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Monitoring Subsurface Hydrocarbon Contamination Using Multi-Level Vapour Phase Piezometers

by
Patricia Pearce

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
August 2000

The Master of Engineering Program in Civil and Environmental
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administered by the Ottawa-Carleton Institute for Civil Engineering

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Department of Civil and Environmental Engineering

The undersigned recommend to the Faculty of Graduate
Studies and Research acceptance of the thesis

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Using Multi-Level Vapour Phase Piezometers

submitted by
Patricia Pearce

in partial fulfillment of the requirements for
the degree of Master of Engineering

Chair, Department of Civil and
Environmental Engineering

Supervisor, Dr. Wayne Parker

Carleton University
Ottawa, Ontario, Canada
August 2000

Abstract

This study assessed the feasibility of using multi-level vapour phase piezometers to monitor gasoline contamination in the vadose zone. The current state of contamination was assessed through both groundwater quality and soil sampling. A series of ten nested soil vapour wells were used for soil gas surveys, which quantified TPH, oxygen, carbon dioxide, and BTEX concentrations in the vapour phase. Soil gas wells located near the source term exhibited more significant fluctuations in TPH, oxygen, and BTEX concentrations with time than did wells impacted by migration of soil vapours. A stoichiometric relationship was observed between TPH, oxygen, and carbon dioxide in the soil vapour wells. Increased soil moisture due to precipitation increased soil vapour TPH concentrations near source terms and led to competitive desorption of hydrocarbons from soil particles. Decreased soil temperatures decreased biodegradation rates. BTEX monitoring provided minimal additional information about contamination at the site as compared to that obtained by analyzing TPH, oxygen and carbon dioxide concentrations. Finally, it was found that groundwater wells located some distance from contaminated soils and screened across the water table provided accurate indications of subsurface soil vapour quality.

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Glossary

Symbols

A	= cross-sectional area for phase transfer
$C_{i,g}$	= concentration of compound i in the gaseous phase, atm or ppmv
$C_{i,p}$	= concentration of compound i in the phase p (g = vapour, w = aqueous, s = solid)
$C_{i,s}$	= concentration of compound i in the solid phase following sorption, mg kg ⁻¹ = equal to the mass of solute sorbed divided by the mass of the solid phase
$C_{i,s}^{max}$	= maximum amount of adsorbate that can be adsorbed, mg kg ⁻¹
$C_{i,w}$	= concentration of compound i in the aqueous phase, mg L ⁻¹
D_{air}	= free air diffusion coefficient, cm ² s ⁻¹
D_{aq}	= aqueous phase diffusion coefficients, cm ² s ⁻¹
$D_{e,p}$	= effective diffusion coefficient in phase p (w = aqueous, g = gaseous), cm ² s ⁻¹
f_i	= the mass fraction of component i in the mixture
$F_{i,d,p}$	= diffusive flux of compound i through phase p (w = aqueous, g = gaseous) cm m ⁻² d ⁻¹
G_s	= specific gravity of soil sample, kg m ⁻³
H	= Henry's law constant, dimensionless = Height of soil column, cm (equation 5.3)
K	= first order decay rate, d ⁻¹
K_b	= BET adsorption coefficient, variable units
K_d	= distribution coefficient, mL g ⁻¹
K_{Fr}	= Freundlich adsorption coefficient, variable units
k_g	= gaseous film transfer coefficient, variable units
K_H	= Henry's law constant, kPa m ³ mole ⁻¹
K_h	= hydraulic conductivity, cm s ⁻¹
k_l	= liquid film transfer coefficient, variable units
K_L	= Langmuir adsorption coefficient, variable units
K_m	= saturation coefficient for Monod kinetic reaction, mg L ⁻¹
K_v	= volatilization mass transfer coefficient, variable units
M_{air}	= molecular mass of air = 28.97 g mole ⁻¹ in dry air = 28.6 g mole ⁻¹ at 25°C, saturated with water
M_i	= molecular mass of the compound i, g mole ⁻¹
$m_i(t)$	= mass of compound i removed at time t
$M_{i,g}$	= molecular mass of gas, g mole ⁻¹
m_i^o	= mass of compound i injected at time t = 0
M_{mix}	= molecular mass of the mixture, g mole ⁻¹
m_s	= mass of soil, g
m_w	= mass of water, g
n	= empirical coefficient or fitting parameter, dimensionless
P	= atmospheric pressure, 1 atm
P_i^o	= vapour pressure of the pure solvent i, atm ⁻¹
$P_{i,solution}$	= vapour pressure of the compound in solution, atm ⁻¹
R	= universal gas constant, 8.3144 kPa L mole ⁻¹ K ⁻¹
r	= retardation factor
r_b	= rate of biodegradation, variable units
r_v	= rate of volatilization, variable units

S_i	= water solubility of pure compound i, g L ⁻¹ or mole L ⁻¹
T	= temperature, °K
t_s	= time of sample, min
V	= average linear velocity, cm s ⁻¹
V_{air}	= Molar volume of air, 20.1 cm ³ mole ⁻¹
V_i	= Molar volume of compound i in vapour phase, cm ³ mole ⁻¹
V_s	= sample volume, cm ³
V_T	= total sample volume, cm ³
X	= biomass concentration, mg L ⁻¹
X_i	= mole fraction of compound i in pure phase mixture
$\frac{dh}{dl}$	= hydraulic gradient, m m ⁻¹
β	= Function of η
δ	= dimensionless factor that accounts for constrictivity of pores
ε_t	= effective transport-through porosity
η	= ratio of mass measured at time t to mass injected
μ_{max}	= maximum specific growth rate, per day
θ	= total porosity
θ_v	= vapour phase porosity
θ_w	= pore water and air porosity of soils
ρ_b	= bulk soil density, g cm ⁻³
τ_f	= dimensionless factor that accounts for tortuosity through porous media

Abbreviations

BCF	= CBrClF ₂
bgs	= below ground surface
BTEX	= benzene, toluene, ethylbenzene, xylenes (m, o, p)
DRO	= diesel range organics
FSG	= Fuller-Schettler-Giddings method for determining free air diffusivity
Gastech	= Gastech 2100 Portable Gas Meter
GC	= gas chromatograph
GC/ECD	= gas chromatograph / electron capture detector
GC/FID	= gas chromatograph / flame ionization detector
GC/MS	= gas chromatograph / mass spectrometer
GRO	= gasoline range organics
HSA	= hollow stem auger
LNAPL	= lighter-than-water non-aqueous phase liquid
NAPL	= non-aqueous phase liquid
PID	= photo-ionization detector
ppbv	= parts per billion by volume
ppm	= parts per million or mg L ⁻¹
ppmv	= parts per million by volume
SF ₆	= sulfur hexafluoride
SPME	= solid phase micro-extraction
TPH	= total petroleum hydrocarbons

Chapter 1 - Introduction

1.1 Background

Subsurface contamination by hydrocarbons is a growing problem as the number of leaking underground storage tanks continues to increase. Natural attenuation is one remedy that is currently available for the remediation of a contaminated site. A portion of this remedy includes groundwater monitoring, which is one technique used to assess the attenuation rate of residual hydrocarbons that is naturally occurring at the site. Parsons Engineering Science, Inc. [1995] proposed a protocol that guides the assessment of groundwater attenuation rates, and provides methods through which the life of the source term can be estimated. The acceptance of natural attenuation as a remedy is contingent upon the observation of multiple lines of proof, which provide support that biodegradation is occurring at an acceptable rate. These lines of proof include evaluating soil and groundwater quality, and identifying microcosms that are indigenous to the site. However, evaluating soil vapour quality as an indicator of subsurface contamination has been overlooked as an alternate line of evidence. This has resulted from the inability of most vapour phase models to describe temporal changes observed in the subsurface. As the impact of climatic and source term changes becomes better understood, modelling of this phase will become more accurate. As such, it is anticipated

subsurface vapour quality might provide an affordable means by which to monitor for volatile compounds.

1.2 Overview

A network of ten permanent multi-level soil vapour monitoring wells were installed at a former gasoline vending station located in Ottawa, Canada. This network spanned the limits of suspected gasoline impacted soils. The subsurface vapour wells were used to monitor the soil gas between July and December 1999 for changes in the total petroleum hydrocarbon (TPH) , oxygen, and carbon dioxide concentrations. Monitoring of BTEX compounds (benzene, toluene, ethylbenzene, and m, o, & p - xylenes) was also completed. Two conceptual models were developed; the first used conventional groundwater and soil sampling, while the second model was developed using the observed soil vapour characteristics. These conceptual models were compared and found similar to one another.

1.3 Objectives

The principle objective of this study was to assess the feasibility of monitoring the subsurface vapour phase as an additional line of evidence in the argument for natural attenuation. As this study is a multi-phase study, the first phase focused on three objectives:

1. Determining the effectiveness of using soil vapour monitoring for identification of contamination,

2. Identifying seasonal trends that may be observed in the subsurface vapour phase. The temporal changes observed included changes in subsurface vapour phase concentrations resulting from changes in the subsurface temperature and moisture contents, and atmospheric effects.
3. Assessing the use of vapour-phase chemical fingerprints as an indicator of contaminant location.

The second phase of this study will attempt to model the temporal changes observed in the subsurface. Once the subsurface vapour phase can be modelled reliably, it may be possible to improve estimates of attenuation rates in the subsurface as volatilization and biodegradation of soil vapours can be included into the mass balance describing the subsurface. Also, characterization of the residual product in the vadose zone might also be improved as soil vapour concentrations are a direct reflection of the contamination in the unsaturated zone, as compared to groundwater contamination. Furthermore, where groundwater is not perceived to be a pathway of risk it may be possible to decrease the frequency of groundwater monitoring in favour of soil gas sampling, which is generally less costly and less labour intensive.

Chapter 2 – Literature Review

Gasoline contamination in soil is a growing concern. In 1983, the Oak Ridge National Laboratory [1983] estimated that approximately 110 billion gallons of gasoline are used as motor fuel each year in the United States. Nearly every gallon of this gasoline is stored underground at some point prior to use. U.S.EPA [1998] estimates indicate 2,130,000 underground storage tanks existed in the United States in 1998. From those tanks, 371,400 confirmed releases had been reported. An additional 30,000 new releases are reported to the U.S.EPA every year. In Canada, it was estimated that by 1994, there were 40,000 leaking underground storage tanks [Government of Canada, 1995]. However, no comprehensive Canadian surveys have been completed at this time.

Three major environmental health and safety problems that result from the release of gasoline to the environment include groundwater pollution, fire, and explosive hazards [Hoag et al., 1986]. The combination of these hazards with the large number of releases reported every year indicate remediation procedures must be established to cost effectively treat gasoline contaminated soils. In order to develop suitable remedies, it is necessary to accurately characterize both the source term and the biodegradative capacity of the soil.

This literature review identifies typical source characteristics of gasoline contaminated soil and transport mechanisms that may influence the spread of

gasoline range hydrocarbons from the original spill location. Emphasis has been placed on assessing the impact of gasoline contamination in clay soils, as the site, which is located in Ottawa, Canada, is predominantly clay soil.

Although heavier hydrocarbon contamination is present at the site, the contamination due to gasoline will be the predominant focus as it is anticipated that the more volatile nature of gasoline will be most accurately predicted using soil gas monitoring.

2.1 Gasoline Contamination

The extent of gasoline contamination in the subsurface is dependent upon several factors including the volume of gasoline released, the duration of the release, the area of infiltration, chemical properties of the gasoline, physical properties of the media, and subsurface flow conditions [Mercer *et al.*, 1990]. Once released into the subsurface, partitioning of gasoline can lead to contamination of the vapour, solid, and water phases in the subsurface. This section will provide background information on gasoline contamination that will assist in development of a conceptual model for the site and analysis of experimental data.

2.1.1 Gasoline Contaminant Sources

Gasoline contamination in the subsurface can be attributed to a number of sources. These sources include infiltration of gasoline resulting from motor vehicle accidents, ruptured pipelines, or more commonly leaking underground

storage tanks. Contamination from service stations often includes a range of hydrocarbons, including, gasoline, diesel fuel, and lubricants. The large variability in hydrocarbons present in gasoline increases the complexity associated with remediation procedures as some contaminants are subject to volatilization while others are subject to either solubilization or sorption [Lecomte et al., 1997].

2.1.2 Distribution of Gasoline in the Subsurface

Gasoline releases to the subsurface have the potential to influence both the vadose zone and the groundwater aquifer. However, the degree to which these systems will be impacted is dependent upon the volume of the non-aqueous phase liquid (NAPL) released, the area of infiltration, and the time duration of release [Mercer et al., 1990]. If the release is sufficiently large, or occurs over a long time, residual contamination will extend through the vadose zone and a pool of free product will form at the capillary fringe. This is compared to the release of a small quantity of product, where the entire volume of the release can be trapped within the soil in the vadose zone. This section will describe how a release of gasoline to the subsurface contaminates the subsurface. The processes involved with the release of gasoline to the subsurface have been described by several sources [Devitt et al, 1992; Hasan, 1996; Palmer et al., 1989].

When a lighter-than-water non-aqueous phase liquid (LNAPL) such as gasoline is spilled into the subsurface, it flows down towards the water table

under the force of gravity. As the spill passes through the soil, it flows through the central portions of the unsaturated pores. If the volume of the spill is small, the gasoline will flow under the influence of gravity until residual saturation of the soil is achieved, as shown in Figure 2.1a. The release of NAPL to the vadose zone creates a three-phase system, consisting of free product, water, and pore gas. As water infiltrates through the contaminated soil, fractions of the gasoline components will dissolve into solution. The infiltrating water may carry the contaminants to the groundwater, where a plume of contaminated water could form. Volatile fractions in the gasoline will partition to the vapour phase and create a vapour plume surrounding the initial spill location.

If the volume of the spill is large, or is continuous, the gasoline will flow along a path to the capillary fringe that is associated with the water table. The characteristic of LNAPLs that differentiates them from other hydrocarbons in the subsurface is that by definition, the density of an LNAPL is less than that of water. Consequently, when the gasoline reaches the capillary fringe, a pool of free product will float on top of the water table. If the volume of release is sufficiently large and rapid, this pool will create a pressure head, which will depress the water table [*Hudak et al., 1993; Farr et al., 1990*].

Spreading of free product along the surface of the capillary fringe will occur in the direction of groundwater flow. This occurs due to the increasing presence of water in the pores, which restricts the pore volume available for the LNAPL.

Figure 2.1: Movement of LNAPL through the subsurface.
 a) distribution of residual LNAPL after a small release,
 b) distribution of LNAPL during a continuous release,
 c) distribution of residual and free product LNAPL following a continuous release.

(Source: Center for Environmental Research Information, and Robert S. Kerr Environmental Research Laboratory. Transport and Fate of Contaminants in the Subsurface, Seminar Publication Number EPA/625/4-89/019. September 1989.)

The restricted pore volume, combined with the lower density of gasoline, will inhibit the downward flow rate, which will subsequently lead to the horizontal spreading of the plume. The spreading will occur in the direction of groundwater flow, as the surface elevation of the water table decreases in the down gradient direction. This slope combined with the effects of gravity will cause the LNAPL to move in the direction of groundwater flow. The spreading along the top of the capillary fringe will reduce the pressure head on the water table and allow the groundwater to return to the previous elevation. However, residual product will remain below the water table, creating a source term within the aquifer. Furthermore, natural changes in the height of the water table will lead to a smudging of the product in the capillary fringe. The distribution of LNAPL in the subsurface following a continuous release is presented in Figures 2.1b and 2.1c.

Dissolved components from the gasoline may also cause a reduction in the residual water content of the capillary fringe by altering the capillary forces. This could lead to changes in the depth of the capillary fringe [Palmer *et al.*, 1989]. The soil characteristics also influence the spread of contamination in the subsurface. For example, clay soils tend to shrink or swell in accordance with the interaction of charges between the soil and the infiltrating liquid. Liquids with high dielectric constants, such as water (dielectric constant = 78.5), lead to swelling of clays, whereas liquids with lower dielectric constants can cause clays

to shrink, and therefore increase in permeability. This increase in permeability is observed in clays following contact with concentrated organic liquids such as hydrocarbons and BTEX compounds [Devitt et al., 1992]. Devitt et al. [1992] reported an increase in permeability of clay with an original permeability of $0.5 \times 10^{-9} \text{ cm}^2$ to $14 \times 10^{-9} \text{ cm}^2$ following contact with pure phase xylene. Clays exposed to benzene (dielectric constant = 2.3) have reported permeabilities ranging from 10^{-4} to $10^{-7} \text{ cm s}^{-1}$. The same clays have water-based permeabilities between 10^{-7} to $10^{-11} \text{ cm s}^{-1}$ [Mesri et al., 1971]. Yong et al. reported contact with dilute solutions, or concentrations below water solubility limits generally did not influence permeability. However, changes in permeability were observed after contact with pure hydrocarbons [Yong et al., 1991].

2.1.3 Residual Saturation by Gasoline

Residual saturation in the subsurface represents a pure phase source term that will influence the partitioning of contaminants between the aqueous, vapour and solid phases. Residual saturation is defined by the degree of saturation where the LNAPL becomes discontinuous and is immobilized by capillary forces [Hasan, 1996]. The degree of residual saturation in the subsurface is dependent on the soil type, moisture content, and the relative permeability of the soil for water, gasoline, and air. The relative proportions of clay and silt in the soil play a dominant role in determining the residual concentration, as the soil type directly influences the moisture content [Hasan, 1996]. The location of residual

product within the soil matrix influences the degree of partitioning that can occur. This section will assist in understanding the nature of the residual saturation in both the vadose and saturated zones.

2.1.3.1 Influence of Wetting Properties of Gasoline on Residual Saturation

The behavior of liquid flowing through a porous media changes depending on the properties of the liquid and soil. When a NAPL such as gasoline flows through soil, neither the water nor the NAPL will occupy the entire pore space. The wettability of the two fluids will determine which parts of the soil pores will be occupied by which fluid.

The wettability of a liquid describes the preferential spreading of one fluid over solid surfaces in a two-fluid system [Mercer *et al.*, 1990]. Wetting fluids tend to coat the surface of grains and occupy the smaller spaces between the porous media due to capillary forces [Hasan, 1996]. Non-wetting fluids flow through the larger pore openings that are not subject to the same degree of capillary forces. These fluids are found as isolated blobs in the center of pores [Hasan, 1996; Mercer *et al.*, 1990]. The wettability of a liquid is determined by degree of contact sought between the liquid and the surface. For example, if water spreads over the surface and oil forms beads on the soil, the system is said to be water-wet. However, if the water beads and the NAPL spreads over the surface, then the system is considered NAPL-wet [Mercer *et al.*, 1990]. This relationship is demonstrated in Figure 2.2.

Figure 2.2: NAPL - Water Interactions
a) Example of a NAPL-wet soil matrix
b) Example of a water-wet soil matrix

In an uncontaminated, two-phase soil system, water is the wetting fluid between water and air. Being the wetting fluid, water tends to line the edges of the pores and cover the soil particles [Palmer *et al.*, 1989]. Capillary forces that hold water near the soil particles create the minimum moisture content for the soil. When NAPL is added to a moist soil system, the water remains the wetting fluid, and like the air, the NAPL flows through and will be contained by the larger pore spaces [Hasan, 1996]. However, if the moisture content of the soil is low, such as is the case in the vadose zone, the NAPL that is introduced to the system will become the wetting fluid, and air will remain the non-wetting fluid. The NAPL flow path will leave behind a residual coating of water-immiscible liquid [Yaron *et al.*, 1996]. The tendency of the NAPL to change between being the wetting fluid and the non-wetting fluid implies that a relatively larger amount of NAPL will be retained within dry soils as compared to the saturated zone [Hasan, 1996; Baehr, 1987]. Furthermore, because of the tendency of the non-wetting fluid to travel through the larger pore spaces, the removal of residual NAPL from the vadose zone will minimally influence the vapour flow paths in the soil [Johnson *et al.*, 1990].

2.1.3.2 Experimental Estimates of Soil Capacity for Residual Saturation

Limited experimentation has been completed for the estimation of residual saturation concentrations in clay soils. Research by Zytner *et al.* [1993] has indicated the gasoline retention capacity of clay soils ranged from 0.167 g to

0.184 g of gasoline per gram of soil. This research also reported the fraction of voids filled by gasoline in dry clays might range from between 0.683 to 0.740. Comparatively, the residual void fraction in soils has also been reported to range between 0.1 to 0.2 of the total void space depending on the hydrocarbon composition and soil type. The larger residual void fractions corresponded with heavier oils, while the lower void fraction corresponded with gasoline contamination [Devitt et al, 1992; Mercer et al., 1990]. However, the results reported by Devitt et al. [1992] are for generalized soil conditions, whereas Zytner et al. [1993] reported the residual void fraction using dry clays containing less than 1.5 % moisture. Hayden et al. [1997] found that residual gasoline saturation in soils with a residual water saturation present were 5 to 10 times lower than residual gasoline saturation in air-dry soil. This difference corresponds with the variations reported by Devitt et al. [1992] and Zytner et al. [1993].

2.1.4 Properties of Gasoline

The chemical composition for gasoline varies considerably because of differences in crude-oil origin and refining processes used to make gasoline [Lecomte et al., 1997; Patnaik, 1997; Riser-Roberts., 1992]. For example, it was found that aromatic hydrocarbon concentrations can vary by more than one order of magnitude [Cline et al., 1991]. However, typical gasoline can be described in terms of carbon molecule ranges, and physical properties such as

boiling points and vapour pressure. The following sections will describe these properties.

2.1.4.1 Chemical Properties

Gasoline is a mixture of C-4 to C-10 hydrocarbons with boiling points ranging from 23 to 204°C. Small fractions of C11 and C12 hydrocarbons are also present. The basic types of hydrocarbons in gasoline are paraffins (alkanes), olefins (alkenes), cycloparaffins (cycloalkanes), and aromatics [Patnaik, 1997; Riser-Roberts, 1992]. In addition to these hydrocarbons, there will also be sulfur, nitrogen, and oxygen, and trace amounts of iron (0.07 to 13 $\mu\text{g mL}^{-1}$), nickel (0.001 to 2 $\mu\text{g mL}^{-1}$), and zinc (0.001 to 2 $\mu\text{g mL}^{-1}$) [Riser-Roberts, 1992]. Between 50% to 70% of the hydrocarbons in gasoline are saturated while 25% to 45% are aromatic compounds [Lecomte et al., 1997]. Table 2.1 lists organic compounds and trace elements found in gasoline, as reported by different references.

As gasoline is degraded in the subsurface through volatile releases to the atmosphere, dissolution to the groundwater, or biodegradation, the ratios of the compounds in the gasoline change. Weathering is the term used to describe the selective loss or disappearance of components from the gasoline source. Gasoline weathering usually results in relative decreases in the amounts of the more volatile compounds.

Table 2.1: Composition of Gasoline

Compound	Number of Carbons	Concentration (w%) ^f		Source
<i>Straight Chain Alkanes</i>				
Propane	3	0.01	to 0.14	1,2,3,4
n-Butane	4	3.93	to 4.70	1,2,3,4
n-Pentane	5	5.75	to 10.92	1,2,3,4
n-Hexane	6	0.24	to 3.50	1,2,3,4
n-Heptane	7	0.31	to 1.96	1,2,3,4
n-Octane	8	0.36	to 1.43	1,2,3,4
n-Nonane	9	0.07	to 0.83	1
n-Decane	10	0.04	to 0.50	1
n-Undecane	11	0.05	to 0.22	1
n-Dodecane	12	0.04	to 0.09	1,4
<i>Branched Alkanes</i>				
Isobutane	4	0.12	to 0.37	1,2,3,4
2,2-Dimethylbutane	6	0.17	to 0.84	1,2,3
2,3-Dimethylbutane	6	0.59	to 1.55	1,2,3,4
2,2,3-Trimethylbutane	7	0.01	to 0.04	1,3,4
Ethylpentane	7			3,4
Neopentane	5	0.02	to 0.05	1
Isopentane	5	6.07	to 10.17	1,2,4
2-Methylbutane	5			3
2-Methylpentane	6	2.91	to 3.85	1,2,3,4
3-Methylpentane	6	2.40	(vol)	1,2,3,4
2,2-Dimethylpentane	7			4
2,3-Dimethylpentane	7	0.32	to 4.17	1,2,3,4
2,4-Dimethylpentane	7	0.23	to 1.71	1,2,3
3,3-Dimethylpentane	7	0.02	to 0.03	1,2,3
2,2,3-Trimethylpentane	8	0.09	to 0.23	1,2,3
2,2,4-Trimethylpentane	8	0.32	to 4.58	1,2,3,4
2,3,3-Trimethylpentane	8	0.05	to 2.28	1,2,3
2,3,4-Trimethylpentane	8	0.11	to 2.80	1,2,3,4
2,4-Dimethyl-3-ethylpentane	9	0.03	to 0.07	1,2
2-Methylhexane	7	0.36	to 1.48	1,2,3
3-Methylhexane	7	0.30	to 1.77	1,2,3,4
2,2-Dimethylhexane	8			3,4
2,3-Dimethylhexane	8			3
2,4-Dimethylhexane	8	0.34	to 0.82	1,2,3
2,5-Dimethylhexane	8	0.24	to 0.52	1,2,3
3,4-Dimethylhexane	8	0.16	to 0.37	1,2,3
3-Ethylhexane	8	0.01		1
2-Methyl-3-ethylhexane	9	0.04	to 0.13	1
2,2,4-Trimethylhexane	9	0.11	to 0.18	1,2,4
2,2,5-Trimethylhexane	9	0.17	to 5.89	1,2
2,3,3-Trimethylhexane	9	0.05	to 0.12	1,2
2,3,5-Trimethylhexane	9	0.05	to 1.09	1,2
2,4,4-Trimethylhexane	9	0.02	to 0.16	1,2
3,3,4-Trimethylhexane	9			4

Table 2.1: Composition of Gasoline (cont'd)

<i>Compound</i>	<i>Number of Carbons</i>	<i>Concentration (w %)^f</i>		<i>Source</i>
<i>Branched Alkanes (cont'd)</i>				
2-Methylheptane	8	0.48	to 1.05	1,3,4
3-Methylheptane	8	0.63	to 1.54	1,3,4
4-Methylheptane	8	0.22	to 0.52	1,3,4
2,2-Dimethylheptane	9	0.01	to 0.08	1,3,4
2,3-Dimethylheptane	9	0.13	to 0.51	1
2,6-Dimethylheptane	9	0.07	to 0.23	1
3,3-Dimethylheptane	9	0.01	to 0.08	1
3,4-Dimethylheptane	9	0.07	to 0.33	1
2,2,4-Trimethylheptane	10	0.12	to 1.07	1,4
2,3,4-Trimethylheptane	10			4
3,3,5-Trimethylheptane	10	0.02	to 0.06	1,4
3-Ethylheptane	10	0.02	to 0.16	1
2-Methyloctane	9	0.14	to 0.62	1
3-Methyloctane	9	0.34	to 0.85	1
4-Methyloctane	9	0.11	to 0.55	1
2,6-Dimethyloctane	10	0.06	to 0.12	1
2-Methylnonane	10	0.06	to 0.41	1
3-Methylnonane	10	0.06	to 0.32	1
4-Methylnonane	10	0.04	to 0.26	1
<i>Cycloalkanes</i>				
Cyclopentane	5	0.19	to 0.58	1,2,3,4
Methylcyclopentane	6	Not Quantified		1,2,4
1-Methyl-cis-2-ethylcyclopentane	8	0.06	to 0.11	1,2,3
1-Methyl-trans-3-ethylcyclopentane	8	0.06	to 0.12	1,2,3
1-cis-2-Dimethylcyclopentane	7	0.07	to 0.13	1,2,3
1-trans-2-Dimethylcyclopentane	7	0.06	to 0.20	1,2,3
1,1,2-Trimethylcyclopentane	8	0.06	to 0.11	1,2
1-trans-2-cis-3-Trimethylcyclopentane	8	0.01	to 0.25	1,2
1-trans-2-cis-4-Trimethylcyclopentane	8	0.03	to 0.16	1,2,3
Ethylcyclopentane	7	0.14	to 0.21	1,2,3
n-Propylcyclopentane	8	0.01	to 0.06	1,2
Isopropylcyclopentane	8	0.01	to 0.02	1,2
1,2-Dimethylcyclohexane	8			3
1-trans-3-dimethylcyclohexane	8	0.05	to 0.12	1,2,3
Methylcyclohexane	7			4
Ethylcyclohexane	8	0.17	to 0.42	1,2,3
<i>Straight Chain Alkenes</i>				
cis-2-Butene	4	0.13	to 0.17	1,2,3,4
trans-2-Butene	4	0.16	to 0.20	1,2,3,4
Pentene -1	5	0.33	to 0.45	1,2,3,4
cis-2-Pentene	5	0.43	to 0.67	1,2,3
trans-2-Pentene	5	0.52	to 0.90	1,2,3,4
cis-2-Hexene	6	0.15	to 0.24	1,2,3
trans-2-Hexene	6	0.18	to 0.36	1,2,3
cis-3-Hexene	6	0.11	to 0.13	1,2,3
trans-3-Hexene	6	0.12	to 0.15	1,2,3
cis-3-Heptene	7	0.14	to 0.17	1,2
trans-2-Heptene	7	0.06	to 0.10	1,2

Table 2.1: Composition of Gasoline (cont'd)

Compound	Number of Carbons	Concentration (w%) [†]			Source
<i>Branched Alkenes</i>					
2-Methyl-1-Butene	5	0.22	to	0.66	1,2,3,4
3-Methyl-1-Butene	5	0.08	to	0.12	1,2,3,4
2-Methyl-2-Butene	5	0.96	to	1.28	1,2,3,4
2,3-Dimethyl-1-Butene	6	0.08	to	0.10	1,2,3,4
2-Methyl-1-Pentene	6	0.20	to	0.22	1,2,3,4
2,3-Dimethyl-1-Pentene	7	0.01	to	0.02	1,2
2,4-Dimethyl-1-Pentene	7	0.02	to	0.03	1,2
4,4-Dimethyl-1-Pentene	7	0.60	(vol)		1,2
2-Methyl-2-Pentene	6	0.27	to	0.32	1,2,3
3-Methyl-cis-2-Pentene	6	0.35	to	0.45	1,2,3
3-Methyl-trans-2-Pentene	6	0.32	to	0.44	1,2,3
4-Methyl-cis-2-Pentene	6	0.04	to	0.05	1,2,3
4-Methyl-trans-2-Pentene	6	0.08	to	0.30	1,2,3
4,4-Dimethyl-cis-2-Pentene	7	0.02			1,2
4,4-Dimethyl-trans-2-Pentene	7	Not Quantified			1,2
3-Ethyl-2-Pentene	7	0.03	to	0.04	1,2
<i>Cycloalkenes</i>					
Cyclopentene	5	0.12	to	0.18	1,2,3
3-Methylcyclopentene	6	0.03	to	0.08	1,2,3
Cyclohexene	6	0.03			1,2,3,4
<i>Alkyl Benzene</i>					
Benzene	6	0.12	to	3.50	1,2,3,4
Toluene	7	2.73	to	21.80	1,2,3,4
o-Xylene	8	0.68	to	2.86	1,2,3,4
m-Xylene	8	1.77	to	3.87	1,2,3,4
p-Xylene	8	0.77	to	1.58	1,2,3,4
1-Methyl-2-ethylbenzene	9	0.19	to	0.56	1,2
1-Methyl-3-ethylbenzene	9	0.31	to	2.86	1,2
1-Methyl-4-ethylbenzene	9	0.18	to	1.00	1,2
1-Methyl-2-n-propylbenzene	10	0.01	to	0.17	1,2,4
1-Methyl-3-n-propylbenzene	10	0.08	to	0.56	1,2,4
1-Methyl-3-isopropylbenzene	10	0.01	to	0.12	1,2,4
1-Methyl-3-t-butylbenzene	11	0.03	to	0.11	1,2
1-Methyl-4-t-butylbenzene	11	0.04	to	0.13	1,2
1,2-Dimethyl-3-ethylbenzene	10	0.02	to	0.19	1,2,4
1,2-Dimethyl-4-ethylbenzene	10	0.50	to	0.73	1,2,4
1,3-Dimethyl-2-ethylbenzene	10	0.21	to	0.59	1,2,4
1,3-Dimethyl-4-ethylbenzene	10	0.03	to	0.44	1,2,4
1,3-Dimethyl-5-ethylbenzene	10	0.11	to	0.42	1,2,4
1,3-Dimethyl-5-t-butylbenzene	12	0.02	to	0.16	1,2
1,4-Dimethyl-2-ethylbenzene	10	0.05	to	0.36	1,2
1,2,3-Trimethylbenzene	9	0.21	to	0.48	1,2
1,2,4-Trimethylbenzene	9	0.66	to	3.30	1,2,4
1,3,5-Trimethylbenzene	9	0.13	to	1.15	1,2,4

Table 2.1: Composition of Gasoline (cont'd)

Compound	Number of Carbons	Concentration (w%) ¹			Source
AlkylBenzene (cont'd)					
1,2,3,4-Tetramethylbenzene	10	0.02	to	0.19	1,2,4
1,2,3,5-Tetramethylbenzene	10	0.14	to	1.06	1,2
1,2,4,5-Tetramethylbenzene	10	0.05	to	0.67	1,2,4
1,2,4,5-Trimethyl-5-ethylbenzene	11				4
Ethylbenzene	8	0.36	to	2.86	1,2,3
1,2-Diethylbenzene	10	0.57			1,2
1,3-Diethylbenzene	10	0.05	to	0.38	1,2
n-Propylbenzene	9	0.08	to	0.72	1,2
Isopropylbenzene	9	<0.01	to	0.23	1,2
n-Butylbenzene	10	0.04	to	0.44	1,2
Isobutylbenzene	10	0.01	to	0.08	1,2
sec-Butylbenzene	10	0.01	to	0.13	1,2
t-Butylbenzene	10	0.12			1,2
n-Pentylbenzene	11	0.01	to	0.14	1,2
Isopentylbenzene	11	0.07	to	0.17	1,2
Indan	9	0.25	to	0.34	1
1-Methylindan	10	0.04	to	0.17	1
2-Methylindan	10	0.02	to	0.10	1
4-Methylindan	10	0.01	to	0.16	1
5-Methylindan	10	0.09	to	0.30	1
Tetralin	10	0.01	to	0.14	1
Polynuclear Aromatic Hydrocarbons					
Naphthylene	10	0.09	to	0.49	1,2,4
Pyrene	16	Not Quantified			1,2
Benz(a)anthracene	18	Not Quantified			1,2
Benzo(a)pyrene	20	0.19 to 2.8 mg/kg			1,2
Benzo(e)pyrene	20	Not Quantified			1,2
Benzo(g,h,i)perylene	21	Not Quantified			1,2
Elements					
Bromine		80	to	345 µg/g	1
Cadmium		0.01	to	0.07 µg/g	1
Chlorine		80	to	300 µg/g	1
Iron		0.07	to	13 µg/ml ⁴	5
Lead		530	to	1120 µg/g	1
Nickel		0.001	to	2 µg/ml ⁴	5
Sodium		<0.6	to	1.4 µg/g	1
Sulfur		0.1	to	0.15 (ASTM)	1
Vandium		<0.02	to	.001 µg/g	1
Zinc		0.001	to	2 µg/ml ⁴	5

Notes:

1: Source: From State of California. Leaking Underground Fuel Tank Field Manual. Academic Press, Orlando, FL. 1987. Quoted in Kenaga, [1980]

2: Source: From Ghassemi, M. et al. *Energ. Sourc.* 7:377-401, 1984. Quoted in Kenaga, [1980]

3: Source: from Jamison, V.W. et al. in *Proc. 3rd Int. Biodegradation Symp.* Sharpley, J.M. and Kaplan, A.M., Eds. Elsevier, New York. 1976. Quoted Kenaga, [1980]

4: Source: Johnson et al., [1990]

5: Source: Riser-Roberts, [1992]

2.1.4.2 Physical Properties

Gasoline is a LNAPL. The components of gasoline are slightly soluble in water, although the solubility of different fractions varies. Gasoline also readily volatilizes to the vapour phase, as most components are highly volatile. As the viscosity of gasoline is similar to water, gravity induces flow through soils that is only retarded by sorption of specific compounds onto the soil particles. Most components of gasoline are biodegradable, although the availability of the carbon molecules to microorganisms varies according to molecule structure and reduction conditions [*Lecomte et al., 1997*]. Table 2.2 lists physical properties of the most common components in gasoline. The impact of the various physical properties of gasoline on the attenuation process will be discussed in following sections.

2.2 Attenuating Processes in the Subsurface

Phase partitioning of contaminants in the subsurface permits contaminants to move between liquid and vapour phases. The transfer of contamination between phases occurs through volatilization, aqueous dissolution, and sorption. Once in these phases, contaminants are able to move from areas of high concentration to areas of lower concentration through advection and diffusion of both soil gas and groundwater. These transport processes result in an overall spreading of contamination. As the contaminant mass is spread over a larger area, the maximum concentration of the contamination is observed to decrease at

Table 2.2: Chemical Properties of Gasoline Components

<i>Compound</i>	<i>Molecular Weight</i>	<i>Boiling Point, °C</i>	<i>Vapor Pressure, kPa</i>	<i>Solubility, g/m³</i>	<i>Henry's Law Constant (K_H), kPa m³/mol</i>
Propane	44.11	-42.1	941	62.4	71.6 ± 2.4
n-Butane	58.13	-0.5	243	61.4	95.9 ± 4.1
n-Pentane	72.5	36.1	68.4	38.5 to 47.6	125 ± 10
n-Hexane	86.17	68.95	20.2	9.5 to 18.3	170 ± 25
n-Heptane	100.21	98.4	6.11	2.93 to 3.37	230 ± 50
n-Octane	114.23	125.7	1.88	0.66 to 0.88	300 ± 50
n-Nonane	128.26	142.4	0.903	0.115	1000 ± 100
n-Decane	148.28	174.1	0.175	0.024 to 0.052	700 ± 300
n-Undecane	156.32	195.9	0.0522	0.044	1855 ± 760
n-Dodecane	170.33	216.3	0.0157	0.0034 to 0.00844	750 ± 250
Isobutane	58.13	-11.7	357	48.9	120 ± 5.2
2,2-Dimethylbutane	86.17	49.7	42.6	18.4 to 23.8	173 ± 16
2,3-Dimethylbutane	86.17	58	31.3	19.1 to 22.5	130 ± 10
Isopentane	72.15	27.9	92.6	47.8 to 49.6	138 ± 5
2-Methylpentane	86.17	60.3	28.25	13.8 to 15.7	170 ± 15
3-Methylpentane	86.17	63.3	25.3	12.8 to 13.1	172 ± 8
2,2-Dimethylpentane	100.21	79.2	14	4.4	318 ± 8
2,3-Dimethylpentane	100.21	89.8	9.18	5.25	175 ± 7
2,4-Dimethylpentane	100.21	80.5	13.1	4.06 to 5.5	300 ± 25
3,3-Dimethylpentane	100.21	86.06	11	5.94	186 ± 10
2,2,4-Trimethylpentane	114.23	99.2	6.56	2.05 to 2.44	330 ± 30
2,3,4-Trimethylpentane	114.23	113.5	3.6	1.36 to 2.3	190 ± 15
2-Methylhexane	100.21	90	8.78	2.54	346 ± 21
3-Methylhexane	100.21	92	8.21	2.64 to 4.95	240 ± 75
2,2,5-Trimethylhexane	128.26	124.1	2.21	0.54 to 1.15	350 ± 120
3-Methylheptane	114.23	115	2.6	0.792	376 ± 15
4-Methyloctane	128.26	142.4	0.903	0.115	1000 ± 100
Cyclopentane	70.14	49.26	42.4	156 to 160	18.5 ± 1.1
Methylcyclopentane	84.16	71.8	18.3	41.8 to 42	36.7 ± 1.4
n-Propylcyclopentane	112.2	103	1.64	2.04	90.2 ± 4.4
Methylcyclohexane	98.19	100.9	6.18	14 to 16	40 ± 3
Pentene -1	70.14	30	85	148	40.3 ± 2
cis-2-Pentene	70.14	36.9	66	203	22.8 ± 1
trans-2-Heptene	98.19	95.7	64.5	15	42.3 ± 4
2-Methyl-1-Pentene	84.16	60.7	26	78	28.1 ± 1.2
Benzene	78.11	80.1	12.7	1740 to 1869	0.55 ± 0.025
Toluene	92.13	110.6	3.8	500 to 627	0.67 ± 0.035
o-Xylene	106.2	144.4	0.882	167 to 204	0.5 ± 0.06
m-Xylene	106.2	139	1.1	134 to 196	0.7 ± 0.1
p-Xylene	106.2	138	1.17	156 to 200	0.71 ± 0.08
1,2,3-Trimethylbenzene	120.2	176.1	0.202	75.2	0.323 ± 0.02
1,2,4-Trimethylbenzene	120.2	169.4	0.271	51.9 to 59	0.59 ± 0.04
1,3,5-Trimethylbenzene	120.2	164.7	0.328	48.2 to 97	0.6 ± 0.2
1,2,4,5-Tetramethylbenzene	134.2	196.8	0.0659	3.48	2.54 ± 0.2
Ethylbenzene	106.2	136.2	1.27	131 to 208	0.8 ± 0.07
n-Propylbenzene	120.2	159.2	0.449	55 to 120	0.7 ± 0.3
Isopropylbenzene	120.2	154.2	0.611	48.3 to 65.30	0.13 ± 0.025
n-Butylbenzene	134.2	183	0.137	11.8 to 17.7	1.3 ± 0.25
Isobutylbenzene	134.2	172.8	0.248	10.1	3.3 ± 0.13
sec-Butylbenzene	134.2	173	0.241	17.6 to 30.9	1.4 ± 0.4
t-Butylbenzene	134.2	169	0.286	29.5 to 34	1.2 ± 0.1
n-Pentylbenzene	148.25	205.4	0.0437	10.5	0.6 ± 0.06
Naphthylene	128.19	218	1.09E-02	22 to 34.4	0.043 ± 0.004
Pyrene	202.3	360	8.86E-07	0.132 to 0.175	0.0012 ± 0.002

Notes:

Data at 25°C unless otherwise stated

Source: Mackay et al., [1981]

Source (Diffusivity and Koc): Heath et al., [1993]

the original point of contamination. Biodegradation is an attenuation process that results in the destruction of contamination, as compared to mass transport processes that spread mass over larger areas. Accurate modelling of the mass transfer and transport in the system requires that each of these processes be accurately described. Figure 2.3 shows a conceptual model of the fate of gasoline contaminants in the subsurface. The following sections will describe each of the partitioning and transport processes.

2.2.1 Aqueous Solubilization

The aqueous phase exists in the subsurface as residual soil moisture, or water associated with either the capillary fringe or the aquifer. Compounds can dissolve into the aqueous phase from contaminated soil gas, residual product, or from compounds desorbed from soil. Partitioning into the aqueous phase occurs in an attempt to obtain equilibrium with both the gas phase and the pure phase.

The maximum extent to which an organic compound dissolves in a solvent is the solubility of the compound [Devitt *et al.*, 1992; Eweis *et al.*, 1998]. A high water solubility of the compound indicates the compound's preference to partition to the water phase. However, where a NAPL mixture is composed of multiple hydrocarbons the solubility of individual components is described by Raoult's law and will be less than aqueous solubilities reported for pure chemicals [Grathwohl, 1998; Mercer *et al.*, 1990]. Raoult's Law can be simplified to that shown in equation 2.1 [Grathwohl, 1998].

Figure 2.3: Phase Partitioning in the Vadose Zone

(Source: Eweis, J.B., Ergas, S.J., Chang, D.P.Y., and Schroeder, E.D. Bioremediation Principles. Boston: McGraw Hill, 1998.)

$$C_{i,w} = X_i S_i \quad (2.1)$$

This simplified version of Raoult's law uses the mass fraction of component i , f_i , and the molecular masses for the mixture and component i , M_{mix} and M_i respectively.

2.2.1.1 Factors Influencing Solubilization

Solubility varies with both the polarity and the structure of the compound. Polar compounds are generally miscible with water while non-polar compounds are not [Grathwohl, 1998; Mercer et al., 1990]. Structural features that affect the solubility of a compound are the molecular volume, and the portion of hydrophobic surface area on the molecule. Solubility decreases as both of these characteristics increase in size [Grathwohl, 1998]. Non-polar compounds exhibit a tendency to sorb to organic matter, and as such, dissolved organic matter in water increases the solubility of non-polar compounds [Mercer et al., 1990].

Variations in the solubility of individual compounds in gasoline contribute to the weathering process of the NAPL. Less soluble compounds will not partition to the aqueous phase as readily, resulting in prolonged, more dilute releases from the source. The most soluble compounds will be quickly released

to solution, leaving behind the weathered, less soluble hydrocarbon

[Devitt et al., 1992; Grathwohl, 1998].

It has also been suggested that in aquifers, compounds may not be found at concentrations equal to the solubility limits, rather, maximum concentrations are generally less than 10 percent of the ideal solubility limit. The observation of the decreased concentrations has been attributed to transfer limitations of compounds to the aqueous phase and the dispersive mixing of the groundwater. Transfer limitations exist between the dissolution of compounds from the pure phase to the aqueous phase as the surface areas over which dissolution can occur may not be maximized. The mixing inherent in the dispersive flow of groundwater would act to dilute the concentration of the compounds in solution *[Riser-Roberts, 1992].*

2.2.2 Volatilization

Volatilization is the movement of contaminants from either the aqueous or pure phase, to the gaseous phase as a result of molecular diffusion caused by a chemical potential gradient between phases *[Eweis et al., 1998; Yaron et al., 1996]*. Each compound has a characteristic saturation vapour pressure that describes the chemical potential between the phases. The vapour pressure is the pressure obtained in a confined system when the vapour phase and pure compound are at equilibrium *[Eweis et al, 1998]*. As the vapour pressure for a compound is attained, the chemical potential gradient begins to approach zero

and volatilization rates slow. As the vapour pressure is achieved, volatilization ceases. Vapour pressures for compounds in gasoline are listed in Table 2.2.

Although gasoline is known to contain up to 250 compounds, the vapour phase only contains significant quantities of between 15 to 70 compounds. From these compounds, approximately 92% of the gasoline vapour can be represented by 25 hydrocarbon compounds [*Riser-Roberts, 1998*]. These compounds are listed in Table 2.3.

Typically, the vapour pressures of compounds in the mixture can vary by several orders of magnitude. The difference in vapour pressures for individual compounds leads to differing volatilization rates. As the compounds volatilize, the residual liquid weathers, resulting in changes to the vapour phase constituents with time [*Yaron et al., 1996*].

