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EVALUATION OF THE IMPACT OF THE SOURCE TERM ON NATURAL ATTENUATION OF JET FUEL CONTAMINATION

By

**Anne-Marie Thompson
B.Eng.**

**A Thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of Master of Engineering***

**Department of Civil and Environmental Engineering
Carleton University
Ottawa, Ontario
Canada**

September 8, 2000

***The Master of Engineering program is a joint program with the University
of Ottawa administered by the Ottawa-Carleton Institute for
Civil Engineering**

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**EVALUATION OF THE IMPACT OF THE SOURCE TERM ON NATURAL
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submitted by

Anne-Marie Thompson, B.Eng.

In partial fulfillment of

The requirements for the degree of

Master of Engineering

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ABSTRACT

Fuel handling practices at the former National Defence POL Tank Farm in Ottawa, Canada have resulted in the release of petroleum hydrocarbons to the subsurface. A site investigation was undertaken to determine the extent of the contamination and to evaluate the effectiveness of natural attenuation as a remedial alternative for the contaminated groundwater. A soil-vapour study, borehole drillings and test pit soil samples aided in conceptualizing the hydrocarbon source term. Groundwater samples collected at 20 wells were analyzed for petroleum hydrocarbons and geochemical indicators of natural attenuation and it was determined that microbial degradation of the hydrocarbons was occurring. Groundwater elevations were monitored to assess the direction and magnitude of the groundwater flow at the site, which were found to vary temporally.

There is often a large degree of uncertainty associated with the source term at contaminated sites. BioRedox-MT3DMS was therefore used to model the dissolution of a residual source term and the biodegradation of the petroleum hydrocarbons in the groundwater for various scenarios. The NAPL saturation and areal extent of the source term, the oxygen transfer from the unsaturated zone and biodegradation rate constants were varied independently to illustrate the impact of the uncertainty in these parameters on the model predictions.

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NOMENCLATURE

ATP	adenosine triphosphate
BTEX	benzene, toluene, ethylbenzene, xylene
CH ₄	methane
Fe ⁺³	ferric iron
Fe ⁺²	ferrous iron
LEL	lower explosive limit
LNAPL	light non-aqueous phase liquid
masl	meters above sea level
mbtop	meters below top of pipe
MOE	Ontario Ministry of the Environment
MOEE	Ontario Ministry of the Environment and Energy
NAD ⁺	nicotinamide adenine dinucleotide
NAPL	non-aqueous phase liquid
NO ₃ ⁻	nitrate
O ₂	dissolved oxygen
PAH	polyaromatic hydrocarbon
PVC	polyvinyl chloride
SO ₄ ⁻²	sulphate
TOG	Top of ground
TOPVC	Top of PVC pipe
TPH	total petroleum hydrocarbons
VOC	volatile organic compound

CHAPTER 1

1.0 Introduction

Contamination of water resources and soils by non-aqueous phase liquids (NAPLs) is a widespread environmental problem. Hydrocarbons, which are light non-aqueous phase liquids, or LNAPLs, have been known to contaminate groundwater resources for extended periods of time, due in part to the low solubility of such compounds. The quantity of free product, residual and/or entrapped hydrocarbons present in the soil and/or groundwater environments will also impact upon the duration of contamination.

Briefly, upon entering subsurface environments, hydrocarbons are subject to a variety of chemical, physical and biological processes that can serve to reduce contaminant concentrations. Such processes are collectively termed natural attenuation and if sufficient, they can be employed as a non-intrusive method for site remediation. Hydrocarbons undergo natural attenuation processes such as volatilization, dilution via dispersion and diffusion and biodegradation as they migrate through the vadose zone. Hydrocarbons will also partition into recharge and groundwater that comes in contact with the pure and gaseous phases. The aqueous phase petroleum hydrocarbons subsequently migrate in the subsurface due to advection and dispersion and a hydrocarbon plume will form downgradient from the source area. Petroleum hydrocarbons have been shown by a number of researchers to degrade via oxidation-reduction reactions, carried out by

indigenous microorganisms present in the groundwater (e.g., Solano-Serena *et al.*, 1999; Libelo *et al.*, 1998; Reichart *et al.*, 1998; Landmeyer *et al.*, 1998; Cho *et al.*, 1997; Kampbell *et al.*, 1996 and Borden *et al.*, 1995). Such reactions cause changes in local groundwater chemistry and as such, distinct patterns may emerge which are indicative of groundwater contamination.

There is generally considerable uncertainty associated with the quantity and distribution of hydrocarbons present at contaminated sites, due to the often sporadic nature of the releases. In this research, a field study was carried out at the National Defence POL Tank Farm in Ottawa, Canada to identify areas impacted by hydrocarbons in both soil and groundwater media. A modelling study was also performed to demonstrate the impact of various parameters, used to define the hydrocarbon source term, on the extent of groundwater contamination and the timeframe over which dissolution of the hydrocarbon residual would occur. BioRedox-MT3DMS, a multi-species transport code, was used to simulate the degradation of the petroleum hydrocarbons and the subsequent changes in the local groundwater environment.

1.1 Research Objectives

The objectives of this research are as outlined:

1. Conduct a field study to ascertain the degree of hydrocarbon contamination in both soil and groundwater environments through the use of various methods.
2. To propose various conceptual models of the hydrocarbon source term.

3. To model the dissolution and degradation of the source term under various scenarios using the multicomponent code, BioRedox-MT3DMS to assess how various parameters affect natural attenuation processes and thus remediation timeframes.

The modelling approach used to meet the third objective is unique in that very few studies have considered NAPL dissolution as a way of introducing hydrocarbons to the aqueous phase. Constant concentration boundaries are usually assumed, thus ignoring the time-dependent dissolution of residual hydrocarbons, which in turn affects the composition of the source term with time. There have also been very few studies that examine the development and kinetics associated with each anaerobic redox zone. Previous studies have distinguished between aerobic and anaerobic redox zones, however there is no differentiation between the anaerobic zones and a single degradation rate is assumed within the anaerobic zone. Lastly, few studies have examined the behaviour of individual fuel compounds. Benzene, toluene, ethylbenzene and xylenes (BTEX) are usually grouped together, while the remaining hydrocarbons are grouped as total petroleum hydrocarbons (TPH). In this study, the behaviour of 8 hydrocarbon groups is assessed.

1.2 Thesis Outline

The remainder of Chapter 1 provides background information on the site studied for this research. Chapter 2 of this thesis outlines concepts related to natural attenuation, specifically the microbial degradation of hydrocarbons and how such processes affect groundwater chemistry. Chapter 3 presents the methodology and results from the field study performed. Chapter 4 describes the conceptual

models for the geology, hydrogeology and contamination at the site. Chapter 5 outlines the numerical models for groundwater flow and contaminant transport. Chapter 6 presents the modelling study and discusses the results obtained for several scenarios where parameters related to the source term were varied. Lastly, conclusions and recommendations for future work are presented in Chapter 7.

1.3 Site Description

The site being considered in this thesis is a former tank farm which operated between 1954 and 1994, where jet fuel was stored in four aboveground storage tanks, each with a capacity of 864 000 litres. A site plan is presented in Figure 1. The site is secured by a fence which is denoted in Figure 1. A rail line along the northern edge of the site was used to deliver fuel to adjacent valve houses 1,2,3 and 4 at the site. Fuel transfer occurred from the valve houses to the storage tanks through aboveground piping. Other transfer points included a pump house and other underground piping systems. Previous field studies performed by Fondex (1994), Dillon (1994) and Dillon (1995) revealed the presence of characteristic fuel compounds in the groundwater, namely benzene, toluene, ethylbenzene, xylenes and heavier petroleum hydrocarbons, near the valve houses and pump house. In order to gain further information pertaining to the extent of soil and groundwater contamination and the hydrogeology, a detailed site characterization study was undertaken for this research.

Figure 1. Site Plan.

CHAPTER 2

2.0 Natural Attenuation

Natural attenuation refers to the overall reduction of contaminant concentration, toxicity, mobility, or mass, achieved through physical, chemical and biological processes. Such processes include dilution, sorption, volatilization, precipitation, ion exchange and biodegradation. If favourable conditions exist at a site, these processes can effectively be used to reach remedial goals (US EPA, 1999).

The use of monitored natural attenuation as a 'cleanup' remedy at contaminated sites has increased dramatically in the past decade. A large reason for its increased use, aside from being a relatively non-intrusive method, is its ability to remediate residual contamination after active remedial methods such as source removal, soil-vapour extraction and pump and treat have been employed. Active methods are capable of removing large masses of contaminants, but often a dissolved contaminant plume or residual phase contamination remains, which has the potential to impact groundwater as a long-term source (Libelo, *et al.*, 1998).

An abundance of literature is available on natural attenuation and its use at various contaminated sites. Petroleum hydrocarbons have been found to be especially susceptible to microbial degradation by numerous researchers

(e.g., Solano-Serena *et al.*, 1999; Libelo *et al.*, 1998; Reichart *et al.*, 1998; Landmeyer *et al.*, 1998; Cho *et al.*, 1997; Kampbell *et al.*, 1996 and Borden *et al.*, 1995). Section 2.1 provides a detailed description of oxidation-reduction reactions and how microorganisms mediate such reactions.

2.1 Redox Reactions

2.1.1 Introduction to Redox Reactions

Oxidation-reduction (redox) reactions involve the transfer of electrons from one reactant to another. A chemical species is oxidized if it loses electrons (electron donor), and the species that accepts the electrons is reduced (electron acceptor). In the case of a petroleum hydrocarbon spill, the dissolved hydrocarbons act as the primary electron donor. Various elements present in the aquifer act as the electron acceptors. The following chemical equation demonstrates the redox process for benzene, where the oxidation states of the involved species are denoted:

In the above reaction, benzene undergoes oxidation (*i.e.*, a loss of electrons). Initially, the oxidation state of the carbon atom is -1. Upon electron transfer, the final oxidation state is +4. Carbon has donated electrons in this process, and is oxidized. Similarly, oxygen has an initial oxidation state of zero and gains the donated electrons. This results in the reduction of oxygen, and a final oxidation state of -2. It can also be said that oxygen is an oxidizing agent.

Microorganisms mediate the transfer of electrons in redox reactions, where an accompanying release of chemical energy can be used by microorganisms to perform metabolic functions and cellular growth. The electrons are accepted by compounds present in the aquifer in the following order of preference:

1. Oxygen, O_2
2. Nitrate, NO_3^-
3. Manganese, $Mn(IV)$
4. Iron, $Fe(III)$
5. Sulphate, SO_4^{2-}
6. Carbon dioxide, CO_2

The use of dissolved oxygen as the electron acceptor yields the greatest amount of energy for the microorganisms, while the use of carbon dioxide releases the least amount of energy. For instance, if toluene is the microbial substrate, the use of oxygen results in a release of 914 kcal/mole of toluene, while the use of carbon dioxide releases 34 kcal/mole of toluene (Wiedemeier *et al.*, 1995).

2.1.2 Oxidation-Reduction Half-Reactions for the Degradation of Organic Compounds

The following list of equations represent the oxidation half-reactions for benzene, toluene, ethylbenzene and xylene and reduction half-reactions for oxygen, nitrate, ferric iron, manganese, sulphate and carbon dioxide, respectively (Wiedemeier *et al.*, 1995):

Oxidation Half-Reactions

Reduction Half-Reactions

Organic molecules react with compounds in the surrounding water in a sequence of enzyme mediated steps to release carbon dioxide, hydrogen ions and electrons. These electrons are then available for the respective reduction half-reaction, where the released hydrogen ions and electrons are used to produce water. The overall redox (degradation) reactions for each of the electron acceptors with toluene as the electron donor are listed below (Wiedemeier *et al.*, 1995):

Aerobic Respiration

Anaerobic Respiration

Denitrification

Manganese reduction

Iron reduction

Sulphate reduction

Fermentation, methanogenic zone

2.1.3 Formation of Redox Zones Beneath Contaminated Area

As contaminants move through an aquifer, the organic species will first be oxidized via microbial reactions through the use of the available dissolved oxygen, acting as the electron acceptor. As previously mentioned, the use of dissolved oxygen results in the greatest production of energy for the

microorganisms. The contaminant that follows is no longer oxidized by oxygen, as it has been depleted. Electrons are instead accepted by nitrate, which results in the second greatest energy release. This process continues until carbon dioxide becomes the final electron acceptor, resulting in the production of methane gas. Through the described phenomena, specific redox zones are established beneath a contaminated site based on the species of electron acceptor present in a given area. As less favourable electron acceptors are consumed in redox reactions, groundwater conditions become more reducing, a concept further discussed in Section 2.2.

2.1.4 Microbial Degradation and Energy Utilization From Redox Reactions

As previously discussed, redox reactions generate energy which may be harnessed by microorganisms. The redox reactions given by equations 13 through 18 are carried out internally by chemoheterotrophs. These microorganisms consume organic molecules for their source of energy, which allows them to perform cellular functions. The following sections detail the electron transfer process within microorganisms and how energy is extracted through the electron transfer.

2.1.5 Aerobic Degradation

Aerobic degradation of organic compounds takes place in the presence of oxygen. As seen in equation 2 for toluene, this liberates 36 electrons and 36 protons (H^+ ions). The coenzyme NAD^+ (nicotinamide adenine dinucleotide)

accepts electrons and protons since it functions as an oxidizing agent and is reduced to NADH (Campbell, 1993).

The potential energy loss associated with the transfer of electrons from NAD^+ to NADH is considered minimal, and NADH therefore represents stored energy for the microorganism. The stored energy is released for cellular use through an electron transport chain, which allows energy to be released in a series of small steps. The chain consists of mainly proteins, and occurs across the plasma membrane of the bacteria (Campbell, 1993).

At the top of the chain is NADH, with the transferred electrons from the substrate. The next member of the chain has a greater affinity for electrons, and therefore strongly 'pulls' on the electrons contained in NADH. The member accepts the electrons and is reduced. It is then oxidized as the electrons propagate down the chain to the next member. This second member has a greater affinity for electrons than the previous member, which caused the electrons to advance. The electrons continue down the chain, releasing energy in each step in what is analogous to a loss of potential energy. The final electron acceptor, oxygen, has the strongest affinity for electrons. The reduced oxygen then combines with the hydrogen proton to form water (Campbell, 1993).

The electron transport chain represents a cascade effect where small quantities of energy are released in each step. These small releases are manageable, as

opposed to a single larger release where losses due to heat would be great. The energy released is then available for adenosine triphosphate (ATP) generation. ATP is imperative for the existence of the microorganism, as it powers most cellular functions (Campbell, 1993).

2.1.6 Anaerobic Degradation

Organic carbon may also be oxidized in the absence of oxygen (anaerobic conditions). During anaerobic processes, electrons are removed from the substrate and travel along an electron transport chain in a similar fashion to that described for aerobic degradation. The key difference is that the final electron acceptor of the chain is not oxygen, but may be nitrate, manganese, ferric iron or sulphate (Campbell, 1993). As previously mentioned, the microorganisms will use the electron acceptor that yields the most energy until it is depleted. An example of a bacterial species involved in anaerobic processes are *Pseudomonas*, which denitrify nitrate to nitrogen gas, as in equation 14 (Campbell, 1993).

Methanogenic bacteria are strict anaerobes that degrade organics in the absence of oxygen, producing methane. Hydrogen from the organic compound is used to reduce carbon dioxide to methane. This process makes a limited amount of ATP from organic molecules without the use of an electron transport chain (Campbell, 1993).

2.2 Geochemical Indicators of Natural Attenuation

Many authors have cited geochemical trends as supporting evidence of natural attenuation (e.g., Borden *et al.*, 1995; Libelo *et al.*, 1998 and Reichart *et al.*, 1998). Wiedemeier (1995) and the American Standard Testing Material (ASTM) (1996) have both cited geochemical data and the associated trends as lines of evidence of natural attenuation in their protocols. Table 1, taken from the ASTM Standard (1996), summarizes parameters of concern and their implications for natural attenuation.

Table 1. Geochemical Indicators of Natural Attenuation.

Parameter	Implication for Natural Attenuation	Trend in Parameter Concentration if Contamination is High
Dissolved Oxygen (DO)	DO concentrations define aerobic versus anaerobic zones. DO is preferentially used by microorganisms as an electron acceptor as its use provides the greatest amount of energy for the organisms. Any oxygen entering the plume is rapidly depleted.	Decreasing
Nitrate (NO_3^-)	Next energetically favourable electron acceptor after DO is consumed ($\text{DO} < 0.5 \text{ ppm}$). Most favourable electron acceptor for anaerobic degradation.	Decreasing
Manganese (Mn^{+2})	Manganese is present as an oxide on sediment as MnO_2 (Mn^{+4}) and is used as an electron acceptor after nitrate is depleted. Upon utilization by organisms, a reduced, water-soluble form of Mn is produced (Mn^{+2}) which can be measured in groundwater samples	Increasing
Ferrous Iron (Fe^{+2})	Similar to manganese. Next favourable electron acceptor for anaerobic degradation after manganese. Ferric iron (Fe^{+3}) is present as an oxide and when reduced it is transformed to the soluble ferrous iron (Fe^{+2}) which can then be measured.	Increasing
Sulphate (SO_4^{-2})	Under strongly reducing conditions, sulphate is used as the electron acceptor after nitrate, manganese and iron. Low sulphate concentrations will be seen within the plume relative to upgradient concentrations. Sulfides are produced as a result of sulphate reduction.	Decreasing
Methane (CH_4)	Under strongly reducing conditions, methanogens (strict anaerobes) use CO_2 or cleave acetate to produce methane (and CO_2 in the case of acetate). Increased methane concentrations will be observed relative to outside the plume where the concentration is usually non-detect.	Increasing
Carbon Dioxide (CO_2)	CO_2 is produced during both aerobic and anaerobic degradation of BTEX compounds.	Increasing

An additional indicator of intrinsic biodegradation is oxidation-reduction (redox) potential. This parameter indicates the relative tendency of a solution to accept or donate electrons (*i.e.*, oxidizing versus reducing conditions). Redox reactions are carried out in groundwater by microorganisms as previously discussed. The parameters listed in Table 1 are electron acceptors and petroleum hydrocarbons are electron donors for such reactions. Some biodegradative processes can only operate within a certain range of redox conditions as denoted in Figure 2. Therefore, the measurement of this parameter upgradient and within the plume can be used to identify specific redox zones.

Figure 2. Redox Potentials, pH 7, 25°C
(taken from Wiedemeier *et al.*, 1995).

Conductivity, pH and temperature are also common parameters measured when sampling groundwater. Differences in pH between contaminated and uncontaminated groundwater may be indicative of microbial activity. Wiedemeier *et al.* (1995) also states that the optimum pH range for microbes capable of degrading hydrocarbons is from 6 to 8. Differences in conductivity between monitoring points may indicate that the samples come from different hydrogeologic zones. Temperature is important for gas solubility in water, namely dissolved oxygen as well as having an impact on biodegradation rates.

Changes over time in electron acceptors and biodegradation by-products (Mn^{+2} , Fe^{+2} , sulfides and methane) in addition to changes in redox potentials are linked to biodegradation processes. Geochemical data coupled with decreasing contaminant concentrations are evidence of in-situ biodegradation and constitute lines of evidence when assessing natural attenuation.

CHAPTER 3

3.0 Field Study

A site investigation was carried out by the author to obtain additional information pertaining to the delineation of soil and groundwater contamination at the site. The soil investigation consisted of a soil-vapour survey, soil test pit samples and borehole data obtained from the installation of monitoring wells. A hydrogeologic study was also performed to determine the direction of groundwater flow, the magnitude of gradients observed and the general groundwater table elevation at the site. The groundwater investigation consisted of four sampling rounds where groundwater concentrations of BTEX, TPH and various geochemical indicators were determined.

3.1 Soil Investigation

3.1.1 Soil-Vapour Survey

3.1.1.1 Methodology

A soil-vapour survey was conducted to delineate the zone of hydrocarbon contamination. The soil-vapour survey was completed over 4 areas (defined as A, B, C and D) at 154 locations, denoted in Figure 3. These areas were selected based on preliminary studies performed by Dillon (1994) that indicated elevated soil-vapour concentrations in these areas. A drive point soil-vapour probe and a GasTech (GT series, CO₂ version) gas monitor were used to measure combustible gas concentrations (ppmv) at depths of 0.5 m and 1.0 m.

Figure 3. Soil-Vapour Survey Sample Locations.

3.1.1.2 Results

The results for the soil-vapour survey at depths of 0.5 m and 1.0 m are provided in Appendix A while Figure 4 and Figure 5 present the krigged data for the 0.5 m and 1.0 m depths, respectively. It was found that the concentrations of combustibles were higher at a depth of 1.0 m than at a depth of 0.5 m. Elevated vapour concentrations were measured in the areas of the storage tank (Grid B), pump house (Grid C) and the four valve houses along the rail line (Grids A and D). Concentrations varied between 0 ppmv and greater than 10 000 ppmv, the upper limit of detection for the instrument used.

Figure 4. Soil-Vapour Contours of Combustibles at 0.5 m Depth (expressed as ppmv).

Figure 5. Soil-Vapour Contours of Combustibles at 1.0 m Depth (expressed as ppmv).

3.1.2 Borehole Drilling

3.1.2.1 Methodology

Upon the removal of the storage tanks in 1997, 6 monitoring wells remained within the fenced area and 8 monitoring wells were present outside of the fenced area. Seven additional wells (BH1-A, BH1-B, BH1-C, BH1-D, BH1-E, BH1-F, and BH1-G) were constructed within the fenced area in July of 1998 using a track mounted drill rig and a hollow stem auger. The wells were constructed with 50 mm, schedule 40, PVC well screen and riser pipes. The wells screens (#10 slot size) were 3 m in length and straddle the water table. The borehole annulus was backfilled with #3 silica sand to a distance of 30 cm below ground surface. A bentonite seal was placed above the well pack and an above-ground protective steel casing and cap were installed. A PVC slip-on cap was placed over the end of the riser pipe, which terminates approximately 1 m above ground surface. The new and existing monitoring wells were developed using a bladder pump with the exception of BH1-29 located west of Uplands Drive. The locations of the existing and new wells are shown in Figure 6.

