University of Alberta

Library Release Form

Name of Author: James Edward Armstrong

Title of Thesis: Variability in groundwater monitoring data used to assess natural attenuation of hydrocarbon contamination at upstream oil and gas facilities

Degree: Doctor of Philosophy

Year this Degree Granted: 2008

Signature

University of Alberta

Variability in groundwater monitoring data used to assess natural attenuation of hydrocarbon contamination at upstream oil and gas facilities

by

James Edward Armstrong

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Geotechnical Engineering

Department of Civil and Environmental Engineering

Edmonton, Alberta
Fall 2008

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Variability in groundwater monitoring data used to assess natural attenuation of hydrocarbon contamination at upstream oil and gas facilities submitted by **James Edward Armstrong** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy**.

Kevin W. Biggar

Robert Donahue

Selma E. Guigard

Carl A. Mendoza

David C. Sego

James F. Barker – External Examiner

Supervisor writes the date that the thesis is approved by committee here

Dedication

This thesis is dedicated to my wife, Norma and children, Daniel, Christina and Michael, for their patience, support and encouragement.

Abstract

Natural attenuation (NA) describes how naturally occurring processes reduce contaminant mass and concentration without human intervention. Interpretation of attenuation process(es) uses spatio-temporal trends in contaminants and terminal electron acceptors (TEAPs); thus is influenced by data variability.

Research well clusters installed at two hydrocarbon-contaminated field sites (A and B) in Alberta undergoing NA were sampled to examine influences related to monitoring well completions and sampling methodology. Historical data showed temporal variability ranged from twofold to two orders of magnitude. Paired sample data collected from 0.7 m to 1.5 m long screened wells using no-purge and low-flow purge protocols were typically within a factor of three, except sulphate (dominant TEAP).

Wells with 3 m long screens had greater sample variability, being influenced more by uncontrollable in-well mixing than sampling method. Multiple data sets from these wells using no-purge and low-flow or specified purge volumes helped identify this variability, and enable characterization of contaminants (factor of two) and TEAs (order-of-magnitude).

Groundwater elevation logging identified short-term variations (days) that affect interpretation of TEA data and natural attenuation. Monthly groundwater sampling events (no-purge and low-flow purge protocols) showed minor differences for most major ions and hydrocarbon contaminants, but evidence of unrecognized, episodic sulphate replenishment. Differences in sulphate concentrations between consecutive monitoring visits enabled estimation of an effective sulphate depletion rate. This approach gave similar sulphate depletion rates (as a biodegradation indicator) to values from two independent studies conducted at the same site: field injection of sulphate-amended water to stimulate hydrocarbon biodegradation, and numerical simulation of reactive transport of dissolved hydrocarbons including interactions with solid phase minerals.

Selection of natural attenuation over other remedial methods is based on: interpreted ability to reach specified targets concentrations within an acceptable time and monitoring cost compared to other methods. Field data from a naturally-attenuating plume (Site C) were used to re-examine the original decision to rely on natural attenuation, through the influence of adding monitoring data on predicting remediation progress. The averaged attenuation rate decreased notably over the first few years of monitoring, underestimating the remediation time required by a factor of two to three.

Acknowledgement

Funding through the Consortium for Research on Natural Attenuation (CORONA) is gratefully acknowledged, particularly from industrial partners including ConocoPhilips Canada, Devon Canada and Alberta Environment, and matching funding provided by Coordination of University Research for Synergy and Effectiveness (COURSE) and Natural Sciences and Engineering Research Council (NSERC). In-kind contributions are appreciated from Maxxxam Analytics Inc., Shell Canada and WorleyParsons (formerly Komex International Ltd.).

The author is extremely grateful to Drs. Kevin Biggar and Carl Mendoza for ongoing discussions and guidance. Other research participants who have helped with many insightful conversations and efforts include Ms. Kim McLeish (U of C), Dr. Dale Van Stempvoort (NWRI), and Mr. Chad Petersmeyer (UBC). Valuable assistance was also provided by fellow students, particularly Stephanie Loster-Anderson (U of Calgary), and Dean Morin, Olumide Iwakun, Xiaoying Fan and Amir Hosseini (U of Alberta). Lastly, assistance is also gratefully acknowledged from Mr. Kent Burkholder, Decision Frameworks LLC for many discussions, advice and the use of their decision modelling software.

Gratitude is extended to many other scientists who contributed to this work in many ways, particularly Mr. Brent Moore, Drs. Mario and Kristin Schirmer, Dr. Tad Dabrowski, Mr. Lucien Lyness and Dr. Jon Fennell. Thanks also to Ms. Jamie Belanger for valuable help in encouraging, formatting and compiling the document.

1. INTRODUCTION

1.1 Background

Natural attenuation (NA) refers to the reduction in contaminant mass by a series of naturally occurring physical, chemical and biological processes (USEPA, 1999b). Evidence gained from a combination of research studies and empirical data has shown that NA can prevent environmental receptors from being negatively affected by some contaminants under certain conditions. As a result environmental regulations have been developed in many jurisdictions that describe the data and actions required for site owners and managers to rely on NA. Key requirements include development of a conceptual model describing the contaminant(s) and attenuation processes, identification of environmental receptors and monitoring activities intended to confirm that contaminant(s) are attenuating under local natural conditions (ASTM, 1998; Carey et al., 2000; USEPA, 1999b).

Appreciation of how NA could constrain groundwater plume migration was initially developed for dissolved petroleum hydrocarbons (PHCs) associated with releases of refined hydrocarbon fuels (e.g., gasoline, diesel, jet fuel). Focus was mainly applied to the most soluble compounds associated with these PHCs, including benzene, toluene, ethylbenzene and xylenes (BTEX). As experience and scientific knowledge increased, it became recognized that other components in gasoline, most notably methyl tert-butyl ether (MTBE), did not attenuate as readily as the BTEX compounds. In other cases, gasoline additives such as ethanol were found to influence attenuation characteristics of BTEX compounds (Da Silva and Alvarez, 2002). These results reinforce the need to consider both individual and joint attenuation characteristics of dissolved groundwater contaminants and their concentrations relative to the original source.

A major potential source of hydrocarbon contamination is associated with exploration, exploitation and conveyance activities for unrefined petroleum fluids such as oil and gas (so-called upstream oil and gas industry). The most common contaminants associated with this industry include the BTEX suite, chloride and sulphate-based salts and a variety of process chemicals (CPA, 1992). The main facilities to consider include: individual well sites, compressor and battery sites where some local gas processing may occur, oil and/or gas-processing plants, and the pipelines connecting all of these facilities.

TABLE OF CONTENTS

List of Tables

List of Figures

List of Appendices

Several Canadian regulatory bodies have the responsibility to set guidelines and requirements that control the upstream oil and gas industry. From an Albertan environmental perspective, characterization and remediation of contaminant situations is broadly controlled by Alberta Environment (AE), based on the Alberta Environmental Protection and Enhancement Act (AEPEA). More specifically, AE has developed a series of regulations, codes, standards and guidelines that provide detailed controls. Broadly stated, key concepts under AEPEA include:

- a duty not to release substances that may cause a significant adverse effect;
- a duty to take all reasonable measures to control or remove the substance(s) and restore the environment to a satisfactory condition (as defined by the government), and,
- the polluter pays.

There is no explicit allowance within the Alberta environmental regulations that permits site owners to rely solely on NA.

A research consortium (Consortium for Research on Natural Attenuation, CORONA) was developed at the University of Alberta with a goal of providing technical guidance and supporting scientific information regarding NA of upstream contaminants for site owners, consultants and regulators. The first task involved conducting a study of common groundwater contaminant situations associated with upstream oil and gas industry activities in Alberta. Reviews of available environmental monitoring data identified PHCs and chloride-based salts as the primary compounds of concern (Armstrong et al., 2002). The review also provided supporting evidence that NA of unrefined PHCs is occurring at many sites throughout Alberta. Other scientific research programs have provided supporting evidence leading to a similar conclusion that upstream PHCs attenuate naturally (Baedecker et al., 1993; Barker et al., 1996; Elshahed et al., 2001; Gieg et al., 1999; Morgan et al., 1993; NRC, 1993; Rueter et al., 1994; Townsend et al., 2004).

The CORONA study (Armstrong et al., 2002) recognized several concerns with the available monitoring data. Most dissolved PHC groundwater plumes were characterized with relatively few monitoring wells, had been incompletely delineated and had been sampled using bailers where the sampling protocol involved a conventional approach of purging three well volumes prior to sampling. Based on evidence of hydrochemical variability and multiple potential underlying causes (e.g., sampling methods, well construction, environmental and hydrogeological conditions), questions existed as to whether these historical data could be considered reliable for

NA assessment. To address some possible causes, two sites (A and B) were selected to examine sampling-related variability and the associated influence on interpreting NA characteristics.

Much of the current understanding regarding NA derived from a combination of detailed, single-process assessment and broad, empirical or field-based observations. Both research styles (process-drive and holistic, respectively) need to be combined to improve understanding of NA processes (Alvarez and Illman, 2006). This strategy was used to develop the scope of CORONA.

The CORONA program consists of a series of research activities developed using a variety of office-, laboratory- and field-based investigations and experiments. Field research sites were initially selected for a variety of NA-related research activities within the scope of CORONA. Sites A and B had adequate monitoring data to support a preliminary hypothesis that natural attenuation was adequately controlling migration of dissolved hydrocarbon contamination. Additional sites have subsequently been added to examine additional aspects of NA that could not be evaluated using the initial sites. As an example, Site C was added to enable examination of issues related to assessing longer-term NA performance, and understanding how monitoring data variability might affect decisions about whether to continue relying on NA to control the dissolved contaminant plume.

A number of other projects related to the overall CORONA project have also been initiated. The projects conducted under CORONA are summarized in Table 1-1, followed by a list of research projects related to CORONA activities summarized in Table 1-2. A list of publications describing various activities related to these projects is provided in Appendix I.

Table 1-1 Overview of CORONA research activities

Project	**Site**	**Aspect**
Site Characterization	A, B	Cone-penetrometer testing with ultraviolet induced fluorescence for free phase hydrocarbon source area delineation (**Armstrong**, U of A)
Site Characterization	A, B	Variability associated with groundwater sampling to support natural attenuation (**Armstrong**, U of A)
Site Characterization	A	Soil sampling and numerical modelling to examine the role of sulphate reduction as a natural attenuation process (Petersmeyer, UBC)

Project	**Site**	**Aspect**
Site Characterization	A, B	Field-based evaluation of various sampling methodologies to monitor natural attenuation processes (Morin, U of A)
Site Characterization	A, B	Durability and construction requirements for natural assessment using dialysis membrane samplers (Olumide, U of A)
Biodegradation Process	A, B	Mesocosm assessment of TEA addition on anaerobic hydrocarbon biodegradation processes (Fan, U of A)
Biodegradation Process	A, B	Biodegradation metabolite detection to support hydrocarbon biodegradation assessment in the field and laboratory (Semple, U of A)
Biodegradation Process		Impact of cold temperatures on biodegradation rates for natural attenuation of petroleum hydrocarbons (Gruber, U of A).
Biodegradation Process	A, B	Microcosm assessment of salinity-induced inhibition of aerobic hydrocarbon biodegradation (Ulrich, U of A)
Long-term NA Assessment	A, C	Analysis of decision uncertainty related to longer-term NA performance (**Armstrong**, U of A)
Long-term NA Assessment	A, B	Modelling of natural attenuation incorporating heterogeneity and geostatistical analyses (Hosseini, U of A)

Table 1-2 Overview of other research projects associated with CORONA

Project	**Site**	**Aspect**
Biodegradation Process		Microcosm assessment of anaerobic biodegradation processes and potential for enhanced biodegradation of diesel-range hydrocarbons (Cross, U of A)
Site Characterization		Improvement of the CPT-UVIF tool for site characterization (Alostaz, U of A)
Site Characterization	A	Enhanced natural attenuation using dissolved sulphate amendment (Van Stempvoort, NWRI)
Site Characterization	A, B	Field-based evaluation of a diffusion-based dissolved gas sampling methodology to monitor natural attenuation processes (McLeish, U of C)

Project	Site	Aspect
Site Characterization		Field-based evaluation of the diffusion-based dialysis membrane sampling system for groundwater monitoring (**Armstrong**, U of A)

The component of the CORONA research program described in this thesis concentrated on assessing variability in monitoring data used to support ongoing NA of PHCs at field sites in Alberta. The research was initiated by a broad review of monitoring data that had been collected at PHC-contaminated sites using conventional monitoring wells and monitoring methodologies. The data review identified a number of dissolved PHC plumes in groundwater associated with upstream oil and gas sites, but that NA generally appeared able to restrict plume growth (Armstrong et al., 2002). Using assessment methods based on field data as described in current NA protocols (USEPA, 1999a), the dominant electron accepting process appeared to be sulphate reduction. At the same time, several concerns were identified by this review. In particular, most monitoring wells had 3 m long screened intervals, and samples had typically been collected after the well recovered following purging of up to three well volumes or until the well was purged dry. Given that variability/bias could be introduced during sampling (see Chapter 2), a main question to address was if, and to what extent, these historical data could be used to assess NA processes. A series of field sampling programs were designed to enable a better understanding of variability associated with groundwater sampling protocols and methodology relative to spatio-temporal variability of the PHC contaminants and associated geochemical indicators used to infer natural attenuation (Cozzarelli et al., 1999). In conjunction with the sampling activities for NA assessment, soil and groundwater samples were also obtained. These samples were used in laboratory experiments to improve understanding of the various biodegradation processes, and to provide site-specific data as input for computer modelling efforts.

The research presented in this thesis focuses on assessing how groundwater analyses collected using varying monitoring well configurations (screen length, completion depth, and duplicate installations) and sampling methods might influence decisions regarding potential for natural attenuation to achieve remediation goals. The issues being considered relate to interpretation of NA processes based on dissolved contaminant concentrations, and the differential concentrations of geochemical indicators commonly used as supporting evidence of natural attenuation (dissolved oxygen, nitrate, manganese, iron, sulphate and methane). The research sites are broadly described below, with additional detail and site plans provided in Appendix II. Analytical data are tabulated in Appendix III.

Site A is an active, natural gas processing facility located in southeast Alberta. The contamination source is interpreted to be historical, intermittent, accidental releases of gas condensate related to a fire-training facility. Fire training is continuing in this area, thus the possibility of future releases cannot be discounted. The Quaternary glacial surficial sediments consist of fine-grained silty sand to sandy silt. There are no nearby groundwater users or ecological receptors in the immediate area. Additional monitoring wells were installed within the dissolved PHC plume area, and helped refine the original conceptual model. The model is that PHC-contaminated groundwater is migrating from the source area to the northwest, within the uppermost groundwater-bearing unit. Groundwater flows at approximately 5 m/year, and the PHC groundwater plume extends approximately 150 m from the fire-training facility.