2.2.2.1 Henry's Law

The equilibrium ratio of gas phase concentration to aqueous phase concentration is described by Henry's law coefficients. Henry's law is a relationship that equates the mole fraction of a compound at equilibrium in the aqueous phase to the atmospheric partial pressure of the compound in the gas phase [*Tchobanoglous et al., 1987*]. Generally, Henry's law is only valid for dilute solutions. The form of Henry's law that describes the ratio between the partial pressure of the vapour phase, in units such as kPa or atm, to the concentration of

Table 2.3: Approximate Composition of Gasoline Vapours

<i>Compound</i>	<i>Number of Carbons</i>	<i>Boiling Point, °C¹</i>	<i>Vapor Pressure, kPa¹</i>	<i>Vapor Phase Concentration (mean vol%)²</i>
<i>Alkanes</i>				
Propane	3	-42.1	941	0.8
n-Butane	4	-0.5	243	38.1
Isobutane	4	-11.7	357	5.2
Isopentane	5	27.9	92.6	22.9
n-Pentane	5	36.1	68.4	7
Cyclopentane	5	49.26	42.4	0.7
2,3-Dimethylbutane	6	58	31.3	0.7
2-Methylpentane	6	60.3	28.2	2.1
3-Methylpentane	6	63.3	25.3	1.6
n-Hexane	6	68.95	20.2	1.5
Methylcyclopentane	6	71.8	18.3	1.3
2,4-Dimethylpentane	7	80.5	13.1	0.4
2,3-Dimethylpentane	7	89.8	9.18	0.7
2,2,4-Trimethylpentane	8	99.2	6.56	0.5
<i>Alkenes</i>				
Isobutylene	4	-6.9	304	1.1
2-Methyl-1-Butene	5	31.2	NA	1.6
cis-2-Pentene	5	36.9	66	1.2
2-Methyl-2-Butene	5	38.6	NA	1.7
<i>Aromatics</i>				
Benzene	6	80.1	12.7	0.7
Toluene	7	110.6	3.8	1.8
Xylene (o,m,p)	8	142*	1.05*	0.5
<i>Total Percent</i>				92.1

Notes:

1: Source: Mackay et al., [1981].

2: Source: Riser-Roberts et al., [1998].

NA: Data not available

the compound in liquid, in molar units, is shown in equation 2.2, where H is the dimensionless Henry's law constant [Mackay *et al.*, 1981]. Table 2.2 includes Henry's law constants for common compounds found in gasoline, in the form of K_H , as shown in equation 2.2. Henry's law constants are strongly sensitive to temperature [Eweis *et al.*, 1998].

$$H = \frac{C_{i,g}}{C_{i,w}} = \frac{K_H}{RT} \quad (2.2)$$

Henry's law is indicative of the tendency of a chemical to volatilize with higher Henry's Law constants corresponding to an increased tendency to partition to the gas phase [Mercer *et al.*, 1990]. A chemical is typically considered volatile if $H > 1.2 \times 10^{-5}$ [Eweis *et al.*, 1998]. Further to this finding, Jury *et al.* [1984] suggested compounds with $H < 10^{-4}$ tend to be found in the dissolved phase as opposed to the vapour phase.

2.2.2.2 Raoult's Law

Where Henry's law is used to describe the partitioning between contaminated water and the soil gas, Raoult's law is often used to estimate the partitioning between pure phase NAPL and air [Mercer *et al.*, 1990]. Raoult's law states that the vapour pressure of the solvent is reduced by the presence of the solute and is proportional to the mole fraction of the solvent [Mercer *et al.*, 1990]. This is described in equation 2.3.

$$P_{i,solution} = X_i P_i^o \quad (2.3)$$

In the situation of pure phase volatilization, the solvent is the NAPL and Raoult's law would be applied, whereas Henry's law would be applied to the previously described aqueous phase, where the water was the solvent, and the NAPL was the solute.

2.2.2.3 Two-Film Model

Volatilization is typically modelled using the two-film model presented in Figure 2.4. In the two-film model, it is assumed that both the air and aqueous phases are well mixed except near the interface between the phases. At the interface, two stagnant films exist. When the bulk phase concentrations are not in equilibrium, a net flux will occur from one phase to the other. This creates a concentration gradient in each of the films, which is controlled by diffusion of molecules across the films [Eweis *et al.*, 1998; Yaron *et al.*, 1996].

The mass transfer equations describing the rate of volatilization are given in equations 2.4 and 2.5. In equation 2.4, the rate of volatilization, r_v , is described by a mass transfer coefficient, K_v , the area across which volatilization occurs, A , and the concentration gradient that exists between the two phases. The mass transfer coefficient is a function of the liquid film transfer coefficient, k_l , and the vapour phase film transfer coefficient, k_g , and the Henry's law constant. The mass transfer coefficient is described by equation 2.5.

Figure 2.4: Two-Film Model for Volatilization

$$r_v = K_v A \left(C_{i,w} - \frac{C_{i,g}}{H} \right) \quad (2.4)$$

$$\frac{1}{K_v} = \frac{1}{k_l} + \frac{1}{k_g H} \quad (2.5)$$

2.2.2.4 Factors Influencing the Rate of Volatilization

As described previously, Henry's Law and Raoult's Law indicate when a liquid and gas system reach equilibrium. When conditions are such that the gas phase concentration is less than the equilibrium concentration, then volatilization will occur. However, as shown by equation 2.2, the gas phase concentration is dependent on the liquid phase concentration. As a result, any factor that influences the concentration of a compound in one phase will influence the concentration in the opposite phase. Environmental factors that influence volatilization are typically those that influence the partitioning between the soil, air, and water phases [Yaron *et al.*, 1996]. Soil conditions that influence volatilization rates include soil moisture, temperature, porosity, clay, and organic content [Eweis *et al.*, 1998].

In the subsurface, the mass balance of the system suggests that when the mass of a compound sorbed onto the soil decreases, the vapour concentration will increase. An increase in the soil moisture content has been found to decrease the mass of gasoline vapours sorbed by the soil particles due to

competitive desorption between polar and nonpolar compounds

[Donaldson et al., 1990]. This results in an increase in the vapour phase concentration. *[Yaron et al., 1996]*.

Porous soils promote the movement of vapours away from the source, which decreases the partial pressure nearby the source term. This increases the mass lost to volatilization, as volatilization of a compound will cease when the vapour pressure is obtained. Increased soil moisture can decrease the diffusivity of soil vapours by limiting the volume through which vapours can flow through the soil. This can limit volatilization by trapping vapours, and therefore the vapour pressures of the different compounds are reached sooner *[Mercer et al., 1990]*.

Soil temperature is a significant environmental factor that influences volatilization rates. An increase in soil temperature will result in an increase in the vapour pressure *[Yaron et al., 1996]*. This is reflected in the dependence of the Henry's law constant on temperature. The increased vapour pressure leads to an increase in the total mass volatilized. Secondly, large temperature gradients within the soil can cause a thermal gradient, which induces advective flow from warmer to cooler regions. This gradient increases the movement of soil vapours away from the source, which decreases the partial pressure in the soil nearby the volatilizing compounds *[Riser-Roberts, 1998]*.

2.2.3 Sorption / Desorption

Sorption is identified as the excess concentration of pollutants at the soil-surface as compared with that in the bulk solution or the gaseous phase. Sorption can remove compounds from the bulk solution and can therefore affect the behavior of the compound in the soil environment [Grathwohl, 1998; Tchobanoglous et al., 1987; Yaron et al., 1996].

Soils have bonding sites that permit the bonding of molecules to the soil particle. As with aqueous dissolution, the interaction between the particles and the molecules is dependent on a number of factors including polarity of the molecules and the fraction of organic matter in the soil. This section will summarize sorption of hydrocarbons on soils. Although a focus has been maintained on clay soils, similar results have been observed for porous soils [Thoma et al., 1999].

2.2.3.1 Bonding Mechanisms

Hydrocarbons generally bond to soil matter through non-ionic sorption mechanisms such as π -Bonds and weak physical forces. π -Bonds occur as a result of the π orbitals in the organic matter overlapping the π orbitals of the hydrocarbon compounds at right angles. This process may be used to explain immobilization of aromatic compounds on soil organic matter [Manahan, 1994]. Compounds subject to this bonding mechanism include alkenes, alkynes, and aromatic compounds [Yaron et al., 1996].

The weakly attractive Van der Waal forces also contribute to the sorption of hydrocarbons that are not permanently immobilized in the soil [Grathwohl, 1998; Yong *et al.*, 1991]. When molecules are very close, attractive Van der Waal forces dominate and the hydrocarbons can be sorbed onto the surface. Compounds subject to Van der Waals forces include alkanes and aromatics [Yong *et al.*, 1991].

The hydrophobic nature of hydrocarbons is an additional factor that encourages sorption. Weak bonding forces called “hydrophobic bonding” lead to an entropy driven reaction between the hydrocarbon molecules and the soil surface. If hydrophobic organic molecules are dissolved in water, they become surrounded by water molecules. By sorbing onto soil, this “casing” that was around the molecule can become partially dismantled or less ordered, which increases the entropy in the system [Grathwohl, 1998; Yaron *et al.*, 1996].

The rate of sorption is limited by diffusive transport of the solute to the sorption site. Once the molecule has diffused through the stagnant layer to the sorption site, sorption is assumed instantaneous [Grathwohl, 1998].

2.2.3.2 Mechanics of Sorption

Sorption of molecules onto soil surfaces is generally perceived as a two-stage process; an initial rapid sorption followed by a slow sorption stage. Two conceptual models have been proposed to describe this occurrence [Morrissey *et*

al., 1999]. Technology has limited the ability of researchers to observe conclusive evidence supporting a specific model.

The first model proposes two types of sorption sites are present in soil. The first is responsible for the formation of a monolayer on the soil surface. Sorption onto these locations results in direct contact between the soil surface and the molecules being sorbed. This layer corresponds with the monolayer described by the BET sorption isotherm. The second sorption stage occurs when additional layers of molecules are sorbed to the primary layer. The second conceptual model proposes that the sorption process is a result of diffusive limitations. In the first stage where rapid sorption occurs, the molecules diffuse into macropores and sorb to the available sites. Following this, slower diffusion occurs and adsorption occurs on the micro-pores.

In experiments with silty-clay soils, Guo et al. [1998] observed a two-step desorption curve. In this experiment, soils were exposed to toluene vapours. In more contaminated soils, where the sorbed concentration of toluene reached 44.5 mg g^{-1} , the two-step desorption curve was observed. However, in less contaminated soils, where the sorbed concentration only reached 24.6 mg g^{-1} , the desorption curve was smooth. These results support the theory that hydrocarbons sorb onto soils in layers, and that the outer layers of hydrocarbons are more weakly attached to the soil than is the monolayer. This results in the difference in the desorption patterns.

Morrissey et al. [1999] have reported evidence in favour of the diffusion model. In this work, investigators examined the sorption curves of acetone, benzene, and toluene on oven-dried clays. Each of these compounds had different free air diffusion rates. This permitted the observation of two-stage sorption curves that could be related to the properties of each gas. It was found that the first portion of the curve represented the macroscopic diffusion through the pores, while the second portion of the curve was related to intra-particle diffusion. It was found that between 30% to 75% of the equilibrium sorbed mass could be attributed to sorption onto external surfaces.

As mentioned previously, hydrocarbons associated with gasoline are generally nonpolar or weakly polar compounds. In dry soils, these compounds partition to the solid phase [Eweis et al., 1998]. However, more polar compounds have a tendency to compete with less polar compounds for sorption sites resulting in the displacement of the less polar compounds. This is due to the preference of polar mineral surfaces to attract polar compounds [Chiou, 1985]. Increases in moisture content, either in the vapour or in the aqueous phases, results in the competitive desorption of hydrocarbons by polar water molecules. [Chen et al., 1998; English et al., 1991; Guo et al., 1998]. Chiou et al. [1998] found that an increase in the relative humidity of the soil gas from 0% to 50% was sufficient to decrease the mass of weakly polar compounds sorbed onto clayey-silt soil. A further increase to 90% relative humidity resulted in nearly a

75% reduction in benzene sorbed onto the soil, as compared to that sorbed with 0% relative humidity. Yong et al. [1991] also observed decreased sorption of hydrocarbons when water was present.

The organic content of soil has also been found to influence the sorption of hydrocarbons onto soil. As competition by water for sorption sites increases, the role of organic carbon in soil increases in importance [Chiou et al., 1985; Yaron et al., 1996]. Organic matter in soil provides a significant increase in sorption sites for organic compounds. Agricultural soils often contain in excess of 2% organic matter [Devitt et al., 1992].

Changes in temperature also affect the rate of sorption. Specifically, an increased temperature decreases the sorption rate [Eweis et al., 1998]. This is attributed to the increased energy absorbed by the compounds when the temperature increases. The increased energy levels permit the molecule to overcome the physical forces that bond the compound to the soil.

2.2.3.3 Sorption Isotherms

Several sorption isotherms have been proposed to describe the sorption of hydrocarbons onto soil. These include the linear approximation model, and the Freundlich, Langmuir, and BET isotherms. The following section will describe each isotherm, as well as the applicability to hydrocarbon sorption on soils.

Inherent to each of the Freundlich, Langmuir, and BET isotherms is the assumption that equilibrium of the system can be achieved.

The linear approximation model assumes that the concentration of the sorbed material is directly proportional to the concentration in the solution. Essentially, this model uses the soil partition coefficient described above to calculate the sorbed concentration. This model assumes there is no limit to the maximum concentration that can be sorbed. This approximation is presented in equation 2.6.

$$C_{i,s} = K_d C_{i,w} \quad (2.6)$$

Sorption of toluene on clayey soils has been investigated. It was found that the linear equilibrium coefficient, K_d , ranged between 11.3 mL g⁻¹ and 26 mL g⁻¹. The wide range in values reflects the difficulty experienced by sorption of toluene on the experimental apparatus [Barone et al., 1992].

The Freundlich isotherm is an empirically derived isotherm that assumes a logarithmic decrease in adsorption energy with increasing coverage of the adsorbent surface. This isotherm is most commonly used to describe the adsorption of contaminants from dilute solutions [Tchobanoglous et al., 1997; Yaron et al., 1996]. The Freundlich isotherm is presented in Equation 2.7.

$$C_{i,s} = K_{Fr} C_{i,w}^{1/n} \quad (2.7)$$

The coefficients K_{Fr} and n can be calculated by plotting the logarithm of the sorbed concentration against the logarithm of the solute concentration. The slope of the line is equal to $1/n$ while the intercept is equal to K_{Fr} .

English et al. [1991] investigated the sorption of benzene and o-xylene vapours onto a fine sandy loam. The results of the sorption study indicated the Freundlich isotherm modelled the sorption data better than the BET model. Reported K_{Fr} and n values for benzene were $2.33E-03 \text{ (mg g}^{-1}\text{)(mg L}^{-1}\text{)}^{-1}$ and 1.08 while the coefficients for o-xylene were $6.17E-03 \text{ (mg g}^{-1}\text{)(mg L}^{-1}\text{)}^{-1}$ and 0.87 respectively.

The Langmuir isotherm was developed as a theoretical adsorption model to describe the adsorption of gases onto solids. The model assumes the adsorbed contaminant is attached to the surface at definite homogeneous localized sites, and the adsorption surface becomes saturated when a monolayer of contaminant has been adsorbed [Eweis et al., 1998; Yaron et al., 1996]. Further, assumptions include that the heat of adsorption is constant over the entire monolayer and is not affected by temperature, and there is no lateral interaction between the adsorbed species [Yaron et al., 1996].

The Langmuir isotherm presents a simplified adsorption surface whereby the system obtains equilibrium once the surface is completely covered. At that point, any sorption onto the solid may only occur after an equal number of sorption sites have been made available through desorption. The net effect of a system at equilibrium is that the sorption process ceases. Equation 2.8 presents the Langmuir isotherm, where K_L is a constant related to the bonding strength

and $C_{i,s}^{\max}$ is the maximum amount of adsorbate that can be adsorbed

[Eweis et al., 1998; Yaron et al., 1996].

$$C_{i,s} = \frac{K_L C_{i,s}^{\max} C_{i,w}}{1 + C_{i,s}^{\max} C_{i,w}} \quad (2.8)$$

The parameters K_L and $C_{i,s}^{\max}$ can be determined by plotting the distribution coefficient, K_d , against the concentration, $C_{i,s}$, and solving for equation 2.9. K_d is equal to the ratio between the amount adsorbed per unit mass of adsorbent, $C_{i,s}$, and the concentration of the solution, $C_{i,w}$ [Yaron et al., 1996; Tchobanoglous et al., 1987].

$$\frac{1}{K_d} = \frac{1}{K_L C_{i,s}^{\max}} + \frac{C_{i,w}}{K_L} \quad (2.9)$$

For small values of K_L , the Langmuir isotherm predicts a linear relationship, similar to the linear approximation model. However, for large values of K_L , the Langmuir isotherm predicts the mass of contaminant sorbed will reach a maximum concentration [Grathohl, 1998].

The BET model was developed by Brunauer and colleagues to describe the adsorption of gas phase compounds onto solid surfaces [Grathwohl, 1998]. This model describes multi-layer adsorption which is characteristic of bonding by Van der Waals forces [Yaron et al., 1996]. In this model, a monolayer is assumed to form, with weaker layers surrounding the monolayer [Morrissey et al., 1999].

The BET model is described in equation 2.10.

$$C_{i,s} = \frac{K_b C_{i,s}^{\max} C_{i,w}}{(S_i - C_{i,w}) \left(1 + (K_b - 1) \frac{C_{i,w}}{S_i} \right)} \quad (2.10)$$

2.2.3.4 Influence of Sorption on Contaminant Transport in the Vadose Zone

Sorption of contaminants on soil impacts the mass transport of compounds through the soil matrix by removing the compound from the bulk solution [Grathwohl, 1998; Tchobanoglous et al., 1987; Yaron et al., 1996]. Removal of these compounds causes the both the liquid and gaseous contaminant fronts to be retarded as they travel through the soil under the influence of diffusion or advection. However, the time for impact by these compounds following a short-term release is extended as the desorption of contaminants continues after the contaminant front has passed [Grathwohl, 1998].

The process of retarding the contaminant fronts can be observed to occur in three stages. Each stage is an attempt for the system to maintain concentration equilibrium between the gas, liquid, and solid phases [Yaron et al., 1996].

The first stage is the accumulation of contaminants on previously unaffected soil particles. This stage decreases the vapour density and the liquid concentrations of contaminated soil and water as the compounds are pulled from these mediums for adsorption. If the sorption continues for sometime due to

slow sorption processes, the time required for the system to arrive at steady-state will increase and in the limit, no steady state step will be achieved.

The second step is observed when the system reaches equilibrium. During this phase, the rate of sorption onto and desorption from the soil particles is equal, which results in no net change in vapour and liquid concentrations.

The final stage is observed once the contaminant front has passed through the soil, and the vapour phase and liquid concentrations decrease below the equilibrium concentrations. In an attempt to maintain equilibrium, the soil desorbs contaminant to the gas and liquid phase. Depending on the characteristics of the compounds and the soil, the time required to desorb all contaminants can vary. In the extreme case, some contaminants will be immobilized permanently onto the soil matrix.

If the contaminant in the gas and liquid phases is a mixture of hydrocarbons with differing vapour pressures and solubilities, the three stages may become more difficult to recognize. In this case, each individual compound may reach the three stages described above, however, the mechanisms of sorption may differ depending on the competitive isotherm for the mixture. It is possible no true steady state for the mixture will be reached, since the component fractions of the gas and liquid will be continuously changing [Yaron *et al.*, 1996].

2.2.4 Diffusion

Contaminant transport of compounds in the subsurface is influenced by diffusion. In the gas phase, diffusion is the primary transport mechanism. Diffusion also influences transport of contamination in the aqueous phase, primarily under conditions of low hydraulic conductivity, as might be seen in clay soils. Regardless of phase, the importance of diffusion as a transport process increases in lower permeability soils such as clays and silts [Grathwohl, 1998]. This section will discuss general modelling approaches for diffusion in the subsurface.

2.2.4.1 Modelling Diffusion

Brownian motion is responsible for the diffusion of compounds through liquids and gases. Brownian motion describes the motion of molecules in a solution that occurs without any apparent external cause such as stirring or convection. Rather, Brownian motion is a direct result of the thermal motion of molecules, where small particles constantly experience collisions with surrounding particles. The imbalance of these collisions causes the movement of particles [Mahan et al., 1987]. The movement of particles from areas of high concentration to areas of low concentration presumably occurs because the decreased number of collisions in dilute solutions permit more particles to continue traveling in their original trajectory. The term diffusion refers to the random molecular walk that causes the mass flux to move down a concentration

gradient, increasing the spreading of a concentration front or peak with time [Grathwohl, 1998]. Because of the dependence on the interactions between molecules, diffusion is dependent on the mass and volume of diffusing molecules, temperature of the solution, and the medium through which diffusion has occurred [Grathwohl, 1998].

Diffusion is described through Fick's 1st law which is presented in equation 2.11 [Eweis et al., 1998; Grathwohl, 1998].

$$F_{i,d,p} = -D_{e,p} \frac{dC_{i,p}}{dx} \quad (2.11)$$

Fick's 1st law describes the mass flux, F , through a surface. The concentration of the solute in the solution is defined by $C_{i,p}$ where p represents the phase of the solution. The effective diffusion coefficient, $D_{e,p}$, is defined in the following sections. Conservation of mass yields Fick's 2nd law which describes the change in solute concentration with the change in time. Fick's 2nd law is presented in equation 2.12 [Grathwohl, 1998].

$$\frac{dC_{i,p}}{dt} = D_{e,p} \frac{d^2C_{i,p}}{dx^2} \quad (2.12)$$

Equation 2.12 can be integrated into a mass balance equation to include the sinks that may be present, such as biodegradation and sorption.

2.2.4.2 Estimating Diffusion Coefficients

Estimating effective diffusion coefficients is imperative to the accurate prediction of mass transport through the vadose zone. Several sources have estimated that diffusion in water is approximately 10,000 times slower than diffusion in the gas phase. Diffusion coefficients have been estimated to range from magnitudes of $10^{-5} \text{ m}^2 \text{ s}^{-1}$ for vapour phase diffusion to $10^{-9} \text{ m}^2 \text{ s}^{-1}$ for water phase diffusion [Palmer *et al.*, 1989].

Millington and Quirk proposed an empirical correlation to predict the effective diffusion coefficient of a vapour in porous media. This correlation is based on the total and air filled porosity of the media, and is presented in equation 2.13 [Devitt *et al.*, 1992; Grathwohl, 1998; Millington *et al.*, 1961].

$$D_{e,g} = D_{air} \frac{\theta_v^{10/3}}{\theta^2} \quad (2.13)$$

Sallam *et al.* [1984] investigated the applicability of several gas diffusivity models. It was found that the Millington-Quirk model for low air filled porosity silt-loam soils provided a superior estimate of the effective diffusivity when the ratio was reduced from 10/3 to 3.1.

Calculation of the diffusivity of a gas in air at near standard conditions can be completed using the Fuller-Schettler-Giddings (FSG) method as described by equation 2.14.

$$D_{air} = \frac{10^{-3} T^{1.75}}{P \left(V_{air}^{1/3} + V_i^{1/3} \right)^2} \left(\frac{1}{M_{air}} + \frac{1}{M_i} \right)^{1/2} \quad (2.14)$$

Equation 2.14 can be reduced to equation 2.15 for diffusion through air by substituting in $P = 1 \text{ atm}$, $V_{air} = 20.1 \text{ cm}^3 \text{ mole}^{-1}$ and $M_{air} = 28.97 \text{ g mole}^{-1}$ [Grathwohl, 1998].

$$D_{air} = \frac{10^{-3} T^{1.75}}{\left(2.72 + V_i^{1/3} \right)^2} \left(0.0345 + \frac{1}{M_i} \right)^{1/2} \quad (2.15)$$

Table 2.4 summarizes diffusion coefficients published by Grathwohl [1998] for several compounds.

The conversion of the free air diffusivity to an effective diffusivity through soil requires accounting for a ratio of soil properties. These properties include porosity, θ , and tortuosity, τ , as shown in equation 2.16 [Logan, 1999].

$$D_{e,g} = \frac{D_{air} \theta}{\tau} \quad (2.16)$$

For the water phase, an effective diffusion coefficient is required that describes the actual diffusion through a porous medium by accounting for porosity and tortuosity, similar to that presented in equation 2.16. Grathwohl [1998] proposed equation 2.17 for the prediction of the effective diffusion coefficient.

Table 2.4: Diffusion Coefficients

<i>Compound</i>	$D_{aq} (cm^2 s^{-1})$	$D_{air} (cm^2 s^{-1})$	D_{eg}^1
Methanol	1.8 E-05	0.162	—
Methane	—	0.2	9.6 E-06
Benzene	1.02 E-05	0.094	4.1 E-06
Toluene	0.906 E-05	0.084	—
o-Xylene	0.819 E-05	0.0735	—
m-Xylene	0.819 E-05	0.0735	—
p-Xylene	0.819 E-05	0.0735	—
Naphthalene	0.795 E-05	0.0702	—
Benzo(a)pyrene	0.563 E-05	0.0513	—
Oxygen (O ₂)	—	0.22	10 E-06
Carbon dioxide (CO ₂)	—	0.15	7.1 E-6

Notes:

1: Effective Diffusion coefficient in clay with total porosity of 0.54

Source: Grathwohl [1998]

$$D_{e,w} = \frac{D_{aq}\epsilon_t\delta}{\tau} \quad (2.17)$$

In equation 2.17, D_{aq} is the diffusion rate through water, while τ and δ are dimensionless factors that account for tortuosity (>1) and constrictivity of the pores (≤ 1) respectively. The effective transport-through porosity is defined by ϵ_t and accounts for the reduced cross-sectional area available for diffusion when diffusion occurs only in the pore space. The effective transport-through porosity can be smaller than the overall porosity if the solute is larger than some pores in the media [Grathwohl, 1998]. Effective aqueous diffusion coefficients of benzene and naphthalene in clay have been estimated between $2 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$ to $2 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1}$ with an ϵ_t between 0.52 to 0.35 [Grathwohl, 1998].

2.2.4.3 Estimating Soil Gas Diffusion in the Field

In situ measurements of gas diffusion coefficients in soil have been attempted by several researchers. Approaches include injecting tracer gases into the subsurface, monitoring the presence of fluorocarbons at depth, and releasing tracer gases into the subsurface to be monitored at surrounding vapour phase piezometers.

Lai et al. [1976] and Jellick et al. [1986] estimated the gas phase diffusion coefficient in the top layer of soil by injecting gases through a syringe to a depth of 10 cm below ground surface. The concentrations of these tracer gases were

then monitored from the injection port to determine the rate of diffusion based on a spherical diffusion pattern. This test was limited to only determining the diffusion rate of gases just below the soil surface.

Weeks et al. [1982] investigated the use of fluorocarbons to identify diffusion in soils. Based on the premise that fluorocarbons had only been manufactured since the 1930's, the identification of the concentrations through the soil allowed for the computation of the gas diffusion coefficient. However, this method is limited to sites where the water table is in excess of 40 m below ground surface.

Kreamer et al. [1988] investigated gas diffusion using CBrClF_2 (also known as BCF, Halon-1211, or F-12-B1) and sulfur hexafluoride (SF_6) tracer gases. This research involved placing slow release permeation devices at the site. These devices limited the release of BCF to 105 ng s^{-1} at 23°C and SF_6 to 3.33 ng s^{-1} at 18.8°C . Surrounding soil locations were then monitored for the tracer gases. Analysis of the data provided estimates for tortuosity and sorption-affected porosity at the site. However, the authors found the method time consuming and expensive, effectively limiting the technique to application at large scale contaminated sites.

Johnson et al. [1998] developed a simple protocol to estimate the gas diffusion coefficient in the subsurface. Like previous investigations, this work was based on the injection of a tracer gas, SF_6 , into the subsurface via a piezometer. However, depletion of the tracer gas was monitored from the

injection port over time. This technique overcame the limitations of depth experienced by Lai et al. [1976], and Jellick et al. [1986]. In this work, Johnson et al. [1998] proposed the effective diffusivity could be related to the porosity, sample volume, sample time, and the initial and measured mass of the tracer gas. This relationship is shown below in equation 2.18.

$$\beta = \left[\frac{\theta_v^{1/3}}{D_{e,g}} \right] \left[\frac{1}{4t_s} \right] \left[\frac{3V_s}{4\pi} \right]^{2/3} \quad (2.18)$$

In equation 2.18, β is a function of η , as described by equation 2.19. A graph of the relationship β versus η was provided in the original paper.

$$\eta = \frac{m_i(t)}{m_i^o} \quad (2.19)$$

An additional advantage of this method was that due to the localized monitoring, a minimum mass of SF_6 is required. This reduces the effect of density-driven diffusion due to the high vapour density of SF_6 that would be associated with more concentrated tracer gases.

2.2.4.4 Effects of Retardation on Diffusion

As mentioned previously, diffusion of gases through the vadose zone can be impeded by several mechanisms such as sorption and dissolution to pore water. These processes can be included in equation 2.12 through the introduction of a retardation term, R , in the denominator below the effective diffusion coefficient,

$D_{e,p}$. This retardation factor is presented in equation 2.20 [Devitt et al., 1992]. Similar retardation factors have been presented by Falta et al. [1989], and Palmer et al. [1989].

$$r = \frac{\rho_b K_d}{H} + \frac{\theta_w}{H} + \theta_v \quad (2.20)$$

2.2.5 Advection

Advective transport of soil gas is caused by subsurface pressure gradients. These subsurface pressure gradients can develop when the soil gas mixture contains sufficient concentrations of compounds other than air to change the density of the gas, or in response to barometric pressure changes. This section will describe the potential impact of these processes on the movement of soil gas in the subsurface.

2.2.5.1 Density Driven Flow

The presence of hydrocarbons in the vapour phase increases the density of the soil gas. This increase in density has the potential to influence the spreading of the vapour plume through density driven flow. However, it has been found that in order for density driven flow to occur, significant differentials in density must exist. The presence of chlorinated compounds are generally required for this differential to exist [Falta et al., 1989, Mendoza et al., 1990]. The impact of density driven flow is also often offset by phase partitioning to either pore water or sorption to the soil [Brusseu, 1991]. Based on the properties of the

compounds, Falta et al. [1989] proposed benzene might be affected by density driven flow. However, compounds such as toluene, ethylbenzene, xylene, and naphthalene were not expected to be affected because of their tendency to partition to the aqueous phase. Finally, density driven flow is generally only observed in a narrow range of soils, having permeabilities between a medium sand and a coarse gravel [Falta et al., 1989].

2.2.5.2 Barometric Pressure Changes

Advective vapour transport caused by changes in barometric pressure has been observed as out-gassing during periods of high winds and low barometric pressures. However, this condition generally influences surface soils [Riser-Roberts, 1998]. Elberling et al. [1998] have reported that changes in barometric pressure of less than 3kPa has resulted in horizontal soil gas migration of up to 10 m d⁻¹ in sandy soils. Massmann et al. [1992] reported fluctuations in barometric pressure resulted in the migration of atmospheric air into the subsurface. Increased pressure resulted in the intrusion of air into the subsurface while decreased pressure resulted in off-gassing [Massmann et al, 1992]. Despite the reported impact of atmospheric pressure changes to soil gas movement, Kerfoot [1991] reported that field studies showed negligible effects of barometric pressure changes on pore gas concentrations of VOCs.

2.2.6 Biodegradation

Biodegradation is the degradation of compounds by microorganisms.

Biodegradation of hydrocarbons is often the most significant natural process that reduces the total mass of contaminant from a system. As previously discussed, partitioning does not remove compounds from the system but instead leads to the transfer of contaminants from one phase to a second phase. The biodegradation of hydrocarbons to the final products of carbon dioxide and water is termed mineralization [Eweis *et al.*, 1998].

2.2.6.1 Chemical Factors Influencing Biodegradation

Chemical properties that lead to the preferential use of hydrocarbons in biodegradation include the compound solubility, degree of branching of hydrocarbon molecules, degree of saturation, and the nature of substitutions. For example, straight chain molecules are generally more easily degraded than branched hydrocarbons [Eweis *et al.*, 1998].

The molecular shape and composition of hydrocarbons strongly influences the biodegradability of compounds. The chemical solubility also influences the rate of biodegradation because all microorganisms obtain nutrients from the bulk solution. If a compound is either highly volatile or exhibits a strong tendency to sorb onto the soil particles, its bioavailability will be sacrificed. For example, light hydrocarbons with high vapour pressures tend to partition to the gaseous phase. Thus, the biodegradation of light hydrocarbons can be reduced by

transfer to the gas phase [Eweis *et al.*, 1998]. Compounds that are sorbed onto soil also have limited availability to microorganisms. Again, this can reduce the efficiency of biodegradation.

Understanding the order of relative biodegradability of hydrocarbons is vital to the characterization of attenuation processes at a contaminated site.

Microorganisms will tend to use the most available compounds first. As the most preferred nutrients are consumed, the microorganisms will begin to use the next most preferred nutrients. Riser-Roberts [1998] proposed the following list as the order of preferential use of hydrocarbons by microorganisms in the subsurface. In order of decreasing degradability the compounds include:

- linear alkanes (C10 to C19),
- hydrocarbon gases (C2 to C4),
- alkanes (C5 to C9),
- branched alkanes to 12 hydrocarbons,
- alkenes (C3 to C11),
- branched alkenes,
- aromatics, and
- cycloalkanes.

The number of microorganisms that can exist on these compounds decreases as the difficulty of biodegradation increases. Generally, any microorganism that can survive on a compound is able to survive on the more degradable compounds [Riser-Roberts, 1998].

2.2.6.2 Environmental Factors Influencing Biodegradation

Environmental factors that influence biodegradation include changes to temperature, pH, moisture content, and nutrient availability including oxygen. Unsuitable environmental conditions can cause microorganisms to become dormant, or in extreme cases, die.

The optimal temperature for microorganisms in soil ranges between 5°C and 40°C, however, optimal temperatures for different microorganisms is species-specific [Eweis *et al.*, 1998]. Microbial utilization of hydrocarbons has been observed between the extreme temperatures of -2°C to 70°C [Riser-Roberts, 1992]. Generally, in colder climates, bacterial populations develop that are more resistant to temperature fluctuations. Populations of microorganisms exposed to cooler temperatures also tend to develop deeper in the subsurface, presumably to moderate their exposure to temperature changes. Biodegradation is highly susceptible to temperature changes. It has been found that an increase of 10°C doubles the biodegradation rate until the maximum optimal rate is reached. Biodegradation rates are generally highest during the spring and lowest during the winter months [Riser-Roberts, 1992].

The optimal pH range for most soil bacteria is between 7 and 8, however, pH ranges between 6 and 9 can be tolerated [Eweis *et al.*, 1998]. Changes in pH also impact the soil conditions. High pH tends to increase the negative charge on clay soils while a lower pH leads to increased anion adsorption [Riser-Roberts, 1992].

The changes in the sorption of material onto soil influence the biodegradation rate by impacting the availability of nutrients in the aqueous phase.

Soil moisture and nutrient availability are directly related to each other with respect to their impact on biodegradation. Since all microorganisms obtain nutrients from the aqueous phase, adequate moisture concentrations must be available. Nutrient requirements for biodegradation include soluble nitrogen, phosphorous, sulfur, and carbon compounds [Eweis *et al.*, 1998; Riser-Roberts, 1992]. These nutrients are generally utilized by microorganisms to meet their required carbon to nitrogen to phosphorous ratio (100:15:3). The biodegradative potential of soils can be estimated by comparing the nutrient availability to the mass of carbon in the pure phase. By assessing the mass balance describing the nutrient availability in the soil, and comparing this balance to the carbon demand from the pure phase, the required concentrations of nutrient amendments can be estimated [Riser-Roberts, 1992].

2.2.6.3 Microbial Factors Influencing Biodegradation

The microbial population will also affect biodegradation rates. Generally, microorganisms are the only rate-limiting step during the lag phase of acclimatization and during the start of the growth phase [Riser-Roberts, 1992]. Once significant microbial populations have developed, the limiting process generally becomes the diffusion of nutrients to the biomass. The biodegradation

rate is dependent on the mass of active microorganisms and can be represented as the product of the degradation rate coefficient and the microbial mass concentration [Eweis et al., 1998].

Other factors that influence the growth of microorganisms include the accumulation of toxic byproducts, depletion of inorganic nutrients and, the presence of competing or inhibiting substrates [Riser-Roberts, 1992]. Inhibitory concentrations of hydrocarbons only influence the microbial populations when the concentration of hydrocarbons is greater than 100 µg contaminant (g soil)⁻¹.

2.2.6.4 Modelling Biodegradation

Modelling biodegradation in the subsurface is difficult due to the large number of interrelated processes that exist. The two types of models generally used to describe the biodegradation process include the first-order rate model and the Monod rate kinetics. The first order decay rate is presented in equation 2.21.

$$r_b = KXC_{i,w} \quad (2.21)$$

Table 2.5 presents first-order decay rates for BTEX compounds as reported by Suarez et al. in their review of 133 groundwater biodegradation rate studies. These reported rates include the 25th percentile, 90th percentile, and the mean value as calculated by Suarez et al. [1999]. Depending on the compounds being examined and the initial concentrations, there was a wide range of potential

Table 2.5: Summary of BTEX First-Order Decay Rates in Groundwater

<i>Compound</i>	<i>Aerobic Respiration</i>	<i>Nitrate Reduction</i>	<i>Iron Reduction</i>	<i>Sulfate Reduction</i>	<i>Methano- genesis</i>	<i>Mixed</i>
Benzene						
Number of Rates	26	41	20	16	15	25
25th percentile	0.028	0.000	0.000	0.000	0.000	0.001
Mean	0.335	0.008	0.009	0.008	0.010	0.009
90th percentile	0.445	0.030	0.024	0.023	0.033	0.019
Toluene						
Number of Rates	16	49	13	14	24	17
25th percentile	0.089	0.015	0.002	0.010	0.008	0.001
Mean	0.262	0.459	0.012	0.062	0.037	0.302
90th percentile	0.390	1.466	0.034	0.181	0.090	0.084
Ethylbenzene						
Number of Rates	--	37	7	8	12	17
25th percentile	--	0.001	0.000	0.000	0.000	0.001
Mean	--	0.270	0.003	0.002	0.010	0.010
90th percentile	--	0.428	0.009	0.006	0.028	0.025
m-Xylene						
Number of Rates	4	41	8	7	12	16
25th percentile	0.025	0.000	0.001	0.017	0.000	0.000
Mean	0.163	0.089	0.010	0.081	0.019	0.004
90th percentile	0.356	0.260	0.025	0.180	0.057	0.010
o-Xylene						
Number of Rates	10	38	8	6	12	16
25th percentile	0.028	0.000	0.001	0.002	0.000	0.001
Mean	0.086	0.012	0.003	0.027	0.026	0.009
90th percentile	0.205	0.030	0.006	0.070	0.069	0.022
p-Xylene						
Number of Rates	3	21	8	4	10	18
25th percentile	--	0.000	0.001	0.004	0.001	0.001
Mean	0.207	0.068	0.010	0.011	0.018	0.006
90th percentile	--	0.207	0.025	0.020	0.060	0.018

Source: Suarez et al., [1999]

parameter values. The spread of the parameter values indicates the first order decay rate might be site specific or perhaps may describe additional influencing mechanisms [Riser-Roberts, 1992].

The Monod kinetic expression is also used to describe the biodegradation of organic contaminants in the subsurface. This reaction expression is presented in equation 2.22.

$$r_b = \frac{\mu_{\max} C_{i,w}}{K_m + C_{i,w}} X \quad (2.22)$$

The Monod reaction kinetic expression is more flexible with respect to describing the biodegradation when the organic compound concentrations vary. When the concentration of substrate in the system is sufficient to saturate the biodegradative abilities of the microbes (i.e. $C_{i,w}$ is large), the reaction approximates a zero-order reaction as the saturation coefficient, K_m , becomes negligible. Once the substrate concentration decreases to below the saturation concentration for the microbial activity, the kinetic expression approximates a first-order reaction. Ostendorf and Kampbell [1991] reported parameter values for $\mu_{\max}$ and K_m in the magnitude of $9 \times 10^{-9} \text{ kg m}^{-3} \text{ s}^{-1}$ and $7 \times 10^{-4} \text{ kg m}^{-3}$ respectively for the vapour phase. These parameter values were for the U.S. Coast Guard Air Station in Traverse City, Michigan, which was contaminated with liquid aviation fuel.

In the subsurface, required nutrients such as oxygen and nitrogen may become limiting depending on the diffusive fluxes in the soil. To describe the limitations imposed by these nutrients on the biodegradative process, switching functions can be added to the biodegradation expression.

2.2.6.5 Biodegradation in Aquifers

Biodegradation of hydrocarbon compounds is linked to specific terminal electron-accepting processes (TEAP). These processes define the various redox zones observed during the intrinsic remediation of a contaminated site. Electron acceptors found in groundwater include oxygen, nitrates, ferric iron, sulfate, and carbon dioxide. As each electron acceptor is depleted, the next preferential electron acceptor is used. As a plume migrates through an aquifer, the use of different electron acceptors defines the redox zones. Figure 2.5 shows a typical sequence of redox zones.

The degradation of hydrocarbons in the aquifer leads to changes in the geochemistry of the aquifer. During aerobic degradation, dissolved oxygen concentrations may be reduced to zero. Nitrate reduction can lead to nitrate concentrations below background levels, and the production of NO_2^- , N_2O , NO , NH_4^+ , or N_2 are observed. Ferric iron is reduced to ferrous iron in the Fe(III) reduction zone. The reduction of sulfate leads to the production of H_2S , while the concentration of SO_4^- decreases. The methanogenic reduction zone is defined by the production of CH_4 and CO_2 [Parsons Engineering Science, Inc., 1995].

Figure 2.5: Redox Zones

Thermodynamically, bioremediation in the aerobic zone is more favourable than reduction in the methanogenic zone as more energy is released from aerobic or nitrate based reduction-oxidation activities than is realized during the methanogenic reduction-oxidation process.

Thermodynamics alone cannot explain the sequential development of redox zones. Although nitrate reduction results in slightly higher energy than does aerobic oxidation offers, the presence of oxygen inhibits the enzyme system responsible for nitrate reduction. This prevents the formation of the denitrification zone prior to the depletion of dissolved oxygen concentrations. Oxygen and nitrate are also toxic to sulfate reducing organisms, thus preventing the formation of the sulfate-reducing zone prior to the completion of the denitrification phase.

2.2.7 Estimating Volatilization Losses from Soils

Limited work has been completed on characterizing volatilization losses of hydrocarbons from soils. However, Jury et al. [1990] used an analytical screening model to estimate the volatilization losses from sand and clay soils for benzene, toluene, and xylene. The models were run for the duration of one year for soils where the contaminant mass was initially present between 1.0 and 1.3 meters below ground surface (bgs). The assumed source term was a hydrocarbon spill in the subsurface, with volatilization losses coming from the pure phase. In this work, it was found that each of the three compounds

experienced different degrees of volatilization losses. In sand soils, xylene lost 72.5% of the initial mass while benzene lost only 34.3% over one year. Only 0.1 % of toluene was lost due to volatilization during this time. In clay soils, xylene volatilization losses amounted to 45.2% of the initial mass, while benzene only decreased by 0.01%. Negligible losses of toluene were recorded for clay soils. However, the differences in volatilization rates in this model were influenced by the assumption of first order biodegradation rate kinetics. The biodegradation rates assumed for xylene, benzene, and toluene were $6.3\text{E-}03$, $1.9\text{E-}03$, and 0.139 d^{-1} . Because of the high biodegradation rate assumed for toluene, it was found that most of the compound was attenuated through biodegradation rather than through volatilization.

A second study by Johnson et al. [1996] calculated gasoline emission losses for gasoline contaminated soils located 5 m bgs. Contamination in this study originated from a leaking subsurface fuel tank. These soils were characteristic of sandy soils, having a porosity of 0.38, a soil moisture content of 0.05. The vapour phase diffusion coefficient for the hydrocarbon vapours in the subsurface was $7,270\text{ cm}^2\text{d}^{-1}$. The calculated emissions flux for this soil was $5.9\text{E-}06\text{ g cm}^{-2}\text{d}^{-1}$.

Lahvis et al. [1999] investigated the influence of biodegradation, aqueous solubilization, and volatilization on the attenuation rates of gasoline contamination. The site under investigation was predominantly silty sand. It was proposed that the combination of these processes might increase the rate of

volatilization above that which would be expected under normal diffusion conditions. In this study, the volatilization rates for benzene, toluene, ethylbenzene, and xylenes were 0.0139-0.0433, 0.361-0.839, 0.0457-0.117, and 0.280-0.691 g m⁻²d⁻¹ respectively. Differences observed between the volatilization rates were attributed to different first-order reaction rates assumed by each author. Reaction rates assumed by Jury et al. [1990] were only consistent with those assumed by Lahvis et al. [1999] for toluene. Reaction rates for benzene and xylene were assumed to be between 0.066-0.31 d⁻¹ and 0.102-0.31 d⁻¹ by Lahvis et al. [1999]. These were more than one order of magnitude greater than values assumed by Jury et al. [1990].

2.3 Monitoring Hydrocarbon Contamination in the Vadose Zone

Sampling soil vapours from the vadose zone is becoming an important part of monitoring for subsurface contamination. The establishment of a subsurface vapour phase monitoring network prior to site use allows for the detection of the onset of hydrocarbon contamination prior to the contamination reaching the groundwater. This early detection system can not only protect the groundwater aquifer, but can also minimize required remediation efforts as minimal residual product is required in order for detection to occur. However, in the instances where contamination is already present, the subsurface vapour phase monitoring network can be used to characterize the extent of the contamination in the vadose

zone. Based on the extents of the contamination, predictions can be made as to where groundwater contamination may exist [*Hudak et al., 1999*].

2.3.1 Sampling Methods

Several sampling methods exist for monitoring hydrocarbon contamination in the vadose zone. Three of the more common methods include passive sampling techniques, headspace sampling, and subsurface vapour phase probes. Passive sampling employs the use of sorbents to monitor the average hydrocarbon losses from soils over the time that the sampling occurred. This sampling is best used for low level hydrocarbon contamination, as high emissions can result in spent sorbent materials prior to the end of the sampling period. Passive samplers are also typically used at or near the soil surface as the sorbent materials must be collected for analysis. Passive sampling techniques provide information as to the location of hydrocarbon contamination, however, this information is limited to relative concentrations, rather than providing quantitative estimates of emissions. Headspace analysis is typically employed at sites to estimate possible contaminant locations. Typical structures used for headspace analysis include existing groundwater monitoring wells and subsurface utility vaults. However, measured concentrations from these sources may include non-contaminant related sources such as methane from sewers, or partitioning of contaminants from the groundwater phase. Subsurface vapour phase probes are typically used to monitor subsurface vapour concentrations.

These probes can either be driven into the ground, typically for initial site investigations, or installed at the site permanently to permit temporal measurements of vapour phase concentrations. Sampling from subsurface probes requires soil vapours be withdrawn from the well to permit the quantification of vapour phase concentrations. As a result, these probes have limited application in wet soils. Minimizing the tube diameter will minimize the required purge volume from the well. This improves sample results by minimizing the disturbances to the subsurface vapour phase [Devitt *et al.*, 1992].

2.3.2 Biochemical Signature of Hydrocarbon Contamination

Several researchers have observed that a biochemical signature forms in the vapour phase near subsurface hydrocarbon contamination [Ostendorf *et al.*, 1991; Wood *et al.*, 1993; Lahvis *et al.*, 1996; Lahvis *et al.*, 1999; Davis *et al.*, 1999]. This chemical signature is created by the biodegradation process, whereby TPH compounds are destroyed by a reduction-oxidation process. In this process, oxygen is obtained from the soil vapour and carbon dioxide is produced, as described by equation 2.23.

