	80	80	80	1	No	-	-
306	4	21-Aug-06	412	412	412	80	80	80	1	No	peach	-
306	4	29-Sep-06								Yes	pink	-
306	4	10-Oct-06	331	331	331	132	132	132	1	Yes	pink	0.07
306	4	15-Nov-06								Yes	light pink	nd
306	5	2-Nov-05	608	608	608	1.3	1.2	1.3	2	No	-	-
306	5	17-Nov-05	601	601	601	1.1	1.1	1.1	1	No	-	-
306	5	23-Mar-06	380	380	381	0.3	0.3	0.4	2	No	-	-
306	5	19-Apr-06	296	296	296	0.4	0.4	0.4	2	No	-	-
306	5	28-Apr-06	175	175	175	0.6	0.6	0.6	2	No	-	-
306	5	19-May-06	175	175	175	0.6	0.6	0.6	1	No	-	-
306	5	29-May-06	237	237	238	30	30	30	2	No	-	-
306	5	2-Jun-06	210	210	210	37	37	37	1	No	-	-
306	5	6-Jun-06	204	204	204	41	41	41	1	No	-	-
306	5	12-Jun-06	215	215	215	46	46	46	1	No	-	-
306	5	21-Jun-06	235	232	238	55	54	55	2	Yes	faint pink	-
306	5	29-Jun-06	251	250	251	63	63	63	2	Yes	light pink	0.02
306	5	7-Jul-06								Yes	light pink	0.02
306	5	27-Jul-06	301	301	301	81	81	81	1	Yes	faint pink	-
306	5	10-Aug-06								Yes	light pink	-
306	5	21-Aug-06	339	339	339	93	92	94	1	No	peach	-
306	5	29-Sep-06								Yes	purple	-
306	5	10-Oct-06	228	228	228	191	191	191	1	Yes	purple	1.51
306	5	15-Nov-06								Yes	pink	0.23
MW307												
307	1	17-Nov-05	497	497	497	0.8	0.8	0.8	1	No	-	-
307	1	28-Apr-06	490	490	490	1.3	1.3	1.3	1	No	-	-
307	1	4-May-06	495	495	495	1.6	1.6	1.6	1	No	-	-
307	1	9-May-06	487	482	492	1.7	1.5	1.8	2	No	-	-
307	1	29-May-06	474	474	474	1.9	1.9	1.9	1	No	-	-
307	1	10-Aug-06	459	459	459	2.9	2.9	2.9	1	No	-	-
307	1	21-Aug-06	455	455	455	2.9	2.9	2.9	1	No	-	-
307	2	17-Nov-05	795	794	795	1.6	1.5	1.7	2	No	-	-
307	2	28-Apr-06	682	682	682	1.5	1.5	1.5	1	No	-	-
307	2	4-May-06	671	671	671	1.4	1.4	1.4	1	No	-	-
307	2	9-May-06	642	642	642	1.8	1.8	1.8	1	No	-	-
307	2	29-May-06	572	572	572	2.1	2.1	2.1	1	No	-	-
307	2	21-Aug-06	510	504	516	3.0	2.9	3.0	2	No	-	-
307	3	3-Nov-05	651	651	652	2.1	2.1	2.1	2	No	-	-
307	3	16-Nov-05	834	834	834	2.1	2.1	2.1	1	No	-	-
307	3	19-Apr-06	767	767	767	1.8	1.8	1.8	1	No	-	-
307	3	28-Apr-06	764	764	764	1.9	1.9	1.9	1	No	-	-

Table C-6 continued: Chloride, Bromide, and $KMnO_4$ Sample Results

Sample Details			Chloride			Bromide				$KMnO_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
307	3	4-May-06	778	778	778	1.3	1.3	1.3	1	No	-	-
307	3	9-May-06	785	785	785	1.9	1.9	1.9	1	No	-	-
307	3	29-May-06	736	736	736	1.6	1.6	1.6	1	No	-	-
307	3	21-Aug-06	589	588	589	2.5	2.4	2.5	2	No	-	-
307	4	3-Nov-05	576	576	576	1.2	1.2	1.2	1	No	-	-
307	4	16-Nov-05	641	641	641	1.3	1.3	1.3	1	No	-	-
307	4	19-Apr-06	759	751	768	1.9	1.8	2.0	2	No	-	-
307	4	28-Apr-06	720	720	720	2.1	2.1	2.1	1	No	-	-
307	4	4-May-06	749	748	750	2.0	2.0	2.0	2	No	-	-
307	4	9-May-06	749	747	751	2.4	2.3	2.5	2	No	-	-
307	4	16-May-06	739	737	741	2.0	1.8	2.1	2	No	-	-
307	4	29-May-06	741	741	741	1.9	1.9	1.9	1	No	-	-
307	4	21-Aug-06	739	738	739	2.1	2.1	2.1	2	No	-	-
307	5	3-Nov-05	502	498	512	0.9	0.8	1.1	6	No	-	-
307	5	16-Nov-05	685	528	842	1.3	1.3	1.3	1	No	-	-
307	5	19-Apr-06	523	519	526	0.7	0.7	0.7	2	No	-	-
307	5	28-Apr-06	485	485	485	11	11	11	1	No	-	-
307	5	4-May-06	467	467	467	22	22	22	1	No	-	-
307	5	9-May-06	491	485	496	18	18	19	2	No	-	-
307	5	16-May-06	489	489	489	33	33	33	1	No	-	-
307	5	29-May-06	496	496	496	45	45	45	1	No	-	-
307	5	21-Aug-06	327	326	327	26	26	26	2	No	-	-
307	5	11-Sep-06	395	395	395	118	118	118	1	No	-	-
MW308												
308	1	16-Nov-05	1203	1198	1213				4	No	-	-
308	1	23-Mar-06	1076	1076	1077	0.7	0.7	0.8	2	No	-	-
308	1	11-Sep-06	622	621	624	2.5	2.4	2.6	2	No	-	-
308	1	10-Oct-06	646	646	646	2.9	2.9	2.9	1	No	-	-
308	2	3-Nov-05	1123	1116	1131				2	No	-	-
308	2	16-Nov-05	1249	1240	1258	2.7	2.7	2.7	2	No	-	-
308	2	11-Sep-06	703	703	703	2.1	2.1	2.1	1	No	-	-
308	2	10-Oct-06	677	675	680	2.3	2.2	2.4	2	No	-	-
308	3	15-Nov-05	712	708	714				3	No	-	-
308	3	10-Oct-06	710	710	710	2.0	2.0	2.0	1	No	-	-
308	4	3-Nov-05	607	605	610				2	No	-	-
308	4	11-Sep-06	449	449	449	1.2	1.2	1.2	1	No	-	-
308	4	10-Oct-06	471	471	471	1.4	1.4	1.4	1	No	-	-
308	5	16-Nov-05	532	530	534				2	No	-	-
308	5	10-Oct-06	496	496	496	31.4	31.4	31.4	1	No	-	-
MW309												
309	1	16-Nov-05	244	244	244	0.0	0.0	0.0	2	No	-	-
309	2	16-Nov-05	466	462	470	0.0	0.0	0.0	2	No	-	-
309	2	23-Mar-06	949	945	952	1.3	1.2	1.4	3	No	-	-
309	2	11-Sep-06	621	621	621	3.0	3.0	3.0	1	No	-	-
309	3	16-Nov-05	525	525	525	0.0	0.0	0.0	3	No	-	-
309	3	23-Mar-06	767	763	771	1.2	1.0	1.5	2	No	-	-
309	3	11-Sep-06	633	633	633	3.0	3.0	3.0	1	No	-	-
309	4	3-Nov-05	1188	1185	1193	0.6	0.0	1.1	4	No	-	-
309	4	16-Nov-05	1154	1150	1162	0.0	0.0	0.0	3	No	-	-
309	4	23-Mar-06	745	741	750	1.0	0.0	1.3	2	No	-	-
309	4	11-Sep-06	646	641	651	0.8	0.0	1.3	2	No	-	-
309	5	3-Nov-05	545	543	546	1.3	1.3	1.3	2	No	-	-
309	5	16-Nov-05	522	519	524	0.0	0.0	0.0	2	No	-	-
309	5	23-Mar-06	241	240	242	0.4	0.4	0.5	2	No	-	-
309	5	11-Sep-06	409	408	411	1.2	1.1	1.2	2	No	-	-
MW310												
310	2	3-Nov-05	903	901	904	0.0	0.0	0.0	2	No	-	-
310	3	3-Nov-05	422	422	422	0.0	0.0	0.0	2	No	-	-
310	3	16-Nov-05	782	782	782	0.0	0.0	0.0	1	No	-	-
310	4	3-Nov-05	690	689	690	0.0	0.0	0.0	2	No	-	-
310	4	16-Nov-05	694	691	697	0.9	0.0	1.7	2	No	-	-
310	5	3-Nov-05	547	545	548	0.0	0.0	0.0	2	No	-	-
310	5	16-Nov-05	571	567	575	0.3	0.0	0.6	2	No	-	-
MW311												
311	2	3-Nov-05	402	400	404	0.0	0.0	0.0	2	No	-	-
311	2	18-Nov-05	383	383	384	0.0	0.0	0.0	3	No	-	-