Site B is an active natural gas and oil producing facility located in a remote part of west central Alberta. The contaminant situation is related to a former flare pit that had been excavated in 1998 before the CORONA program started. Remaining subsurface contamination is related to free-phase hydrocarbon and chloride-based salt that had migrated from the former pit. The Quaternary glacial surficial sediments generally comprise sand, silt and clay layers, with the sand layers located mainly near the former pit. There are no groundwater users or ecological receptors in the immediate area. The extent of the source contamination was determined to be relatively well constrained by using samples obtained from monitoring wells installed in boreholes for cone penetrometer with ultraviolet-induced fluorescence (CPT-UVIF) testing. The CPT-UVIF work identified a much more complicated and heterogeneous contaminant and geologic situation than had originally been inferred from previous monitoring information. The PHC plume extends approximately 50 m from the source area; the average groundwater flow rate is around 10 m/year.

Site C is an active gas processing facility located in southwest Alberta. A single-event release of natural gas condensate occurred in fall 1998 under well-constrained conditions. Approximately half of the estimated release volume was recovered immediately, followed by a period of in-situ PHC recovery using soil vapour extraction (SVE). Monitoring data have shown that the dissolved PHC plume generally appears to be undergoing natural attenuation. The identified PHC plume length is on the order of 40 m Average groundwater flow velocity is estimated to be on the order of < 10 m/year. There are no nearby groundwater users or ecological receptors.

1.2 Thesis Overview

The thesis is based on a paper format, and is structured as follows. Chapter 2 provides a general background and literature review regarding natural attenuation concepts, with particular focus on monitoring data variability and complexity. In Chapter 3, results from field groundwater sampling at Sites A and B are presented with a focus on how different sampling methodologies and well constructions affect monitoring data variability and interpretation of natural attenuation. Chapter 4 examines notable short-term variations in dissolved sulphate concentrations recorded at Site A. The data are used to see how differing sampling protocols might be used to gain insight regarding sulphate depletion rates as an indicator of biodegradation rates. The results are compared to sulphate depletion rate estimates derived from natural attenuation research conducted by others at the same site. The fifth chapter reviews changes in projected remediation time frames based on groundwater monitoring data collected from Site C where the PHC source has been controlled and dissolved PHC contamination appears to be naturally degrading. Decision trees and reliability estimation tools are used to examine how projections regarding time to reach clean-up objectives are affected as new data are gathered. In Chapter 6, the results of the natural attenuation assessment programs conducted at all three sites are summarized. Future research directions are discussed in Chapter 7.

1.3 References

Alvarez, P.J.J. and Illman, W.A., 2006. Bioremediation and Natural Attenuation: process fundamentals and mathematical models. John Wiley and Sons, Inc., 609 pp.

Armstrong, J.E., Cross, K., M. and Biggar, K.W., 2002. Assessment of Monitored Natural Attenuation at Upstream Oil & Gas Facilities in Alberta – final report. 2001-0010, Canadian Association of Petroleum Producers (CAPP), Calgary.

ASTM, 1998. Standard Guide for Remediation of Ground Water by Natural Attenuation at Petroleum Release Sites. E 1943 - 98, American Society for Testing and Materials.

Baedecker, M.J., Cozzarelli, I.M., Eganhouse, R.P., Siegel, D.I. and Bennett, P.C., 1993. Crude oil in a shallow sand and gravel aquifer--Ill. Biogeochemical reactions and mass balance modeling in anoxic groundwater. Applied Geochemistry, 8(6): 569-586.

Barker, G.W., Raterman, K.T., Fisher, J.B., Corgan, J.M., Trent, G.L., Brown, D.R., Kemp, N. and Sublette, K.L., 1996. A case study of the natural attenuation of gas condensate hydrocarbons in soil and groundwater. Applied Biochemistry and Biotechnology, 57/58(8): 791-802.

Carey, M.A., Finnamore, J.R., Morrey, M.J. and Marsland, P.A., 2000. Guidance on the Assessment and Monitoring of Natural Attenuation of Contaminants in Groundwater. R&D Publication 95, Environmental Agency, Bristol.

Cozzarelli, I.M., Herman, J.S., Baedecker, M.J. and Fischer, J.M., 1999. Geochemical heterogeneity of a gasoline-contaminated aquifer. Journal of Contaminant Hydrology, 40(3): 261-284.

CPA, 1992. Effectiveness of Subsurface Treatment Technology at Alberta Sour Gas Plants, Phase 11A: Assessment of Subsurface Contamination and Remediation at Alberta Sour Gas Plants, Canadian Petroleum Association, Calgary.

Da Silva, M.L.B. and Alvarez, P.J.J., 2002. Effects of ethanol versus MTBE on benzene, toluene, ethylbenzene, and xylene natural attenuation in aquifer columns. Journal of Environmental Engineering, 128(9): 862-867.

Elshahed, M.S., Gieg, L.M., McInerney, M.J. and Suflita, J.M., 2001. Signature metabolites attesting to the in situ attenuation of alkylbenzenes in anaerobic environments. Environmental Science & Technology, 25(4): 682-689.

Gieg, L.M., Kolhatkar, R.V., McInerney, M.J., Tanner, R.S., Harris, S.H.J., Sublette, K.L. and Suflita, J.M., 1999. Intrinsic bioremediation of petroleum hydrocarbons in a gas condensate-contaminated aquifer. Environmental Science & Technology, 33(15): 2550-2560.

Morgan, P., Lewis, S.T. and Watkinson, R.J., 1993. Biodegradation of benzene, toluene, ethylbenzene and xylenes in gas condensate ground water. Environmental Pollution, 82: 181-190.

NRC, 1993. In Situ Bioremediation: When Does It Work. National Academy Press, Washington, DC.

Rueter, P., Rabus, R., Wilkes, H., Aeckersberg, F., Rainey, F.A., Jannasch, H.W. and Widdel, F., 1994. Anaerobic oxidation of hydrocarbons in crude oil by new types of sulphate-reducing bacteria. Nature, 372: 455-458.

Townsend, G.T., Prince, R.C. and Suflita, J.M., 2004. Anaerobic biodegradation of alicyclic constituents of gasoline and natural gas condensate by bacteria from an anoxic aquifer. FEMS Microbiology Reviews, 49: 129-135.

USEPA, 1999a. Monitored Natural Attenuation of Petroleum Hydrocarbons:US EPA Remedial Technology Fact Sheet. EPA/600/F-98/021, Office of Research and Development and National Risk Management Laboratory, Washington, DC and Ada, Oklahoma.

USEPA, 1999b. Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites. OSWER Directive 9200.4-17P, Office of Solid Waste and Emergency Response Directive, Washington, DC.

2. LITERATURE REVIEW

2.1 Natural Attenuation

Natural attenuation (NA) refers to the reduction in contaminant mass or concentration by a suite of naturally occurring processes. The term is taken here to encompass the sum effect of (i) physico-chemical processes (e.g., dilution, dispersion, volatilization, adsorption, chemical transformation); and (ii) biodegradation by indigenous bacteria. Natural attenuation processes form the underlying basis for an alternative remediation strategy to active engineered systems. The NA strategy is controversial, because of a perception that site owners relying on NA are actually trying to 'do nothing' other than watch and measure (NRC, 2000; Rittmann, 2004).

The concept of using natural attenuation (NA) to manage groundwater contaminant situations has rapidly gained widespread acceptance from site owners throughout the world (NRC, 2000). The overview of issues related to using the basic principles of NA for a variety of other compounds (including comments against incautious application of NA principles) is worth consideration (NRC, 2000). In the remainder of this document, NA is considered only for contamination by petroleum hydrocarbons (PHC). For PHC releases, biodegradation can be a key process, in that contaminant mass is destroyed.

While hydrocarbon biodegradation had been recognized for several decades, appreciation of its role as an attenuation mechanism for subsurface contamination situations mainly developed during the 1990's (Chapelle, 1999). During that time, a series of reviews for hydrocarbon plumes (so-called plume-a-thons) provided empirical evidence of dissolved PHC attenuation (Mace et al., 1997; Rifai and Newell, 1998). Concurrently empirical evidence had also been accumulating regarding the relatively high level of difficulty and cost involved in engineered groundwater remediation programs.

Recognition of NA led to the development and promulgation of guidelines regarding the technical basis and practical implementation of a plume management strategy based on natural attenuation (ASTM, 1998; USEPA, 1999; Wiedemeier et al., 1995). These various protocols differ in detail, but generally proposed similar basic approaches. A notable feature of these protocols was the requirement to develop a conceptual model of attenuation processes, and to continue collecting suitable monitoring data to confirm that plume behaviour was consistent with the hypothesized attenuation model. This monitoring component for plume surveillance, combined with the need to control the contaminant source, are two key elements of the remediation strategy referred to as 'monitored natural attenuation', or MNA. Engineered remediation techniques may be required to remove contaminant mass in the source area.

Protocols for NA assessment generally use a 'line-of-evidence' approach. The concept requires collecting a series of independent and/or complementary data that support the interpretation of contaminant attenuation processes. In very general terms, the first step typically involves developing a conceptual site model for basic hydrogeology, contaminant distribution, sensitive potential environmental receptors and corresponding transport and attenuation mechanisms. If natural attenuation appears to be occurring, the conceptual model may be refined and appropriate confirmatory monitoring data are collected. For most PHC contaminant situations, the supporting data represent groundwater samples to demonstrate:

- stable or decreasing PHC concentrations over space and/or time; and,
- characteristic differential patterns of biodegradation 'indicators' associated with electron-accepting processes.

Groundwater monitoring data can provide multiple lines of evidence to the extent that they link 'cause and effect' between attenuation processes and plume management. These data must continue to conform to the conceptual understanding of site conditions (contaminant(s) distribution, transport behaviour and attenuation characteristics). Uncertainty in monitoring data represents lack of clarity regarding underlying process(es) and estimated time required to attain specified remediation goals (either established generic standards or site-specific criteria).

Lines of evidence obtained from hydrochemical monitoring data depend on the compounds of concern (Alvarez and Illman, 2006; ASTM, 1998; NRC, 2000; USEPA, 1999; Wiedemeier et al., 1999). Relative attenuation susceptibilities of PHC contaminants, including biodegradation, are well documented in the scientific literature, thus are only summarized here for completeness. Measured hydrocarbon concentrations must decrease spatially away from the source area at a rate faster than their corresponding transport rate (allowing for sorption and dispersion). Over time, hydrocarbon concentrations should be decreasing. Biodegradation activity can be inferred from differences in concentrations of electron-accepting compounds (so-called indicators) between groundwater samples collected from within-plume compared to background locations. Characteristic changes in groundwater chemistry between monitoring wells representing background conditions and wells installed within a PHC plume have been identified. In relation to aerobic biodegradation, the characteristic change is decreased dissolved oxygen concentration within PHC-containing wells. Characteristic patterns (from background wells to PHC-contaminated wells) have been identified for several anaerobic biodegradation processes including denitrification (decreased nitrate+nitrite), sulphate reduction (decreased sulphate), iron reduction (increased concentrations of dissolved iron as Fe^{2+}), manganese reduction (increased dissolved Mn^{2+}) and methanogenesis (increased dissolved methane). Hydrocarbon biodegradation by one or more of these various terminal electron accepting processes (TEAPs) has been clearly demonstrated and can generally be assumed unless proven otherwise (Chapelle, 1993).

A number of other tools have also been used, including computer modelling of transport and degradation processes (Azadpour-Keeley et al., 2001), sediment sampling and analysis (Kennedy et al., 1998), isotope analyses of contaminants (Richnow et al., 2003), metabolites (McKelvie et al., 2005) and indicator compounds (Aggarwal et al., 1997; Kleikemper et al., 2002; McKelvie et al., 2005) and a variety of laboratory- and field-based microbial experiments to understand biodegradation potential and/or capacity (Alvarez and Vogel, 1991; Borden et al., 1997; Braddock et al., 1997). Experiments had considered a number of process-specific issues including microbial inhibition (Deeb and Alvarez-Cohen, 2000), competition (Powers et al., 2001), and temperature effects (Margesin and Schinner, 1999), among others. Present understanding includes an appreciation of the general ubiquity of PHC-degrading microbes under a wide variety of environmental conditions, but also an appreciation that complete mineralization of PHCs may be slow or limited by local conditions. Numerous published papers and textbooks are available that summarize the various attenuation processes (Alvarez and Illman, 2006; NRC, 2000; Suthersan, 2002; Wiedemeier et al., 1999), thus the material is not repeated here.

Present understanding of NA for PHCs includes an appreciation of the general ubiquity of PHC-degrading microbes, and also an appreciation that complete mineralization of PHCs (conversion to biomass, CO_2 and water) may be slow or limited under local environmental conditions. As a result, current practice focuses on drawing inferences about natural attenuation based on qualitative and quantitative assessment of PHC and geochemical indicator trends. Although it is well known that these concentrations can vary with time, space, and sampling methodology (Cozzarelli et al., 1999; Smith et al., 1991; Vroblesky and Chapelle, 1994), it is sometimes less clear how such variations should be addressed. In particular, how to assess and incorporate uncontrollable variability (e.g., due to natural influences of changes in temperature, water table elevation, local geologic conditions, contact (reaction) time between soil and water, and groundwater recharge) while minimizing controllable variability (e.g., inappropriate sampling, sample handling, analytical methods).

Scientific (and regulatory) acceptance of NA processes has been rapidly followed by its ubiquitous application, sometimes with minimal consideration given to potential limitations. Many complicating factors have been identified with inferring NA from water sample analyses. Geochemical indicator patterns based on groundwater samples may not recognize influences from a number of closely inter-related factors (Davis et al., 1999; Lee et al., 2001a), including mineralogical and abiotic interactions (Kennedy et al., 1998); and geochemical changes (Cozzarelli et al., 2001). In such cases, expected patterns of geochemical indicators may not directly imply hydrocarbon biodegradation (Cozzarelli et al., 1995; Salanitro et al., 1996; Salanitro et al., 1997). Research has also identified a variety of fine-scale variations in dissolved analytes in groundwater samples over space and/or time (Cozzarelli et al., 2001; Cozzarelli et al., 1999; Gibs et al., 1993; Thornton et al., 2001). Furthermore, influences have been shown at varying scales due to a variety of spatially and/or temporally varying factors such as well completion interval and sampling method (Martin-Hayden and Robbins, 1997), interactions between contaminants and terminal electron acceptors (Wilson et al., 2004), redox conditions (Thornton et al., 2001), recharge (Davis et al., 1999; Prommer et al., 1998; Scholl et al., 2006), water table fluctuations (Pelayo and Evangelista, 2003), biological activity (for a variety of reasons) (Bekins et al., 2001a; Bekins et al., 2001b; Borden et al., 1997; Ghiorse and Wilson, 1988; Simoni et al., 2001) and contaminant source function (Guilbeault, 1999; Poulsen and Kueper, 1992).

Despite the many potential methodological and data set limitations associated with collecting groundwater samples, empirical and experimental evidence continues to support the general concept of natural attenuation. Many cases studies have reported successful plume management using natural attenuation, and the individual attenuation processes have been clearly demonstrated under controlled laboratory conditions. The logical inference is therefore that all of the individual, complicating factors interact such that the net effect is consistent with the general overview of natural attenuation.