In areas where hydrocarbon contamination is sufficient to meet the carbon demands of the microorganisms, oxygen is often found in depleted concentrations as compared to atmospheric levels. Also, as a result of the biodegradation process, carbon dioxide is observed in elevated concentrations as

compared to levels observed in the atmosphere. As the source of contamination is approached, the elevated TPH and carbon dioxide concentrations and depleted oxygen concentrations become more pronounced. Monitoring the three compounds near the soil surface indicates that the TPH, carbon dioxide, and oxygen concentrations return to ambient concentrations. Soil vapour monitoring wells located at a distance from contaminated soils typically do not have as pronounced of a chemical signature as those wells located near the contamination. Figure 2.6 shows an example of the chemical signature that may be observed at a contaminated well.

2.4 Summary

This literature review has focused on describing the individual mechanisms in the subsurface that have potential to impact on the observed soil vapour concentrations. Once the interactions between these mechanisms is understood more fully, it may be possible to construct a temporal model that can be used to estimate natural attenuation rates in the subsurface.

A detailed description of residual gasoline contamination in the subsurface was presented to assist in understanding the differences in the source terms that are located in the saturated and unsaturated regions of the subsurface. A summary of each attenuating process was also included. Aqueous solubilization was shown to influence both partitioning to the groundwater phase and the availability of compounds for biodegradation. Volatilization was presented,

Figure 2.6: Sample Soil Vapour Chemical Signature

including a summary of Henry's law and Raoult's law. These laws will be used to estimate concentrations of hydrocarbons in the aqueous and vapour phases. A summary of factors that influence volatilization was also included to assist in drawing conclusions about why concentrations in the vapour phase change over time. Sorption was described as a process that can impact on attenuation, by both reducing concentrations in the aqueous and vapour phases, and also by acting as a long-term source after the bulk of the residual product is removed. Diffusion and advection directly impact the spreading of compounds at a contaminated site, while the mineralization of hydrocarbons was shown to be achieved through biodegradation. These processes form the basis from which the changes observed in the subsurface might be modelled.

Chapter 3.0 - Methods

The development of a conceptual model for the site required an investigation of the soil, groundwater, and soil gas phases. The investigation included construction of monitoring wells, sampling, and analysis of samples. This section will detail the methods and material used to complete the required monitoring.

3.1 Well Construction

Monitoring of the groundwater and soil vapour phases at the site required the installation of two types of monitoring wells; the groundwater monitoring well, and the soil gas monitoring well. The construction details for each type of well are documented in the following sections.

3.1.1 Groundwater Monitoring Well Construction

Groundwater monitoring wells were required to monitor the groundwater quality through the life of this investigation. Upon receipt of the site, nine groundwater wells existed. These wells were MW02, MW03, MW04, MW05, MW06, MW08, MW09, MW13, and MW14. Three additional groundwater monitoring wells (MW15, MW16, and MW17) were installed at the site following the initial groundwater investigation. These wells completed the sampling grid, providing additional information about the groundwater at the former tank

location (MW15) and at two background locations (MW16 and MW17).

Figure 3.1 presents the locations of each of the groundwater wells.

The groundwater wells extended below the groundwater table and were mounted flush on the bedrock layer. Each well was installed using the soil sample boreholes that were drilled using a 100 mm hollow stem auger (HSA). A 50 mm split spoon was advanced ahead of the auger to permit collection of undisturbed soil samples. Monitoring wells were constructed from 52 mm diameter polyvinyl chloride (PVC) piping. Each well consisted of a sump, a well screen, a riser pipe, a well cap, and a flush-mounted protective steel locking well casing [Byrnes, 1994]. The screened interval for the original nine wells was 3.0 m. The screened interval for monitoring wells MW15, MW16, and MW17 was 1.5 m. The screening material was 52 mm diameter, slot 10 PVC well screening. The annulus outside the screened section was filled with silica sand well pack. Bentonite seals were used above the well pack to protect the well from infiltration. Figure 3.2 shows a conceptual cross section of the groundwater wells.

Each well was fitted with two sampling tubes. Waterra pumps were placed within the wells to permit rapid pumping of the well during well development and well purging. A second tube, a 6.4 mm outside diameter PVC volatile sampling tube, was also placed within each well to permit access to groundwater

Figure 3.1: Location of Groundwater Monitoring Wells

Figure 3.2: Groundwater Monitoring Well Construction Details

using a surface mounted peristaltic pump. The tubing was dedicated to each well to prevent cross-contamination between wells.

3.1.2 Soil Vapour Monitoring Well Construction

Soil vapour monitoring wells were installed at the site to facilitate on-going monitoring of soil vapours. Ten wells were installed, as shown on Figure 3.3, to form a grid pattern across the anticipated zone of contamination. Each well was installed using the soil sample boreholes. The 100 mm HSA was used to drill boreholes in the sand wells GP05 and GP06, and the first 1.5 m of the remaining soil gas wells. Where the soils were sufficiently cohesive, the remaining portions of the boreholes were developed using a 50 mm split spoon sampler. This minimized the required fill for each of the soil vapour monitoring wells, and minimized soil disturbance near the sampling ports.

Each well was constructed as a four-level nested soil vapour well. Stainless steel tubes with an outside diameter of 6.4 mm formed the access tube to each depth. The screened intervals were placed to facilitate monitoring of the subsurface at depths of 0.75, 1.5, 2.25, and 3.0 meters below ground surface. Each tube had three holes drilled at the end to form a screened interval. The tubes were placed within 0.3 m depths of gravel pack. Each layer was separated by a 0.45 m bentonite seal. Flush-mount locking steel well caps were used to protect the soil vapour wells. Teflon tubes were securely fitted over the stainless steel

Figure 3.3: Location of Soil Vapour Monitoring Wells

tubes to facilitate sampling. Figure 3.4 presents the construction details for the soil vapour monitoring wells.

Thermocouples were installed at GP02 to permit monitoring of subsurface soil temperatures. Three thermocouples were placed within the well, at depths of 0.75, 1.5, and 3.0 m below ground surface. Thermocouples were placed such that there was no contact with the stainless steel tubing to ensure accurate measurement of soil temperatures. Type T thermocouples were used as the working range of these thermocouples is -20°C to 50°C . The type T thermocouples were constructed from copper and constantan wire [*Canadian Society of Soil Science, 1993*]. The end of the thermocouple that was inserted below ground was tig-welded, and coated for corrosion prevention. An Omega 2168A digital thermometer was used to monitor the subsurface temperatures.

3.2 Sampling Methods

Sampling of the soil, groundwater, and soil vapour phases was conducted at the site. Soil sampling was completed during installation of the monitoring wells. Groundwater sampling was completed in June, October, and December 1999. Soil vapour sampling was divided into two sampling events. Regular soil vapour monitoring was completed at short-term intervals, on average 3 times per week. Soil vapour BTEX monitoring was completed at approximately 6-week intervals in July, September, October, and December 1999. The following sections will detail procedures followed during each of the monitoring events.

Figure 3.4: Soil Vapour Well Construction Details

3.2.1 Groundwater Sampling

Groundwater monitoring samples were collected in June, October, and December 1999. Sampling procedures included the development of the monitoring wells, precautions to prevent contamination, and sample collection.

3.2.1.1 Sampling Preparation

Groundwater wells were developed prior to the June 1999 sampling event. The last known use of the wells prior to this sampling round was in June 1992. Well development was accomplished by flushing the wells of three pore volumes, or in the case of the low flow wells, until dry twice. In addition, immediately prior to sampling, each well was purged of the volumes shown in Table 3.1. Monitoring wells MW04, MW08, MW14, MW15, and MW16 were purged of three pore volumes. The remaining wells were purged until dry three times. Dedicated Waterra pumps were used at each well to purge the wells. Following recovery after the third purge, samples were collected prior to the water level returning to normal levels.

Prior to sampling, sample bottles were decontaminated. This procedure included washing with hot water andalconox, followed by a soak in a 50% hydrochloric acid bath to wash away any remaining organic matter. Bottles were then rinsed with distilled water and allowed to air dry prior to capping.

Table 3.1: Groundwater Well Purge Volumes

<i>Well</i>	<i>Well Volume Purged (L)</i>					
	<i>Jun-99</i>	<i>Dry?</i>	<i>Oct-99</i>	<i>Dry?</i>	<i>Dec-99</i>	<i>Dry?</i>
MW02	34	Yes	13	Yes	52	Yes
MW03	10	Yes	13	Yes	26	Yes
MW04	22	No	92	No	96	No
MW05	27	Yes	26	Yes	69	Yes
MW06	64	Yes	52	Yes	112	No
MW08	96	No	96	No	96	No
MW09	16	Yes	21	Yes	37	Yes
MW13	16	Yes	17	Yes	30	No
MW14	75	No	76	No	76	No
MW15	na	na	112	No	112	No
MW16	na	na	96	No	96	No
MW17	na	na	8	Yes	14	Yes

na - Wells did not exist at time of sampling

3.2.1.2 Sample Collection

Prior to purging, the water level was recorded for each well. The water levels were measured with a water level tape and referenced to a surveyed elevation.

Sampling was completed using the dedicated 6.4 mm volatile sampling tubing. Each dedicated tube was connected to a surface mounted peristaltic pump that pumped water from the well at a flow rate of 2.6 L min^{-1} . BTEX and TPH samples were collected in two 40 mL VOA vials, which were capped with Teflon lined septum. These vials were filled upstream of the pump to eliminate the risk of cross contamination from the pump tubing. Collection of samples for geochemical indicators was completed at the downstream end of the pump. These samples were collected in two 250 mL amber glass sample bottles. Once collected, samples were placed in a cooler prior to transport to the lab.

3.2.2 Soil Sampling

Soil sampling was completed using a 50 mm diameter split spoon. Where soils were sufficiently cohesive to maintain the integrity of the hole, only the 50 mm split spoon was used to create the boreholes for the soil gas wells. This minimized the required volumes of gravel pack and bentonite for the wells. Drilling for the groundwater wells and soil vapour wells, where the soil was not cohesive was completed using a 100 mm HSA. The auger was advanced

following the collection of the split spoon samples. The groundwater and soil vapour wells were installed using the boreholes created during sampling.

3.2.2.1 Split Spoon

Split-spoon sampling was completed using a 50 mm diameter split spoon. The sampler was driven by a 64 kg weight dropped at 0.76 m intervals [U.S.EPA, 1993]. The number of blows required to advance the sampler by intervals of 0.6 m was recorded. Samples were collected at depths as shown in the borehole stratigraphic logs that are included in Appendices 1 and 2.

3.2.2.2 Sample Collection

When the split-spoon was brought to the surface, it was disassembled and the soil characteristics of the core were recorded. Soil samples were immediately collected from the center of the core to ensure accurate soil representation and to minimize volatile soil vapour loss. These samples were collected in 40 mL VOA vials. These samples were analyzed for both BTEX compounds and total TPH. The remaining soil was collected and placed in zip-lock bags. After a time of no less than one hour, and no more than 8 hours, the headspace within the zip-lock bags was analyzed for combustibles using the Gastech 2100 Portable Combustibles Gas Meter (Gastech). The samples were then retained for further physical analysis.

3.2.2.3 Decontamination Procedures

Efforts were made to prevent cross-contamination of soil samples. Prior to arrival at the site, and prior to departure from the site, the drill rig and all associated equipment was decontaminated using a high pressure wash to reduce the risk of contaminating off-site soils. Prior to obtaining each sample, all equipment in contact with soil samples was scraped to remove loose soil. Equipment was then washed usingalconox, and rinsed using distilled water. A methanol rinse was used to remove any traces ofalconox remaining on the equipment. The equipment was then allowed to air dry prior to use. *[U.S.EPA, 1999]*.

3.2.3 Soil Gas Sampling

Two types of soil vapour investigations were completed. Soil vapour TPH surveys were completed at least once per week, equipment permitting. Soil vapour BTEX surveys were completed approximately once every six weeks.

The soil vapour TPH survey was completed using the Gastech portable meter. This meter monitored combustibles (as methane), oxygen, and carbon dioxide in the subsurface. The meter recorded the combustibles, or TPH, concentrations in parts per million by volume (ppmv) from 0 to 10,000 ppmv. Above this level, the combustibles measurement was recorded as a percent of the lower explosive limit (%LEL). Each increase of 1% corresponded to incremental increases of 500 ppmv. The meter also measured soil gas oxygen and carbon

dioxide concentrations in the subsurface as a percent of volume. Sampling using the Gastech was completed by attaching the intake of the meter to the flexible Teflon tubes. The onboard pump was used to sample the soil vapour at an approximate flow rate of 1.6 standard cubic feet per hour. In wells where clay soils were wet, the flow rate was decreased because of the vacuum created within the well. This vacuum frequently resulted in the pump stalling. Where the pump did not stall, the TPH, oxygen, and carbon dioxide concentrations peaked in response to the vacuum. Measurements were taken until either the soil vapour concentration stabilized, or in the case of wells installed in clay soils, until the extreme soil vapour concentration was identified. Headspace measurements for the groundwater wells were also completed. Immediately after removing the cap on the groundwater well, a 0.6 m length of tube was inserted into the well casing. From this depth, the TPH, oxygen, and carbon dioxide concentrations for the headspace in the well were recorded.

The soil vapour BTEX survey samples were collected in parallel when measurements for TPH, oxygen, and carbon dioxide were obtained. Samples were obtained from a tee in the intake tube. A septum was inserted into the tee to allow for removal of gas using a 10 mL gas tight syringe, the contents of which were then analyzed using the field gas chromatograph. The procedure for this analysis is described in Section 3.3.3.2.

3.3 Analytical Methods

3.3.1 Groundwater Analysis

Analysis of groundwater samples was completed using several methods. The June 1999 sampling event used a gas chromatograph / mass spectrometer (GC/MS) equipped with a purge and trap for analysis of BTEX compounds. A gas chromatograph / flame ionization detector (GC/FID) equipped with a purge and trap was used to determine the TPH present in the groundwater. The October 1999 sampling event was analyzed using solid phase micro-extraction (SPME) in conjunction with a GC/FID. The BTEX compounds were measured using a straight SPME extraction to the GC/FID while the Gasoline Range Organics (GRO) and Diesel Range Organics (DRO) were first extracted using pentane, then injected into the GC/FID. The December 1999 sampling event was analyzed at an independent lab due to equipment failure. Although separate methods were used for the analysis, it is not expected that significant errors were introduced into the investigation. This was due to the use of external calibration curves specific to each method. The following sections will detail the analytical procedures followed for each of the June and October 1999 sampling events.

3.3.1.1 BTEX Compounds

Analysis of BTEX compounds (benzene, toluene, ethylbenzene, m-xylene, o-xylene, and p-xylene) in groundwater was completed using two methods; the purge and trap and SPME methods.

Standards for the purge and trap and the SPME methods were developed following the same procedure. In each case, a stock solution was created using water as the solvent. Each of the six BTEX compounds was added to obtain concentrations of 8.1 mg L⁻¹ per compound. Following agitation, the stock solution was left for a minimum of 2 hours without headspace to ensure all compounds had dissolved. BTEX standards were then made by diluting the stock solution to the required concentrations. Calibration curves were created using no less than four data points in the anticipated concentration range.

All samples and standard solutions were allowed to warm to room temperature prior to analysis using the purge and trap equipment. Samples were injected into the unit in 5 mL volumes using luer-lock air tight syringes. Where the sample concentrations exceeded the limit of the GC/MS, a diluted sample was used.

Samples were purged for 12 minutes using an inert purge gas. Following purging, the compounds captured on the trap were desorbed to the GC/MS by heating the trap to 180°C for 5 minutes. Following desorption, the trap was reconditioned prior to the introduction of the next sample. This was achieved by maintaining the trap at 180°C for an additional 8 minutes while the device was set to purge mode. This method was based on the method suggested by EPA method SW-846-5030B [U.S.EPA, 1999].

A GC/MS equipped with a 30 m, 0.25 mm id, 0.25 μ m film thickness DB-5 column was used to analyze the compounds captured during the purge and trap procedure described above. In the method, an initial column temperature of 45°C was maintained for five minutes. The column temperature was then increased by 10°C/minute to a maximum temperature of 280°C. The MS detector temperature was 220°C while the injector temperature was 280°C. This method was based on EPA method SW-846-8015B [U.S.EPA, 1999].

The October 1999 sampling round was analyzed using solid phase micro-extraction (SPME) followed by analysis using the GC/FID. A 50/30 μ m divinylbenzene/carboxen on polydimethylsiloxane SPME fiber by Supelco was used. This fiber was specific to hydrocarbon compounds ranging from C3 to C20. The procedure involved a 15 minute sorption period with rapid stirring, followed by a five minute desorption at 250°C [Supelco, 1995]. The sample volume used for each analysis was 1.8 mL, placed inside a 2 mL vial, with a Teflon lined septum. Duplicate vials were prepared for each sample to avoid dilution of the sample due to the sorption effects of the SPME fiber, or also loss of volatile compounds through the punctured septum following sampling. The column used on the Varian 3800 gas chromatograph was a DB-1 that was 15m long by 0.32 mm ID with a 0.25 μ m thickness film. The column method was initiated at 30°C for five minutes, and then increased at 10°C per minute to a maximum temperature of 280°C [Supelco, 1995].

3.3.1.2 TPH Compounds

The standards prepared for the June 1999 sampling event used a Wisconsin Diesel Range Organics (DRO) standard. A TPH stock solution was prepared to a concentration of 880 mg/L using GC grade pentane. The stock solution was then diluted into less concentrated standard solutions for analysis. An external calibration curve was created using no fewer than four calibration points.

Aqueous samples were extracted using pentane for direct injection into the GC/FID. Extraction involved placing 10 mL of each of the sample and GC grade pentane into a 50 mL separatory funnel. The funnel was sealed and shaken vigorously for 1 to 2 minutes with periodic venting to release excess pressure. The organic layer was separated from the aqueous phase after settling and collected for use in the GC/FID. This method was based on EPA method SW-846-3510C [U.S.EPA, 1999].

A GC/FID fitted with a 30 m, 0.25 mm id, 0.25 μ m film thickness DB-5 column was used to analyze the TPH concentrations for the June 1999 sampling event. The injection method involved direct injection of the pentane extracts. The 1 μ L injection was made into an injector that was held at a temperature of 300°C. The initial column temperature was held at 45°C for 5 minutes. The temperature was then increased by 10°C/minute until a maximum temperature of 280°C was attained. TPH was calculated as the total area of all detected peaks between C6 and C20.

The samples collected in the October 1999 sampling round were analyzed for TPH using the pentane extraction method described in the June 1999 sampling round. The TPH range was divided into GRO and DRO ranges. The GRO range was defined as C6 to C10, while the DRO range was defined as C10 to C20. The solutes used to prepare these standards were gasoline, diesel, and the Wisconsin DRO standards. The Wisconsin DRO standard was used to define the points where C10 and C20 compounds were detected. Benzene was used to identify the initial C6 peak. Summer grade gasoline and diesel were used to make external standards. It was believed that the use of these mixtures for standards would provide the most accurate assessment of the true concentrations in the aqueous phase. The standards were prepared to maximum concentrations of 700 mg L⁻¹ GRO and 600 mg L⁻¹ DRO in a pentane base. These standards were then diluted to create a series of standards in the anticipated concentration ranges. An external calibration curve was developed for each of the GRO and DRO compounds.

The GC/FID method used for analysis of GRO and DRO in the October 1999 groundwater samples was the same method as was provided for the June 1999 sampling method. However, the column was a DB-1 15m by 0.32 mm ID column with a 0.25 µm thickness film. TPH was calculated as the total of GRO and DRO compounds in the sample.

3.3.1.3 Geochemical Indicators

Selected geochemical indicators were measured in each groundwater sampling round. In addition, temperature, dissolved oxygen, and the reduction-oxidation (redox) potential were also measured. The temperature and dissolved oxygen concentrations were measured, following the purging of the well using the YSI Model 50B dissolved oxygen meter paired with the down-well YSI 5700 series dissolved oxygen probe. The redox potential was monitored using a 250 mL flow-through cell. The redox potential was measured using the Orion pH meter model 420A paired with the Cole-Palmer ORP electrode with platinum band. The oxidation-reduction probe was inserted into a glass container through a rubber septum. The sample flowed through the container at a flow rate of 2.6 L min^{-1} , ensuring no headspace existed that could influence the redox potential of the sample.

Several parameters were also monitored within 24 hours of sample collection. These parameters included sample pH, and nitrate, sulfate, and ferrous iron concentrations. The sample pH was monitored with the Orion pH meter model 420A paired with the Orion pH Triode 3-in-1 combination pH/ ATC electrode for temperature compensated measurements. The nitrate, sulfate, and ferrous iron concentrations were analyzed using the respective Hach kits. The nitrate and ferrous iron Hach kits measure the concentrations based on colour matching. In this method reagents were added to the samples and allowed to

react with the respective compounds resulting in the development of a colour in the sample. This colour is compared to a standardized colour meter in order to determine the concentration of the compound in the sample. The sulfate Hach kit uses a reagent that reacts with the sulfate in the water to form a suspended precipitate, thus enabling a calibrated turbidity meter to determine the concentration of sulfate in the water.

3.3.2 Soil Analysis

3.3.2.1 Moisture Content

Each soil sample was analyzed for soil moisture content. This permitted the expression of soil contaminant concentrations in terms of dry weight. Soil samples were weighed in aluminum weigh trays immediately following sample collection. The samples were then dried in an oven at 105°C for 24 hours. Immediately following drying, the samples were weighed. The water content of the samples was calculated as the mass of water lost divided by the mass of dry soil [*Canadian Society of Soil Science, 1993; Tan, 1996*].

3.3.2.2 TPH / BTEX

The hydrocarbon components in the soil samples were extracted to pentane using ultrasonic extraction. Approximately 10 g of soil (wet mass) was placed in a VOA vial with 10 mL of GC grade pentane, ensuring the pentane covered the soil sample. The mass of soil added was recorded. The vials were sealed with Teflon lined caps and then placed in a sonicator for 20 minutes. Following

sonication, the sample was removed and reweighed, assuming any mass lost was directly from volatilized pentane. The pentane was collected for injection into the GC/FID.

Using the dry mass and the volume of pentane used in the extraction, a dilution factor for the sample was calculated. The dilution factor was used to convert the concentration of the extractant to the concentration based on the mass of dry soil used. Equations 3.1 and 3.2 shows the required calculations.

$$\frac{\text{mg compound}}{\text{L pentane}} \times \text{Dilution Factor} = \frac{\text{mg compound}}{\text{kg dry soil}} \quad (3.1)$$

$$\text{Dilution Factor} = \frac{\text{L pentane}}{\text{kg dry soil}} \quad (3.2)$$

External standards were used for the analysis of hydrocarbons in the soil sample extracts. Summer grade gasoline and diesel were used as the standard solutes, while pentane was used as the solvent. The Wisconsin DRO standard was used to identify the location of the C10 and C20 peaks within the gas chromatograph, while benzene was used to identify the peak corresponding with C6. Using these detected peaks to define the limits of the GRO and DRO ranges, the gasoline and diesel standards were used to develop the external calibration curves. Each curve was developed from at least four calibration points. The June 1999 groundwater analysis GC/FID method was used to analyze the soil samples.

BTEX compounds were identified using the output from the GC/FID analysis of the GRO and DRO concentrations. BTEX standards were developed using pentane as the solvent. External calibration curves were used to calculate the concentrations of the BTEX compounds in the samples.

3.3.3 Soil Gas Analysis

3.3.3.1 TPH Soil Vapour Survey

The soil vapour TPH survey was generally completed at least three times per week, and often daily. As described in Section 3.2.3, the TPH soil vapour survey consisted of monitoring each soil vapour well for TPH, oxygen, and starting in November, carbon dioxide. Analysis of the gas concentrations was completed using the onboard detectors.

3.3.3.2 BTEX Soil Vapour Survey

The soil vapour BTEX survey was completed to analyze the soil vapour gases for BTEX compounds. Standards for the BTEX compounds were made using each of the six BTEX compounds, and GC grade methanol as the solvent. A stock solution containing 200 mg L⁻¹ of each of the six compounds was made. Gas standards were made using 40 mL amber VOA vials, sealed with Teflon lined caps and containing BTEX free air. Injections into the vial through the septum were then completed to introduce known masses of the standard solution into the vials. This liquid solution was permitted to volatilize. No more than 5 µL was injected into a single vial to ensure complete volatilization occurred.

The BTEX gas standards were then sampled using a gas tight syringe so that known masses of BTEX gas could be introduced to the H-Nu GC. The H-Nu GC was fitted with a 100/120 Supelcoport 6 foot by 1/8 inch stainless steel column, with a packing that consisted of 5% SP1200 and 1.75% Bentone 34. A photo-ionization detector (PID) equipped with a 10.2 eV lamp, which is applicable for BTEX compounds was employed.

The H-Nu GC was run isothermally at 100°C. The method required 12 minutes with a carrier gas flow of 20 mL per minute to complete the run. Method detection limits for this analysis were found by decreasing the mass of BTEX introduced to the unit by 0.05 ng increments until the unit was unable to detect the compound. Once in the field, 2 mL samples were introduced to the unit directly from the gas tight syringes that were used to collect the samples.

3.4 Sulfur Hexafluoride Tracer Gas Study

A tracer gas study was completed to estimate the effective diffusivity of the soil vapour at the site. The tracer gas study was designed following the protocol suggested by Johnson et al. [1998].

3.4.1 Analytical Method

An inert tracer gas, sulfur hexafluoride, was used to experimentally determine the effective diffusivity of the gas in the soil. Sulfur hexafluoride can be easily detected by an electron capture device in the range of parts per billion, and as such was chosen as the tracer gas. The Varian 3800 GC/electron capture

detector (GC/ECD) was used to analyze the soil gas samples. This equipment employed a WCOT fused silica, 30 m, 0.53 mm ID CP-Select 624 DF-3 column.

Standards and the tracer gas for the field were prepared in the lab using plastic luer lock syringes fitted with air-tight valves. These syringes were also used in the field to collect samples. External standards were prepared ranging from 1 part per billion by volume (ppbv) to 1 ppmv. Standards were prepared by diluting sulfur hexafluoride from the standard cylinder at 1000 ppmv with atmospheric air that did not contain measurable quantities of the tracer gas. Dilutions were completed using a series of luer lock syringes fitted with air-tight valves and microbore tubing connecting the syringes.

Standards and samples of no more than 2 mL were injected into the GC/ECD. The injector port and column were maintained isothermally at 50°C.

3.4.2 Field Method

Microbore tubing, with an inside diameter of 0.56 mm, was fit onto the end of syringes by matching the outside diameter of the needle to a tube with a slightly smaller inside diameter. The ends of the 16 gauge needles were fit with luer lock valves to prevent atmospheric air from entering the tubing during the experiment. The microbore tubing was fed to the bottom of the soil gas wells, and the space between the top of the well and the microbore tubing was sealed.

Two wells were selected for the tracer test; GP05 and GP07. Vapour well GP05 was located at the former tank location and is situated in sandy soils. Vapour well GP07 was located beneath the former gasoline pumps, and is situated in clay soils. Three depths were monitored at soil vapour well GP05. GP05-3 was used as the injection point for the tracer gas, providing a depth of 1.5 m bgs. The sample locations immediately above, GP05-2, and below, GP05-4, were also monitored for the tracer gas. Two depths were monitored at soil vapour well GP07. The soil gas was injected into GP07-3, which provided an injection depth of 2.3 m bgs. Soil gas well GP07-2, which was located 1.5 m bgs, was also monitored for tracer gases.

Ten milliliters of 1000 ppmv sulfur hexafluoride were injected into GP05-3 and GP07-3. The injection was completed in less than 30 seconds. The maximum concentration of the tracer gas in the well was the stabilized concentration after mixing within the gravel pack was permitted.

Samples were collected in 10 mL plastic luer lock syringes fitted with a second air-tight luer lock valve to prevent dilution of the sample. The two luer lock valves were connected and opened in order to access the soil gas at the bottom of the monitoring well. The microbore tubing provided access to soil vapours at the base of the well while limiting the dead volume within the tubing.

Sampling at GP05 was conducted at 2.5 minute intervals for a minimum of 30 minutes. Two tracer tests were conducted on separate days to ensure no

residual tracer gas remained in the system. Sampling at GP07 was conducted initially at 5 minute intervals for the first 30 minutes, with increasing intervals to 43 hours.

Chapter 4.0 - Results of Soil and Groundwater Sampling

Currently, groundwater monitoring and subsurface soil sampling are generally considered the appropriate means by which to assess site contamination. This section will describe the site based on specific parameters considered part of the Weidemeier Protocol [*Parsons Engineering Science, Inc., 1995*]. This includes a description of the geotechnical aspects of the site, as well as subsurface contamination.

4.1 Site History

This study was located at a former gasoline vending station in Ottawa, Canada. Aerial photographs of the site suggest the site was established as a gasoline vending station between 1960 and 1967. Prior to establishment of the gasoline vending station, the site existed as part of a crop farming operation.

The site is subject to substantial atmospheric temperature variations. The Canadian Climate Normals indicate average daily air temperatures at the site range between 26.4°C in July to -15.5°C in January. Extreme daily temperatures can range from 37.8°C to -36.7°C. Average rainfall for the area is 910.5 mm per year, with 701.8 mm falling as rain throughout the duration of the spring, summer and fall months [*Environment Canada, 2000*].

Several subsurface tanks were installed at the site. These included three subsurface gasoline tanks, and one subsurface heating oil tank. Subsurface

piping was installed for the transport of gasoline to the two pumping islands. The subsurface gasoline tanks were replaced in the mid 1980's with corrosion resistant reinforced fiberglass tanks. The heating oil tank was located east of the building. The locations of these tanks, the piping network, and the pumping islands are shown in Figure 4.1.

Historical records suggest two known sources of contamination exist at the site. The first is from a leak that occurred while filling the heating oil tank. At the time of the spill the subsurface tank and surrounding soils were excavated and replaced with clean fill. However, due to the proximity of the tank to the building, the fuel was not completely captured. Consequently, a suspected plume of free product exists in the capillary fringe beneath the building.

The second source is from the leaking pipe network that connected the subsurface gasoline tanks to the pumping island. Suspected contamination also existed beneath the subsurface gasoline tanks. However, when the tanks were removed, affected soil near the tanks was also excavated and replaced with clean sand fill. The soils surrounding the subsurface pipe network were not removed, and as such, residual gasoline is believed to be present in the subsurface just beyond the extent of the excavation.

Figure 4.1: Site Plan

4.2 Subsurface Soil Conditions

The overburden at the site consists mainly of grey clay overlying a till and bedrock aquifer. The front portion of the site was filled so that the site would be graded above the top elevation of the subsurface gasoline and heating oil tanks. This section will provide details on the structure of the subsurface. Appendices 1 and 2 contain boring logs for the groundwater and soil vapour monitoring wells respectively. Appendix 3 contains results of soil sampling for the physical analysis, including soil type and soil moisture contents, and the chemical analysis, including TPH and BTEX compounds.

4.2.1 Subsurface Soils

The fill that was used to grade the site above the level of the subsurface tanks consisted mainly of fine gravel and sand with various bulking items such as crushed red brick. Soils in this layer were dry, with soil moistures generally less than 5% by mass.

Beneath the fill layer, grey clay exists in a layer ranging from 2.2 m at the north end to 3.0 m in thickness at the south end. The bottom of the clay is generally between 4.2 m to 4.8 m bgs at the north and south ends of the site respectively. The soil moisture of the clay samples ranged from 14% to 29% by mass. The clay overlies a thin layer of till. This till consists mainly of gravel and ranges in thickness from 0.5 m to 1.5 m. It is believed that the aquifer flows through this layer and the bedrock layer beneath.

The excavation areas were filled with clean sandy soils following the removal of the subsurface tanks. This region includes the area marked as the former fuel tanks and piping to the pumping island on Figure 4.1. The clay soil surrounding the excavation may have created a bathtub effect in the excavated soils where free product might be trapped. The soil moisture in this region ranged from 4% to 20% by mass above the groundwater table. This layer extended to the till layer.

4.2.2 Contamination of Soils

Split spoon samples were collected at intervals ranging from 0.6 m to 0.75 m. The total depth of each split spoon sample was 0.6 m. Visual observations were made to identify any staining or foreign materials within the soil core. Soil samples were collected and analyzed for TPH (as GRO and DRO) and BTEX compounds.

The results of soil sampling indicate three areas of contamination exist at the site. The first source was located near GP01, the second was near GP04, while the third was located near GP10. The identification of subsurface contamination was based on the collection of soils from the soil borings completed in June 1999. The locations and concentrations of TPH contamination at each well are shown as radial plots on Figure 4.2.

The perceived source of contamination near GP01 was the leaking pipe network that connected the gasoline tanks to the pumping island. The results of

Figure 4.2: Average TPH Concentrations in Soil

the soil sampling supported this hypothesis. Physical evidence from the soil borings indicated that the pipe network was located between 1 m to 1.5 m bgs. In addition to the observation of non-native materials in the soil, significant staining was observed at 1.35 m bgs. TPH measurements in the soil immediately above the staining indicated a concentration of 57 mg kg⁻¹. At the 1.8 m depth, which most closely represented the soil gas probe, GP01-3, the concentration was 540 mg kg⁻¹. To further support the finding that gasoline was the main contaminant in this area, the GC/FID analysis produced patterns consistent with gasoline finger printing. Gasoline is typically characterized by a significant portion of the detected peaks ranging between the C6 to C10 compounds.

Soil borings at GP07 and GP02 indicated that contamination might have spread along the capillary fringe. The results of the GC/FID analysis at these locations suggested that the contamination was predominantly gasoline range organics. Given the proximity to the contamination at GP01, it is believed that the contamination detected at each of these wells reflects a possibility of a smudge zone in the capillary fringe, where excess gasoline accumulated.

The contamination at GP04 is believed to be a combination of heating oil and gasoline. This hypothesis has been supported by the following points. Soil borings at GP04 indicated the highest concentrations of TPH were present at GP04-4, which is located within the capillary fringe. The concentration at this level was 981 mg kg⁻¹ as compared to that measured at GP04-3, which was

505 mg kg⁻¹. Soil concentrations at levels 1 and 2 were significantly lower. Results from the GC/FID analysis suggested that between 23% to 49% of the TPH contamination could be attributed to DRO compounds. This is compared to the results at GP01 where only 15% of the contamination was described by DRO compounds.

The residual heating oil located at GP04-4 spilled from the subsurface tanks and is believed to have resulted in pooling of LNAPL on top of the water table beneath the building. This area was not accessible during the cleanup following the spill because of structural limitations imposed by the building. This LNAPL may have spread to contaminate both the soil and groundwater via a smear zone located beneath the building. It is believed that the capillary fringe encompasses the soil surrounding GP04-4, as this soil was saturated for the duration of the monitoring. Although the heating oil is considered the main source of contamination, gasoline contamination at this well must be considered for two reasons. First, the well is nearby the pumping island. Secondly, the gasoline range organics that were detected could not be differentiated between either a gasoline pattern or a heavy oil pattern because weathering had influenced the composition of the fuel.

Soil contamination detected at GP10 was localized within the sand unit at a depth of 1.5 m bgs. This contamination was located significantly above the groundwater table, which exists 3 m bgs, and is below the top portion of the clay

unit. The distance from the former heating oil tank, and the separation by the clay unit suggests that the contamination at this location was not directly related to the heating oil fuel spill. Results from the GC/FID analysis suggested although some gasoline range organics were present, the bulk of the contamination was in the diesel range. Given the use of this part of the site for storage of older vehicles and heavy equipment, and the visible staining on the soil, it is believed that leaks from vehicles may have been responsible for the contamination.

Total BTEX contamination in the subsurface soils is shown in Figure 4.3. As seen there are two locations with significant BTEX concentrations in the soil. The first was located at GP01 and corresponded with the TPH contamination discussed previously. The second area of BTEX contamination in the subsurface was located at GP04. This contamination was predominantly located at the lower level, which provided further evidence that the contamination at this well was located along the capillary fringe. BTEX concentrations in the remaining boreholes were negligible.

4.3 Groundwater Monitoring

A series of 12 groundwater monitoring wells were installed at the site to permit monitoring of both the water quality beneath the site, and groundwater flow directions. The following section will investigate the groundwater flow patterns at the site. The geochemical properties of the groundwater will also be

Figure 4.3: Average BTEX Concentrations in Soil

assessed, in conjunction with the TPH analysis, to determine the status of the contaminated groundwater plume that exists below the site.

4.3.1 Groundwater Aquifer

A groundwater aquifer exists at the site in the lower till and bedrock layers. This aquifer is connected to two nearby surface water courses. The first is a creek that exists approximately 600 m northwest of the site. The Ottawa River exists approximately 2.5 km north east of the site and flows in an easterly direction.

Groundwater levels were obtained as described in Section 3.2.1.2. The water levels were plotted and the elevation gradients were assessed to determine the direction of groundwater flow, and to estimate the rate at which the groundwater is flowing. The groundwater elevations were kriged using a linear variogram to estimate the approximate patterns of the groundwater contours

The groundwater flow changed directions throughout the year. Three plots of groundwater flow directions are shown in Figure 4.4a through 4.4c. The groundwater flow direction was generally toward the northeast. The addition of MW16 following the first sampling round provided data that indicated the groundwater flow at the southwest corner of the site was towards the southwest. The absence of asphalt cover at the location of the former pumping island is anticipated to provide a local recharge area that leads to the groundwater flow direction at this part of the site. During the June and December sampling rounds, the direction of groundwater flow at the north end of the site was

Figure 4.4a: Kriged Water Level Surface (June 1999)

Figure 4.4b: Kriged Water Level Surface (October 1999)

Figure 4.4c: Kriged Water Level Surface (December 1999)

towards the northeast. However, during the October sampling round, the groundwater flow in this area was towards the northwest. This is believed to be a response to the dry summer conditions that existed. The changes in direction of the flow at the site may tend to shorten the length and increase the width of the plume as compared to a scenario with flow in one direction throughout the year. This change in flow direction has also been observed in previous studies at the site. Appendix 4 contains historical groundwater elevation data.

Average linear flow velocities were calculated by applying Darcy's law to the till portion of the aquifer. The till layer was assumed to have a hydraulic conductivity in the range of $10^{-3} \text{ cm s}^{-1}$, while a porosity of 0.2 was used in the calculations. These values were based on typical mixed sand and gravel [Fetter, 1994]. The hydraulic gradient at the site was found to vary between 0.009 m m^{-1} and 0.015 m m^{-1} as the direction of the groundwater flow shifted through out the year. Equation 4.1 was used to calculate the average linear velocity of the groundwater through the till unit [Fetter, 1994].

$$V = \frac{K_h}{\theta} \frac{dh}{dl} \quad (4.1)$$

Based on the assumed values of hydraulic conductivity and porosity, and the range of hydraulic gradients measured at the site, it has been estimated that the groundwater flows between 14.2 and 23.6 m year^{-1} through the till layer. During

the fall, the average linear flow velocity to the northwest was estimated to be 18.9 m year^{-1} where the hydraulic gradient was found to be 0.012 m m^{-1} . This flow pattern indicates that contaminated groundwater could travel to the limits of the property within one year.

4.3.2 Contamination

Measuring contaminant concentrations in groundwater provides not only information about the contaminant plume, but these measurements can also assist in identifying the location of free product within the aquifer. This was accomplished by comparing the observed concentrations to the maximum expected concentrations based upon solubilities. As the groundwater concentrations approach the maximum expected values, the presence of free product becomes more likely. Table 4.1 shows the calculation of the maximum contaminant concentrations expected for a typical gasoline. The mole fraction of each compound was found using the concentrations by weight, converting these concentrations to moles given a known mass of gasoline, and finally finding the mole fraction. The maximum concentration was calculated using Raoult's law (equation 2.1), which calculates the maximum concentration as a function of the mole fraction of the compound in the NAPL and the solubility of the compound in water. The composition of gasoline varies and as a result, typical minimum and maximum mole fractions have been reported in Table 4.1. The solubility of compounds also varies in groundwater, and as such, these variations have been

Table 4.1: Calculation of Maximum Expected Concentrations of Gasoline in Groundwater

Compound	Molecular Weight	Concentration (w %)		Mass, g (Assume 1000 g)		Moles of Compound		Mole Fraction		Solubility (mg/L)		Max. Expected Solubility (mg/L)	
		min	max	min	max	min	max	min	max	min	max	min	max
Propane	44.11	0.01	0.14	10	140	0.2	3.2	0.00	0.00	62.4	62.4	0.03	0.16
n-Butane	58.13	3.93	4.70	3930	4700	67.6	80.9	0.16	0.06	61.4	61.4	9.64	3.93
n-Pentane	72.5	5.75	10.92	5750	10920	79.3	150.6	0.18	0.12	38.5	47.6	7.09	5.68
n-Hexane	86.17	0.24	3.50	240	3500	2.8	40.6	0.01	0.03	9.5	18.3	0.06	0.59
n-Heptane	100.21	0.31	1.96	310	1960	3.1	19.6	0.01	0.02	2.93	3.37	0.02	0.05
n-Octane	114.23	0.36	1.43	360	1430	3.2	12.5	0.01	0.01	0.66	0.88	0.00	0.01
n-Nonane	128.26	0.07	0.83	70	830	0.5	6.5	0.00	0.01	0.115	0.115	0.00	0.00
n-Decane	148.28	0.04	0.50	40	500	0.3	3.4	0.00	0.00	0.024	0.052	0.00	0.00
n-Undecane	156.32	0.05	0.22	50	220	0.3	1.4	0.00	0.00	0.044	0.044	0.00	0.00
n-Dodecane	170.33	0.04	0.09	40	90	0.2	0.5	0.00	0.00	0.0034	0.0084	0.00	0.00
Isobutane	58.13	0.12	0.37	120	370	2.1	6.4	0.00	0.01	48.9	48.9	0.23	0.25
2,2-Dimethylbutane	86.17	0.17	0.84	170	840	2.0	9.7	0.00	0.01	18.4	23.8	0.08	0.18
2,3-Dimethylbutane	86.17	0.59	1.55	590	1550	6.8	18.0	0.02	0.01	19.1	22.5	0.30	0.32
Isopentane	72.15	6.07	10.17	6070	10170	84.1	141.0	0.20	0.11	47.8	49.6	9.34	5.54
2-Methylpentane	86.17	2.91	3.85	2910	3850	33.8	44.7	0.08	0.04	13.8	15.7	1.08	0.56
3-Methylpentane	86.17	2.40	2.40	2400	2400	27.9	27.9	0.06	0.02	12.8	13.1	0.83	0.29
2,3-Dimethylpentane	100.21	0.32	4.17	320	4170	3.2	41.6	0.01	0.03	5.25	5.25	0.04	0.17
2,4-Dimethylpentane	100.21	0.23	1.71	230	1710	2.3	17.1	0.01	0.01	4.06	5.5	0.02	0.07
3,3-Dimethylpentane	100.21	0.02	0.03	20	30	0.2	0.3	0.00	0.00	5.94	5.94	0.00	0.00
2,2,4-Trimethylpentane	114.23	0.32	4.58	320	4580	2.8	40.1	0.01	0.03	2.05	2.44	0.01	0.08
2,3,4-Trimethylpentane	114.23	0.11	2.8	110	2800	1.0	24.5	0.00	0.02	1.36	2.3	0.00	0.04
2-Methylhexane	100.21	0.36	1.48	360	1480	3.6	14.8	0.01	0.01	2.54	2.54	0.02	0.03
3-Methylhexane	100.21	0.3	1.77	300	1770	3.0	17.7	0.01	0.01	2.64	4.95	0.02	0.07
2,2,5-Trimethylhexane	128.26	0.17	5.89	170	5890	1.3	45.9	0.00	0.04	0.54	1.15	0.00	0.04
3-Methylheptane	114.23	0.63	1.54	630	1540	5.5	13.5	0.01	0.01	0.792	0.792	0.01	0.01
4-Methyloctane	128.26	0.11	0.55	110	550	0.9	4.3	0.00	0.00	0.115	0.115	0.00	0.00
Cyclopentane	70.14	0.19	0.58	190	580	2.7	8.3	0.01	0.01	156	160	0.98	1.05
n-Propylcyclopentane	112.2	0.01	0.06	10	60	0.1	0.5	0.00	0.00	2.04	2.04	0.00	0.00
Pentene -1	70.14	0.33	0.45	330	450	4.7	6.4	0.01	0.01	148	148	1.62	0.75
cis-2-Pentene	70.14	0.43	0.67	430	670	6.1	9.6	0.01	0.01	203	203	2.89	1.54
trans-2-Heptene	98.19	0.06	0.1	60	100	0.6	1.0	0.00	0.00	15	15	0.02	0.01
2-Methyl-1-Pentene	84.16	0.2	0.22	200	220	2.4	2.6	0.01	0.00	78	78	0.43	0.16
Benzene	78.11	0.12	3.5	120	3500	1.5	44.8	0.00	0.04	1740	1869	6.21	66.35
Toluene	92.13	2.73	21.8	2730	21800	29.6	236.6	0.07	0.19	500	627	34.40	117.54

Table 4.1: Calculation of Maximum Expected Concentrations of Gasoline in Groundwater (cont'd)

Compound	Molecular Weight	Concentration (w%) ¹		Mass, g (Assume 1000 g)		Moles of Compound		Mole Fraction		Solubility (mg/L)		Max. Expected Solubility (mg/L)	
		min	max	min	max	min	max	min	max	min	max	min	max
o-Xylene	106.2	0.68	2.86	680	2860	6.4	26.9	0.01	0.02	167	204	2.48	4.35
m-Xylene	106.2	1.77	3.87	1770	3870	16.7	36.4	0.04	0.03	134	196	5.18	5.66
p-Xylene	106.2	0.77	1.58	770	1580	7.3	14.9	0.02	0.01	156	200	2.63	2.36
1,2,3-Trimethylbenzene	120.2	0.21	0.48	210	480	1.7	4.0	0.00	0.00	75.2	75.2	0.31	0.24
1,2,4-Trimethylbenzene	120.2	0.66	3.3	660	3300	5.5	27.5	0.01	0.02	51.9	59	0.66	1.28
1,3,5-Trimethylbenzene	120.2	0.13	1.15	130	1150	1.1	9.6	0.00	0.01	48.2	97	0.12	0.74
1,2,4,5-Tetramethylbenzene	134.2	0.02	0.19	20	190	0.1	1.4	0.00	0.00	3.48	3.48	0.00	0.00
Ethylbenzene	106.2	0.36	2.86	360	2860	3.4	26.9	0.01	0.02	131	208	1.03	4.44
n-Propylbenzene	120.2	0.08	0.72	80	720	0.7	6.0	0.00	0.00	55	120	0.08	0.57
Isopropylbenzene	120.2	0.01	0.23	10	230	0.1	1.9	0.00	0.00	48.3	65.3	0.01	0.10
n-Butylbenzene	134.2	0.04	0.44	40	440	0.3	3.3	0.00	0.00	11.8	17.7	0.01	0.05
Isobutylbenzene	134.2	0.01	0.08	10	80	0.1	0.6	0.00	0.00	10.1	10.1	0.00	0.00
sec-Butylbenzene	134.2	0.01	0.13	10	130	0.1	1.0	0.00	0.00	17.6	30.9	0.00	0.02
t-Butylbenzene	134.2	0.12	0.12	120	120	0.9	0.9	0.00	0.00	29.5	34	0.06	0.02
n-Pentylbenzene	148.25	0.01	0.14	10	140	0.1	0.9	0.00	0.00	10.5	10.5	0.00	0.01
Naphthylene	128.19	0.09	0.49	90	490	0.7	3.8	0.00	0.00	22	34.4	0.04	0.10
Total						430.7	1262.3					88	225

Notes:

1. Data at 25°C unless otherwise stated

Source: Mackay et al. [1981]

Source (Diffusivity and K_{oc}): Heath et al. [1993]

reported as maximum and minimum solubilities. The solubilities for different compounds were obtained from Table 2.2. The minimum and maximum expected solubilities of each compound were calculated by multiplying the respective minimum and maximum values for each of the mole fractions and solubility values.