Figure 6. Location of New and Existing Monitoring Wells.

Soil samples were collected with the use of a split spoon sampler as the monitoring wells were being constructed. Soil samples were logged according to soil type, texture, colour and visual or olfactory evidence of hydrocarbon contamination. One half of each soil sample was retained in a glass mason jar. The jar was covered with aluminum foil and a cover to minimize vapour losses and to allow equilibrium conditions to occur. The headspace concentration of combustibles as a percentage of the lower explosive limit (LEL) was measured using a GasTech sampler. The stratigraphy and headspace concentrations are presented on the borehole logs provided in Appendix B.

3.1.2.2 Results

The soil characteristics observed for the 7 recently constructed boreholes were in agreement with results obtained from Dillon (1994) for the 14 previously constructed boreholes. It was determined that the site is underlain by a shallow, medium to fine sand aquifer, which is approximately 4 meters deep. The sand unit is underlain by a silty sand layer of approximately 1.5 m in depth, which is in turn underlain by a clay aquitard that acts as a confining unit. Slug test results from previous investigations by Dillon (1994) indicated a range of hydraulic conductivity values of 5×10^{-3} cm/s to 1×10^{-2} cm/s for the sand unit.

The borehole logs also quantitatively and qualitatively indicate the level of contamination observed at various depths. It can be seen that the greatest degree of contamination generally occurred between 1 to 2 meters below the ground surface. This depth largely coincided with the depth to the water table, and elevated concentrations at this depth are in agreement with the results from the soil-vapour survey. A rapid decline in combustibles concentration was observed for depths greater than 2.5 meters. The highest percentages were detected at BH1-A and BH1-B, while moderate levels were detected at BH1-C, BH1-D and BH1-G and no combustible gas was detected at boreholes BH1-E and BH1-F.

3.1.3 Soil Test Pit Samples

3.1.3.1 Methodology

Upon completion of the soil-vapour survey, the location of the source areas was better defined through a soil sampling program. Thirty soil test pit locations were selected based on the vapour survey results. Figure 7 denotes the location of the test pits. Some locations were selected from areas of low soil-vapour concentrations, while others were selected in the most contaminated regions. A background sample was also collected in the southeast corner of the site. Samples were taken at a depth of 1.0 m in the excavated pits. To obtain a sample, a minimum of 2.5 cm of soil was removed from the excavation face and a soil sample was collected and placed directly into a 20 mL amber glass sample jar. The sample jar was filled completely and sealed with a teflon-lined cap. The samples were stored in a cooler at 4°C, followed by refrigeration until the time of analysis.

Figure 7. Test Pit and Soil Sampling Locations.

The samples were analyzed for benzene, toluene, ethylbenzene, m- and p-xylene, o-xylene and TPH at Carleton University. BTEX and TPH raw data, in addition to calibration data are provided in Appendix C. A solvent extraction process was employed with HPLC grade pentane as the solvent. The following procedure was employed for the extraction and analysis of the soil samples:

- extract hydrocarbons from soil by combining 10 mL of pentane with 10g of soil
- sonicate sample for 20 minutes to ensure thorough mixing and adequate extraction
- decant pentane and store at 4°C in autosampler vial with teflon lined septum
- all samples were extracted within 8 days of collection
- inject sample into a Varian Saturn II GC/mass spectrometer (MS) to determine BTEX concentrations
- inject sample into a Varian Model 3300 GC/flame ionization detector (FID) to determine total petroleum hydrocarbons (TPH), C5 to C20 range
- all samples were analyzed for BTEX and TPH within 50 days and 70 days, respectively

BTEX standards were made in pentane with 99% pure compounds. TPH standards were made from a 0.2 mg/ml Wisconsin Diesel Range Hydrocarbons standard in hexane that was purchased from AccuStandard Inc..

Six soil samples were packaged in a cooler with ice packs and shipped directly to a certified laboratory at Queens/RMC for QA/QC analysis. The QA/QC results for the 6 samples are provided in Appendix C

3.1.3.2 Results

QA/QC results for the 6 soil samples are summarized in Table 2. It can be seen that there is generally good agreement between the 2 sets of analyses for ethylbenzene and xylenes while there are discrepancies in the reported toluene concentrations. It can also be seen that greater TPH concentrations were consistently reported by Queen's University, with the exception of sample D11. Differences in analytical techniques and data analysis could be partially responsible for the observed discrepancies.

Table 2. QA/QC Results for Soil Samples.

Sample	Benzene ppb	Toluene ppb	Ethylbenzene ppb	Xylenes ppb	TPH ppm
A11 (C)	nd	3000	nd	nd	20
A11 (Q)	nd	nd	nd	nd	130
B16 (C)	nd	2000	2000	16000	620
B16 (Q)	nd	2600	1800	11000	1100
B28 (C)	nd	nd	nd	37000	1200
B28 (Q)	nd	nd	340	16000	7100
C28 (C)	nd	nd	30000	99000	5000
C28 (Q)	nd	1100	57000	280000	11100
C36 (C)	nd	nd	5000	28000	2900
C36 (Q)	nd	nd	2500	9000	3400
D11 (C)	nd	2000	nd	nd	29
D11 (Q)	nd	nd	nd	nd	nd

(C) – Carleton University

(Q) – Queen's University

Soil analysis results are summarized in Table 3. Of the 30 soil samples collected at a 1.0 m depth, 11 exceeded the Ministry of Environment (MOE) Table B criterion of 1000 mg/kg soil for total petroleum hydrocarbons (MOEE 1997). These values are denoted by the bold font in Table 3. Samples A2 and A9, located in the vicinity of valve houses 3 and 4 exceeded the TPH criteria, while the remainder of the exceedences occurred in the pump house area and the western edge of the area where the tanks were located (samples B7, B28, B31, C9, C24, C26, C28, C36 and C37). Soil samples B28, B31, C9, C24, C26, and C28 also exceeded the criterion for total xylenes. None of the soil samples were found to exceed benzene, toluene or ethylbenzene criteria. Sample locations that exceeded the mentioned criteria are denoted in Figure 8.

Table 3. Soil Analytical Results (µg/g).

Sample	Benzene	Toluene	Ethyl.	m,p-xyl.	o-xyl.	Total xyl.	Total BTEX	TPH
A2	nd	nd	46	140	41	181	227	19000
A9	nd	2	46	146	37	183	229	12000
A11	nd	3	nd	nd	nd	nd	3	20
A22	nd	2	nd	nd	nd	nd	2	450
A25	nd	2	nd	nd	nd	nd	2	9
B7	nd	nd	3	34	nd	34	37	1600
B9	nd	nd	nd	nd	nd	nd	nd	34
B16	nd	2	2	13	3	16	19	620
B25	nd	nd	nd	nd	nd	nd	nd	36
B28	nd	nd	nd	36	1	37	37	1200
B31	nd	nd	10	57	7	64	74	1700
B40	nd	nd	nd	nd	nd	nd	nd	35
B43	nd	nd	nd	nd	nd	nd	nd	33
B46	nd	nd	nd	nd	nd	nd	nd	230
C6	nd	nd	nd	nd	nd	nd	nd	26
C9	nd	1	32	89	21	110	143	6200
C24	nd	nd	10	56	18	74	84	3000
C26	nd	1	27	68	nd	68	96	1500
C28	nd	nd	30	76	23	99	129	5000
C36	nd	nd	5	26	2	28	33	2900
C37	nd	nd	nd	2	nd	2	2	4200
C39	nd	nd	nd	nd	nd	nd	nd	28
C48	nd	nd	nd	nd	nd	nd	nd	40
C52	nd	1	nd	nd	nd	nd	1	25
D5	nd	3	nd	4	1	5	8.0	230
D8	nd	2	nd	14	nd	14	16	520
D11	nd	2	nd	nd	nd	nd	2	29
D21	nd	1	nd	3	nd	3	4	340
D25	nd	4	nd	nd	nd	nd	4	44
Background	nd	nd	nd	nd	nd	nd	nd	nd
MOE	5.3	34	290			34		1000

nd – non detect ~ 1 ppm

Figure 8. Soil Analyses which Exceeded MOEE – Table B Criteria.

Visual observations were noted as the test pits were being excavated and these results are summarized in Table 4. It was noted that the colour of the soil horizon changed significantly at a depth of approximately 1.2 m to 1.5 m in many of the test pits, corresponding with high hydrocarbon odours. A hydrocarbon sheen was also noted on water that collected in some of the pits.

The visual and olfactory observations, noted in Table 4, generally agree with the corresponding soil analyses. For example the sharp contrast noted between B25 and B28 in Table 4 concur with the soil analysis at these locations. Test pit B25 indicated a sand of uniform colour over the depth of the excavation and no hydrocarbon odour was noted. At test pit B28, a very different soil profile was observed with darker stained soils at depth. The soil analysis indicated a high

TPH concentration (1200 µg/g) for B28 in comparison to a relatively low TPH concentration (36 µg/g) for B25. Likewise the soil-vapour concentration at B25 (800 ppm) was considerably lower than the concentration at B28 (>10000 ppm).

Table 4. Summary of Observations from Soil Test Pit Excavations.

Test Pit	Observation
A2	Gravel underlain with brown sand, slightly darker soil at depth, hydrocarbon (hc) odour
A9	Topsoil underlain with brown sand changing to a darker stained sand at depth
A11	Brown sand, darker stained soil layer at depth > 1.0 m
A22	Topsoil underlain with brown sand changing to a darker stained sand at depth, hc odour
A25	Topsoil underlain with bright rust/brown sand, darker grey/brown sand at depth, several very thin dark soil striations within sand
B7	Brown sand and several rocks, dark stained soil over top 0.3 m
B9	Brown sand, darker brown sand at bottom of excavation
B16	Darker stained sand at depth of 1 – 1.5 m, definite hc odour, hydrocarbon sheen on water collecting at the base of the excavation
B25	Topsoil underlain with bright rust/brown sand throughout depth of excavation
B28	Sharp contrast in soils from soils encountered at B25, brown sand changing to a darker stained soil at depth, wires encountered
B31	Coarse sand underlain with fine brown sand, darker brown/grey sand at depth, water flowing into excavation from coarse sand layer, sheen present on water collecting at the base of the excavation
B40 or B43	Brown sand, slight darker sand at depth, tar paper encountered at approx. depth of 0.5 m
B46	Brown sand, darker stained sand at depth > 1.0 m, hc odour
C6	Topsoil underlain with brown sand over entire depth
C9	
C18	Brown sand, darker stained sand at depth > 1.0 m, hc odour
C24	Distinct black cohesive soil layer 10 cm in thickness located at a depth of approximately 0.3 m, which was not continuous through the excavation; strong hydrocarbon odour; dark stained sand at base of excavation.
C26	Distinct black cohesive soil layer 10 cm in thickness located at a depth of approximately 0.3 m, which was not continuous through the excavation; infiltrating water from above the black layer was covered with a sheen; strong hydrocarbon odour.
C28	Topsoil underlain with brown sand changing to light brown/grey at depth
C36	
C37	Topsoil underlain with light brown sand
C39	

C52	Gravel underlain by a bright rust/brown sand over entire depth of excavation
D5	Encountered clay conduit labeled electrical cables at a depth of 0.5 m, brown sand, dark staining at 0.5 m depth, strong hc odour, sample taken at 0.45 m
D8	Gravel underlain with brown sand, hc odour, sheen present on water infiltrating the excavation
D11	Gravel underlain with bright rust/brown sand, lighter brown at depth
D21	
D25	Topsoil underlain with brown sand, no hc odour

3.1.3.2.1 Heavy Metals, VOCs and PAHs

Two soil samples were analyzed for heavy metals, VOCs and PAHs. One soil sample was collected at a depth of 1 m at test pit C24 and a background sample was collected near the southeast corner of the site. Test pit C24 is located in an area known to be impacted by petroleum hydrocarbons. The analytical results are contained in Appendix C. Copper, nickel and arsenic were detected in both sample C24 and the background sample at concentrations below 10 µg/g. Comparison of the results at C24 and background indicate that the soil at C24 has not been impacted by heavy metal contamination. The VOC and PAH concentrations for the background soil sample were below the detection limit. The VOCs and PAHs detected in sample C24 indicate that the soil has been impacted by petroleum hydrocarbons, as indicated in Section 3.1.3.2. The naphthalene, acenaphthene, fluorene and phenanthrene concentrations detected in the sample are below MOEE Table B guidelines of 40, 1300, 350 and 40 ppm, respectively.

3.2 Hydrogeologic Investigation

Groundwater elevations were recorded with an electronic water level meter to determine the depth to the water table and the magnitude and direction of the

gradient that exists at the site. Water levels were measured on 16 occasions including monthly measurements for a period of 1 year (April 1999 to March 2000). Groundwater elevations and the depth to the water table at each well location for the 16 monitoring events are reported in Table 5 and Table 6, respectively.

Table 5. Groundwater Elevations.

Well	Groundwater Elevations (masl)															
	13-Jul 1998	31-Aug 1998	30-Oct 1998	11-Dec 1998	29-Apr 1999	28-May 1999	30-Jun 1999	20-Jul 1999	23-Aug 1999	19-Sep 1999	24-Oct 1999	28-Nov 1999	27-Dec 1999	25-Jan 2000	22-Feb 2000	31-Mar 2000
BH1-1	100.18	99.91	99.93	99.99	100.55	100.23	99.98	99.92	99.77	99.78	99.84	99.89	100.02	100.05	99.85	100.53
BH1-12	100.15	99.83	99.90	100.01	100.60	100.22	99.90	99.84	99.69	99.72	99.81	99.88	100.05	100.00	99.82	100.68
BH1-14	99.90	99.50	99.76	99.88	100.29	99.82	99.69	99.61	99.46	99.60	99.53	99.57	99.17	99.47	99.47	99.62
BH1-15	99.99	99.64	99.77	99.91	100.48	100.07	99.72	99.67	99.51	99.55	99.67	99.79	99.93	99.85	99.67	100.62
BH1-19	100.09	99.70	99.87	100.04	100.73	100.20	99.78	99.72	99.56	99.62	99.75	99.92	100.08	99.97	99.77	101.02
BH1-21	100.18	99.90	99.90	99.96	100.54	100.21	99.96	99.91	99.76	99.76	99.82	99.85	100.00	100.03	99.82	100.48
BH1-24			99.88	100.02	100.60	100.19	99.84	99.79	99.63	99.67	99.78	99.90	100.05	99.99	99.81	100.75
BH1-25	100.48	99.65	99.91	100.12	100.62	100.18	99.75	99.69	99.53	99.61	99.78	100.00	100.10	99.94	99.81	100.99
BH1-27			99.98		100.57	99.25	99.96	99.92	99.76	99.79	99.87	99.97	100.07	100.06		100.65
BH1-28	100.12	99.83	99.86	99.94	100.55	100.17	99.70	99.84	99.69	99.70	99.78	99.82		99.98	99.79	100.55
BH1-29	100.17	99.91			100.52	100.20	99.96	99.91	99.76	99.76	99.81	99.83				
BH1-32	100.02	99.75	99.91	100.08	100.66		99.75	99.73	99.61	99.64	99.81	99.96		100.01	99.79	100.98
BH1-33	100.03	99.60	99.94	100.21	100.84	100.21	99.66	99.57	99.45	99.51	99.73	99.94	100.22	100.02	99.82	101.27
BH1-34	100.11	99.75	99.91	100.12	100.72	100.11	99.82	99.76	99.61	99.66	99.80	100.06	100.21	100.04	99.79	
BH1-A	100.19	99.91	99.93	100.00	100.56	100.24	99.97	99.92	99.77	99.78	99.84	99.89	100.02	100.04	99.84	100.55
BH1-B	100.18	99.90	99.90	99.97	100.56	100.23	99.96	99.91	99.76	99.77	99.82	99.85	100.01	100.03	99.83	100.54
BH1-C	100.13	99.80	99.90	100.02	100.58	100.18	99.85	99.79	99.63	99.67	99.78	99.88	100.03	99.96	99.78	100.70
BH1-D	100.16	99.84	99.92	100.04	100.62	100.23	99.91	99.85	99.70	99.74	99.82	99.93	100.06	100.02	99.83	100.82
BH1-E	100.15	99.81	99.92	100.06	100.57	100.22	99.87	99.85	99.68	99.72	99.82	99.95	100.08	100.01	99.84	100.88
BH1-F	100.10	99.71	99.92	100.10	100.59	100.19	99.79	99.74	99.58	99.66	99.79	99.98	100.10	99.93	99.78	100.97
BH1-G	100.18	99.76	99.97	100.25	100.70	100.24	99.88	99.81	99.66	99.73	99.94	100.09	100.28	100.08	99.88	101.22

Table 6. Depth to the Water Table.

Depth to the Water Table (mbgs)																
Well	13-Jul 1998	31-Aug 1998	30-Oct 1998	11-Dec 1998	29-Apr 1999	28-May 1999	30-Jun 1999	20-Jul 1999	23-Aug 1999	19-Sep 1999	24-Oct 1999	28-Nov 1999	27-Dec 1999	25-Jan 2000	22-Feb 2000	31-Mar 2000
BH1-1	1.43	1.70	1.68	1.62	1.06	1.38	1.63	1.69	1.84	1.83	1.77	1.72	1.59	1.56	1.76	1.08
BH1-12	1.67	1.99	1.92	1.81	1.23	1.61	1.92	1.98	2.14	2.11	2.01	1.94	1.77	1.82	2.00	1.15
BH1-14	1.43	1.83	1.57	1.45	1.04	1.51	1.64	1.72	1.87	1.73	1.80	1.76	2.16	1.86	1.86	1.71
BH1-15	1.53	1.88	1.75	1.61	1.04	1.45	1.80	1.85	2.01	1.97	1.85	1.73	1.59	1.67	1.85	0.90
BH1-19	1.43	1.82	1.65	1.48	0.79	1.32	1.74	1.80	1.96	1.90	1.77	1.60	1.44	1.55	1.75	0.50
BH1-21	1.46	1.73	1.73	1.68	1.10	1.42	1.67	1.72	1.88	1.87	1.82	1.78	1.64	1.61	1.81	1.15
BH1-24			1.71	1.57	1.00	1.40	1.75	1.81	1.97	1.92	1.81	1.69	1.54	1.60	1.79	0.84
BH1-25	1.24	1.64	1.38	1.17	0.66	1.11	1.54	1.59	1.75	1.67	1.50	1.29	1.19	1.35	1.48	0.30
BH1-27			1.04		0.46	1.77	1.06	1.11	1.27	1.24	1.15	1.05	0.95	0.96		0.37
BH1-28	2.33	2.62	2.59	2.52	1.91	2.28	2.75	2.61	2.76	2.75	2.67	2.63		2.47	2.67	1.90
BH1-29	1.35	1.61			1.00	1.31	1.55	1.60	1.75	1.76	1.71	1.68				
BH1-A	1.32	1.60	1.58	1.51	0.95	1.27	1.54	1.59	1.74	1.73	1.67	1.62	1.49	1.47	1.67	0.96
BH1-B	1.48	1.76	1.76	1.69	1.10	1.43	1.70	1.75	1.90	1.89	1.84	1.81	1.65	1.63	1.83	1.12
BH1-C	1.52	1.85	1.75	1.62	1.07	1.47	1.80	1.85	2.01	1.97	1.87	1.77	1.62	1.69	1.87	0.95
BH1-D	1.35	1.67	1.59	1.47	0.89	1.28	1.60	1.66	1.81	1.77	1.69	1.58	1.45	1.49	1.68	0.69
BH1-E	1.18	1.52	1.41	1.27	0.76	1.11	1.46	1.48	1.65	1.61	1.51	1.38	1.25	1.32	1.49	0.45
BH1-F	1.16	1.55	1.34	1.16	0.67	1.07	1.46	1.51	1.67	1.60	1.47	1.28	1.15	1.33	1.47	0.29
BH1-G	1.29	1.71	1.49	1.21	0.77	1.23	1.58	1.65	1.80	1.73	1.53	1.38	1.18	1.38	1.59	0.25

Table 7 contains the magnitude and direction of the gradient for the 16 water level measurements. The maximum and minimum groundwater elevations and depth to the water table for each of the 16 monitoring events are provided in Table 8. Groundwater contour plots for each date listed in Table 7 are provided in Appendix D.

Table 7. Groundwater Gradient and Direction.

Date	Gradient (m/m)	Direction
July 13 1998	0.00067	NNE
August 31 1998	0.0013	NE
October 30 1998	0.00045	NW
December 11 1998	0.00095	SW
April 29 1999	0.0013	SSW
May 28 1999	0.00014	NNE
June 30 1999	0.00098	NNE
July 20 1999	0.00091	NNE
August 23 1999	0.00095	NNE
September 19 1999	0.00073	N
October 24 1999	0.00019	ENE
November 28 1999	0.00063	WSW
December 27 1999	0.00029	SSW
January 25 2000	0.00037	NNE
February 22 2000	0.00034	NNE
March 31 2000	0.0022	SSW

Table 8. Summary of Maximum and Minimum Groundwater Elevations and Depth to the Water Table.