Table C-6 continued: Chloride, Bromide, and $KMnO_4$ Sample Results

Sample Details			Chloride			Bromide				$KMnO_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
311	2	29-Sep-06	220	220	220	0.5	0.5	0.5	1	No	-	-
311	3	3-Nov-05	404	403	405	0.0	0.0	0.0	2	No	-	-
311	3	18-Nov-05	379	378	380	0.0	0.0	0.0	3	No	-	-
311	3	29-Sep-06	260	260	260	1.0	1.0	1.0	1	No	-	-
311	4	3-Nov-05	592	590	593	0.0	0.0	0.0	2	No	-	-
311	4	18-Nov-05	585	583	588	0.0	0.0	0.0	2	No	-	-
311	4	29-Sep-06	530	530	530	1.2	1.2	1.2	1	No	-	-
311	5	29-Sep-06	443	443	443	0.9	0.9	0.9	1	No	-	-
MW312												
312	2	11-Nov-05	61	61	62	0.0	0.0	0.0	2	No	-	-
312	3	11-Nov-05	59	59	59	0.0	0.0	0.0	3	No	-	-
312	5	11-Nov-05	86	86	86	0.5	0.5	0.5	1	No	-	-
MW313												
313	2	17-Nov-05	299	299	300	0.0	0.0	0.0	2	No	-	-
313	2	30-Mar-06	342	340	344	0.6	0.6	0.7	2	No	-	-
313	2	15-Sep-06	535	528	543	2.7	2.6	2.8	2	No	-	-
313	3	18-Nov-05	356	355	356	0.0	0.0	0.0	3	No	-	-
313	3	30-Mar-06	344	343	344	0.8	0.7	0.9	2	No	-	-
313	3	15-Sep-06	545	545	545	2.2	2.2	2.2	1	No	-	-
313	3	29-Sep-06	547	547	547	2.3	2.3	2.3	1	No	-	-
313	4	3-Nov-05	381	380	383	0.4	0.0	1.1	3	No	-	-
313	4	18-Nov-05	403	403	403	1.2	1.1	1.2	2	No	-	-
313	4	30-Mar-06	372	371	374	1.3	1.3	1.3	2	No	-	-
313	4	15-Sep-06	467	466	467	1.5	1.4	1.6	2	No	-	-
313	5	3-Nov-05	372	372	372	1.3	1.3	1.3	1	No	-	-
313	5	18-Nov-05	330	329	332	0.7	0.0	1.4	2	No	-	-
313	5	30-Mar-06	300	298	301	1.5	1.5	1.5	2	No	-	-
313	5	15-Sep-06	284	281	286	1.4	1.4	1.4	2	No	-	-
313	5	29-Sep-06	284	283	285	1.4	1.2	1.5	2	No	-	-
MW314												
314	1	21-Jun-06	143	143	143	0.3	0.3	0.3	1	No	-	-
314	1	17-Jul-06	298	298	298	0.5	0.5	0.5	1	No	-	-
314	1	27-Jul-06	251	251	251	0.5	0.5	0.5	1	No	-	-
314	1	10-Aug-06	112	111	112	4.5	4.3	4.7	2	No	-	-
314	1	10-Oct-06	125	125	125	13	13	13	2	No	-	-
314	1	15-Nov-06	81	81	81	13	13	13	1	No	-	-
314	2	11-Nov-05	431	428	433	0.0	0.0	0.0	2	No	-	-
314	2	18-Nov-05	420	420	420	0.0	0.0	0.0	2	No	-	-
314	2	21-Jun-06	414	414	415	0.5	0.5	0.6	2	No	-	-
314	2	29-Jun-06	374	374	374	0.5	0.5	0.5	1	No	-	-
314	2	17-Jul-06	483	478	488	0.6	0.6	0.6	2	No	-	-
314	2	27-Jul-06	495	495	495	0.6	0.6	0.6	1	No	-	-
314	2	10-Aug-06	367	367	368	0.9	0.9	1.0	2	No	-	-
314	2	21-Aug-06	475	475	475	1.0	1.0	1.0	1	No	-	-
314	2	15-Sep-06	578	576	580	0.8	0.6	0.9	2	No	-	-
314	2	29-Sep-06	436	436	436	1.6	1.6	1.6	1	No	-	-
314	2	10-Oct-06	344	343	345	3.3	3.3	3.3	2	No	-	-
314	2	15-Nov-06	130	130	130	8.3	8.3	8.3	1	No	-	-
314	3	3-Nov-05	373	373	374	0.6	0.0	1.3	4	No	-	-
314	3	18-Nov-05	396	395	398	0.0	0.0	0.0	2	No	-	-
314	3	29-Jun-06	479	479	479	0.5	0.5	0.5	1	No	-	-
314	3	27-Jul-06	484	484	484	0.5	0.5	0.5	1	No	-	-
314	3	10-Aug-06	426	426	426	0.6	0.6	0.6	1	No	-	-
314	3	21-Aug-06	415	407	419	0.7	0.6	0.8	3	No	-	-
314	3	15-Sep-06	504	502	506	0.8	0.7	0.8	2	No	-	-
314	3	29-Sep-06	454	453	456	1.5	1.5	1.5	2	No	-	-
314	3	10-Oct-06	367	364	370	2.6	2.5	2.6	4	No	-	-
314	3	15-Nov-06	169	169	169	8.0	8.0	8.0	1	No	-	-
314	4	3-Nov-05	485	484	486	0.0	0.0	0.0	4	No	-	-
314	4	18-Nov-05	490	489	491	0.0	0.0	0.0	2	No	-	-
314	4	21-Jun-06	491	491	491	0.5	0.5	0.5	1	No	-	-
314	4	29-Jun-06	515	512	516	0.6	0.6	0.7	3	No	-	-
314	4	17-Jul-06	501	501	501	0.7	0.7	0.7	1	No	-	-
314	4	27-Jul-06	486	486	486	0.7	0.7	0.7	1	No	-	-
314	4	10-Aug-06	486	486	486	0.6	0.6	0.6	1	No	-	-

Table C-6 continued: Chloride, Bromide, and $KMnO_4$ Sample Results

Sample Details			Chloride			Bromide				$KMnO_4$		
Well ID	Port	Date Collected	Avg (mg/L)	Min (mg/L)	Max (mg/L)	Avg (mg/L)	Min (mg/L)	Max (mg/L)	No. Samples	Visual Presence	Visible Colour	Avg (g/L)
314	4	21-Aug-06	487	487	487	0.7	0.7	0.7	1	No	-	-
314	4	15-Sep-06	478	475	481	0.6	0.6	0.7	2	No	-	-
314	4	29-Sep-06	456	456	456	0.7	0.6	0.7	2	No	-	-
314	4	10-Oct-06	477	477	477	1.0	1.0	1.0	1	No	-	-
314	4	15-Nov-06	330	330	330	4.3	4.3	4.3	1	No	-	-
314	5	3-Nov-05	690	687	692	0.0	0.0	0.0	4	No	-	-
314	5	18-Nov-05	704	702	705	0.0	0.0	0.0	2	No	-	-
314	5	29-Jun-06	660	660	660	1.5	1.5	1.5	1	No	-	-
314	5	27-Jul-06	635	635	635	1.7	1.7	1.7	1	No	-	-
314	5	10-Aug-06	643	643	643	2.3	2.3	2.3	1	No	-	-
314	5	15-Sep-06	626	620	631	3.1	3.0	3.3	2	No	-	-
314	5	29-Sep-06	612	608	616	3.5	3.4	3.7	2	No	-	-
314	5	10-Oct-06	605	605	606	4.6	4.5	4.7	2	No	-	-
314	5	15-Nov-06	590	590	590	7	7	7	1	No	-	-