The results of these calculations suggest that maximum concentrations of total BTEX compounds are expected to range between 51 mg L⁻¹ and 200 mg L⁻¹. Observed concentrations exceeding 51 mg L⁻¹ are expected to reflect the possible presence of free product within the aquifer system. Total TPH concentrations would be expected to range between 88 mg L⁻¹ to 225 mg L⁻¹. Again, concentrations exceeding 88 mg L⁻¹ may suggest the presence of free product.

Analysis of groundwater samples for TPH, DRO, and GRO was completed for the October and December 1999 sampling rounds. Analysis was also completed for the June 1999 sampling round, however, difficulties with the calibration of the GC/FID rendered this data unusable. Reported values of TPH and BTEX compounds for the three monitoring events are contained in Appendix 5.

The results of the October 1999 sampling event identified significant groundwater contamination near monitoring wells MW04, MW05, MW06, MW13, MW14, and MW15, as shown on Figure 4.5a. Nearly two-thirds of the contamination observed at the site was attributed to gasoline range organics.

Figure 4.5a: TPH Concentration in Groundwater with Kriged Contours
(October 1999)

Contamination due to diesel range organics was spread throughout the contaminated region. The maximum TPH concentration detected at the site was 198 mg L^{-1} at MW04, while 136 mg L^{-1} was attributed to gasoline range organics. The fit of the calibration curves for the October sampling event was excellent. Lab duplicates for TPH indicated excellent agreement, varying by less than 1 percent of the original value. The contours shown were constructed by kriging the data to estimate the patterns of contamination at the site. The contours do not reflect true contours, but rather estimated patterns of contamination at the site.

A similar pattern of contamination was detected during the December 1999 sampling event (Figure 4.5b), with the exception that MW13 did not contain detectable concentrations of TPH. The maximum concentration of TPH detected in this sampling round was 161 mg L^{-1} and was located at MW06. Only small quantities of diesel range organics were detected during the December sampling round. These concentrations were generally less than 3 mg L^{-1} . Given the magnitude of the observed TPH contamination, in comparison with the expected maximum concentrations shown on Table 4.1, it is expected residual hydrocarbon exists at the site.

BTEX concentrations for each of the three sampling events are presented as Figures 4.6a through 4.6c. The BTEX plume appears to be located in the same

Figure 4.5b: TPH Concentrations in Groundwater with Kriged Contours
(December 1999)

Figure 4.6b: Total BTEX Concentrations in Groundwater with Kriged Contours (October 1999)

Figure 4.6c: Total BTEX Concentrations in Groundwater with Kriged Contours
(December 1999)

area as where TPH was detected. Total BTEX concentrations ranged from 24.4 mg L⁻¹ in June at monitoring well MW04 to 75.5 mg L⁻¹ in December at the same well. The maximum concentrations for total BTEX were calculated to range between 52 mg L⁻¹ and 200 mg L⁻¹, as shown in Table 4.1. The concentrations observed at the site are sufficiently close to this range to suspect free product contamination. This further supports the finding that the TPH concentrations were sufficiently high to suspect the presence of free product.

4.3.3 Geochemical Indicators

Geochemical indicators such as the concentrations of dissolved oxygen, nitrate, ferrous iron, and sulfate, and the reduction-oxidation (redox) potential are also useful in identifying hydrocarbon plume locations. As a hydrocarbon plume moves through the aquifer, biodegradation results in the consumption of the different terminal electron acceptors. As each electron acceptor is used in preferential order, a plume is formed where either depleted dissolved oxygen, nitrate, or sulfate, or elevated ferrous iron is present. This section will assess the presence of these indicators at the site to further support the location of contamination. Appendix 5 also presents the observed geochemical indicator parameters.

Average values of the redox potential from the October and December groundwater monitoring events are presented in Figure 4.7. The redox potential

Figure 4.7: Average REDOX Potential in Groundwater with Kriged Contours

was not measured during the June sampling round. As can be seen on the figure, a zone of low redox potential surrounded monitoring wells MW04, MW08, MW14, and MW15. This zone corresponded with the location of the observed TPH and BTEX contamination. The higher levels at MW05 and MW06 suggest that sufficient flow of groundwater from the south, or the upstream flow direction, may have provided additional electron acceptors to the microorganisms, resulting in a less-reduced area. The redox potential at monitoring well MW15 averaged -228 mV. On the border of the plume at MW06, the redox potential averaged -35 mV. Background redox potentials at the site were monitored using upstream monitoring wells MW02 and MW16. These wells indicated the local redox potential averaged 200 mV. Monitoring well MW17 was not suitable as a background well as the depleted redox potential indicated that the well may be located within the contaminant plume. As each of the terminal electron accepting processes are discussed, the redox potential at each location will be examined to determine if the observed redox pattern concurs with the observed geochemical indicator patterns [Parsons Engineering Science, Inc., 1995].

The dissolved oxygen at the site showed a similar pattern of depleted levels near MW04, MW08, MW14, and MW15, as shown in Figure 4.8. These average concentrations ranged from 1.2 mg L⁻¹ to 2.9 mg L⁻¹. Surrounding dissolved oxygen concentrations were found to range from 3.7 mg L⁻¹ to 7.4 mg L⁻¹. The

Figure 4.8: Average Dissolved Oxygen Concentrations in Groundwater with Kriged Contours

modestly low dissolved oxygen concentration at MW16, which averaged 6.0 mg L^{-1} , suggests the dissolved oxygen concentration of the groundwater flowing onto the site may be impacted by off-site processes. However, the accuracy of the measurements at MW02 and MW17 are questionable, as the dissolved oxygen concentrations at the wells did not agree with the redox potentials reported. MW02 had an average dissolved oxygen concentration of 3.7 mg L^{-1} , which was low considering it also had the highest average redox potential of 212 mV. Monitoring well MW17 had the highest average dissolved oxygen concentration of 7.4 mg L^{-1} despite the low redox potential which was reported to average 55 mV. However, monitoring at this location may have been influenced by the low groundwater level within the well, as the probe may not have been sufficiently submerged in water. Also, wells that had sufficiently low redox potentials to indicate the water should have been anoxic reported dissolved oxygen concentrations in excess of 1 mg L^{-1} .

The difference in the findings of the observed redox potential and the dissolved oxygen concentrations at MW02 and MW17 may be related to the difference in analysis. The dissolved oxygen was measured using a down-well probe, where as the redox potential was measured using the flow-through cell. The purging may have introduced small quantities of dissolved oxygen into the groundwater. Thus, dissolved oxygen concentrations in excess of 1 mg L^{-1} were measured in wells where the redox potential indicated the dissolved oxygen

should have been depleted. Although, as will be discussed, the redox potentials reported were in agreement with other geochemical indicators, the reported values may be higher than the true values if oxygen was introduced into the groundwater during purging. Due to the low water levels and slow recharge, a surface mounted high flow peristaltic pump may be preferable for use during purging as compared to the Waterra hand pumps. Also, a flow-through measuring approach may provide more accurate measurements of the dissolved oxygen concentrations, as there would be no question as to the complete submersion of the probe.

Depleted nitrate concentrations can be the first indication of anaerobic biodegradation in the groundwater. The average nitrate concentrations observed over the three sampling rounds are presented on Figure 4.9. The background nitrate concentrations at the site ranged from an average of 1.42 mg L^{-1} to 0.25 mg L^{-1} at monitoring wells MW08 and MW02 respectively. This background level is low, and indicates that nitrate was not a substantial electron accepting process at the site. Monitoring well MW16, which was considered the best background well at the site had an average nitrate concentration of 0.55 mg L^{-1} . The monitoring wells located in the southeast corner of the site all showed negligible concentrations of nitrate in the groundwater. This indicates that the groundwater in this portion of the site has been reduced to at least nitrate-reducing conditions. This was further supported by the redox potential, as it

was less than -35 mV in this area, which is equivalent to the range where nitrate reduction occurs.

The reduction of ferric iron to ferrous iron is generally found to be the next reduction process observed in the biodegradation of contaminated groundwater. Elevated levels of ferrous iron indicate a greater degree of biodegradation may be occurring since biodegradation leads to the reduction of ferric iron to ferrous iron. Figure 4.10 presents the average ferrous iron concentrations observed during the three monitoring events. Monitoring wells MW03, MW04, MW05, MW06, MW09, MW13, MW14, and MW15 had detectable concentrations of ferrous iron present in the groundwater. This corresponded with the area of low nitrate concentrations, indicating that this zone is at least associated with the reduction of ferric iron to ferrous iron. Monitoring wells MW04, MW05, and MW15 contained the highest average concentrations of ferrous iron, ranging from 2.3 mg L^{-1} to 4.7 mg L^{-1} . The use of ferric iron as an electron acceptor is generally observed at redox potentials below -50 mV. As was mentioned previously, the area impacted with ferrous iron generally had average redox potentials less than -50 mV.

The groundwater was also monitored for sulfate reduction. Average background sulfate levels ranged from 123 mg L^{-1} to 208 mg L^{-1} as shown on Figure 4.11. A small zone of depleted sulfate concentrations was observed at MW04, MW06, and MW15, indicating substantial utilization was occurring in

Figure 4.10: Average Ferrous Iron Concentrations in Groundwater with Kriged Contours

Figure 4.11: Average Sulfate Concentrations in Groundwater with Kriged Contours

this region. This is the area that spans between the suspected gasoline contamination and the location of the heating oil fuel spill. Average redox potentials at MW04 and MW15 were -112 and -228 mV respectively, which is in the expected range where sulfate reduction occurs. These wells also had elevated ferrous iron concentrations.

4.4 Summary of Areas of Contamination

Once the results of the soil data and groundwater data were linked, a clear picture of the contamination at the site was formed as shown on Figure 4.12. As mentioned in Section 4.2.2, where the contamination of soils was discussed, two areas of contamination exist at the site. Specifically an area impacted by gasoline near MW06 and GP01, and an area impacted by heating oil, near MW04, MW14, and GP04. TPH concentrations in the groundwater suggest an area of contaminated groundwater exists within the area bounded by monitoring wells MW04, MW05, MW06, MW14, and MW15. Contaminated groundwater in this area is expected based on the groundwater flow patterns at the site, which alternate from flowing to the northeast when the water table is higher, and to the northwest during drier periods. BTEX contamination in the groundwater also showed a similar pattern in the groundwater. Geochemical indicators suggested the most reduced groundwater zone spans between MW04 and MW06, including MW15. A zone of elevated ferrous iron at the southeast corner of the site indicates substantial biodegradation has occurred. Nitrate concentrations in this

Figure 4.12: Conceptual Model of Groundwater Contamination

same area were also depleted, further suggesting anaerobic biodegradation is occurring. The redox potentials at the site correspond with these findings. Given the findings of this section, the following section will detail the application of multi-level vadose zone piezometers to monitoring the location of contamination at the site.

Chapter 5.0 - Use of Soil Vapour Monitoring Wells to Characterize Hydrocarbon Contamination

Monitoring of the soil gas was completed using a series of ten multi-level soil vapour wells. The wells were located to span both areas of suspected contamination and various soil types. Figure 5.1 shows the location of each soil vapour monitoring well. The wells were installed as described in Section 3.1.2. Appendix 2 contains the borehole stratigraphic logs for GP01 through GP10.

5.1 Categorization of Soil Vapour Monitoring Wells

Ten monitoring wells were installed to span the locations where the suspected contamination appeared to exist. Based on the findings of the soil sampling, it was identified that the clay portions of GP01, GP02, and GP04 were impacted by hydrocarbon contamination. As mentioned in Section 4.2.2, soil vapour well GP01 is located in gasoline impacted soils and, as will be demonstrated, this contamination impacts upon the soil vapours at well GP02. The clay soils at GP04 were impacted mainly by heating oil contamination. The remaining wells were located beyond the direct influence of hydrocarbon contamination. As there was no immediate source for the vapours, it is believed that the hydrocarbon vapours detected in these seven wells were attributed to the migration of hydrocarbon contaminated soil vapours into the well. The wells impacted by soil vapour migration include GP03, GP05, GP06, GP07, GP08, GP09, and GP10.

Figure 5.1: Location of Soil Vapour Monitoring Wells

In addition to categorizing the wells as contaminant impacted or migratory wells, the soil type at the well was also considered when investigating the response patterns at the wells. Sand wells were those that did not contain any native clay soils. The two wells meeting this criterion were GP05 and GP06. The remaining wells were defined as clay wells. These categories have been summarized in Table 5.1. Appendix 6 includes the observations collected for each of the vapour phase constituents monitored for the duration of the study.

5.2 Tracer Gas Study

A tracer gas study was conducted in November 1999 to estimate field values for the diffusivity of gases in the clay and sand soils. The tracer study followed the protocol suggested by Johnson et al. [1998] and was described in Section 2.2.4.3. The use of this method required the estimation of several soil properties including the moisture content and void space. Based on measured soil moisture values and average porosities reported in literature of 0.55 for clay and 0.35 for sand [Craig, 1995; Fetter, 1994], the void porosities, θ_v , of the soils were calculated using equation 5.1. The void porosity of the soils described the porosity through which gases could diffuse. In equation 5.1, the mass of the soil and water in the soil sample is defined by m_s and m_w , the total volume and volume of the solids is defined by V_T and V_s , while the specific gravity of the soil sample is defined by G_s . The porosity is defined by θ , and is equal to the volume of voids divided by the total volume of the sample.

Table 5.1: Soil Vapour Monitoring Well Categories

	Hydrocarbon Impacted Wells	Migratory Wells
Clay Wells	GP01 GP02 GP04	GP03 GP07 GP08 GP09 GP10
Sand Wells		GP05 GP06

$$\theta_v = \theta \left(1 - \frac{m_w V_s G_s}{m_s V_T} \right) \quad (5.1)$$

The average void porosity for clay soils was 0.36 while the average for sand soils was 0.27. Equation 2.18 was then used to calculate the effective diffusivity observed at each step, assuming the point source solution where the volume of gas sampled was less than 10 percent of the volume of the tracer gas injected. An average effective diffusivity was calculated for each run by minimizing the sum of the squares of the β_{observed} and the $\beta_{\text{calculated}}$ (equation 2.18) when an average effective diffusivity was used.

The tracer study included one run in clay soils and two runs in sandy soils. Two runs were possible in the sand soils as the concentrations of sulfur hexafluoride dissipated to below detectable levels in less than 24 hours whereas the clay soils had detectable concentrations remaining after 43 hours. Soils above and below the injection levels were monitored for sulfur hexafluoride. However, concentrations at these locations remained below detection limits. Thus, only the piezometer levels used for the injections were considered for analysis. The observed decay rates of sulfur hexafluoride concentrations in the soil vapour wells are presented in Figures 5.2 and 5.3 for the clay and sand soils. Figures 5.4 and 5.5 show the calculated effective diffusivities in $\text{cm}^2 \text{s}^{-1}$ of sulfur hexafluoride in the clay and sand soils respectively.

Figure 5.2: Observed Response of Sulfur Hexafluoride Decay in Clay Soils

Figure 5.3: Observed Response of Sulfur Hexafluoride Decay in Sand Soils

Figure 5.4: Effective Diffusivity of Sulfur Hexafluoride in Clay Soils

Figure 5.5: Effective Diffusivity of Sulfur Hexafluoride in Sand Soils

Figure 5.2 shows the observed decay response of sulfur hexafluoride in the clay well. As can be seen by this graph, the concentration in the well did not stabilize until nearly 6 hours had past. The initial decay observed in the first 30 minutes was expected to be sharp, as the sulfur hexafluoride would require some mixing time with the soil gas that was in the gravel pack. However, the response did not stabilize for some time following the 30 minutes that were expected to be required for this mixing. It is believed that the reason for this lack of stabilization may be attributed to a heterogeneity in soil moisture near the injection point. The soil vapour wells were open to the atmosphere when not in use. This may have provided an opportunity for the clay soils surrounding the gravel packs to dry slightly. The decreased water content might impact the rate at which the tracer gas was able to diffuse through the soils. As shown in Figure 5.4, the calculated effective diffusivity of sulfur hexafluoride in the clay soils changed by nearly one order of magnitude within the first six hours of the tracer test. It is believed that following this point in time, the sulfur hexafluoride began to diffuse through the soils that had more uniform, higher moisture contents. It is believed the effective diffusivities calculated beyond this point are accurate representations of the ability of sulfur hexafluoride to diffuse through the clay soils. Although the effective diffusivity of the sulfur hexafluoride in the clay soils did not stabilize initially, an average effective diffusivity of $0.0077 \text{ cm}^2 \text{ s}^{-1}$ was calculated using the observed data for times following the first 30 minutes.

However, the true effective diffusivity of sulfur hexafluoride is expected to be closer to $0.002 \text{ cm}^2 \text{ s}^{-1}$ based on the response curve.

The sand soils demonstrated a significantly more stable response for both runs. The responses of the two runs are shown on Figure 5.3. Figure 5.5 shows the calculated effective diffusivity of sulfur hexafluoride in the sand soils. The results of the two runs indicated good replication existed between runs. The first run resulted in an average effective diffusivity of $0.03 \text{ cm}^2 \text{ s}^{-1}$ while the second run had an average of $0.021 \text{ cm}^2 \text{ s}^{-1}$.

As a second approximation of the effective gas diffusivity, the Millington-Quirk approximation was used, as described by equation 2.13. The Fuller-Schettler-Giddings (FSG) method was used to estimate the free air diffusivity of sulfur hexafluoride, as described by equation 2.15. The free air diffusivity of sulfur hexafluoride was $0.0850 \text{ cm}^2 \text{ s}^{-1}$, based on a molecular volume of $69.7 \text{ cm}^3 \text{ mole}^{-1}$ and a molecular weight of $146.05 \text{ g mole}^{-1}$. Using the soil porosities and void fractions mentioned above, the effective diffusivity was calculated to be $0.005 \text{ cm}^2 \text{ s}^{-1}$ for clay soils. Adjusting the exponent in equation 2.13 to 3.1, as suggested by Sallam et al. [1984], resulted in an increase to $0.0065 \text{ cm}^2 \text{ s}^{-1}$ for clay soils. This was compared to the measured value in the tracer study, which ranged between $0.007 \text{ cm}^2 \text{ s}^{-1}$ to $0.002 \text{ cm}^2 \text{ s}^{-1}$. Excellent agreement exists between the theoretical and experimental effective diffusivity values. However, the required duration of this tests in order to achieve agreement between the

theoretical and experimental estimates is significantly longer for clay soils than for sandy soils.

The application of the Millington-Quirk approach for the sand required the use of the dry soils approach because the soil moisture content was less than 5%. As such, the soil moisture was approaching dry soil conditions. In this case, as the air filled porosity, θ_v , in equation 2.13 approaches the total porosity, θ , the equation is reduced to equation 5.2 [Logan, 1999].

$$D_{e,g} = D_{air} \theta^{4/3} \quad (5.2)$$

Using equation 5.2, the effective gas diffusivity in the sand soils was expected to be $0.02 \text{ cm}^2 \text{ s}^{-1}$, as compared to the range of $0.021 \text{ cm}^2 \text{ s}^{-1}$ to $0.03 \text{ cm}^2 \text{ s}^{-1}$ measured in the tracer study. Hence, the values obtained using Millington-Quirk were within the ranges observed using the protocol suggested by Johnson et al. [1998].

Prior to using the calculated effective diffusivities to estimate the flux of hydrocarbons from the soil, the effective diffusivities of sulfur hexafluoride were employed to estimate the effective diffusivities of gasoline vapours in the subsurface. The first step was to determine the ratio between porosity and tortuosity in the soils that impacted the diffusion of gases through the soil. This ratio was described in equation 2.16 and will be constant regardless of the gas that is diffusing through the soil. Rearranging equation 2.16, it is found that this ratio is described by the ratio between the effective diffusivity of a gas in soil and

the free air diffusivity. In the case of the sulfur hexafluoride tracer study, this ratio was 0.247 for sand soils and 0.024 for clay soils (assuming the average effective gas diffusivity of sulfur hexafluoride was $0.002 \text{ cm}^2 \text{ s}^{-1}$).

The effective diffusivity of gasoline vapours was estimated using the ratios between the porosity and tortuosity of the soils, and the free air diffusivity of gasoline vapours. The calculation of the free air diffusivity of gasoline is presented in Table 5.2. The FSG method for calculating the free air diffusivity presented in Grathwohl [1998] was followed. This method involved using the number of each type of atom in the compound to calculate a diffusive volume for each compound. Equation 2.15 was then applied to calculate the free air diffusivity of each compound. The molar average of the free air diffusivity for gasoline was then calculated to be $0.73 \text{ cm}^2 \text{ s}^{-1}$. Applying the ratio from equation 2.16, which was determined to be 0.247 for sand soils and 0.024 for clay soils, the effective diffusivity of gasoline vapours was found to be $0.018 \text{ cm}^2 \text{ s}^{-1}$ and $0.0018 \text{ cm}^2 \text{ s}^{-1}$ for sand and clay soils respectively.

The flux of hydrocarbon vapours from the subsurface due to diffusion, originating from a vapour phase source in the subsurface, has been estimated following the work of Johnson et al. [1996]. The flux was estimated using equation 5.3 where C is the maximum observed concentration of hydrocarbon vapours at the site, H is the depth of soil layer n , and $D_{e,g}$ is the effective diffusivity for the n th soil layer.

Table 5.2: Calculation of Free Air Diffusivity of Gasoline Vapour

Compound	Molecular Weight	Mole Fraction	Carbon (#)	Hydrogen (#)	Diffusive Volume ($\text{cm}^3 \text{ mole}^{-1}$)	FCS Free Air Diffusivity ($\text{cm}^2 \text{ s}^{-1}$)	Molar Weighted D_{air} ($\text{cm}^2 \text{ s}^{-1}$)
Propane	44.11	0.00	3	8	65.34	0.104	5.46E-05
n-Butane	58.13	0.16	4	10	85.8	0.088	1.39E-02
n-Pentane	72.5	0.18	5	12	106.26	0.078	1.44E-02
n-Hexane	86.17	0.01	6	14	126.72	0.071	4.58E-04
n-Heptane	100.21	0.01	7	16	147.18	0.065	4.68E-04
n-Octane	114.23	0.01	8	18	167.64	0.061	4.44E-04
n-Nonane	128.26	0.00	9	20	188.1	0.057	7.22E-05
n-Decane	148.28	0.00	10	28	220.44	0.052	3.28E-05
n-Undecane	156.32	0.00	11	24	229.02	0.051	3.80E-05
n-Dodecane	170.33	0.00	12	26	249.48	0.049	2.66E-05
Isobutane	58.13	0.00	4	10	85.8	0.088	4.24E-04
2,2-Dimethylbutane	86.17	0.00	6	14	126.72	0.071	3.24E-04
2,3-Dimethylbutane	86.17	0.02	6	14	126.72	0.071	1.13E-03
Isopentane	72.15	0.20	5	12	106.26	0.078	1.53E-02
2-Methylpentane	86.17	0.08	6	14	126.72	0.071	5.55E-03
3-Methylpentane	86.17	0.06	6	14	126.72	0.071	4.58E-03
2,3-Dimethylpentane	100.21	0.01	7	16	147.18	0.065	4.83E-04
2,4-Dimethylpentane	100.21	0.01	7	16	147.18	0.065	3.47E-04
3,3-Dimethylpentane	100.21	0.00	7	16	147.18	0.065	3.02E-05
2,2,4-Trimethylpentane	114.23	0.01	8	18	167.64	0.061	3.94E-04
2,3,4-Trimethylpentane	114.23	0.00	8	18	167.64	0.061	1.36E-04
2-Methylhexane	100.21	0.01	7	16	147.18	0.065	5.43E-04
3-Methylhexane	100.21	0.01	7	16	147.18	0.065	4.53E-04
2,2,5-Trimethylhexane	128.26	0.00	9	20	188.1	0.057	1.75E-04
3-Methylheptane	114.23	0.01	8	18	167.64	0.061	7.76E-04
4-Methyloctane	128.26	0.00	9	20	188.1	0.057	1.13E-04
Cyclopentane	70.14	0.01	5	10	102.3	0.080	5.02E-04
n-Propylcyclopentane	112.2	0.00	8	16	163.68	0.061	1.27E-05
Pentene -1	70.14	0.01	5	10	102.3	0.080	8.71E-04
cis-2-Pentene	70.14	0.01	5	10	102.3	0.080	1.14E-03
trans-2-Heptene	98.19	0.00	6	26	150.48	0.065	9.17E-05
2-Methyl-1-Pentene	84.16	0.01	6	12	122.76	0.072	3.97E-04
Benzene	78.11	0.00	6	6	110.88	0.076	2.71E-04
Toluene	92.13	0.07	7	8	131.34	0.069	4.76E-03
o-Xylene	106.2	0.01	8	10	151.8	0.064	9.49E-04

Table 5.2: Calculation of Free Air Diffusivity of Gasoline Vapour

Compound	Molecular Weight	Mole Fraction	Carbon (#)	Hydrogen (#)	Diffusive Volume ($\text{cm}^3 \text{ mole}^{-1}$)	FCS Free Air Diffusivity ($\text{cm}^2 \text{ s}^{-1}$)	Molar Weighted D_{air} ($\text{cm}^2 \text{ s}^{-1}$)
m-Xylene	106.2	0.04	0.03	8	10	0.064	2.47E-03
p-Xylene	106.2	0.02	0.01	8	10	0.064	1.07E-03
1,2,3-Trimethylbenzene	120.2	0.00	0.00	9	12	0.060	2.42E-04
1,2,4-Trimethylbenzene	120.2	0.01	0.02	9	12	0.060	7.60E-04
1,3,5-Trimethylbenzene	120.2	0.00	0.01	9	12	0.060	1.50E-04
1,2,4,5-Tetramethylbenzene	134.2	0.00	0.00	10	14	0.056	1.94E-05
Ethylbenzene	106.2	0.01	0.02	8	10	0.064	5.03E-04
n-Propylbenzene	120.2	0.00	0.00	9	12	0.060	9.21E-05
Isopropylbenzene	120.2	0.00	0.00	9	12	0.060	1.15E-05
n-Butylbenzene	134.2	0.00	0.00	10	14	0.056	3.88E-05
Isobutylbenzene	134.2	0.00	0.00	10	14	0.056	9.70E-06
sec-Butylbenzene	134.2	0.00	0.00	10	14	0.056	9.70E-06
t-Butylbenzene	134.2	0.00	0.00	10	14	0.056	1.16E-04
n-Pentylbenzene	148.25	0.00	0.00	11	16	0.053	8.32E-06
Naphylene	128.19	0.00	0.00	10	8	0.058	9.45E-05
Total					180.84		7.52E-02
Average							7.30E-02

Notes:

Mole Fractions derived from Table 4.1

Source (FCS Diffusive Volume): Grathwohl [1998]

* - Assume average soil temperature of 12°C

$$F_{i,d,g} = C_{i,g} \left(\frac{1}{\sum_n \frac{H_n}{(D_{e,g})_n}} \right) \quad (5.3)$$

Equation 5.3 permitted the calculation of the maximum flux due to diffusion from the soil surrounding GP01 assuming no asphalt cover. As the well was located near the edge of the asphalt, the influence of the cover was neglected.

Two soil layers were assumed in the calculation of the flux of hydrocarbons from the soil. Based on soil boring logs, the top sandy layer was 76 cm deep while the underlying clay layer was 158 cm deep. The source term concentration, $C_{i,g}$, was assumed equal to the maximum observed vapour phase concentration which was 11,500 ppmv TPH. The values for effective diffusivity that were used were $0.0018 \text{ cm}^2 \text{ s}^{-1}$ and $0.018 \text{ cm}^2 \text{ s}^{-1}$ for the clay and sand soils respectively. Using these values the estimated flux of hydrocarbon vapours from this soil was estimated to be $0.41 \text{ g m}^{-2} \text{ d}^{-1}$.

Based on the estimated volatilization rate, the predicted remedial timeline was estimated for the gasoline contamination located at GP01. The contamination was believed to be located in clay soils over a depth of 1.5 m and an area of 27 m^2 . Given the porosity of the clay was 0.55, the total volume of soil was estimated to be 18.225 m^3 . Following the work of Zytner et al. [1993], which

indicated moist clay soils have a residual capacity of $0.16 \text{ g (g soil)}^{-1}$, an estimated 7727 kg of gasoline was estimated to exist in the subsurface. At the estimated volatilization rate of 11 g d^{-1} , which was based on the $0.41 \text{ g m}^{-2}\text{d}^{-1}$ over an area of 27 m^2 , the spill would require 1912 years to be remediated through volatilization alone. However, this estimate is extremely conservative as it does not account for the impact of partitioning to the aqueous phase or biodegradation.

5.3 Monitoring the Subsurface using Soil Vapour Monitoring Wells

Soil vapour wells were used to monitor the subsurface TPH and oxygen concentrations in the soil vapour. Monitoring of carbon dioxide concentrations was added to the sampling regime in November 1999. It was hypothesized that soil conditions and the proximity of the well to contamination would be factors that influence the observed response of the wells. As such, the wells were categorized into three groups, as was discussed in Section 5.1. The following section will describe the use of soil vapour monitoring wells for monitoring contamination, describe relationships observed between TPH concentrations and changes in climate, and relationships observed between the various gases that were monitored.

5.3.1 Identification of Hydrocarbon Contamination

Subsurface soil vapours were monitored for six months, between July and December 1999. Table 5.3 presents a statistical summary of the soil vapour

Table 5.3: Statistical Summary of Soil Vapour Monitoring Results

Well	Level	Statistic	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
GP01	1	Average	605	19.5	1.2
		Count (#)	29	30	4
		Minimum	100	17.7	0.6
		Maximum	1,300	20.9	2.7
	2	Average	4,594	6.6	7.4
		Count (#)	29	30	4
		Minimum	140	0.1	3.7
		Maximum	7,560	14.8	12.2
	3	Average	4,500	8.3	—
		Count (#)	1	1	—
		Minimum	4,500	8.3	—
		Maximum	4,500	8.3	—
	4	Average	14,250	0.2	—
		Count (#)	6	6	—
		Minimum	12,000	0.0	—
		Maximum	16,500	0.7	—
GP02	1	Average	748	15.2	2.4
		Count (#)	29	30	4
		Minimum	240	2.0	0.6
		Maximum	2,420	19.7	3.6
	2	Average	7,395	5.2	6.9
		Count (#)	30	31	4
		Minimum	380	0.2	0.6
		Maximum	13,000	18.7	14.7
	3	Average	11,914	1.4	16.9
		Count (#)	27	28	2
		Minimum	5,500	0.0	16.7
		Maximum	16,500	7.0	17.0
GP03	1	Average	710	12.0	2.4
		Count (#)	29	30	4
		Minimum	140	9.6	0.6
		Maximum	1,320	16.2	4.2
	2	Average	777	3.6	5.6
		Count (#)	29	30	4
		Minimum	120	2.2	1.6
		Maximum	1,340	6.9	9.5
	3	Average	710	1.2	—
		Count (#)	8	8	—
		Minimum	360	0.3	—
		Maximum	1,120	3.3	—

Table 5.3: Statistical Summary of Soil Vapour Monitoring Results (cont'd)

Well	Level	Statistic	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
GP04	1	Average	398	20.1	0.4
		Count (#)	29	30	4
		Minimum	100	11.7	0.1
		Maximum	2,940	20.9	0.6
	2	Average	1,717	12.3	7.0
		Count (#)	29	30	4
		Minimum	380	2.8	3.8
		Maximum	4,020	20.9	11.3
	3	Average	3,072	7.1	5.4
		Count (#)	22	22	4
		Minimum	1,920	0.6	2.2
		Maximum	4,580	18.6	12.7
GP05	1	Average	629	16.1	1.9
		Count (#)	28	29	3
		Minimum	220	14.1	0.4
		Maximum	940	18.7	2.8
	2	Average	676	14.1	3.2
		Count (#)	28	29	3
		Minimum	200	12.1	1.2
		Maximum	1,040	17.2	4.3
	3	Average	696	11.1	4.3
		Count (#)	29	30	3
		Minimum	180	9.0	1.2
		Maximum	1,230	15.1	6.0
	4	Average	695	8.5	7.0
		Count (#)	27	28	2
		Minimum	180	5.1	6.7
		Maximum	980	14.1	7.2
GP06	1	Average	518	18.0	1.1
		Count (#)	30	31	4
		Minimum	160	13.1	0.2
		Maximum	820	20.9	1.5
	2	Average	635	14.2	2.3
		Count (#)	30	31	4
		Minimum	180	12.1	0.4
		Maximum	1,000	17.4	3.8
	3	Average	663	13.5	2.5
		Count (#)	29	30	4
		Minimum	160	11.4	0.8
		Maximum	1,080	16.9	4.2
	4	Average	630	12.2	0.0
		Count (#)	23	23	0
		Minimum	160	10.6	0.0
		Maximum	860	13.9	0.0

Table 5.3: Statistical Summary of Soil Vapour Monitoring Results (cont'd)

Well	Level	Statistic	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
GP07	1	Average	686	19.1	0.8
		Count (#)	28	29	4
		Minimum	140	16.8	0.2
		Maximum	1,800	20.4	1.3
	2	Average	794	6.4	1.8
		Count (#)	29	30	4
		Minimum	180	0.1	0.4
		Maximum	1,220	18.4	5.6
	3	Average	886	8.3	4.8
		Count (#)	28	29	4
		Minimum	140	6.5	0.8
		Maximum	1,360	12.5	8.4
GP08-1	1	Average	382	19.5	0.6
		Count (#)	29	30	4
		Minimum	120	11.5	0.0
		Maximum	720	20.9	1.2
	2	Average	626	13.4	2.7
		Count (#)	29	30	4
		Minimum	140	10.0	0.2
		Maximum	1,000	17.7	5.0
	3	Average	845	12.9	2.8
		Count (#)	29	30	4
		Minimum	120	9.7	0.6
		Maximum	6,610	18.6	5.0
	4	Average	511	7.2	—
		Count (#)	9	9	—
		Minimum	100	1.5	—
		Maximum	1,720	11.7	—
GP09-1	1	Average	515	17.8	2.0
		Count (#)	29	30	4
		Minimum	140	15.9	0.8
		Maximum	860	19.8	2.8
	2	Average	627	15.7	2.8
		Count (#)	29	30	4
		Minimum	160	13.6	1.0
		Maximum	1,200	18.6	4.5
	3	Average	674	13.3	3.5
		Count (#)	29	30	4
		Minimum	120	9.7	1.2
		Maximum	1,340	17.7	6.4
	4	Average	663	12.4	4.7
		Count (#)	28	29	3
		Minimum	80	7.9	0.7
		Maximum	1,200	17.7	7.1

Table 5.3: Statistical Summary of Soil Vapour Monitoring Results (cont'd)

Well	Level	Statistic	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
GP10-1	1	Average	651	7.6	3.1
		Count (#)	29	30	4
		Minimum	140	3.7	1.3
		Maximum	1,340	18.0	6.9
	2	Average	679	3.8	3.7
		Count (#)	29	30	4
		Minimum	140	0.8	1.8
		Maximum	1,320	19.0	7.2
	3	Average	696	2.8	5.8
		Count (#)	28	29	4
		Minimum	160	0.6	2.4
		Maximum	1,280	11.5	9.5
MW02		Average	678	5.2	5.4
		Count (#)	29	30	4
		Minimum	120	2.7	0.8
		Maximum	1,280	13.5	9.7
MW03		Average	658	15.5	3.1
		Count (#)	29	30	4
		Minimum	180	12.8	0.8
		Maximum	1,240	18.3	5.6
MW04		Average	755	8.8	7.0
		Count (#)	29	30	4
		Minimum	100	5.7	1.4
		Maximum	2,220	14.6	11.5
MW05		Average	1,914	5.6	8.5
		Count (#)	29	30	4
		Minimum	560	0.0	1.6
		Maximum	7,860	11.1	13.7
MW06		Average	1,537	15.1	5.1
		Count (#)	29	30	4
		Minimum	420	11.2	2.0
		Maximum	8,860	17.7	8.4
MW08		Average	764	18.3	3.5
		Count (#)	28	29	4
		Minimum	240	5.4	0.4
		Maximum	2,460	20.2	7.0
MW09		Average	1,236	9.0	3.8
		Count (#)	29	30	4
		Minimum	280	3.0	0.8
		Maximum	11,500	18.4	7.9
MW13		Average	627	13.8	2.4
		Count (#)	29	30	4
		Minimum	160	9.0	0.6
		Maximum	1,080	21.3	5.4

Table 5.3: Statistical Summary of Soil Vapour Monitoring Results (cont'd)

Well	Statistic	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
MW14	Average	784	12.1	4.5
	Count (#)	29	30	4
	Minimum	200	6.6	0.5
	Maximum	2,060	16.8	9.4
MW15	Average	1,006	21.0	0.1
	Count (#)	29	30	4
	Minimum	200	19.4	0.0
	Maximum	9,000	21.6	0.4
MW16	Average	506	19.5	0.6
	Count (#)	20	21	4
	Minimum	300	13.9	0.4
	Maximum	860	21.0	0.8
MW17	Average	657	11.6	5.0
	Count (#)	29	30	4
	Minimum	160	6.3	0.7
	Maximum	1,280	16.9	8.3

database, which is presented in Appendix 6. Subsurface soil vapour monitoring was completed on 31 separate occasions. Not all piezometers were sampled at each monitoring event due to equipment limitations and high moisture contents in the clay soils. The average well had 29 samples taken. Samples were not obtained between August 21, 1999 to September 11, 1999 due to technical difficulties with the Gastech meter. Sampling frequency was decreased from several times per week to weekly monitoring starting the first week of October once it was established that relatively slow variations in soil vapour concentrations were occurring.

The Gastech meter measured soil gas concentrations for TPH (as combustibles), oxygen, and carbon dioxide. The observed TPH values, which ranged from 80 parts per million by volume (ppmv) to 16,500 ppmv were well within the detection range for the Gastech. The detectable range of TPH reported in ppmv for the Gastech ranged from 20 ppmv to 10,000 ppmv. For values greater than 10,000 ppmv, the Gastech reported concentrations in terms of percent of the lower explosive limit. The conversion of the percent to parts per million by volume required the conversion factor of 500 ppmv per percent. Thus, values in excess of 10,000 ppmv are accurate to the nearest 500 ppmv. The observed oxygen concentrations in the subsurface ranged from 0% to 21.3%. This range encompassed the entire monitoring range of the meter, which is designed to detect the range between 0% and atmospheric concentrations. The

meter measured the concentrations of oxygen in increments of 0.1%. The observed carbon dioxide concentrations ranged from 0% to 17% in the subsurface. The one-point carbon dioxide calibration curve for the Gastech ranged from 0% to 10%. The meter detected carbon dioxide concentrations in 0.1% increments.

Soil gas concentrations were detected simultaneously using the Gastech. Concentrations were obtained from the wells once the three concentrations had stabilized. In the case of the lower unit clay wells, availability of soil gas for monitoring was limited due to the high soil moisture content. As a result, the pump drew sufficient air to create suction within the well. This frequently resulted in the pump stalling. Where the pump did not stall, the concentrations at the wells were determined by the maximum TPH and carbon dioxide concentrations and the minimum oxygen concentrations recorded. This was required as the suction led to a peak response as compared to a stabilized response. Duplicates were not obtained using the Gastech as the premise of the screening was that the soil vapour concentrations in the gravel pack would reach equilibrium with the surrounding soils. Excessive sampling had the potential to alter the soil vapour chemistry, which would result in inaccurate duplicate concentrations. In place of duplicate samples, sampling frequency at the beginning of the study was at least once in two days. The daily results were compared to identify if variability was being observed between the days, or if

consistent patterns were being observed for both TPH concentrations and oxygen concentrations. Once confidence was obtained in October that the sample values observed were temporally consistent, sampling frequency was decreased to once per week.

Figure 5.6 presents average soil vapour TPH concentrations for the subsurface vapour phase monitoring wells. The radial plots were used to gain a three-dimensional perspective of the location of hydrocarbon contamination. Although average values were employed to identify areas of contamination, it will be demonstrated later that there was considerable temporal variation in the observed TPH values.

A comparison of Figure 5.6 with the results from the soil sample analysis shown in Figure 4.2 indicate that the two distinct sources detected using soil samples were also detected through monitoring the soil vapour phase. The highest concentrations of vapour phase hydrocarbons were located at GP01 and GP02 where the concentrations were 14,240 ppmv and 11,914 ppmv respectively. The second area of contamination detected was located at GP04 where the maximum vapour phase concentration was 3,072 ppmv. However, the relative magnitude of contamination differed between the soil sampling and the soil vapour monitoring despite the similar geological conditions at these wells. The soil sampling analysis suggested that the most contaminated soil was located at GP04 (981 mg kg⁻¹) with additional contamination located at GP01 (540 mg kg⁻¹).

Figure 5.6: Average Soil Vapour TPH Concentrations

Comparatively, the soil gas sampling analysis suggested the most concentrated contamination was located near GP01 and GP02, with some additional contamination at GP04. It is believed that the difference in behaviour at the two sources lies with the chemical and physical properties of the contaminants.

The perceived source of contamination near GP01 and GP02 was the leaking pipe network that connected the gasoline tanks to the pumping island. The results of the soil sampling supported this hypothesis, as described in Section 4.2.2. The soil vapour analysis supported the findings of the soil sampling analysis, which indicated the bulk of the contamination was located below 1.5 m bgs. Average soil vapour concentrations were measured in excess of 14,000 ppmv at GP01-4 while levels 2 and 3 at the same well indicated TPH concentrations of approximately 4,500 ppmv. Soil vapour concentrations at GP02-3 reached a maximum of 11,000 ppmv. Soil vapour concentrations for both vapour wells at level 1 were generally negligible. The increased concentrations of hydrocarbon contamination in both the vapour and soil phases indicated the soil below 1.5 m bgs may have been contaminated with gasoline leaking from the pipe network.

The source term at GP04 is believed to be a combination of heating oil and gasoline. Although the soil samples obtained from this well indicated similar degrees of contamination, the magnitudes of the soil gas concentrations were

20% of those observed at GP01 and GP02. This finding concurred with the soil sampling GC/FID analysis, as diesel range organics are generally less volatile than gasoline range organics. The soil contamination at GP04 ranged from between 23% to 49% DRO as compared to the soil contamination observed at GP01, which was a maximum of 15% DRO compounds. The higher proportion of contamination being related to the DRO compounds, in combination with the difference in volatility of these compounds, was expected to result in lower observed soil vapour TPH concentrations, as was observed. The difference in the relative soil gas to soil sample concentrations were found to be consistent with the hypothesized source term for this location.

The wells impacted chiefly by migration of soil vapours, as defined by Table 5.1, had average soil vapour TPH concentrations below 1000 ppmv as compared to the concentrations observed at the source wells. As shown on Figure 4.2, TPH concentrations measured in the soil samples were generally low, with the exception of GP10. The soil vapour concentrations reflected the background concentrations observed in the soils. As will be discussed in the following section, the low concentrations observed at the migratory wells were also accompanied by a temporal consistency not observed in wells directly impacted by contamination.

A comparison of the contamination found during soil sampling and soil vapour sampling indicated soil vapour wells were successful in identifying

locations of contamination for both gasoline and heating oil impacted soils. Although both types of contamination were detected, gasoline contamination was more apparent. This was attributed to the more volatile nature of compounds in gasoline. As a result of sampling procedures, soil gas wells may provide increased sensitivity to volatile compounds than soil sampling, as there is less potential for loss of volatile components to the atmosphere prior to analysis.

5.3.2 Soil Gas TPH Concentrations With Time

As mentioned previously, there were two main sources of hydrocarbon contamination at the site, as characterized by gas wells GP01, GP02, and GP04. When the characteristics of measured TPH vapours were assessed based on contaminated versus lesser-contaminated locations, one important trend became apparent; impacted wells were found to exhibit a significantly larger range in TPH vapour concentrations with time. The lesser-contaminated wells that were chiefly impacted by migration of soil vapours demonstrated more consistency with time.

Figures 5.7 and 5.8 show TPH vapour concentrations with time for the lightly and heavily contaminated wells respectively for each of the piezometer levels. Figure 5.7 has five parts, Figures 5.7a through 5.7e, that are divided by well type. Figure 5.7a shows the response of the sand wells that were impacted by migration. Figure 5.7b through 5.7d show the response of the clay wells that

Figure 5.7a Daily Soil Gas TPH with Time
(Sand Migration Wells)

Figure 5.7b Daily Soil Gas TPH with Time
(Clay Migration Wells - GP03 and GP07)

Figure 5.7c Daily Soil Gas TPH with Time
(Clay Migration Wells - GP08 and GP09)

Figure 5.7d Daily Soil Gas TPH with Time
(Clay Migration Wells - GP10)

Figure 5.7e Daily Soil Gas TPH with Time
(Surface Source Wells)

Figure 5.8a: Daily Soil Gas TPH with Time
(GP01)

Figure 5.8b: Daily Soil Gas TPH with Time
(GP02)

Figure 5.8c: Daily Soil Gas TPH with Time
(GP04)

were impacted by migration. Figure 5.7e shows the response of the level 1 piezometers at each of the impacted wells. The surface piezometers at GP01, GP02, and GP04 were considered non-source wells as the sandy soil used as fill led to no limitations of the escape of soil vapours from this level. As shown by these figures, there were some variations in soil vapour TPH concentrations with time for the lightly contaminated wells. This long-term change in TPH concentrations have been attributed to a decrease in bioactivity due to changes in the climate. This will be discussed in Section 5.3.8. Furthermore, within a well there was minimal change in soil vapour TPH concentration with depth. The small vertical concentration gradients measured at the wells may be indicative of the vapour phase migrating laterally towards the well from the source area. Of further interest, in the lesser-contaminated wells, the soil gas response for wells located in both sand and clay was similar.

Figure 5.8 shows the results obtained for wells where average TPH concentrations were greater than 1000 ppmv. These correspond to the clay portions of GP01, GP02 and GP04. Figure 5.8 has three parts, each one showing the response of each of the three contaminated wells. From Figures 5.8a through 5.8c, a seasonal trend is apparent where the concentration of TPH in the soil gas generally increased during October, but then declined towards the end of December. The variation in TPH concentrations was significant compared to that observed in the lesser-contaminated wells. In addition to the increased variation

in TPH concentrations, it was also observed that TPH concentrations generally increased with depth. The increased contamination with depth is indicative of either a point or planar source located below the monitoring location.

The results of this study suggest that the presence of either soil vapour TPH concentrations in excess of 1,000 ppmv or a significant vertical TPH gradient is indicative of a nearby source of contamination. Also, the increased variation in concentrations at contaminated wells suggests that monitoring frequency should be increased for piezometers that are located nearer sources of contamination than those that are located at some distance away from the sources. A true measure of source term degradation should be based on long term monitoring where seasonal trends could be predicted and observed. This is consistent with long time frames often associated with natural attenuation remedies.