This type of behaviour is characteristic of a 'dissipative structure', where self-organization arises from processes acting 'far from equilibrium' in a nonlinear manner. These characteristics include unpredictable selection from among a variety of "stable" states, where the system adapts to the local environment (e.g., dynamically stable and complex relationships between predator and prey). A more detailed description of dissipative structures and the need to abandon deterministic models in favour of probabilistic approaches is beyond the present scope, but is covered elsewhere (Prigogine, 1997).

2.2 Variability and Complexity

Variability is a well-known problem in trying to understand hydrogeological systems due to inherent heterogeneity in geologic media. The problem of developing a process-based understanding (thus enabling projection into the future) is compounded for NA assessment by the number of inter-related factors (contaminant source, geologic, geochemical, microbiological and environmental) and their variations in ranges and spatial scales. Some of the individual factors researched already include bacterial distribution (Bekins et al., 2001a; Brockman and Murray, 1997), transient flow effects on plume behaviour (Cirpka, 2005; Schirmer et al., 2001), transient microbial growth dynamics (Miralles-Wilhelm and Gelhar, 2000) and selection of representative biodegradation rates (Beyer et al., 2006; Chapelle et al., 1996; Kao and Prosser, 2001). The central problems in incorporating heterogeneity into a process-related model for NA is that many input factors are often unknown (or even unknowable) for practical purposes. The problem is exacerbated for many sites by inadequate or even complete absence of information regarding the original contaminant source/composition/mass/flux/location in relation to plume history (plumes may be decades old).

A review of complexity theory (Cilliers, 2005) illustrates important characteristics, and resulting insights, relevant to natural attenuation. In summary, complex systems operate under non-equilibrium conditions, with outputs being a function of nonlinear inputs. Multiple interactions between components can occur, and asymmetrical structure is developed, maintained and adapted over space and time. System behaviour occurs over divergent time scales, and the system develops a 'memory' of adaptations to environmental changes. Lastly, a complex system can be described in more than one way, where each description may dissect the system differently and with different degrees of complexity. There are two relevant implications of these characteristics for assessing natural attenuation:

1. Each alternative description of a complex system relies on a limited set of characteristics. While there is no way to select the completely correct description, some provide more interesting (insightful) results.
2. Description of macro behaviour cannot account for all micro-features, even though the former results from the latter. The scientific description of natural attenuation therefore relies on making approximations.

These points highlight the need to gain process understanding using multiple and detailed data collection methods (Smets and Pritchardy, 2003). However, this approach can require so much time, effort and expense, that it is rarely applied at sites. Perhaps a better approach is to extract as much learning from test sites as possible to define requirements for collecting monitoring data of suitable quality to support NA interpretation (Yeskis and Zavala, 2002).

Reliance on natural attenuation for plume management involves initial assessment of field data (from a short time period) to show attenuation is occurring, and then long term forward projection of future plume behaviour (spreading behaviour and/or expected time to reach established cleanup goals). Varying interactions between hydrogeologic, geochemical and microbiological processes inherently mean that plume behaviour must be assessed for each site individually (Chapelle et al., 2003). As a result more sophisticated data analysis methods have been developed to identify complex interactions between processes. Examples include a proposed method to separate variation due to NA processes from water table fluctuations (Pelayo and Evangelista, 2003) or use of multivariate statistical methods to interpret changes over time noted in spatial site monitoring data (Lee et al., 2001b). Geostatistical tools have been used to examine spatial correlation and data density requirements (Wachter et al., 2005), and relative efficiencies of various biodegradation reactions (Christensen et al., 2004). Another approach uses differences in mass flux across two or more control planes to determine a net biodegradation rate (Kao and Prosser, 2001). Yet another mass-flux method involves modelling chemical analyses of water samples collected at two control planes in combination with active pumping (Bockelmann et al., 2001).

Computer modelling provides a means to examine the influence of implicit or explicit assumptions about attenuation processes. Two styles can be generalized for incorporation of attenuation processes, using either variability or complexity. Variability approaches typically use relatively simple processes, and try to extract insight regarding NA from variable data inputs. In contrast, the complexity approach tries to gain understanding about NA by including multiple processes and more interactions, but at the cost of having to provide additional input parameters (Rifai and Rittaler, 2005).

Data variability has been examined in several ways. The Monte Carlo method has been used to generate synthetic plumes for comparison with real site data to improve understanding of plume behaviour (McNab, 2001; McNab and Dooher, 1998). Another approach has been to use a simulated heterogeneous aquifer to look at the influence of reaction kinetics (Beyer et al., 2006). Insight about possible field cases is sought by comparing the 'known' solution using the full data set to a series of simulations based on a data subset drawn from the ensemble. This approach has also been used to examine the effect of variations in reaction kinetics and dispersion for a simulated homogeneous aquifer (Maier and Grathwohl, 2006), and the effect of variations in seasonal groundwater flow patterns (Schirmer et al., 2001).

Complexity models for NA have developed because research has shown that there are multiple interacting processes and/or uncertain input parameters (Essaid et al., 1995; Landmeyer et al., 1998; McNab and Dooher, 1998; Rifai et al., 2000). Modelling studies have looked at projected plume response relative to methods used to simulate (or neglect) multiple inputs including flow and boundary conditions (Prommer et al., 2002; Schirmer et al., 2001; Scholl, 2000), biodegradation kinetics (Bekins et al., 1998; Brauner and Widdowson, 2001; Lu et al., 1999; Schreiber et al., 2004), source history and complex biochemical reaction pathways (Schaefer, 2001; van Breukelen et al., 2004; Watson et al., 2005). Increased process complexity is typically recognized as influential when model simulations based on simpler processes fail to capture detailed field data.

The main challenge to the complexity approach is appropriate parameter estimation. Without a physical basis, matching model and field data is a curve-fitting exercise. Encouraging results have been reported for research sites, where models describing reaction complexity were parameterized using laboratory-determined parameters (Schirmer et al., 2000; Watson et al., 2005; Watson et al., 2003). The general effect of having many inputs with complexity is that models based on mean values tend to overestimate the effective plume decay rates (hence underestimate plume size or half-life) (Beyer et al., 2006; Miralles-Wilhelm and Gelhar, 2000).

In summary, increasing complexity in conceptual model formulation affects ‘scaling’ considerations for how best to interpret NA effectiveness at a generic site. This leads to the question: what data resolution is required to identify ‘significant’ results without excessive ‘fine-scale’ influences? Typical NA data might include samples collected from wells (10^{-1} m) over relatively short time frames (years) that have to identify inter-related effects acting across a wide range of scales (groundwater flow and transport: 10^{2} metres, soil lithology changes and groundwater sampling interval: 10^{0} m, grain mineralogy: 10^{-4} m and microbial activity: 10^{-6} m). These monitoring well data are then relied upon to provide support for assessing plume lifetime (decades to centuries?) and lateral extent (10^{2} to 10^{3} m). Given so many sources of inherent and potential variability that may affect groundwater samples (Keith et al., 1983), it is key to reconcile small-scale changes with a general lack of variability at the plume scale (Cozzarelli et al., 2001).

2.3 Sampling Method Considerations

The need to install monitoring wells into the appropriate zone to provide monitoring data for NA assessment has historically been considered as self-evident. Wells are required to provide data from which the NA concepts were originally developed. In reality, monitoring wells can provide seemingly confusing results for a variety of reasons. Wells may be installed inappropriately (or incorrectly) for many reasons (Nichols and Roth, 2006; Odermatt, 1999), especially during preliminary phases of site characterization. The need to use appropriate well drilling and sampling construction materials is intuitive, and has been investigated for many common contaminants (Barcelona and Helfrich, 1986; Barcelona et al., 1988; Keith et al., 1983). Changes in local hydrochemistry (so-called well installation trauma) is known from well drilling and construction activities (Pennino, 1988), while longer-term influences have been noted as being related to borehole sealant contamination (Barcelona and Helfrich, 1986; Remenda and van der Kamp, 1997) and drilling activities (Kim, 2003). Recognition of such situations can be complicated, if there is no previous information to provide a contrast.

Monitoring data are used to assess prevailing hydrochemical conditions, and to evaluate spatio-temporal trends, if any. After accounting for well installation issues, other factors that may affect measured concentrations include:

- current and historical sampling approach(es) (equipment, construction materials and protocols);
- uncontrollable and potentially correlated factors such as geologic, hydrogeologic, geochemical and microbiological heterogeneity;
- environmental factors such as climate, precipitation, infiltration and seasonal water table fluctuations;
- physical influences such as land use changes, unknown source area; and,
- in-well artefacts such as mixing due to purging, density gradients due to temperature or concentration, vertical hydraulic gradient and chemical transformations.

Other potentially influential factors (e.g., differences in laboratory analytical methods, sample preservation and shipping techniques) were closely controlled by using consistent practices.

The influence of sampling methodology on analytical results has long been recognized; thus, reviewing changes in recommendations provides insight regarding improved understanding of sampling complexities (Barcelona et al., 2005; Herzog et al., 1991; Schuller et al., 1981). In some cases, sampling methods are directed toward specific contaminant(s) of interest e.g., when sampling for metals (Puls and Barcelona, 1989), volatile organic compounds (Barker and Dickhout, 1988; McAlary and Barker, 1987), semi-volatile organic compounds (Gustavson and Harkin, 2000) and salinity (e.g., chloride, sulphate, and nitrate) (Ronen et al., 1986). Therefore consideration of the sampling purpose(s) is required in order to best use previous information and recommendations. This point is relevant when considering how best to collect samples for NA assessment, when a variety of chemical types require analyses.

The influence of well screen placement relative to the contaminated zone can introduce variability due to mixing in several ways. Mixing due to natural flow and/or purging can cause over- or underestimation of the contaminant distribution (Elci et al., 2001; Gibs et al., 1993; Hutchins and Acree, 2000; Robbins and Martin-Hayden, 1991), and even incorrect interpretation of flow direction or attenuation behaviour (Martin-Hayden and Robbins, 1997). The situation is exacerbated if the screened interval connects more than one water-bearing unit with varying hydraulic conductivity values and/or a vertical flow component. Field data have shown that vertical variability is common, thus short screens should be used (Church and Granato, 1996), but understanding of what is ‘short’ has changed. Church and Granato (1996) compared results between 'short' 3 m screens and a 21 m long-screen well, while vertical heterogeneity has been identified using sampling scales of 1 m (Jones et al., 1999) and 0.03 m (Ronen et al., 1986).

Efforts to select the best well screen length may be misguided, based on results of modelling and field data leading to the conclusion that typical monitoring wells cannot provide quantitative indications of groundwater contamination, independent of the construction and sampling methods used (Elci et al., 2001; Martin-Hayden and Robbins, 1991). On this basis, perhaps the goal of sound groundwater sampling practice should be to provide 'representative' data based on minimal induced variability. This approach includes uncontrollable factors, and specifically recognizes data uncertainty and variability.

Groundwater sampling methods were developed based on conceptual and measured interactions between well water above the screen (stagnant), water in the screen, and water in the outside formation (fresh). Pore water in filter pack sand around the well screen is less well understood. Early sampling protocols (Gibs and Imbrigiotta, 1990) called for removing (purging) several borehole volumes to ensure that sample chemistry was not affected by the stagnant water. Research indicated that minimal purging would be required when groundwater flows freely through the screen (Robin and Gillham, 1987). As an extension, the idea of low-flow Powell purging was developed to minimize sample turbidity and interactions with stagnant water by pumping from the screened interval at approximately the same rate as water entered the well details (Barcelona et al., 1994; Powell and Puls, 1993; Puls and Barcelona, 1995; Puls and Paul, 1995). A literature review identified water quality effects due to a variety of then-available sampling methods (Parker, 1994).

More recently, there has been a move toward no-purge sampling. A review of samples bailed (before and after purging) and showed no statistically significant differences for common petroleum fuel-related contaminants (benzene, toluene, ethylbenzene, xylenes; BTEX and methyl-tertiary-butyl-ether, MTBE) (Byrnes et al., 1996; SECOR, 1996), although questions remain about some of these results (Varljen, 1997). Research into the validity of no-purge sampling has generally focussed on two main types of no-purge type sampling protocol (Parker and Clark, 2002). Diffusion samplers are left in a well to equilibrate over some time period (typically order of weeks), while 'thief' sampling devices are used to collect a 'snapshot in time' sample. Diffusion sampler trials have been published for various common contaminants (Ehlke et al., 2004; Vrana et al., 2005; Vroblesky et al., 2002). Another style of diffusion-based sampler uses a time-weighted mass partitioning approach to estimate time-integrated mass loading (Bopp et al., 2005; Martin et al., 2003). Opinions continue to be divided regarding the suitability of no-purge sampling concepts, with both supporters (API, 1998; Newell et al., 2000) and opponents (Barcelona et al., 2005; Varljen, 1997) providing evidence and discussion of the relative merits.

Field studies show a range of outcomes when comparing sampling methods. Little difference was reported for metals analyses during a comparison of conventional purge sampling and low flow sampling (Kearl et al., 1994). A comparison of discrete interval samples using both a multilevel passive system and a Geoprobe-installed direct-push and sample method, showed greater heterogeneity for dissolved metal concentrations than the depth-integrated low-flow purge and “traditional” bailer (lowest result) samples but minimal differences for chloride (Puls and Paul, 1997). A comparison of analytical results for samples collected by the low flow and passive diffusion bag method showed generally similar results in terms of contaminant detection, but a tendency for lower concentration in the diffusion samplers (Archfield and LeBlanc, 2005). For NA application, a key consideration is comparing variability due to the combination of field personnel and sampling system, the well being used, and in the complex hydrogeologic system being sampled.

All sampling methods are challenged when trying to collect ‘representative’ samples from wells in low permeability formations (Herzog et al., 1988; Puls and Barcelona, 1995). Installation of any sampling method through standing water will cause significant mixing. Traditional methods involving specified purge volumes typically lead to excessive purging, exposing the recovering water to atmospheric air, which in turn can cause geochemical alteration (oxidation of reduced compounds, gas exchange and/or volatilization losses). Low-flow purging is not optimal either, requiring excessively slow flow rates (long collection times). Diffusion-based sampling may only capture local, in-well effects that depend on the relative rates of diffusive equilibration compared to the rates and degrees of flushing and in-well mixing. Lastly, the concept of ‘representativeness’ is challenged by the intrusive nature of wells that may cause local geochemical effects (Pennino, 1988; Varljen, 1997).

2.4 References

Aggarwal, P.K., Fuller, M.E., Gurgas, M.M., Manning, J.F. and Dillon, M.A., 1997. Use of stable oxygen and carbon isotope analyses for monitoring the pathways and rates of intrinsic and enhanced in situ biodegradation. Environmental Science & Technology, 31(2): 590-596.

Alvarez, P.J.J. and Illman, W.A., 2006. Bioremediation and Natural Attenuation: process fundamentals and mathematical models. John Wiley and Sons, Inc., 609 pp.

Alvarez, P.J.J. and Vogel, T.M., 1991. Substrate interactions of benzene, toluene and para-xylene during microbial degradation by pure cultures and mixed culture aquifer slurries. Applied and Environmental Microbiology, 57(10): 2981-2985.