Table C-7: VC Sample Results

Well ID	Port	Date Collected	Avg (µg/L)	Min (µg/L)	Max (µg/L)	No. Samples
208		22-Apr-05	13.0	nd	28.7	3
208		22-Apr-05	<LOQ	<LOQ	<LOQ	3
208		24-Apr-06	<LOQ	<LOQ	<LOQ	2
208		16-May-06	<LOQ	<LOQ	<LOQ	1
208		19-May-06	nd	nd	nd	1
208		06-Jun-06	<LOQ	<LOQ	<LOQ	1
208	3	12-Jun-06	nd	nd	nd	1
208		21-Jun-06	nd	nd	nd	5
208		21-Aug-06	<LOQ	<LOQ	<LOQ	3
208	2	15-Sep-06	13.1	<LOQ	20.6	3
208	2	29-Sep-06	<LOQ	nd	<LOQ	4
208		10-Nov-06	<LOQ	<LOQ	<LOQ	3
208		20-Nov-06	nd	nd	<LOQ	3
MW301						
301	1	20-Nov-06	nd	nd	nd	2
301	2	20-Nov-06	<LOQ	<LOQ	<LOQ	2
301	3	20-Nov-06	nd	nd	nd	2
301	4	02-Nov-05	nd	nd	nd	3
301	4	16-Nov-05	19.4	nd	38.8	2
301	4	20-Nov-06	<LOQ	nd	<LOQ	3
301	5	02-Nov-05	nd	nd	nd	3
301	5	16-Nov-05	12.8	nd	23.5	2
301	5	20-Nov-06	<LOQ	nd	<LOQ	3
MW302						
302	1	29-May-06	<LOQ	<LOQ	<LOQ	1
302	1	06-Jun-06	nd	nd	nd	1
302	1	21-Jun-06	<LOQ	nd	<LOQ	3
302	1	21-Aug-06	<LOQ	nd	<LOQ	2
302	1	15-Sep-06	<LOQ	nd	25.9	3
302	1	29-Sep-06	<LOQ	<LOQ	<LOQ	1
302	1	15-Nov-06	11.6	nd	27.0	3
302	2	02-Nov-05	715	650	769	3
302	2	17-Nov-05	704	691	716	2
302	2	21-Jun-06	366	323	444	3
302	2	21-Aug-06	236	216	257	2
302	2	15-Sep-06	134	122	153	3
302	2	29-Sep-06	76.7	76.7	76.7	1
302	2	15-Nov-06	<LOQ	nd	18.9	3
302	3	02-Nov-05	182	169	196	2
302	3	17-Nov-05	475	408	540	3
302	3	21-Jun-06	479	441	530	5
302	3	21-Aug-06	615	615	615	1
302	3	15-Sep-06	592	508	645	3
302	3	29-Sep-06	739	739	739	1
302	3	15-Nov-06	221	167	260	3

Table C-7 continued: VC Sample Results

Well ID	Port	Date Collected	Avg (µg/L)	Min (µg/L)	Max (µg/L)	No. Samples
302	4	02-Nov-05	143	139	147	2
302	4	17-Nov-05	136	117	160	3
302	4	16-May-06	389	389	389	1
302	4	29-May-06	480	480	480	1
302	4	21-Jun-06	455	406	504	2
302	4	21-Aug-06	609	609	609	1
302	4	15-Nov-06	416	322	503	3
302	5	02-Nov-05	174	174	174	1
302	5	17-Nov-05	116	96	135	2
302	5	29-May-06	232	232	232	1
302	5	06-Jun-06	255	255	255	1
302	5	21-Jun-06	322	310	334	2
302	5	21-Aug-06	187	187	187	1
302	5	15-Sep-06	143	117	169	3
302	5	29-Sep-06	168	168	168	1
302	5	15-Nov-06	116	97	129	3
MW303						
303	1	17-Nov-05	31	29	34	2
303	1	19-Jan-06	<LOQ	<LOQ	<LOQ	2
303	1	04-May-06	nd	nd	nd	1
303	1	16-May-06	nd	nd	nd	2
303	1	29-May-06	nd	nd	nd	1
303	1	06-Jun-06	nd	nd	nd	1
303	1	21-Jun-06	nd	nd	nd	1
303	1	21-Aug-06	nd	nd	<LOQ	3
303	1	15-Nov-06	nd	nd	<LOQ	3
303	2	17-Nov-05	280	219	327	3
303	2	19-Jan-06	105	75	135	2
303	2	04-May-06	nd	nd	nd	1
303	2	29-May-06	nd	nd	<LOQ	2
303	2	06-Jun-06	nd	nd	nd	1
303	2	21-Jun-06	<LOQ	<LOQ	<LOQ	2
303	2	21-Aug-06	nd	nd	nd	3
303	2	15-Nov-06	<LOQ	nd	<LOQ	3
303	3	02-Nov-05	299	299	299	1
303	3	17-Nov-05	164	161	168	2
303	3	04-May-06	<LOQ	<LOQ	<LOQ	1
303	3	29-May-06	nd	nd	nd	1
303	3	06-Jun-06	nd	nd	nd	1
303	3	21-Jun-06	<LOQ	<LOQ	<LOQ	2
303	3	21-Aug-06	<LOQ	<LOQ	<LOQ	2
303	3	15-Nov-06	<LOQ	<LOQ	<LOQ	3
303	4	02-Nov-05	382	307	458	2
303	4	17-Nov-05	465	433	496	2
303	4	19-Jan-06	195	185	204	2

Table C-7 continued: VC Sample Results

Well ID	Port	Date Collected	Avg (µg/L)	Min (µg/L)	Max (µg/L)	No. Samples
303	4	17-Apr-06	167	167	167	1
303	4	16-May-06	nd	nd	nd	1
303	4	29-May-06	77	77	77	1
303	4	06-Jun-06	nd	nd	nd	1
303	4	21-Jun-06	nd	nd	<LOQ	2
303	4	21-Aug-06	nd	nd	nd	2
303	4	15-Nov-06	<LOQ	<LOQ	<LOQ	3
303	5	02-Nov-05	76	76	76	1
303	5	17-Nov-05	68	67	69	2
303	5	19-Jan-06	57	53	61	2
303	5	16-May-06	82	82	82	1
303	5	29-May-06	72	72	72	1
303	5	06-Jun-06	70	70	70	1
303	5	21-Jun-06	93	69	105	3
303	5	21-Aug-06	133	133	133	1
303	5	15-Nov-06	<LOQ	nd	<LOQ	3
MW304						
304	1	29-May-06	nd	nd	nd	1
304	1	21-Jun-06	nd	nd	nd	4
304	1	15-Nov-06	<LOQ	<LOQ	<LOQ	3
304	2	02-Nov-05	202	202	202	1
304	2	17-Nov-05	181	124	222	3
304	2	29-May-06	57	57	57	1
304	2	06-Jun-06	107	103	110	2
304	2	21-Jun-06	100	96	102	3
304	2	15-Nov-06	314	253	375	2
304	3	02-Nov-05	481	481	481	1
304	3	17-Nov-05	258	247	269	2
304	3	15-Nov-06	252	227	277	2
304	4	02-Nov-05	1499	1408	1590	2
304	4	17-Nov-05	1924	1871	1994	3
304	4	29-May-06	371	371	371	1
304	4	21-Jun-06	438	411	464	2
304	4	15-Nov-06	547	535	559	2
304	5	02-Nov-05	242	242	242	1
304	5	17-Nov-05	222	219	224	2
304	5	29-May-06	90	90	90	1
304	5	06-Jun-06	139	124	153	2
304	5	21-Jun-06	206	186	234	3
304	5	15-Nov-06	100	37	161	3
MW305						
305	1	17-Nov-05	14	13	14	2
305	1	12-Jan-06	nd	nd	nd	2
305	1	19-Jan-06	nd	nd	nd	2
305	2	17-Nov-05	34	32	36	2