5.3.3 Monitoring Headspace Samples from Groundwater Monitoring Wells for TPH

Headspace measurements from groundwater monitoring wells have historically been used to monitor the vapour phase in the vadose zone. This section investigates the accuracy of using the headspace TPH measurements from the groundwater wells as indicators of subsurface contamination. This was accomplished by comparing observed soil gas TPH concentrations from nearby vapour phase piezometers to the observed headspace TPH concentrations.

Comparisons were completed between wells that were physically close to one another, and that had similar geological characteristics. The pairs of wells that were investigated included the two source well pairs of GP01 and GP02 versus MW06 and GP04 versus MW14, and the migratory well pairs of GP03 versus MW08, GP05 and GP06 versus MW15, GP07 versus MW09, GP08 versus MW04, and GP09 versus MW03.

As described by Henry's law, contamination in the aqueous phase has potential to impact the concentrations of TPH vapours observed in the headspace of a groundwater well. In order to use groundwater well headspace measurements effectively, it is necessary to establish that the contribution of the mass of hydrocarbon vapours from equilibrium partitioning in the headspace is negligible compared to the total mass contributed from the surrounding soil vapours. Figure 5.9 presents the paired data between the observed groundwater TPH concentrations and the observed headspace concentrations for two groundwater monitoring rounds. The vapour phase TPH concentrations were obtained within two days of the groundwater sample collection. This figure shows an independent relationship between the concentrations observed in the groundwater and those observed in the vapour phase.

The relationship between the observed TPH concentrations in the groundwater well headspace and the soil vapour concentrations measured from

Figure 5.9: Comparison of Headspace Vapour Quality in Groundwater Monitoring Wells to Groundwater Quality

Figure 5.10: Comparison of Headspace TPH in Groundwater Monitoring Well to Soil Vapour Monitoring Well

the soil vapour piezometers was evaluated. Figure 5.10 presents the pairs of data for the migratory wells, excluding GP05, GP06 and the corresponding monitoring well MW15. Those wells are described in Figures 5.11 and 5.12. The data presented in Figure 5.10 are averaged soil gas concentrations across the four levels of the vapour wells, versus the observed concentration in the groundwater well. Given the minimal vertical gradient in the TPH concentrations in the migratory wells, it was believed that comparing the average concentration of the soil vapour wells with the average concentrations of the groundwater wells would provide an accurate picture of any relationships that may exist. As shown in Figure 5.10, a significant trend exists between the observed vapour phase concentrations obtained from the soil vapour piezometer wells and the headspace measurements obtained from the groundwater wells. Groundwater monitoring wells MW03, MW 04, MW08, and MW09 were screened across the water table.

Figures 5.11 and 5.12 compare the observed TPH concentrations from the vapour phase piezometers GP05 and GP06 to the headspace measurements from MW15. These wells were also considered to be migratory wells, however, the correlation observed on Figure 5.10 did not exist. This was attributed to the difference in screening at MW15, whereby the well was screened below the water table. This would prevent the soil gases above the water table from entering the groundwater well. Thus, it is believed that in the case of migratory wells,

Figure 5.11: Comparison of Headspace TPH in Groundwater Monitoring Well MW15 to Soil Vapour Monitoring Well GP05

Figure 5.12: Comparison of Headspace TPH in Groundwater Monitoring Well MW15 to Soil Vapour Monitoring Well GP06

headspace measurements from groundwater wells are only indicative of the average soil gas concentrations if the wells are screened above the water table. This permits the soil gas vapours to reach equilibrium with the vapour in the headspace region.

Figures 5.13 through 5.15 show the comparison of the soil gas TPH concentrations observed for each level of the soil gas piezometers to the observed groundwater monitoring well headspace concentrations for the heavily contaminated well pairs. Individual levels were compared for the source wells due to the variability in TPH concentrations between levels. These figures present the results for the three source wells, GP01, GP02, and GP04 respectively. The groundwater monitoring wells in these comparisons are screened across the water table. As can be seen in these figures, no clear correlation existed between the headspace measurements and the soil vapour quality. As will be noted later about source wells, significant variations in soil gas TPH concentrations with time are typical of wells located nearby contaminated soils. These graphs indicate that headspace measurements from groundwater wells located nearby contamination do not reflect this range in soil vapour TPH concentration. As a result, the groundwater wells cannot be used as an indicator of soil vapour quality. Soil vapour piezometers appear to provide more detailed and accurate information.

Figure 5.13: Comparison of Headspace TPH in Groundwater Monitoring Well MW06 to Soil Vapour Monitoring Well GP01

Figure 5.14: Comparison of Headspace TPH in Groundwater Monitoring Well MW06 to Soil Vapour Monitoring Well GP02

Figure 5.15: Comparison of Headspace TPH in Groundwater Monitoring Well MW14 to Soil Vapour Monitoring Well GP04

5.3.4 Characteristics of Soil Gas Oxygen Concentrations with Time

The oxygen concentrations measured in the wells as a function of time are presented in Figures 5.16, and 5.17 for sand wells, and Level 2 clay piezometers respectively. These graphs demonstrate characteristic changes that occur in the subsurface oxygen concentrations with time. The oxygen concentrations ranged from between 0% where the oxygen had been depleted from the soil vapours to 21%, which is the atmospheric concentration. The depletion of oxygen in the subsurface is believed to be influenced by two mechanisms; the presence of an oxygen sink in the subsurface such as bioactivity, and limited oxygen diffusion into the subsurface from the atmosphere [Ostendorf et al., 1991; Davis et al., 1999].

Figure 5.16 shows the response of soil wells that were surrounded by sand. These wells represent a subset of the lesser-contaminated well set that had average TPH concentrations less than 1000 ppmv. A general pattern was observed where the oxygen concentration in the subsurface increased with time over the period from August to December. For example, at the level 4 piezometers, the oxygen concentration increased from approximately 6% in September to more than 12% in December. However, there were some differences observed between the different piezometer depths. The shallow gas piezometers (Level 1) experienced a gradual increase in oxygen concentrations with time. This increase was limited to a change between 15% oxygen at level 1

Figure 5.16: Daily Soil Gas Oxygen Response with Time
(Sand Soils)

Figure 5.17: Daily Soil Gas Oxygen Response with Time
(Clay Soils, Level 2 Piezometers)

in September to just over 18% in December. As the soil depth increased, a decline of nearly 3% was first observed in September, which was followed by an increase of nearly 9% in oxygen concentrations. The seasonal trends observed in the subsurface oxygen concentrations indicated that modest long term variations in oxygen concentrations can occur, and these trends are more pronounced as the depth below ground surface increases.

Figure 15.7 shows the response of six clay wells at Level 2. Here, it was observed that the wells experienced more variation in oxygen concentration over time. However, different clay wells experienced different responses in oxygen concentration with depth. For example, GP01-2 and GP02-2 showed substantial decreases in oxygen, from 12% in August to less than 1% in October, as compared to the migration-impacted wells GP03-2, GP04-2, and GP07-2. As will be discussed in Section 5.3.8, this is believed to be a reflection of biodegradation processes and diffusion limitations in the subsurface. The soil gas oxygen response with time was not shown for the level 3 contaminated wells because there was significant scatter in the oxygen concentrations. In subsequent sections, the inter-relationship between oxygen levels and hydrocarbon contamination will be investigated.

5.3.5 Monitoring Headspace Samples from Groundwater Wells for Oxygen

Headspace measurements from existing groundwater monitoring wells have also been used to monitor the oxygen concentrations in the subsurface.

However, due to the large diameter opening at the top of the well casing, the accuracy of this type of measurement is questionable. This section will investigate the reliability of using the headspace measurement as an indication of subsurface oxygen concentrations.

Figure 5.18 shows the pairs of average oxygen concentrations between the groundwater monitoring wells and the associated soil vapour wells. The well pairings were consistent with those comparisons made in Section 5.3.3 and the values used for the soil vapour wells were the averaged values over the four levels of the wells. In this figure, it is apparent that at the migration impacted wells, a general correlation exists where the oxygen concentrations recorded in the headspace of the groundwater wells do reflect the oxygen concentrations observed in the soil vapour wells. For example, between GP09 and MW04, the oxygen concentrations ranged between 12% to 18% for both wells. For GP08 and MW03, the range of oxygen concentrations observed in the soil vapour well was from 12% to 18% whereas the range in the groundwater monitoring well headspace was from 6% to 15%. Similar results were observed between GP07 and MW09. However, the results from comparing GP03 with MW08 show that opposite trend as to that observed between GP08 and MW03. At GP08 and MW03 the oxygen concentration in the groundwater monitoring well headspace was lower than that observed in the soil vapour well, whereas at the former pair the oxygen concentration in the groundwater monitoring well headspace was

Figure 5.18: Comparison of Oxygen Concentrations in Grounwater Monitoring Well
Headspace to Vapour Phase Monitoring Wells
(Migratory Wells)

higher than that observed in the soil vapour well. Also, in the sand wells of GP05 and GP06, the comparison with the results from MW15 indicated that where the groundwater well was screened below the water table, the oxygen concentration did not reflect the observed oxygen concentrations in the soil vapour wells.

Figures 5.19 through 5.21 show the comparison of GP01 and GP02 to MW06, and GP04 to MW14 respectively. As a result of the vertical oxygen gradient observed in the subsurface, the soil vapour monitoring wells were compared on the basis of individual levels to the oxygen concentrations observed in the headspace of the groundwater monitoring wells. These figures show the headspace measurements in the groundwater monitoring wells located near contaminated soils consistently reported oxygen concentrations between 9% and 18%. However, measurements from the soil vapour wells reported values ranging from 0% to 21%, varying with depth. It has been found that near sources of contamination, headspace measurements from groundwater monitoring wells cannot be relied upon as a true reflection of the oxygen concentrations in the subsurface.

5.3.6 Relationship between TPH and Oxygen in the Soil Gas

Historically, research conducted by Ostendorf and Kampbell [1991], Davis et al. [1998], and Lahvis and Baehr [1996] have suggested there is interaction between TPH and oxygen in the subsurface. This interaction is based on the

Figure 5.19: Comparison of Oxygen Concentrations in Groundwater Monitoring Well Headspace (MW06) to Vapour Phase Monitoring Well (GP01)

Figure 5.20: Comparison of Oxygen Concentrations in Groundwater Monitoring Well Headspace (MW06) to Vapour Phase Monitoring Well (GP02)

Figure 5.21: Comparison of Oxygen Concentrations in Groundwater Monitoring Well Headspace (MW14) to Vapour Phase Monitoring Well (GP04)

stoichiometric relationship given by equation 2.23. This equation describes the ratio of hydrocarbon and oxygen consumption to carbon dioxide production. It was found that where biodegradation is occurring, oxygen concentrations are generally depleted, while carbon dioxide concentrations are elevated. At the same point, hydrocarbon vapour concentrations are generally elevated indicating a sufficient source term exists upon which to sustain the microcosm.

To date, the observed the ratios between hydrocarbon vapour, oxygen, and carbon dioxide content have primarily been made with respect to depth in the subsurface. Figure 5.22 shows that at a contaminated well, GP02-2, a similar interaction was observed over time. The sharp increase in TPH during mid September corresponded to a significant decrease in oxygen. At this time, the oxygen decreased from approximately 12% to less than 1% in the subsurface, while the hydrocarbon concentration increased from less than 1000 ppmv to more than 11,000 ppmv. Following the peak in hydrocarbon concentrations, the TPH began to decrease over time while the oxygen slowly began to recover. This variation in TPH and oxygen in the subsurface has been attributed to climatic changes and will be discussed in detail in Section 5.3.8. However, as previously discussed in Section 5.3.4, it was also observed that oxygen concentrations in the subsurface varied with time in lesser-contaminated sand wells, where the

Figure 5.22: TPH and Oxygen Soil Gas with Time at GP02-2

observed TPH concentrations were stable. To further investigate this interaction the oxygen and TPH concentrations for all of the wells were compared.

Figure 5.23 shows the relationship between TPH concentrations and the oxygen concentrations averaged over time for each monitoring location for all of the piezometers in the subsurface. This graph demonstrates two responses; mainly a declining relationship, and an independent relationship between oxygen and TPH. In the former, oxygen concentrations declined from 9% to 0% with increasing TPH concentrations, which ranged from 3,000 ppmv to 14,000 ppmv, while in the latter TPH concentrations were essentially constant while oxygen concentrations varied from 0% to 21%.

The independent relationship between TPH and oxygen was found to occur mainly in wells with low TPH concentrations. The observed independence likely resulted from the different means by which each component arrived at the piezometer. As shown by Figure 5.24, the TPH compounds are believed to have migrated to these wells horizontally from a source of contamination that was located some distance away. Mechanisms that would have controlled the concentrations present at a well would include the rate of release from the source, diffusive limitations, biodegradation, and sorptive retardation. In addition, there may be a portion of the TPH vapours that was not biodegradable, and may result in a low level background concentration that would dissipate

Figure 5.23: Time-Averaged TPH Soil Gas Concentrations
versus Time-Averaged Oxygen Concentrations

Figure 5.24: Conceptual Model of Independent versus Dependent
Gas Diffusion Pathways

only through volatilization. The oxygen would have migrated from the surface and been subject to diffusive limitations, biodegradation and dissolution in soil water. This combination of factors led to low level TPH concentrations and a range of oxygen concentrations in the subsurface.

The declining relationship was observed at the heavily contaminated wells. This relationship supports previously held beliefs that where biodegradation is an active process, this relationship could be described by stoichiometry between TPH oxidation and oxygen consumption. Figure 5.25 shows a summary of all oxygen and TPH concentrations for the heavily contaminated wells. While the declining trend is still evident in this plot, increased scatter of the data can be observed. The increased scatter was likely due to variations in depth and its impact upon oxygen availability.

5.3.7 Relationship between TPH, Oxygen, and Carbon Dioxide in Soil Gas

Monitoring of subsurface vapours for carbon dioxide was started in November 1999. Although the dataset for the carbon dioxide monitoring is not as extensive as the TPH and oxygen monitoring sets, trends were still apparent. Figure 5.26 shows an example soil gas profile for a well that is located nearby contaminated soils (GP02). This figure shows the increase in carbon dioxide and decrease in oxygen with depth that is indicative of biodegradation processes. Figure 5.27 shows an example profile of a lesser-contaminated sand well. In this

Figure 5.25: TPH Soil Gas Concentrations versus Oxygen Concentrations for Contaminated Wells

Figure 5.26: Chemical Signature of a Hydrocarbon Contaminated Vapour Well (GP02)

Figure 5.27: Chemical Signature of a Hydrocarbon Contaminated Vapour Well (GP05)

figure, although there is a decrease in oxygen and increase in carbon dioxide with depth, the changes are not as significant. In the less contaminated well, the oxygen decreased by approximately 8% whereas in the contaminated well, the oxygen decreased by nearly 12%. The carbon dioxide increased by approximately 8% in GP05, which was the lesser-contaminated sand well, as compared to the increase of 14% that was observed in the contaminated well. As suggested by Ostendorf et al. [1991] and Davis et al. [1999], the pattern shown in Figure 5.26 is indicative of biodegradation, whereas the pattern observed in Figure 5.27 indicates biodegradation is a less important mechanism, and that gas diffusion may be the controlling process

5.3.8 Impact of Climatic Changes on Soil Gas Concentrations

Climatic Data for the site was collected through a combination of on-site measurements and the use of climatic data recorded by Environment Canada at the MacDonald Cartier International Airport. Climatic data collected at the site included air temperature, barometric pressure, and subsurface soil temperature. This data is included in Appendix 7.

5.3.8.1 Barometric Pressure Changes

Barometric pressure changes have been reported to influence the flow of soil vapours in the subsurface [Elberling et al., 1998; Massmann et al., 1992]. It has been reported that subsurface gases move toward the surface when atmospheric pressure decreases, and away from it when the pressure is increased [Elberling

et al., 1998]. This would result in an increased TPH concentration at the surface during periods of low pressure.

To assess the potential impact of barometric pressure changes, subsurface TPH concentrations were monitored frequently during September 1999. These results were compared to the changes in barometric pressure. The soil vapour wells were divided into the three categories shown in Table 5.1. It was expected that the prevalence of off-gassing might vary between these groups of wells.

Inspection of graphs comparing TPH concentration fluctuations to barometric pressure variations indicated no consistent pattern was observed at the site for any of the three groups, at each monitored level. These graphs have been included in Appendix 8. However, this may have been due to the infrequent monitoring of the TPH concentrations. Attempts were made to monitor the wells at intervals no greater than once every two days. It may be necessary to continually monitor the soil gas wells to capture minor fluctuations that might be caused by changes in atmospheric pressure. Although future work is required for confirmation, it is expected that incorporating changes in barometric pressure into temporal models will result in limited improvement in the predicted concentrations.

5.3.8.2 Subsurface Conditions

Soil moisture content and temperature are two factors that are expected to impact upon the migration of subsurface soil vapours. An increased soil

moisture content is expected to decrease the effective diffusivity of vapours and, in some cases, might cause desorption of substances from the solid to the gaseous phases. A reduction in the effective diffusivity of a hydrocarbon may cause its accumulation in the gas phase near the source of contamination. A reduction in the effective diffusivity of oxygen will reduce its migration into the subsurface thereby limiting its availability for participation in biodegradation reactions. A decrease in temperature will reduce the diffusivity of a substance as well as reduce the rate of biodegradation reactions. In addition, a reduction in temperature will increase the solubility of oxygen in subsurface water.

To investigate the relationship between these factors and the observed vapour phase responses, data was collected for the daily precipitation depths and soil temperature profiles. The precipitation data was obtained from the Atmospheric Environment Branch of Environment Canada. The data was obtained from the monthly climatological summaries, which are maintained for the Ottawa MacDonald-Cartier International Airport. The precipitation data for the monitoring period is presented on Figure 5.28. As can be seen in this figure, a period of heavy precipitation occurred in early September, where more than 85 mm of rain fell in 5 days. With the exception of this event, the precipitation was spread evenly for the duration of the monitoring period.

The soil temperature profiles were created by recording the temperatures at 0.75m, 1.5m, and 3m bgs, using the thermocouples that were installed at GP02.

Figure 5.28: Measured Precipitation, MacDonald-Cartier International Airport, Ottawa, Ontario

Figure 5.29: Subsurface Soil Temperatures During Monitoring Period

Figure 5.29 presents the subsurface soil temperature profiles. This figure shows that the subsurface soil temperatures decreased towards December, and that the surface soils were influenced by the air temperature more than the soils located 3 m bgs.

Soil moisture and subsurface temperatures were two factors that were expected to influence the concentrations of TPH and oxygen in the subsurface vapour phase. In order to further investigate these relationships, the wells were divided into the three groups, as was described in Section 5.1.

The two wells classified as sand wells included GP05 and GP06. These wells are believed to have been impacted chiefly by the migration of soil vapours to the wells, as the wells are located in sand fill that was placed at the site following the excavation of the tanks. Figures 5.30 and 5.31 show the oxygen response and TPH response of the level 2 piezometers for the sand wells respectively, which were typical responses for the sand wells. The plots also include subsurface soil temperature and the precipitation data for the monitoring period. Distinct patterns in the soil vapour concentrations were observed at different time intervals in these wells. Immediately following the rain event in early September, there was a significant increase in subsurface TPH soil vapour concentrations. The average increase in TPH was 500 ppmv from an initial value ranging from 200 to 300 ppmv. Following this increase, the TPH continued to increase gradually until December. In conjunction with this gradual increase, the

Figure 5.30: Oxygen Concentration and Soil Temperature with Time (Level 2, Sand Wells)

Figure 5.31: Precipitation and TPH Concentrations with Time (Level 2, Sand Wells)

subsurface vapour phase oxygen concentrations also increased from September to December. Similar results were observed for the other piezometer levels of these wells. The gradual changes observed in soil gas concentrations were attributed to a decrease in the biodegradation rate, associated with the decrease in subsurface temperature. The sudden change in soil vapour TPH concentrations was attributed to desorption of TPH compounds from the soil, which was triggered by competition for sorption sites between the polar water molecules and the less polar hydrocarbon compounds.

The second set of wells that were investigated were the clay wells impacted by the migration of TPH to the wells. These wells included GP03, GP07, GP08, GP09, and GP10. Figures 5.32 and 5.33 present the oxygen and TPH responses for these wells at level two. Soil vapour piezometers at level 1 were not selected, as these soils were predominantly sandy fill soils. Thus, it was found that the behaviour of the wells at this level was not indicative of what would be expected from clay soils. The soil vapour piezometers at levels 3 and 4 were not selected for inspection because the monitoring wells became difficult to sample accurately as the soil moisture increased during the season. As a result, data for this period was not available. Subsurface soil temperatures and precipitation data are also included for reference.

Similar observations were made at these five wells as were made at the sand wells. The oxygen concentrations increased with time as the subsurface soils

Figure 5.32: Oxygen Concentration and Soil Temperature with Time (Level 2, Clay Migration Wells)

Figure 5.33: Precipitation and TPH Concentrations with Time (Level 2, Migratory Clay Wells)

cooled, there was an immediate increase in TPH concentrations following the rain event, and finally there was a gradual increase in TPH concentrations with time following the rain event.

The increase in soil gas TPH concentrations in the clay wells resulting from the rain event were in the same magnitude as those observed in the sand wells. Generally, the increase was in the order of 400 ppmv to 600 ppmv from base concentrations ranging from 200 ppmv to 300 ppmv. Again, this increase has been attributed to desorption of hydrocarbon compounds. The gradual increase in soil vapour TPH with time in conjunction with the increasing subsurface oxygen concentrations and decreasing soil temperatures provided evidence that biodegradation processes also slowed in the clay soils. Similar observations were made for the remaining depths of the migratory wells.

The responses of the clay wells that were directly impacted by subsurface contamination differed from those observed at the migratory wells. The responses for oxygen and TPH vapour concentrations are shown in Figures 5.34 and 5.35. As before, the subsurface soil temperatures and precipitation data is included for reference.

The soil vapour TPH concentrations at level 2 increased significantly following the rain event in September whereas soil vapour concentrations at the respective level 3 piezometers maintained their concentrations in excess of 2000 ppmv. The responses of the soil vapours from the level 3 piezometers

Figure 5.34: Oxygen Concentration and Soil Temperature with Time (Level 2, Clay Source Wells)

Figure 5.35: Precipitation and TPH Concentrations with Time (Level 2, Source Wells)

indicated that the hydrocarbon contamination was present in sufficient quantities to flood the soil gas with hydrocarbon vapours. The concentrations at these wells did not change significantly with time. However, the level 2 piezometers may have been located at a sufficient distance from the water table such that, until the soils were moistened by the rain event, there would have been sufficient diffusion through the dryer soils to maintain the lower concentrations. To further support the reduced diffusion theory, the oxygen concentrations were substantially reduced after the rain event. These concentrations did not recover for the remainder of the monitoring period. As each of the three source wells, GP01, GP02, and GP04, have slightly different influencing characteristics, the response of each well will be discussed separately.

Monitoring well GP01 exhibited a rapid increase in TPH concentrations, from a base less than 1000 ppmv to more than 4000 ppmv, immediately following the September rain event. At this point, the soil gas TPH concentrations stabilized at a new quasi-equilibrium. In conjunction with this increase in TPH, the subsurface oxygen vapour phase was depleted to less than 1% oxygen. Once depleted, the oxygen concentrations did not recover. Soil vapour TPH concentrations below GP01-2 were elevated prior to the rainfall event and did not change significantly for the duration of the monitoring period.

As detected by the soil sampling, GP01 was the central point of the gasoline contamination. Thus, an abundant supply of residual product is available in the

soil from which volatilization can occur. The results of the soil vapour analysis suggest that biodegradation in this area is likely oxygen limited. Once the rainfall event occurred, the soil moisture content of the soils at the top of the clay layer increased. The increased moisture content would have impeded the diffusion of oxygen into the clay layer, resulting in an oxygen limited condition in the subsurface. The oxygen limitation would have the effect of slowing the biodegradation processes to meet the diffusional supply of oxygen to the area. The net result of the decreased oxygen concentration was that a higher TPH equilibrium state was established. The moist soil conditions at level 3 resulted in limited oxygen diffusion through out the season, and as a result, TPH concentrations at this level remained elevated for the duration of the monitoring program.

In well GP04, soil vapour TPH concentrations at GP04-3 were elevated for the duration of the monitoring period, however, soil vapour TPH concentrations at GP04-2 experienced an increase in concentration following the rain event. This increase did not occur as quickly as was observed at GP01. The vapour phase oxygen concentrations at GP04 were also reduced following the rain event, although the oxygen concentration remained above 3%. The difference in the rate of oxygen consumption in this area may reflect the difference in hydrocarbon contamination at this location. Fuel oil, which has a smaller fraction of easily biodegradable hydrocarbons, was the predominant

contaminant at GP04. The driving force for the oxygen consumption was the biodegradation of the fuel oil. Thus, given the lower fraction of easily biodegradable materials, the driving force was low and the rate of oxygen use was likely lower as well. Once the supply of oxygen was reduced by the increase in moisture content, and the corresponding decrease in the effective diffusivity of oxygen through the soil occurred, the oxygen supply would be depleted, although this would require more time to occur than at GP01.

The response of GP02 was somewhat different from that of GP01 and GP04. At this well, the TPH peaked a maximum concentration in excess of 12,000 ppmv shortly after the rain event, and then declined until December. The oxygen concentrations associated with this well were reduced to less than 1% immediately following the rain event. It has been hypothesized that the rain event led to an increase in the soil moisture, and an associated decrease in gas diffusivity through the soil. This led to the initial increase in soil gas TPH as the vapours were trapped by the soil moisture and could not diffuse outward to reduce the total concentration. As the soil began to dry, a slow release of TPH through diffusion away from the well occurred, in conjunction with an increase in the oxygen reaching the soils. This increase in oxygen would have the effect of increasing the biodegradation rate in the soil. Where GP01 had sufficient residual product to produce a maximum vapour phase concentration, the same degree of source was not available at GP02. Because the source was located a

short distance away, the combination of diffusion of TPH away from the well and the increase in biodegradation caused by an increasing oxygen supply may have led to the steady decline in the TPH concentration.

In Section 5.3.4, the concept of the dependent and independent relationships between TPH and oxygen were discussed as a means by which the location of source terms could be identified. This theory is further supported by the observed responses of the various wells to the climatic changes in the subsurface. The independent relationship described gas wells impacted by the migration of soil gas TPH from the source term. In these soils, TPH concentrations were observed to be sufficiently low, and have sufficient oxygen transport into the soils so that biodegradation was not oxygen limited. It has also been hypothesized that the independent relationship was also created by the presence of a portion of the soil vapour TPH not being readily available for biodegradation. These factors likely combined to form the independent relationship. The dependent relationship was observed at the source wells where TPH was available in sufficient quantities through the residual product to create a total oxygen sink through biodegradation. As a result, the soil gas relationship near residual product was defined by biodegradation which led to the observation of low oxygen concentrations corresponding with higher TPH concentrations.

5.3.9 Monitoring BTEX Compounds in the Vadose Zone

Soil vapour BTEX concentrations in the vadose zone were monitored at the site approximately once every six weeks. The goal of the monitoring was to identify if a relationship existed between TPH and BTEX compounds in the vadose zone and to identify what changes occurred in BTEX concentrations with time. Also, BTEX concentrations within each well were plotted to determine if chemical signatures could be traced for the individual compounds as an indicator of the degree of weathering.

Subsurface soil vapour BTEX concentrations were monitored four times between July and December 1999. The BTEX sampling events occurred on July 27, 1999, September 11, 1999, October 25, 1999, and December 6, 1999. Table 5.4 presents the statistical summary of the database, which is included in Appendix 9. Table 5.5 presents a summary of the successfully sampled soil vapour wells, as well as the number of duplicates obtained at each well. Some clay wells were not successfully sampled as a result of inadequate soil vapour sample volumes. Duplicate samples were collected during the September, October, and December sampling rounds as a measure of quality control. Table 5.6 presents the individual measurements from each set of duplicate samples. The duplicate analysis indicated excellent duplication of results in all wells except GP01 and GP02, which experienced variations of up to 25 times

Table 5.4: Statistical Summary of Soil Vapour BTEX Monitoring Results

Well	Level	Statistic	Benzene	Toluene	Ethylbenzene	M&P Xylene	O Xylene	Total BTEX
GP01	1	Average (ppmv)	0.2	0.3	0.6	1.2	0.5	2.8
		Count (#)	5	5	5	5	5	5
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.5	0.5	1.3	2.3	1.4	5.4
	2	Average (ppmv)	3.9	1.1	1.8	1.9	0.4	9.1
		Count (#)	5	5	5	5	5	5
		Minimum (ppmv)	0.5	0.0	0.0	0.0	0.0	0.7
		Maximum (ppmv)	9.6	1.8	3.7	3.9	2.1	18.0
	3	Average (ppmv)	1.3	1.5	0.9	3.2	0.0	6.9
		Count (#)	1	1	1	1	1	1
		Minimum (ppmv)	—	—	—	—	—	—
		Maximum (ppmv)	—	—	—	—	—	—
	4	Average (ppmv)	28.6	20.9	1.4	20.4	16.3	87.6
		Count (#)	1	1	1	1	1	1
		Minimum (ppmv)	—	—	—	—	—	—
		Maximum (ppmv)	—	—	—	—	—	—
GP02	1	Average (ppmv)	0.1	0.1	0.0	0.0	0.0	0.2
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.2	0.3	0.0	0.0	0.0	0.5
	2	Average (ppmv)	3.6	0.7	1.7	1.6	0.0	7.6
		Count (#)	7	7	7	7	7	7
		Minimum (ppmv)	0.2	0.0	0.0	0.0	0.0	0.4
		Maximum (ppmv)	14.5	2.8	5.4	6.0	0.0	24.7
	3	Average (ppmv)	11.1	4.3	3.9	10.7	3.6	33.6
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.6	0.5	0.0	0.8	0.0	2.0
		Maximum (ppmv)	16.2	8.5	7.1	20.0	9.4	61.2
	4	Average (ppmv)	11.3	9.1	3.9	11.4	7.4	43.1
		Count (#)	1	1	1	1	1	1
		Minimum (ppmv)	—	—	—	—	—	—
		Maximum (ppmv)	—	—	—	—	—	—
GP03	1	Average (ppmv)	0.1	0.2	0.1	0.4	0.4	1.2
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.3	0.5	0.4	1.3	1.8	4.2
	2	Average (ppmv)	0.2	0.3	0.1	0.5	0.3	1.4
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.1	0.0	0.4
		Maximum (ppmv)	0.4	0.8	0.4	1.5	1.4	4.5
	3	Average (ppmv)	0.0	0.4	0.0	0.0	0.0	0.4
		Count (#)	1	1	1	1	1	1
		Minimum (ppmv)	—	—	—	—	—	—
		Maximum (ppmv)	—	—	—	—	—	—
GP04	1	Average (ppmv)	0.0	0.1	0.1	0.2	0.0	0.3
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.1	0.2	0.2	0.3	0.0	0.6
	2	Average (ppmv)	3.2	0.4	0.2	0.5	0.1	4.2
		Count (#)	7	7	7	7	7	7
		Minimum (ppmv)	0.2	0.0	0.0	0.0	0.0	0.6
		Maximum (ppmv)	5.8	0.9	0.6	1.4	0.4	8.7
	3	Average (ppmv)	0.3	0.1	0.2	0.7	0.2	1.5
		Count (#)	3	3	3	3	3	3
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.7	0.3	0.4	1.4	0.6	3.3

Table 5.4: Statistical Summary of Soil Vapour BTEX Monitoring Results (cont'd)

Well	Level	Statistic	Benzene	Toluene	Ethylbenzene	M&P Xylene	O Xylene	Total BTEX
GP05	1	Average (ppmv)	0.0	0.1	0.0	0.0	0.0	0.1
		Count (#)	5	5	5	5	5	5
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.0	0.2	0.0	0.0	0.0	0.2
	2	Average (ppmv)	0.1	0.1	0.0	0.1	0.0	0.2
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.2	0.3	0.0	0.3	0.0	0.8
	3	Average (ppmv)	0.0	0.1	0.0	0.0	0.0	0.1
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.0	0.2	0.0	0.0	0.0	0.2
	4	Average (ppmv)	0.1	0.1	0.0	0.0	0.0	0.2
		Count (#)	3	3	3	3	3	3
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.2	0.3	0.0	0.0	0.0	0.5
GP06	1	Average (ppmv)	0.0	0.1	0.0	0.0	0.0	0.1
		Count (#)	6	6	6	6	6	6
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.0	0.2	0.0	0.0	0.0	0.2
	2	Average (ppmv)	0.0	0.1	0.0	0.0	0.0	0.1
		Count (#)	5	5	5	5	5	5
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.0	0.2	0.0	0.0	0.0	0.2
	3	Average (ppmv)	0.0	0.1	0.0	0.0	0.0	0.1
		Count (#)	5	5	5	5	5	5
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.0	0.2	0.0	0.0	0.0	0.2
	4	Average (ppmv)	0.1	0.2	0.0	0.2	0.0	0.5
		Count (#)	2	2	2	2	2	2
		Minimum (ppmv)	0.0	0.1	0.0	0.0	0.0	0.1
		Maximum (ppmv)	0.2	0.3	0.0	0.3	0.0	0.9
GP07	1	Average (ppmv)	0.0	0.1	0.1	0.3	0.1	0.5
		Count (#)	5	5	5	5	5	5
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.1	0.2	0.2	0.7	0.4	1.5
	2	Average (ppmv)	0.2	0.2	0.2	0.7	0.4	1.7
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.3	0.4	0.5	1.5	0.8	3.4
	3	Average (ppmv)	0.1	0.1	0.1	0.1	0.0	0.4
		Count (#)	5	5	5	5	5	5
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.2	0.2	0.5	0.3	0.0	0.9

Table 5.4: Statistical Summary of Soil Vapour BTEX Monitoring Results (cont'd)

Well	Level	Statistic	Benzene	Toluene	Ethylbenzene	M&P Xylene	O Xylene	Total BTEX
GP08	1	Average (ppmv)	0.1	0.2	0.1	0.0	0.0	0.4
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.4	0.6	0.5	0.0	0.0	1.5
	2	Average (ppmv)	0.1	0.1	0.0	0.0	0.0	0.3
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.4	0.5	0.0	0.0	0.0	0.9
	3	Average (ppmv)	0.1	0.2	0.0	0.2	0.0	0.5
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.4	0.7	0.1	0.6	0.0	1.7
	4	Average (ppmv)	0.2	0.3	0.0	0.3	0.0	0.9
		Count (#)	2	2	2	2	2	2
		Minimum (ppmv)	0.0	0.1	0.0	0.0	0.0	0.1
		Maximum (ppmv)	0.4	0.6	0.0	0.6	0.0	1.6
GP09	1	Average (ppmv)	0.1	0.2	0.1	0.1	0.0	0.5
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.1
		Maximum (ppmv)	0.2	0.5	0.3	0.4	0.1	1.0
	2	Average (ppmv)	0.1	0.1	0.0	0.2	0.0	0.5
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.4	0.5	0.0	0.6	0.0	1.5
	3	Average (ppmv)	0.1	0.2	0.0	0.2	0.0	0.5
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.4	0.6	0.0	0.6	0.0	1.6
	4	Average (ppmv)	0.1	0.1	0.0	0.0	0.0	0.2
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.4	0.5	0.0	0.0	0.0	0.9
GP10	1	Average (ppmv)	0.0	0.1	0.0	0.0	0.0	0.2
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.1	0.4	0.0	0.1	0.0	0.4
	2	Average (ppmv)	0.1	0.1	0.1	0.1	0.0	0.5
		Count (#)	5	5	5	5	5	5
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.4	0.5	0.5	0.6	0.0	2.0
	3	Average (ppmv)	0.1	0.3	0.1	0.2	0.3	1.0
		Count (#)	4	4	4	4	4	4
		Minimum (ppmv)	0.0	0.0	0.0	0.0	0.0	0.0
		Maximum (ppmv)	0.5	1.0	0.6	0.7	1.1	3.9

Table 5.5: Summary of Soil Vapour BTEX Samples Obtained

Well	Level	27-Jul-99		11-Sep-99		25-Oct-99		06-Dec-99	
		Sample	Dup.	Sample	Dup.	Sample	Dup.	Sample	Dup.
GP01	1	Yes		Yes	1	Yes		Yes	
	2	Yes		Yes		Yes		Yes	1
	3	Yes							
	4	Yes							
GP02	1	Yes		Yes		Yes		Yes	
	2	Yes		Yes		Yes		Yes	3
	3	Yes		Yes	1	Yes			
	4	Yes							
GP03	1	Yes		Yes		Yes		Yes	
	2	Yes		Yes		Yes		Yes	
	3	Yes							
GP04	1	Yes		Yes		Yes		Yes	
	2	Yes		Yes		Yes	2	Yes	1
	3			Yes		Yes		Yes	
GP05	1	Yes		Yes		Yes		Yes	1
	2	Yes		Yes		Yes		Yes	
	3	Yes		Yes		Yes		Yes	
	4	Yes		Yes		Yes			
GP06	1	Yes		Yes	1	Yes		Yes	1
	2	Yes		Yes	1	Yes		Yes	
	3	Yes		Yes		Yes	1	Yes	
	4	Yes		Yes					
GP07	1	Yes		Yes		Yes		Yes	1
	2	Yes		Yes		Yes		Yes	
	3	Yes		Yes		Yes	1	Yes	
GP08	1	Yes		Yes		Yes		Yes	
	2	Yes		Yes		Yes		Yes	
	3	Yes		Yes		Yes		Yes	
	4	Yes		Yes					
GP09	1	Yes		Yes		Yes		Yes	
	2	Yes		Yes		Yes		Yes	
	3	Yes		Yes		Yes		Yes	
	4	Yes		Yes		Yes		Yes	
GP10	1	Yes		Yes		Yes		Yes	
	2	Yes		Yes		Yes	1	Yes	
	3	Yes		Yes		Yes		Yes	

Table 5.6: Summary of Soil Vapour BTEX Duplicate Results

Date	Sample Location	Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	M&P Xylene (ppmv)	O Xylene (ppmv)	Total BTEX (ppmv)
11-Sep-99	GP01-1	0.4	0.5	0.7	2.3	1.4	5.4
		0.1	0.2	0.3	0.9	0.5	2.0
	GP06-1	0.0	0.1	0.0	0.0	0.0	0.1
25-Oct-99		0.0	0.1	0.0	0.0	0.0	0.1
	GP06-2	0.0	0.1	0.0	0.0	0.0	0.1
		0.0	0.1	0.0	0.0	0.0	0.1
25-Oct-99	GP04-2	5.0	0.7	0.6	1.4	0.0	7.7
		5.8	0.9	0.6	1.4	0.0	8.7
		4.8	0.7	0.0	0.0	0.0	5.5
06-Dec-99	GP06-3	0.0	0.0	0.0	0.0	0.0	0.1
		0.0	0.0	0.0	0.0	0.0	0.0
	GP07-3	0.1	0.0	0.0	0.0	0.0	0.1
06-Dec-99		0.0	0.0	0.0	0.0	0.0	0.0
	GP10-2	0.0	0.0	0.0	0.0	0.0	0.0
		0.0	0.0	0.0	0.0	0.0	0.0
06-Dec-99	GP01-2	0.7	0.0	0.0	0.0	0.0	0.7
		9.6	0.8	3.7	3.9	0.0	18.0
	GP02-2	1.4	0.4	0.4	0.3	0.0	2.6
06-Dec-99		1.1	0.3	0.3	0.2	0.0	1.9
		5.0	0.7	1.3	0.9	0.0	8.0
		2.5	2.8	5.4	3.6	0.0	14.3
06-Dec-99	GP05-1	0.0	0.0	0.0	0.0	0.0	0.0
		0.0	0.0	0.0	0.0	0.0	0.0
	GP06-1	0.0	0.0	0.0	0.0	0.0	0.0
06-Dec-99		0.0	0.0	0.0	0.0	0.0	0.0
	GP07-1	0.0	0.0	0.0	0.0	0.0	0.0
		0.0	0.0	0.0	0.0	0.0	0.0

from the original values in the reported data. This variation was most apparent at GP01 during the December monitoring event. In the clay soils, some variation was attributed to the limitations imposed on sample collection by the soil moisture. When the clay soils were moist, the onboard pump on the Gastech lowered the pressure within the well, as a vacuum was drawn. The collection of a sample volume may have been influenced by this pressure differential. The limitations imposed by the subsurface pressure were magnified at GP01 and GP02 by the high concentrations of BTEX vapours.

Reported soil vapour BTEX concentrations ranged from non-detectable concentrations, where the detection limits for individual compounds were as shown in Table 5.7, to 87.6 ppmv total BTEX at GP01-4. BTEX concentrations were higher during the summer monitoring rounds, and for most wells, were below detection limits in the December monitoring round. Table 5.7 presents a summary of detection limits for the soil gas BTEX analysis. This table includes the average, minimum, and maximum detection limits for each sampling event and compound. The detection limits varied depending on the volume of sample injected into the H-Nu GC. As can be seen, in Table 5.7, detection limits for benzene and toluene were less than 0.07 ppmv. The detection limit for ethylbenzene was less than 0.2 ppmv, while the detection limits for the xylene compounds were generally less than 0.5 ppmv.

Table 5.7: Summary of Soil Vapour BTEX Detection Limits

Date	Statistic	Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	m&p- Xylene (ppmv)	o-Xylene (ppmv)	Total BTEX (ppmv)
27-Jul-99	Average	0.01	0.02	0.04	0.08	0.19	0.34
	Minimum	0.00	0.01	0.02	0.03	0.09	0.15
	Maximum	0.02	0.04	0.08	0.15	0.37	0.66
11-Sep-99	Average	0.01	0.02	0.03	0.06	0.16	0.28
	Minimum	0.01	0.02	0.03	0.05	0.13	0.23
	Maximum	0.03	0.06	0.11	0.21	0.52	0.93
25-Oct-99	Average	0.01	0.03	0.07	0.07	0.15	0.33
	Minimum	0.01	0.02	0.05	0.05	0.10	0.24
	Maximum	0.03	0.07	0.21	0.21	0.42	0.94
06-Dec-99	Average	0.01	0.01	0.06	0.12	0.06	0.27
	Minimum	0.01	0.01	0.05	0.10	0.05	0.23
	Maximum	0.03	0.05	0.21	0.42	0.21	0.92

Total BTEX concentrations were compared to TPH concentrations in the vapour phase to determine if a relationship existed between the two parameters. Figure 5.36 shows the relationship between these compounds for source wells. As can be seen in Figure 5.36, a relationship may exist between total BTEX and TPH concentrations where the BTEX concentrations exceeded 10 ppmv. However, at concentrations below this level, significant scatter was observed. This scatter is believed to have been due to weathering of the gasoline. While the BTEX compounds had been significantly removed through natural process, heavier hydrocarbons that are not as available for degradation remained, resulting in a wide range of TPH concentrations while the BTEX concentrations were low. This scattered relationship was also observed at wells impacted by soil gas migration.

The temporal response of BTEX compounds in the vadose zone was investigated and two responses were observed. A decrease in total BTEX concentrations with time at the gas wells impacted by migration of soil gas TPH was observed, as shown in Figures 5.37 and 5.38. However, the reduction in total BTEX concentrations was limited to less than 5 ppmv, which could be attributed to seasonal variation. As a result of the limited BTEX concentration data that exists, continued monitoring will be required to determine the cause of the changes in BTEX concentrations with time.

Figure 5.36: Total BTEX versus TPH Concentrations
(Clay Source Wells)

Figure 5.37: Total BTEX Concentrations with Time
(Sand Wells)

Figure 5.38: Total BTEX Concentration with Time
(Clay Migration Wells)

In the contaminant impacted wells, which were GP01, GP02, and GP04, the total BTEX concentration did not change significantly over time, as shown by Figure 5.39. The maximum total BTEX concentration observed was 61 ppmv at GP02-3 during the September 1999 monitoring event. With the exception of this observation, the remaining impacted wells generally had total BTEX concentrations less than 20 ppmv. The steady concentrations suggest the residual product has not yet weathered significantly.

The dataset on BTEX compounds in the subsurface was evaluated to identify if chemical signatures exist in the vapour phase that maybe indicative of chemical weathering. However, there were no consistent patterns with respect to monthly variations in the wells. Patterns were also not observed between wells that were either impacted or not impacted by contamination. This variation suggests that BTEX compounds were being degraded by natural processes at different rates with respect to both aerial distribution and temporal changes.

The interdependence of BTEX compounds in the vadose and aqueous phase was assessed to determine if aqueous phase TPH concentrations may have impacted the vapour phase. The vapour wells in the sand soils were selected for comparison because the soils are known to be clean fill that was placed in the area following the excavation of the tanks. As such, the sand soils should have minimal contamination. Maximum groundwater concentrations of BTEX in this area were 6.6 mg L⁻¹ benzene, 27.6 mg L⁻¹ toluene, 5.3 mg L⁻¹ ethylbenzene,

**Figure 5.39: Total BTEX Concentration with Time
(Clay Source Wells)**

21.5 mg L⁻¹ m&p-xylene, and 8.2 mg L⁻¹ o-xylene. Using Henry's law, as defined by equation 2.2, and an average subsurface soil temperature of 10°C, it was found that the maximum total BTEX concentration in the vapour phase should be approximately 4,340 ppmv in a closed system. Given that the vadose zone is not a closed system, it was expected only some fraction of this concentration might be present in the vapour phase. Detection limits for the vapour phase methods used in the field were more than 2,000 times smaller than the expected maximum concentration. However, no trace of BTEX compounds were detected in the vapour phase at these wells. Therefore, it has been concluded that TPH compounds in the groundwater may only minimally impact the TPH concentrations observed in the vadose zone. Only compounds with high Henry's law constants would be expected to influence the concentrations in the vadose zone, however, these compounds generally do not partition to the aqueous phase as readily. As such the impact of groundwater would be minimal. To further support this finding, Figure 5.9 indicated partitioning of TPH compounds in groundwater to the headspace in a groundwater monitoring well had negligible impact on the headspace vapour concentration.

A final consideration regarding monitoring BTEX compounds was to assess the potential benefits of monitoring these compounds in the vapour phase. BTEX compounds generally have low Henry's law constants, which reflects the tendency of these compounds to partition to the aqueous phase. As a result, it is

possible that BTEX compounds may be present in the aqueous phase at low concentrations, yet not detectable in the vapour phase. It has been concluded that the presence of BTEX in the vapour phase supports the conceptual model of residual product being available at the site, and therefore groundwater contamination is a risk. Conversely, the absence of BTEX in the vapour phase does not guarantee the absence of BTEX in the aqueous phase.

5.4 Critical Assessment of the Application of Multi-Level Vapour Phase Piezometers

Multi-level vapour phase piezometers have been shown to provide valuable information about attenuating processes in the vadose zone. Soil vapour wells also have potential benefits at sites that are at risk for hydrocarbon contamination. The existence of these wells at a site can provide an early warning system to detect releases of hydrocarbon contamination prior to the contamination reaching the groundwater system. This early warning can minimize costs associated with remedial activities as detection of contamination will occur at a more localized state, and thus limit the volume of soils requiring treatment.

Once a site has been contaminated by volatile hydrocarbon compounds, multi-level vapour phase piezometers can be used to precisely identify the location of contamination in the vadose zone. In addition, areas of bioactivity can be identified by investigating the stoichiometric relationships observed

between TPH, oxygen, and carbon dioxide in the subsurface. The use of multi-level wells provides a three-dimensional view of the subsurface, whereby the depths of contamination can be detected.