API, 1998. Evaluation of sampling and analytical methods for measuring indicators of intrinsic bioremediation. 5, American Petroleum Institute, Washington, DC.

Archfield, S.A. and LeBlanc, D.R., 2005. Comparison of Diffusion- and Pumped-Sampling Methods to Monitor Volatile Organic Compounds in Ground Water, Massachusetts Military Reservation, Cape Cod, Massachusetts, July 1999–December 2002. Scientific Investigations Report 2005-5010, USGS, Reston, Virginia.

ASTM, 1998. Standard Guide for Remediation of Ground Water by Natural Attenuation at Petroleum Release Sites. E 1943 - 98, American Society for Testing and Materials.

Azadpour-Keeley, A., Keeley, J.W., Russell, H.H. and Sewell, G.W., 2001. Monitored natural attenuation of contaminants in the subsurface: Applications. Ground Water Monitoring & Remediation, 21(3): 136-143.

Barcelona, M.J. and Helfrich, J.A., 1986. Well construction and purging effects on ground-water samples. Environmental Science & Technology, 20(11): 1179-1184.

Barcelona, M.J., Helfrich, J.A. and Garske, E.E., 1988. Verification of sampling methods and selection of material for ground-water contamination studies. ASTM STP 963, American Society for Testing and Materials, Philadelphia.

Barcelona, M.J., Varljen, M.D., Puls, R.W. and Kaminski, D., 2005. Ground water purging and sampling methods: history vs. hysteria. Ground Water Monitoring & Remediation, 25(1): 52-62.

Barcelona, M.J., Wehrmann, H.A. and Varljen, M.D., 1994. Reproducible well-purging procedures and VOC stabilization criteria for groundwater sampling. Ground Water, 32(1): 12-22.

Barker, J.F. and Dickhout, R., 1988. An evaluation of some systems for sampling gas-charged groundwater for volatile organic analysis. Ground Water Monitoring Review, 8(4): 112-120.

Bekins, B.A., Cozzarelli, I.M., Godsy, E.M., Warren, E., Essaid, H.I. and Tuccillo, M.E., 2001a. Progression of natural attenuation processes at a crude oil spill site: II. Controls on spatial distribution of microbial populations. Journal of Contaminant Hydrology, 53(3-4): 387-406.

Bekins, B.A., Cozzarelli, I.M., Warren, E. and Godsy, E.M., 2001b. Microbial ecology of a crude oil contaminated aquifer. In: S.T.a.S. Oswald (Editor), Groundwater Quality: Natural and Enhanced Restoration of Groundwater Pollution. IAHS, Sheffield, UK, pp. 57-63.

Bekins, B.A., Warren, E. and Godsy, E.M., 1998. A comparison of zero-order, first-order, and Monod biotransformation models. Ground Water, 36(2): 261-268.

Beyer, C., Bauer, S. and Kolditz, O., 2006. Uncertainty assessment of contaminant plume length estimates in heterogeneous aquifers. Journal of Contaminant Hydrology, 87(1-2): 73-95.

Bockelmann, A., Ptak, T. and Teutsch, G., 2001. An analytical quantification of mass fluxes and natural attenuation rate constants at a former gasworks site. Journal of Contaminant Hydrology, 53(3-4): 429-453.

Bopp, S., Weiss, H. and Schirmer, K., 2005. Time-integrated monitoring of polycyclic aromatic hydrocarbons (PAHs) in groundwater using the Ceramic Dosimeter passive sampling device. Journal of Chromatography A, 1072: 137-147.

Borden, R.C., Hunt, M.J., Schafer, M.B. and Barlaz, M.A., 1997. Anaerobic Biodegradation of BTEX in Aquifer Material, National Risk Management Research Laboratory, Ada, OK, Washington, DC.

Braddock, J.F., Ruth, M.L., Catterall, P.H., Walworth, J.L. and McCarthy, K.A., 1997. Enhancement and inhibition of microbial activity in hydrocarbon-contaminated arctic soils: Implications for nutrient-amended biodegradation. Environmental Science & Technology, 31(7): 2078-2084.

Brauner, J.S. and Widdowson, M.A., 2001. Numerical simulation of a natural attenuation experiment with a petroleum hydrocarbon NAPL source. Ground Water, 39(6): 939-952.

Brockman, F.J. and Murray, C.J., 1997. Subsurface microbiological heterogeneity: current knowledge, descriptive approaches and applications. FEMS Microbiology Reviews, 20(3, 4): 231-247.

Byrnes, P.G., Briglia, J.E. and Bealer, L.J., 1996. Evaluation of well purging in ground-water sampling for BTEX and MTBE, Proceedings of the 1996 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation Conference. National Ground Water Association, pp. 221-236.

Chapelle, F.H., 1993. Ground-Water Microbiology & Geochemistry. John Wiley & Sons, Inc., New York, 424 pp.

Chapelle, F.H., 1999. Bioremediation of petroleum hydrocarbon-contaminated ground water: The perspectives of history and hydrology. Ground Water, 37(1): 122-132.

Chapelle, F.H., Bradley, P.M., Lovley, D.R. and Vroblesky, D.A., 1996. Measuring rates of biodegradation in a contaminated aquifer using field and laboratory methods. Ground Water, 34(4): 691-698.

Chapelle, F.H., Widdowson, M.A., Brauner, J.S., Mendez, E.I. and Casey, C.C., 2003. Methodology for estimating times of remediation associated with monitored natural attenuation. 03-4057, US Geological Survey, Columbia.

Christensen, O.F., Cassiani, G., Diggle, P.J., Ribeiro, J.P. and Andreotti, G., 2004. Statistical estimation of the relative efficiency of natural attenuation mechanisms in contaminated aquifers. Stochastic Environmental Research and Risk Assessment, 18(5): 339-350.

Church, P.E. and Granato, G.E., 1996. Bias in ground-water data caused by well-bore flow in long-screen wells. Ground Water, 34(2): 262-273.

Cilliers, P., 2005. Complexity, deconstruction and relativism. Theory, Culture & Society, 22(5): 255-267.

Cirpka, O.A., 2005. Effects of sorption on transverse mixing in transient flows. Journal of Contaminant Hydrology, 78(3): 207-229.

Cozzarelli, I.M., Bekins, B.A., Baedecker, M.J., Aiken, G.R., Eganhouse, R.P. and Tuccillo, M.E., 2001. Progression of natural attenuation processes at a crude-oil spill site - I. Geochemical evolution of the plume. Journal of Contaminant Hydrology, 53(3-4): 369-385.

Cozzarelli, I.M., Herman, J.S. and Baedecker, M.J., 1995. Fate of microbial metabolites of hydrocarbons in a coastal plain aquifer: the role of electron acceptors. Environmental Science & Technology, 29(2): 458-469.

Cozzarelli, I.M., Herman, J.S., Baedecker, M.J. and Fischer, J.M., 1999. Geochemical heterogeneity of a gasoline-contaminated aquifer. Journal of Contaminant Hydrology, 40(3): 261-284.

Davis, G.B., Barber, C., Power, T.R., Thierrin, J., Patterson, B.M., Rayner, J.L. and Wu, Q.L., 1999. The variability and intrinsic remediation of a BTEX plume in anaerobic sulphate-rich groundwater. Journal of Contaminant Hydrology, 36(3-4): 265-290.

Deeb, R.A. and Alvarez-Cohen, L., 2000. Aerobic transformation of gasoline aromatics in multicomponent mixtures. Bioremediation Journal, 4(2): 171-179.

Ehlke, T.A., Imbrigiotta, T.E. and Dale, J.M., 2004. Laboratory comparison of polyethylene and dialysis membrane diffusion samplers. Ground Water Monitoring & Remediation, 24(1): 53-59.

Elci, A., Molz III, F.J. and Waldrop, W.R., 2001. Implications of observed and simulated ambient flow in monitoring wells. Ground Water, 39(6): 853-862.

Essaid, H.I., B.A, B., Godsy, E.M., Warren, E., M.J, B. and I.M, C., 1995. Simulation of aerobic and anaerobic biodegradation processes at a crude oil spill site. Water Resources Research, 31(12): 3309-3327.

Ghiorse, W.C. and Wilson, J.T., 1988. Microbial ecology of the terrestrial subsurface. Advances in Applied Microbiology, 33: 107-171.

Gibs, J., Brown, G.A., Turner, K.S., MacLeod, C.L., Jelinski, J.C. and Koehnlein, S.A., 1993. Effects of small-scale vertical variations in well-screen inflow rates and concentrations of organic compounds on the collection of representative groundwater quality samples. Ground Water, 31(2): 201-208.

Gibs, J. and Imbrigiotta, T.E., 1990. Well-purging criteria for sampling purgeable organic compounds. Ground Water, 28(1): 68-78.

Guilbeault, M.A., 1999. Suspended DNAPL source zones in three sandy aquifers: plume anatomy, mass discharge and sampling scale considerations. M.Sc. Thesis, University of Waterloo, Waterloo, ON, 154 pp.

Gustavson, K.E. and Harkin, J.M., 2000. Comparison of sampling techniques and evaluation of semipermeable membrane devices (SPMDs) for monitoring polynuclear aromatic hydrocarbons (PAHs) in groundwater. Environmental Science & Technology, 34(20): 4445-4451.

Herzog, B.L., Chou, S.-F.J., Valkenburg, J.R. and Griffin, R.A., 1988. Changes in volatile organic chemical concentrations after purging slowly recovering wells. Ground Water Monitoring Review, 8(4): 93-99.

Herzog, B.L., Pennino, J. and Nielsen, G., 1991. Ground-water sampling. In: D.M. Nielsen (Editor), Practical Handbook of Ground-Water Monitoring. Lewis Publishing Inc., Chelsea, pp. 449-499.

Hutchins, S.R. and Acree, S.D., 2000. Ground water sampling bias observed in shallow, conventional wells. Ground Water Monitoring & Remediation, 20(1): 86-93.

Jones, I., Lerner, D.N. and Baines, O.P., 1999. Multiport sock samplers: A low-cost technology for effective multilevel ground water sampling. Ground Water Monitoring & Remediation, 19(1): 134-142.

Kao, C.M. and Prosser, J., 2001. Evaluation of natural attenuation rate at a gasoline spill site. Journal of Hazardous Materials, 82(3): 275-289.

Kearl, P.M., Korte, N.E., Stites, M. and Baker, J., 1994. Field comparison of micropurging vs. traditional ground water sampling. Ground Water Monitoring & Remediation, 14(4): 183-190.

Keith, S.J., Wilson, L.G., Fitch, H.R. and Esposito, D.M., 1983. Sources of spatial-temporal variability in groundwater quality data and methods of control. Ground Water Monitoring Review, 3(2): 21-32.

Kennedy, L.G., Everett, J.W., Ware, K.J., Parsons, R. and Green, V., 1998. Iron and sulfur mineral analysis methods for natural attenuation assessments. Bioremediation Journal, 2(3&4): 259-276.

Kim, K., 2003. Long-term disturbance of ground water chemistry following well installation. Ground Water, 41(6): 780-789.

Kleikemper, J., Schroth, M.H., Sigler, W.V., Schmucki, M., Bernasconi, S.M. and Zeyer, J., 2002. Activity and diversity of sulfate-reducing bacteria in a petroleum hydrocarbon-contaminated aquifer. Applied and Environmental Microbiology, 68(4): 1516-1523.

Landmeyer, J.E., Chapelle, F.H., Petkewich, M.D. and Bradley, P.M., 1998. Assessment of natural attenuation of aromatic hydrocarbons in groundwater near a former manufactured-gas plant, South Carolina, USA. Environmental Geology, 34(4): 279-292.

Lee, J.Y., Cheon, J.Y., Lee, K.K., Lee, S.Y. and Lee, M.H., 2001a. Factors affecting the distribution of hydrocarbon contaminants and hydrogeochemical parameters in a shallow sand aquifer. Journal of Contaminant Hydrology, 50(1-2): 139-158.

Lee, J.Y., Cheon, J.Y., Lee, K.K., Lee, S.Y. and Lee, M.H., 2001b. Statistical evaluation of geochemical parameter distribution in a ground water system contaminated with petroleum hydrocarbons. Journal of Environmental Quality, 30(5): 1548-1563.

Lu, G.P., Clement, T.P., Zheng, C.M. and Wiedemeier, T.H., 1999. Natural attenuation of BTEX compounds: Model development and field-scale application. Ground Water, 37(5): 707-717.

Mace, R.E., Fisher, R.S., Welch, D.M. and Parra, S.P., 1997. Extent, Mass, and Duration of Hydrocarbon Plumes from Leaking Petroleum Storage Tank Sites in Texas. Geologic Circular 97-1, Bureau of Economic Geology, University of Texas, Austin.

Maier, U. and Grathwohl, P., 2006. Numerical experiments and field results on the size of steady state plumes. Journal of Contaminant Hydrology, 85(1-2): 33– 52.

Margesin, R. and Schinner, F., 1999. Review: biological decontamination of oil spills in cold environments. Journal of Chemical Technology and Biotechnology, 74(5): 381-389.

Martin, H., Patterson, B.M. and Davis, G.B., 2003. Field trial of contaminant groundwater monitoring: comparing time-integrating ceramic dosimeters and conventional water sampling. Environmental Science & Technology, 37(7): 1360-1364.

Martin-Hayden, J.M. and Robbins, G.A., 1991. Mass balance evaluation of monitoring well purging: Part II, Field tests at a gasoline contamination site. Journal of Contaminant Hydrology, 8(3-4): 225-241.

Martin-Hayden, J.M. and Robbins, G.A., 1997. Plume distortion and apparent attenuation due to concentration averaging in monitoring wells. Ground Water, 35(2): 339-346.

McAlary, T.A. and Barker, J.F., 1987. Volatilization losses of organics during ground water sampling from low permeability materials. Ground Water Monitoring Review, 7(4): 63-68.

McKelvie, J.R., Lindstrom, J.E., Beller, H.R., Richmond, S.A. and Sherwood Lollar, B., 2005. Analysis of anaerobic BTX biodegradation in a subarctic aquifer using isotopes and benzylsuccinates. Journal of Contaminant Hydrology, 81(1-4): 167-186.

McNab, W.W., 2001. A Monte Carlo simulation method for assessing biotransformation effects on groundwater fuel hydrocarbon plume lengths. Computers & Geosciences, 27(1): 31-42.

McNab, W.W. and Dooher, B.P., 1998. Uncertainty analyses of fuel hydrocarbon biodegradation signatures in ground water by probabilistic modeling. Ground Water, 36(4): 691-698.

Miralles-Wilhelm, F. and Gelhar, L.W., 2000. Stochastic analysis of oxygen-limited biodegradation in heterogeneous aquifers with transient microbial dynamics. Journal of Contaminant Hydrology, 42(1): 69-97.

Newell, C.J., Lee, R.S. and Spextet, A.H., 2000. No-Purge Groundwater Sampling: An Approach for Long-Term Monitoring, American Petroleum Institute (API) Bulletin 12, pp. 1-10.