Well	Maximum elevation/ distance to water table (masl)	Minimum elevation/ distance to water table (masl)	Difference (m)
BH1-1	100.55 / 1.84	99.77 / 1.60	0.78
BH1-12	100.68 / 2.14	99.69 / 1.15	0.99
BH1-14	100.29 / 2.16	99.17 / 1.04	1.12
BH1-15	100.62 / 2.01	99.51 / 0.90	1.11
BH1-19	101.02 / 1.96	99.56 / 0.50	1.46
BH1-21	100.54 / 1.88	99.76 / 1.10	0.78
BH1-24	100.75 / 1.97	99.63 / 0.84	1.13
BH1-25	100.99 / 1.75	99.53 / 0.30	1.46
BH1-27	100.65 / 1.77	99.25 / 0.37	1.40
BH1-28	100.55 / 2.76	99.69 / 1.90	0.86
BH1-29	100.52 / 1.76	99.76 / 1.00	0.76
BH1-32	100.98	99.61	1.38
BH1-33	101.27	99.45	1.82
BH1-34	100.72	99.61	1.11
BH1-A	100.56 / 1.74	99.77 / 0.95	0.80
BH1-B	100.56 / 1.90	99.76 / 1.10	0.80
BH1-C	100.70 / 2.01	99.63 / 0.95	1.07
BH1-D	100.82 / 1.81	99.70 / 0.69	1.13
BH1-E	100.88 / 1.65	99.68 / 0.45	1.20
BH1-F	100.97 / 1.68	99.58 / 0.29	1.39
BH1-G	101.22 / 1.80	99.66 / 0.25	1.55

The results presented in Table 5 indicate that groundwater elevations varied during the year from 99.17 masl to 101.27 masl at the well locations across the site and that the higher elevations occurred in the spring when recharge is significant. The depth to the water table, presented in Table 6, varied from 2.76 mbgs to 0.25 mbgs at well locations across the site, indicating that the water table is shallow. The maximum fluctuation in groundwater elevations at each well are also presented in Table 8. The greatest fluctuation in water elevation at a specific well location occurred at BH1-G, where a difference of 1.56 m was

observed. The results in Table 7 indicate that the direction and magnitude of groundwater flow at the site are variable with time.

3.3 Groundwater Contamination

3.3.1 Sampling Methodology

Groundwater samples were collected from the monitoring wells by first purging the wells of 40 litres of groundwater using dedicated 'Waterra' inertial hand pumps. The sampling apparatus used for groundwater sampling is illustrated in Figure 9.

Figure 9. Groundwater Sampling Apparatus.

Dedicated ¼ inch low density polyethylene tubing was also installed in each well for groundwater sampling. The tubing was secured to a flow-through, glass sampling vial to minimize exposure to ambient air. Water exiting the sampling vial then flowed through flexible Masterflex tubing which was passed through a peristaltic pump. The water then entered the flow cell (Micropurge Flow Cell, Model 4000) where dissolved oxygen, temperature, pH, conductivity and redox potential were measured via probes and a meter reported their values. Once readings had stabilized, samples were collected by disconnecting the glass vial and headspace was minimized during their collection. Triplicate groundwater samples were collected in 80 ml glass vials and were sealed with teflon/silicon septa. Two samples were retained for BTEX/TPH analyses and the last sample was used to determine the concentration of ferrous iron in the groundwater collected at each well. An additional 200 ml of groundwater were collected in high density polyethylene bottles and were used for geochemical analyses. Upon their collection, the samples were immediately stored in a cooler to maintain a temperature of approximately 4°C until they could be transferred to an appropriate refrigeration unit.

Groundwater levels were also monitored during sample collection to ensure that the water level remained constant while sampling. This ensured that water was being drawn from the surrounding formation and not from within the well itself.

3.3.2 Groundwater Analyses

3.3.2.1 BTEX and TPH

BTEX compounds were analyzed with a Varian Saturn II GC/MS, while TPH concentrations were determined through the use of a Varian Model 3300 GC/FID. For the first sampling round, a separatory funnel liquid-liquid extraction method was employed with HPLC grade pentane as the solvent:

- extract hydrocarbons from groundwater by combining 10 mL pentane with 10 mL groundwater sample
- shake sample in separatory funnel to ensure complete extraction
- decant pentane and store in autosampler vial with teflon lined septum
- samples were extracted within 3 days of collection
- inject sample into GC/MS to determine BTEX concentrations
- inject sample into GC/FID to determine total petroleum hydrocarbons (TPH), C5 to C20 range.
- samples were analyzed within 30 days of extraction

In the 2 subsequent rounds, a Tekmar Model LSC 2000 purge and trap apparatus was employed to determine BTEX concentrations in conjunction with the GC/MS. Samples were purged at ambient temperature for 12 minutes with helium, where the volatile compounds were transferred to the vapour phase. The vapour phase was then swept through a sorbent Tenax column and the volatiles were transferred to the solid medium. After purging had ceased, the column temperature was rapidly increased to 180°C to ensure complete desorption of the volatile compounds, which were then swept to the GC column. The samples were subsequently analyzed for BTEX compounds with the use of a mass spectrometer. BTEX and TPH raw data, in addition to calibration data for the 3 sampling rounds are provided in Appendix C. Seprotech Laboratories analyzed

samples collected during the May 2000 sampling round and the results are provided in Appendix C.

BTEX standards were made in water with 99% pure compounds. TPH standards were made from a 0.2 mg/ml Wisconsin Diesel Range Hydrocarbons standard in hexane, purchased from AccuStandard Inc..

QA/QC samples were sent to the Queens/RMC Laboratory for the November 1998 and August 1999 sampling rounds. The QA/QC results for the 2 sampling rounds are located in Appendix C.

3.3.2.2 Nitrate, Ferrous Iron and Sulphate

Nitrate, ferrous iron and sulphate were analyzed in groundwater samples with the use of various HACH kits (0-10 mg/L Model NI-14, 0-10 mg/L Model IR-18C and Pocket Colorimeter for nitrate, ferrous iron and sulphate respectively). Ferrous iron analyses were carried out immediately in the field upon collection of samples to minimize the possibility of exposure to ambient oxygen. Sulphate and nitrate analyses were performed in the laboratory at Carleton University on the same day as sample collection. The analyses of nitrate and ferrous iron were colorimetric in nature while analysis of sulphate was based on changes in turbidity. All analyses involved comparing a reacted water sample with an unreacted water sample. All samples were allowed to come to ambient temperature before analyses were performed.

3.3.3 Results

The 4 groundwater sampling rounds were conducted in November 1998, June 1999, August 1999 and May 2000 to assess the degree of groundwater contamination existing at the site. QA/QC results for the November 1998 and August 1999 sampling rounds are presented in Table 9 and Table 10, respectively. No QA/QC samples were analyzed for the June 1999 sampling event and Seprotech Laboratories conducted the analyses for the groundwater samples collected in May 2000.

For the November 1998 sampling round, greater toluene and TPH concentrations were measured at Carleton University than at Queen's University. Benzene concentrations reported by both laboratories are in good agreement, while minor discrepancies are noted for ethylbenzene and xylenes.

Table 9. QA/QC Results for November 1998.

Sample	Benzene ppb	Toluene ppb	Ethylbenzene ppb	Xylenes ppb	TPH ppm
BH1-14 (C)	490	1500	1600	16100	52
BH1-14 (Q)	400	1100	2400	9800	18
BH1-19 (C)	280	710	nd	nd	92
BH1-19 (Q)	550	nd	190	200	nd
BH1-32 (C)	nd	560	nd	nd	39
BH1-32 (Q)	nd	nd	nd	nd	nd
BH1-33 (C)	nd	630	nd	nd	nd
BH1-33 (Q)	nd	nd	270	nd	nd
BH1-34 (C)	250	790	nd	nd	38
BH1-34 (Q)	260	nd	380	1100	nd

(C) – Carleton University

(Q) – Queen's University

The results presented for the August 1999 sampling round are in good agreement for benzene, toluene and xylenes while some discrepancies exist for ethylbenzene and TPH. As mentioned in Section 3.1.3.2, differences in analytical and data analysis techniques could be partially responsible for the noted discrepancies.

Table 10. QA/QC Results for August 1999.

Sample	Benzene ppb	Toluene ppb	Ethylbenzene ppb	Xylenes ppb	TPH ppm
BH1-21 (C)	2341	9	1190	3934	6
BH1-21 (Q)	2600	11	590	6600	13
BH1-27 (C)	nd	nd	nd	nd	nd
BH1-27 (Q)	nd	nd	nd	2	nd
BH1-28 (C)	43	nd	1	38	nd
BH1-28 (Q)	38	nd	nd	32	nd
BH1-A (C)	1676	2	639	2554	28
BH1-A (Q)	2600	9	4	4400	8
BH1-C (C)	70	nd	89	155	45
BH1-C (Q)	23	nd	nd	32	nd

(C) – Carleton University

(Q) – Queen's University

Sample results are presented in Table 11. Table 11 also includes provincial (Ontario Ministry of the Environment and Energy (MOEE), Guidelines for Use at Contaminated Sites in Ontario, Revised February 1997, Table B, Nonpotable groundwater criteria) guidelines for nonpotable groundwater.

Table 11. Groundwater Analytical Results

Sample	Date	Benzene ppb	Toluene ppb	Ethyl. ppb	m,p-xyl. ppb	o-xyl. ppb	Total xyl. ppb	Total BTEX ppb	TPH ppm
BH1-1	Nov-98	nd	910	nd	nd	nd	nd	910	46
	Jun-99	nd	nd	nd	nd	nd	nd	nd	4
	Aug-99	nd	nd	nd	nd	nd	nd	nd	1
	May-00	nd	nd	nd	nd	nd	nd	nd	nd
BH1-12	Nov-98	nd	920	nd	nd	nd	nd	920	55
	Jun-99	nd	1	nd	nd	157	157	158	4
	Aug-99	10	5	5	7	165	23	252	nd
	May-00	nd	nd	nd	nd	nd	nd	nd	nd
BH1-14	Nov-98	490	1500	1600	11000	5100	16100	19690	52
	Jun-99	8	32	71	nd	702	702	814	15
	Aug-99	192	50	314	1717	820	2537	3094	1
	May-00	380	1800	75	7500	3500	11000	13255	58
BH1-15	Nov-98	nd	750	nd	nd	nd	nd	750	39
	Jun-99	nd	nd	1	nd	13	13	13	5
	Aug-99	1	3	18	81	40	121	143	5
	May-00	nd	nd	nd	nd	nd	nd	nd	nd
BH1-19	Nov-98	280	710	nd	nd	nd	nd	990	92
	Jun-99	1	nd	nd	nd	nd	nd	1	3
	Aug-99	447	nd	34	410	nd	410	891	22
	May-00	nd	nd	nd	nd	nd	nd	nd	nd
BH1-21	Nov-98	6000	890	1300	10000	nd	10000	18000	2
	Jun-99	1060	nd	nd	nd	nd	nd	1060	12
	Aug-99	2341	9	1190	3934	nd	3934	7474	6
	May-00	1600	25	nd	3900	130	4030	5655	8
BH1-24	Nov-98	580	800	110	4500	nd	4500	6000	14
	Jun-99	12	nd	2	nd	nd	nd	14	4
	Aug-99	316	nd	148	3111	nd	3111	3574	3
	May-00	nd	nd	2	2	nd	2	4	nd
BH1-25	Nov-98	nd	740	nd	nd	nd	nd	740	41
	Jun-99	nd	nd	nd	nd	nd	nd	nd	3
	Aug-99	nd	nd	nd	1	nd	1	1	4
	May-00	nd	nd	nd	nd	nd	nd	nd	1
BH1-27	Nov-98	nd	730	nd	nd	nd	nd	730	25
	Jun-99	nd	nd	nd	nd	nd	nd	nd	4
	Aug-99	nd	nd	nd	nd	nd	nd	nd	nd
	May-00	nd	nd	nd	nd	nd	nd	nd	nd
BH1-28	Nov-98	nd	490	nd	nd	nd	nd	490	35
	Jun-99	nd	nd	6	nd	nd	nd	6	2
	Aug-99	43	nd	1	38	nd	38	82	nd
	May-00	59	nd	5	310	4	314	378	1

Table 11 (Continued)

Sample	Date	Benzene ppb	Toluene ppb	Ethyl. ppb	m,p-xyl. ppb	o-xyl. ppb	Total xyl. ppb	Total BTEX ppb	TPH ppm
BH1-32	Nov-98	nd	560	nd	nd	nd	nd	560	39
	Jun-99	nd	nd	nd	nd	nd	nd	nd	5
	Aug-99	242	nd	nd	nd	nd	nd	242	nd
	May-00	nd	nd	nd	nd	nd	nd	nd	nd
BH1-33	Nov-98	nd	630	nd	nd	nd	nd	630	nd
	Jun-99	16	nd	nd	nd	7	7	23	3
	Aug-99	30	nd	534	nd	nd	nd	564	15
	May-00	nd	nd	2	nd	3	3	5	nd
BH1-34	Nov-98	250	790	nd	nd	nd	nd	1040	38
	Jun-99	4	nd	nd	nd	nd	nd	4	3
	Aug-99	8	nd	25	229	nd	229	263	nd
BH1-A	Nov-98	5000	790	870	6800	nd	6800	13460	43
	Jun-99	701	nd	nd	19	nd	19	720	9
	Aug-99	1617	3	157	1175	nd	1175	2952	8
	May-00	1100	nd	nd	2400	nd	2400	3500	7
BH1-B	Nov-98	3700	820	1200	13000	nd	13000	18720	38
	Jun-99	295	nd	nd	41	nd	41	336	14
	Aug-99	1676	2	639	2554	nd	2554	4871	28
	May-00	505	nd	nd	1100	5	1105	1610	3
BH1-C	Nov-98	nd	760	nd	nd	nd	nd	760	43
	Jun-99	9	nd	nd	nd	nd	nd	9	2
	Aug-99	70	nd	89	155	nd	155	314	45
	May-00	nd	nd	nd	nd	nd	nd	nd	nd
BH1-D	Nov-98	580	4100	200	10000	1900	11900	16780	49
	Jun-99	3	nd	nd	4	32	36	39	7
	Aug-99	309	189	649	1954	607	2561	3708	10
	May-00	nd	nd	nd	nd	nd	nd	nd	nd
BH1-E	Nov-98	nd	590	nd	nd	nd	nd	590	nd
	Jun-99	nd	nd	nd	nd	nd	nd	nd	5
	Aug-99	nd	nd	nd	1	nd	1	1	nd
	May-00	nd	nd	1	nd	nd	nd	1	nd
BH1-F	Nov-98	nd	860	nd	nd	nd	nd	860	42
	Jun-99	nd	nd	nd	nd	1	1	1	4
	Aug-99	nd	nd	nd	1	nd	1	1	104
	May-00	nd	nd	nd	nd	nd	nd	nd	nd
BH1-G	Nov-98	540	1900	1200	8900	2100	11000	14640	54
	Jun-99	104	111	nd	26	460	486	700	15
	Aug-99	1292	2410	942	4174	4911	9085	13729	20
	May-00	280	25	nd	2500	830	3330	3635	4
MOE		1900	5900	28000			5600		

nd – non detect ~ 1 ppb for BTEX
~ 1 ppm for TPH

The results presented in Table 11 indicate that the highest petroleum hydrocarbon concentrations occurred in the vicinity of the contaminated areas identified by the soil-vapour survey and soil analyses, corresponding to BH1-12, BH1-14, BH1-21, BH1-24, BH1-A, BH1-B, BH1-D and BH1-G. The MOEE criterion of 1900 ppb for benzene was exceeded at BH1-21, BH1-A and BH1-B for various sampling rounds. The toluene and ethylbenzene criteria were never exceeded, while the total xylenes criterion of 5600 ppb was exceeded at BH1-14, BH1-21, BH1-A, BH1-B, BH1-D and BH1-G. BTEX concentrations less than the MOE criteria were also detected at wells downgradient of the identified contaminated areas, including BH1-15, BH1-19, BH1-33 and BH1-C. Figure 10 illustrates the locations where MOEE criteria were exceeded.

Figure 10. Groundwater Analyses which Exceeded MOEE – Table B Criteria.

The results presented in Table 11 indicate that petroleum hydrocarbon concentrations in groundwater samples collected at each of the 20 wells varied with time. This was attributed to the variable nature of the groundwater flow at the site, which influences the migration of contaminants.

The geochemical indicators of biodegradation activity (dissolved oxygen, nitrate, ferrous iron, sulphate and redox potential), along with pH, temperature and conductivity measurements are presented in Table 12. The dissolved oxygen concentrations measured in water samples collected in the area of the former pump house and valve houses (BH1-12, BH1-14, BH1-15, BH1-21, BH1-24, BH1-28, BH1-A, BH1-B, BH1-C, BH1-D and BH1-G) were low (generally less than 1.0 mg/L) indicating the depletion of oxygen and anaerobic conditions. The values for redox potential are in agreement with the dissolved oxygen concentrations measured in groundwater samples collected from wells in the area of the valve houses and pump house in that low dissolved oxygen concentrations correspond to negative redox potentials (0 to -170 mV). Positive values for redox potential for the November 1998 and June 1999 rounds existed in groundwater samples collected from wells BH1-32, BH1-33, BH1-34, and BH1-19 to the north, wells BH1-E, BH1-F and BH1-25 to the east, and well BH1-1 to the southwest of the identified contaminated areas. The redox potentials in groundwater samples collected in August 1999 and May 2000 were all negative, however the least negative values coincided with the wells for which positive

measurements had previously been observed. This indicates less reducing conditions at these locations and hence less impact of hydrocarbon degradation. The hydrocarbon concentrations were generally found to be lower in these areas as well.

Nitrate was not deemed a significant electron acceptor at this site as it was only detected in groundwater samples at BH1-1, BH1-E and BH1-F at relatively low concentrations (*i.e.*, less than 5 mg/l). Elevated iron concentrations were observed in groundwater samples collected in the former valve house and pump house areas, while relatively low levels of ferrous iron were measured in groundwater samples collected outside of the identified source areas. The high ferrous iron concentrations, reduced dissolved oxygen concentrations and negative redox potential values are indicative of high levels of microbial activity in the area of the former valve and pump house areas.

The sulphate concentrations do not support the other geochemical indicators at all the wells. The elevated sulphate concentrations at BH1-1 and BH1-E agree with the high dissolved oxygen and redox values noted in the groundwater at these wells, but elevated sulphate values at BH1-12 do not agree with the low redox values. The low redox values indicate reduced conditions, which should result in lower sulphate concentrations in comparison to background levels.

Table 12. Geochemical Indicator Concentrations

Sample	Date	Temp. (°C)	pH	Cond. (uS/cm)	Redox Potential (mV)	O ₂ (mg/L)	N-NO ₃ ⁻ (mg/L)	Fe ⁺² (mg/L)	SO ₄ ⁻² (mg/L)
BH1-1	Nov-98	8.4	7.18	239	12.0	4.70	nd	nd	12
	Jun-99	13.85	7.27	277	26.2	2.07	0.02	nd	6
	Aug-99	12.93	6.76	319	-104.7	1.90	nd	nd	12
	May-00	7.22	7.38	1112	-65.7	6.84	nd	nd	1
BH1-12	Nov-98	9.2	6.88	584	-145.0	1.50	nd	3.0	>70
	Jun-99	17.01	6.90	523	-127.9	0.62	nd	0.4	1
	Aug-99	15.45	7.13	701	-130.7	0.53	nd	4.4	100
	May-00	8.80	7.00	1967	-130.3	1.39	nd	4.6	nd
BH1-14	Nov-98	9.6	6.96	413	-101.0	-	nd	5.2	nd
	Jun-99	10.54	6.98	430	-104.8	1.40	nd	5.8	nd
	Aug-99	14.06	7.92	448	-144.4	0.57	nd	7.4	nd
	May-00	9.39	6.87	1893	-170.0	1.19	nd	7.6	nd
BH1-15	Nov-98	8.5	7.08	385	-80.0	0.80	nd	4.5	nd
	Jun-99	12.06	6.60	346	-114.2	0.62	nd	4.0	1
	Aug-99	15.33	7.34	316	-125.7	0.92	nd	5.4	14
	May-00	9.98	7.02	1684	-116.2	1.34	nd	3.6	nd
BH1-19	Nov-98	8.8	-	<10	97.0	-	nd	4.4	nd
	Jun-99	10.06	7.20	321	-15.7	0.70	nd	1.0	1
	Aug-99	13.93	8.33	408	-112.0	0.73	nd	4.2	nd
	May-00	8.70	7.02	1523	-104.5	1.63	nd	1.2	2
BH1-21	Nov-98	10.2	6.76	567	-71.0	1.30	nd	6.7	nd
	Jun-99	13.85	6.47	905	-102.4	1.06	nd	8.0	nd
	Aug-99	15.37	6.63	651	-118.1	0.99	nd	7.0	1
	May-00	7.53	6.54	1828	-107.1	1.69	nd	6.4	nd
BH1-24	Nov-98	7.8	6.64	395	186.0	-	nd	6.4	nd
	Jun-99	12.4	6.98	378	-83.0	1.20	nd	5.7	nd
	Aug-99	14.65	7.84	482	-139.7	1.20	nd	5.8	nd
	May-00	8.54	6.92	1503	-168.8	1.74	nd	6.5	1
BH1-25	Nov-98	8.9	7.16	142	64.0	-	nd	nd	9
	Jun-99	19.87	7.71	211	206.3	3.91	nd	0.3	nd
	Aug-99	14.59	8.19	156	-112.3	0.80	nd	0.5	5
	May-00	8.76	7.30	945	-25.3	4.83	nd	nd	2
BH1-27	Nov-98	8.4	6.98	428	-59.0	nd	nd	5	54
	Jun-99	11.93	6.82	490	-78.4	nd	nd	4.4	58
	Aug-99	14.12	7.94	493	-129.1	0.75	nd	4.2	62
	May-00	6.98	6.75	1361	-133.3	1.25	nd	4.2	47
BH1-28	Nov-98	9.4	7.18	737	-66.0	1.20	nd	4.7	16
	Jun-99	13.69	6.51	563	-113.8	0.94	nd	6.2	nd
	Aug-99	16.13	7.17	1402	-128.3	0.81	nd	6.2	46
	May-00	10.34	6.47	1773	-102.8	3.03	nd	6.2	nd