The strategic placement of multi-level vapour phase piezometers has potential to minimize monitoring costs associated with natural attenuation monitoring protocols, as soil vapour monitoring is both more cost efficient and less labour intensive than groundwater monitoring. If the source term is located in the vadose zone, data collected from tracer studies, which are facilitated by the presence of soil vapour wells, can be used to estimate the diffusive flux of hydrocarbons out of the soil. Stoichiometric relationships can be used, as were by Ostendorf and Kampbell [1991], and Lahvis et al. [1999], to estimate biodegradation rates in the subsurface. This information could be combined with groundwater monitoring data improve the estimated attenuation rates at the site. Where groundwater quality is not a specific risk hazard, soil vapour monitoring may be used in place of more regular groundwater monitoring activities to monitor the state of contamination.

Factors for consideration in determining the placement of soil vapour monitoring wells includes soil type, depth to the aquifer, potential distribution of contaminants at the site, and the size of the site. Soil type and soil moisture, which is impacted by the location of the aquifer, directly impact the use of soil vapour monitoring wells. Sand soils are ideal for soil vapour monitoring wells,

as the void porosity of the soil is usually sufficient to allow for vapour extraction from the wells. However, this study has shown the wells can be applied to less permeable soils, although some limitations exist near the capillary fringe.

The potential distribution of contamination at the site is also important in the placement of soil vapour wells. For example, clay soils will typically contain a spill more efficiently than will sand soils. As such, placement of soil vapour wells in contaminated clay soils requires a more precise placement of the wells to capture the contaminated region. As was shown by this investigation, soil vapour wells located in contaminated soils experience substantial variation due to seasonal effects as compared to wells impacted by soil vapour migration. As a result, soil vapour wells are ideally placed at the suspected location of contamination, just beyond the contaminated region, and in clean soils. The wells located in clean soils will provide background contaminant concentrations based on the migration of soil vapours through the subsurface. Wells located just beyond and within the contaminated soils have potential to be used to identify the growth or decay of the contamination over time. As was shown in Sections 5.3.3 and 5.3.5, headspace measurements from groundwater wells can be used in place of soil vapour wells if the screened interval crosses the water table. Due to the minimal vertical gradients observed in the migratory wells, it is believed the use of groundwater wells for this purpose will not result in

significant loss of information and will improve the cost efficiency of the monitoring network. The size of both the site and source term will impact the number of monitoring wells required at the site. Depending on the level of detail required for statistical purposes, the number of required monitoring wells should be adjusted. For example, in a site not previously contaminated, soil vapour wells placed near the potential sources of contamination would be sufficient as an early detection system. Should contamination occur, additional wells could be added to facilitate the additional monitoring requirements.

BTEX monitoring in the soil vapour phase provided limited additional information to the study. BTEX concentrations varied significantly over time within contaminated soils. In migration-impacted wells, BTEX concentrations approached detection limits. Chemical signatures using individual BTEX concentrations did not provide evidence as to the degree of weathering of the plume. This has been attributed to the tendency of BTEX compounds to partition to the aqueous phase. Thus, monitoring aqueous phase BTEX concentrations may provide more valuable information as to the weathered state of the gasoline contaminated soils. Directly resulting from the tendency of BTEX compounds to partition to the groundwater phase, the detection of BTEX in the vapour phase could be used as a strong indicator of probable BTEX contamination in the aqueous phase. However, the negative detection of BTEX in the soil vapour does not imply the absence of BTEX contamination in the groundwater system.

Groundwater analysis must be completed to verify the absence of BTEX compounds.

The assessment of observed soil vapour concentrations requires consideration of climatic influences such as temperature and precipitation. As has been shown during periods of high soil moisture content, such as following the spring snow melt or following heavy precipitation, soil vapour TPH concentrations should be expected to be elevated. This may either be the result of diffusion limitations or desorption of contaminants from soils. Also, soil temperature may influence soil vapour TPH concentrations as the bioactivity of micro-organisms is slowed during cooler periods. As a result, comparison of soil vapour TPH concentrations should occur over similar periods on a climatic basis.

In order to collect sufficient data so that these comparisons can be made, regular soil vapour surveys should be completed, as well as the collection of corresponding precipitation and soil temperature data. At the beginning of the monitoring schedule, weekly monitoring may be appropriate to determine the degree of fluctuations that may be observed at a specific site. Once consistency in the observed soil vapour concentrations is observed, frequency of monitoring could be decreased. Also, monitoring of migration impacted soil vapour wells is not required as frequently as monitoring of contaminated soil vapour wells.

Chapter 6.0 - Conclusions and Recommendations

6.1 Conclusions

Contamination at a former gasoline vending station was monitored using multi-level vapour phase soil piezometers. Monitoring of contamination present in the soil vapour indicated strong correlations with direct measurements of soil contamination, which were collected during well construction. Contamination in the vadose zone was located with improved precision using soil vapour wells as compared to the assessment of the contaminated groundwater plume. This improved precision may have positive repercussions with respect to minimizing remedial costs.

Two patterns of responses were observed in the wells with time. In wells that were located some distance away from the primary sources of contamination, TPH concentrations were essentially constant with time. In wells located near the sources of contamination, strong seasonal trends in TPH concentrations were observed.

Oxygen in the soil gas was observed to demonstrate several trends. Wells located in sand, which were lightly contaminated, had generally high concentrations of oxygen that tended to increase over the period from August to December. Clay-based soils that were located closer to the sources of contamination demonstrated a greater range of oxygen concentrations and also

more substantial variations in concentration with time. Oxygen concentrations tended to decrease in depth at all well locations.

In wells located near the sources of contamination, a strong relationship between TPH, oxygen, and carbon dioxide concentrations was observed with decreasing oxygen values corresponding to increasing TPH and carbon dioxide values. In wells that were located some distance from the sources of contamination, the TPH and oxygen concentrations were essentially independent of each other.

Climatic influences such as soil moisture and soil temperature were found to impact subsurface soil vapour concentrations. The results suggest increased soil moisture tended to decrease the diffusivity of soil vapours through the soil. This led to an increase in TPH concentrations near contaminant sources, and limited supply of oxygen to the subsurface layers. Thus, soil moisture content had a direct impact of the efficiency of biodegradation near contaminated soils. Soil temperature was also found to impact the biodegradation rates in the subsurface, as the decrease in subsurface temperatures corresponded with an increase in oxygen concentrations and an increase in TPH concentrations.

The assessment of BTEX compounds in the subsurface provided minimal additional information not already obtained through the assessment of subsurface TPH, oxygen, and carbon dioxide concentrations. A weak relationship existed between BTEX concentrations and TPH concentrations. No

significant pattern was observed that could be used to estimate the weathered age of the gasoline contamination. Furthermore, concentrations and BTEX signatures varied significantly both spatially and temporally. Finally, as a result of the tendency of BTEX compounds to partition to the aqueous phase, the presence of BTEX compounds in the vapour phase can be used as a reasonable predictor of BTEX contamination in the aqueous phase.

6.2 Recommendations

It has been found that substantial valuable information can be obtained through monitoring the soil vapour phase of the vadose zone for hydrocarbon contamination. Future phases of the study will require additional monitoring of the site to confirm if the climatic influences observed in the first year of the study will be replicated in future years.

The prediction of biodegradation rates based on soil vapour monitoring is contingent on the ability of a model to predict and respond to climatic changes. Future work will be required to identify specific climatic influences and potential relationships between the event and the response in the subsurface. This will facilitate the construction of a temporal model that can be used to predict future attenuation rates.

Future work should be completed to confirm the findings of the BTEX monitoring. Although minimal information was obtained from the BTEX monitoring that was completed, annual comparison of BTEX values may provide

the additional information with respect to the degree of weathering that the contaminant plume has undergone.

Chapter 7.0 – References

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APPENDIX 1:

Groundwater Monitoring Well Stratigraphic Logs

Groundwater Monitoring Well Legend

(Intera)

STRATIGRAPHIC AND INSTRUMENTATION LOG

LEGEND

H. C. = Hydrocarbon

G/S = Grab Sample

* = Sample Submitted for Analysis

BOREHOLE STRATIGRAPHIC LOG									
PROJECT NAME AND No.: [REDACTED]					BOREHOLE No.: BH-2				
CLIENT: [REDACTED]					DATE COMPLETED: JUNE 10 1992				
LOCATION: [REDACTED]					DRILLING METHOD: HOLLOW STEM AUGERING				
BOREHOLE DIAMETER: 0.11 m (I.D.) 0.22 m (O.D.)					WELL DIAMETER: 0.052 m (O.D.)				
REFERENCE ELEVATION: 99.457 m AD					DRILL SUPERVISOR: M.R.F./G.A.P.				
DEPTH m BG	BLOW COUNT	SAMPLE LOCATION	QVW PPM	STRATIGRAPHIC DESCRIPTION	DEPTH (m AD)	WELL INSTALLATION			
0	G/S		0	FILL	99.83				
0.5				-brown dry sand with minor gravel	99.46				
				-loose	99.33				
1	23/10		0	-brown dry sand	98.72				
				-loose	98.56				
				-med. grain					
1.5	48/10		0	CLAYEY SILT TO SILTY CLAY	97.95				
2				-tan brown clayey silt					
				-firm and dry					
				-fine grain					
2.5	38/10		0	-brown, wet clayey silt					
				-compact					
				-fine grain					
3				-greyish wet clayey silt	96.66				
				-firm					
				-fine grain					
3.5	32/10		0	TILL	95.82				
				-brown gravel fill with cobbles					
				-wet					
4	47/10		0	REFUSAL bedrock @ 4.11 m	95.52				
4.5									
5									
5.5									
6									
6.5									

BOREHOLE STRATIGRAPHIC LOG						
PROJECT NAME AND No.: XXXXXXXXXX				BOREHOLE No.: BH-3		
CLIENT: XXXXXXXXXX				DATE COMPLETED: JUNE 10 1992		
LOCATION: XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX				DRILLING METHOD: HOLLOW STEM AUGERING		
BOREHOLE DIAMETER: 0.11 m (I.D.) 0.22 m (O.D.)				WELL DIAMETER: 0.052 m (O.D.)		
REFERENCE ELEVATION: 99.859 m AD				DRILL SUPERVISOR: M.R.F./G.A.P.		
DEPTH m BG	BLOW COUNT	SAMPLE LOCATION	OVM PPM	STRATIGRAPHIC DESCRIPTION	DEPTH (m AD)	WELL INSTALLATION
0	G/S		0	ASPHALT FILL	99.79	
0.5				-brown moist sand with minor gravel -loose, uniformly graded	99.66 99.49	
1	1 1/2		0	-brown dry sand -loose, well graded -fine grain		
1.5	1 1/2		0	CLAYEY SILT TO SILTY CLAY	98.27	
2				-brown clayey silt -loose and dry -fine grain	98.42 98.04	
2.5	2 3/4		0	-grey, dry clayey silt -loose -fine grain		
3				-grey moist clay -firm, staining-grey -fine grain -odour	96.53	
3.5	2 1/4		200	TILL	96.13	
4	1 3/4		500 PK L.L.	-grey clayey gravel till with cobbles -moist, strong odour		
4.19				REFUSAL bedrock @ 4.19 m	95.60	
4.5						
5						
5.5						
6						
6.5						

BOREHOLE STRATIGRAPHIC LOG							
PROJECT NAME AND No.: [REDACTED]				BOREHOLE No.: BH-4			
CLIENT: [REDACTED]				DATE COMPLETED: JUNE 10 1992			
LOCATION: [REDACTED]				DRILLING METHOD: HOLLOW STEM AUGERING			
BOREHOLE DIAMETER: 0.11 m (I.D.) 0.22 m (O.D.)				WELL DIAMETER: 0.052 m (O.D.)			
REFERENCE ELEVATION: 99.873 m AD				DRILL SUPERVISOR: M.R.F./G.A.P.			
DEPTH m BG	BLOW COUNT	SAMPLE LOCATION	QVM PPM	STRATIGRAPHIC DESCRIPTION	DEPTH (m AD)	WELL INSTALLATION	
0	G/S		0	FILL	99.80		0
0.5				-brown dry sand	99.67		0.5
				-loose, uniformly graded	99.50		
1	32234		0	-brown dry sand with gravel			1
				-loose, well graded			
				-fine grain			
1.5	14888		0	-brown compact sand			1.5
				-fine grain	97.97		
2				-brown clay at tip	97.82		2
				CLAYEY SILT TO SILTY CLAY	97.82		
2.5	14866		300	-greyish brown silty clay			2.5
				-loose, uniformly graded			
				-fine grain			
				-strong H.C. odour at tip of spoon			
3				-grey moist clay			3
	14864		> 500	-firm, staining-grey	96.52		
				-fine grain			
3.5				-odour			3.5
4				-grey moist clay, with silt seams			4
	14862		> 800	-compact to dense, uniformly graded			
				-strong H.C. odour			4.5
				-fine grain			
4.5				-grey clay, moist strong odour			4.5
				with staining			
	6778		> 800	-loose and uniformly graded	94.92		5
5				TILL	94.50		
				-grey clayey gravel till with cobbles			
				-strong H.C. odour with staining			
5.5				REFUSAL boulder ? @ 5.03 m			5.5
6							6
6.5							6.5

BOREHOLE STRATIGRAPHIC LOG						
PROJECT NAME AND No.: [REDACTED]				BOREHOLE No.: BH-5		
CLIENT: [REDACTED]				DATE COMPLETED: JUNE 10 1992		
LOCATION: [REDACTED]				DRILLING METHOD: HOLLOW STEM AUGERING		
BOREHOLE DIAMETER: 0.11 m (I.D.) 0.22 m (O.D.)				WELL DIAMETER: 0.052 m (O.D.)		
REFERENCE ELEVATION: 99.464 m AD				DRILL SUPERVISOR: M.R.F./G.A.P.		
DEPTH m BG	BLOW COUNT	SAMPLE LOCATION	OVM PPM	STRATIGRAPHIC DESCRIPTION	DEPTH (m AD)	WELL INSTALLATION
0	G/S		0	ASPHALT FILL	99.60	
0.5				-brown dry sand -loose, uniformly graded	99.46 99.30	
1	3/4/87		0	-loose, uniformly graded -fine grain	99.38	
1.5			0	CLAYEY SILT TO SILTY CLAY -greyish brown clayey silt		
2	4/8/87		0	-brown dry silty clay with roots -compact -fine grain	97.77	
2.5	2/2/87		200	-grey, dry clayey silt -compact with cracks along silt seams -fine grain	97.39	
3				-grey moist clayey silt -firm, strong H.C. odour -fine grain	96.59	
3.5	1/1/87		>800 80% L.S.			
4	8/7/87		400	-brown wet clayey silt -strong H.C. odour -loose and uniformly graded		
4.5				TILL	95.10	
5	8/7/87		0	-brown sandy till with gravel -no H.C. odour -compact	94.34	
5.5				REFUSAL bedrock @ 5.26 m		
6						
6.5						

INTERA

BOREHOLE STRATIGRAPHIC LOG									
PROJECT NAME AND No.: [REDACTED]					BOREHOLE No.: BH-6				
CLIENT: [REDACTED]					DATE COMPLETED: JUNE 11 1992				
LOCATION: [REDACTED]					DRILLING METHOD: HOLLOW STEM AUGERING				
BOREHOLE DIAMETER: 0.11 m (I.D.) 0.22 m (O.D.)					WELL DIAMETER: 0.052 m (O.D.)				
REFERENCE ELEVATION: 99.463 m AD					DRILL SUPERVISOR: M.R.F./G.A.P.				
DEPTH m BG	BLOW COUNT	SAMPLE LOCATION	QVM PPM	STRATIGRAPHIC DESCRIPTION	DEPTH (m AD)	WELL INSTALLATION			
0	G/S		0	ASPHALT FILL	99.52 99.46 99.22				
0.5				-light brown dry sand and gravel -loose, uniformly graded -brown sand, with clay and silt seams -red brick fragments -med. grain					
1	1/2/2/5		0	CLAYEY SILT TO SILTY CLAY	98.30				
1.5	1/2/3/5		0	-brown moist clayey silt with pebbles -compact, uniformly graded -fine grain					
2					97.39				
2.5	1/2/2/5		100	-tan moist clayey silt -compact with H.C. odour -fine grain	97.08				
3	*		200	-grey wet clay with silt seams -loose, H.C odour -fine grain	96.64				
3.5									
4	1/4/2/1		25	-brown wet silty clay till with minor sand and gravel -loose and uniformly graded -fine grain	95.25				
4.5				TILL					
5	1/2/2/2		10	-grey clayey silt till -slight H.C. odour -compact -med. to fine grain					
5.5				REFUSAL bedrock @ 5.49 m	94.04				
6									
6.5									

BOREHOLE STRATIGRAPHIC LOG									
PROJECT NAME AND No.: [REDACTED]					BOREHOLE No.: BH-8				
CLIENT: [REDACTED]					DATE COMPLETED: JUNE 11 1992				
LOCATION: [REDACTED]					DRILLING METHOD: HOLLOW STEM AUGERING				
BOREHOLE DIAMETER: 0.11 m (I.D.) 0.22 m (O.D.)					WELL DIAMETER: 0.052 m (O.D.)				
REFERENCE ELEVATION: 99.717 m AD					DRILL SUPERVISOR: M.R.F./G.A.P.				
DEPTH m BG	BLOW COUNT	SAMPLE LOCATION	QVM PPM	STRATIGRAPHIC DESCRIPTION	DEPTH (m AD)	WELL INSTALLATION			
0	G/S		0	ASPHALT FILL	99.77				
0.5				-brown dry sand -loose, uniformly graded -brown dry sand -med. grain	99.72 99.47				
1	37/18/7		0	CLAYEY SILT TO SILTY CLAY					
1.5					98.40				
2	27/17/4		0	-greyish brown dry clayey silt -loose, uniformly graded -med. grain	97.94 97.79				
2.5	19/7/4		20	-greyish brown moist clayey silt -loose, uniformly graded -med. to fine grain					
3				-greyish brown wet clayey silt -loose, strong H.C. odour -med. grain	96.91				
3.5	17/17/7		>400 10% L.S.	-greyish brown moist clay silt -strong H.C. odour -loose and uniformly graded -med. grain					
4	17/17/2		>400 10% L.S.						
4.5				TILL	95.27				
5	N/R		180	-greyish brown, moist clayey silt till -H.C. odour with oil staining -loose REFUSAL bedrock @ 5.03 m	94.74				
5.5									
6									
6.5									

BOREHOLE STRATIGRAPHIC LOG							
PROJECT NAME AND No.: XXXXXXXXXX				BOREHOLE No.: BH-9			
CLIENT: XXXXXXXXXX				DATE COMPLETED: JUNE 11 1992			
LOCATION: XXXXXXXXXX				DRILLING METHOD: HOLLOW STEM AUGERING			
BOREHOLE DIAMETER: 0.11 m (I.D.) 0.22 m (O.D.)				WELL DIAMETER: 0.052 m (O.D.)			
REFERENCE ELEVATION: 99.901 m AD				DRILL SUPERVISOR: M.R.F./G.A.P.			
DEPTH m BG	BLOW COUNT	SAMPLE LOCATION	CWA PPM	STRATIGRAPHIC DESCRIPTION	DEPTH (m AD)	WELL INSTALLATION	
0	3/4/91		0	ASPHALT FILL	99.85		
0.5				-brown dry sand -loose, uniformly graded -brown dry sand -med. grain	99.60 99.35		
1	6/3/91		0	CLAYEY SILT TO SILTY CLAY			
1.5				-brown dry sand	98.15		
2	7/3/91		0	-greyish brown moist clayey silt -loose, uniformly graded -med. to fine grain	97.82 97.52		
2.5	1/1/91		0	-brown moist clayey silt -loose, uniformly compact -fine grain			
3				-brown moist clayey silt -loose, strong H.C odour -fine grain	96.74		
3.5	1/7/77		>500 PPM UEL				
4	2/2/92		400	-brown moist clayey silt till -strong H.C. odour -loose and uniformly graded -fine grain TILL	95.54		
4.5				-brown moist, clayey silt till -slight H.C. odour -compact			
5			80	REFUSAL bedrock @ 5.18 m	94.74		
5.5							
6							
6.5							

□ = 20/10/17/10

INTERA

BOREHOLE STRATIGRAPHIC LOG						
PROJECT NAME AND No.: [REDACTED]				BOREHOLE No.: BH-13		
CLIENT: [REDACTED]				DATE COMPLETED: JUNE 12 1992		
LOCATION: [REDACTED]				DRILLING METHOD: HOLLOW STEM AUGERING		
BOREHOLE DIAMETER: 0.11 m (I.D.) 0.22 m (O.D.)				WELL DIAMETER: 0.052 m (O.D.)		
REFERENCE ELEVATION: 99.485 m AD				DRILL SUPERVISOR: M.R.F./G.A.P.		
DEPTH m BG	BLOW COUNT	SAMPLE LOCATION	OVM PPM	STRATIGRAPHIC DESCRIPTION	DEPTH (m AD)	WELL INSTALLATION
0				FILL -brown dry sand and gravel -loose, uniformly graded -brown dry sand -loose, well graded -med. grain	99.55	
0.5					99.49	
					99.25	
1				CLAYEY SILT TO SILTY CLAY -brown dry clayey silt -compact, uniformly graded -fine grain	98.33	1
1.5	46/64		0		98.18	1.5
2					98.05	2
2.5	108/21		0	-brownish grey moist clayey silt -compact, uniformly graded -med. grain		2.5
3					96.46	3
3.5	128/5		0		95.89	3.5
4	78/78		250	TILL -fill pebbles starting @ 3.51 m -fill grey moist pebbles with clayey silt -compact -fine grain -H.C. odour REFUSAL bedrock @ 4.42 m		4
4.5					95.13	4.5
5						5
5.5						5.5
6						6
6.5						6.5

INTERA

BOREHOLE STRATIGRAPHIC LOG							
PROJECT NAME AND No.: [REDACTED]				BOREHOLE No.: BH-14			
CLIENT: [REDACTED]				DATE COMPLETED: JUNE 12 1992			
LOCATION: [REDACTED]				DRILLING METHOD: HOLLOW STEM AUGERING			
BOREHOLE DIAMETER: 0.11 m (I.D.) 0.22 m (O.D.)				WELL DIAMETER: 0.052 m (O.D.)			
REFERENCE ELEVATION: 99.798 m AD				DRILL SUPERVISOR: M.R.F./G.A.P.			
DEPTH m BG	BLOW COUNT	SAMPLE LOCATION	QVM PPM	STRATIGRAPHIC DESCRIPTION	DEPTH (m AD)	WELL INSTALLATION	
0	1/2/3/2		0	ASPHALT FILL	99.84		0
0.6				-brown dry sand -loose, uniformly graded -fine grain	99.80 99.84		0.5
1	2/2/3/3		0	CLAYEY SILT TO SILTY CLAY -grey moist clayey silt	98.77		1
1.6							1.5
2	2/7/7/4		3%	-greyish brown moist clayey silt -loose, uniformly graded -med. grain	98.19 98.01		2
2.6	1/7/3/5		>800 10% L.S.	-grey moist clayey silt -compact, uniformly graded -fine grain			2.5
3							3
3.6	2/2/2/4		>800 10% L.S.	-grey moist clayey silt -compact, strong H.C odour -fine grain	96.65		3.5
4	1/1/1/3		>800 10% L.S.	-grey moist clayey silt -strong H.C. odour -uniformly graded -fine grain			4
4.6							4.5
5	5/2/2/3		>800 10% L.S.	-grey moist clayey silt -H.C. odour -loose and stratified REFUSAL bedrock @ 4.88 m	94.96		5
5.6							5.5
6							6
6.6							6.5

Groundwater Monitoring Well Legend

(Wells installed June 1999)

BOREHOLE STRATIGRAPHIC LOG						
BOREHOLE NO.: MW15				DATE COMPLETED: June 25, 1999		
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)		
REFERENCE ELEVATION (m): 99.69				DRILL SUPERVISOR: PEP		
DEPTH (m BGS)	BLVD COUNTS	SAMPLE LOCATION	CONDUIT/TILES (gpm)	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION
-0.5	10/8/4/5		300	FILL - brown dry sand - light gravel/FILL	99.69 99.39	
-1.0	13/2/2/6		360	FILL - gravel FILL	98.75	
-1.5					98.12	
-2.0	3/4/3/5		380			
-2.5	2/2/3/2		380			
-3.0					96.92 96.68 96.50	
-3.5	1/1/3/1		380	- wet gravel		
-4.0					95.91	
-4.5	1/3/4/1		1120	FILL - silty sand with gravel - hydrocarbon odor - shewn on split-spoon	95.58	
-5.0	2/6/3/9		480			
-5.5				REFUSAL bedrock @ 5.31 m	94.38	
-6.0						
-6.5						
-7.0						

BOREHOLE STRATIGRAPHIC LOG

BOREHOLE NO.: MW16

DATE COMPLETED: June 24, 1999

BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)

WELL DIAMETER: 0.052 m (OD)

REFERENCE ELEVATION (m): 99.63

DRILL SUPERVISOR: PEP

BOREHOLE STRATIGRAPHIC LOG

BOREHOLE NO.: MW17

DATE COMPLETED: June 24, 1999

BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)

WELL DIAMETER: 0.052 m (OD)

REFERENCE ELEVATION (m): 99.30

DRILL SUPERVISOR: PEP

APPENDIX 2:

Soil Vapour Monitoring Well Stratigraphic Logs

Soil Vapour Monitoring Well Stratigraphic Log Legend

BOREHOLE STRATIGRAPHIC LOG						
BOREHOLE NO: GP01				DATE COMPLETED: June 25, 1999		
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)		
REFERENCE ELEVATION (m): 99.63				DRILL SUPERVISOR: PEP		
DEPTH (m BGS)	BLOT COUNTS	SAMPLE LOCATION	COMBUSTIBLES (g/m)	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION
-0.5	9/8/7/7		320	FILL - gravel fill FILL - broken sand	99.48 99.32	
-1.0	4/5/3/4		488	CLAY - grey silty clay - hydrocarbon odour, heavy staining	98.87 98.81	LEVEL 1
-1.5			620		98.64 98.57 98.53	
-2.0	1/2/2/4		620	- thin roots	98.25 98.16	LEVEL 2
-2.5	4/5/4/5		908	- no staining	97.93	
-3.0	6/5/4/3		2648		97.58 97.45	LEVEL 3
-3.5				- end of borehole	97.29 97.84 96.89	
-4.0					96.61 96.53	LEVEL 4
-4.5					96.28	
-5.0						
-5.5						
-6.0						
-6.5						
-7.0						

BOREHOLE STRATIGRAPHIC LOG						
BOREHOLE NO.: GP02				DATE COMPLETED: June 25, 1999		
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)		
REFERENCE ELEVATION (m): 99.60				DRILL SUPERVISOR: PEP		
DEPTH (m BGS)	SLUG COUNTS	SAMPLE LOCATION	COMBUSTIBLES (ppm)	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION
-0.5	11/8/8/6		460	FILL - grey gravel FILL - brown sand	99.45 99.39	
-1.0	2/3/3/3		380 480	- decomposing wood - free product observed Hydrocarbons - sandy silt with gravel	98.84 98.85 98.69 98.79 98.61	LEVEL 1
-1.5			520		98.51	
-2.0	1/2/3/4		660	CLAY: - grey clay - shewn on split spoon	98.23 98.18 98.08 98.03 97.97	LEVEL 2
-2.5	4/3/3/3		680		97.46 97.39 97.29	LEVEL 3
-3.0	5/4/4/3		1200		97.03 96.86	
-3.5				TILL - grey silty till with sand - increasing moisture - hydrocarbon colour - end of borehole	96.58 96.39 96.25	LEVEL 4
-4.0						
-4.5						
-5.0						
-5.5						
-6.0						
-6.5						
-7.0						

BOREHOLE STRATIGRAPHIC LOG						
BOREHOLE NO.: GP03				DATE COMPLETED: June 24, 1999		
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)		
REFERENCE ELEVATION (m): 99.77				DRILL SUPERVISOR: PEP		
DEPTH (m BGS)	BLDV COUNTS	SAMPLE LOCATION	CONDUIT/STUBS (gpm)	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION
-0.5	4/6/3/8		380	FILL: - grey gravel FILL: - brown sand	99.62 99.52	
-1.0	5/6/10/8		380	- crushed red brick - dark brown sand with organics	99.16 99.8 98.83	LEVEL 1
-1.5	1/2/3/4		440	CLAY: - dark grey silty sand changing to grey silty clay - hydrocarbon odours	98.53 98.40 98.25	LEVEL 2
-2.0			440		98.82 97.89	LEVEL 3
-2.5	4/6/6/3		440	- grey clay - hydrocarbon odours - organic matter	97.64	
-3.0	6/3/4/3		420		97.83 97.83 96.90 96.72	LEVEL 4
-3.5				- end of borehole	96.42	
-4.0						
-4.5						
-5.0						
-5.5						
-6.0						
-6.5						
-7.0						

BOREHOLE STRATIGRAPHIC LOG							
BOREHOLE NO.: GP04				DATE COMPLETED: June 25, 1999			
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)			
REFERENCE ELEVATION (m): 99.70				DRILL SUPERVISOR: PEP			
DEPTH (m BGS)	BLOW COUNTS	SAMPLE LOCATION	CONDUIT/STILES (gpm)	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION	
-0.5	12/18/7/7	340		FILL - gravel FILL - brown sand	99.30 99.35 99.40		0.5
-1.0	2/4/6/3	360			99.89 99.14 98.54 98.89 98.76		1.0
-1.5	1/1/3/3	1340		TILL - grey sandy silt - hydrocarbon odour	98.33 98.38 98.18 98.18 97.93		1.5
-2.0							2.0
-2.5	3/4/4/3	1760		CLAY - grey clay - slight odour	97.57 97.44 97.36		2.5
-3.0	6/3/3/6	4600			97.11 96.96		3.0
-3.5				- end of borehole	96.68 96.58 96.42 96.33		3.5
-4.0							4.0
-4.5							4.5
-5.0							5.0
-5.5							5.5
-6.0							6.0
-6.5							6.5
-7.0							7.0

BOREHOLE STRATIGRAPHIC LOG						
BOREHOLE NO.: GP05				DATE COMPLETED: June 25, 1999		
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)		
REFERENCE ELEVATION (m): 99.68				DRILL SUPERVISOR: PEP		
DEPTH (m BGS)	INLOG COUNTS	SAMPLE LOCATION	CONDUIT/STILES (cm)	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION
				FILL: - sandy gravel	99.53	
					99.38	
-0.5	10/9/10/12		440	FILL: - gravel fill - plastic liner (0.53m top) - end of borehole	99.27	
					99.15	
					99.07	
					98.92	
-1.0	6/7/6/3		380		98.66	LEVEL 1
-1.5					98.31	
					98.16	
					98.03	LEVEL 2
-2.0	2/3/3/2		480		97.83	
-2.5					97.55	
					97.39	LEVEL 3
-3.0	1/2/2/2		380		97.32	
-3.5	2/1/1/1		340		97.04	
					96.94	
					96.68	LEVEL 4
				- end of borehole	96.23	
-3.5						
-4.0						
-4.5						
-5.0						
-5.5						
-6.0						
-6.5						
-7.0						

BOREHOLE STRATIGRAPHIC LOG						
BOREHOLE NO.: GP06				DATE COMPLETED: June 24, 1999		
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)		
REFERENCE ELEVATION (m): 99.57				DRILL SUPERVISOR: PEP		
DEPTH (m BGS)	BLOW COUNTS	SAMPLE LOCATION	CONDUIT/STAINLESS (gpm)	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION
-0.5	10/7/4/3		640	FILL - gravel FILL - brown sand	99.37 99.42 99.27	LEVEL 1 0.5 LEVEL 2 1.5 LEVEL 3 2.0 LEVEL 4 3.0
-1.0	1/15/3/4		300		98.96 98.81	
-1.5				FILL - coarse gravel	98.25 98.20	
-2.0	15/25/4/3		300		97.97 97.69	
-2.5	15/15/15/15		640		97.42 97.24 97.26 97.28	
-3.0	15/15/15		300		96.67 96.60 96.58	
-3.5				- end of borehole	96.22	
-4.0						
-4.5						
-5.0						
-5.5						
-6.0						
-6.5						
-7.0						

BOREHOLE STRATIGRAPHIC LOG						
BOREHOLE NO.: GP07				DATE COMPLETED: June 25, 1999		
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)		
REFERENCE ELEVATION (m): 99.69				DRILL SUPERVISOR: PEP		
DEPTH (m BGS)	SIGNED COPY	SAMPLE LOCATION	CORRECTIONS (ppm)	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION
-0.5	9/15/8/8	600		FILL - gravel	99.54 99.39	
-1.0	3/4/2/3	400		FILL - brown sand	99.08 98.93 98.85	
-1.5				CLAY - dark grey clayey silt - organic matter	98.70 98.60 98.42	
-2.0	0.5/1.5/2/3	420		- black staining	98.32 98.24 98.17	
-2.5	2/4/5/5	1900		- grey clay, no staining	97.66 97.56	
-3.0	5/5/5/5	900		- increasing moisture - hydrocarbon odour	97.10 96.95	
-3.5				- end of borehole	96.72 96.57 96.34	
-4.0						
-4.5						
-5.0						
-5.5						
-6.0						
-6.5						
-7.0						

BOREHOLE STRATIGRAPHIC LOG						
BOREHOLE NO.: GP08				DATE COMPLETED: June 24, 1999		
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)		
REFERENCE ELEVATION (m): 99.69				DRILL SUPERVISOR: PEP		
DEPTH (m BGS)	BLOW COUNTS	SAMPLE LOCATION	CONDUCTIONS (gpm)	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION
-0.5	6/6/3/4		329	FILL - gravel FILL - brown sand	99.54 99.39	LEVEL 1
-1.0	15/15/15/15		264		99.08 98.93 98.78	
-1.5					98.32	
-2.0	15/3/2/3		329	FILL - dark grey gravel fill	98.17 98.09	
-2.5	15/15/15/25		280		97.86	LEVEL 2
-3.0	15/15/15		346	CLAY - grey clay	97.56 97.40 97.30	
-3.5			368	- end of borehole	96.90 96.79 96.64	LEVEL 3
-4.0					96.34	
-4.5						LEVEL 4
-5.0						
-5.5						
-6.0						
-6.5						
-7.0						

BOREHOLE STRATIGRAPHIC LOG						
BOREHOLE NO: GP09				DATE COMPLETED: June 25, 1999		
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)		
REFERENCE ELEVATION (m): 99.67				DRILL SUPERVISOR: PEP		
DEPTH (m BGS)	BLVD COUNTS	SAMPLE LOCATION	CONDUSTIBLES (cmv)	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION
-0.5	5/4/3/2	560	560	FILL - gravel FILL - brown sand	-99.47 99.52 99.29	
-1.0	1/1/1/1	—	—	- no recovery	98.96 98.88	
-1.5	1/1/3/3	620	620	- brown sand CLAY - brown clay with organics	98.58 98.27 98.15	LEVEL 2
-2.0	4/6/7/6	620	620	- grey clay	-97.89 97.84 97.43 97.33	LEVEL 3
-2.5	8/6	680	680	- end of borehole	97.80 96.65 96.57 96.44	LEVEL 4
-3.0					-96.32	
-3.5						
-4.0						
-4.5						
-5.0						
-5.5						
-6.0						
-6.5						
-7.0						

BOREHOLE STRATIGRAPHIC LOG						
BOREHOLE NO.: GP10				DATE COMPLETED: June 24, 1999		
BOREHOLE DIAMETER: 0.11m (ID) 0.22m (OD)				WELL DIAMETER: 0.052 m (OD)		
REFERENCE ELEVATION (m): 99.52				DRILL SUPERVISOR: PEP		
DEPTH (m BGS)	BLOW COUNTS	SAMPLE LOCATION	CORRELATION	STRATIGRAPHIC DESCRIPTION	DEPTH (m BGS)	WELL INSTALLATION
-0.5	6/5/3/4	260		FILL: - sand and gravel SAND: - dry sandy silt	99.37 99.22	0.5 LEVEL 1 1.0 LEVEL 2 1.5 LEVEL 3 2.5 LEVEL 4 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0
-1.0	1/1/15/45	300			96.83 96.78 96.53	
-1.5	1/4/3/9	260		- brown sandy silt with organic matter	96.12 96.80 97.79	
-2.0	1/3/3/2	-		FILL: - gravel, crushed red brick, sand CLAY: - grey clay	97.46 97.29 97.23	
-2.5					96.90	
-3.0	4/25/25/9	360			96.78 96.17	
-3.5				- end of borehole		
-4.0						
-4.5						
-5.0						
-5.5						
-6.0						
-6.5						
-7.0						

APPENDIX 3:

Analytical Results: Soils

Physical Properties:

Soil Classification

Soil Moisture

Chemical Properties:

TPH Analysis

BTEX Analysis

Appendix 3: Results of Soil Analysis (Physical Properties)

Well Location	Soil Class (Well)	Sample ID	Soil Class (Sample)	Duplicate (Yes/No?)	% Moisture
GP01	clay	GP01-1	sand	No	3%
		GP01-2A	silty clay	No	5%
		GP01-2B	Clay	No	18%
		GP01-3	Clay	No	25%
		GP01-4	Clay	No	27%
		GP01-5	Clay	No	29%
GP02	clay	GP02-1	sand	No	3%
		GP02-2A	sand	No	6%
		GP02-2B	wood	No	43%
		GP02-2C	sandy silt	No	18%
		GP02-3	sandy silt	No	21%
		GP02-4	Clay	No	24%
		GP02-5	silty clay	No	26%
GP03	clay	GP03-1	sand	No	4%
		GP03-2	sand	No	11%
		GP03-3	silty clay	No	19%
		GP03-4	Clay	No	27%
		GP03-5	Clay	No	24%
GP04	clay	GP04-1	sand	No	3%
		GP04-1	sand	Yes	3%
		GP04-2	sand	No	5%
		GP04-3	sandy silt	No	21%
		GP04-3	sandy silt	Yes	21%
		GP04-4	Clay	No	25%
		GP04-5	Clay	No	29%
GP05	sand	GP05-1	gravel	No	4%
		GP05-2	gravel	No	2%
		GP05-2	gravel	Yes	2%
		GP05-2	gravel	Yes	2%
		GP05-3	gravel	No	5%
		GP05-4	gravel	No	5%
		GP05-5	gravel	No	5%
GP06	sand	GP06-1	gravel	No	5%
		GP06-2	sand	No	8%
		GP06-3	gravel	No	17%
		GP06-4	gravel	No	13%
		GP06-5	gravel	No	9%
GP07	clay	GP07-1	sand	No	2%
		GP07-2	Clay	No	14%
		GP07-3	Clay	No	17%
		GP07-4	Clay	No	19%
		GP07-5	Clay	No	22%

Appendix 3: Results of Soil Analysis (Physical Properties) (cont'd)

Well Location	Soil Class (Well)	Sample ID	Soil Class (Sample)	Duplicate (Yes/No?)	% Moisture
GP08	clay	GP08-1	gravel	No	4%
		GP08-2	sand	No	9%
		GP08-3	gravel	No	1%
		GP08-4A	gravel	No	2%
		GP08-4B	Clay	No	22%
		GP08-5	Clay	No	25%
GP09	sand	GP09-1	sand	No	4%
		GP09-2	sand	No	6%
		GP09-3	sand	No	14%
		GP09B-1	gravel	No	3%
		GP09B-2	gravel	No	6%
		GP09B-3	sand	No	9%
		GP09-4	Clay	No	17%
		GP09B-5	Clay	No	25%
GP10	clay	GP10-1	gravel	No	10%
		GP10-2	sandy silt	No	20%
		GP10-3	Clay	No	14%
		GP10-4	Clay	No	19%
		GP10-5	Clay	No	24%
MW15	sand	MW15-1	sand	No	5%
		MW15-1	sand	Yes	5%
		MW15-2	sand	No	7%
		MW15-3	gravel	No	3%
		MW15-4	gravel	No	3%
		MW15-5	gravel	No	2%
		MW15-6	gravel	No	8%
		MW15-7	sand	No	9%
		MW15-7	sand	Yes	9%
MW16	clay	MW16-1	sand	No	25%
		MW16-2	sand	No	19%
		MW16-3	Clay	No	21%
		MW16-4	Clay	No	23%
		MW16-5	Clay	No	27%
		MW16-6	Clay	No	3%
		MW16-7	Clay	No	24%
		MW16-8	Clay	No	24%
MW17	clay	MW17-1	sand	No	2%
		MW17-2	sand	No	10%
		MW17-3	Clay	No	21%
		MW17-4	silty clay	No	25%
		MW17-4	silty clay	Yes	19%
		MW17-5	sandy silt	No	9%
		MW17-7	bedrock	No	9%

Appendix 3: Results of Soil Analysis (Chemical Properties: TPH)

Well Location	Sample ID	Duplicate (Yes/No?)	DRO (mg/kg)	GRO (mg/kg)	TPH (mg/kg)
GP01	GP01-1	No	0	41	41
	GP01-2A	No	0	33	33
	GP01-2B	No	0	58	58
	GP01-3	No	72	468	540
	GP01-5	No	56	421	477
GP02	GP02-1	No	0	41	41
	GP02-2A	No	0	55	55
	GP02-2B	No	0	273	273
	GP02-2C	No	0	58	58
	GP02-3	No	0	61	61
	GP02-5	No	32	249	281
GP03	GP03-1	No	0	55	55
	GP03-2	No	3	43	46
	GP03-3	No	0	71	71
	GP03-4	No	0	83	83
	GP03-5	No	0	69	69
GP04	GP04-1	No	0	36	36
	GP04-1	Yes	0	31	31
	GP04-2	No	0	43	43
	GP04-3	No	211	219	430
	GP04-3	Yes	223	357	580
	GP04-5	No	222	759	981
GP05	GP05-1	No	10	0	10
	GP05-2	No	0	0	0
	GP05-2	Yes	0	0	0
	GP05-2	Yes	0	31	31
	GP05-3	No	1	0	1
	GP05-5	No	0	32	32
GP06	GP06-1	No	0	38	38
	GP06-2	No	0	57	57
	GP06-3	No	0	56	56
	GP06-5	No	0	63	63
GP07	GP07-1	No	6	0	6
	GP07-2	No	0	0	0
	GP07-3	No	5	57	62
	GP07-5	No	80	271	351
GP08	GP08-1	No	0	37	37
	GP08-2	No	0	43	43
	GP08-3	No	0	52	52
	GP08-4A	No	41	43	84
	GP08-4B	No	0	53	53
	GP08-5	No	48	68	116
GP09	GP09-1	No	14	52	65
	GP09-2	No	0	43	43
	GP09-3	No	11	53	65
	GP09B-1	No	0	45	45
	GP09B-3	No	0	44	44
	GP09B-5	No	0	72	72

Appendix 3: Results of Soil Analysis (Chemical Properties: TPH) (cont'd)

Well Location	Sample ID	Duplicate (Yes/No?)	DRO (mg/kg)	GRO (mg/kg)	TPH (mg/kg)
GP10	GP10-1	No	0	63	63
	GP10-2	No	509	61	571
	GP10-3	No	0	76	76
	GP10-5	No	2	0	2
MW15	MW15-1	No	0	35	35
	MW15-1	Yes	0	48	48
	MW15-2	No	0	42	42
	MW15-3	No	0	35	35
	MW15-4	No	0	34	34
	MW15-5	No	1	30	32
	MW15-6	No	0	39	39
	MW15-7	No	0	26	26
MW16	MW15-7	Yes	0	25	25
	MW16-1	No	0	48	48
	MW16-2	No	5	42	47
	MW16-3	No	0	41	41
	MW16-4	No	0	45	45
	MW16-5	No	0	0	0
	MW16-6	No	0	0	0
MW17	MW16-7	No	0	42	42
	MW17-1	No	12	64	75
	MW17-2	No	16	53	69
	MW17-3	No	0	51	51
	MW17-4	No	13	26	40
	MW17-4	Yes	0	36	36
	MW17-5	No	0	11	11
	MW17-7	No	0	37	37

Appendix 3: Results of Soil Analysis (Chemical Properties: BTEX)

Well Location	Sample ID	Duplicate (Yes/No?)	Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	M&P Xylene (mg/kg)	O Xylene (mg/kg)	Total BTEX (mg/kg)
GP01	GP01-1	No	0	0	0	0	0	0
	GP01-2A	No	0	0	0	0	0	0
	GP01-2B	No	0	0	0	0	0	0
	GP01-3	No	0	10	10	37	33	90
	GP01-5	No	0	9	9	34	30	82
GP02	GP02-1	No	0	0	0	0	0	0
	GP02-2A	No	0	0	0	0	0	0
	GP02-2B	No	0	0	0	0	0	0
	GP02-2C	No	0	0	1	2	2	5
	GP02-3	No	0	0	0	0	0	0
	GP02-5	No	0	13	4	14	14	45
GP03	GP03-1	No	0	0	0	0	0	0
	GP03-2	No	0	0	0	0	1	1
	GP03-3	No	0	0	0	0	2	2
	GP03-4	No	0	0	0	0	0	0
	GP03-5	No	0	0	0	0	0	0
GP04	GP04-1	No	0	0	0	0	0	0
	GP04-1	Yes	0	0	0	0	0	0
	GP04-2	No	0	0	0	0	0	0
	GP04-3	No	0	0	2	7	2	11
	GP04-3	Yes	0	0	2	10	2	14
	GP04-5	No	0	17	15	57	51	140
GP05	GP05-1	No	0	0	0	0	0	0
	GP05-2	No	0	0	0	0	0	0
	GP05-2	Yes	0	0	0	0	0	0
	GP05-2	Yes	0	0	0	0	0	0
	GP05-3	No	0	0	0	0	0	0
	GP05-5	No	0	0	0	0	0	0
GP06	GP06-1	No	0	0	0	0	0	0
	GP06-2	No	0	0	0	0	0	0
	GP06-3	No	0	0	0	0	0	0
	GP06-5	No	0	0	0	0	0	0
GP07	GP07-1	No	0	0	0	0	0	0
	GP07-2	No	0	0	0	0	0	0
	GP07-3	No	0	0	0	0	0	0
	GP07-5	No	0	0	3	7	2	13
GP08	GP08-1	No	0	0	0	0	0	0
	GP08-2	No	0	0	0	0	0	0
	GP08-3	No	0	0	0	0	0	0
	GP08-4A	No	0	0	0	0	0	0
	GP08-4B	No	0	0	0	0	0	0
	GP08-5	No	0	0	0	0	0	0
GP09	GP09-1	No	0	0	0	0	0	0
	GP09-2	No	0	0	0	0	0	0
	GP09-3	No	0	0	0	0	0	0
	GP09B-1	No	0	0	0	0	0	0
	GP09B-3	No	0	0	0	0	0	0
	GP09B-5	No	0	0	0	0	0	0

Appendix 3: Results of Soil Analysis (Chemical Properties: BTEX) (cont'd)