Nichols, E.M. and Roth, T.L., 2006. Downward solute plume migration: assessment, significance, and implications for characterization and monitoring of "diving plumes". American Petroleum Institute (API) Bulletin, 24: 1-29.

NRC, 2000. Natural Attenuation for Groundwater Remediation. National Academy Press, Washington. DC, 274 pp.

Odermatt, J.R., 1999. Remediation by natural attenuation? Ground Water Monitoring & Remediation, 19(3): 58-60.

Parker, L.V., 1994. The effects of ground water sampling devices on water quality: a literature review. Ground Water Monitoring Review, 14(2): 130-141.

Parker, L.V. and Clark, C.H., 2002. Study of Five Discrete Interval-Type Groundwater Sampling Devices, US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, NH.

Pelayo, A.M. and Evangelista, F.S., 2003. A statistical F test for the natural attenuation of contaminants in groundwater. Environmental Monitoring and Assessment, 83(1): 47-70.

Pennino, J., 1988. There's no such thing as a representative ground water sample. Ground Water Monitoring Review, 8(3): 4-9.

Poulsen, M. and Kueper, B.H., 1992. A field experiment to study the behaviour of tetrachloroethylene in unsaturated porous media. Environmental Science & Technology, 26(5): 889-895.

Powell, R.M. and Puls, R.W., 1993. Passive sampling of groundwater monitoring wells without purging: multilevel well chemistry and tracer disappearance. Journal of Contaminant Hydrology, 12(1): 51-77.

Powers, S.E., Hunt, C.S., Heermann, S.E., Corseuil, H.X., Rice, D. and Alvarez, P.J.J., 2001. The transport and fate of ethanol and BTEX in groundwater contaminated by gasohol. Critical Reviews in Environmental Science and Technology, 31(1): 79-123.

Prigogine, I., 1997. The End of Certainty: Time, Chaos, and the New Laws of Nature. The Free Press, New York, 228 pp.

Prommer, H., Barry, D.A. and Davis, G.B., 1998. The effect of seasonal variability on intrinsic biodegradation of a BTEX plume, GQ'98. Groundwater Quality: Remediation and Protection. IAHS, Tubingen, Germany, pp. 213-244.

Prommer, H., Barry, D.A. and Davis, G.B., 2002. Modelling of physical and reactive processes during biodegradation of a hydrocarbon plume under transient groundwater flow conditions. Journal of Contaminant Hydrology, 59(1-2): 113-131.

Puls, R.W. and Barcelona, M.J., 1989. Ground water sampling for metals analyses. United States Environmental Protection Agency, Office of Research and Development, Ada, OK.

Puls, R.W. and Barcelona, M.J., 1995. Low-flow (minimal drawdown) groundwater sampling procedures. EPA/540/S-95/504, USEPA, Ada, OK.

Puls, R.W. and Paul, C.J., 1995. Low-flow purging and sampling of ground water monitoring wells with dedicated systems. Ground Water Monitoring Review, 15(1): 116-123.

Puls, R.W. and Paul, C.J., 1997. Multi-layer sampling in conventional monitoring wells for improved estimation of vertical contaminant distributions and mass. Journal of Contaminant Hydrology, 25(1-2): 85-111.

Remenda, V.H. and van der Kamp, G., 1997. Contamination from sand-bentonite seal in monitoring wells installed in aquitards. Ground Water, 35(1): 39-46.

Richnow, H.H., Annweiler, E., Michaelis, W. and Meckenstock, R.U., 2003. Microbial in situ degradation of aromatic hydrocarbons in a contaminated aquifer monitored by carbon isotope fractionation. Journal of Contaminant Hydrology, 65(1-2): 101-120.

Rifai, H.S. and Newell, C.J., 1998. Estimating first-order decay rates for BTEX using data from 115 sites. In: NGWA (Editor), 1998 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Remediation. National Ground Water Association, Houston, TX, pp. 31-41.

Rifai, H.S., Newell, C.J., Gonzales, J.R. and Wilson, J.T., 2000. Modelling natural attenuation of fuels with Bioplume III. Journal of Environmental Engineering, 126(5): 428-438.

Rifai, H.S. and Rittaler, T., 2005. Modeling natural attenuation of benzene with analytical and numerical models. Biodegradation, 16: 291-304.

Rittmann, B.E., 2004. Definition, objectives and evaluation of natural attenuation. Biodegradation, 15: 349-357.

Robbins, G.A. and Martin-Hayden, J.M., 1991. Mass balance evaluation of monitoring well purging: Part I, Theoretical models and implications for representative sampling. Journal of Contaminant Hydrology, 8(3-4): 203-224.

Robin, M.J.L. and Gillham, R.W., 1987. Field evaluation of well purging procedures. Ground Water Monitoring Review, 7(4): 85-93.

Ronen, D., Margaritz, M. and Levy, I., 1986. A multi-layer sampler for the study of detailed hydrochemical profiles in groundwater. Water Research, 20(3): 311-315.

Salanitro, J.P., Wisniewski, H.L., Byers, D.L., Neaville, C.C. and Schroder, R.A., 1996. The potential and limits of aerobic and anaerobic BTEX biodegradation in aquifers, Third International Petroleum Environmental Conference, Albuquerque, NM, pp. 24-27.

Salanitro, J.P., Wisniewski, H.L., Byers, D.L., Neaville, C.C. and Schroder, R.A., 1997. Use of aerobic and anaerobic microcosms to assess BTEX biodegradation in aquifers. Ground Water Monitoring & Remediation, 17(3): 210-221.

Schaefer, W., 2001. Predicting natural attenuation of xylene in groundwater using a numerical model. Journal of Contaminant Hydrology, 52(1-4): 57-83.

Schirmer, M., Durrant, G.C., Molson, J.W. and Frind, E.O., 2001. Influence of transient flow on contaminant biodegradation. Ground Water, 39(2): 276-282.

Schirmer, M., Molson, J.W., Frind, E.O. and Barker, J.F., 2000. Biodegradation modelling of a dissolved gasoline plume applying independent laboratory and field parameters. Journal of Contaminant Hydrology, 46(3-4): 339-374.

Scholl, M.A., 2000. Effects of heterogeneity in aquifer permeability and biomass on biodegradation rate calculations - Results from numerical simulations. Ground Water, 38(5): 702-712.

Scholl, M.A., Cozzarelli, I.M. and Christenson, S.C., 2006. Recharge processes drive sulfate reduction in an alluvial aquifer contaminated with landfill leachate. Journal of Contaminant Hydrology, 86(3-4): 239-261.

Schreiber, M.E., Carey, G.R., Feinstein, D.T. and Bahr, J.M., 2004. Mechanisms of electron acceptor utilization: implications for simulating anaerobic biodegradation. Journal of Contaminant Hydrology, 73(1-4): 99-127.

Schuller, R.M., Gibb, J.P. and Griffin, R.A., 1981. Recommended sampling procedures for monitoring wells. Ground Water Monitoring Review, 1(2): 42-46.

SECOR, S.I.I., 1996. Final Report The California Groundwater Purging Study for Petroleum Hydrocarbons, Western States Petroleum Association, Glendale, CA.

Simoni, S.F., Schaefer, A., Harms, H. and Zehnder, A.J.B., 2001. Factors affecting mass transfer limited biodegradation in saturated porous media. Journal of Contaminant Hydrology, 50(1-2): 99-120.

Smets, B.F. and Pritchardy, P.H., 2003. Elucidating the microbial component of natural attenuation. Current Opinion in Biotechnology, 14(3): 283-288.

Smith, R.L., Harvey, R.W. and LeBlanc, D.R., 1991. Importance of closely spaced vertical sampling in delineating chemical and microbiological gradients in groundwater studies. Journal of Contaminant Hydrology, 7(3): 285-300.

Suthersan, S.S., 2002. Natural and Enhanced Remediation Systems. CRC-Lewis Publishers, Boca Raton, Florida, 419 pp.

Thornton, S.F., Quigley, S., Spence, M.J., Banwart, S.A., Bottrell, S.H. and Lerner, D.N., 2001. Processes controlling the distribution and natural attenuation of dissolved phenolic compounds in a deep sandstone aquifer. Journal of Contaminant Hydrology, 53: 223-267.

USEPA, 1999. Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites. OSWER Directive 9200.4-17P, Office of Solid Waste and Emergency Response Directive, Washington, DC.

van Breukelen, B.M., Griffioen, J., Roling, W.F.M. and van Verseveld, H.W., 2004. Reactive transport modelling of biogeochemical processes and carbon isotope geochemistry inside a landfill leachate plume. Journal of Contaminant Hydrology, 70(3-4): 249-269.

Varljen, M.D., 1997. No-purge sampling: here's the beef. Ground Water Monitoring Review, 17(3): 87-89.

Vrana, B., Mills, G.A., Allan, I.J., Dominiak, E., Svensson, K., Knutsson, J., Morrison, G. and Greenwood, R., 2005. Passive sampling techniques for monitoring pollutants in water. Trends in Analytical Chemistry, 24(10): 845-868.

Vroblesky, D.A. and Chapelle, F.H., 1994. Temporal and spatial changes of terminal electron-accepting processed in a petroleum hydrocarbon-contaminated aquifer and the significance for contaminant biodegradation. Water Resources Research, 30(5): 1561-1570.

Vroblesky, D.A., Petkewich, M.D. and Campbell, T.R., 2002. Field Tests of Diffusion Samplers for Inorganic Constituents in Wells and at a Ground-Water-Discharge Zone. 02-4031, U.S. Geological Survey, Columbia.

Wachter, T., Schaefer, D., Grandel, S. and Dahmke, A., 2005. Raeumliche and zeitliche Variabilitaet hydrochemischer Parameter am BTEX-kontaminierten Standort in Zeitz/Sachsen-Anhalt. Grundwasser, 10(4): 237-253.

Watson, I.A., Oswald, S.E., Banwart, S.A., Crouch, R.S. and Thornton, S.F., 2005. Modeling the dynamics of fermentation and respiratory processes in a groundwater plume of phenolic contaminants interpreted from laboratory- to field-scale. Environmental Science & Technology, 39(22): 8829-8839.

Watson, I.A., Oswald, S.E., Mayer, K.U., Wu, Y. and Banwart, S.A., 2003. Modeling kinetic processes controlling hydrogen and acetate concentrations in an aquifer-derived microcosm. Environmental Science & Technology, 37(17): 3910-3919.

Wiedemeier, T.H., Rifai, H.S., Newell, C.J. and Wilson, J.T., 1999. Natural attenuation of fuels and chlorinated solvents in the subsurface. John Wiley, New York, 617 pp.

Wiedemeier, T.H., Wilson, J.T., Kampbell, D.H., Miller, R.N. and Hansen, J.E., 1995. Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater (Volume I and II), AFCEE, Technology Transfer Division, Brooks Air Force Base, San Antonio, Texas.

Wilson, R.D., Thornton, S.F. and Mackay, D.M., 2004. Challenges in monitoring the natural attenuation of spatially variable plumes. Biodegradation, 15(6): 359-369.

Yeskis, D. and Zavala, B., 2002. Groundwater sampling guidelines for superfund and RCRA project managers. EPA 542-S-02-001, U.S. EPA, Chicago, IL.

3. GROUNDWATER SAMPLING DATA VARIABILITY AND NATURAL ATTENUATION ASSESSMENT

3.1 Background

Natural attenuation (NA) refers to the reduction in contaminant mass or concentration by a suite of naturally occurring physical, chemical or biological processes (USEPA, 1999). Here, NA is taken to encompass the sum effect of (i) physico-chemical processes (e.g., dilution, dispersion, volatilization, adsorption, chemical transformation); and (ii) biodegradation by indigenous bacteria. Natural attenuation is an alternative remedial strategy to active, engineered remediation systems. The NA approach is controversial to some people based on a perception that reliance on NA is an attempt by site owners to 'do nothing' (NRC, 2000; Rittmann, 2004). Guidelines established for NA implementation counter this perception by recommending use of 'multiple lines of evidence' to support the NA conceptual model (ASTM, 1998; USEPA, 1999; Wiedemeier et al., 1999).

The purpose of developing a conceptual model for NA is to identify the main contaminant(s) of concern, the contaminant mass distribution within the geologic units, and the rates of groundwater flow, contaminant transport and attenuation processes that may be active. Incomplete understanding of site conditions directly influences the level of confidence in a conceptual model. Monitoring data therefore represent a key line of evidence because they provide both direct and indirect 'cause and effect' links between the conceptual attenuation processes and actual plume response. Accordingly, understanding of the types and causes of uncertainty associated with monitoring data provides a measure of the confidence that can be placed in the conceptual model.

Groundwater (hydrochemical) monitoring data can provide several independent lines of evidence for attenuation, depending on the contaminants of concern (Alvarez and Illman, 2006; NRC, 2000; Wiedemeier et al., 1999). The possible lines of evidence for attenuation of dissolved petroleum hydrocarbon (PHC) contaminants are well documented in the scientific literature so are only briefly noted here. Biodegradation is indicated by PHC concentrations decreasing downgradient from the source area at a rate faster than the corresponding transport rate (after allowing for volatilization, sorption and dispersion). Over the remediation timeframe, hydrocarbon concentrations must decrease at downgradient locations. Biodegradation activity can be inferred from characteristic changes in concentrations of terminal electron acceptors (TEAs) between groundwater samples collected from within-plume and background locations. Characteristic changes identified between plume and background wells indicate aerobic biodegradation (decreased dissolved oxygen concentration) and/or a variety of anaerobic biodegradation processes including denitrification (decreased nitrate+nitrite), sulphate reduction (decreased sulphate), iron reduction (increased concentrations of dissolved iron as Fe^{2+}), manganese reduction (increased dissolved Mn^{2+}) and methanogenesis (increase in dissolved methane). PHC biodegradation by one or more of these various terminal electron accepting processes (TEAPs) has been demonstrated, thus is generally accepted unless proven otherwise (Chapelle, 1993).

Scientific acceptance of the NA strategy as a remediation method has encouraged its widespread application, sometimes with minimal consideration of potential limitations. For example, hydrocarbon biodegradation may not always be inferred from measuring expected patterns of geochemical indicators in groundwater samples (Cozzarelli et al., 1995; Salanitro et al., 1996; Salanitro et al., 1997). These geochemical indicator patterns may be influenced by a number of closely inter-related factors (Davis et al., 1999; Lee et al., 2001a), including mineralogical and abiotic interactions (Kennedy et al., 1998). Another confounding factor is when concentration changes (contaminant and/or geochemical indicators) occur at a finer scale than observable in monitoring wells (Cozzarelli et al., 2001). Other detailed studies have also shown how monitoring well data may be influenced by fine-scale variations in groundwater sample concentrations over space and/or time (Cozzarelli et al., 1999; Gibs et al., 1993; Thornton et al., 2001). Potential influences include spatially and/or temporally varying factors such as TEA-contaminant interactions (Wilson et al., 2004), redox conditions (Thornton et al., 2001), recharge (Davis et al., 1999; Prommer et al., 1998; Scholl et al., 2006), water table fluctuations (Pelayo and Evangelista, 2003), biological activity (for a variety of reasons) (Bekins et al., 2001a; Bekins et al., 2001b; Borden et al., 1997; Ghiorse and Wilson, 1988; Simoni et al., 2001) and contaminant source behaviour (Guilbeault, 1999; Poulsen and Kueper, 1992).