Table 12 (Continued)

Sample	Date	Temp. (°C)	pH	Cond. (uS/cm)	Redox Potential (mV)	O ₂ (mg/L)	N-NO ₃ ⁻ (mg/L)	Fe ⁺² (mg/L)	SO ₄ ⁻² (mg/L)
BH1-32	Nov-98	8.4	-	33	85.0	-	nd	0.6	nd
	Jun-99	10.84	7.36	469	13.9	1.77	nd	nd	nd
	Aug-99	12.26	7.84	504	-103.9	2.33	nd	0.4	4
	May-00	7.67	7.31	1567	-74.5	5.40	0.10	nd	nd
BH1-33	Nov-98	8.9	-	40.3	90.0	-	nd	1.0	9
	Jun-99	11.89	7.16	625	7.7	6.75	nd	0.7	27
	Aug-99	15.13	7.83	685	-100.8	2.35	nd	1.0	nd
	May-00	7.95	7.09	1832	-35.7	3.85	nd	nd	27
BH1-34	Nov-98	7.9	7.10	404	69.0	-	nd	2.8	nd
	Jun-99	10.8	7.26	424	28.7	1.84	nd	0.4	24
	Aug-99	12.27	8.24	306	-122.8	0.65	nd	0.6	nd
BH1-A	Nov-98	7.9	6.75	401	-92.0	0.7	nd	5.5	nd
	Jun-99	16.17	6.37	609	-102.7	0.95	nd	7.4	nd
	Aug-99	15.99	6.72	495	-137.4	0.97	nd	6.8	nd
	May-00	7.46	6.58	1515	-94.2	1.34	nd	6.0	nd
BH1-B	Nov-98	9.4	6.81	542	-66.0	0.8	nd	6.7	nd
	Jun-99	18.75	6.42	903	-113.9	1.27	nd	6.4	26
	Aug-99	17.53	6.74	780	-114.0	0.93	nd	8.2	1
	May-00	9.79	7.17	2083	-114.7	1.67	nd	6.0	80
BH1-C	Nov-98	9.3	6.66	292	-60.0	0.8	nd	6.7	nd
	Jun-99	11.54	6.41	471	-74.3	0.58	nd	4.6	15
	Aug-99	15.4	7.35	342	-106.7	0.62	nd	3.8	2
	May-00	8.87	6.35	1517	-56.4	1.43	nd	5.2	6
BH1-D	Nov-98	8.9	6.79	455	-60.0	0.7	nd	6.5	nd
	Jun-99	17.72	6.45	907	-120.6	1.05	nd	5.0	47
	Aug-99	16.15	8.07	973	-129.3	0.84	nd	7.8	nd
	May-00	10.71	6.60	2754	-147.7	1.39	nd	5.5	220
BH1-E	Nov-98	7.9	7.03	635	22.0	7.0	5.00	nd	>70
	Jun-99	18.93	6.78	1072	17.7	3.26	0.92	0.2	268
	Aug-99	17.67	7.8	1020	-77.1	1.93	1.70	nd	385
	May-00	13.66	7.21	1714	-50.8	7.94	0.24	nd	54
BH1-F	Nov-98	9	7.48	194	100.0	6.8	0.05	nd	11
	Jun-99	16.55	7.49	244	-26.0	0.65	nd	nd	11
	Aug-99	14.34	8.31	253	-113.2	0.71	nd	nd	14
	May-00	6.65	7.27	885	-36.8	6.67	0.08	nd	2
BH1-G	Nov-98	8.9	6.71	423	-58.0	0.4	nd	9.0	nd
	Jun-99	11.93	6.26	477	-77.5	1.04	nd	6.2	3
	Aug-99	17.71	7.84	491	-93.9	1.47	nd	6.6	nd
	May-00	6.97	6.98	774	-141.3	1.35	nd	4.5	nd

nd for N-NO₃⁻ = 0.01 mg/LFe⁺² = 0.1 mg/LSO₄⁻² = 0.5 mg/L

CHAPTER 4

4.0 Conceptual Model Development

4.1 Regional Geology/Hydrogeology Conceptual Model

Through the collection of groundwater elevation data, it was determined that the magnitude and direction of groundwater flow at the Tank Farm site varied temporally. Dillon (1995) made similar observations. An examination of the regional geology by Dillon (1994) revealed the following:

- *There is a glacial till ridge that is oriented from the southwest to northeast across the Base-MCIA lands (west of the Tank Farm). The till is a silty sand containing some gravel and boulders and is present near surface in the general area;*
- *Deposited on either side of this till ridge are sands and gravels and uniform sands, deposited in either a fluvial or near-shore environment;*
- *The sands and sandy till deposits comprise a regionally significant water table (unconfined) aquifer. The depth to the water table is greatest along the topographically high areas;*
- *There is a regional water table divide that is generally coincident with the height of the land and till ridge; and*
- *The Tank Farm area is located several hundred meters east of the height of land and the regional groundwater divide. The location is east of the till ridge and uniform sands and/or some fine gravel underlie the Tank Farm.*

A conceptual model of the site hydrogeology was proposed based on regional geological maps for surficial materials, geological knowledge of the general area including the site under investigation and other nearby sites, groundwater elevation data collected and conversations with Dr. Fred Michel in the Department of Earth Sciences at Carleton University. As stated in Section

3.1.2.2, the site is underlain by an unconfined medium to fine sand aquifer. The lower limit of the aquifer is defined by a clay aquitard, located at a depth of approximately 5.5 m. The clay aquitard pinches out along the edge of the glacial till ridge located southwest of the site. The top of the clay unit slopes to the northwest towards the Ottawa River. The geology found at the sites is consistent with the proposed geologic history in this area, which is shown schematically in Figure 11. The till ridge was formed by the movement of glaciers. The clay unit resulted from the depositional environment when the Champlain Sea covered the area. The medium to fine sands located at the site are identified as being deposited in either a fluvial or near-shore environment which is consistent with the environment present as the Champlain Sea receded towards what is now known as the Ottawa River. The clay unit present below the site is exposed in areas south of the Ottawa River and north and northeast of the site.

Figure 11. Regional Hydrogeology Conceptual Model.

As identified by Dillon (1994), the glacial till ridge forms a topographic high which is aligned with a regional groundwater divide. The fuel dispensing area, to which the Tank Farm supplied fuel via an underground pipeline, is located approximately 1300 m southwest of the Tank Farm within the area defined by the glacial till ridge. Hydrogeologic studies at this location indicated the water table is at a depth of approximately 9 m and groundwater is flowing to the southwest towards the Rideau River. Hence, the groundwater divide is located to the northeast of the dispensing area.

The variations in groundwater flow direction observed at the site can be attributed to the fact that the site is located on or very close to a groundwater divide and that the site is located at the edge of a shallow unconfined aquifer, which is strongly influenced by the local topography and groundwater recharge. Monthly groundwater elevation data collected over the one-year period from April 1999 to March 2000 indicated that the groundwater flow was predominately to the north-northeast with the exception of 2 periods where the flow direction appeared to be to the south-southwest as seen in Table 7. Groundwater flow to the south-southwest occurred during the spring and late fall. The change in the spring is very abrupt and appears to coincide with spring runoff and high recharge. The change in groundwater flow in the fall is more gradual and is also assumed to be linked to the increase in recharge experienced in late fall. An increase in groundwater recharge at the site will impact the relatively thin aquifer and shallow water table at the site. The increased recharge appears to create a mound at the site, causing the groundwater divide to move to the northeast, across the site. The result is a reversal in the direction of groundwater flow from the north-northeast to the south-southwest, as illustrated in Figure 11. As the recharge subsides, the local mounding disappears and the groundwater divide moves back across the site, restoring the groundwater flow direction to the north-northeast. The observed groundwater elevations indicate that this occurred abruptly in the spring resulting in an elevated water table and more gradually in

the fall as a depressed water table rose between September 1999 and December 1999.

For the purposes of this study, a steady state groundwater flow was assumed to accommodate the numerical modelling. The groundwater was assumed to flow to the north-northeast with an average gradient of 0.00048 m/m. Note that changes in groundwater flow direction will impact the contaminant levels within the monitoring wells at the site and the variable groundwater flow direction will tend to smear the contaminant in all directions.

4.2 Source Term Conceptual Model

Jet fuel is a mixture of many different hydrocarbons and is a light non-aqueous phase liquid (LNAPL). When an LNAPL enters the subsurface, it migrates downward due to gravity and capillary forces until it encounters the water table. If the release is below the water table, the LNAPL will migrate upwards due to buoyant forces. Since LNAPLs are less dense than water, they will collect or pool above the water table. As the volume of LNAPL above the water table increases, the LNAPL will spread laterally forming a thin layer above the capillary fringe and water table. The LNAPL will migrate due to gravity in the direction of the slope of the water table. If the water table fluctuates, the LNAPL pool will be displaced upwards and downwards generating an entrapped and residual LNAPL phase; also referred to as a smear zone. The LNAPL present as a mobile phase within the LNAPL pool and as an immobile residual or entrapped phase will act

as a contaminant source to the groundwater. A conceptual model of the NAPL residual source term is depicted in Figure 12.

Figure 12. Conceptual Model of the Source Term.

The magnitude of a source term is very difficult to determine, however, a conceptual model of the source term could be inferred from the TPH content of the soil. Soil in the area of the former pump house and in the area adjacent to the former rail line and valve houses 3 and 4 was impacted to levels above the MOEE criteria for TPH. In these areas, the petroleum hydrocarbons present in the soil will partition into the infiltrating water and act as a source term to underlying groundwater.

Evidence of a smear zone at the water table was inferred from the head space analysis conducted on soil samples collected during drilling. At a number of

boreholes completed at the site, the head space soil concentrations were highest at a depth of between 1.5 and 2.5 m, as stated in Section 3.1.2.2. The water table was encountered between 0.25 m and 2.76 m below ground surface. The water table elevation at a single location (BH1-G) varied by as much as 1.56 m over the 16 water level measurements collected. Evidence of a smear zone was also inferred from the test pit excavations. At 11 of the 31 test pits, a stained dark soil layer was noted at a depth of approximately 1.3 m below the ground surface. At 3 locations, water that collected in the excavation was noted to have a thin sheen covering the water surface. Figure 13 indicates the borehole and test pit locations where evidence of a smear zone exists. Borehole data from the Dillon (1994) report (denoted as 'old boreholes' in Figure 13) was also incorporated in this figure to further confirm the location of the smear zone. A description of how the source term was represented for modelling purposes is located in Section 5.2.

Figure 13. Evidence of a Smear Zone.

4.2.1 Jet Fuel Composition

As mentioned, jet fuel is a combination of many different hydrocarbons. In order to facilitate contaminant transport modelling, a generic jet fuel was selected (Smith *et al.*, 1981) and the compounds were divided into 8 groups according to several criteria: 1) number of carbon atoms in the molecule 2) solubility in water 3) aliphatic or aromatic in nature. The BTEX compounds were not grouped in this manner as they are of particular interest due to their relatively high solubilities. Table 13 presents the general groupings and the overall properties of each group. The overall solubility of each group was calculated as a weighted average of all compounds within a group. A complete list of the hydrocarbons that comprise the groups is located in Appendix E.

Table 13. Hydrocarbon Grouping.

Hydrocarbon Group	Weight %	Solubility (mg/L)	Density (kg/m³)
Benzene	0.73	1780	878.60
Toluene	1.95	515	867.00
Ethylbenzene	0.54	168	867.00
Xylenes	3.41	173	879.47
C4-C7	30.44	15.52	693.60
C8-C10	37.11	0.52	713.76
>C10	11.63	0.004	907.36
Aromatics	14.19	34.54	748.91

CHAPTER 5

5.0 Numerical Model Development

5.1 Groundwater Flow Model Development

The first modelling task involved establishing the groundwater flow domain. This was done using the three-dimensional, finite difference, saturated flow code MODFLOW. Figure 14 illustrates the size and dimensions of the domain used to simulate flow conditions and the location of the site within the flow domain. A uniform, finite difference grid was constructed, consisting of 50X100 gridblocks, each with dimensions of 8mX10m.

Figure 14. Model Domain and Discretization.

The groundwater flow model had four 1 m layers, which represented the 4 m sand aquifer at the site. The decision to represent the aquifer in this fashion as opposed to using finer or coarser discretization is related to contaminant transport and is discussed in Section 5.3.

5.1.1 Boundary Conditions

Although the groundwater flow at the site varies with time as discussed in Sections 3.2 and 4.1, a steady state groundwater flow scenario was assumed since BioRedox-MT3DMS cannot accommodate transient flow conditions. Based on groundwater elevation data collected, the overall average direction and magnitude of the gradient across the site was estimated to be towards the north-northeast and was approximately equal to 0.00048 m/m. This represents the estimated average net groundwater flow at the site. In order to simulate groundwater flow such that these conditions were satisfied, the following boundary conditions were employed:

- a no-flow boundary was assumed at the base of the model domain at a depth of 4 m which simulated a low permeability silt layer, which is underlain by a clay aquitard
- constant head boundaries were placed at the two grid extremes (north-northeast and south-southwest) and were assigned values of 99.8 masl
- no-flow boundaries were specified along the east-southeast and west-northwest boundaries
- a uniform recharge value of 30 mm/year was applied to the top layer of the domain

The placement of the two constant head boundaries of equal value at the gird extremities caused a mound and hence a groundwater divide to develop at 500 m, immediately upgradient from the site. This was also reflective of the conditions that exist at the site, where a groundwater divide is present at various locations at the site throughout the year.

The low net recharge value was required to meet the existing groundwater elevations and gradients at the site. It was attributed to the shallowness of the aquifer and to evapotranspiration losses which were deemed significant as the areas to the north, west and south of the site are heavily treed. Steady state conditions were modelled and the resulting equipotential lines are shown in Figure 15.

Figure 15. Equipotential Flow Lines.

5.1.2 Aquifer Properties

The sand aquifer was assigned a porosity of 0.35 and a hydraulic conductivity of 1×10^{-2} cm/s. An anisotropy factor of 10 was assumed. This hydraulic conductivity value corresponded to the highest value reported by Dillon (1994). Using the highest value implies that water moves faster within the porous media and as such a higher recharge value could be assigned to the domain (30 mm/year). Using the values specified for hydraulic conductivity, porosity and gradient, a seepage velocity of 4 m/year was estimated.

5.2 Contaminant Transport Model Development

Contaminant transport was modelled using the multicomponent transport code BioRedox-MT3DMS which simultaneously models the transport and degradation of multiple electron donor and electron acceptor species. The electron donor species modelled were the 8 hydrocarbon groups specified in Table 13. Dissolved methane and ferrous iron were also included as electron donors in the model and are by-products of degradation in the methanogenic and ferrogenic zones, respectively. Electron acceptor species included oxygen, nitrate, ferric iron, sulphate and carbon dioxide. An unlimited source of carbon dioxide, the electron acceptor in the methanogenic redox zone, was assumed and its transport was therefore not modelled. The transport domain, which is a subsection of the groundwater domain, is illustrated in Figure 16. Also illustrated

are the placement of boundary conditions for the electron acceptors, which are further discussed in Section 5.2.3.

Figure 16. Transport Domain and Boundary Conditions.

5.2.1 LNAPL Source Term

To model the hydrocarbon source zones, a residual saturation of 6.8% (volume of NAPL/volume of voids) was calculated based on one of the highest levels of soil contamination measured in the test pit samples collected at the site. For model simulations, a residual saturation of 10% was assumed over a 1.0 m smear zone which was located in the top layer of the model domain. The total areal extent of the source for the 3 identified source areas is illustrated in Figure 17 and was set equal to 1200 m². These areas include the former valve house and pump house areas. A total initial mass of 27045 kg of jet fuel was calculated

based on the specified residual saturation and areal extent. The initial composition of the residual LNAPL is as listed in Table 13.

Figure 17. Identified Source Term Areas and Oxygen Recharge Boundaries.

5.2.1.1 NAPL Dissolution

The NAPL dissolution term within BioRedox-MT3DMS (Carey *et al.* 1999) is based on work by Mackay *et al.* (1991) and assumes the groundwater and recharge water passing through the upper model layer containing the source term will contact the NAPL and equilibrium partitioning will occur. The assumption of equilibrium partitioning was considered valid as the groundwater flow is quite low at the site in question. The dissolution model calculates the aqueous phase concentrations based on the product of the solubility limit of each compound group in water, the mole fraction within the NAPL residual, which changes with time, and an efficiency factor that defines the amount of contact that occurs between the NAPL and aqueous phases (Carey *et al.* 1999):

$$C_{\text{sat},i} = S_i f_i X_i \quad (\text{Eq. 19})$$

Where: $C_{\text{sat},i}$ = saturated groundwater concentration for solute i [ML^{-3}]
 S_i = solubility limit of solute i in water [ML^{-3}]
 f_i = an efficiency factor for solute i
 X_i = mole fraction of solute i in the NAPL phase [mole/mole]

A 1D model simulation was performed to illustrate the dissolution pattern of the 8 hydrocarbon groups in the absence of biodegradation. The same flow and transport parameters detailed in Section 5.1 to Section 5.2.1 were used for the 1D simulation (*i.e.*, same gradient, NAPL residual, etc.). The source term was placed in the first of 101 blocks, each with dimensions of 1mX1mX1m. A schematic of the 1D column is illustrated in Figure 18.

Figure 18. 1D Model Domain.

The simulated concentrations for the 8 hydrocarbon groups within the source block are presented in Figure 19 and Figure 20. Figure 19 presents the groundwater concentration of each of the hydrocarbon groups with time and Figure 20 presents the TPH concentrations with time.

Figure 19. Dissolution of 8 Hydrocarbon Groups.

Figure 20. TPH Dissolution.

Initially, there is rapid dissolution of benzene from the source term due to its high solubility. Toluene and the xylenes exhibit similar patterns, while a slower rate of decline is observed for ethylbenzene due to its relatively lower solubility and smaller mole fraction (Table 13). An increase in concentration is observed for the heavier hydrocarbons with time. Although these compounds are present in substantially higher mole fractions relative to the BTEX compounds, they also have significantly lower solubilities, which limits their dissolution. However, as the BTEX compounds are rapidly depleted, the mole fraction of the remaining hydrocarbons increases, thus increasing the aqueous phase concentrations as predicted by equation 19. As time increases, the mole fraction of these groups will also decline and the concentrations will begin to decrease.

5.2.2 Electron Donors

As mentioned, the 8 hydrocarbon groups were considered as aqueous phase electron donors in the contaminant transport model. Dissolved methane and ferrous iron, produced in the methanogenic and ferrogenic zones, respectively, were also considered as electron donors as they may oxidized upon being transported downgradient of the source term.

5.2.3 Electron Acceptors

The electron acceptors modelled included oxygen, nitrate, ferric iron and sulphate. Oxygen, nitrate and sulphate were specified as initial (background) concentrations and were assumed to enter the site in the groundwater flowing beneath the site as well as in the recharge. A constant concentration boundary was placed at the upstream boundary of the transport domain, as illustrated in Figure 16, and recharge concentrations were specified over the transport domain. The values specified for these electron acceptors were based on field observations and are provided in Table 14.

Table 14. Electron Acceptor Input Parameters

Electron Acceptor		Boundary and Initial Conditions		
		C_{initial} (mg/L)	C_{recharge} (mg/L)	C_{boundary} (mg/L)
Oxygen	outside plume boundary		6.8	
	within plume boundary	6.8	60.8	6.8
Nitrate		0.2	0.2	0.2
Ferric Iron		1600	-	-
Sulphate		10	10	10

As previously stated, the net recharge in the model simulations is recognized as being low, due to evapotranspiration losses. However, dissolved oxygen

entering through recharge would not be lost and would be used in microbial reactions in the groundwater environment. Additional oxygen would also enter the groundwater system through diffusive transport from the vadose zone (Holder *et al.*, 1999). As oxygen is consumed within the plume boundaries, a concentration gradient would be established between the vadose zone and the groundwater, causing the downward diffusion of oxygen. This phenomenon is termed reaeration. A reaeration constant of 0.001 m/d was assumed in the model simulations within the plume boundary, which corresponds to an oxygen mass flux of 5 mg/m²/d. The reaeration constant selected reflects the lower end of a range of values presented by Holder *et al.* (1999). To account for this influx of oxygen, the oxygen concentration in the recharge was specified to be 60.8 mg/L within the plume boundary as illustrated in Figure 17.

Ferric iron (Fe⁺³) exists in solid form as a coating on soil particles. A fraction of the ferric iron is bioavailable to the microorganisms. Dr. Syed Wasay, a post-doctoral fellow in the Department of Civil and Environmental Engineering at Carleton University, conducted several batch microcosm studies using the soil from the site to determine the bioavailable iron present in the soil. Dr. Wasay found a bioavailable ferric iron concentration of approximately 350 mg/kg for the soil at the site. BioRedox-MT3DMS allows the user to model the solid phase as an immobile aqueous phase. Hence the ferric iron concentration in the soil was converted to an equivalent aqueous phase concentration of 1600 mg/l assuming a dry density and soil porosity of 1600 kg/m³ and 0.35 respectively. Upon

reduction, ferric iron is transformed to ferrous iron (Fe^{+2}), which is mobile as a dissolved species.

5.2.4 Transport Model Parameters

To complete the contaminant transport model, longitudinal, transverse and vertical dispersivity values of 10 m, 1 m and 1 m were assigned to the aquifer. Adsorption was considered negligible as the aquifer is largely composed of sand with very little organic matter. Diffusion was also considered negligible in comparison to the mechanical dispersion.