Well Location	Sample ID	Duplicate (Yes/No?)	Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	M&P Xylene (mg/kg)	O Xylene (mg/kg)	Total BTEX (mg/kg)
GP10	GP10-1	No	0	0	0	0	0	0
	GP10-2	No	0	0	0	0	0	0
	GP10-3	No	0	0	0	0	0	0
	GP10-5	No	0	0	0	0	0	0
MW15	MW15-1	No	0	0	0	0	1	1
	MW15-1	Yes	0	7	0	0	0	7
	MW15-2	No	0	0	0	0	0	0
	MW15-3	No	0	0	0	0	0	0
	MW15-4	No	0	0	0	0	0	0
	MW15-5	No	0	0	0	0	0	0
	MW15-6	No	0	0	0	0	1	1
	MW15-7	No	0	0	0	0	0	0
MW16	MW15-7	Yes	0	0	0	0	0	0
	MW16-1	No	0	0	0	0	0	0
	MW16-2	No	0	0	0	0	0	0
	MW16-3	No	0	0	0	0	0	0
	MW16-4	No	0	0	0	0	0	0
	MW16-5	No	0	0	0	0	0	0
	MW16-6	No	0	0	0	0	0	0
MW17	MW16-7	No	0	0	0	0	0	0
	MW17-1	No	0	0	0	0	0	0
	MW17-2	No	0	0	0	0	0	0
	MW17-3	No	0	0	0	0	0	0
	MW17-4	No	0	0	0	0	0	0
	MW17-4	Yes	0	0	0	0	0	0
	MW17-5	No	0	0	0	0	0	0
	MW17-7	No	0	0	0	0	0	0

APPENDIX 4:

Historical Groundwater Elevation Data

Appendix 4: Historical Ground Water Elevation Data

Date	MW02	MW03	MW04	MW05	MW06	MW08	MW09	MW13	MW14	MW15	MW16	MW17
Reference Elevation (m)	99.52	99.65	99.60	99.40	99.54	99.62	99.55	99.44	99.71	99.61	99.54	99.24
01/13/93		96.87		96.79		96.73	96.84		96.74			
04/08/93	97.91	97.30	97.28	97.16		97.39	97.28	97.32	97.29			
05/06/93	97.79	97.32	97.29	97.18	97.37	97.32	97.30	97.31	97.35			
06/17/93	97.05	96.76	96.71	96.70	97.11	96.92	96.90	96.71	96.79			
07/21/93	96.38	96.48	96.36	96.37	95.78	96.72	96.67	96.14	96.41			
11/30/93	96.54	96.66		96.59	96.72	96.66	96.75		96.63			
06/10/94	97.44	97.15	97.06	96.99	96.93	97.09	96.92	97.05	97.04			
09/14/94	96.05	96.41		96.39	96.48	96.52	96.46	96.06	96.38			
12/09/94	95.90	96.39		96.52	96.62	96.51	96.61	96.37	96.38			
03/14/95	95.91	96.38		96.49	96.50			96.30				
06/07/95	97.52	97.15		97.10	97.12	97.09	97.15	97.08	97.06			
09/15/95	95.84	96.25	96.10	96.37	96.51	96.46	96.60	95.92	96.27			
04/12/96	98.08	97.53	97.45	97.38	97.45	97.35	97.38	97.51				
07/10/96	96.53		96.47	96.59	96.70	96.69	96.72	96.33				
10/15/96	95.83	96.51	96.45	96.60	96.70	96.70	96.78	96.30				
04/16/97	98.19	97.59	97.56	97.49	97.51	97.58	97.52	97.57	97.52			
07/14/97	96.07	96.37	96.30	96.49	96.63	96.59	96.67	96.05	96.47			
10/23/97	95.82	96.30	96.20	96.45	96.57	96.55	96.68	95.99	96.36			
04/23/98	97.67	97.23	97.18	97.16	97.22	97.25	97.26	97.13	97.19			
07/15/98	96.79	96.61	96.53	96.67	96.78	96.78	96.83	96.34	96.64			
10/21/98	96.59	96.30	96.26	96.59	96.87	96.59	96.81	96.38	96.35			
01/21/99	96.51	96.25	96.21	96.59	96.76	96.50	96.67	96.49	96.26			
06/16/99	96.65	96.48	96.43	96.52	96.77	96.77	96.84	96.38	96.64			
10/14/99	96.50	96.46	96.46	96.56	96.74	96.70	96.81	96.53	96.56	96.50	96.56	96.35
12/08/99	96.99	96.68	96.68	96.65	96.86	96.82	96.89	96.72	96.74	96.68	96.70	96.83
Min	95.82	96.25	96.10	96.37	95.78	96.46	96.46	95.92	96.26	96.50	96.56	96.35
Max	98.19	97.59	97.56	97.49	97.51	97.58	97.52	97.57	97.52	96.68	96.70	96.83

APPENDIX 5:

Analytical Results: Groundwater

Chemical Properties:

TPH Analysis

BTEX Analysis

Geochemical Indicators

Appendix 5: Results of Groundwater Analysis (TPH)

Sample Date	Sample ID	Duplicate (Yes/No?)	DRO (mg/L)	GRO (mg/L)	TPH (mg/L)
06/11/99	MW 02	No	--	--	4834
06/11/99	MW 03	No	--	--	10605
06/11/99	MW 04	No	--	--	8922
06/11/99	MW 05	No	--	--	9603
06/11/99	MW 06	No	--	--	15098
06/11/99	MW 08	No	--	--	29600
06/11/99	MW 09	No	--	--	10230
06/11/99	MW 13	No	--	--	5333
06/11/99	MW 14	No	--	--	13525
06/11/99	Analytical Blank	No	--	--	0
06/11/99	Field Blank	No	--	--	0
06/11/99	Trip Blank	No	--	--	0
10/16/99	MW 02	No	0	0	0
10/16/99	MW 03	No	59	0	59
10/16/99	MW 04	No	62	136	198
10/16/99	MW 05	No	60	130	191
10/16/99	MW 06	No	61	132	193
10/16/99	MW 08	No	0	0	0
10/16/99	MW 09	No	0	0	0
10/16/99	MW 13	No	62	132	194
10/16/99	MW 14	No	59	129	188
10/16/99	MW 15	No	60	130	190
10/16/99	MW 16	No	0	0	0
10/16/99	MW 17	No	0	0	0
10/16/99	Field Blank	No	0	0	0
10/16/99	Trip Blank	No	0	0	0
12/08/99	MW 02	No	0	0	0
12/08/99	MW 03	No	1	3	4
12/08/99	MW 04	No	3	105	108
12/08/99	MW 05	No	2	50	52
12/08/99	MW 06	No	2	159	161
12/08/99	MW 08	No	0	1	1
12/08/99	MW 09	No	2	52	54
12/08/99	MW 13	No	0	0	0
12/08/99	MW 14	No	1	28	29
12/08/99	MW 15	No	1	38	40
12/08/99	MW 16	No	0	0	0
12/08/99	MW 17	No	0	0	0
12/08/99	Field Blank	No	0	0	0
12/08/99	Trip Blank	No	0	0	0

Appendix 5: Results of Groundwater Analysis (BTEX)

Sample Date	Sample ID	Duplicate (Yes/No?)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	m&p Xylene (mg/L)	o Xylene (mg/L)	Total BTEX (mg/L)
06/11/99	MW 02	No	0	0	0	0	0	0
	MW 03	No	0	1	0	0	0	1
	MW 04	No	0	19	1	4	1	24
	MW 05	No	1	2	1	3	3	9
	MW 05	Yes	0	1	1	2	2	5
	MW 05	Yes	0	1	0	1	1	4
	MW 06	No	0	8	1	4	5	18
	MW 06	Yes	0	9	1	5	6	22
	MW 06	Yes	1	9	1	4	6	21
	MW 08	No	0	1	0	1	1	2
	MW 09	No	0	1	0	1	1	3
	MW 09	Yes	0	1	0	1	1	3
	MW 09	Yes	0	1	0	1	1	3
	MW 13	No	0	0	0	1	0	2
	MW 14	No	0	3	1	2	2	8
	Analytical Blank	No	0	0	0	0	0	0
	Field Blank	No	0	0	0	0	0	0
	Trip Blank	No	0	0	0	0	0	0
10/16/99	MW 02	No	0	0	0	0	0	0
	MW 03	No	2	1	1	3	3	10
	MW 04	No	2	12	3	8	8	33
	MW 05	No	2	2	4	6	5	19
	MW 06	No	4	10	5	9	9	36
	MW 08	No	0	0	0	0	0	1
	MW 09	No	2	2	4	7	4	19
	MW 13	No	0	0	0	0	0	1
	MW 14	No	2	3	0	6	4	14
	MW 15	No	3	3	3	5	6	20
	MW 16	No	0	0	0	0	0	0
	MW 17	No	0	0	0	0	0	0
	Field Blank	No	0	0	0	0	0	0
	Trip Blank	No	0	0	0	0	0	0

Appendix 5: Results of Groundwater Analysis (BTEX) (cont'd)

Sample Date	Sample ID	Duplicate (Yes/No?)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	m&p Xylene (mg/L)	o Xylene (mg/L)	Total BTEX (mg/L)
12/08/99	MW 02	No	0	0	0	0	0	0
	MW 03	No	0	0	0	0	0	0
	MW 04	No	3	37	4	22	9	75
	MW 05	No	7	2	3	10	3	24
	MW 06	No	6	28	5	22	8	68
	MW 08	No	0	0	0	0	0	0
	MW 09	No	1	2	4	13	1	21
	MW 13	No	0	0	0	0	0	0
	MW 14	No	0	2	0	9	1	12
	MW 15	No	2	6	0	14	8	30
	MW 16	No	0	0	0	0	0	0
	MW 17	No	0	0	0	0	0	0
	Field Blank	No	0	0	0	0	0	0
	Trip Blank	No	0	0	0	0	0	0

Appendix 5: Results of Groundwater Analysis (Geochemical Indicators)

Sample Date	Sample ID	Duplicate (Yes/No?)	Temp (°C)	pH	DO (mg/L)	Redox Potential (mV)	Nitrate (NO ³)	Ferrous Iron (Fe ²⁺)	Sulfate (SO ₄ ²⁻)
06/11/99	MW 02	No	8.7	6.83	2.42	--	0.68	0	156 D
06/11/99	MW 03	No	9.5	6.74	1.30	--	0	3.6	0
06/11/99	MW 04	No	10.1	6.77	0.55	--	0	4.5	1
06/11/99	MW 05	No	10.1	6.76	3.52	--	0	5.4	64
06/11/99	MW 05	Yes	--	--	--	--	--	--	72
06/11/99	MW 06	No	10.1	6.73	1.80	--	0	1.5	0
06/11/99	MW 06	Yes	--	--	--	--	0	--	0
06/11/99	MW 08	No	10.4	6.76	1.31	--	0.41	0	204 D
06/11/99	MW 09	No	10.1	7.01	5.02	--	0	1.5	40
06/11/99	MW 13	No	9.3	6.56	4.50	--	0.2	0.3	74
06/11/99	MW 14	No	11.2	6.83	1.05	--	0	1.6	36
06/11/99	Field Blank	No	--	7.37	--	--	0	0	2
06/11/99	Trip Blank	No	--	7.42	--	--	0	0	0
10/16/99	MW 02	No	12.7	--	5.12	130.6	0.08	0	110
10/16/99	MW 03	No	13.4	--	5.36	-106.8	0.04	0.9	78
10/16/99	MW 04	No	12.6	--	2.61	-121.6	0	5.5	0
10/16/99	MW 05	No	13.1	--	5.47	-66.2	0	3.2	0
10/16/99	MW 06	No	14.5	--	6.95	-41.2	0.06	0.8	0
10/16/99	MW 08	No	13.3	--	1.04	-204.8	3.6	0	140
10/16/99	MW 09	No	13.5	--	3.58	-39	0	0	0
10/16/99	MW 13	No	12.7	--	6.65	88.7	0.06	0	68
10/16/99	MW 14	No	14.1	--	1.06	-170.7	0	0.6	0
10/16/99	MW 15	No	14.4	--	1.89	-277.8	0	1.4	0
10/16/99	MW 16	No	13.1	--	3.66	202.5	0.42	0	204
10/16/99	MW 17	No	13.1	--	7.3	101.3	0.23	0	176
10/16/99	Field Blank	No	--	--	--	--	0	0	1
10/16/99	Trip Blank	No	--	--	--	--	0	0	0
12/08/99	MW 02	No	11.2	6.47	3.5	292.6	0	0	104
12/08/99	MW 03	No	12.4	6.53	6.41	-23.7	0	1.8	2
12/08/99	MW 04	No	12.7	6.52	0.4	-101.4	0	4	0
12/08/99	MW 05	No	12.4	6.54	7.07	-43.5	0	4.5	0
12/08/99	MW 06	No	13.4	6.57	5.5	-29.1	0	1.5	1
12/08/99	MW 08	No	12.9	6.52	3.8	-90.1	0.24	0	200
12/08/99	MW 09	No	13.1	6.73	9.6	-25.5	0	0.5	0
12/08/99	MW 13	No	11.5	6.33	8.76	97.7	0.12	0.1	76
12/08/99	MW 14	No	13.3	6.68	6.71	-87.6	0	1	0
12/08/99	MW 15	No	12.7	6.53	2.63	-178.5	0	3.2	0
12/08/99	MW 16	No	13.6	6.58	8.4	159.6	0.68	0	212
12/08/99	MW 17	No	10.7	6.56	7.54	9.61	0.3	0	160
12/08/99	Field Blank	No	--	6.95	--	--	0	0	0
12/08/99	Trip Blank	No	--	7	--	--	0	0	0

Notes:

D - Dilution Required

APPENDIX 6:

Analytical Results: TPH Soil Vapour Survey Results

Appendix 6: TPH Soil Vapour Survey Results

Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)	Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
28-Jul-99	GP01-1	220	18.4		16-Aug-99	MW04	300	6.3	
28-Jul-99	GP01-2	680	13.4		16-Aug-99	MW05	4,500	0.0	
28-Jul-99	GP01-3	4,500	8.3		16-Aug-99	MW06	500	15.8	
28-Jul-99	GP01-4	16,500	0.3		16-Aug-99	MW08	280	17.3	
28-Jul-99	GP02-1	540	2.0		16-Aug-99	MW09	340	8.1	
28-Jul-99	GP02-2	720	2.0		16-Aug-99	MW13	240	12.8	
28-Jul-99	GP02-3	11,500	0.5		16-Aug-99	MW14	340	12.2	
28-Jul-99	GP03-1	380	9.6		16-Aug-99	MW15	2,500	20.4	
28-Jul-99	GP03-2	380	4.8		16-Aug-99	MW17	240	10.9	
28-Jul-99	GP04-1	400	19.4		17-Aug-99	GP01-1	220	19.2	
28-Jul-99	GP04-2	420	18.9		17-Aug-99	GP01-2	300	14.1	
28-Jul-99	GP05-1	240	15.7		17-Aug-99	GP02-1	240	13.8	
28-Jul-99	GP05-2	280	13.8		17-Aug-99	GP02-2	700	9.0	
28-Jul-99	GP05-3	280	10.6		17-Aug-99	GP02-3	11,500	1.0	
28-Jul-99	GP05-4	280	7.5		17-Aug-99	GP03-1	140	10.2	
28-Jul-99	GP06-1	260	16.8		17-Aug-99	GP03-2	120	4.3	
28-Jul-99	GP06-2	280	12.7		17-Aug-99	GP03-3	360	1.9	
28-Jul-99	GP06-3	300	12.1		17-Aug-99	GP04-1	100	20.4	
28-Jul-99	GP06-4	300	11.8		17-Aug-99	GP04-2	380	17.7	
28-Jul-99	GP07-1	320	18.3		17-Aug-99	GP04-3	2,000	4.5	
28-Jul-99	GP07-2	360	5.8		17-Aug-99	GP05-1	220	16.1	
28-Jul-99	GP07-3	560	9.6		17-Aug-99	GP05-2	200	13.6	
28-Jul-99	GP08-1	220	18.3		17-Aug-99	GP05-3	180	10.3	
28-Jul-99	GP08-2	280	12.6		17-Aug-99	GP05-4	180	6.7	
28-Jul-99	GP08-3	300	12.3		17-Aug-99	GP06-1	160	18.1	
28-Jul-99	GP08-4	280	5.4		17-Aug-99	GP06-2	180	13.0	
28-Jul-99	GP09-1	380	16.0		17-Aug-99	GP06-3	160	12.3	
28-Jul-99	GP09-2	380	13.6		17-Aug-99	GP06-4	160	11.7	
28-Jul-99	GP09-3	340	10.3		17-Aug-99	GP07-1	140	19.3	
28-Jul-99	GP09-4	360	9.6		17-Aug-99	GP07-2	180	3.4	
28-Jul-99	GP10-1	460	7.8		17-Aug-99	GP07-3	140	7.2	
28-Jul-99	GP10-2	440	2.5		17-Aug-99	GP08-1	120	19.7	
28-Jul-99	GP10-3	440	1.8		17-Aug-99	GP08-2	140	12.3	
28-Jul-99	MW02	340	5.4		17-Aug-99	GP08-3	120	11.4	
28-Jul-99	MW03	500	13.6		17-Aug-99	GP08-4	100	10.2	
28-Jul-99	MW04	400	5.7		17-Aug-99	GP09-1	160	17.1	
28-Jul-99	MW05	5,000	0.0		17-Aug-99	GP09-2	160	15.3	
28-Jul-99	MW06	840	14.0		17-Aug-99	GP09-3	120	10.9	
28-Jul-99	MW08	480	16.5		17-Aug-99	GP09-4	80	10.4	
28-Jul-99	MW09	580	9.6		17-Aug-99	GP10-1	140	4.5	
28-Jul-99	MW13	260	11.2		17-Aug-99	GP10-2	140	1.0	
28-Jul-99	MW14	640	12.4		17-Aug-99	GP10-3	160	0.7	
28-Jul-99	MW15	9,000	19.4		17-Aug-99	MW02	120	2.7	
28-Jul-99	MW17	800	12.1		17-Aug-99	MW03	220	15.5	
16-Aug-99	GP01-1	200	18.8		17-Aug-99	MW04	100	7.3	
16-Aug-99	GP01-2	280	14.8		17-Aug-99	MW05	4,120	3.1	
16-Aug-99	GP02-1	260	13.5		17-Aug-99	MW06	480	15.4	
16-Aug-99	GP02-2	380	9.6		17-Aug-99	MW09	280	8.7	
16-Aug-99	GP02-3	5,500	0.6		17-Aug-99	MW13	220	16.3	
16-Aug-99	GP03-1	240	10.0		17-Aug-99	MW14	200	11.4	
16-Aug-99	GP03-2	240	4.2		17-Aug-99	MW15	1,500	20.8	
16-Aug-99	GP03-3	420	3.3		17-Aug-99	MW17	200	11.8	
16-Aug-99	GP04-1	200	20.1		18-Aug-99	GP01-1	100	19.2	
16-Aug-99	GP04-2	580	17.9		18-Aug-99	GP01-2	140	14.5	
16-Aug-99	GP04-3	3,500	2.7		18-Aug-99	GP02-1	260	14.0	
16-Aug-99	GP05-1	280	15.6		18-Aug-99	GP02-2	560	11.5	
16-Aug-99	GP05-2	300	13.3		18-Aug-99	GP02-3	9,000	0.6	
16-Aug-99	GP05-3	300	10.3		18-Aug-99	GP03-1	200	10.3	
16-Aug-99	GP05-4	280	7.2		18-Aug-99	GP03-2	180	4.0	
16-Aug-99	GP06-1	280	17.3		18-Aug-99	GP03-3	460	0.5	
16-Aug-99	GP06-2	300	12.7		18-Aug-99	GP04-1	140	20.2	
16-Aug-99	GP06-3	300	12.0		18-Aug-99	GP04-2	580	16.7	
16-Aug-99	GP06-4	300	11.5		18-Aug-99	GP04-3	2,000	0.9	
16-Aug-99	GP07-1	140	18.9		18-Aug-99	GP05-1	260	15.3	
16-Aug-99	GP07-2	380	0.1		18-Aug-99	GP05-2	260	13.5	
16-Aug-99	GP07-3	180	7.3		18-Aug-99	GP05-3	240	10.2	
16-Aug-99	GP08-1	240	19.3		18-Aug-99	GP05-4	200	7.0	
16-Aug-99	GP08-2	300	12.1		18-Aug-99	GP06-1	200	17.4	
16-Aug-99	GP08-3	300	11.3		18-Aug-99	GP06-2	200	12.9	
16-Aug-99	GP08-4	280	6.7		18-Aug-99	GP06-3	200	12.3	
16-Aug-99	GP09-1	260	17.1		18-Aug-99	GP06-4	200	11.7	
16-Aug-99	GP09-2	280	14.3		18-Aug-99	GP07-1	160	19.0	
16-Aug-99	GP09-3	260	11.1		18-Aug-99	GP07-2	220	3.8	
16-Aug-99	GP09-4	300	10.1		18-Aug-99	GP07-3	160	6.8	
16-Aug-99	GP10-1	240	3.7		18-Aug-99	GP08-1	140	19.5	
16-Aug-99	GP10-2	240	0.9		18-Aug-99	GP08-2	180	12.7	
16-Aug-99	GP10-3	260	0.7		18-Aug-99	GP08-3	180	12.1	
16-Aug-99	MW02	200	3.0		18-Aug-99	GP08-4	180	11.7	
16-Aug-99	MW03	260	14.8		18-Aug-99	GP09-1	200	16.9	

Appendix 6: TPH Soil Vapour Survey Results

Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)	Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
18-Aug-99	GP09-2	200	14.7		20-Aug-99	GP06-3	280	11.8	
18-Aug-99	GP09-3	180	12.1		20-Aug-99	GP06-4	280	11.2	
18-Aug-99	GP09-4	160	11.0		20-Aug-99	GP07-1	520	19.1	
18-Aug-99	GP10-1	220	5.7		20-Aug-99	GP07-2	720	4.8	
18-Aug-99	GP10-2	200	1.3		20-Aug-99	GP07-3	600	7.3	
18-Aug-99	GP10-3	260	0.7		20-Aug-99	GP08-1	220	19.3	
18-Aug-99	MW02	200	3.6		20-Aug-99	GP08-2	280	12.3	
18-Aug-99	MW03	180	14.4		20-Aug-99	GP08-3	280	11.7	
18-Aug-99	MW04	160	8.4		20-Aug-99	GP08-4	260	9.1	
18-Aug-99	MW05	1,900	4.5		20-Aug-99	GP09-1	240	16.6	
18-Aug-99	MW06	420	15.3		20-Aug-99	GP09-2	260	14.1	
18-Aug-99	MW08	240	17.5		20-Aug-99	GP09-3	260	11.0	
18-Aug-99	MW09	300	9.0		20-Aug-99	GP09-4	240	11.2	
18-Aug-99	MW13	160	12.3		20-Aug-99	GP10-1	200	4.6	
18-Aug-99	MW14	240	12.4		20-Aug-99	GP10-2	200	1.1	
18-Aug-99	MW15	1,020	20.9		20-Aug-99	GP10-3	220	1.0	
18-Aug-99	MW17	160	12.1		20-Aug-99	MW02	180	3.3	
19-Aug-99	GP01-1	240	18.4		20-Aug-99	MW03	240	14.4	
19-Aug-99	GP01-2	340	13.7		20-Aug-99	MW04	240	7.9	
19-Aug-99	GP02-1	280	13.8		20-Aug-99	MW05	560	5.1	
19-Aug-99	GP02-2	400	9.9		20-Aug-99	MW06	700	15.6	
19-Aug-99	GP02-3	15,000	0.6		20-Aug-99	MW08	320	17.3	
19-Aug-99	GP03-1	280	9.9		20-Aug-99	MW09	420	7.9	
19-Aug-99	GP03-2	260	3.6		20-Aug-99	MW13	240	11.3	
19-Aug-99	GP03-3	640	0.3		20-Aug-99	MW14	360	11.9	
19-Aug-99	GP04-1	200	19.6		20-Aug-99	MW15	700	20.7	
19-Aug-99	GP04-2	480	17.4		20-Aug-99	MW17	240	11.5	
19-Aug-99	GP04-3	3,620	0.6		11-Sep-99	GP01-1	500	19.2	
19-Aug-99	GP05-1	280	15.0		11-Sep-99	GP01-2	4,320	10.6	
19-Aug-99	GP05-2	320	12.9		11-Sep-99	GP02-1	1,340	15.7	
19-Aug-99	GP05-3	320	9.9		11-Sep-99	GP02-2	6,280	8.2	
19-Aug-99	GP05-4	300	6.7		11-Sep-99	GP02-3	6,440	11.5	
19-Aug-99	GP06-1	260	16.9		11-Sep-99	GP03-1	14,500	0.9	
19-Aug-99	GP06-2	300	12.3		11-Sep-99	GP03-2	660	11.4	
19-Aug-99	GP06-3	320	11.7		11-Sep-99	GP04-1	760	4.2	
19-Aug-99	GP06-4	300	11.2		11-Sep-99	GP04-2	300	19.9	
19-Aug-99	GP07-1	220	18.6		11-Sep-99	GP05-1	700	16.0	
19-Aug-99	GP07-2	300	3.9		11-Sep-99	GP05-2	2,720	8.1	
19-Aug-99	GP07-3	240	6.5		11-Sep-99	GP05-3	520	14.8	
19-Aug-99	GP08-1	240	18.9		11-Sep-99	GP05-4	600	13.1	
19-Aug-99	GP08-2	280	12.1		11-Sep-99	GP06-1	520	10.9	
19-Aug-99	GP08-3	280	11.3		11-Sep-99	GP06-2	660	9.3	
19-Aug-99	GP08-4	300	10.5		11-Sep-99	GP06-3	660	7.2	
19-Aug-99	GP09-1	240	16.3		11-Sep-99	GP06-4	380	17.1	
19-Aug-99	GP09-2	260	13.9		11-Sep-99	GP07-1	580	13.1	
19-Aug-99	GP09-3	260	10.5		11-Sep-99	GP07-2	560	13.5	
19-Aug-99	GP09-4	220	9.9		11-Sep-99	GP07-3	400	17.4	
19-Aug-99	GP10-1	240	6.7		11-Sep-99	GP08-1	580	12.6	
19-Aug-99	GP10-2	260	0.8		11-Sep-99	GP08-2	640	12.8	
19-Aug-99	GP10-3	280	0.6		11-Sep-99	GP08-3	360	18.0	
19-Aug-99	MW02	200	3.3		11-Sep-99	GP08-4	620	4.3	
19-Aug-99	MW03	220	13.7		11-Sep-99	GP09-1	640	4.2	
19-Aug-99	MW04	240	7.8		11-Sep-99	GP09-2	720	7.6	
19-Aug-99	MW05	860	4.1		11-Sep-99	GP09-3	360	17.8	
19-Aug-99	MW06	640	16.1		11-Sep-99	GP09-4	620	12.6	
19-Aug-99	MW08	320	17.1		11-Sep-99	GP10-1	620	11.7	
19-Aug-99	MW09	360	9.8		11-Sep-99	GP10-2	700	5.1	
19-Aug-99	MW13	240	11.4		11-Sep-99	GP10-3	540	15.9	
19-Aug-99	MW14	360	11.0		11-Sep-99	MW02	560	16.5	
19-Aug-99	MW15	880	20.4		11-Sep-99	MW03	480	16.3	
19-Aug-99	MW17	260	11.2		11-Sep-99	MW04	580	12.2	
20-Aug-99	GP01-1	380	18.7		11-Sep-99	MW05	680	7.0	
20-Aug-99	GP01-2	460	14.4		11-Sep-99	MW06	700	3.0	
20-Aug-99	GP01-4	12,000	0.0		11-Sep-99	MW08	620	4.4	
20-Aug-99	GP02-1	740	13.8		11-Sep-99	MW09	640	4.8	
20-Aug-99	GP02-2	880	9.0		11-Sep-99	MW13	600	12.9	
20-Aug-99	GP02-3	11,000	0.2		11-Sep-99	MW14	680	6.1	
20-Aug-99	GP03-1	300	10.3		11-Sep-99	MW15	7,180	2.2	
20-Aug-99	GP03-2	300	3.9		11-Sep-99	GP01-1	960	11.5	
20-Aug-99	GP03-3	620	0.7		11-Sep-99	GP01-2	740	18.2	
20-Aug-99	GP04-1	220	19.9		11-Sep-99	GP01-4	1,020	3.0	
20-Aug-99	GP04-2	460	17.3		11-Sep-99	GP01-1	600	9.7	
20-Aug-99	GP05-1	380	15.9		11-Sep-99	GP01-2	740	6.6	
20-Aug-99	GP05-2	380	13.5		11-Sep-99	GP01-4	280	20.8	
20-Aug-99	GP05-3	360	10.2		11-Sep-99	GP01-1	600	13.9	
20-Aug-99	GP05-4	340	6.9		11-Sep-99	GP01-2	540	19.4	
20-Aug-99	GP06-1	280	17.3		13-Sep-99	GP01-1	4,880	10.1	
20-Aug-99	GP06-2	280	12.5		13-Sep-99	GP01-2	16,500	0.0	

Appendix 6: TPH Soil Vapour Survey Results

Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)	Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
13-Sep-99	GP02-1	960	17.6		14-Sep-99	MW08	740	19.0	
13-Sep-99	GP02-2	6,800	9.0		14-Sep-99	MW09	880	7.2	
13-Sep-99	GP02-3	11,000	0.1		14-Sep-99	MW13	660	9.1	
13-Sep-99	GP03-1	820	10.7		14-Sep-99	MW14	660	9.2	
13-Sep-99	GP03-2	880	3.2		14-Sep-99	MW15	420	21.1	
13-Sep-99	GP04-1	700	20.1		14-Sep-99	MW16	860	15.8	
13-Sep-99	GP04-2	1,360	14.2		14-Sep-99	MW17	640	14.8	
13-Sep-99	GP05-1	680	15.3		16-Sep-99	GP01-1	740	19.5	
13-Sep-99	GP05-2	740	12.7		16-Sep-99	GP01-2	4,720	7.2	
13-Sep-99	GP05-3	800	9.0		16-Sep-99	GP02-1	640	14.6	
13-Sep-99	GP05-4	860	5.2		16-Sep-99	GP02-2	8,940	8.2	
13-Sep-99	GP06-1	680	17.8		16-Sep-99	GP02-3	13,000	7.0	
13-Sep-99	GP06-2	780	12.4		16-Sep-99	GP03-1	740	11.2	
13-Sep-99	GP06-3	820	11.4		16-Sep-99	GP03-2	800	3.7	
13-Sep-99	GP06-4	860	10.6		16-Sep-99	GP04-1	320	20.3	
13-Sep-99	GP07-1	560	18.9		16-Sep-99	GP04-2	820	13.9	
13-Sep-99	GP07-2	680	3.4		16-Sep-99	GP05-1	560	15.0	
13-Sep-99	GP07-3	800	6.7		16-Sep-99	GP05-2	640	13.0	
13-Sep-99	GP08-1	500	19.3		16-Sep-99	GP05-3	680	9.9	
13-Sep-99	GP08-2	740	10.0		16-Sep-99	GP05-4	720	6.8	
13-Sep-99	GP08-3	740	10.3		16-Sep-99	GP06-1	500	17.3	
13-Sep-99	GP08-4	780	4.6		16-Sep-99	GP06-2	640	12.7	
13-Sep-99	GP09-1	800	16.6		16-Sep-99	GP06-3	720	11.4	
13-Sep-99	GP09-2	860	13.6		16-Sep-99	GP06-4	680	11.8	
13-Sep-99	GP09-3	900	9.7		16-Sep-99	GP07-1	500	18.6	
13-Sep-99	GP09-4	900	7.9		16-Sep-99	GP07-2	680	10.1	
13-Sep-99	GP10-1	740	6.3		16-Sep-99	GP07-3	840	7.6	
13-Sep-99	GP10-2	760	1.8		16-Sep-99	GP08-1	380	19.2	
13-Sep-99	GP10-3	780	1.7		16-Sep-99	GP08-2	640	11.7	
13-Sep-99	MW02	760	4.7		16-Sep-99	GP08-3	660	11.2	
13-Sep-99	MW03	800	12.8		16-Sep-99	GP09-1	540	16.5	
13-Sep-99	MW04	760	6.6		16-Sep-99	GP09-2	620	14.5	
13-Sep-99	MW05	3,260	4.9		16-Sep-99	GP09-3	660	11.5	
13-Sep-99	MW06	1,180	13.5		16-Sep-99	GP09-4	680	9.7	
13-Sep-99	MW08	960	5.4		16-Sep-99	GP10-1	660	5.7	
13-Sep-99	MW09	780	18.4		16-Sep-99	GP10-2	720	1.8	
13-Sep-99	MW13	740	9.1		16-Sep-99	GP10-3	740	1.6	
13-Sep-99	MW14	820	9.1		16-Sep-99	MW02	700	4.3	
13-Sep-99	MW15	620	20.9		16-Sep-99	MW03	660	13.0	
13-Sep-99	MW16	660	13.9		16-Sep-99	MW04	740	6.9	
13-Sep-99	MW17	720	13.1		16-Sep-99	MW05	1,040	4.9	
14-Sep-99	GP01-1	740	19.6		16-Sep-99	MW06	1,540	14.2	
14-Sep-99	GP01-2	5,380	5.5		16-Sep-99	MW08	640	19.0	
14-Sep-99	GP01-4	15,000	0.0		16-Sep-99	MW09	940	5.6	
14-Sep-99	GP02-1	720	14.8		16-Sep-99	MW13	680	9.0	
14-Sep-99	GP02-2	8,260	7.2		16-Sep-99	MW14	700	10.4	
14-Sep-99	GP02-3	15,500	3.2		16-Sep-99	MW15	300	20.9	
14-Sep-99	GP03-1	720	10.9		16-Sep-99	MW16	580	17.3	
14-Sep-99	GP03-2	800	2.5		16-Sep-99	MW17	660	12.0	
14-Sep-99	GP04-1	480	20.5		17-Sep-99	GP01-1	980	19.0	
14-Sep-99	GP04-2	800	15.3		17-Sep-99	GP01-2	6,420	8.1	
14-Sep-99	GP05-1	560	15.3		17-Sep-99	GP01-4	13,500	0.7	
14-Sep-99	GP05-2	620	12.9		17-Sep-99	GP02-1	2,420	15.3	
14-Sep-99	GP05-3	660	9.2		17-Sep-99	GP02-2	10,000	6.9	
14-Sep-99	GP05-4	700	5.1		17-Sep-99	GP02-3	16,500	0.1	
14-Sep-99	GP06-1	500	18.0		17-Sep-99	GP03-1	900	10.8	
14-Sep-99	GP06-2	620	12.5		17-Sep-99	GP03-2	980	3.6	
14-Sep-99	GP06-3	660	11.5		17-Sep-99	GP03-3	1,120	0.6	
14-Sep-99	GP06-4	700	10.7		17-Sep-99	GP04-1	380	20.2	
14-Sep-99	GP07-1	1,080	19.3		17-Sep-99	GP04-2	1,560	10.9	
14-Sep-99	GP07-2	1,140	4.3		17-Sep-99	GP05-1	720	14.1	
14-Sep-99	GP07-3	1,140	6.9		17-Sep-99	GP05-2	760	12.1	
14-Sep-99	GP08-1	380	20.2		17-Sep-99	GP05-3	800	9.4	
14-Sep-99	GP08-2	620	11.1		17-Sep-99	GP05-4	840	6.8	
14-Sep-99	GP08-3	620	10.6		17-Sep-99	GP06-1	620	16.3	
14-Sep-99	GP08-4	1,720	1.5		17-Sep-99	GP06-2	740	12.1	
14-Sep-99	GP09-1	500	17.1		17-Sep-99	GP06-3	700	11.7	
14-Sep-99	GP09-2	560	14.6		17-Sep-99	GP06-4	820	11.2	
14-Sep-99	GP09-3	620	11.4		17-Sep-99	GP07-1	860	18.8	
14-Sep-99	GP09-4	640	8.8		17-Sep-99	GP07-2	1,040	5.1	
14-Sep-99	GP10-1	640	5.1		17-Sep-99	GP07-3	1,160	6.7	
14-Sep-99	GP10-2	700	0.9		17-Sep-99	GP08-1	500	16.9	
14-Sep-99	GP10-3	700	0.9		17-Sep-99	GP08-2	660	10.6	
14-Sep-99	MW02	700	3.6		17-Sep-99	GP08-3	700	9.7	
14-Sep-99	MW03	620	13.9		17-Sep-99	GP09-1	600	15.9	
14-Sep-99	MW04	740	7.1		17-Sep-99	GP09-2	700	13.6	
14-Sep-99	MW05	1,240	6.5		17-Sep-99	GP09-3	760	9.9	
14-Sep-99	MW06	1,480	13.9		17-Sep-99	GP09-4	780	8.5	

Appendix 6: TPH Soil Vapour Survey Results

Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)	Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
17-Sep-99	GP10-1	660	11.2		20-Sep-99	GP08-3	780	10.5	
17-Sep-99	GP10-2	720	6.4		20-Sep-99	GP09-1	580	19.7	
17-Sep-99	MW02	740	4.8		20-Sep-99	GP09-2	740	15.8	
17-Sep-99	MW03	700	13.6		20-Sep-99	GP09-3	780	14.4	
17-Sep-99	MW04	740	6.8		20-Sep-99	GP09-4	800	13.1	
17-Sep-99	MW05	1,080	5.8		20-Sep-99	GP10-1	700	10.1	
17-Sep-99	MW06	1,920	14.5		20-Sep-99	GP10-2	780	1.5	
17-Sep-99	MW08	760	18.6		20-Sep-99	GP10-3	820	1.2	
17-Sep-99	MW09	1,880	7.0		20-Sep-99	MW02	760	3.9	
17-Sep-99	MW13	680	11.8		20-Sep-99	MW03	700	15.6	
17-Sep-99	MW14	820	10.5		20-Sep-99	MW04	760	7.0	
17-Sep-99	MW15	260	20.9		20-Sep-99	MW05	920	5.1	
17-Sep-99	MW16	660	18.2		20-Sep-99	MW06	1,500	14.8	
17-Sep-99	MW17	600	11.5		20-Sep-99	MW08	800	19.3	
18-Sep-99	GP01-1	620	19.2		20-Sep-99	MW09	1,080	7.4	
18-Sep-99	GP01-2	5,760	7.3		20-Sep-99	MW13	740	13.3	
18-Sep-99	GP01-4	12,000	0.0		20-Sep-99	MW14	840	10.9	
18-Sep-99	GP02-1	660	15.1		20-Sep-99	MW15	380	21.3	
18-Sep-99	GP02-2	10,000	4.9		20-Sep-99	MW16	560	20.2	
18-Sep-99	GP02-3	14,000	0.1		20-Sep-99	MW17	700	12.0	
18-Sep-99	GP03-1	1,320	10.8		21-Sep-99	GP01-1	520	20.1	
18-Sep-99	GP03-2	1,280	2.8		21-Sep-99	GP01-2	6,160	6.9	
18-Sep-99	GP04-1	380	20.7		21-Sep-99	GP02-1	700	15.2	
18-Sep-99	GP04-2	2,980	13.3		21-Sep-99	GP02-2	11,000	2.9	
18-Sep-99	GP05-1	820	14.7		21-Sep-99	GP02-3	13,500	0.0	
18-Sep-99	GP05-2	840	12.3		21-Sep-99	GP03-1	820	11.5	
18-Sep-99	GP05-3	860	9.3		21-Sep-99	GP03-2	900	3.0	
18-Sep-99	GP05-4	860	6.4		21-Sep-99	GP03-3	1,040	0.6	
18-Sep-99	GP06-1	620	17.7		21-Sep-99	GP04-1	2,940	11.7	
18-Sep-99	GP06-2	740	12.5		21-Sep-99	GP04-2	1,220	20.9	
18-Sep-99	GP06-3	780	11.8		21-Sep-99	GP04-3	2,280	15.9	
18-Sep-99	GP06-4	800	11.2		21-Sep-99	GP05-1	820	15.9	
18-Sep-99	GP08-1	480	19.3		21-Sep-99	GP05-2	880	13.6	
18-Sep-99	GP08-2	700	10.5		21-Sep-99	GP05-3	900	10.3	
18-Sep-99	GP08-3	720	9.9		21-Sep-99	GP05-4	920	7.4	
18-Sep-99	GP09-1	640	17.2		21-Sep-99	GP06-1	680	17.9	
18-Sep-99	GP09-2	720	14.4		21-Sep-99	GP06-2	800	13.3	
18-Sep-99	GP09-3	800	11.3		21-Sep-99	GP06-3	800	12.7	
18-Sep-99	GP09-4	780	10.6		21-Sep-99	GP06-4	840	12.1	
18-Sep-99	GP10-1	660	6.9		21-Sep-99	GP07-1	760	19.8	
18-Sep-99	GP10-2	740	1.5		21-Sep-99	GP07-2	940	4.1	
18-Sep-99	GP10-3	780	1.3		21-Sep-99	GP07-3	1,040	7.6	
18-Sep-99	MW02	720	4.3		21-Sep-99	GP08-1	420	20.1	
18-Sep-99	MW03	720	15.2		21-Sep-99	GP08-2	720	12.0	
18-Sep-99	MW04	700	6.9		21-Sep-99	GP08-3	760	11.1	
18-Sep-99	MW05	940	7.6		21-Sep-99	GP09-1	580	17.9	
18-Sep-99	MW06	1,500	14.7		21-Sep-99	GP09-2	660	15.8	
18-Sep-99	MW08	720	19.1		21-Sep-99	GP09-3	760	12.3	
18-Sep-99	MW09	1,020	7.9		21-Sep-99	GP09-4	740	11.8	
18-Sep-99	MW13	720	13.3		21-Sep-99	GP10-1	760	4.5	
18-Sep-99	MW14	740	10.6		21-Sep-99	GP10-2	760	2.5	
18-Sep-99	MW15	380	21.1		21-Sep-99	GP10-3	780	2.4	
18-Sep-99	MW16	600	19.1		21-Sep-99	MW02	760	3.7	
18-Sep-99	MW17	680	11.1		21-Sep-99	MW03	660	15.1	
20-Sep-99	GP01-1	660	20.0		21-Sep-99	MW04	740	7.5	
20-Sep-99	GP01-2	5,920	6.9		21-Sep-99	MW05	940	4.9	
20-Sep-99	GP02-1	720	16.3		21-Sep-99	MW06	1,240	15.3	
20-Sep-99	GP02-2	10,000	5.2		21-Sep-99	MW08	740	19.6	
20-Sep-99	GP02-3	13,500	0.0		21-Sep-99	MW09	980	7.9	
20-Sep-99	GP03-1	860	11.6		21-Sep-99	MW13	760	12.4	
20-Sep-99	GP03-2	940	3.4		21-Sep-99	MW14	700	10.8	
20-Sep-99	GP03-3	1,020	1.9		21-Sep-99	MW15	260	21.6	
20-Sep-99	GP04-1	440	20.9		21-Sep-99	MW16	360	20.1	
20-Sep-99	GP04-2	820	16.6		21-Sep-99	MW17	700	11.7	
20-Sep-99	GP04-3	2,260	3.7		22-Sep-99	GP01-1	580	20.0	
20-Sep-99	GP05-1	760	17.2		22-Sep-99	GP01-2	5,960	6.5	
20-Sep-99	GP05-2	820	13.8		22-Sep-99	GP02-1	740	15.2	
20-Sep-99	GP05-3	840	10.3		22-Sep-99	GP02-2	11,000	0.2	
20-Sep-99	GP05-4	880	6.0		22-Sep-99	GP02-3	13,500	0.1	
20-Sep-99	GP06-1	500	20.9		22-Sep-99	GP03-1	860	11.7	
20-Sep-99	GP06-2	760	14.1		22-Sep-99	GP03-2	920	3.6	
20-Sep-99	GP06-3	780	13.0		22-Sep-99	GP04-1	260	20.9	
20-Sep-99	GP06-4	860	12.5		22-Sep-99	GP04-2	1,040	11.5	
20-Sep-99	GP07-1	1,800	20.3		22-Sep-99	GP04-3	3,220	7.8	
20-Sep-99	GP07-2	1,220	3.0		22-Sep-99	GP05-1	760	15.6	
20-Sep-99	GP07-3	1,220	7.2		22-Sep-99	GP05-2	800	13.6	
20-Sep-99	GP08-1	460	20.7		22-Sep-99	GP05-3	840	10.6	
20-Sep-99	GP08-2	740	11.4		22-Sep-99	GP05-4	860	8.1	