Despite the complicating factors and environmental drivers, experimental and empirical evidence supports NA. The individual attenuation processes have been demonstrated under controlled laboratory conditions, while case studies have reported successful plume management using NA (Suarez and Rifai, 1999). Accordingly plume management by NA is considered at two levels. At the plume scale, evidence that net attenuation behaviour is clearly able to reach remedial objectives lessens the need for a detailed understanding of the potentially complex set of processes. In contrast, a detailed appreciation of interactions may be required to infer that NA processes are adequately protective at “sensitive” wells and/or for contaminants of concern. Risk management concepts can help in identifying sensitivities and selecting the appropriate level.

3.2 Complexity Inherent in Monitoring Data

Natural attenuation represents the outcome of a complex system operating under non-equilibrium conditions. The controlling processes are nonlinear, being affected by hydrogeological, geochemical, microbiological and environmental conditions that can change widely over varying time and spatial scales. These parameters represent a complex system, having multiple and interdependent interactions between components that may lead to asymmetrical outcomes (e.g., contaminant concentrations) that can change over space and time (Cilliers, 2005). Such systems have processes that occur over divergent time scales, but the system develops a ‘memory’ of adaptations to environmental changes. While it may not be possible to describe a complex system such as NA in just one way, NA assessment should consider:

1. Complex systems are described using a limited set of characteristics. While there is no single correct description, some descriptions provide more insight than others.
2. Description of macro behaviour cannot account for all micro-features, even though the former results from the latter. NA requires making reliable approximations.

These points highlight why use of multiple and detailed data collection methods (Smets and Pritchardy, 2003) helps to gain understanding of attenuation processes. This understanding then forms a basis for defining the appropriate monitoring data to support NA interpretation (Yeskis and Zavala, 2002).

Dissolved PHC plume management by NA initially involves assessment of field data to show attenuation is occurring, and then forward projection of expected plume behaviour (e.g., spreading behaviour and/or time-to-remediate). Each plume must be considered individually to account for varying interactions between hydrogeologic, geochemical and microbiological processes (Chapelle et al., 2003). As a result, data analysis methods have gained sophistication to identify complex interactions between processes. Examples include recognition of geochemical heterogeneity (Cozzarelli et al., 1999), development of a method to separate variation due to NA processes from water table fluctuations (Pelayo and Evangelista, 2003) and use of multivariate statistical methods to interpret changes over time noted in spatial site monitoring data (Lee et al., 2001b). Other methods reported include use of geostatistical tools to examine spatial correlation and data density requirements (Wachter et al., 2005), and relative efficiencies of various biodegradation reactions (Christensen et al., 2004). Another approach uses differences in mass flux across two or more control planes to determine a net biodegradation rate (Kao and Prosser, 2001). Mass flux has also been addressed through modelling chemical analyses of water samples collected at two control planes in combination with active pumping (Bockelmann et al., 2001).

Computer modelling provides a means to examine the influence of implicit or explicit assumptions about attenuation processes. Two general approaches have been used to incorporate attenuation process complexity: data variability or process detail. Variability approaches use statistical data inputs to relatively simple processes to gain insight regarding NA. In contrast, the other approach includes multiple processes and interactions, but at the cost of having to provide additional input parameters (Rifai and Rittaler, 2005).

Data variability has been examined in several ways. The Monte Carlo method was used to generate synthetic plumes for comparison with real site data to improve understanding of plume behaviour (McNab, 2001; McNab and Dooher, 1998). Another approach has been to use a simulated heterogeneous aquifer to look at the influence of reaction kinetics (Beyer et al., 2006). Insight about possible field cases is sought by comparing the ‘known’ solution (modelled using the full data set) to a series of simulations based on data subsets drawn from the ensemble. This approach has also been used to examine the effect on biodegradation from variations in reaction kinetics and dispersion (Maier and Grathwohl, 2006), and from variations in seasonal groundwater flow patterns (Schirmer et al., 2001).

Complexity models for NA have developed because research has shown multiple interacting processes and/or uncertain input parameters (Essaid et al., 1995; Landmeyer et al., 1998; McNab and Dooher, 1998; Rifai et al., 2000). Modelling studies have looked at projected plume response relative to methods used to simulate (or neglect) multiple inputs including flow and boundary conditions (Prommer et al., 2002; Schirmer et al., 2001; Scholl, 2000), biodegradation kinetics (Bekins et al., 1998; Brauner and Widdowson, 2001; Lu et al., 1999; Schreiber et al., 2004), source history and complex biochemical reaction pathways (Schaefer, 2001; van Breukelen et al., 2004; Watson et al., 2005). Increased process complexity is typically recognized as significant when model simulations based on simpler processes fail to capture detailed field data.

The main challenge to the complexity approach is appropriate parameter estimation. Without a physical basis, matching model and field data is a curve-fitting exercise, although encouraging modelling results have been reported for research sites where reaction complexity was parameterized using laboratory-determined parameters (Schirmer et al., 2000; Watson et al., 2005; Watson et al., 2003). The general effect of having many inputs with complexity is that models based on mean values tend to overestimate the effective plume decay rates (hence underestimate plume size or half-life) (Beyer et al., 2006; Miralles-Wilhelm and Gelhar, 2000).

In summary, increasing complexity in conceptual model formulation affects ‘scaling’ considerations for how best to interpret NA effectiveness at a generic site. Awareness of the complexity and spatio-temporal variability in NA processes might lead one to infer that more detailed data are needed to describe these processes. This inference contrasts with development of the NA concept, having been originally derived from broad-scale reviews of overall plume behaviour (McGuire et al., 2004; Rice et al., 1995; Suarez and Rifai, 1999). What data resolution is required to identify ‘significant’ results without excessive ‘fine-scale’ influences? Typical NA data might include samples collected from wells (10^{-1} m) over relatively short time frames (years) that have to identify inter-related effects acting across a wide range of scales (groundwater flow and transport: 10^{2} metres, soil stratigraphy and groundwater sampling interval: 10^{0} m, grain mineralogy: 10^{-4} m and microbial activity: 10^{-6} m). These monitoring well data are then relied upon to provide support for assessing plume lifetime (decades to centuries) and lateral extent (10^{2} to 10^{3} m). Given so many sources and scales of variability that may affect groundwater samples (Keith et al., 1983), perhaps the biggest surprise is the relative lack of variability noted at the plume scale compared to local scales (Cozzarelli et al., 2001).

3.3 Sampling Method Considerations

Interpretation about NA is commonly based on groundwater samples collected over space and time. Variability associated with these samples often includes influences from uncontrollable factors such as:

- potentially correlated factors such as geologic, hydrogeologic, geochemical and microbiological heterogeneity;
- environmental factors such as climate, precipitation, recharge and water table changes;
- physical influences such as land use changes, unknown source area(s); and,

- in-well artefacts such as mixing induced by temperature or concentration density gradients, vertical hydraulic gradients and chemical transformations.

Variability is also related to factors that can be controlled within a sampling plan (e.g., well completion, groundwater sampling method and protocol). These influences are discussed below.

Monitoring wells for collecting groundwater samples for NA assessment may generate confounding data if they are installed inappropriately (or incorrectly) (Nichols and Roth, 2006; Odermatt, 1999) especially during early site characterization phases. Issues associated with use of appropriate well drilling and sampling construction materials have been investigated for many common contaminants (Barcelona and Helfrich, 1986; Barcelona et al., 1988; Keith et al., 1983). Other complicating influences include changes in local hydrochemistry due to well installation activities (so-called well trauma) (Pennino, 1988), while longer-term influences have been noted as being related to contamination associated with material used to seal the annular borehole space above a well screen (Barcelona and Helfrich, 1986; Remenda and van der Kamp, 1997), drilling-induced geochemical effects (Kim, 2003) and microbiological changes within the aquifer and around the well bore (Kwon et al., 2008). Recognition of such situations can be complicated, especially in the absence of historical information to provide perspective or contrast.

The influence of well screen placement relative to the contaminant zone can introduce variability due to mixing in several ways. Mixing due to natural flow and/or purging can cause over-or underestimation of the contaminant distribution (Elci et al., 2001; Gibs et al., 1993; Hutchins and Acree, 2000; Martin-Hayden, 2000; Robbins and Martin-Hayden, 1991). The situation is exacerbated if the screened interval connects more than one water-bearing unit with varying hydraulic conductivity values and/or a vertical flow component. Field data have shown that vertical variability is common, thus short screens should be used (Church and Granato, 1996). Notably the concept of “short screen” has changed since their work compared results between ‘short’ 3 m screens and a 21 m long well screen. Other research using modelling and field data showed that monitoring wells with 3 m screens can not provide a quantitative indication of groundwater contamination, independent of the construction and sampling methods used (Elci et al., 2001; Martin-Hayden and Robbins, 1991; Martin-Hayden and Robbins, 1997). Vertical heterogeneity has been identified using shorter sampling scales of 1 m (Jones et al., 1999), 0.2 m (Barker et al., 1987) down to 0.03 m (Ronen, 1986), suggesting that the scale of vertical variability decreases with screen length. Selection of well screen lengths for monitoring groundwater impacts therefore requires decisions based on budgetary, practical and data quality constraints (Martin-Hayden, 2000).

Groundwater sampling methods have developed based on understanding of conceptual and measured interactions between water above the well screen (stagnant), within the screen, and outside in the formation (fresh). Sampling protocols currently use any of several variations of purging style (ASTM, 2005). These protocols developed as modifications to the concept of purging specified borehole volumes to ensure that sample chemistry was not affected by stagnant water (Gibs and Imbrigiotta, 1990) . An alternative view suggested that minimal purging would be required when groundwater flows freely through the screen (Robin and Gillham, 1987). As an extension of this idea, low-flow purging methods were developed to minimize sample turbidity and interactions with stagnant water by pumping from the screened interval at approximately the same rate as water entered the well (Barcelona et al., 1994; Powell and Puls, 1993; Puls and Barcelona, 1995; Puls and Paul, 1995).

More recently, there has been a move toward no-purge sampling. Research of no-purge sampling has generally focussed on two main types of protocol, diffusion-based and ‘thief’ styles (Parker and Clark, 2002). Diffusion samplers are left in a well to equilibrate over some time period (typically order of weeks), while ‘thief’ sampling devices are used to collect a ‘snapshot in time’ sample within the screened interval. Diffusion sampler trials have been published for various common contaminants (Ehlke et al., 2004; Vroblesky et al., 2002). Another style of diffusion-based sampler uses a time-weighted mass partitioning approach to estimate time-integrated mass loading (Bopp et al., 2005; Martin et al., 2003). Grab samples collected before and after purging showed no significant differences for BTEX and methyl-tert-butyl ether (MTBE) (SECOR, 1996). Evidence and discussion of the relative merits and limitations of no-purge sampling are provided by supporters (API, 1998; Byrnes et al., 1996; Newell et al., 2000) and opponents (Barcelona et al., 2005; Varljen, 1997).

Recommendations regarding sampling protocols have changed with improved understanding of sampling complexities (Barcelona et al., 2005; Herzog et al., 1991; Schuller et al., 1981). As examples, sampling methods have developed for specific contaminant(s) of interest e.g., when sampling for metals (Puls and Barcelona, 1989), volatile organic compounds (Barker and Dickhout, 1988; McAlary and Barker, 1987), semi-volatile organic compounds (Gustavson and Harkin, 2000) and agricultural contaminants (Ronen et al., 1986).

Field studies comparing sampling methods show a range of outcomes. Little significant difference was reported for metals analyses during a comparison of conventional purge sampling and low flow sampling (Kearl et al., 1994). A comparison of discrete interval samples using both a multilevel passive system and a Geoprobe-installed direct-push and sample method, showed much greater dissolved metal heterogeneity than the depth-integrated low-flow purge and "traditional" bailer (lowest result) but minimal differences for chloride (Puls and Paul, 1997). A comparison of analytical results for samples collected by the low flow and passive diffusion bag methods showed generally similar results in terms of volatile organic contaminant detection (Archfield and LeBlanc, 2005). These authors noted that the degree of reproducibility at a given well was consistent between the two methods, but varied between wells. Shorter screen wells (0.6 m) tended to have better reproducibility than longer screen wells (1.6 m).

All sampling methods are challenged when trying to collect 'representative' samples from wells in low permeability formations (Herzog et al., 1988). Traditional methods typically cause excessive purging, exposing the recovering water to atmospheric air and causing geochemical alteration (oxidation of reduced compounds, gas exchange and/or volatilization losses). Low-flow purging is not optimal either, requiring excessively slow flow rates. Finally diffusion-based sampling may be affected by in-well effects such as thermal convective mixing or biodegradation and redox-sensitive processes related to diffusion of dissolved oxygen from the water surface.

In Alberta, groundwater monitoring wells are commonly constructed using commercially-available 1.5 to 3 m screens. Such wells enable seasonal groundwater sampling given that water table elevation fluctuations commonly range on the order of 1-2 metres. Sampling protocols call for some form of well purging (stabilization of indicators such as pH, electrical conductivity, or specified number of borehole volumes) prior to sampling. Accordingly, practitioners, site owners and regulators need to incorporate an understanding of data variability from such wells when making decisions regarding site suitability and/or progress with NA.

3.4 Problem Statement

A research consortium (Consortium for Research on Natural Attenuation, CORONA) was developed to help provide technical guidance and supporting scientific information for site owners, consultants and regulators in Alberta. The first task reviewed available groundwater monitoring data at upstream oil and gas industry sites in Alberta (exploration and production of unrefined petroleum products). The review identified hydrocarbons and salt as the primary compounds of concern (Armstrong et al., 2002), and provided qualitative empirical evidence of PHC attenuation consistent with the scientific literature (Baedecker et al., 1993; Barker et al., 1996; Elshahed et al., 2001; Gieg et al., 1999; Morgan et al., 1993; NRC, 1993; Rueter et al., 1994; Townsend et al., 2004). The CORONA study recognized several concerns with the available monitoring data. Most plumes were characterized with relatively few wells, often screened over 3 m lengths. Also, the standard sampling protocol involved purging three well volumes or until the well was dry before sampling with a dedicated bailer or Waterra® pump. Based on data variability due to potential underlying causes, there was concern as to whether these historical data could be relied on for NA assessment.

Two sites associated with oil and gas production in Alberta were selected to examine sampling-related variability and associated influence on interpreting natural attenuation characteristics. Both sites had approximately ten years of historical groundwater monitoring data, but no focus on trying to show active NA. Groundwater data were obtained using several well types and sampling method combinations to look at sampling data variability and its influence on inferences regarding NA. Insight gained by examining data variability will help provide guidance on appropriate sampling methodology and interpreting sample results.