5.2.4.1 Biodegradation Kinetics

First-order degradation kinetics were assumed for the biological reactions within each of the redox zones. Several researchers have published data related to the degradation rates of the BTEX compounds for both field and laboratory studies (e.g., Suarez and Rifai, 1999; Weidemeier *et al.*, 1995). Table 15 presents the redox dependent degradation rates used in this study for the 8 hydrocarbons groups, dissolved methane and ferrous iron.

Table 15. Redox Reaction Rate Constants.

Solute	Redox Zone	Reaction Rate Constant (1/d)	Referenced Rates (1/d)*		Half Life (d)	Number of Electrons Transferred**
			Minimum	Maximum		
Benzene	Aerobic	6.93E-01	0.000	2.500	1	30
Benzene	Methanogenic	2.30E-02	0.000	0.077	30	30
Toluene	Aerobic	6.93E-01	0.016	1.630	1	36
Toluene	Nitrate Reducing	1.39E-01	0.000	4.320	5	36
Toluene	Ferrogenic	3.50E-02	0.000	0.045	20	36
Toluene	Sulfidogenic	2.30E-02	0.000	0.210	30	36
Toluene	Methanogenic	2.30E-02	0.000	0.186	30	36
Ethylbenzene	Aerobic	6.93E-01			1	42
Ethylbenzene	Nitrate Reducing	6.90E-02	0.000	6.048	10	42
Ethylbenzene	Ferrogenic	3.50E-02	0.000	0.017	20	42
Ethylbenzene	Sulfidogenic	2.30E-02	0.000	0.007	30	42
Ethylbenzene	Methanogenic	2.30E-02	0.000	0.054	30	42
Xylene	Aerobic	6.93E-01	0.008	0.430	1	42
Xylene	Nitrate Reducing	6.90E-02	0.000	0.490	10	42
Xylene	Ferrogenic	3.50E-02	0.000	0.037	20	42
Xylene	Sulfidogenic	2.30E-02	0.000	0.320	30	42
Xylene	Methanogenic	2.30E-02	0.000	0.057	30	42
C4-C7	Aerobic	2.31E-01			3	40
C8-C10	Aerobic	2.31E-01			3	52
>C10	Aerobic	2.31E-01			3	75
Aromatics	Aerobic	1.39E-01			5	52
Methane	Aerobic	1.10E-02			63	8
Methane	Nitrate Reducing	8.50E-04			815	8
Methane	Ferrogenic	8.50E-04			815	8
Methane	Sulfidogenic	8.50E-04			815	8
Methane	Methanogenic	8.50E-04			815	8
Ferrous Iron	Aerobic	instantaneous			-	1

* Referenced from Suarez and Rifai (1999)

** the number of electron equivalents that are transferred during the reaction of 1 mole of the electron donor in the half-reaction (eq/mole)

There is a great range of biodegradation rates reported in the literature, as they are site-specific and can be difficult to quantify (Suarez and Rifai, 1999). The rates listed in Table 15 for the BTEX compounds fall within the range of values provided by Suarez and Rifai (1999). Although Suarez and Rifai (1999) cite studies that report the degradation of benzene under nitrate, iron and sulphate reducing conditions, many studies suggest that benzene is recalcitrant under such conditions and is only degraded aerobically and under methanogenic

conditions. Hence, for the simulations conducted in this study, benzene was assumed to degrade under aerobic and methanogenic conditions only.

For toluene, ethylbenzene and xylenes, it was recognized that aerobic degradation rates are generally faster than anaerobic degradation rates. Hence, for this study, a first order degradation rate equivalent to a half-life of 1 day was set for aerobic degradation and a first order degradation rate equivalent to a 30 day half-life was assumed for methanogenic conditions. Biodegradation rates under sulphate reducing conditions were assumed to equal those assumed for methanogenic conditions. The iron and nitrate reducing rates were assumed to be slightly faster than the sulphate reducing and methanogenic rates based on the trends given in the literature.

It is known that the heavier hydrocarbons do not degrade with the same ease as BTEX and as such, slower aerobic rates were assumed for these compounds as compared to the aerobic rates assumed for BTEX. The aromatic structure associated with PAHs makes these compounds less susceptible to degradation, which is reflected in the aerobic degradation rate assumed for these compounds. Little is known about the degradation of heavier hydrocarbons under anaerobic conditions. These compounds were therefore assumed to degrade solely under aerobic conditions for the base case simulation. To assess the significance of this assumption, a simulation was performed where anaerobic degradation of these compounds was assumed.

Aerobic degradation of methane has been well documented and is carried out by methanotrophic organisms where the enzyme methane monooxygenase catalyzes the incorporation of oxygen into the carbon-based molecule (Madigan *et al.*, 1997). Anaerobic degradation of methane has been observed by several researchers, although the exact mechanism has yet to be determined. Lyngkilde and Christensen (1992) note that the rates of methane oxidation under nitrate and sulphate reducing conditions are not well understood but are expected to be slow. Several researchers have studied methane oxidation under sulfidogenic and methanogenic conditions (*e.g.*, Niewöhner *et al.*, 1998; Blair and Aller, 1995 and Hoehler *et al.*, 1994) where the postulated oxidation mechanism under methanogenic conditions involves the use of water as an electron acceptor. The anaerobic rates listed for methane were assumed to be considerably less than those related to the BTEX compounds. Oxidation of ferrous iron was assumed to occur instantaneously under aerobic conditions.

5.3 2-D versus 3D model

Preliminary modelling was conducted to determine the impact of the dimensionality on the model predictions. The 4 m deep aquifer was represented in plan view in two dimensions (2D), in three dimensions (3D) with four 1 m layers, and in 3D with eight 0.5 m layers. For the 3D simulations, the source term was placed in the top 1 m of the model (as depicted in Figure 12), while for the 2D simulation, the source term spanned the entire 4 meter depth. It was

hypothesized that changing the efficiency factor to 0.25 in the 2D simulation would effectively simulate one-quarter of the total flow contacting the source term and would potentially result in a similar outcome as in the 3D simulations where the efficiency factor was 1.0. The efficiency factor was also changed to 0.5 and 1.0 in the 2D simulation to ascertain how this parameter affects the dissolution of the source term. The mass of benzene remaining in the source term versus time for the five simulations is shown in Figure 21.

Figure 21. Mass of Benzene Remaining Under Varying Model Conditions.

The dissolution pattern for benzene for all simulations shown in Figure 21 is characterized by a relatively slow dissolution rate initially, followed by a dramatic increase in the rate of dissolution until complete dissolution has occurred. The time at which the increase in rate occurs corresponds to the time of formation of a methanogenic redox zone.

The results illustrated in Figure 21 indicate that none of the 2D simulations resulted in the same dissolution rate for benzene as in the 3D simulations, while the two 3D simulations had similar outcomes. Similar results were obtained for the remaining 7 hydrocarbon groups, where the two 3D simulations were alike and the 2D simulations deviated from the 3D model results. This was attributed to the fact that the 3D model better reflects field conditions related to the vertical flow and recharge at the site while a 2D representation could not properly account for such conditions. It was therefore concluded that the 3D model with four 1 m layers would provide sufficient representation of the aquifer and source term for this study.

CHAPTER 6

6.0 Modelling Study

6.1 Base Case

The model parameters used for the base case simulations are those defined in Section 5. Figure 22 illustrates the simulated distribution of the redox zones downgradient of the source areas after 20 years. Given the complex nature associated with the groundwater movement at the site, a broad assessment was made where the simulated redox zones were compared to observed field data. The distribution of the simulated redox zones agree reasonably well with the geochemical field data, where zones of depleted oxygen and elevated ferrous iron observed in the field coincide with ferrogenic zones shown in Figure 22. The methanogenic zones observed in Figure 22 are coincident with the source term areas, implying the complete depletion of the other more favourable electron acceptors in these areas. Field data revealed that wells in the vicinity of the source areas often had the lowest redox potential, implying highly reducing conditions, which could be indicative of methanogenic activity. The nitrate and sulfidogenic zones are small in comparison to the ferrogenic zone due to their presence in small concentrations in the initial, upgradient and recharge waters. The simulated redox zones (*i.e.*, the nitrate reducing zone) extend approximately 50 m north of the northern fenceline at the site.

Figure 22. Redox Zones After 20 years for Base Case.

The predicted percent mass remaining in the source term for each hydrocarbon group after 20 years are provided in Table 16. Numbers in parentheses indicate the year that a compound was completely depleted from the source term. It should also be noted that values of 100 percent are rounded up and are in fact slightly less than 100 percent.

Table 16. Mass Percent Remaining in Source Term After 20 Years.

Compound	% Mass Remaining after 20 years
Benzene	0(3)
Toluene	0(10)
Ethylbenzene	33.9
Xylenes	32.1
C4-C7	99.3
C8-C10	100
>C10	100
Aromatics	98.9

Note: numbers in brackets reflect the time of complete depletion of a compound from the source term

It can be seen that significant dissolution of the BTEX compounds was predicted, while very little dissolution of the heavier hydrocarbons was predicted. The reasons for the predicted dissolution pattern observed are discussed in Section 6.3.

6.2 Development of Redox Zones

The simulated redox zones for 1, 10, 50 and 100 years are illustrated in Figure 23. The same model parameters used for the base case simulation were used for these simulations. It can be seen that anaerobic conditions were predicted in the vicinity of the source areas at 1 year. This occurs due to the low quantity of available dissolved oxygen at this site, resulting from the small hydraulic gradients and low recharge rate. As a result, less favourable electron acceptors are used in lieu of oxygen. The extent of the redox zones increases with time, as seen after 10 years, due to the increase in mass of hydrocarbons in the groundwater. The contaminants migrate farther because they are not being utilized as quickly under anaerobic conditions as compared to aerobic conditions. At 50 years, all of the BTEX compounds have been depleted from the source

term. However, dissolved methane, produced in the methanogenic zone as a result of BTEX degradation, is still migrating downgradient of the source areas and has not been completely utilized due to the slow degradation kinetics associated with its degradation. As dissolved methane was assumed to degrade in all of the redox zones, it exerts a demand on the electron acceptors and consequently anaerobic redox zones are still present. The heavier hydrocarbon groups are also present and are also utilizing available dissolved oxygen. At 100 years, only the C4-C7, C8-C10, >C10 and aromatic hydrocarbon groups remain in the source term and groundwater. As they only degrade aerobically, available dissolved oxygen is consumed. The nitrate reducing zone illustrated in Figure 23 (d) is indicative of oxygen depleted regions.

Figure 23. Development of Redox Zones at 1 (a), 10 (b), 50 (c) and 100 (d) Years.

6.3 Hydrocarbon and Geochemical Indicator Concentration Profiles

Simulated concentration profiles of the hydrocarbon species, after 20 years, are illustrated in Figure 24 to Figure 31. In Figure 24, it can be seen that the predicted benzene concentrations remain relatively elevated within the boundary of the anaerobic zone which are illustrated in Figure 22. As conditions are anaerobic within this boundary, benzene is not significantly degraded. A small amount of aerobic degradation will occur within this boundary as dissolved oxygen enters the domain through recharge. However, the recharge rate is very low and hence aerobic degradation within this boundary is minimal.

As indicated by the model results in Table 16, all of the toluene is predicted to have depleted from the source term after 10 years due to its high solubility and the assumption that toluene degrades under all redox conditions. After 20 years, all of the toluene that is dissolved in the groundwater was predicted to have degraded. This is in contrast with the behavior of the benzene, which was depleted from the source term after 3 years but remains in the groundwater due to its assumed biodegradation under only aerobic and methanogenic conditions. Ethylbenzene and xylenes were predicted to be remaining in the source term after 20 years and continue to dissolve into the groundwater. These compounds are therefore still present in the groundwater after 20 years, as indicated in Figure 25 and Figure 26. As with toluene, these compounds degrade under all redox conditions and their concentrations therefore decrease rapidly with distance downgradient of the source areas.

The plumes shown for the heavier hydrocarbons extend slightly beyond the anaerobic zone. As with benzene, these compounds do not significantly degrade under anaerobic conditions and therefore migrate through the anaerobic zones untransformed. Upon reaching the aerobic zone, these compounds are degraded.

It can be seen from Figure 31 that significant quantities of methane are present in the groundwater downgradient of the source zones due to methane generation within the methanogenic zone. Methane was assumed to degrade under all redox conditions at first order rate constants considerably lower than those assumed for toluene, ethylbenzene and xylenes. For the base case simulation, toluene, ethylbenzene, xylenes and methane are the only compounds that were assumed to degrade under all redox conditions. Hence, the biodegradation of these compounds is responsible for the anaerobic zones generated downgradient of the source. As stated earlier, the toluene within the source zones and within the groundwater has been depleted and the ethylbenzene and xylenes plumes do not extend to the boundary of the anaerobic zone. Hence, the methane generated by the methanogenic biodegradation of the petroleum hydrocarbons in the source areas is subsequently degraded anaerobically downgradient of the source areas and contributes to the formation of the anaerobic redox zones.

Figure 24. Benzene Concentration Profile.

Figure 25. Ethylbenzene Concentration Profile.

Figure 26. Xylenes Concentration Profile. **Figure 27. C₄-C₇ Concentration Profile.**

Figure 28. C₈-C₁₀ Concentration Profile.

Figure 29. >C₁₀ Concentration Profile.

Figure 30. Aromatics Concentration Profile.

Figure 31. Methane Concentration Profile.

The maximum concentration of each hydrocarbon group at 20 years, as predicted by the model simulations, is presented in Table 17. When comparing the values in Table 17 to the results presented in Table 8, it can be seen that the benzene concentrations observed in groundwater samples collected at wells BH1-14, BH1-19, BH1-21, BH1-24, BH1-32, BH1-34, BH1-A, BH1-B, BH1-D and BH1-G exceed the predicted value of 103 ppb, listed in Table 17. Similar statements can be made with regard to ethylbenzene and total xylene concentrations, which are notably higher than 977 ppb and 6340 ppb, respectively, in groundwater samples collected at BH1-14, BH1-21, BH1-B, BH1-D and BH1-G and BH1-14, BH1-21, BH1-A, BH1-B, BH1-D and BH1-G. Model simulations also predict that all of the toluene would be degraded by 20 years. However, significant quantities of toluene were detected in samples collected at BH1-14 and BH1-G. TPH concentrations in groundwater samples collected at most of the wells exceed those predicted in Table 17. These results could be due to a number of reasons, including the following:

1. spills of a more recent nature may have occurred in these locations, resulting in higher concentrations;
2. the estimated quantity of jet fuel assumed within the source areas for modelling purposes may not accurately reflect the volume of fuel present in the soil;
3. the assumed degradation kinetics used for modelling purposes may have been too fast;
4. the simplified representation of groundwater flow in the model simulations does not account for the variable nature of the groundwater flow at the site which impacts the distribution of the dissolved contaminants; and

5. the generic jet fuel composition used for modelling purposes may not be exactly representative of the jet fuel stored at the tank farm.

Table 17. Maximum Simulated Hydrocarbon Concentrations at 20 years.

Compound	Concentration (ppb)
Benzene	103
Ethylbenzene	977
Xylenes	6340
C4-C7	5950
C8-C10	176
>C10	0.310
Aromatics	4270
TPH	17816

Simulated concentration profiles of the geochemical indicator species after 20 years are illustrated in Figure 32 to Figure 36. The dissolved oxygen concentration is depleted in the vicinity of the source areas as noted in Figure 32. This occurs as any available oxygen will be used by microorganisms to oxidize organic species. It can be seen that the dissolved oxygen concentration begins to increase beyond the boundary of the anaerobic redox zone illustrated in Figure 22. It should be noted that dissolved oxygen concentrations in excess of the solubility limit are shown and are a result of the increased dissolved oxygen concentration in the recharge water as discussed in Section 5.2.3. Dissolved oxygen is still being consumed beyond this boundary as methane and the heavier hydrocarbons travel beyond this boundary and are subsequently oxidized under aerobic conditions. However, they are present in minute concentrations and as such do not completely deplete the dissolved oxygen from the groundwater. Groundwater downgradient of the site is slowly reoxygenated via mixing with recharge water and surrounding groundwater.

As with the dissolved oxygen concentration profile, the concentrations of nitrate and sulphate are below their maximum values of 0.2 mg/L and 10 mg/L, respectively, beyond the extent of the redox zones. Water travelling downgradient of the source areas is devoid of nitrate and sulphate and they are replenished through mixing with recharge and surrounding groundwater. Nitrate and sulphate were not deemed to be significant electron acceptors at this site as they were not detected in large concentrations in groundwater samples collected from the upgradient wells.

As with the previously discussed geochemical indicators, ferric iron concentrations also decrease in the vicinity of the source term, indicating the utilization of ferric iron as an electron acceptor. Since ferric iron is present as a solid in the soil matrix and is present in finite concentrations, it is not replenished as in the case of oxygen, nitrate and sulphate.

As discussed in Table 1, the reduction of ferric iron results in the formation of ferrous iron, which is soluble under anaerobic conditions. Instantaneous oxidation of ferrous iron was assumed under aerobic conditions, and as such, ferrous iron is not found beyond the extent of the nitrate reducing zone illustrated in Figure 22.

Figure 32. Dissolved Oxygen Concentration Profile. **Figure 33. Nitrate Concentration Profile.**

Figure 34. Sulphate Concentration Profile. **Figure 35. Ferric Iron Concentration Profile.**

Figure 36. Ferrous Iron Concentration Profile.

Table 18 summarizes the mass of each compound that was predicted to degrade under each redox condition over the 20 year simulation period. It is clear from Table 18 that a significant mass of the petroleum hydrocarbons was degraded under methanogenic conditions. Hence, the elevated methane concentrations in the downgradient groundwater and the subsequent anaerobic degradation of methane. The ferric iron, present in solid form, is immobile and a fixed mass is available for biodegradation. Ferric iron was the second largest electron acceptor utilized. As stated earlier, nitrate and sulphate are present in low concentrations in the recharge and groundwater and hence contribute the least to the biodegradation of the petroleum hydrocarbons over the 20 year simulation.

A significant mass of oxygen was utilized during the 20 year simulation. It is important to note that the oxidation of the ferrous iron was assumed to be instantaneous and hence during the simulation, the ferrous iron was oxidized first before any oxygen was utilized for the biodegradation of the petroleum hydrocarbons. Hence, the dissolved ferrous iron acted as a significant oxygen sink downgradient of the source areas.

Table 18. Mass of Hydrocarbon Degraded in Each Redox Zone.

Solute	Redox Zone	Mass Degraded (kg)
Benzene	Aerobic	18.14
Benzene	Methanogenic	187.08
Toluene	Aerobic	3.22
Toluene	Nitrate Reducing	0.14
Toluene	Ferrogenic	86.96
Toluene	Sulfidogenic	6.55
Toluene	Methanogenic	435.75
Ethylbenzene	Aerobic	0.49
Ethylbenzene	Nitrate Reducing	1.08E-02
Ethylbenzene	Ferrogenic	9.15
Ethylbenzene	Sulfidogenic	1.59
Ethylbenzene	Methanogenic	85.08
Xylene	Aerobic	3.20
Xylene	Nitrate Reducing	7.00E-02
Xylene	Ferrogenic	59.40
Xylene	Sulfidogenic	10.33
Xylene	Methanogenic	552.32
C4-C7	Aerobic	33.63
C8-C10	Aerobic	1.00
>C10	Aerobic	1.75E-03
Aromatics	Aerobic	23.69
Methane	Aerobic	13.96
Methane	Nitrate Reducing	0.25
Methane	Ferrogenic	51.52
Methane	Sulfidogenic	2.37
Methane	Methanogenic	35.58
Ferrous Iron	Aerobic	1663.37

6.4 Degradation Driven NAPL Dissolution

As previously described, the hydrocarbon source term was conceptualized as a 1 m thick NAPL residual, and was placed in the top layer of the model domain. A representation of the source term is illustrated in Figure 12. Hydrocarbons dissolve into recharge water and groundwater that contact the NAPL residual. Aqueous phase concentrations were calculated as the solubility limit of the hydrocarbon in water multiplied by the mole fraction in the NAPL residual, which changed with time due to dissolution.

In order for the hydrocarbons to dissolve out of the NAPL residual and into surrounding water, a concentration differential had to exist. This implies that aqueous phase concentrations in the vicinity of the source areas had to be less than the equilibrium (*i.e.*, maximum) aqueous phase concentrations predicted by Equation 19 for each hydrocarbon group. If aqueous phase concentrations in the vicinity of the source areas were less than those predicted by Equation 19, the NAPL dissolution model within BioRedox-MT3DMS allowed a sufficient mass of hydrocarbons to dissolve from the NAPL residual such that the aqueous phase concentration for each hydrocarbon group would be equal to that predicted by Equation 19.

The rate of dissolution of the NAPL residual is therefore dependent on aqueous phase concentrations within the vicinity of the source areas, in addition to the solubility of the jet fuel compounds. If aqueous phase hydrocarbon

concentrations are not rapidly reduced in the vicinity of the source areas, a driving force for further dissolution will not exist and the source term will remain for extended periods of time. If hydrocarbon concentrations are rapidly reduced in the vicinity of the source areas, a larger driving force, promoting dissolution of the NAPL residual, will exist and the NAPL residual will deplete more rapidly.

Processes within the numerical model that cause decreases in aqueous phase concentrations include flushing, where dissolved hydrocarbons migrate downgradient due to advection/dispersion processes, and biodegradation processes where contaminant concentrations are reduced due to their utilization in oxidation-reduction reactions. Due to the small gradients at the site, flushing was not found to cause substantial reductions in contaminant concentrations within the source areas. The rate of NAPL dissolution was instead found to be largely driven by the biodegradation of the BTEX compounds, which are also the most soluble compounds in jet fuel. The BTEX compounds were allowed to degrade under all the redox conditions, with the exception of benzene, which was assumed to degrade in the aerobic and methanogenic zones only, as seen in Table 15. Hence, the formation of the anaerobic redox zones is primarily due to the degradation of toluene, ethylbenzene and xylenes, as they degrade in all zones. The heavier hydrocarbon groups were assumed to degrade only under aerobic conditions. Therefore, if anaerobic conditions exist within the source areas, the dissolution of the heavier compounds will be due to flushing and not biodegradation processes. Since these compounds have a very low solubility,

and gradients at the site under study are small, the heavier compounds will remain as a source term for a long period of time.