Table C-7 continued: VC Sample Results

Well ID	Port	Date Collected	Avg (µg/L)	Min (µg/L)	Max (µg/L)	No. Samples
305	2	12-Jan-06	<LOQ	<LOQ	<LOQ	2
305	2	19-Jan-06	nd	nd	nd	2
305	2	15-Nov-06	49	45	53	2
305	3	02-Nov-05	<LOQ	<LOQ	<LOQ	1
305	3	17-Nov-05	36	31	40	3
305	3	12-Jan-06	59	59	60	2
305	3	19-Jan-06	28	15	40	2
305	3	15-Nov-06	56	51	61	2
305	4	02-Nov-05	90	90	90	1
305	4	17-Nov-05	82	82	82	1
305	4	12-Jan-06	69	66	72	2
305	4	19-Jan-06	41	36	46	2
305	4	19-Apr-06	35	31	38	2
305	4	04-May-06	36	21	52	2
305	4	15-Nov-06	42	37	47	2
305	5	02-Nov-05	50	50	50	1
305	5	17-Nov-05	nd	nd	nd	2
305	5	12-Jan-06	<LOQ	<LOQ	<LOQ	2
305	5	19-Jan-06	<LOQ	<LOQ	<LOQ	2
305	5	15-Nov-06	nd	nd	<LOQ	2
MW306						
306	1	17-Nov-05	<LOQ	<LOQ	<LOQ	2
306	1	15-Nov-06	<LOQ	nd	<LOQ	3
306	2	21-Aug-06	<LOQ	<LOQ	<LOQ	2
306	2	15-Nov-06	<LOQ	nd	<LOQ	3
306	3	17-Nov-05	<LOQ	<LOQ	<LOQ	2
306	3	19-Apr-06	nd	nd	nd	1
306	3	24-Apr-06	<LOQ	<LOQ	<LOQ	1
306	3	15-Nov-06	<LOQ	nd	17.8	3
306	4	02-Nov-05	<LOQ	<LOQ	<LOQ	2
306	4	17-Nov-05	<LOQ	<LOQ	<LOQ	2
306	4	15-Nov-06	nd	nd	<LOQ	2
306	5	02-Nov-05	<LOQ	<LOQ	<LOQ	1
306	5	17-Nov-05	nd	nd	nd	2
306	5	21-Aug-06	<LOQ	<LOQ	<LOQ	2
306	5	15-Nov-06	<LOQ	nd	<LOQ	3
MW307						
307	3	03-Nov-05	nd	nd	nd	1
307	4	03-Nov-05	<LOQ	<LOQ	<LOQ	1
307	5	03-Nov-05	nd	nd	nd	1
307	5	16-Nov-05	nd	nd	nd	2
MW308						
308	1	16-Nov-05	nd	nd	nd	2
308	2	03-Nov-05	<LOQ	<LOQ	<LOQ	1
308	2	16-Nov-05	<LOQ	<LOQ	<LOQ	2

Table C-7 continued: VC Sample Results

Well ID	Port	Date Collected	Avg (µg/L)	Min (µg/L)	Max (µg/L)	No. Samples
308	3	16-Nov-05	<LOQ	<LOQ	<LOQ	2
308	4	03-Nov-05	<LOQ	<LOQ	<LOQ	1
308	5	16-Nov-05	nd	nd	nd	2
MW309						
309	1	16-Nov-05	nd	nd	nd	2
309	2	16-Nov-05	nd	nd	nd	2
309	3	16-Nov-05	<LOQ	<LOQ	<LOQ	2
309	4	03-Nov-05	nd	nd	nd	1
309	4	16-Nov-05	nd	nd	nd	2
309	5	03-Nov-05	nd	nd	nd	2
309	5	16-Nov-05	nd	nd	nd	2
MW310						
310	3	03-Nov-05	nd	nd	nd	1
310	3	16-Nov-05	nd	nd	nd	2
310	4	03-Nov-05	nd	nd	nd	1
310	4	16-Nov-05	nd	nd	nd	2
310	5	03-Nov-05	nd	nd	nd	1
310	5	16-Nov-05	nd	nd	nd	2
MW311						
311	1	29-Sep-06	69	69	69	1
311	2	03-Nov-05	20	20	20	1
311	2	18-Nov-05	468	455	481	2
311	2	29-Sep-06	623	623	623	1
311	3	03-Nov-05	16	16	16	1
311	3	18-Nov-05	41	14	61	3
311	4	03-Nov-05	16	16	16	1
311	4	18-Nov-05	10.6	<LOQ	11.5	2
311	4	29-Sep-06	<LOQ	<LOQ	<LOQ	1
MW312						
312	2	11-Nov-05	nd	nd	nd	1
312	3	11-Nov-05	nd	nd	nd	1
312	4	11-Nov-05	nd	nd	nd	1
312	5	11-Nov-05	nd	nd	nd	1
MW313						
313	2	18-Nov-05	137	125	149	2
313	2	15-Sep-06	<LOQ	<LOQ	<LOQ	1
313	2	29-Sep-06	270	270	270	1
313	2	20-Nov-06	368	339	396	2
313	3	18-Nov-05	229	220	238	2
313	3	15-Sep-06	324	144	505	2
313	3	29-Sep-06	626	626	626	1
313	3	20-Nov-06	841	752	908	3
313	4	03-Nov-05	194	194	194	1
313	4	18-Nov-05	312	283	341	2

Table C-7 continued: VC Sample Results

Well ID	Port	Date Collected	Avg (μg/L)	Min (μg/L)	Max (μg/L)	No. Samples
313	4	15-Sep-06	329	310	348	2
313	4	20-Nov-06	423	385	460	2
313	5	03-Nov-05	25	25	25	1
313	5	18-Nov-05	23	23	24	2
313	5	29-Sep-06	13	13	13	1
313	5	20-Nov-06	12	12	13	2
MW314						
314	1	21-Jun-06	<LOQ	<LOQ	<LOQ	2
314	1	15-Nov-06	18	13	21	3
314	2	18-Nov-05	15	12	19	2
314	2	21-Aug-06	<LOQ	<LOQ	<LOQ	2
314	2	15-Sep-06	20.5	<LOQ	34.4	2
314	2	29-Sep-06	10	10	10	1
314	2	15-Nov-06	11	10	13	2
314	3	03-Nov-05	84	76	91	2
314	3	18-Nov-05	78	75	81	2
314	3	21-Jun-06	14	13	16	2
314	3	21-Aug-06	27	26	28	2
314	3	15-Sep-06	36	31	40	2
314	3	29-Sep-06	14	14	14	1
314	3	15-Nov-06	15	12	17	3
314	4	03-Nov-05	833	801	865	2
314	4	18-Nov-05	1369	1293	1444	2
314	4	21-Jun-06	147	138	160	3
314	4	21-Aug-06	308	273	353	3
314	4	15-Sep-06	402	394	411	2
314	4	15-Nov-06	78	69	87	3
314	5	03-Nov-05	433	433	433	1
314	5	18-Nov-05	739	675	802	2
314	5	21-Jun-06	1209	1147	1271	2
314	5	15-Sep-06	2205	2140	2271	2
314	5	29-Sep-06	1611	1611	1611	1
314	5	15-Nov-06	1243	1003	1465	3