3.5 Field Methods

3.5.1 Site Description

Two demonstration sites (Sites A and B) were selected for this program, based on a monitoring data review (Armstrong et al., 2002). Approximate site locations are shown in Figure 3-1, with local site plans showing monitoring well locations and general plume hydrochemistry at Sites A and B provided in Figures 3-2 and 3-3, respectively. The sites provide typical environmental and contaminant situations common to Alberta, with site details provided in Appendix 2. Plumes at both sites were inferred to be at steady state, with some residual hydrocarbon remaining in the source zone.

Figure 3-1 Map Showing Site A and B Locations within Alberta, Canada

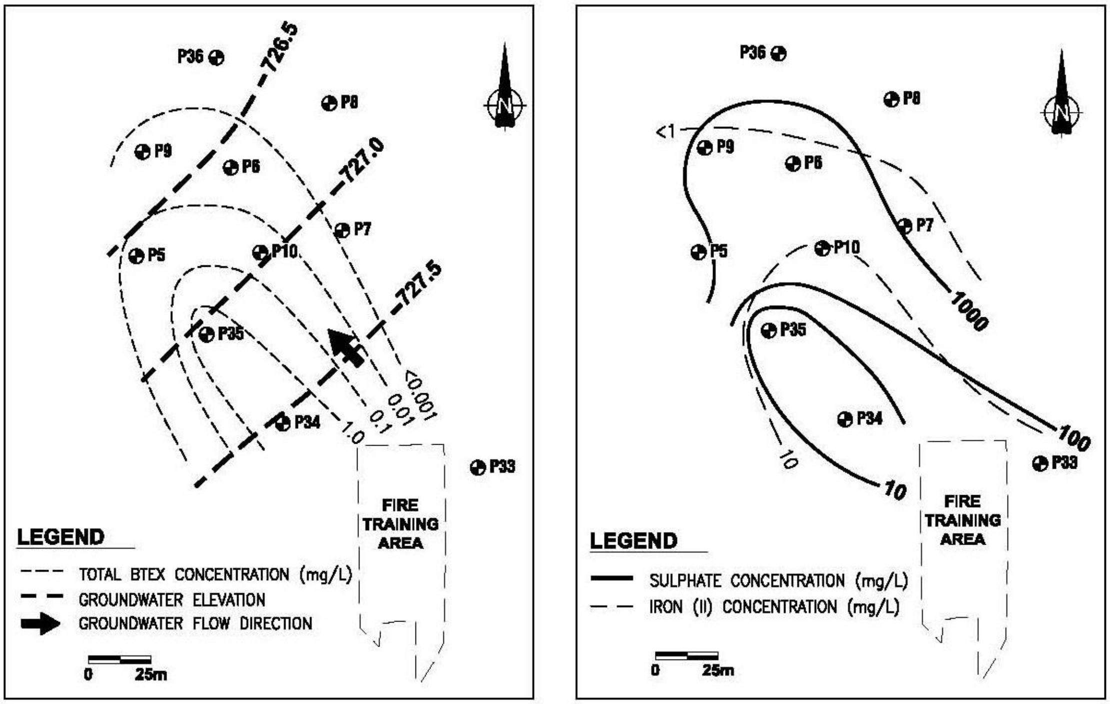


Figure 3-2 Site A Plan Showing Average Local Groundwater Flow Direction and Concentration Contours for Total BTEX, iron (II) and Sulphate. Research well clusters installed at P34 and P35 locations; hydrocarbon source was Fire Training Area

Site A is located in southeast Alberta. Grain size analysis showed the soil profile broadly consists of shallow silt overlying a silty fine sand unit that grades finer with depth, with clayey silt and silty clay underlying the fine silty sand (Van Stempvoort et al., 2007). The groundwater surface is located approximately 2 to 3 metres below ground surface (mbgs), within the fine sand and underlying silt. The main suspected source of the natural gas condensate contaminant (compositional analysis provided in Appendix III) was a previously unlined fire-fighting training area. The condensate had been used as the burning liquid; thus pulsed releases may have occurred during intermittent practice. Following one such training period, site staff commented on a safety issue related to inadvertent entrainment of condensate drops in the water spray. Consultant reports had noted free phase condensate near the training area, with a hydrocarbon sheen (no measurable thickness of free phase hydrocarbon) observed in P34 and P35 along the groundwater flow direction. Using an average measured hydraulic gradient (0.015), a range of hydraulic conductivity values estimated from slug tests (0.2 to $3x10^{-6}$ m/s) and an effective porosity of 0.2, groundwater flows to the northwest with an estimated velocity on the order of 0.5 to 7 m/year.

Site B is located in west central Alberta. Shallow soil comprises discontinuous, interbedded layers of sand, silt and clay (Armstrong et al., 2003) with a topographic slope to the south away from the original source area (a former flare pit located north of 01CP01). The bulk of heavily-contaminated soil beneath and surrounding the flare pit was excavated, but some hydrocarbon-contaminated soil could not be removed. The depth to groundwater varies across the site, due mainly to topographic influence. At the local topographic high near the former flare pit, groundwater is encountered more than 6 mbgs. The land slopes southward in the direction of groundwater flow, so groundwater depths become shallower, being less than 1 mbgs at the plume's distal end.

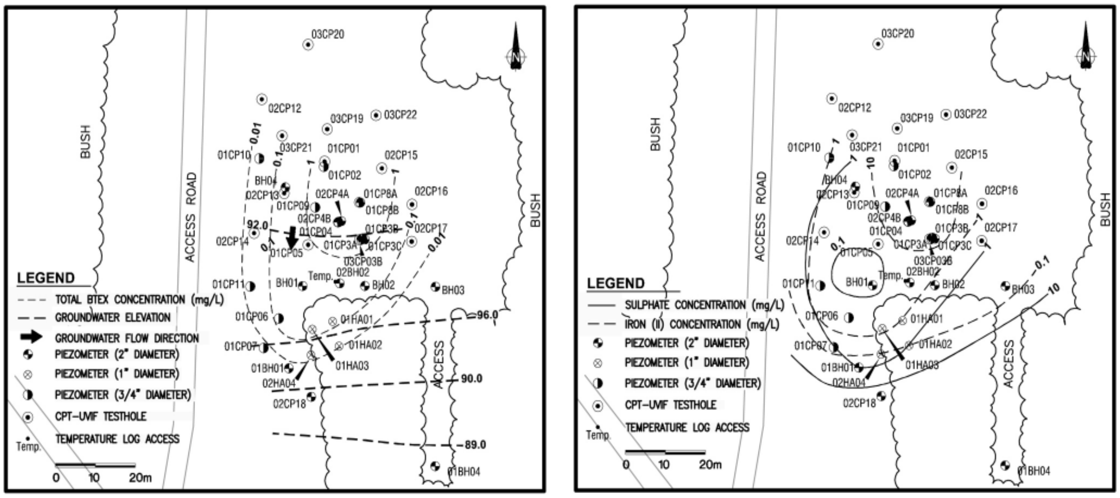


Figure 3-3 Site B Plan Showing Average Local Groundwater Flow Direction and Concentration Contours for Total BTEX, Iron (II) and Sulphate. Research well cluster installed at BH01 location; hydrocarbon source was former flare pit north of 01CP01

Groundwater monitoring had occurred at both sites prior to this program; however, those data are generally relied upon only to provide historical comparisons. Using available groundwater elevation data, seasonal groundwater surface elevations indicate an annual fluctuation of approximately 1 to 2 m at both sites. The contribution of surface recharge is not well characterized at either site.

Groundwater samples collected from selected wells at each site had been analyzed using biological activity response tests (BARTs; DBI, Regina, SK) to identify potential bioactivity associated with a variety of TEAPs (aerobic, nitrate-reducing, iron-related and sulphate-reducing). Water samples had also shown evidence of putative PHC biodegradation metabolites (Gieg and Suflita, 2002).

3.5.2 Well Installation

Site A

Research well clusters were installed beside two pre-existing monitoring wells (P34 and P35, Figure 3.2) installed for the site owner by a consulting company. Each cluster comprised a nest of closely-spaced monitoring wells including: the original well (P-series), two replicate wells

(MW-series; 3 m screened intervals, 0.05 m diameter PVC), three direct push wells (DP-series; 0.75 m screened intervals, 0.025 m diameter, standard Prepak, Geoinsight, Las Cruces, NM), and a multi-level well (ML-series; effective screened intervals of 0.6 m, 0.01 m diameter, 7 channel MLS, Solinst, Waterloo, ON). The original wells (P34 and P35) used 1.5 m long screens. Completion depths were intended to facilitate comparison of results from the various wells over similar monitoring intervals. The direct push screens and multi-level wells were installed approximately near the top, middle and bottom of the 3 m screened intervals. A photograph of a typical installation, and a schematic cross section illustrating well types and coding are provided in Figure 3-4. Six additional monitoring wells (P5-P10; 3 m screens, 0.05 m diameter PVC pipe) were installed to improve spatial delineation of dissolved hydrocarbon presence and geochemical changes (Figure 3-2).

Well cluster P34 is the nearest well downgradient (~30 m) of the suspected PHC source; thus has had longer exposure to hydrocarbons at higher concentrations. The ground surface in this area is variably covered with grass, although gravel-covered areas are nearby (greater potential for infiltration of precipitation). Cluster P35 is located in a grass-covered field, approximately 45m further downgradient along the inferred groundwater transport pathway.

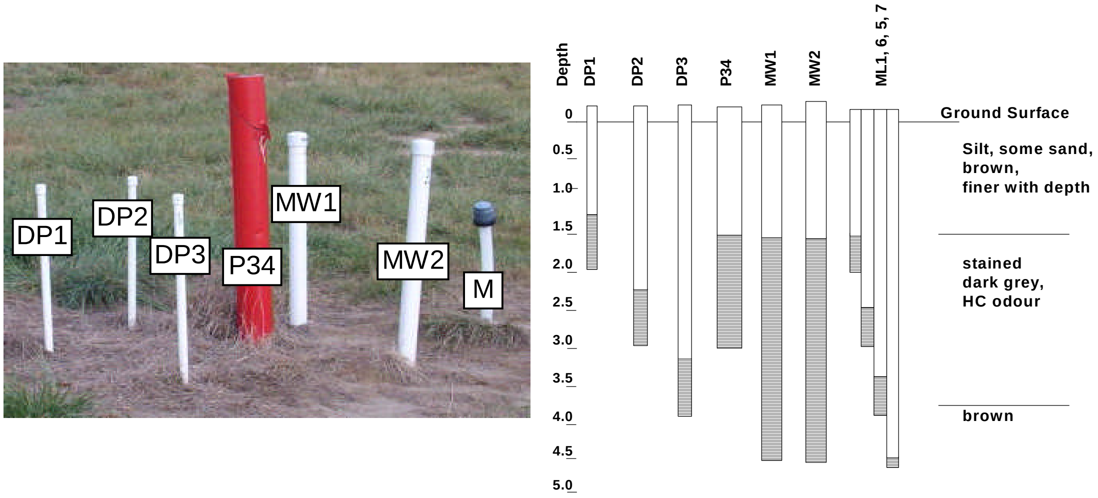


Figure 3-4 Photograph of P34 Research Well Cluster (Site A) and Well Cluster Schematic Cross section

Prior to this study, dissolved hydrocarbon impact was characterized by two monitoring wells P34 and P35, and delineated laterally and downgradient by two more wells. Soil impact was inferred from notable black staining in conjunction with a hydrocarbon odour. As part of the research activities, soil samples were collected from the stained and unstained intervals at several locations. Samples were analyzed using sequential extraction techniques to characterize presence and concentrations of sulphur and iron-related compounds. Sampling and analytical protocols are reported elsewhere (Petersmeyer, 2006; Van Stempvoort et al., 2007). These data showed concentration spikes in reduced sulphur and iron species in the zone of hydrocarbon contamination compared to soil above or below this interval.

Drilling for the MW well installations was conducted using standard solid stem auger techniques. The DP wells were installed using a direct push method, while the ML series were installed using a hollow stem auger technique. The MW wells were constructed in a conventional manner (Aller et al., 1989), with clean silica frac sand being used to backfill the annulus from the bottom to approximately 0.2 to 0.3 m above the screened interval. The remaining annular space was filled using a primary sealing layer of bentonite pellets (typically 0.3 m thickness) and then bentonite chips to surface. Given limited access, steel casing protectors were not installed.

After pushing in the pre-packed DP well screens, the annular space above the screen was sealed using an expanded foam primary seal overlain by a 0.7 m long bentonite powder seal (pre-wrapped in disposable paper) and then sealed to surface with bentonite grout. Each ML series well was equipped with a hand sewn mesh pre-pack assembly incorporating 0.6 m long sand packs around the sampling intervals and separated by bentonite pellets and chips. The entire assemblage was lowered into the hollow-stem augers, and held in place while the augers were withdrawn (Morin, in preparation).

Site B

Data from previous site investigations was used to design detailed site characterization activities during the CORONA program using cone penetration testing (CPT), with ultraviolet-induced fluorescence (UVIF). The program examined detailed soil stratigraphy and free phase hydrocarbon presence. Borehole logs, combined with a geostatistical assessment of the CPT data indicated a heterogeneous distribution of silt and clay units with some interbedded sand layers (Armstrong et al., 2003). Selected CPT holes were subsequently instrumented as monitoring wells, typically using 1.0 m screened intervals and 0.02 m diameter pipe (ConeTec, Vancouver, B.C.). Conventional 3 m long, 0.05 m diameter wells (PVC casing and screen, Rice Engineering, Edmonton, AB) were subsequently installed in selected locations relative to zones of suspected free phase hydrocarbon. Limited access within a heavily-treed area at the south end of the plume meant that monitoring was conducted using four shallow monitoring wells (1 m screened interval, 0.025 m diameter) installed by hand auger.

The single research cluster by BH01 at Site B (Figure 3-5) followed a similar strategy as at Site A. Minor exceptions included: the original monitoring well (BH01) had a 3 m screen, sand pack and bentonite layers for the ML-series were installed through the hollow stem auger (no pre-packed mesh), and a fourth discrete-interval DP-series well was installed to assess potential for lateral plume migration of a deeper zone of contamination identified during the CPT-UVIF testing program.