A model simulation, where no biodegradation reactions occurred, was carried out to illustrate the impact of biodegradation processes on the dissolution of the NAPL residual. The mass remaining in the source term for the base case simulation and 'flushing' simulation for benzene and the C4-C7 group are presented in Figure 37 and Figure 38, respectively.

Figure 37. Mass of Benzene Remaining With and Without Biodegradation Reactions.

Figure 38. Mass of C4-C7 Remaining With and Without Biodegradation Reactions.

The significance of biodegradation processes over flushing processes on the rate of BTEX dissolution is evident. In the base case scenario presented in Figure 37, all of the benzene is depleted from the source term by year 3, while in the flushing scenario, approximately 20% of the initial mass of benzene remains in the NAPL residual after 20 years. It can be inferred from Figure 37 that biodegradation processes have a greater potential to reduce aqueous phase concentrations of the BTEX compounds within the source areas than do flushing processes at this site. This is due to the fact that these compounds degrade both aerobically and anaerobically and groundwater conditions in the vicinity of the source term are anaerobic before 1 year for the base case, as seen in Figure 23, promoting the dissolution of the BTEX compounds. As noted earlier in Table 16, benzene and toluene are completely depleted from the source term by 10 years and significant depletion of ethylbenzene and xylenes has occurred by 20 years.

The impact of biodegradation and flushing processes on the heavier hydrocarbon groups is illustrated in Figure 38. As the groundwater conditions in the vicinity of the source term are anaerobic, flushing processes are responsible for the dissolution of the heavier hydrocarbon groups as they only degrade aerobically. The available dissolved oxygen that contacts the source term via recharge and groundwater is low and as such do not significantly impact the rate of dissolution of the heavier hydrocarbons as demonstrated in Figure 38. The results in Table 16 indicate that less than 2% of the heavier hydrocarbons has been depleted from the source term after 20 years, while approximately 9% has been depleted

after 100 years. The low solubility of these groups, in addition to the low groundwater flow and recharge rate at the site hinder the dissolution of the heavier hydrocarbons, and as such, the source term will remain for an extended period of time.

6.5 Sensitivity Analyses

As there is considerable uncertainty associated with parameters that define and impact the source term, variations in the following parameters were made to assess their impact on the extent of the redox zones and the rate of NAPL dissolution:

1. NAPL saturation within the source term;
2. areal extent of the source term;
3. oxygen transfer from the unsaturated zone; and
4. biodegradation rate constants.

6.5.1 NAPL Saturation Within the Source Term

The base case simulation assumed a residual saturation within the smear zone of 10%. To determine the impact of this assumption on the model predictions, the residual NAPL saturation was set equal to 5% and 15%. This effectively changed the initial total mass within the source volume from 27045 kg for the base case to 13522.5 kg and 40567.5 kg for the 5% and 15% residual saturation scenarios, respectively. The simulated redox zones after 20 years for both 5% and 15% residual saturation simulations are illustrated in Figure 39 and Figure 40, respectively. It can be seen that the extent of the simulated redox zones for a residual saturation of 5% is marginally smaller than for the base case where

the residual is 10%. It can also be seen that the methanogenic zone is much smaller than in the base case scenario. Both the extent and distribution of the redox zones for a 15% residual saturation are very similar to that predicted for the base case simulation. These results can be explained by the data presented in Table 19, where the percent mass remaining in the source term for each hydrocarbon group after 20 years for the 3 simulations are provided.

Figure 39. Redox zones after 20 years for 5% residual saturation. **Figure 40. Redox zones after 20 years for 15% residual saturation.**

Table 19. Mass percent remaining in source term at the end of 20 years for varying residual NAPL saturations.

Compound	% Mass Remaining after 20 years		
	Base Case (10 %)	5 %	15 %
Benzene	0(3)	0(2)	0(5)
Toluene	0(10)	0(5)	0(15)
Ethylbenzene	33.9	0(17)	56.0
Xylenes	32.1	0(17)	54.7
C4-C7	99.3	98.6	99.5
C8-C10	100	99.9	100
>C10	100	100	100
Aromatics	98.9	97.8	99.3

Note: numbers in brackets reflect the time of complete depletion of a compound from the source term

For the 5% residual saturation simulation, the BTEX compounds were predicted to have completely dissolved by 20 years. The absence of BTEX in the source term by year 20 implies that the concentrations of the BTEX compounds in the groundwater are not elevated enough to cause the formation of a large methanogenic zone. The simulated redox zones indicate more reducing conditions within the source areas for both the 10% and 15% residual saturation scenarios. This indicates that the BTEX compounds are primarily responsible for the generation of the redox zones due to their higher solubility and subsequent degradation under anaerobic conditions. Table 19 indicates that in 20 years, the BTEX compounds have been completely removed from the source term for the 5% residual saturation scenario, while less than 4% of the remaining hydrocarbons have been removed. Note that once the BTEX compounds have

degraded, the remaining hydrocarbons were assumed to only degrade aerobically and as such their dissolution is limited, as discussed in Section 6.3.

Figure 41 compares the percent mass of the NAPL residual remaining in the source term for the simulations where the residual saturation was varied. It can be seen that different percentages of the initial mass remain after 20 years for the three simulations. The rate of depletion is fastest for a 5% residual saturation, and slowest for a residual saturation of 15%. For the simulation with a 5% residual saturation, the gradual decline between 0 and 17 years is followed by a relatively level curve. This time coincides with the time of complete depletion for BTEX compounds in the source term as seen in Table 19. Once the BTEX compounds have dissolved, low solubility compounds remain and the percent mass remaining in the source term depletes slowly. For the 10% and 15% residual saturation simulations, ethylbenzene and xylenes are still present in the source term after 20 years, hence the leveling effect seen for a 5% residual is not seen for these simulations.

Figure 41. Percent mass remaining in the source term for variations in residual saturation.

6.5.2 Areal Extent of the Source Term

Model simulations were performed where the areal extent of the source term was increased from 1200 m² for the base case to 4160 m² and 7520 m². The recharge area with elevated dissolved oxygen, defined in Figure 17, was expanded in these simulations to reflect the changes. Figure 42 and Figure 43 present the redox zone distributions for these simulations. The predicted redox zones for both simulations are larger than for the base case simulation, and they extend approximately 60 m further in the direction of groundwater flow than for the base case simulation. As previously stated, the presence of methanogenic zones suggests the presence of some or all of the BTEX compounds in the source term. The results in Table 20 indicate that ethylbenzene and xylenes remain in the source term after 20 years for the three simulations.

Figure 42. Redox zones after 20 years for areal extent of 4160 m².

Figure 43. Redox zones after 20 years for areal extent of 7520 m².

Table 20. Mass percent remaining in source term at the end of 20 years for varying areal extents of the source term.

Compound	% Mass Remaining after 20 years		
	Base Case (1200 m ²)	4160 m ²	7520 m ²
Benzene	0(3)	0(11)	0(13)
Toluene	0(10)	0(19)	0(19)
Ethylbenzene	33.9	42.3	41.1
Xylenes	32.1	40.7	39.4
C4-C7	99.3	99.6	99.7
C8-C10	100	100	100
>C10	100	100	100
Aromatics	98.9	99.3	99.5

Note: numbers in brackets reflect the time of complete depletion of a compound from the source term

Figure 44 compares the percent mass of NAPL residual remaining in the source term with time for the simulations varying the areal extent of the source term. It can be seen that the rates of decline are similar for all three cases and that a similar percent remains at the end of 20 years. Similar results are presented in Table 20 for areal extents of 4160 m² and 7520 m², where benzene and toluene have completely dissolved in similar amounts of time and comparable amounts of the remaining compounds remain after 20 years. For the base case simulation, it was predicted that there would be moderately less source mass remaining for all compounds after 20 years as compared to the other 2 cases. Although an increase in areal extent is coupled with an increase in total mass within the source areas, similar source term depletion rates were predicted. This is due in part to the fact that the biodegradation kinetics remain unchanged, in addition to the fact that a significant portion of the water migrating through the NAPL source

areas is recharge water as opposed to horizontal flow from an upgradient boundary. Since recharge is uniform over the surface of the source area, the same quantity of hydrocarbons will dissolve per unit area of hydrocarbon source due to flushing processes. Also, the same quantity of electron acceptors is available per unit area and as such, biodegradation processes remain unchanged. Therefore, the rate of source dissolution will not be greatly affected by changes in the areal extent of the source term for this particular site.

Figure 44. Percent mass remaining in the source term for varying areal extents.

6.5.3 Oxygen Transfer From the Unsaturated Zone

As mentioned in Section 5.2.3, the consumption of dissolved oxygen within the plume boundary causes reaeration to occur due to the concentration gradient that is established between the vadose zone and groundwater environment. In the base case, the dissolved oxygen recharge concentration was 6.8 mg/L

outside the plume boundary and 60.8 mg/L within the plume boundary. In a subsequent simulation, the dissolved oxygen recharge concentration within the plume boundary was specified to be 30.4 mg/L and 6.8 mg/L outside the plume boundary. A third variation on the dissolved oxygen recharge concentration involved having a recharge concentration of 6.8 mg/L over the entire transport domain. Figure 45 and Figure 46 illustrate the simulated distribution of the redox zones downgradient of the source term areas after 20 years for the 2 latter scenarios mentioned. The extent of the redox zones shown in Figure 45 is slightly larger than in the base case and extends approximately 30 m further downgradient of the site. Similarly, the extent of the redox zones shown in Figure 46 is beyond that of the base case and extends approximately 80 m further downgradient of the site. The extent of the redox zones increased with decreasing dissolved oxygen in the recharge water as contaminants travel further before they are oxidized, due to the lower concentration of electron acceptor. Methanogenic zones are present in both figures, suggesting the presence of some of the BTEX compounds in the source term after 20 years. The percent remaining in the source term for the 8 hydrocarbon groups for the simulations are presented in Table 21.

Figure 45. Redox zones after 20 years for $O_2 = 6.8+ 30.4$ mg/L. **Figure 46. Redox zones after 20 years for $O_2 = 6.8$ mg/L.**

Table 21. Mass percent remaining in source term at the end of 20 years for varying dissolved oxygen recharge concentrations.

Compound	% Mass Remaining after 20 years		
	Base Case (6.8 + 60.8 mg/L)	6.8 + 30.4 mg/L	6.8 mg/L
Benzene	0(3)	0(3)	0(3)
Toluene	0(10)	0(10)	0(10)
Ethylbenzene	33.9	33.9	33.9
Xylenes	32.1	32.1	32.1
C4-C7	99.3	99.3	99.4
C8-C10	100	100	100
>C10	100	100	100
Aromatics	98.9	98.9	99.0

Note: numbers in brackets reflect the time of complete depletion of a compound from the source term

All 3 simulations resulted in the same percent mass remaining for each group of hydrocarbons, indicating that the dissolved oxygen concentration in the recharge water had a minimal impact on the source term dissolution rates, but impacted the distribution of the dissolved compounds and redox zones downgradient of the source areas as seen in Figure 45 and Figure 46. There were in fact slight differences in the percent mass remaining in the source term for each group which are not seen in Table 21 since the numbers have been rounded off to 1 decimal place. Slight variations were expected, as the mass of oxygen entering the source area via recharge will impact the rate of oxidation in the vicinity of the source term. This in turn will impact the dissolution for the reasons previously mentioned. However, significant differences were not noted as the increase in available dissolved oxygen with increasing recharge concentration would be small as the recharge rate is small.

6.5.4 Biodegradation Rate Constants

Given the uncertainty associated with biodegradation kinetics at field sites, 2 additional simulations were performed to determine the impact of the assumed biodegradation rates on the development of redox zones and the rate of NAPL dissolution. For the first simulation, the biodegradation rates assumed in the base case, listed in Table 15, were divided by 2. For the second simulation, the anaerobic degradation for the C4-C7, C8-C10, >C10 and aromatic groups were assumed in the nitrate, iron and sulphate reducing zones and the methanogenic zone. A half-life of 90 days, corresponding to a degradation rate of $7.70 \times 10^{-3} \text{ day}^{-1}$, was assumed for the 4 groups in the 4 zones. The simulated redox zones after 20 years are illustrated in Figure 47 and Figure 48.

Figure 47. Redox zones after 20 years for reduced biodegradation rates.

Figure 48. Redox zones after 20 years for the addition of anaerobic rates.

A decrease in biodegradation rates did not significantly affect the extent nor the distribution of the redox zones. If the hydrocarbon mass flux to the aquifer were constant, one would expect the extent of the redox zones to increase as the biodegradation rate kinetics decreased. However, the depletion of the source term is driven by the biodegradation rate kinetics and hence the mass flux to the aqueous phase decreases as the biodegradation rate kinetics decrease.

The extent of the redox zones is predicted to be smaller when anaerobic degradation was assumed for the heavier hydrocarbons, as illustrated in Figure 48. However, when compared to the base case simulation, it can be seen that the methanogenic zone is larger when anaerobic degradation was assumed. With the assumption of anaerobic degradation for all compounds, more mass is degraded within the anaerobic zones, specifically in the methanogenic zone, as an unlimited supply of carbon dioxide was assumed. Therefore, hydrocarbons do not migrate as far as in the base case simulation and the redox zones are consequently smaller. The percent mass remaining in the source term for the hydrocarbon groups are located in Table 22.

Table 22. Mass percent remaining in source term at the end of 20 years for varying degradation rates.

Compound	% Mass Remaining after 20 years		
	Base Case	Half-Rate	Anaerobic Rates
Benzene	0(3)	0(5)	0(3)
Toluene	0(10)	0(16)	0(10)
Ethylbenzene	33.9	58.4	34.0
Xylenes	32.1	57.2	32.2
C4-C7	99.3	99.3	96.7
C8-C10	100	100	99.9
>C10	100	100	100
Aromatics	98.9	98.9	94.9

Note: numbers in brackets reflect the time of complete depletion of a compound from the source term

In the first case where the rates were halved, a longer period of time was required for benzene and toluene to be depleted from the source term and a greater percentage of ethylbenzene and xylenes remained in the source term after 20 years. As previously discussed, the dissolution of the NAPL residual is driven by biodegradation rather than flushing and hydrocarbons that dissolve are not transported very far from the source area. It is the degradation of the hydrocarbons that causes dissolution to occur due to the driving force that is established between the aqueous phase and the NAPL residual. Therefore, if the biodegradation rates are reduced, a smaller driving force for dissolution will exist between the aqueous phase and the NAPL residual, as the hydrocarbons are not being utilized as quickly.

The addition of anaerobic biodegradation rates did not significantly impact the behaviour of the BTEX compounds due to their greater solubility in water and faster biodegradation kinetics in comparison to the heavier compounds. However, the heavier hydrocarbons were depleted to a larger extent as compared to the base case. The assumption of anaerobic degradation would cause a greater percentage of these compounds to degrade within the source area and hence a greater mass to dissolve into the aqueous phase due to the greater concentration differential that would exist in the source areas for these compounds.

Figure 49 presents the percent mass remaining of NAPL residual in the source term for the various cases. The greatest percent removal and rate of source depletion occurred for the case where anaerobic degradation was assumed for the heavier compounds due to the previously mentioned reasons. The greatest percent mass remaining occurred in the case where the biodegradation rates were reduced, as NAPL dissolution was slowest.

Figure 49. Percent mass remaining in the source term for varying degradation rates.

6.5.5 Significance of Sensitivity Analyses

The results of the sensitivity analyses are summarized in Table 23.

Table 23. Summary of Sensitivity Analyses.

		Extent of Redox Zones	Rate of Source Term Depletion
Residual Saturation	Increase	Minimal Effect	↓
	Decrease	Minimal Effect	↑
Areal Extent	Decrease	Slight ↑	Minimal Effect
Oxygen Transfer	Decrease	↑	Minimal Effect
Biodegradation Rate Constants	Half-Rate	Minimal Effect	↓
	Assumption of Anaerobic Degradation	↓	↑

It is recognized that there is uncertainty in the magnitude and distribution of the source term, specifically related to the assumed residual saturation and areal extent of the source term. To assess the impact of the uncertainty in the source term, model simulations were conducted where the residual saturation and areal extent of the source term were varied. It was determined that variations in these parameters had little impact on the extent of the redox zones and distance that the contamination migrated off-site. Increasing the residual saturation increased

the timeframe over which dissolution will occur and hence the predicted level of soil contamination is greater after 20 years. This result has implications when considering remedial action at the site under consideration.

In addition to uncertainty associated with the source term, there is also uncertainty associated with oxygen transfer from recharge and the unsaturated zone. Decreasing the dissolved oxygen concentration in the system had minimal impact on source term dissolution, while a reduction in oxygen transfer caused the redox zones to extend further off-site. However, conservative estimates of oxygen transfer were used for all simulations and the value used for the base case simulation reflects the lower end of a range of values suggested by Holder *et al.*, (1999).

There is considerable uncertainty associated with the biodegradation kinetics of organic compounds under various redox conditions. A model simulation was therefore conducted where the assumed rates were reduced by a factor of 2 to assess the impact of this parameter on the model predictions. A reduction in biodegradation rates did not impact upon the extent of the redox zones, however it did cause a decrease in the rate of source term dissolution. This was attributed to the fact that the dissolution of the source term is driven by degradation processes rather than flushing processes. A further model simulation was conducted where the heavier hydrocarbons were assumed to degrade under anaerobic conditions. The extent of the redox zones decreased in this scenario

and the rate of source term depletion increased as a greater driving force for dissolution was created.

The results discussed above are specific to the site under investigation, which is characterized by slow groundwater flow and a low recharge rate. As such, the dissolution of the source term was determined to be driven by biodegradation processes rather than flushing processes.

CHAPTER 7

7.0 Conclusions

A detailed site investigation at a former jet fuel storage facility was undertaken to determine the impact of petroleum hydrocarbons on the underlying soil and groundwater environments. A soil-vapour survey, soil test pits and borehole drillings aided in the delineation of the extent of soil contamination while contaminant and geochemical analyses of groundwater samples collected at 20 wells served to identify impacted areas. The following conclusions can be drawn pertaining to the impacted soil and groundwater:

1. The results of the soil-vapour survey agree well with the results of an earlier soil-vapour survey completed by Fondex (1994). Elevated vapour concentrations at a depth of 0.5 and 1.0 m were measured in the areas of the storage tanks, pump house and the four valve houses located adjacent to the rail line.
2. Soil samples collected at a depth of 1.0 m in the vicinity of the former rail line and valve houses 3 and 4 (samples A2 and A9), and in the vicinity of the former pump house and storage tanks (samples B7, B28, B31, C9, C24, C26, C28, C36, and C37) exceeded the TPH and total xylenes MOEE Table B criteria for industrial/commercial land use of 1000 ppm and 34 ppm, respectively.
3. Groundwater samples collected in the vicinity of the former rail line and valve houses 3 and 4 (wells BH1-14 and BH1-G), and in the vicinity of the former pump house and storage tanks (wells BH1-21, BH1-A, BH1-B and BH1-D) exceeded the benzene and total xylenes MOEE Table B criteria for nonpotable groundwater of 1900 ppb and 5600 ppb, respectively.
4. A highly contaminated soil sample collected in the former pump house area and a background soil sample collected at the northeast corner of the site were analyzed for heavy metals, VOCs and PAHs. A comparison of the analyses indicates that the site has been impacted by petroleum hydrocarbons and no evidence of another contaminant source exists.

5. Analysis of groundwater samples collected at the site indicated strongly reduced conditions in groundwater within and near the source areas. Groundwater analyses for samples collected downgradient of the source areas indicated lower petroleum hydrocarbon concentrations and less reduced conditions. The reduced petroleum hydrocarbon concentrations downgradient of the source and the highly reduced conditions within the source areas indicates that natural attenuation is occurring at the site and that biodegradation of the petroleum hydrocarbons is occurring.

Numerical modelling was conducted to further support the evidence of natural attenuation at the site and to determine the impact of the uncertainty in the source term on the model predictions. The results from the field investigation were used to develop a conceptual model for the site. BioRedox-MT3DMS was used to simulate the conditions at the site using the proposed conceptual model. The results from the model simulations for the site under study indicated that:

1. The more soluble compounds in jet fuel (*i.e.*, BTEX) were found to partition the fastest to the aqueous phase from the pure phase source term due to the high solubility associated with these compounds. The dissolution of the heavier hydrocarbons was limited by their low solubilities.
2. Due to the low net movement of groundwater at this site, the dissolution of the source term was driven by degradation processes rather than flushing.
3. Given the complex nature of groundwater movement at the site, the model predictions for both hydrocarbon and geochemical indicators agree relatively well with field values.
4. Differences between field and model results may be largely due to uncertainties related to the occurrences of the spills, the estimated quantity of jet fuel assumed within the source areas, the assumed degradation kinetics and the jet fuel composition selected for modelling purposes.