Appendix 6: TPH Soil Vapour Survey Results

Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)	Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
22-Sep-99	GP06-1	580	18.1		28-Sep-99	GP03-2	820	2.9	
22-Sep-99	GP06-2	720	13.8		28-Sep-99	GP04-1	360	20.8	
22-Sep-99	GP06-3	740	13.3		28-Sep-99	GP04-2	840	13.2	
22-Sep-99	GP06-4	800	12.6		28-Sep-99	GP04-3	1,920	13.6	
22-Sep-99	GP07-1	860	19.7		28-Sep-99	GP05-1	620	16.6	
22-Sep-99	GP07-2	1,020	6.0		28-Sep-99	GP05-2	700	13.9	
22-Sep-99	GP07-3	1,100	7.4		28-Sep-99	GP05-3	720	10.2	
22-Sep-99	GP08-1	420	19.5		28-Sep-99	GP05-4	760	8.1	
22-Sep-99	GP08-2	720	12.0		28-Sep-99	GP06-1	540	19.0	
22-Sep-99	GP08-3	740	11.4		28-Sep-99	GP06-2	680	13.8	
22-Sep-99	GP09-1	620	17.9		28-Sep-99	GP06-3	700	13.0	
22-Sep-99	GP09-2	680	15.9		28-Sep-99	GP06-4	720	12.5	
22-Sep-99	GP09-3	760	13.1		28-Sep-99	GP07-1	880	19.9	
22-Sep-99	GP09-4	780	12.8		28-Sep-99	GP07-2	980	3.3	
22-Sep-99	GP10-1	720	7.5		28-Sep-99	GP07-3	1,080	7.5	
22-Sep-99	GP10-2	740	3.1		28-Sep-99	GP08-1	360	20.7	
22-Sep-99	GP10-3	740	2.5		28-Sep-99	GP08-2	620	13.2	
22-Sep-99	MW02	800	4.0		28-Sep-99	GP08-3	640	12.7	
22-Sep-99	MW03	680	16.4		28-Sep-99	GP09-1	520	18.4	
22-Sep-99	MW04	760	7.9		28-Sep-99	GP09-2	660	15.3	
22-Sep-99	MW05	920	6.4		28-Sep-99	GP09-3	700	12.9	
22-Sep-99	MW06	1,520	15.6		28-Sep-99	GP09-4	700	12.6	
22-Sep-99	MW08	700	19.8		28-Sep-99	GP10-1	660	4.0	
22-Sep-99	MW09	1,060	8.9		28-Sep-99	GP10-2	680	1.2	
22-Sep-99	MW13	720	14.1		28-Sep-99	GP10-3	700	1.0	
22-Sep-99	MW14	740	12.1		28-Sep-99	MW02	660	4.0	
22-Sep-99	MW15	420	20.9		28-Sep-99	MW03	640	15.1	
22-Sep-99	MW16	480	20.5		28-Sep-99	MW04	660	7.6	
22-Sep-99	MW17	740	11.1		28-Sep-99	MW05	860	3.4	
23-Sep-99	GP01-1	720	20.0		28-Sep-99	MW06	1,280	15.3	
23-Sep-99	GP01-2	7,440	7.0		28-Sep-99	MW08	720	19.5	
23-Sep-99	GP02-1	720	15.6		28-Sep-99	MW09	840	7.5	
23-Sep-99	GP02-2	11,500	2.4		28-Sep-99	MW13	640	12.6	
23-Sep-99	GP02-3	13,000	0.1		28-Sep-99	MW14	740	12.4	
23-Sep-99	GP03-1	840	11.5		28-Sep-99	MW15	260	21.0	
23-Sep-99	GP03-2	900	3.3		28-Sep-99	MW17	640	9.0	
23-Sep-99	GP04-1	360	20.9		29-Sep-99	GP01-1	740	20.2	
23-Sep-99	GP04-2	900	13.9		29-Sep-99	GP01-2	6,240	4.6	
23-Sep-99	GP04-3	2,840	7.9		29-Sep-99	GP02-1	740	16.0	
23-Sep-99	GP05-1	720	15.6		29-Sep-99	GP02-2	11,000	1.3	
23-Sep-99	GP05-2	780	13.3		29-Sep-99	GP02-3	13,000	2.1	
23-Sep-99	GP05-3	820	10.4		29-Sep-99	GP03-1	800	12.1	
23-Sep-99	GP05-4	840	7.9		29-Sep-99	GP03-2	880	2.9	
23-Sep-99	GP06-1	540	18.9		29-Sep-99	GP04-1	380	20.9	
23-Sep-99	GP06-2	740	13.6		29-Sep-99	GP04-2	900	11.7	
23-Sep-99	GP06-3	740	13.0		29-Sep-99	GP04-3	2,340	4.8	
23-Sep-99	GP06-4	780	12.3		29-Sep-99	GP05-1	760	16.9	
23-Sep-99	GP07-1	1,000	19.8		29-Sep-99	GP05-2	780	14.5	
23-Sep-99	GP07-2	1,120	7.3		29-Sep-99	GP05-3	800	11.2	
23-Sep-99	GP07-3	1,140	7.2		29-Sep-99	GP05-4	820	8.4	
23-Sep-99	GP08-1	720	11.5		29-Sep-99	GP06-1	560	19.5	
23-Sep-99	GP08-2	720	11.8		29-Sep-99	GP06-2	740	14.3	
23-Sep-99	GP08-3	740	11.3		29-Sep-99	GP06-3	740	13.4	
23-Sep-99	GP09-1	560	18.2		29-Sep-99	GP06-4	760	12.9	
23-Sep-99	GP09-2	680	15.7		29-Sep-99	GP07-1	940	20.4	
23-Sep-99	GP09-3	740	13.1		29-Sep-99	GP07-2	1,020	5.8	
23-Sep-99	GP09-4	760	12.9		29-Sep-99	GP07-3	1,080	8.3	
23-Sep-99	GP10-1	700	8.4		29-Sep-99	GP08-1	440	20.9	
23-Sep-99	GP10-2	740	2.1		29-Sep-99	GP08-2	720	13.4	
23-Sep-99	GP10-3	740	1.8		29-Sep-99	GP08-3	720	13.2	
23-Sep-99	MW02	760	3.8		29-Sep-99	GP09-1	600	18.7	
23-Sep-99	MW03	680	16.7		29-Sep-99	GP09-2	720	15.7	
23-Sep-99	MW04	760	8.3		29-Sep-99	GP09-3	740	13.5	
23-Sep-99	MW05	880	6.6		29-Sep-99	GP09-4	780	12.9	
23-Sep-99	MW06	1,140	15.7		29-Sep-99	GP10-1	700	4.9	
23-Sep-99	MW08	740	19.9		29-Sep-99	GP10-2	740	1.5	
23-Sep-99	MW09	900	9.0		29-Sep-99	GP10-3	760	1.2	
23-Sep-99	MW13	660	16.7		29-Sep-99	MW02	740	3.8	
23-Sep-99	MW14	780	12.6		29-Sep-99	MW03	720	16.2	
23-Sep-99	MW15	280	21.5		29-Sep-99	MW04	760	8.8	
23-Sep-99	MW16	460	20.8		29-Sep-99	MW05	860	5.2	
23-Sep-99	MW17	700	11.0		29-Sep-99	MW06	1,420	15.8	
28-Sep-99	GP01-1	620	19.8		29-Sep-99	MW08	780	19.6	
28-Sep-99	GP01-2	7,560	5.2		29-Sep-99	MW09	880	7.9	
28-Sep-99	GP02-1	720	15.4		29-Sep-99	MW13	740	12.6	
28-Sep-99	GP02-2	13,000	1.2		29-Sep-99	MW14	800	12.8	
28-Sep-99	GP02-3	12,500	0.1		29-Sep-99	MW15	340	21.3	
28-Sep-99	GP03-1	740	11.8		29-Sep-99	MW17	700	11.2	

Appendix 6: TPH Soil Vapour Survey Results

Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)	Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
30-Sep-99	GP01-1	920	20.1		1-Oct-99	MW06	1,580	15.9	
30-Sep-99	GP01-2	7,160	5.5		1-Oct-99	MW08	640	19.8	
30-Sep-99	GP02-1	720	15.4		1-Oct-99	MW09	740	8.8	
30-Sep-99	GP02-2	11,500	0.9		1-Oct-99	MW13	720	12.9	
30-Sep-99	GP02-3	13,000	3.7		1-Oct-99	MW14	680	13.3	
30-Sep-99	GP03-1	680	12.1		1-Oct-99	MW15	200	21.5	
30-Sep-99	GP03-2	760	4.3		1-Oct-99	MW16	340	19.9	
30-Sep-99	GP04-1	260	20.9		1-Oct-99	MW17	720	11.2	
30-Sep-99	GP04-2	860	10.9		2-Oct-99	GP01-1	860	20.3	
30-Sep-99	GP04-3	2,400	6.6		2-Oct-99	GP01-2	5,220	2.8	
30-Sep-99	GP05-1	640	16.9		2-Oct-99	GP02-1	700	15.3	
30-Sep-99	GP05-2	700	14.8		2-Oct-99	GP02-2	10,000	0.3	
30-Sep-99	GP05-3	740	11.4		2-Oct-99	GP02-3	11,500	0.4	
30-Sep-99	GP05-4	760	8.1		2-Oct-99	GP03-1	720	12.5	
30-Sep-99	GP06-1	540	18.6		2-Oct-99	GP03-2	800	3.5	
30-Sep-99	GP06-2	700	14.5		2-Oct-99	GP04-1	260	20.9	
30-Sep-99	GP06-3	700	13.6		2-Oct-99	GP04-2	860	12.4	
30-Sep-99	GP06-4	720	13.1		2-Oct-99	GP04-3	2,400	10.9	
30-Sep-99	GP07-1	880	19.8		2-Oct-99	GP05-1	660	16.6	
30-Sep-99	GP07-2	980	8.2		2-Oct-99	GP05-2	700	14.8	
30-Sep-99	GP07-3	1,080	8.0		2-Oct-99	GP05-3	740	12.0	
30-Sep-99	GP08-1	300	20.9		2-Oct-99	GP05-4	760	10.3	
30-Sep-99	GP08-2	640	13.8		2-Oct-99	GP06-1	520	18.6	
30-Sep-99	GP08-3	6,610	13.5		2-Oct-99	GP06-2	660	14.6	
30-Sep-99	GP09-1	520	18.4		2-Oct-99	GP06-3	700	13.9	
30-Sep-99	GP09-2	600	16.2		2-Oct-99	GP06-4	700	13.5	
30-Sep-99	GP09-3	680	13.7		2-Oct-99	GP07-1	520	19.2	
30-Sep-99	GP09-4	700	13.3		2-Oct-99	GP07-2	620	12.1	
30-Sep-99	GP10-1	660	4.6		2-Oct-99	GP07-3	800	8.3	
30-Sep-99	GP10-2	720	1.4		2-Oct-99	GP08-1	340	20.4	
30-Sep-99	GP10-3	720	1.4		2-Oct-99	GP08-2	660	14.4	
30-Sep-99	MW02	720	3.9		2-Oct-99	GP08-3	700	13.9	
30-Sep-99	MW03	640	15.7		2-Oct-99	GP09-1	580	18.3	
30-Sep-99	MW04	700	9.7		2-Oct-99	GP09-2	660	16.2	
30-Sep-99	MW05	800	5.4		2-Oct-99	GP09-3	720	14.0	
30-Sep-99	MW06	2,100	16.0		2-Oct-99	GP09-4	740	13.5	
30-Sep-99	MW08	640	20.1		2-Oct-99	GP10-1	660	9.6	
30-Sep-99	MW09	740	8.7		2-Oct-99	GP10-2	700	1.9	
30-Sep-99	MW13	440	21.3		2-Oct-99	GP10-3	720	1.2	
30-Sep-99	MW14	680	11.8		2-Oct-99	MW02	740	4.4	
30-Sep-99	MW15	240	21.5		2-Oct-99	MW03	700	15.9	
30-Sep-99	MW16	400	19.6		2-Oct-99	MW04	740	9.9	
30-Sep-99	MW17	620	11.5		2-Oct-99	MW05	840	8.1	
1-Oct-99	GP01-1	460	19.9		2-Oct-99	MW06	1,300	16.5	
1-Oct-99	GP01-2	5,180	1.8		2-Oct-99	MW08	680	20.2	
1-Oct-99	GP02-1	600	14.8		2-Oct-99	MW09	840	9.9	
1-Oct-99	GP02-2	10,000	0.7		2-Oct-99	MW13	680	13.1	
1-Oct-99	GP02-3	13,000	0.8		2-Oct-99	MW14	720	13.3	
1-Oct-99	GP03-1	640	12.1		2-Oct-99	MW15	280	21.6	
1-Oct-99	GP03-2	740	4.1		2-Oct-99	MW16	420	20.4	
1-Oct-99	GP04-1	260	20.8		2-Oct-99	MW17	700	11.5	
1-Oct-99	GP04-2	3,160	10.8		5-Oct-99	GP01-1	740	20.0	
1-Oct-99	GP04-3	4,580	4.3		5-Oct-99	GP01-2	5,120	2.0	
1-Oct-99	GP05-1	820	16.2		5-Oct-99	GP02-1	660	15.1	
1-Oct-99	GP05-2	860	14.4		5-Oct-99	GP02-2	10,500	1.3	
1-Oct-99	GP05-3	860	11.4		5-Oct-99	GP02-3	11,000	4.9	
1-Oct-99	GP05-4	860	9.7		5-Oct-99	GP03-1	720	12.6	
1-Oct-99	GP06-1	580	18.1		5-Oct-99	GP03-2	820	3.4	
1-Oct-99	GP06-2	720	14.4		5-Oct-99	GP04-1	180	20.8	
1-Oct-99	GP06-3	740	13.7		5-Oct-99	GP04-2	3,420	8.3	
1-Oct-99	GP06-4	760	13.1		5-Oct-99	GP04-3	3,960	7.5	
1-Oct-99	GP07-1	800	18.7		5-Oct-99	GP05-1	860	16.2	
1-Oct-99	GP07-2	960	7.6		5-Oct-99	GP05-2	880	14.6	
1-Oct-99	GP07-3	1,000	8.0		5-Oct-99	GP05-3	900	12.3	
1-Oct-99	GP08-1	320	20.5		5-Oct-99	GP05-4	880	10.8	
1-Oct-99	GP08-2	620	14.1		5-Oct-99	GP06-1	580	18.0	
1-Oct-99	GP08-3	660	13.6		5-Oct-99	GP06-2	740	14.5	
1-Oct-99	GP09-1	520	18.1		5-Oct-99	GP06-3	740	14.1	
1-Oct-99	GP09-2	640	16.1		5-Oct-99	GP06-4	740	13.9	
1-Oct-99	GP09-3	720	13.6		5-Oct-99	GP07-1	740	18.6	
1-Oct-99	GP09-4	740	13.2		5-Oct-99	GP07-2	880	8.5	
1-Oct-99	GP10-1	700	10.8		5-Oct-99	GP07-3	1,000	8.4	
1-Oct-99	GP10-2	760	3.1		5-Oct-99	GP08-1	340	19.8	
1-Oct-99	GP10-3	780	1.6		5-Oct-99	GP08-2	700	14.4	
1-Oct-99	MW02	780	3.4		5-Oct-99	GP08-3	720	14.0	
1-Oct-99	MW03	640	15.4		5-Oct-99	GP09-1	560	17.8	
1-Oct-99	MW04	680	9.7		5-Oct-99	GP09-2	640	16.0	
1-Oct-99	MW05	860	6.0		5-Oct-99	GP09-3	720	13.9	

Appendix 6: TPH Soil Vapour Survey Results

Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)	Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
5-Oct-99	GP09-4	740	13.5		14-Oct-99	GP07-3	900	8.1	
5-Oct-99	GP10-1	640	9.4		14-Oct-99	GP08-1	400	20.5	
5-Oct-99	GP10-2	740	2.8		14-Oct-99	GP08-2	720	15.3	
5-Oct-99	GP10-3	780	1.6		14-Oct-99	GP08-3	720	14.8	
5-Oct-99	MW02	760	4.6		14-Oct-99	GP09-1	580	19.1	
5-Oct-99	MW03	700	15.9		14-Oct-99	GP09-2	680	17.5	
5-Oct-99	MW04	780	8.9		14-Oct-99	GP09-3	740	16.0	
5-Oct-99	MW05	860	6.0		14-Oct-99	GP09-4	760	15.9	
5-Oct-99	MW06	1,560	16.6		14-Oct-99	GP10-1	720	5.3	
5-Oct-99	MW08	680	20.2		14-Oct-99	GP10-2	720	4.5	
5-Oct-99	MW09	820	8.7		14-Oct-99	GP10-3	720	4.6	
5-Oct-99	MW13	720	15.1		14-Oct-99	MW02	720	9.9	
5-Oct-99	MW14	680	14.1		14-Oct-99	MW03	880	18.3	
5-Oct-99	MW15	360	21.1		14-Oct-99	MW04	2,220	13.7	
5-Oct-99	MW16	340	20.7		14-Oct-99	MW05	7,860	10.3	
5-Oct-99	MW17	720	9.9		14-Oct-99	MW06	8,860	17.7	
6-Oct-99	GP01-1	640	19.9		14-Oct-99	MW08	2,460	19.0	
6-Oct-99	GP01-2	5,060	1.4		14-Oct-99	MW09	11,500	9.2	
6-Oct-99	GP02-1	580	15.3		14-Oct-99	MW13	660	16.5	
6-Oct-99	GP02-2	11,000	1.2		14-Oct-99	MW14	2,060	15.7	
6-Oct-99	GP02-3	10,000	5.4		14-Oct-99	MW15	2,160	21.4	
6-Oct-99	GP03-1	680	12.6		14-Oct-99	MW16	340	21.0	
6-Oct-99	GP03-2	780	3.6		14-Oct-99	MW17	520	16.9	
6-Oct-99	GP04-1	240	20.7		25-Oct-99	GP01-1	500	20.1	
6-Oct-99	GP04-2	3,940	7.7		25-Oct-99	GP01-2	4,300	0.4	
6-Oct-99	GP04-3	4,500	7.5		25-Oct-99	GP02-1	740	15.9	
6-Oct-99	GP05-1	640	16.0		25-Oct-99	GP02-2	9,600	0.9	
6-Oct-99	GP05-2	700	14.2		25-Oct-99	GP02-3	8,900	0.4	
6-Oct-99	GP05-3	740	11.8		25-Oct-99	GP03-1	760	13.8	
6-Oct-99	GP05-4	780	10.3		25-Oct-99	GP03-2	880	3.0	
6-Oct-99	GP06-1	640	17.8		25-Oct-99	GP04-1	260	20.9	
6-Oct-99	GP06-2	760	14.5		25-Oct-99	GP04-2	3,060	5.5	
6-Oct-99	GP06-3	780	14.1		25-Oct-99	GP04-3	3,720		
6-Oct-99	GP06-4	780	13.7		25-Oct-99	GP05-1	760	17.1	
6-Oct-99	GP07-1	920	18.7		25-Oct-99	GP05-2	820	15.7	
6-Oct-99	GP07-2	1,040	7.3		25-Oct-99	GP05-3	700	14.7	
6-Oct-99	GP07-3	1,080	8.1		25-Oct-99	GP05-4	720	13.5	
6-Oct-99	GP08-1	380	19.2		25-Oct-99	GP06-1	660	19.1	
6-Oct-99	GP08-2	700	14.1		25-Oct-99	GP06-2	820	16.7	
6-Oct-99	GP08-3	740	13.6		25-Oct-99	GP06-3	800	16.9	
6-Oct-99	GP09-1	620	17.9		25-Oct-99	GP07-1	480	18.9	
6-Oct-99	GP09-2	700	16.1		25-Oct-99	GP07-2	780	4.3	
6-Oct-99	GP09-3	780	13.5		25-Oct-99	GP07-3	900	10.1	
6-Oct-99	GP09-4	800	13.3		25-Oct-99	GP08-1	480	20.9	
6-Oct-99	GP10-1	680	10.9		25-Oct-99	GP08-2	840	16.1	
6-Oct-99	GP10-2	720	7.1		25-Oct-99	GP08-3	880	15.6	
6-Oct-99	GP10-3	780	2.2		25-Oct-99	GP09-1	660	19.5	
6-Oct-99	MW02	800	4.3		25-Oct-99	GP09-2	760	17.7	
6-Oct-99	MW03	760	15.5		25-Oct-99	GP09-3	800	15.9	
6-Oct-99	MW04	780	9.7		25-Oct-99	GP09-4	820	15.8	
6-Oct-99	MW05	900	6.7		25-Oct-99	GP10-1	700	8.8	
6-Oct-99	MW06	1,520	16.4		25-Oct-99	GP10-2	740	4.5	
6-Oct-99	MW08	700	20.2		25-Oct-99	GP10-3	800	3.7	
6-Oct-99	MW09	820	9.8		25-Oct-99	MW02	860	8.2	
6-Oct-99	MW13	720	15.3		25-Oct-99	MW03	880	18.0	
6-Oct-99	MW14	1,080	14.2		25-Oct-99	MW04	1,040	10.7	
6-Oct-99	MW15	440	21.4		25-Oct-99	MW05	1,080	7.8	
6-Oct-99	MW16	300	20.8		25-Oct-99	MW06	1,120	16.9	
6-Oct-99	MW17	720	10.0		25-Oct-99	MW08	760	19.0	
14-Oct-99	GP01-1	680	19.9		25-Oct-99	MW09	1,320	9.4	
14-Oct-99	GP01-2	5,560	0.4		25-Oct-99	MW13	800	16.1	
14-Oct-99	GP02-1	580	15.3		25-Oct-99	MW14	940	14.7	
14-Oct-99	GP02-2	10,500	0.3		25-Oct-99	MW15	1,020	21.6	
14-Oct-99	GP02-3	11,000	0.9		25-Oct-99	MW16	420	20.6	
14-Oct-99	GP03-1	1,000	13.2		25-Oct-99	MW17	780	12.0	
14-Oct-99	GP03-2	960	3.0		2-Nov-99	GP01-1	540	20.8	
14-Oct-99	GP04-1	160	20.7		2-Nov-99	GP01-2	7,400	0.1	
14-Oct-99	GP04-2	3,840	6.9		2-Nov-99	GP02-1	640	19.0	
14-Oct-99	GP04-3	4,300	6.1		2-Nov-99	GP02-2	7,420	0.6	
14-Oct-99	GP05-1	580	16.6		2-Nov-99	GP02-3	7,160	0.3	
14-Oct-99	GP05-2	680	14.9		2-Nov-99	GP03-1	740	14.4	
14-Oct-99	GP05-3	720	12.5		2-Nov-99	GP03-2	820	3.2	
14-Oct-99	GP05-4	760	11.2		2-Nov-99	GP04-1	280	20.9	
14-Oct-99	GP06-1	460	18.7		2-Nov-99	GP04-2	4,020	7.3	
14-Oct-99	GP06-2	640	15.5		2-Nov-99	GP04-3	4,040	7.8	
14-Oct-99	GP06-3	700	14.9		2-Nov-99	GP05-1	900	18.7	
14-Oct-99	GP07-1	640	18.6		2-Nov-99	GP05-2	960	16.1	
14-Oct-99	GP07-2	800	4.0		2-Nov-99	GP05-3	960	13.3	

Appendix 6: TPH Soil Vapour Survey Results

Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)	Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
2-Nov-99	GP05-4	960	10.9		15-Nov-99	GP04-1		20.0	0.4
2-Nov-99	GP06-1	520	20.8		15-Nov-99	GP04-2		2.8	11.3
2-Nov-99	GP06-2	720	17.1		15-Nov-99	GP04-3		2.5	12.7
2-Nov-99	GP06-3	740	16.3		15-Nov-99	GP05-1		17.5	2.6
2-Nov-99	GP07-1	980	20.3		15-Nov-99	GP05-2		15.7	4.3
2-Nov-99	GP07-2	1,100	5.3		15-Nov-99	GP05-3		11.7	6.0
2-Nov-99	GP07-3	1,140	9.8		15-Nov-99	GP05-4		13.3	7.2
2-Nov-99	GP08-1	420	20.7		15-Nov-99	GP06-1		18.4	1.3
2-Nov-99	GP08-2	680	16.1		15-Nov-99	GP06-2		16.8	3.2
2-Nov-99	GP08-3	720	15.8		15-Nov-99	GP06-3		16.3	4.0
2-Nov-99	GP09-1	560	19.8		15-Nov-99	GP07-1		18.1	1.3
2-Nov-99	GP09-2	680	17.4		15-Nov-99	GP07-2		6.9	5.6
2-Nov-99	GP09-3	740	16.0		15-Nov-99	GP07-3		11.7	7.8
2-Nov-99	GP09-4	760	15.7		15-Nov-99	GP08-1		19.6	1.2
2-Nov-99	GP10-1	700	6.7		15-Nov-99	GP08-2		17.3	4.6
2-Nov-99	GP10-2	760	4.0		15-Nov-99	GP08-3		16.3	4.9
2-Nov-99	GP10-3	800	3.7		15-Nov-99	GP09-1		18.7	2.8
2-Nov-99	MW02	760	6.8		15-Nov-99	GP09-2		17.4	4.5
2-Nov-99	MW03	720	17.3		15-Nov-99	GP09-3		15.7	6.4
2-Nov-99	MW04	860	10.8		15-Nov-99	GP09-4		15.7	7.1
2-Nov-99	MW05	980	5.6		15-Nov-99	GP10-1		18.0	2.4
2-Nov-99	MW06	1,240	16.0		15-Nov-99	GP10-2		19.0	1.8
2-Nov-99	MW08	780	18.6		15-Nov-99	GP10-3		8.5	9.5
2-Nov-99	MW09	1,080	8.5		15-Nov-99	MW02		7.6	9.7
2-Nov-99	MW13	720	14.9		15-Nov-99	MW03		17.6	5.6
2-Nov-99	MW14	860	13.0		15-Nov-99	MW04		11.7	10.8
2-Nov-99	MW15	740	21.5		15-Nov-99	MW05		6.9	13.4
2-Nov-99	MW16	480	20.7		15-Nov-99	MW06		15.7	7.8
2-Nov-99	MW17	740	6.3		15-Nov-99	MW08		16.8	7.0
8-Nov-99	GP01-1	600	20.9	0.8	15-Nov-99	MW09		11.0	7.9
8-Nov-99	GP01-2	5,040	6.8	9.6	15-Nov-99	MW13		19.2	1.7
8-Nov-99	GP02-1	720	19.7	3.1	15-Nov-99	MW14		11.5	9.4
8-Nov-99	GP02-2	6,480	11.9	7.1	15-Nov-99	MW15		20.8	0.0
8-Nov-99	GP02-3	9,120	2.1	16.7	15-Nov-99	MW16		19.9	0.7
8-Nov-99	GP03-1	820	16.2	4.2	15-Nov-99	MW17		9.8	8.3
8-Nov-99	GP03-2	1,000	4.0	9.2	6-Dec-99	GP01-1	980	17.7	0.6
8-Nov-99	GP04-1	280	20.9	0.4	6-Dec-99	GP01-2	6,000	0.3	3.7
8-Nov-99	GP04-2	3,540	8.9	8.6	6-Dec-99	GP02-1	640	18.9	0.6
8-Nov-99	GP04-3	3,160	18.6	2.2	6-Dec-99	GP02-2	1,220	18.7	0.6
8-Nov-99	GP05-1	860	18.4	2.8	6-Dec-99	GP03-1	1,120	15.2	0.7
8-Nov-99	GP05-2	900	17.2	4.1	6-Dec-99	GP03-2	1,300	6.9	2.2
8-Nov-99	GP05-3	1,000	15.1	5.7	6-Dec-99	GP04-1	480	19.8	0.6
8-Nov-99	GP05-4	980	14.1	6.7	6-Dec-99	GP04-2	3,100	3.1	4.4
8-Nov-99	GP06-1	740	20.1	1.5	6-Dec-99	GP04-3	3,140	2.6	3.4
8-Nov-99	GP06-2	860	17.1	3.8	6-Dec-99	GP05-1	940	17.4	0.4
8-Nov-99	GP06-3	860	16.7	4.2	6-Dec-99	GP05-2	1,040	16.3	1.2
8-Nov-99	GP07-1	600	20.4	1.2	6-Dec-99	GP05-3	1,230	14.3	1.2
8-Nov-99	GP07-2	740	15.9	0.6	6-Dec-99	GP06-1	760	18.6	1.2
8-Nov-99	GP07-3	1,020	12.5	8.4	6-Dec-99	GP06-2	1,000	17.4	1.6
8-Nov-99	GP08-1	640	20.5	0.8	6-Dec-99	GP06-3	1,080	16.8	0.8
8-Nov-99	GP08-2	940	16.3	5.0	6-Dec-99	GP07-1	740	17.9	0.2
8-Nov-99	GP08-3	900	16.1	5.0	6-Dec-99	GP07-2	1,020	11.2	0.4
8-Nov-99	GP09-1	780	19.3	2.4	6-Dec-99	GP07-3	1,320	11.3	2.2
8-Nov-99	GP09-2	860	18.6	3.8	6-Dec-99	GP08-1	440	20.2	0.2
8-Nov-99	GP09-3	980	17.7	4.6	6-Dec-99	GP08-2	1,000	17.2	0.8
8-Nov-99	GP09-4	1,020	16.6	6.2	6-Dec-99	GP08-3	920	18.6	0.8
8-Nov-99	GP10-1	980	9.4	6.9	6-Dec-99	GP09-1	140	18.5	1.8
8-Nov-99	GP10-2	1,000	8.0	7.2	6-Dec-99	GP09-2	1,200	17.7	1.8
8-Nov-99	GP10-3	1,040	6.0	8.6	6-Dec-99	GP09-3	1,340	16.0	1.2
8-Nov-99	MW02	1,020	9.1	8.3	6-Dec-99	GP09-4	1,200	17.7	0.7
8-Nov-99	MW03	920	17.7	5.2	6-Dec-99	GP10-1	1,320	10.8	1.6
8-Nov-99	MW04	1,120	10.8	11.5	6-Dec-99	GP10-2	1,260	12.4	3.7
8-Nov-99	MW05	1,120	7.1	13.7	6-Dec-99	GP10-3	1,280	10.6	2.4
8-Nov-99	MW06	1,340	11.2	8.4	6-Dec-99	MW02	1,280	10.2	2.6
8-Nov-99	MW08	880	18.6	5.8	6-Dec-99	MW03	1,240	16.8	0.8
8-Nov-99	MW09	1,060	14.0	5.2	6-Dec-99	MW04	1,320	13.0	4.4
8-Nov-99	MW13	900	16.6	5.4	6-Dec-99	MW05	1,560	6.1	5.4
8-Nov-99	MW14	1,020	15.1	6.4	6-Dec-99	MW06	1,460	13.5	2.2
8-Nov-99	MW15	660	20.9	0.0	6-Dec-99	MW08	1,320	18.4	0.4
8-Nov-99	MW16	420	20.1	0.8	6-Dec-99	MW09	1,360	9.4	0.8
8-Nov-99	MW17	1,020	8.6	8.3	6-Dec-99	MW13	1,080	17.1	1.8
15-Nov-99	GP01-1		19.7	0.6	6-Dec-99	MW14	1,600	10.0	1.5
15-Nov-99	GP01-2		0.9	12.2	6-Dec-99	MW15	400	20.9	0.4
15-Nov-99	GP02-1		18.0	2.4	6-Dec-99	MW16	740	20.1	0.4
15-Nov-99	GP02-2		0.9	14.7	6-Dec-99	MW17	1,260	14.2	2.6
15-Nov-99	GP02-3		2.6	17.0	18-Dec-99	GP01-1	1,300	18.3	2.7
15-Nov-99	GP03-1		15.7	4.2	18-Dec-99	GP01-2	4,220	4.0	4.0
15-Nov-99	GP03-2		2.2	9.5	18-Dec-99	GP02-1	1,720	15.6	3.6

Appendix 6: TPH Soil Vapour Survey Results

Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
18-Dec-99	GP02-2	5,780	2.4	5.1
18-Dec-99	GP03-1	1,080	14.7	0.6
18-Dec-99	GP03-2	1,340	4.3	1.6
18-Dec-99	GP04-1	320	19.0	0.1
18-Dec-99	GP04-2	3,160	5.8	3.8
18-Dec-99	GP04-3	2,680	12.0	3.3
18-Dec-99	GP06-1	820	17.1	0.2
18-Dec-99	GP06-2	980	16.4	0.4
18-Dec-99	GP06-3	1,060	16.1	0.8
18-Dec-99	GP07-1	820	16.8	0.4
18-Dec-99	GP07-2	860	18.4	0.4
18-Dec-99	GP07-3	1,360	10.5	0.8
18-Dec-99	GP08-1	420	20.1	0.0
18-Dec-99	GP08-2	960	17.7	0.2
18-Dec-99	GP08-3	1,040	17.5	0.6
18-Dec-99	GP09-1	860	18.9	0.8
18-Dec-99	GP09-2	1,060	18.0	1.0

Date	Location	TPH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
18-Dec-99	GP09-3	1,200	16.5	1.7
18-Dec-99	GP10-1	1,340	10.3	1.3
18-Dec-99	GP10-2	1,320	10.8	2.2
18-Dec-99	GP10-3	1,280	11.5	2.6
18-Dec-99	MW02	1,230	13.5	0.8
18-Dec-99	MW03	1,200	16.7	0.8
18-Dec-99	MW04	1,420	14.6	1.4
18-Dec-99	MW05	1,580	11.1	1.6
18-Dec-99	MW06	2,240	14.4	2.0
18-Dec-99	MW08	1,160	18.3	0.7
18-Dec-99	MW09	1,020	10.9	1.4
18-Dec-99	MW13	1,030	18.3	0.6
18-Dec-99	MW14	1,200	16.8	0.5
18-Dec-99	MW15	2,860	20.5	0.0
18-Dec-99	MW16	700	20.3	0.4
18-Dec-99	MW17	1,280	13.3	0.7

APPENDIX 7:

Climate Data (Collected On-Site)

Appendix 7: Climatic Data (Collected On-Site)

Date	Air Temperature (°C)	Barametric Pressure (kPa)	Soil Temperature (°C)		
			(0.75 m bgs)	(1.5 m bgs)	(3.0 m bgs)
16-Aug-99	13.6	102.28	24	22	15
17-Aug-99	17.5	101.08	24	22	15
18-Aug-99	17.2	101.24	24	22	15
19-Aug-99	16.5	101.8	24	22	15
20-Aug-99	16.2	101.96	24	22	15
11-Sep-99	22.1	101.14	21	21	15
13-Sep-99	23.4	101.71	21	21	15
14-Sep-99	18.9	101.71	21	21	15
16-Sep-99	16.5	101.83	21	21	15
17-Sep-99	18.4	101.47	21	21	15
18-Sep-99	20.9	101.81	21	21	15
20-Sep-99	18.3	100.97	22	21	16
21-Sep-99	9.4	101.76	22	21	15
22-Sep-99	8.9	101.25	22	21	15
23-Sep-99	12.9	100.68	22	21	15
23-Sep-99	12.9	100.68	22	21	15
23-Sep-99	12.9	100.68	22	21	15
23-Sep-99	12.9	100.68	22	21	15
28-Sep-99	26.4	102.01	19	20	16
29-Sep-99	20.8	101.43	19	20	16
30-Sep-99	10.3	99.93	19	20	16
01-Oct-99	16.2	100.98	19	20	16
02-Oct-99	12.1	101.8	19	20	16
05-Oct-99	3.9	102.3	18	18	16
06-Oct-99	5.1	101.69	18	18	16
14-Oct-99	5.6	101.71	18	18	16
25-Oct-99	2.8	101.74	12	15	15
02-Nov-99	14.9	100.71	14	14	15
08-Nov-99	-0.4	102.45	11	13	15
15-Nov-99	—	—	9	12	14
06-Dec-99	4	100.4	6	10	10
18-Dec-99	-1.6	101.46	5	9	12

APPENDIX 8:

Barometric Pressure with Soil Gas TPH Concentrations

Barometer (kPa) vs. TPH
Clay Source Wells, Level 1

— GP01-1 — GP02-1 — GP04-1 — Barometer (kPa)

Barometer (kPa) vs. TPH Clay Source Wells, Level 2

Barometer (kPa) vs. TPH
Clay Source Wells, Level 3

Barometer (kPa) vs. TPH Clay Migration Wells, Level 1

*— GP03-1   □— GP07-1   ○— GP08-1   △— GP09-1   ◇— GP10-1   — Barometer (kPa)

Barometer (kPa) vs. TPH Clay Migration Wells, Level 2

* GP03-2 □ GP07-2 ○ GP08-2 △ GP09-2 ◇ GP10-2 — Barometer

Barometer (kPa) vs. TPH Clay Migration Wells, Level 3

Barometer (kPa) vs. TPH Clay Migration Wells, Level 4

Barometer (kPa) vs. TPH
Sand Wells, Level 1

△ GP05-1 ○ GP06-1 — Barometer

Barometer (kPa) vs. TPH
Sand Wells, Level 2

—△— GP05-2 —○— GP06-2 — Barometer

Barometer (kPa) vs. TPH
Sand Wells, Level 3

△ GP05-3 ○ GP06-3 — Barometer

Barometer (kPa) vs. TPH
Sand Wells, Level 4

—△— GP05-4 —○— GP06-4 — Barometer

APPENDIX 9:

Analytical Results: BTEX Soil Vapour Survey Results

Appendix 9: BTEX Soil Vapour Survey Results

Date	Sample Location	Duplicate (Yes/No?)	Detection Limits (ppmv)				Concentration (ppmv)						
			Benzene	Toluene	Ethylbenzene	M&P Xylene	O Xylene	Benzene	Toluene	Ethylbenzene	M&P Xylene	O Xylene	Total BTEX
27-Jul-99	GP01-1	No	0.01	0.03	0.05	0.10	0.26	0.0	0.5	0.5	0.7	0.0	1.8
	GP01-2	No	0.01	0.01	0.02	0.05	0.12	0.6	1.8	0.0	2.9	2.1	7.4
	GP01-3	No	0.02	0.04	0.08	0.15	0.37	1.3	1.5	0.9	3.2	0.0	6.9
	GP01-4	No	0.01	0.03	0.05	0.10	0.26	28.6	20.9	1.4	20.4	16.3	87.6
	GP02-1	No	0.01	0.02	0.03	0.05	0.13	0.2	0.3	0.0	0.0	0.0	0.5
	GP02-2	No	0.01	0.02	0.03	0.05	0.13	0.3	0.5	0.3	0.4	0.0	1.4
	GP02-3	No	0.01	0.03	0.05	0.10	0.26	0.6	0.5	0.0	0.8	0.0	2.0
	GP02-4	No	0.01	0.03	0.05	0.10	0.26	11.3	9.1	3.9	11.4	7.4	43.1
	GP03-1	No	0.01	0.02	0.03	0.05	0.13	0.3	0.5	0.4	1.3	1.8	4.2
	GP03-2	No	0.01	0.02	0.04	0.07	0.17	0.4	0.8	0.4	1.5	1.4	4.5
	GP03-3	No	0.01	0.02	0.04	0.07	0.17	0.0	0.4	0.0	0.0	0.0	0.4
	GP04-1	No	0.00	0.01	0.02	0.03	0.09	0.0	0.2	0.2	0.2	0.0	0.6
	GP04-2	No	0.00	0.01	0.02	0.03	0.09	0.2	0.3	0.0	0.4	0.4	1.2
	GP05-1	No	0.01	0.02	0.03	0.05	0.13	0.0	0.2	0.0	0.0	0.0	0.2
	GP05-2	No	0.01	0.02	0.03	0.05	0.13	0.2	0.3	0.0	0.3	0.0	0.8
	GP05-3	No	0.01	0.02	0.03	0.05	0.13	0.0	0.2	0.0	0.0	0.0	0.2
	GP05-4	No	0.01	0.02	0.03	0.05	0.13	0.2	0.3	0.0	0.0	0.0	0.5
	GP06-1	No	0.01	0.02	0.03	0.05	0.13	0.0	0.2	0.0	0.0	0.0	0.2
	GP06-2	No	0.01	0.02	0.03	0.05	0.13	0.0	0.2	0.0	0.0	0.0	0.2
	GP06-3	No	0.01	0.02	0.03	0.05	0.13	0.0	0.2	0.0	0.0	0.0	0.2
	GP06-4	No	0.01	0.02	0.03	0.05	0.13	0.2	0.3	0.0	0.3	0.0	0.9
	GP07-1	No	0.00	0.01	0.02	0.03	0.09	0.0	0.2	0.0	0.3	0.0	0.4
	GP07-2	No	0.01	0.02	0.03	0.06	0.15	0.3	0.4	0.4	0.8	0.8	2.6
	GP07-3	No	0.01	0.02	0.03	0.05	0.13	0.2	0.2	0.5	0.0	0.0	0.9
	GP08-1	No	0.01	0.03	0.05	0.10	0.26	0.4	0.6	0.5	0.0	0.0	1.5
	GP08-2	No	0.01	0.03	0.05	0.10	0.26	0.4	0.5	0.0	0.0	0.0	0.9
	GP08-3	No	0.01	0.03	0.05	0.10	0.26	0.4	0.7	0.0	0.6	0.0	1.7
	GP08-4	No	0.01	0.03	0.05	0.10	0.26	0.4	0.6	0.0	0.6	0.0	1.6
	GP09-1	No	0.01	0.03	0.05	0.10	0.26	0.0	0.5	0.0	0.0	0.0	0.5
	GP09-2	No	0.01	0.03	0.05	0.10	0.26	0.4	0.5	0.0	0.6	0.0	1.5
	GP09-3	No	0.01	0.03	0.05	0.10	0.26	0.4	0.6	0.0	0.6	0.0	1.6
	GP09-4	No	0.01	0.03	0.05	0.10	0.26	0.4	0.5	0.0	0.0	0.0	0.9
	GP10-1	No	0.01	0.03	0.05	0.10	0.26	0.0	0.4	0.0	0.0	0.0	0.4
	GP10-2	No	0.01	0.03	0.05	0.10	0.26	0.4	0.5	0.5	0.6	0.0	2.0
	GP10-3	No	0.01	0.03	0.05	0.10	0.26	0.5	1.0	0.6	0.7	1.1	3.9

Appendix 9: BTEX Soil Vapour Survey Results (cont'd)

Date	Sample Location	Duplicate (Yes/No?)	Detection Limits (ppmv)				Concentration (ppmv)						
			Benzene	Toluene	Ethylbenzene	M&P Xylene	O Xylene	Benzene	Toluene	Ethylbenzene	M&P Xylene	O Xylene	Total BTEX
11-Sep-99	GP01-1	No	0.01	0.02	0.03	0.05	0.13	0.4	0.5	0.7	2.3	1.4	5.4
	GP01-2	No	0.01	0.03	0.05	0.10	0.26	8.0	1.6	1.9	2.8	0.0	14.3
	GP02-1	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP02-2	No	0.01	0.03	0.05	0.10	0.26	0.2	0.2	0.0	0.0	0.0	0.4
	GP02-3	No	0.03	0.06	0.11	0.21	0.52	16.2	8.5	7.1	20.0	9.4	61.2
	GP03-1	No	0.01	0.02	0.03	0.05	0.13	0.1	0.1	0.1	0.4	0.0	0.7
	GP03-2	No	0.01	0.02	0.03	0.05	0.13	0.1	0.1	0.1	0.2	0.0	0.4
	GP04-1	No	0.01	0.02	0.03	0.05	0.13	0.1	0.1	0.1	0.3	0.0	0.6
	GP04-2	No	0.01	0.02	0.03	0.05	0.13	0.4	0.1	0.0	0.1	0.0	0.6
	GP04-3	No	0.01	0.03	0.05	0.10	0.26	0.7	0.3	0.4	1.4	0.6	3.3
	GP05-1	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP05-2	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP05-3	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP05-4	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP06-1	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP06-2	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP06-3	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP06-4	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP07-1	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP07-2	No	0.01	0.02	0.03	0.05	0.13	0.1	0.1	0.1	0.2	0.7	0.4
	GP07-3	No	0.01	0.02	0.03	0.05	0.13	0.1	0.1	0.1	0.1	0.4	0.0
	GP08-1	No	0.01	0.02	0.03	0.05	0.13	0.1	0.1	0.1	0.0	0.0	0.0
	GP08-2	No	0.01	0.02	0.03	0.05	0.13	0.1	0.1	0.1	0.0	0.0	0.0
	GP08-3	No	0.01	0.02	0.03	0.05	0.13	0.1	0.1	0.1	0.0	0.1	0.0
	GP08-4	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.1	0.0	0.0	0.1
	GP09-1	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.1	0.0	0.0	0.1
	GP09-2	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.1	0.0	0.0	0.1
	GP09-3	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.1	0.0	0.0	0.1
	GP09-4	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.1	0.0	0.0	0.1
	GP10-1	No	0.01	0.02	0.03	0.05	0.13	0.1	0.1	0.1	0.0	0.1	0.0
	GP10-2	No	0.01	0.02	0.03	0.05	0.13	0.1	0.2	0.2	0.0	0.1	0.0
	GP10-3	No	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.0	0.0	0.0	0.1
	GP01-1	Yes	0.01	0.02	0.03	0.05	0.13	0.1	0.2	0.2	0.3	0.9	0.5
	GP02-3	Yes	0.01	0.03	0.05	0.10	0.26	14.6	2.9	2.9	5.3	12.9	5.0
	GP06-1	Yes	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.1	0.0	0.0	0.0
	GP06-2	Yes	0.01	0.02	0.03	0.05	0.13	0.0	0.1	0.1	0.0	0.0	0.0

Appendix 9: BTEX Soil Vapour Survey Results (cont'd)

Date	Sample Location	Duplicate (Yes/No?)	Detection Limits (ppmv)				Concentration (ppmv)					Total BTEX	
			Benzene	Toluene	Ethylbenzene	M&P Xylene	O Xylene	Benzene	Toluene	Ethylbenzene	M&P Xylene		O Xylene
25-Oct-99	GP01-1	No	0.01	0.02	0.05	0.05	0.10	0.5	0.3	1.3	2.2	0.7	5.0
	GP01-2	No	0.01	0.04	0.11	0.10	0.21	0.5	1.3	3.2	0.0	0.0	5.1
	GP02-1	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP02-2	No	0.01	0.04	0.11	0.10	0.21	14.5	0.0	4.2	6.0	0.0	24.7
	GP02-3	No	0.03	0.07	0.21	0.21	0.42	12.8	5.3	3.3	9.1	0.0	30.6
	GP03-1	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP03-2	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.1	0.3	0.0	0.4
	GP04-1	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.1	0.0	0.1
	GP04-2	No	0.01	0.04	0.11	0.10	0.21	5.0	0.7	0.6	1.4	0.0	7.7
	GP04-3	No	0.01	0.02	0.05	0.05	0.10	0.2	0.1	0.2	0.6	0.0	1.2
	GP05-1	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP05-2	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP05-3	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP05-4	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP06-1	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP06-2	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP06-3	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.1
	GP07-1	No	0.01	0.02	0.05	0.05	0.10	0.1	0.0	0.2	0.4	0.0	0.6
	GP07-2	No	0.01	0.02	0.05	0.05	0.10	0.3	0.3	0.5	1.5	0.8	3.4
	GP07-3	No	0.03	0.07	0.21	0.21	0.42	0.1	0.0	0.0	0.0	0.0	0.1
	GP08-1	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP08-2	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP08-3	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP09-1	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.1	0.1	0.1	0.2
	GP09-2	No	0.01	0.02	0.05	0.05	0.10	0.1	0.0	0.1	0.1	0.1	0.5
	GP09-3	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.2	0.2	0.2
	GP09-4	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.1	0.1	0.1
	GP10-1	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP10-2	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP10-3	No	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP04-2	Yes	0.03	0.07	0.21	0.21	0.42	5.8	0.9	0.6	1.4	0.0	8.7
	GP06-3	Yes	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP07-3	Yes	0.01	0.04	0.11	0.10	0.21	0.0	0.0	0.0	0.0	0.0	0.0
	GP10-2	Yes	0.01	0.02	0.05	0.05	0.10	0.0	0.0	0.0	0.0	0.0	0.0
	GP04-2	Yes	0.01	0.04	0.11	0.10	0.21	4.8	0.7	0.0	0.0	0.0	5.5

Appendix 9: BTEX Soil Vapour Survey Results (cont'd)

Date	Sample Location	Duplicate (Yes/No?)	Detection Limits (ppmv)				Concentration (ppmv)						
			Benzene	Toluene	Ethylbenzene	M&P Xylene	O Xylene	Benzene	Toluene	Ethylbenzene	M&P Xylene	O Xylene	Total BTEX
6-Dec-99	GP01-1	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP01-2	No	0.01	0.02	0.11	0.21	0.10	0.7	0.0	0.0	0.0	0.0	0.7
	GP01-2	Yes	0.01	0.01	0.05	0.10	0.05	9.6	0.8	3.7	3.9	0.0	18.0
	GP02-1	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP02-2	No	0.01	0.01	0.05	0.10	0.05	1.4	0.4	0.4	0.3	0.0	2.6
	GP02-2	Yes	0.01	0.01	0.05	0.10	0.05	1.1	0.3	0.3	0.2	0.0	1.9
	GP02-2	Yes	0.01	0.01	0.05	0.10	0.05	5.0	0.7	1.3	0.9	0.0	8.0
	GP02-2	Yes	0.03	0.05	0.21	0.42	0.21	2.5	2.8	5.4	3.6	0.0	14.3
	GP03-1	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP03-2	No	0.01	0.01	0.05	0.10	0.05	0.1	0.1	0.0	0.1	0.0	0.4
	GP04-1	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP04-2	No	0.01	0.02	0.11	0.21	0.10	1.0	0.0	0.0	0.0	0.0	1.0
	GP04-2	Yes	0.01	0.02	0.11	0.21	0.10	4.9	0.0	0.0	0.0	0.0	4.9
	GP04-3	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP05-1	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP05-1	Yes	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP05-2	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP05-3	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP06-1	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP06-1	Yes	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP06-2	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP06-3	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP07-1	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP07-1	Yes	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP07-2	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP07-3	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP08-1	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP08-2	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP08-3	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP09-1	No	0.01	0.01	0.05	0.10	0.05	0.2	0.0	0.3	0.4	0.0	1.0
	GP09-2	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP09-3	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP09-4	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP10-1	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP10-2	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0
	GP10-3	No	0.01	0.01	0.05	0.10	0.05	0.0	0.0	0.0	0.0	0.0	0.0