<LOQ =<10 μg/L
nd =<2.5 μg/L

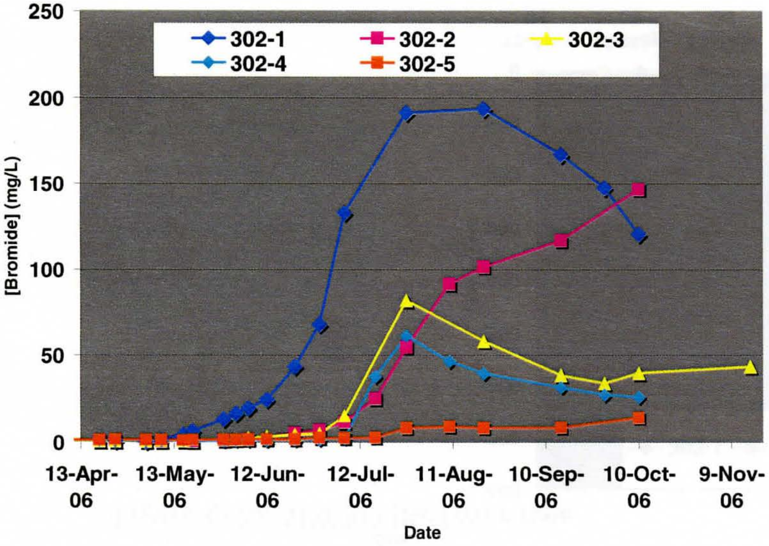


Figure C-1a: MW302 [Br⁻] over time

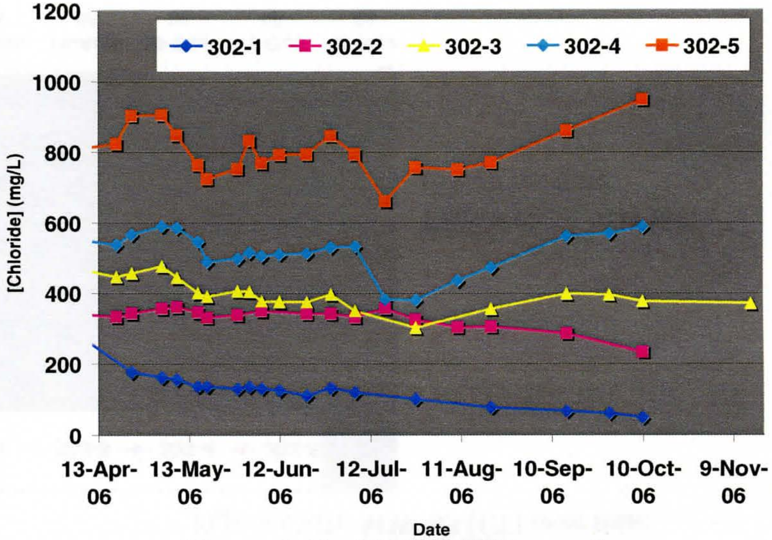


Figure C-1b: MW302 [Cl⁻] over time

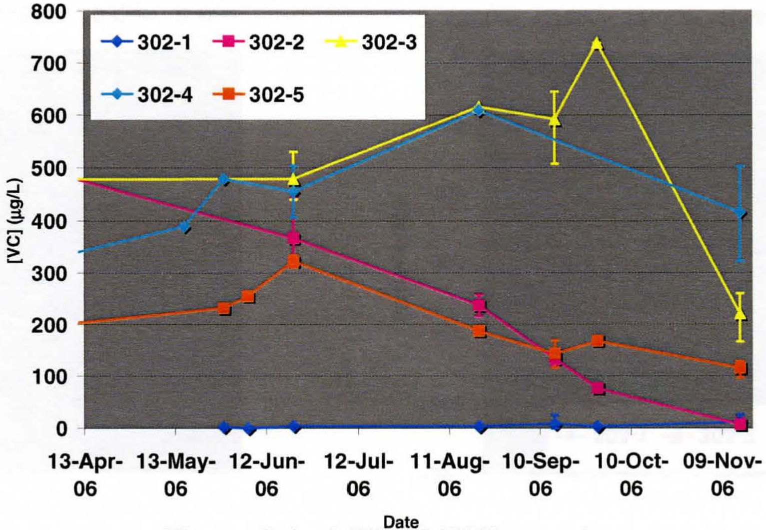


Figure C-1c: MW302 [VC] over time

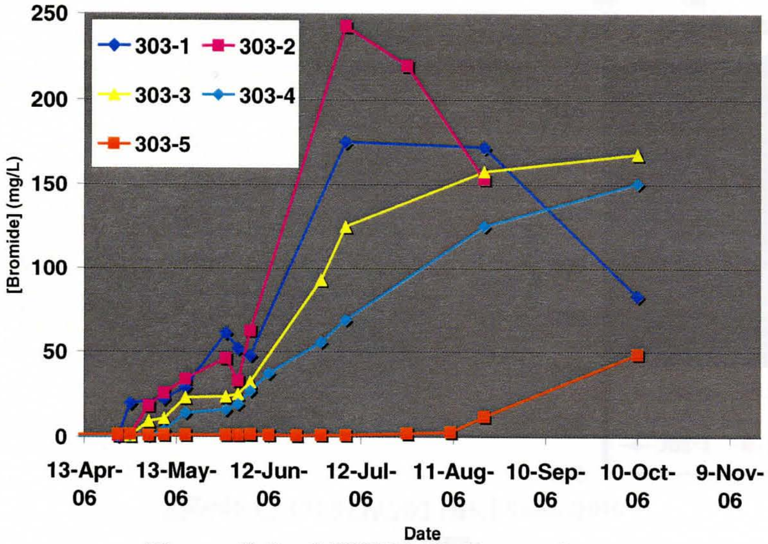


Figure C-2a: MW303 [Br⁻] over time

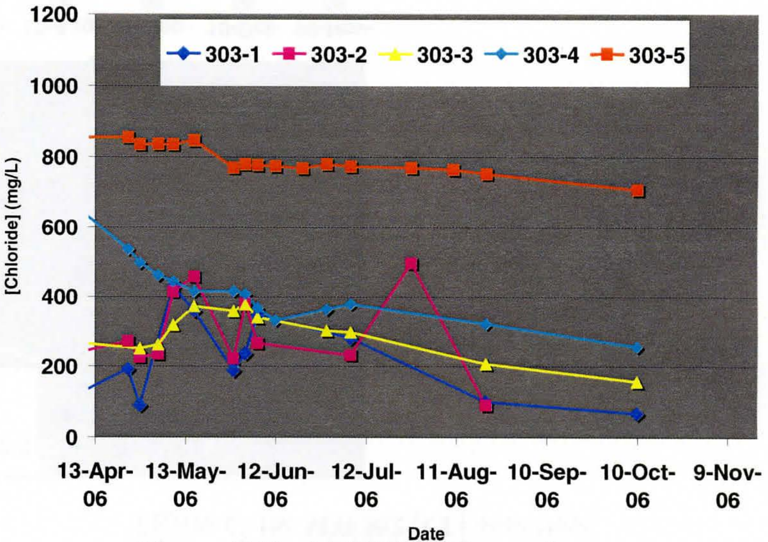


Figure C-2b: MW303 [Cl⁻] over time

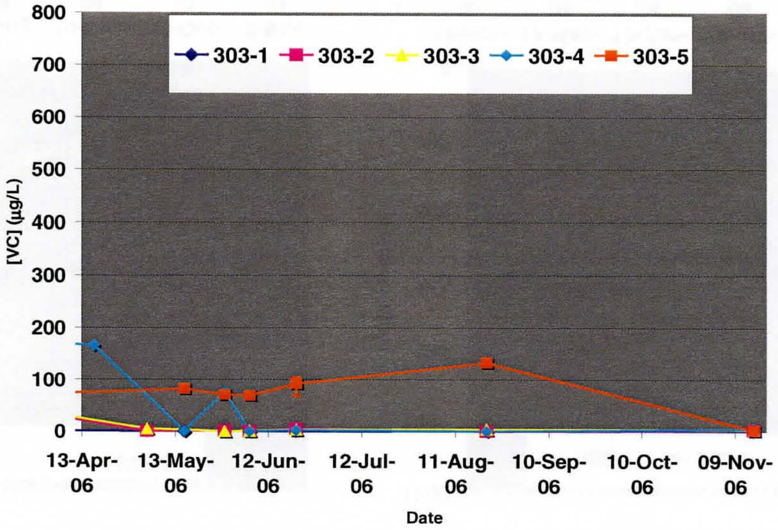


Figure C-2c: MW303 [VC] over time

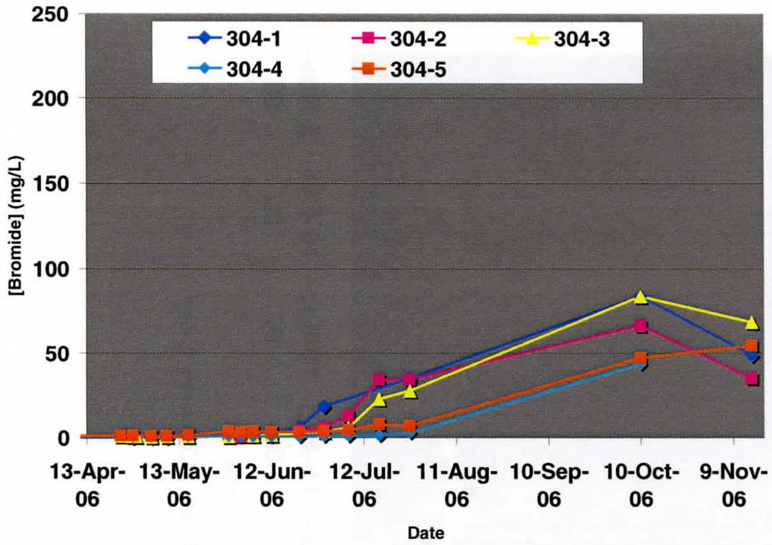


Figure C-3a: MW304 [Br⁻] over time

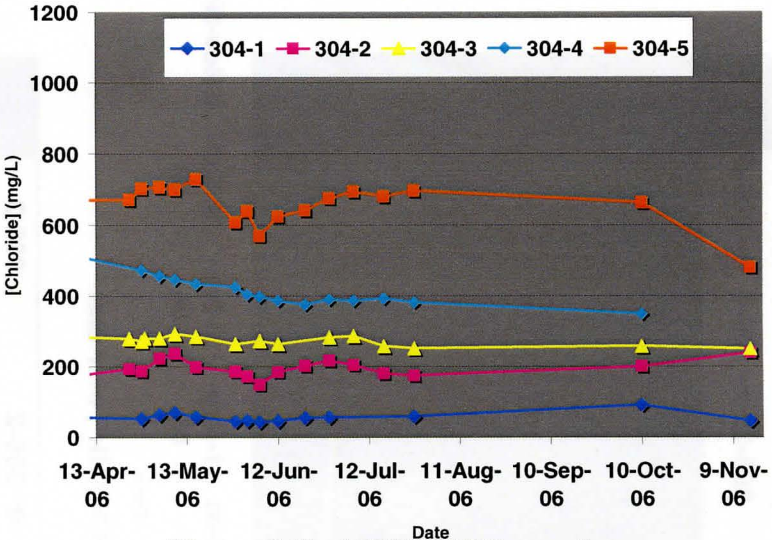


Figure C-3b: MW304 [Cl⁻] over time

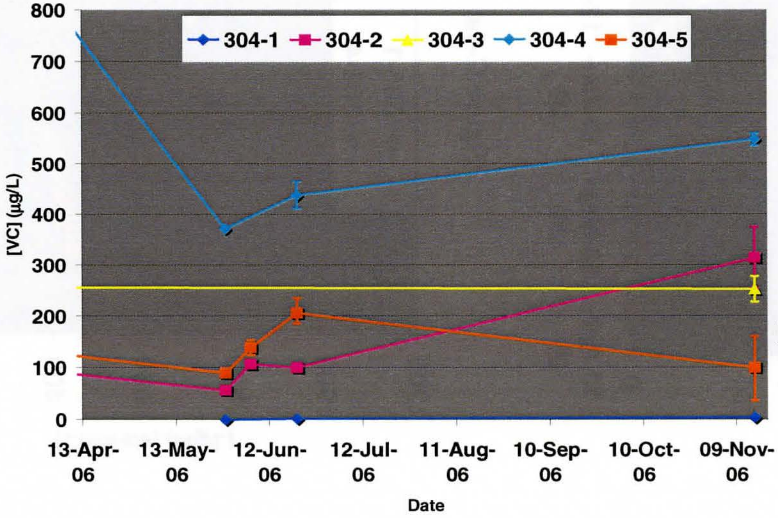