It is recognized that there is great uncertainty associated with parameters used to define the source term, oxygen transfer from the unsaturated zone and biodegradation kinetics. In an effort to assess the impact of various model parameters on the distribution of the redox zones and the rate of depletion of the source term, model simulations varying the NAPL saturation within the source term, the areal extent of the source term, the oxygen transfer from the unsaturated zone and biodegradation rate constants were conducted. The following conclusions, which are specific to the site under study, were arrived at based on these simulations:

1. Increasing the residual jet fuel saturation within the source term by a factor of 1.5 did not impact upon the extent or distribution of the redox zones. Decreasing the residual saturation within the source term by a factor of 2 caused an estimated 5% reduction in the width of the redox zones and an estimated 90% reduction in the size of the methanogenic zone, as compared to the base case simulation after 20 years. The rate of source depletion decreased with increasing residual saturation. For the simulations where 15% and 5% residual saturations were assumed, 95.3% and 92.6% of the initial mass of hydrocarbons was predicted to be remaining in the source term after 20 years, respectively. For the simulation in which a 5% residual saturation was assumed within the source term areas, all of the BTEX compounds had dissolved from the residual jet fuel after 20 years and hence the 92.6% mass remaining after 20 years consists of the heavier, less soluble fraction of the jet fuel.
2. Increasing the areal extent of the source term by factors of 3.5 and 6 caused the extent of the anaerobic zones to extend approximately 50 m further downgradient of the source areas in comparison to the base case simulation. The rate of source term depletion was very similar for the 3 simulations in that only a 0.5% difference in percent mass of hydrocarbons remaining in the source term after 20 years was observed between simulations. Variations in the areal extent of the source term had minimal effect on the rate of source term depletion since its dissolution was driven by biodegradation reactions within the

source areas and the availability of the electron acceptors per unit area remained relatively constant

3. Decreasing the dissolved oxygen concentration in the system had minimal impact on source term dissolution where a difference of 0.02% in percent mass of hydrocarbons remaining in the source term after 20 years was observed. In the simulation where oxygen transfer from the vadose zone was ignored, the extent of the anaerobic zones extended approximately 90 m further downgradient than that observed for the base case simulation.
4. A reduction in biodegradation rates did not impact upon the extent of the redox zones, however it did cause a decrease in the rate of source term dissolution in that 1% more mass was predicted to be remaining in the source term after 20 years as compared to the base case simulation. This was attributed to the fact that the dissolution of the source term is driven by degradation processes rather than flushing processes. A reduction in the degradation rates decreases the rate of dissolution of the source term and therefore the mass flux of hydrocarbons to the aqueous phase is reduced. The reduced mass flux and reduced rate kinetics resulted in minimal impact on the extent of the redox zones. A further model simulation was conducted where the heavier hydrocarbons were assumed to degrade under anaerobic conditions. The extent of the anaerobic zone decreased by approximately 40 m in this scenario and the rate of source term depletion increased as a greater driving force for dissolution was created. A difference in the mass of hydrocarbons remaining in the source term after 20 years of 1.4% was predicted between the base case simulation and this simulation.

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APPENDIX A

Figure A. 1 and Figure A. 2 provide the soil-vapour concentrations, expressed as ppmv combustibles, at depths of 0.5m and 1.0m, respectively.

Figure A. 1. Soil-Vapour Concentrations of Combustibles at 0.5 m Depth (expressed as ppmv).

**Figure A. 2. Soil-Vapour Concentration of Combustibles at 1.0 m Depth
(expressed as ppmv).**

APPENDIX B

Figure B. 1. Borehole Log for BH1-A.

Figure B. 2. Borehole Log for BH1-B.

Figure B. 4. Borehole Log for BH1-D.

Figure B. 5. Borehole Log for BH1-E.

APPENDIX C

Client : ESG
 12 Verite Ave
 Dept. of Chem. / Chem. Eng., RMC
 P.O. Box 17000, Stn. Forces
 Kingston, Ontario K7K 7B4
 (613) 541-8000 ext 8567
 Fax: (613) 541-8598

ASG Login No. : 646
Site : Carleton Univ.
Date of analysis : 1-Dec-98
Method No. : ASG 010
Revision Test Report I.C Not Applicable
Sampling Method : Grab Sample
Date of Sampling : Summer 98

RESULTS OF TPH IN SOIL ANALYSIS

Sample I.D.	Unit	TPH (total ppm)	% Fuel Oils	Lubricating Oils, Grease
A11	µg/g	130	100	0
B16	µg/g	1100	100	0
B28	µg/g	7100	100	0
C28	µg/g	11100	100	0
C36	µg/g	3400	100	0
D11	µg/g	< 40	n/a	n/a
Background	µg/g	< 40	n/a	n/a
C24	µg/g	6100	100	0
Blank	µg/g	< 40	n/a	n/a

Spiked Recovery of 200 ppm TPH

110%

ASU #	524	Report ID:	Carl-BTEX1
Client:	ASG 646	Date Submitted:	1-Nov-98
		Analysis Initiated:	18-Nov-98
Site:	Carleton	Date:	27-Nov-98
		Matrix:	soil

All results are in ng/g (ppb)

SAMPLE	Benzene	Toluene	Ethyl Benzene	Xylenes
A11	<50	<100	<100	<100
B16	<50	2600	1800	11000
B28	<50	<100	340	16000
C28	<50	1100	57000	280000
C36	<50	<100	2500	9000
D11	<50	<100	<100	<100
C24	<50	<100	9000	80000
RMC background	<50	<100	<100	<100

laboratory QA/QC

Blank	<50	<100	<100	<100
Duplicate				
C24	<50	<100	11000	89000
C24	<50	<100	6100	70000

ASU # 524
Client: ASG 646

Report ID: Carl-S1
Date Submitted: 1-Nov-98
Analysis Initiated: 23-Nov-98

Site: Carleton

Date: 30-Nov-98

Matrix: soil

Preliminary Report

All results are in ug/g

SAMPLE	CU	NI	CO	CD	PB	ZN	CR	AS
Background	3.8	5.0	<5.0	<1.0	<10	<15	<20	0.3
C24	5.9	6.9	<5.0	<1.0	<10	<15	<20	0.3
blk	<3.0	<5.0	<5.0	<1.0	<10	<15	<20	<0.2
MESS-2	35.9	41.5	12.8	<1.0	14	138	51	18.3

ASU # 524
Client: ASG 646

Site: Carleton

Report ID: Carl-voc1
Date Submitted: 12-Nov-98
Analysis Initiated: 17-Nov-98
Date: 27-Nov-98

Matrix: soil

All results are in ng/g (ppb)

Compound #	Compound	C24	RMC backg
1	dichlorodifluoromethane	<60	<60
2	chloromethane	<60	<60
3	vinyl chloride	na	na
4	bromomethane	<60	<60
5	chloroethane	<60	<60
6	trichlorofluoromethane	<60	<60
7	1,1-dichloroethene	<60	<60
8	methylene chloride	<200	<200
9	trans-1,2-dichloroethene	<60	<60
10	1,1-dichloroethane	<60	<60
11	2,2-dichloropropane	<60	<60
12	cis-1,2-dichloroethene	<60	<60
13	chloroform	<60	<60
14	bromochloromethane	<60	<60
15	1,1,1-trichloroethane	<60	<60
16	1,1-dichloropropene	<60	<60
17	carbon tetrachloride	<60	<60
18	1,2-dichloroethane	<60	<60
19	benzene	<60	<60
20	trichloroethene	<60	<60
21	1,2-dichloropropane	<60	<60
22	bromodichloromethane	<60	<60
23	dibromomethane	<60	<60
24	cis-1,3-dichloropropene	<60	<60
25	toluene	<60	<60
26	trans-1,3-dichloropropene	<60	<60
27	1,1,2-trichloroethane	<60	<60
28	1,3-dichloropropane	<60	<60
29	tetrachloroethene	<60	<60
30	dibromochloromethane	<60	<60
31	1,2-dibromoethane	<60	<60

32	chlorobenzene	<60	<60
33	1,1,1,2-tetrachloroethane	<60	<60
34	ethylbenzene	11000	<60
35+36	p+m-xylene	65000	<60
37	o-xylene	25000	<60
38	styrene	<60	<60
39	isopropylbenzene	2400	<60
40	bromoform	<60	<60
41	1,1,2,2-tetrachloroethane	<60	<60
42	1,2,3-trichloropropane	<60	<60
43	n-propylbenzene	3000	<60
44	bromobenzene	<60	<60
45	1,3,5-trimethylbenzene	12000	<60
46	2-chlorotoluene	<60	<60
47	4-chlorotoluene	<60	<60
48	tert-butylbenzene	<60	<60
49	1,2,4-trimethylbenzene	44000	<100
50	sec-butylbenzene	1700	<60
51	p-isopropyltoluene	3600	<60
52	1,3-dichlorobenzene	<60	<60
53	1,4-dichlorobenzene	<60	<60
54	n-butylbenzene	11000	<60
55	1,2-dichlorobenzene	<60	<60
56	1,2-dibromo-3-chloropropane	<100	<100
57	1,2,4-trichlorobenzene	<100	<100
58	hexachlorobutadiene	<200	<200
59	naphthalene	5400	<200
60	1,2,3-trichlorobenzene	<200	<200

Client :

ESG
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Fax: (613) 541-8598

ASG LogIn No. : 648
Site : Carleton U.
Date of analysis : Dec. 3/98
Method No. : ASG 002
Revision Test Report I.D. : Not Applicable
Sampling Method : Grab Sample
Date of Sampling : n/a

RESULTS OF PAH IN SOIL / SEDIMENT ANALYSIS

PAH	Peak #	Sample I.D.					Control Target	Detection Limit	ESG Criteria
		Background	C-24 D	C-24	Blank	Control			
UNIT (ug/g)									
Naphthalene	1	< 0.06	11.37	12.64	< 0.06	2.89	4.10	0.06	ppm
Acenaphthylene	2	< 0.05	< 0.05	< 0.05	< 0.05	0.31	0.19	0.05	0.6** / 5.0
Acenaphthene	3	< 0.05	0.80	0.85	< 0.05	0.17	0.23	0.05	
Fluorene	4	< 0.05	0.35	0.38	< 0.05	0.28	0.47	0.05	
Phenanthrene	5	< 0.05	0.09	0.11	< 0.05	2.99	3.00	0.05	5.0
Anthracene	6	< 0.05	< 0.05	< 0.05	< 0.05	0.85	1.10	0.05	
Fluoranthene	7	< 0.05	< 0.05	< 0.05	< 0.05	4.24	3.54	0.05	
Pyrene	8	< 0.05	< 0.05	< 0.05	< 0.05	2.83	3.00	0.05	10.0
Benzo(a)anthracene	9	< 0.05	< 0.05	< 0.05	< 0.05	1.30	1.80	0.05	1.0
Chrysene	10	< 0.05	< 0.05	< 0.05	< 0.05	1.55	2.00	0.05	
Benzo(b)fluoranthene	11	< 0.05	< 0.05	< 0.05	< 0.05	2.38	2.80	0.05	1.0
Benzo(k)fluoranthene	12	< 0.05	< 0.05	< 0.05	< 0.05	1.32	1.43	0.05	1.0
Benzo(a)pyrene	13	< 0.05	< 0.05	< 0.05	< 0.05	1.68	2.20	0.05	0.7** / 1.0
Indeno(1,2,3-cd)pyrene	14	< 0.05	< 0.05	< 0.05	< 0.05	2.94	1.95	0.05	1.0
Dibenz(a,h)anthracene	15	< 0.05	< 0.05	< 0.05	< 0.05	0.37	0.49	0.05	1.0
Benzo(ghi)perylene	16	< 0.05	< 0.05	< 0.05	< 0.05	1.82	1.78	0.05	
ENC** / N.E.C. / E.C. *		N.E.C.	E.C., E.N.C., E.C.	E.N.C.	n/a	n/a			
Total (ppm)		< 1.0	12.60	13.98	< 1.0	27.96			
Comments:									
All results corrected for the recoveries of the deuterated surrogates naphthalene, phenanthrene, anthracene and benzo(a)anthracene									

* N.E.C. = Not exceeding any individual criteria,

ENC** = Exceeding NEW criteria, Naphthalene and Benzo(a)pyrene only

E.C. = Exceeding one or more individual criteria

ENC** = Exceeding NEW criteria, Naphthalene and Benzo(a)pyrene only

Client : **ESG**
 12 Verite Ave
 Dept. of Chem. / Chem. Eng., RMC
 P.O. Box 17000, Str. Forces
 Kingston, Ontario K7K 7B4
 (613) 541-6000 ext 6567
 Fax: (613) 541-6596

ASG Login No. : **691**
Site : **Carleton**
Date of analysis : **4-Dec-98**
Method No. : **ASG 010**
Revision Test Report I.C **Not Applicable**
Sampling Method : **Grab Sample**
Date of Sampling : **Summer 98**

RESULTS OF TPH IN WATER ANALYSIS

Sample I.D.	Unit	TPH (total ppm)	% Fuel Oils	Lubricating Oils, Grease
BH 14	µg/g	18	100	0
BH 19	µg/g	< 5	n/a	n/a
BH 32	µg/g	< 5	n/a	n/a
BH 33	µg/g	< 5	n/a	n/a
BH 34	µg/g	< 5	n/a	n/a

ASU # **561**
Client: **ASG 691**

Report ID: **Carl-BTEX2w**

Date Submitted: **25-Nov-98**

Analysis Initiated: **26-Nov-98**

Site: **Carleton**

Date: **1-Dec-98**

Matrix: **water**

All results are in ug/L (ppb)

SAMPLE	Benzene	Toluene	Ethyl Benzene	Xylenes
BH14	400	1100	2400	9800
BH19	550	<10	190	200
BH32	<10	<10	<10	<10
BH33	<10	<10	270	<10
BH34	260	<10	380	1100

Laboratory QA/QC

Blank	<10	<10	<10	<10
--------------	---------------	---------------	---------------	---------------

Duplicate

BH34	270	<10	370	1200
BH34	250	<10	390	1100

ASU# 1427

Report I.D.: Carleton BTX-TPH

Client: Dept. Civil & Enviro. Eng.

Date Submitted: 2-Sept-99

Carleton University

Date Analysed: 3-Sept-99

Ottawa, ON K1S 5B6

Date Reported: 20-Sept-99

Matrix: water

Attn: Anne-Marie Thompson

Method: GC/MS and GC/FID

Results:

Sample	Benzene	Toluene	Ethyl Benzene	Xylenes	TPH
	ng/mL				ug/mL
BH H	<2.0	5.8	<2.0	3.8	<0.2
BH 21	2600	11	590	6600	13.2
BH A	2600*	9.2*	3.8*	4400*	7.6
BH C	23	<2.0	<2.0	32	<0.2
BH 28	38	<2.0	<2.0	32	<0.2
BH 27	<2.0	<2.0	<2.0	2.0	<0.2

* Samples run in duplicate and results averaged.

Page 1 of 2

Prepared By:

Authorization:

Laboratory QA/QC

Sample	Benzene	Toluene	Ethyl Benzene	Xylenes	TPH
	ng/mL				ug/mL
Duplicate BH A	2600; 2600	9.6; 8.7	5.9; 1.8	4400; 4400	-
Blank	<2.0	<2.0	<2.0	<2.0	<0.2
Control	22	32	28	93	-
Control Target	25	25	25	75	-

Seprotech Laboratories

Certificate of Analysis:

Report: 200002932

Date Received: May 17 2000

Parameter	Benzene	Ethylbenzene	m/p Xylene	o-Xylene	Toluene	TPH (sum)
Unit	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
MDL	0.0005	0.0005	0.001	0.0005	0.0005	0.1
Sample ID						
BH1-1	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-12	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-14-1	0.380	0.0750	7.500	3.500	1.800	58
BH1-14-3						
BH1-15	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-19	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-21	1.600	<0.025	3.900	0.1300	0.0250	8.3
BH1-24-1	<0.0005	<0.0005	0.002	<0.0005	<0.0005	<0.23
BH1-24-2	<0.0005	0.0015	0.002	<0.0005	<0.0005	<0.23
BH1-25	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	0.5
BH1-27	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-28	0.059	0.0050	0.310	0.0035	<0.0005	1.2
BH1-32	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-33	<0.0005	0.0020	<0.001	0.0025	<0.0005	<0.23
BH1-A	1.100	<0.025	2.400	<0.025	<0.025	6.9
BH1-B-1	0.530	0.0050	1.200	<0.0005	<0.0005	2.5
BH1-B-2	0.480	<0.0005	1.100	0.005	<0.0005	2.6
BH1-C	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-D	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-E	<0.0005	0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-F-1	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-F-2	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23
BH1-G	0.280	<0.025	2.500	0.830	0.0250	3.7
BH1-H	<0.0005	<0.0005	<0.001	<0.0005	<0.0005	<0.23

Table C. 1. Calibration Results for November 1998 Groundwater and Soil Sampling Round.

Benzene	Slope of Calibration Equation (area counts/ng)	1252.8
	R ²	0.890
Toluene	Slope of Calibration Equation (area counts/ng)	2109.1
	R ²	0.985
Ethylbenzene	Slope of Calibration Equation (area counts/ng)	1270.5
	R ²	0.946
m,p-Xylene	Slope of Calibration Equation (area counts/ng)	807.01
	R ²	0.557
o-Xylene	Slope of Calibration Equation (area counts/ng)	854.38
	R ²	0.931
TPH*	Standard mass (ng)	4136
	Standard Area Counts	23108562

*TPH concentrations based on 1 standard for this round

BTEX Concentration (mg/L) = (area counts determined from chromatogram/
slope) / volume injected into the GC (μL) X
(1 mg/ 1 X 10⁶ ng) X (1 x 10⁶ μL/ 1 L)

TPH Concentration (mg/L) = (standard mass * area counts determined from
chromatogram / standard area counts) / (2 μL) X
(1 mg/ 1 X 10⁶ ng) X (1 x 10⁶ μL/ 1 L)

Table C. 2. BTEX Area Counts for Soil Samples, November 1998.

Sample	volume (ul)	Area (Counts)			
		Toluene	Ethylbenzene	m,p-xylene	o-xylene
A2	1		58941	112839	35046
A9	1	3167	57887	117975	31295
A11	1.05	5483			
A22	1.05	3257			
A25	1.1	4554			
B7	1.3		4983	35572	
B9	1.22				
B16	1.1	3697	2169	11847	2457
B25	1.05				
B28	1.15			33636	854
B31	1.2		14530	54994	6664
B40	1.1				
B43	1.15				
B46	1.2				
C6	1.22				
C9	1.25	2725	50450	89257	22889
C24	1.25		15379	56291	19250
C26	1.25	2804	43288	68709	
C28	1.22		47018	74709	24248
C36	1.15		6792	23711	1730
C37	1.2			1542	
C39	1.22				
C48	1.2				
C52	1.25	2696			
D5	1.2	7747		3404	1098
D8	1.22	5326		13457	
D11	1.25	6254			
D21	1.35	3231		3576	
D25	1.2	9559			
Background	1.25				

Table C. 3. BTEX Area Counts for Groundwater Samples, November 1998.

Sample	volume (ul)	Area (Counts)				
		Benzene	Toluene	Ethylbenzene	m,p-xylene	o-xylene
BH1-1	1.3		2488			
BH1-12	1.3		2515			
BH1-14	1.25	775	3961	2477	11009	5420
BH1-15	1.25		1987			
BH1-19	1.2	426	1797			
BH1-21	1.15	8630	2168	1834	9549	
BH1-24	1.25	915		178	4519	
BH1-25	1.25		1947			
BH1-27	1.25		1929			
BH1-28	1.25		1299			
BH1-32	1.25		1485			
BH1-33	1.25		1656			
BH1-34	1.2	371	1992			
BH1-A	1.35	8381	2241	1490	7376	
BH1-B	1.2	5576	2080	1788	12658	
BH1-C	1.2	16	1933			
BH1-D	1.25	911	10774	315	10372	2035
BH1-E	1.15		1439			
BH1-F	1.4		2531			
BH1-G	1.3	881	5219	1949	9294	2374

Table C. 4. TPH Area Counts for Soil Samples, November 1998.

Sample	Area (Counts)
A2	210056864
A9	127858288
A11	223103
A22	4988583
A25	95289
B7	17422428
B9	373376
B16	6784104
B25	398839
B28	13034240
B31	18707634
B40	387177
B43	362063
B46	2495357
C6	289907
C9	68318760
C24	33061564
C26	16794782
C28	54983692
C36	31322920
C37	46532828
C39	309714
C48	437677
C52	272325
D5	2490706
D8	5674679
D11	312814
D21	3716385
D25	477970

Table C. 5. TPH Area Counts for Groundwater Samples, November 1998.

Sample	Area (Counts)
BH1-1	506625
BH1-12	608655
BH1-14	569801
BH1-15	424772
BH1-19	1014761
BH1-21	25819
BH1-24	149392
BH1-25	445305
BH1-27	269869
BH1-28	388254
BH1-32	427706
BH1-33	
BH1-34	416137
BH1-A	476840
BH1-B	416907
BH1-C	473248
BH1-D	492225
BH1-E	
BH1-F	461879
BH1-G	597364

Table C. 6. Calibration Results for June 1999 Groundwater Sampling Round.

Benzene	Slope of Calibration Equation (area counts/ng)	21630
	R ²	0.985
Toluene	Slope of Calibration Equation (area counts/ng)	19538
	R ²	0.994
Ethylbenzene	Slope of Calibration Equation (area counts/ng)	22751
	R ²	0.963
m,p-Xylene	Slope of Calibration Equation (area counts/ng)	66300
	R ²	0.996
o-Xylene	Slope of Calibration Equation (area counts/ng)	28458
	R ²	0.987
TPH	Slope of Calibration Equation (area counts/ng)	6021.6
	Intercept of Calibration Equation (area counts)	24814
	R ²	0.999

BTEX Concentration (mg/L) = (area counts determined from chromatogram/ slope)
/volume injected into the GC (mL) / (1 X 10⁶ ng / 1 mg) X
(1 x 10³ mL/ 1 L) X Dilution Factor

TPH Concentration (mg/L) = [(area counts determined from chromatogram – intercept)/
slope] /volume injected into the GC (μL) X (1 mg/ 1 X 10⁶
ng) X (1 x 10⁶ μL/ 1 L)

Table C. 7. BTEX Area Counts for Groundwater Samples, June 1999.