Figure C-3c: MW304 [VC] over time

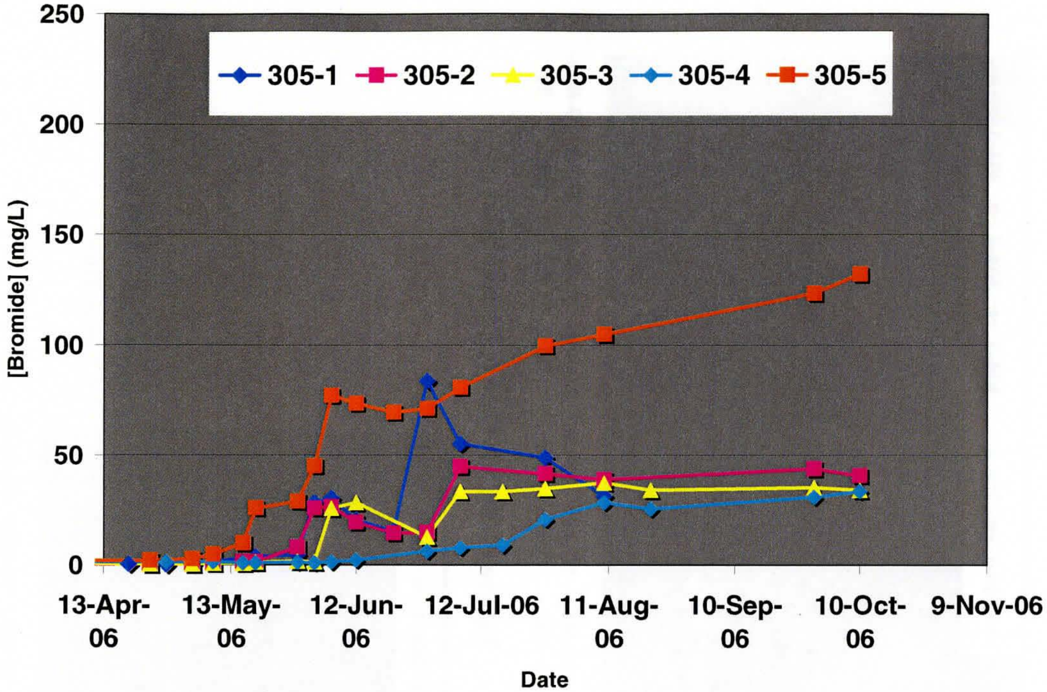


Figure C-4a: MW305 [Br⁻] over time

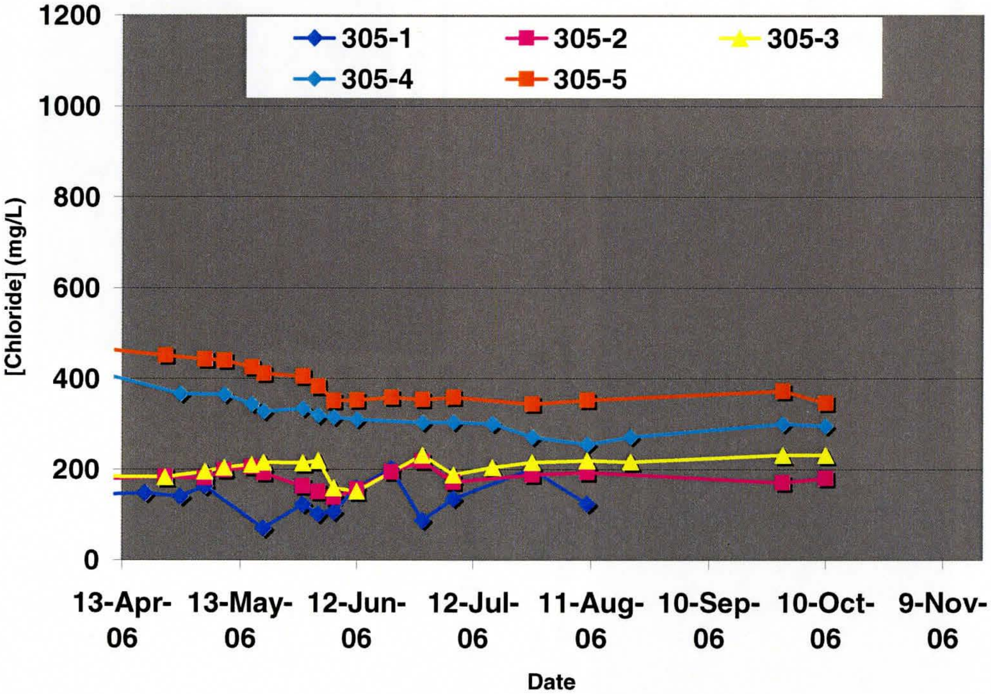


Figure C-4b: MW305 [Cl⁻] over time

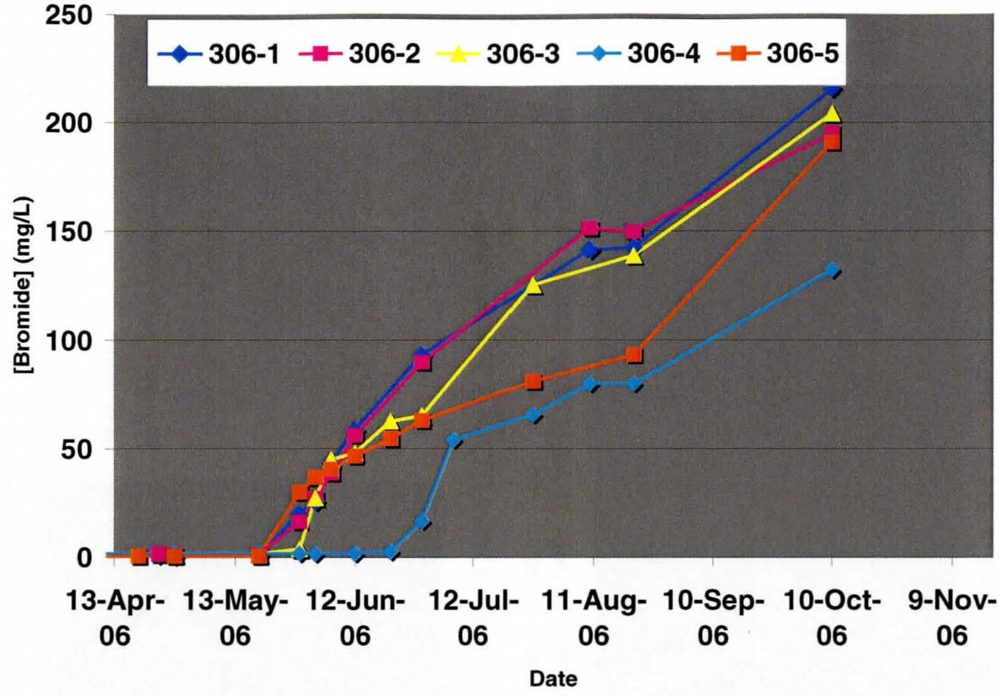


Figure C-5a: MW306 [Br⁻] over time

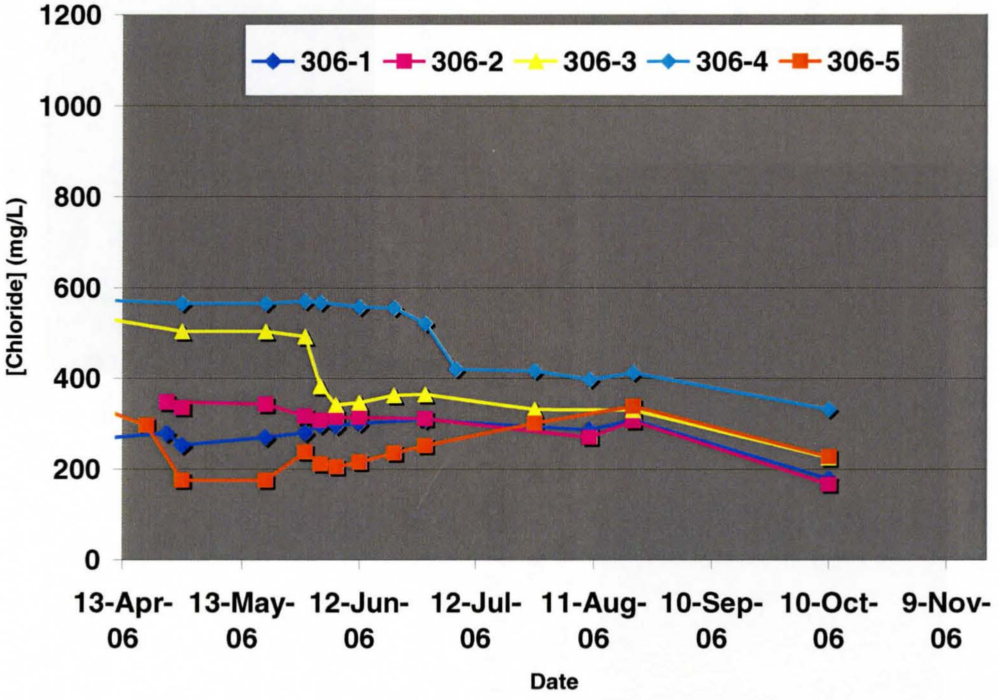


Figure C-5b: MW306 [Cl⁻] over time

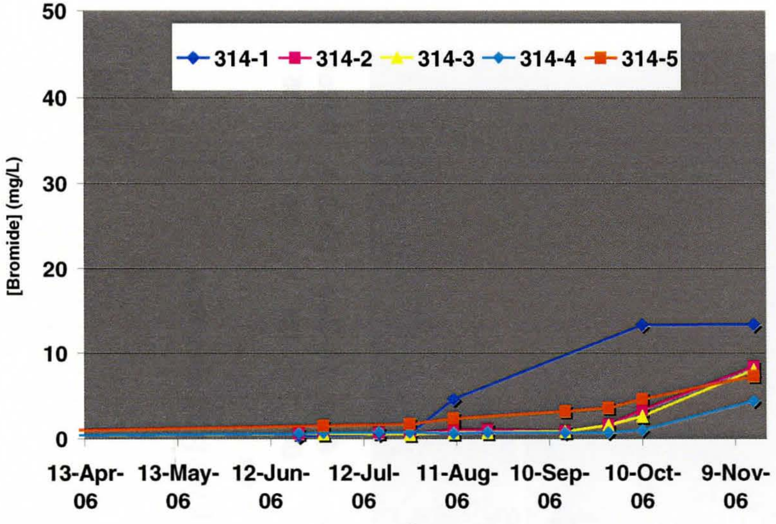


Figure C-6a MW314 $[Br^-]$ over time

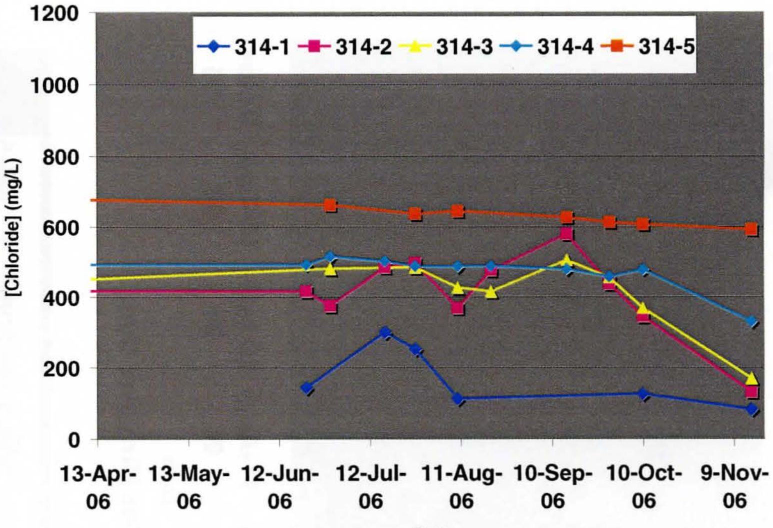


Figure C-6b MW314 $[Cl^-]$ over time

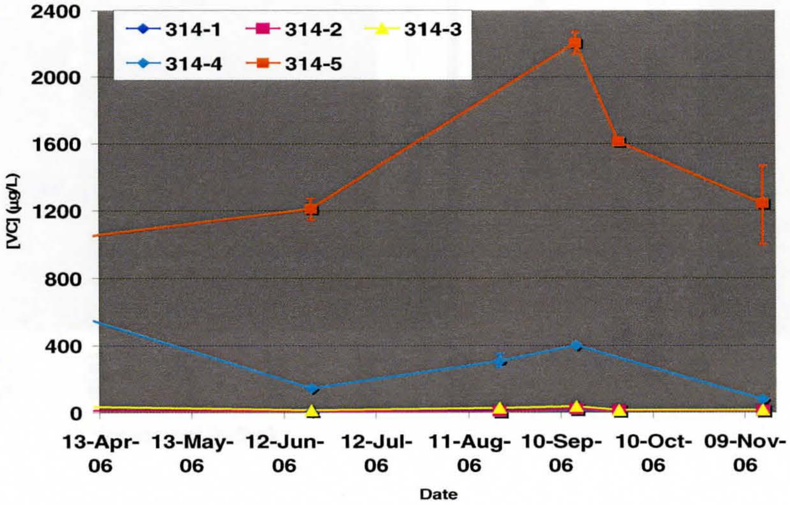


Figure C-6c: MW314 [VC] over time

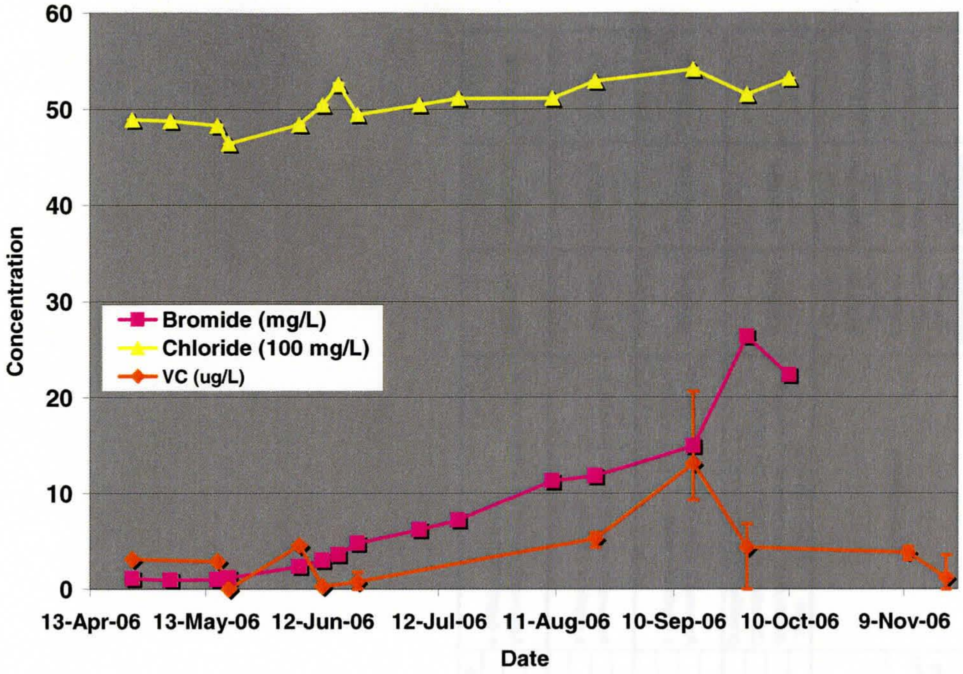


Figure C-7a: BH208 [Br$^-$, Cl$^-$, VC] over time

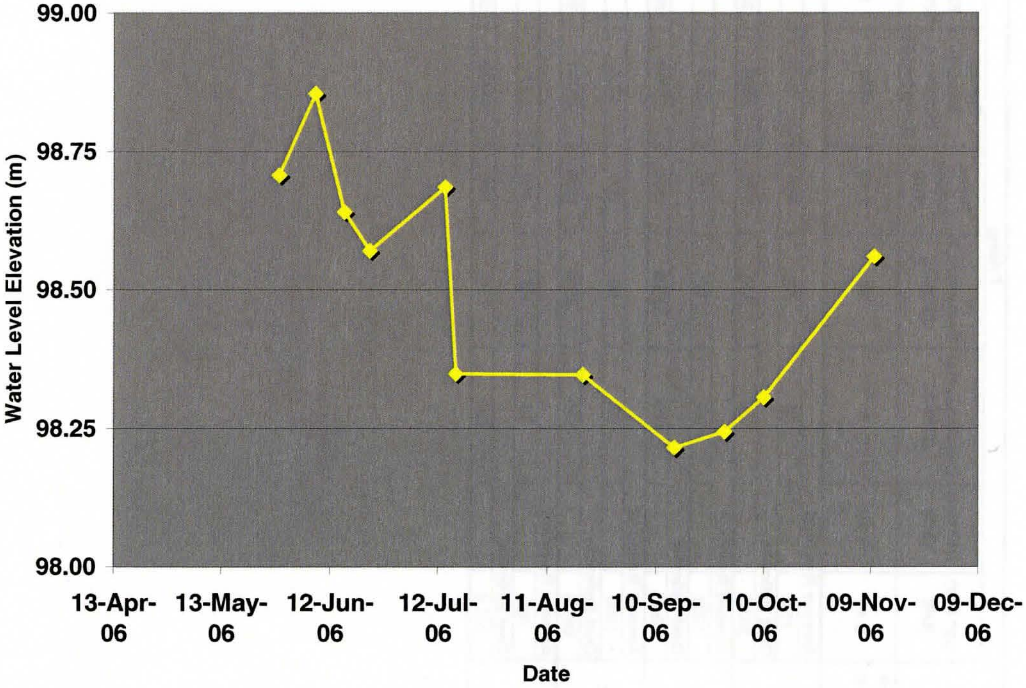