Sample	dilution factor (1/x)	volume (mL)	Area (Counts)				
			Benzene	Toluene	Ethylbenzene	m,p-xylene	o-xylene
BH1-1A	1	5					
BH1-1B	1	7					
BH1-12	4	1		3843		1327756	1117813
BH1-14	10	1	18155	62915	161094	4261900	1998969
BH1-15	4	1			3420	203476	88976
BH1-19	1	7	125649		6786	4656	4409
BH1-21	20	1	1140657			4172284	
BH1-24	1	1	268162		36128	8376083	
BH1-25A	1	2				8283	
BH1-25B	1	3				6765	
BH1-27	1	5				7064	
BH1-28	4	1			33454	182389	
BH1-32	1	5	8427			13565	
BH1-33-2	1	2	705861				398197
BH1-33-3	3	1				133451	
BH1-34	1	3	248911			28982	10549
BH1-A	20	1	758107		22043	1095004	
BH1-B	20	1	319119		46103	1483991	
BH1-C	1	5	1021523		228	933807	
BH1-D	2	1	29294		50386	1241021	449518
BH1-E	1	5					
BH1-F	1	5		38254	4820	56010	106367
BH1-GA	5	1	370215	394421	112980	4410568	2548371
BH1-GB	5	1	522169	470458	123555	4693701	2684489

Table C. 8. TPH Area Counts for Groundwater Samples, June 1999.

Sample	Volume (ul)	Area (Counts)
BH1-1	0.98	45424
BH1-12	1.5	62394
BH1-14	1.52	163717
BH1-15A	0.98	50556
BH1-15B	1.05	54334
BH1-19	1.07	41816
BH1-21	1.4	123227
BH1-24	1.14	48545
BH1-25A	1.13	42320
BH1-25B	1.1	45891
BH1-27	1.19	49695
BH1-28	1.3	42109
BH1-32	0.9	49053
BH1-33	1.4	48326
BH1-34A	0.95	40369
BH1-34B	1	44450
BH1-A	1.6	109370
BH1-B	1.4	141484
BH1-C	1.5	38822
BH1-D	1.07	67203
BH1-E	0.98	52426
BH1-F	1	47360
BH1-GA	1.4	168794
BH1-GB	1.4	126698

Table C. 9. Calibration Results for August 1999 Groundwater Sampling Round.

Benzene	Slope of Calibration Equation (area counts/ng)	13667
	R ²	0.999
Toluene	Slope of Calibration Equation (area counts/ng)	16266
	R ²	0.999
Ethylbenzene	Slope of Calibration Equation (height/ng)	1199.1
	R ²	0.984
m,p-Xylene	Slope of Calibration Equation (height/ng)	1521.4
	R ²	0.987
o-Xylene	Slope of Calibration Equation (height/ng)	332.87
	R ²	0.998
TPH	Slope of Calibration Equation (area counts/ng)	2766.8
	Intercept of Calibration Equation (area counts)	44409
	R ²	0.999

Benzene and Toluene Concentration (mg/L) = (area counts determined from chromatogram/ slope) /volume injected into the GC (mL) / (1 X 10⁶ ng / 1 mg) X (1 x 10³ mL/ 1 L) X Dilution Factor

Ethylbenzene and Xylene Concentrations (mg/L) = [(height – baseline) / slope] /volume injected into the GC (mL) / (1 X 10⁶ ng / 1 mg) X (1 x 10³ mL/ 1 L) X Dilution Factor

TPH Concentration (mg/L) = [(area counts determined from chromatogram – intercept)/ slope] /volume injected into the GC (μL) X (1 mg/ 1 X 10⁶ ng) X (1 x 10⁶ μL/ 1 L)

Table C. 10. BTEX Area Counts for Groundwater Samples, August 1999.

Sample	dilution factor (1/x)	volume (ml)	Benzene		Toluene		Ethylbenzene		m,p-xylene		o-xylene	
			Area	Area	Area	Area	Height	baseline	Height	baseline	Height	baseline
BH1-1	1	5										
BH1-12	1	2	28058	151470			37858	25319	226225	25319	152193	42033
BH1-14	10	1	262393	81393			51902	14193	275395	14193	54490	27186
BH1-15-1	1	1	26945	79425			57682	22442	218959	22442	53597	33448
BH1-15-2	1	1	8132	18580			19029	11972	62265	11972	26103	19460
BH1-19	4	1	1527601				38264	28145	184194	28145		
BH1-21	10	1	3199801	14019			159357	16628	615107	16628		
BH1-24-1	1	1	6751426				308652	32418	7418439	32418		
BH1-24-2	5	1	375768				27519	11674	427411	11674		
BH1-25	1	2							19481	16873		
BH1-27	1	4										
BH1-28	1	1	585226				18699	17569	75295	17569		
BH1-32	1	4	13220233									
BH1-33-1	4	1	49344				57683	16007				
BH1-33-2	1	2	1257232				2253776	26036				
BH1-34	1	2	222546				92674	32323	729770	32323		
BH1-A	10	1	2209960	4558			30062	11225	189938	11225		
BH1-B	10	1	2290269	3900			88883	12301	400831	12301		
BH1-C	1	4	3805419				457003	29049	974570	29049		
BH1-D-1	2	1	1681313	1315774			325576	23131	1242113	23131	130414	43365
BH1-D-2	4	1	1268503	878980			251589	13723	890670	13723	89922	32398
BH1-E	1	4							20169	15744		
BH1-F	1	4							22091	16933		
BH1-G	5	1	3531562	7841106			250780	24894	1294842	24894	391590	64640

Table C. 11. TPH Area Counts for Groundwater Samples, August 1999.

Sample	Volume (ul)	Area (Counts)
BH1-1	1	48053
BH1-12	1	
BH1-14	1	46446
BH1-15-1	1	55202
BH1-15-2	1	59950
BH1-19	1	104451
BH1-21	1	61187
BH1-24-1	1	51444
BH1-24-2	1	51519
BH1-25	1	55937
BH1-27	1	
BH1-28	1	
BH1-32	1	
BH1-33-1	1	128606
BH1-33-2	1	30275
BH1-34	1	41305
BH1-A	1	65215
BH1-B	1	121371
BH1-C	1	169472
BH1-D-1	1	77598
BH1-D-2	1	67805
BH1-E	1	
BH1-F	1	333304
BH1-G	1	99463

APPENDIX D

Figures D.1 through D.16 present groundwater contour plots for the 16 monitoring events. Table D. 1 lists groundwater elevation data for the 16 monitoring events.

Figure D. 1. Groundwater contour plot for July 13, 1998 (masl).

Figure D. 2. Groundwater contour plot for August 31, 1998 (masl).

Figure D. 3. Groundwater contour plot for October 30, 1998 (masl).

Figure D. 4. Groundwater contour plot for December 11, 1998 (masl).

Figure D. 5. Groundwater contour plot for April 29, 1999 (masl).

Figure D. 6. Groundwater contour plot for May 28, 1999 (masl).

Figure D. 7. Groundwater contour plot for June 30, 1999 (masl).

Figure D. 8. Groundwater contour plot for July 20, 1999 (masl).

Figure D. 9. Groundwater contour plot for August 23, 1999 (masl).

Figure D. 10. Groundwater contour plot for September 19, 1999 (masl).

Figure D. 11. Groundwater contour plot for October 24, 1999 (masl).

Figure D. 14. Groundwater contour plot for January 25, 2000 (masl).

Figure D. 15. Groundwater contour plot for February 22, 2000 (masl).

Figure D. 16. Groundwater contour plot for March 31, 2000 (masl).

Table D. 1. Groundwater Elevation Data.

Well	Depth (m) (length of pipe)	TOPVC (masl)	TOG (masl)	Pipe Length Above Ground (m)	13-July-98		31-Aug.-98	
					Tape Depth (mbtop)	Elevation (masl)	Tape Depth (mbtop)	Elevation (masl)
BH1-1	4.57	102.267	101.609	0.658	2.085	100.182	2.36	99.907
BH1-12	4.57	102.574	101.828	0.746	2.42	100.154	2.74	99.834
BH1-14	3.66	102.291	101.328	0.963	2.39	99.901	2.79	99.501
BH1-15	3.66	102.499	101.521	0.978	2.51	99.989	2.855	99.644
BH1-19	3.66	102.361	101.517	0.844	2.27	100.091	2.66	99.701
BH1-21	3.96	102.49	101.631	0.859	2.315	100.175	2.59	99.900
BH1-24	3.66	102.623	101.596	1.027				
BH1-25	8.23	102.068	101.283	0.785	2.02	100.048	2.42	99.648
BH1-27	3.66	102.001	101.024	0.977				
BH1-28	5.18	103.252	102.452	0.800	3.13	100.122	3.42	99.832
BH1-29	3.96	102.257	101.512	0.745	2.09	100.167	2.35	99.907
BH1-32	3.73	102.186			2.17	100.016	2.44	99.746
BH1-33	3.68	102.159			2.13	100.029	2.555	99.604
BH1-34	3.77	102.239			2.13	100.109	2.49	99.749
BH1-A	4.505	102.538	101.508	1.030	2.35	100.188	2.63	99.908
BH1-B	4.51	102.689	101.662	1.027	2.51	100.179	2.79	99.899
BH1-C	4.59	102.736	101.641	1.095	2.61	100.126	2.94	99.796
BH1-D	4.52	102.535	101.507	1.028	2.38	100.155	2.70	99.835
BH1-E	4.325	102.407	101.328	1.079	2.26	100.147	2.60	99.807
BH1-F	4.59	102.298	101.258	1.040	2.20	100.098	2.59	99.708
BH1-G	4.50	102.477	101.464	1.013	2.30	100.177	2.72	99.757

Notes: TOPVC - Top of PVC pipe, TOG - Top of Ground, masl - meters above sea level
mbtop - meters below top of pipe

Well	30-Oct.-98			11-Dec-98			29-Apr-99			28-May-99			30-Jun-99		
	Tape Depth (mbtop)	Elevation (masl)		Tape Depth (mbtop)	Elevation (masl)		Tape Depth (mbtop)	Elevation (masl)		Tape Depth (mbtop)	Elevation (masl)		Tape Depth (mbtop)	Elevation (masl)	
BH1-1	2.34	99.927		2.275	99.992		1.72	100.547		2.04	100.227		2.29	99.977	
BH1-12	2.67	99.904		2.56	100.014		1.975	100.599		2.355	100.219		2.67	99.904	
BH1-14	2.53	99.761		2.415	99.876		2.005	100.286		2.475	99.816		2.605	99.686	
BH1-15	2.73	99.769		2.585	99.914		2.02	100.479		2.43	100.069		2.78	99.719	
BH1-19	2.49	99.871		2.32	100.041		1.635	100.726		2.165	100.196		2.58	99.781	
BH1-21	2.59	99.9		2.535	99.955		1.955	100.535		2.28	100.21		2.53	99.96	
BH1-24	2.74	99.883		2.6	100.023		2.025	100.598		2.43	100.193		2.78	99.843	
BH1-25	2.16	99.908		1.95	100.118		1.445	100.623		1.89	100.178		2.32	99.748	
BH1-27	2.02	99.981					1.435	100.566		2.75	99.251		2.04	99.961	
BH1-28	3.39	99.862		3.315	99.937		2.705	100.547		3.08	100.172		3.55	99.702	
BH1-29							1.74	100.517		2.055	100.202		2.295	99.962	
BH1-32	2.28	99.906		2.11	100.076		1.53	100.656					2.44	99.746	
BH1-33	2.22	99.939		1.95	100.209		1.315	100.844		1.95	100.209		2.5	99.659	
BH1-34	2.33	99.909		2.12	100.119		1.515	100.724		2.125	100.114		2.42	99.819	
BH1-A	2.61	99.928		2.54	99.998		1.975	100.563		2.3	100.238		2.565	99.973	
BH1-B	2.785	99.904		2.72	99.969		2.13	100.559		2.46	100.229		2.725	99.964	
BH1-C	2.84	99.896		2.715	100.021		2.16	100.576		2.56	100.176		2.89	99.846	
BH1-D	2.615	99.92		2.495	100.04		1.92	100.615		2.31	100.225		2.63	99.905	
BH1-E	2.485	99.922		2.35	100.057		1.835	100.572		2.19	100.217		2.535	99.872	
BH1-F	2.38	99.918		2.2	100.098		1.71	100.588		2.11	100.188		2.505	99.793	
BH1-G	2.505	99.972		2.225	100.252		1.78	100.697		2.24	100.237		2.595	99.882	

Well	20-Jul-99		23-Aug-99		19-Sep-99		24-Oct-99	
	Tape Depth (mbtop)	Elevation (masl)	Tape Depth (mbtop)	Elevation (masl)	Tape Depth (mbtop)	Elevation (masl)	Tape Depth (mbtop)	Elevation (masl)
BH1-1	2.345	99.922	2.495	99.772	2.49	99.777	2.43	99.837
BH1-12	2.73	99.844	2.885	99.689	2.855	99.719	2.76	99.814
BH1-14	2.685	99.606	2.83	99.461	2.69	99.601	2.76	99.531
BH1-15	2.83	99.669	2.99	99.509	2.95	99.549	2.83	99.669
BH1-19	2.64	99.721	2.8	99.561	2.745	99.616	2.61	99.751
BH1-21	2.58	99.91	2.735	99.755	2.73	99.76	2.675	99.815
BH1-24	2.835	99.788	2.995	99.628	2.95	99.673	2.84	99.783
BH1-25	2.375	99.693	2.535	99.533	2.455	99.613	2.285	99.783
BH1-27	2.085	99.916	2.245	99.756	2.215	99.786	2.13	99.871
BH1-28	3.41	99.842	3.56	99.692	3.55	99.702	3.47	99.782
BH1-29	2.345	99.912	2.495	99.762	2.5	99.757	2.45	99.807
BH1-32	2.46	99.726	2.58	99.606	2.55	99.636	2.38	99.806
BH1-33	2.585	99.574	2.71	99.449	2.65	99.509	2.43	99.729
BH1-34	2.48	99.759	2.63	99.609	2.58	99.659	2.44	99.799
BH1-A	2.615	99.923	2.77	99.768	2.76	99.778	2.695	99.843
BH1-B	2.78	99.909	2.93	99.759	2.92	99.769	2.865	99.824
BH1-C	2.945	99.791	3.105	99.631	3.065	99.671	2.96	99.776
BH1-D	2.685	99.85	2.84	99.695	2.8	99.735	2.72	99.815
BH1-E	2.56	99.847	2.73	99.677	2.685	99.722	2.59	99.817
BH1-F	2.555	99.743	2.715	99.583	2.64	99.658	2.51	99.788
BH1-G	2.665	99.812	2.815	99.662	2.745	99.732	2.54	99.937

Well	28-Nov-99		27-Dec-99		25-Jan-00		22-Feb-00		31-Mar-00	
	Tape Depth (mbtop)	Elevation (masl)	Tape Depth (mbtop)	Elevation (masl)	Tape Depth (mbtop)	Elevation (masl)	Tape Depth (mbtop)	Elevation (masl)	Tape Depth (mbtop)	Elevation (masl)
BH1-1	2.38	99.887	2.25	100.017	2.22	100.047	2.42	99.847	1.74	100.527
BH1-12	2.69	99.884	2.52	100.054	2.57	100.004	2.75	99.824	1.895	100.679
BH1-14	2.72	99.571	3.12	99.171	2.825	99.466	2.82	99.471	2.675	99.616
BH1-15	2.705	99.794	2.57	99.929	2.65	99.849	2.83	99.669	1.875	100.624
BH1-19	2.445	99.916	2.28	100.081	2.395	99.966	2.59	99.771	1.34	101.021
BH1-21	2.64	99.85	2.495	99.995	2.465	100.025	2.67	99.82	2.01	100.48
BH1-24	2.72	99.903	2.57	100.053	2.63	99.993	2.815	99.808	1.87	100.753
BH1-25	2.07	99.998	1.97	100.098	2.13	99.938	2.26	99.808	1.08	100.988
BH1-27	2.03	99.971	1.93	100.071	1.94	100.061			1.35	100.651
BH1-28	3.43	99.822			3.27	99.982	3.465	99.787	2.7	100.552
BH1-29	2.425	99.832								
BH1-32	2.23	99.956			2.18	100.006	2.4	99.786	1.205	100.981
BH1-33	2.22	99.939	1.94	100.219	2.135	100.024	2.335	99.824	0.89	101.269
BH1-34	2.18	100.059	2.03	100.209	2.195	100.044	2.45	99.789		
BH1-A	2.645	99.893	2.52	100.018	2.5	100.038	2.7	99.838	1.99	100.548
BH1-B	2.835	99.854	2.68	100.009	2.655	100.034	2.855	99.834	2.15	100.539
BH1-C	2.86	99.876	2.71	100.026	2.78	99.956	2.96	99.776	2.04	100.696
BH1-D	2.61	99.925	2.48	100.055	2.515	100.02	2.705	99.83	1.715	100.82
BH1-E	2.46	99.947	2.33	100.077	2.4	100.007	2.565	99.842	1.53	100.877
BH1-F	2.32	99.978	2.195	100.103	2.37	99.928	2.515	99.783	1.33	100.968
BH1-G	2.39	100.087	2.195	100.282	2.395	100.082	2.6	99.877	1.26	101.217

APPENDIX E

Table E. 1 lists the major components of jet fuel that were considered for this study.

**Table E. 1. Potential Constituents of Jet Fuel.
(taken from Smith, Harper and Jaber, 1981)**

C	H	Fuel Component	Concentration (wt. %)	Solubility (mg/L)
BTEX				
7	8	Toluene	1.33	515
8	10	Ethylbenzene	0.37	168.3
8	10	m-Xylene	0.96	162
8	10	p-Xylene	0.35	198
8	10	o-Xylene	1.01	175
6	6	Benzene	0.5	1780
C4-C7				
4	10	n-Butane	0.12	61
4	10	Isobutane	0.66	49
5	12	n-Pentane	1.06	40
6	14	2,2-Dimethylbutane	0.1	20
6	14	2-Methylpentane	1.28	14
6	14	3-Methylpentane	0.89	13
6	14	n-Hexane	2.21	13
6	12	Methylcyclopentane	1.16	42
6	12	Cyclohexane	1.24	55
7	16	2,2-Dimethylpentane	0.25	4.4
7	16	2-Methylhexane	2.35	
7	16	3-Methylhexane	1.97	4
7	14	trans-1,3-Dimethylcyclopentane	0.36	
7	14	cis-1,3-Dimethylcyclopentane	0.34	
7	14	cis-2,2-Dimethylcyclopentane	0.54	
7	16	n-Heptane	3.67	3
7	14	Methylcyclohexane	2.27	14
7	14	Ethylcyclopentane	0.26	
C8-C10				
8	18	2,2,3,3-Tetramethylbutane	0.24	
8	18	2,5-Dimethylhexane	0.37	1.5
8	18	2,4-Dimethylhexane	0.58	1.5
8	19	1,2,4-Trimethylcyclopentane	0.25	
8	18	3,3-Dimethylhexane	0.28	1.5
8	19	1,2,3-Trimethylcyclopentane	0.25	
8	18	2,2-Dimethylhexane	0.71	1.5

C	H	Fuel Component	Concentration (wt. %)	Solubility (mg/L)
8	18	2-Methylheptane	2.7	0.9
8	18	4-Methylheptane	0.92	
8	16	cis-1,3-Dimethylcyclohexane	0.42	
8	18	3-Methylheptane	3.04	0.8
8	16	Dimethylcyclohexane	0.43	
8	18	n-Octane	3.8	0.7
9	16	1-Methyl-3-ethylcyclohexane	0.17	
9	16	1-Methyl-2-ethylcyclohexane	0.39	
9	18	1,3,5-Trimethylcyclohexane	0.99	
9	18	1,1,3-Trimethylcyclohexane	0.48	
9	20	2,5-Dimethylheptane	0.52	
9	20	3,4-Dimethylheptane	0.43	0.3
9	20	4-Ethylheptane	0.18	
9	20	4-Methyloctane	0.86	
9	20	2-Methyloctane	0.88	
9	20	3-Methyloctane	0.79	
9	18	1-Methyl-4-ethylcyclohexane	0.48	
9	20	n-Nonane	2.25	0.15
10	22	n-Decane	2.16	
10	20	n-Butylcyclohexane	0.7	
>C10				
12	26	2-Methylundecane	0.64	
12	26	n-Dodecane	2	0.004
11	24	n-Undecane	2.32	
13	28	2,6-Dimethylundecane	0.71	
13	28	n-Tridecane	1.52	
14	30	n-Tetradecane	0.73	
Aromatics				
9	12	Isopropylbenzene	0.3	
9	12	n-Propylbenzene	0.71	60
9	12	1-Methyl-3-ethylbenzene	0.49	
9	12	1-Methyl-4-ethylbenzene	0.43	
9	12	1,3,5-Trimethylbenzene	0.42	73
9	12	1-Methyl-2-ethylbenzene	0.23	
9	12	1,2,4-Trimethylbenzene	1.01	57
10	14	1,3-Diethylbenzene	0.46	
10	14	1-Methyl-4-propylbenzene	0.4	6.8
10	14	1,3-Dimethyl-5-ethylbenzene	0.61	21
10	14	1-Methyl-2- <i>l</i> -propylbenzene	0.29	6.8
10	14	1,4-Dimethyl-2-ethylbenzene	0.7	21
10	14	1,2-Dimethyl-4-ethylbenzene	0.77	21
10	14	1,2,3,4-Tetramethylbenzene	0.75	21
10	8	Naphthalene	0.5	33
11	10	2-Methylnaphthalene	0.56	27
11	10	1-Methylnaphthalene	0.78	27
12	12	2,6-Dimethylnaphthalene	0.25	