Table C-8: Cost Estimate Details

		Pricing											
		1/2" PVC ($/ft)	1/4" PVC ($/ft)	Caps/Coupling ($/each)	Swagelock T ($/each)	Teflon Tubing ($/ft)	Pumps ($/each) Includes 4 Pump heads	$KMnO_4$ ($/150 kg)	Drilling ($/30 IPs)	Assumptions	Estimated Capital Costs Using Delivery Point Method (CDN)	Estimated Capital Costs Using Delivery Point Method (USD)	Actual Capital Cost from Project Description
Location	Volume to Treat (m^3)	0.45	1.53	6	28	1.45	1200	1002	3155				
42 Voyager Court	400	Amount Required								Larger IP for better in-tube distribution; two rows of 15 IP each (30 total), and double the pumps to provide direct flow to each IP	$17,719	$15,821	-
		450		30	30	300	8	3.3	1				
		Cost Estimate											
		202.5		180	840	435	9600	3306.6	3155				
A	924	Amount Required								Assume 3 rows of 30 IPs per row, to a depth of 4 mbg.	$48,010	$42,866	$38,969
		1260		90	90	900	22.5	6.6	3				
		Cost Estimate											
		567		540	2520	1305	27000	6613.2	9465				
B	1040	Amount Required								Assume 3 rows of 30 IPs per row, to a depth of 4.5 mbg.	$48,051	$42,902	$102,400
		1350		90	90	900	22.5	6.6	3				
		Cost Estimate											
		607.5		540	2520	1305	27000	6613.2	9465				
C	497	Amount Required								Assume 2 rows of 24 IPs per row, to a depth of 4.6 mbg.	$24,997	$22,318	$84,400
		768		48	48	400	12	3.3	1.5				
		Cost Estimate											
		345.6		288	1344	580	14400	3306.6	4732.5				