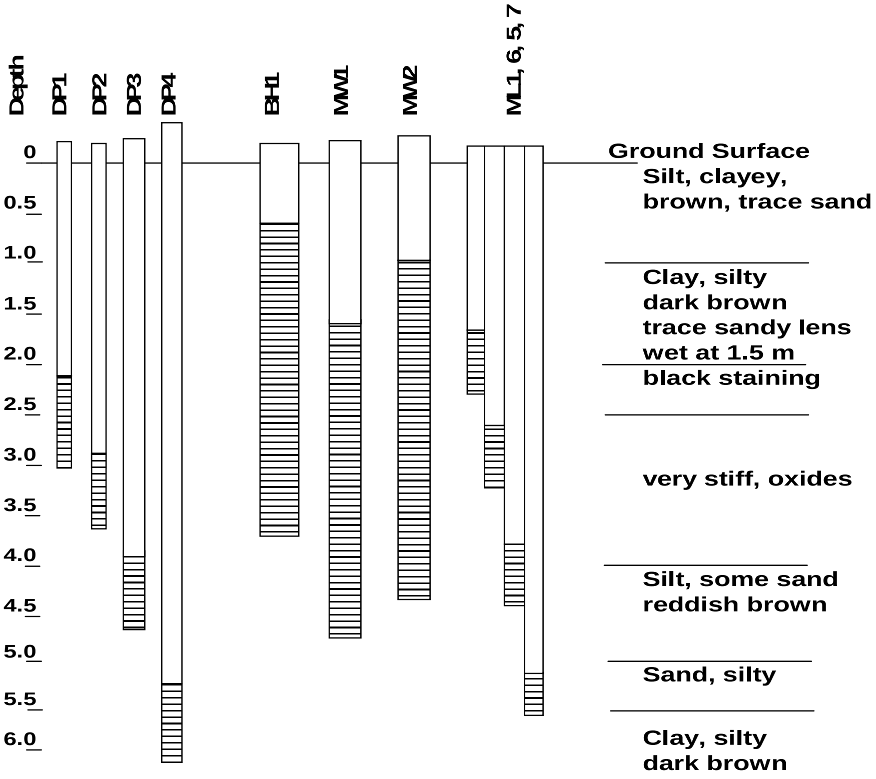


Figure 3-5. Site B Well Cluster Schematic Cross-section

3.5.3 Site Sampling

A key component of using NA to manage a contaminant situation is collecting suitable monitoring data to evaluate and update the conceptual model, particularly through chemical analyses of groundwater samples. In this study, samples were collected quarterly over approximately two years. Each visit typically involved collecting a low-flow sample from the DP wells, a pre-purge sample and one or more other type of sampling method or purging protocol from the cluster wells, and a set of samples from the other site characterization wells. More limited data were collected from the ML wells (suspected installation problems) and using the HydroPunch-style (one set only). Sampling methods included purge, no-purge and low-flow sampling, while collection methods included use of dedicated bailers, Waterra® inertial pumps, BarCad gas lift system, dialysis membrane diffusion samplers (DDS) (conventional 3 m screen well) and peristaltic pump. Exceptions included when DDS samplers were used (required weeks to months for equilibration), or when multiple replicates were collected using low-flow techniques.

Analytical uncertainty in the laboratory was assessed through a program of blanks, duplicates and laboratory-prepared standards. In contrast, uncertainty in the sample results due to temporal and spatial variability, well completion geometry, construction materials, sampling methods and protocols is not as readily addressed, as shown by simulations of changing well lengths and purging practices (Martin-Hayden and Robbins, 1997).

The influence of purging was evaluated by comparing chemical analyses of samples from the same well collected using three techniques: minimal purging, aggressive purging, and low-flow purging. Minimal purging (no-purge) involved collecting a sample after having rinsed the dedicated sampler (i.e., fill and discard one bailer or length of dedicated Waterra® hose). Aggressive purging involved bailing or Waterra® pumping until either three borehole volumes had been removed, or (typically) the well was dry (post-purge). Low flow purging used a peristaltic pump operating at a low flow rate, thus creating minimal drawdown. Wells were selected for low-flow purging if a flow rate of approximately 100 mL/min could be maintained with drawdown limited to less than 10 to 25 cm.

Variability in groundwater monitoring data over space and time is commonly dealt with explicitly. This study examined several effects that might influence this variability using groundwater samples collected at three research well clusters at the two sites. Each cluster was designed to provide replicate sampling points for comparing samples collected using various methods. A summary of the different sample issues, methods and datasets considered is compiled in Table 3-1. Analytical results are provided in detail in Appendix 3.

Table 3-1 Replicate Samples for Variability Assessment at Site A

Issue	Sampling Method	Data Set Size
Site A		
Purging		
	No purge, re-sample after purging dry, re-sample after water level recovery	3 sets of 3 samples each
	No purge vs. after recovery	4 (2 samples each)
	Long term purging	3 sets (3-7 repeated samples)
Compare Methods		
	No purge bailer vs. low flow	7 sets (1 to 7 repeat low flow samples)
	No purge Waterra® vs. low flow	2 (1 low flow set)
	No purge vs. DDS	2 (2 DDS for each set)
Duplicates		
	Various sampling methods	7 sets of paired samples
P34 Location	2 wells, each with 3 m screen	6 samples by Waterra®
	1 well with 1.5 m screen	7 samples by bailer
	0.7 m discrete depth (2 levels)	6 samples each by minimal purge
	0.5 m multi-channel well (2 levels)	5 samples by minimal purge
P35 Location	2 wells, each with 3 m screen	4 samples by Waterra®,
	2 wells, each with 3 m screen	3 samples by DDS
	1 well with 1.5 m screen	7 samples by bailer
	0.7 m discrete depth (2 levels)	6 samples each by minimal purge
	0.5 m multi-channel well (2 levels)	5 samples each by minimal purge
Site B		
Purging		
	No purge, re-sample after purging dry; re-sample after recovery	3 sets of 3 samples each
	No purge vs. after recovery	14
Compare Methods		
	No purge bailer vs. low flow	2 (1 low flow set in sequence)
	No purge Waterra® vs. low flow	2 (1 low flow set each)
	No purge vs. DDS	5 (1-3 DDS for each set)
Duplicates		
	Various sampling methods	8-40 sets of paired samples
BH01 Location	2 wells, each with 3 m screen	6 samples by Waterra®
	1.5 m screen	7 samples by bailer
	0.7 m discrete depth (3-4 levels)	7 samples by minimal purge
	0.5 m multi-channel well (3-4 levels)	5 samples by minimal purge

Given the extreme climate at Site B, a thermistor string (0.5 m intervals to 3 mbgs, then 4 and 5 mbgs) was installed in a sealed, dedicated well filled with vegetable oil to record the vertical distribution of subsurface temperatures. Quarterly groundwater sampling at this site showed some evidence of temperature-related variation in geochemical response (see Section 3.6.3.1). Temperature logging was not conducted at Site A.

For all sampling methods, efforts were made to sample groundwater from within the screened interval, and avoid collecting stagnant water from above the screened interval. Except as detailed below, efforts were made to minimize groundwater aeration and contact with atmospheric gas by minimizing drawdown during sampling. Effort was also made to minimize turbulence during sample decanting into laboratory-supplied bottles. Water surface elevation measurements taken before and after sampling showed that net drawdown was typically on the order of 0.05 to 0.1 m in the 0.05 m diameter monitoring wells.

Groundwater samples were collected for laboratory analysis of main ions (calcium, magnesium, sodium, potassium, bicarbonate, carbonate, chloride and sulphate), general water quality indicators (pH, electrical conductivity (EC) , alkalinity, mineralization as total dissolved solids, hardness), nitrite and nitrate, dissolved iron and manganese (field filtered with 0.45 μm cartridge filters and acidified with 1.25 mL of 1:1 HNO_3 supplied by the laboratory), BTEX hydrocarbon compounds and CCME petroleum hydrocarbon fraction F1 (nC_6 to nC_{10} – BTEX). Other analyses collected intermittently included dissolved sulphide, total extractable hydrocarbons (C_{11}-C_{30+}), and polycyclic aromatic hydrocarbons (PAHs). Maxxam performed all analyses using their standard operating procedures, including ion chromatography (IC: anions) or inductively coupled plasma (ICP: cations), titration (bicarbonate) and gas chromatography/mass spectrometry (GC/MS with purge and trap: PHCs). All samples were preserved according to lab specifications. Samples were stored on ice in coolers immediately upon collection until delivery to the laboratory, typically within one to two days of collection.

Field-measured water quality indicators were generally collected during sampling visits, except in winter, due to risk of equipment damage by freezing conditions. Field-measured indicators included dissolved oxygen, pH, EC, oxidation-reduction potential (ORP) and temperature. Field determinations of sulphide concentrations were done intermittently. Samples were also collected at Site B for dissolved gas compounds (McLeish et al., 2007).

A summary of all analyses at each research well cluster is provided in Appendix 3. General comments regarding each sampling system are summarized here, with illustrative photographs and/or schematics also shown in Appendix 2. Sampling protocol required clean neoprene gloves when collecting each sample, and avoiding contact between sampling equipment and the ground surface.

Bailer: Historically, dedicated bailers with bottom check valves were used to sample each site. Between visits, bailers were stored empty within each well above the groundwater surface. Purging typically involved bailing down from the water surface. In contrast samples were bailed gently from the middle of the water column in the screened interval. For no-purge samples, the bailer was gently submerged once to fill and rinse it. After discarding this water, the sample was bailed from the screened interval as described above. In all cases, care was taken to minimize turbulence and atmospheric air contact by controlled decanting of samples from the bailer bottom via a tube to open the bottom check valve.

Waterra®: Dedicated Waterra® tubing and foot valves were installed in selected wells. Given the remote locations and seasonal freezing conditions, Waterra® tubing was stored upside down in the wells. As with the bailers, contact with the ground was avoided. If Waterra® tubing was removed to provide well access for another sampling method, it was either temporarily stored on site in a clean plastic bag (if the other method was a grab sample) or replaced (between dialysis sampling periods). A gentle pumping motion was specified when collecting Waterra® samples from the bottom metre of the screened interval. During sampling, care was taken to minimize atmospheric contact by decanting the water gently into the sample bottles.

For some of the very slow recharge wells within the research cluster at Site B, sampling might take several hours of periodic decanting. During the process, partially-filled bottles were stored closed in a cooler, either on ice (summer) or in a truck (winter). Minor drawdown (<0.15 m) was experienced at most Site A and B wells.

Low flow: Dedicated tubing was used to sample the DP-series wells using a peristaltic pump. These wells had slow recovery rates. Slow sampling rates combined with water level monitoring were required to avoid drawing the water surface into the screened interval and potentially causing adverse impacts by aeration/oxidation of sampled and recharging groundwater. During the initial low-flow purging, the pump intake was kept approximately 0.3 m above the screened interval. If the water level approached that depth pumping was halted to ensure that the screened interval was never exposed to atmospheric air. During sampling, the pump intake was lowered into the screened interval, and a thin wire water level tape was used to ensure that pumping was halted if the water level reached 0.3 m above the screen top during sampling. Between site visits, the empty tubing for each well was stored individually in a sealed, marked Ziploc bag. Disposable clean tubing was used whenever low-flow samples were collected from other wells already equipped with another dedicated sampling device.

BarCad: This system involved installing a 0.8 m long, 0.0125 m diameter sintered metal well screen to the desired depth. The annular space above the screen was sealed with an inflatable packer. The sample was recovered at surface by gas lift. Nitrogen pressure was applied to a 0.0125 m PVC external casing attached to the screen, causing the accumulated water to be gas lifted to surface through an internal 0.005 m Teflon sampling tube. Gas pressure was periodically released to allow more water to enter the well. This approach avoided air contact, but required caution to avoid over pressuring the sample line and spraying the sample. After sampling a well, the entire well assembly was removed and cleaned with distilled water. Dedicated sampling tube was used for each well.

Hydro-punch-style sampling: A drill rig was used to push in a 0.7 m long sampling screen assembly to a similar depth as the shallowest DP well. A groundwater sample was recovered via peristaltic pump. The screen assembly was recovered, replaced with a clean one, and then pushed deeper to the next sampling interval corresponding to the deeper DP wells. The method was slow due to the slow groundwater recharge rate in the silty soil. Purging was restricted to one sample tube pore volume. Samples were collected once at both P34 and P35 clusters at Site A.

DDS: Samplers consisted of pre-cleaned tubular regenerated cellulose dialysis membrane (Membrane Filtration Products Inc. MPFI) filled with deoxygenated distilled water (DeI) (Iwakun et al., 2008). The dialysis membrane has a wall thickness of 30μm, nominal pore size of about 0.002μm, a closed flat width of 50mm and a filled volume of 7.94 mL/cm (i.e., millilitres per cm-length of sampler). A 30 cm length was cut from the roll of the membrane, rinsed in DeI water, and knotted at one end. After filling with DeI water, the samplers were sealed with a brass fitting and threaded cap.

Dialysis samplers were placed within the 3 m screened interval of the MW wells (0.05 m diameter), and allowed to equilibrate within the well. The first round of sampling used an equilibration time of three weeks before collection (Morin, in preparation). Subsequent experiments and modelling showed that DeI water did not need to be deoxygenated (Iwakun et al., 2005). As part of this work, longer equilibration times were used to examine DDS durability (Iwakun et al., 2008). The samplers were recovered, and the water within each sampler was decanted into bottles for analysis.

3.6 Results

At both sites, nonaqueous phase liquid (NAPL) hydrocarbon samples were obtained from monitoring wells located upgradient of the research areas. These samples, possibly representing weathered NAPL rather than the original released liquid, were analyzed by Maxxam (Maxxam Analytics, Calgary, AB). Complete analyses are given in Appendix 3. Raoult's Law was used to compare theoretical BTEX concentrations derived from NAPL molar fractions with maximum dissolved concentrations reported at Sites A and B (Table 3.2).

Table 3-2 Measured and theoretical BTEX concentrations based on Raoult's Law

	Benzene	**Toluene**	**Ethylbenzene**	**Xylenes**
Site A				
Theoretical	19	3.7	0.06	0.26
Actual (P34)	0.077	0.4	1.05	9.6
Actual (P35)	0.27	1.79	1.66	19.1
Site B				
Theoretical	1.3	0.4	0.4	1.2
Actual (DP1)	0.003	<0.0009	0.214	0.22

The data from Site A suggest that either the source material has changed over time, or that residual NAPL near these wells (likely present based on xylenes concentrations greater than 5% of pure liquid solubility) has undergone notable weathering (based on apparent preferential dissolution of the more soluble benzene and toluene components).

Variability was assessed from several perspectives, depending on the size of the data set. Paired analyses (two samples from the same well) were cross-plotted, along with the theoretical perfect match (line with 1:1 slope). Between-well comparisons were plotted over time. Basic parametric or nonparametric statistical hypothesis methods were used to compare mean values. Data are first presented and then implications are reviewed in Section 3.7.

The first step was to examine hydrochemical variability (accuracy and precision) based on laboratory spikes and a series of field duplicates and replicates from both Sites. These results were used to develop error bars for subsequent plots. Monitoring data were then reviewed separately for the various well types at Sites A and B using plots of concentration versus time for results from each research cluster. Historical plume data (including pre-CORONA data) were considered for evidence of attenuation behaviour over time and space. Sampling methods were then considered at each research cluster to examine further scales of spatial and temporal variability. Suspected influential factors included PHC contaminant concentration, relative thickness of contaminated interval and sampling interval, local vertical geochemical change (related to PHC presence), infiltration and water table fluctuation. Conclusions about data monitoring needs and interpretation tools are then summarized.

3.6.1 Duplicate and Replicate Samples

Duplicate sample sets (paired samples collected sequentially using the same sampling method) were collected from Site A over time for various combinations of well and sampling method. Data from Site A (4 sets) are cross-plotted in Figure 3-6 along with the 1:1 slope line. Two outliers are evident on the inorganic compounds plot. Data review showed that these two cases were NA indicators, iron (II) (P34, peristaltic low-flow) and sulphate (35MW2, Waterra®).

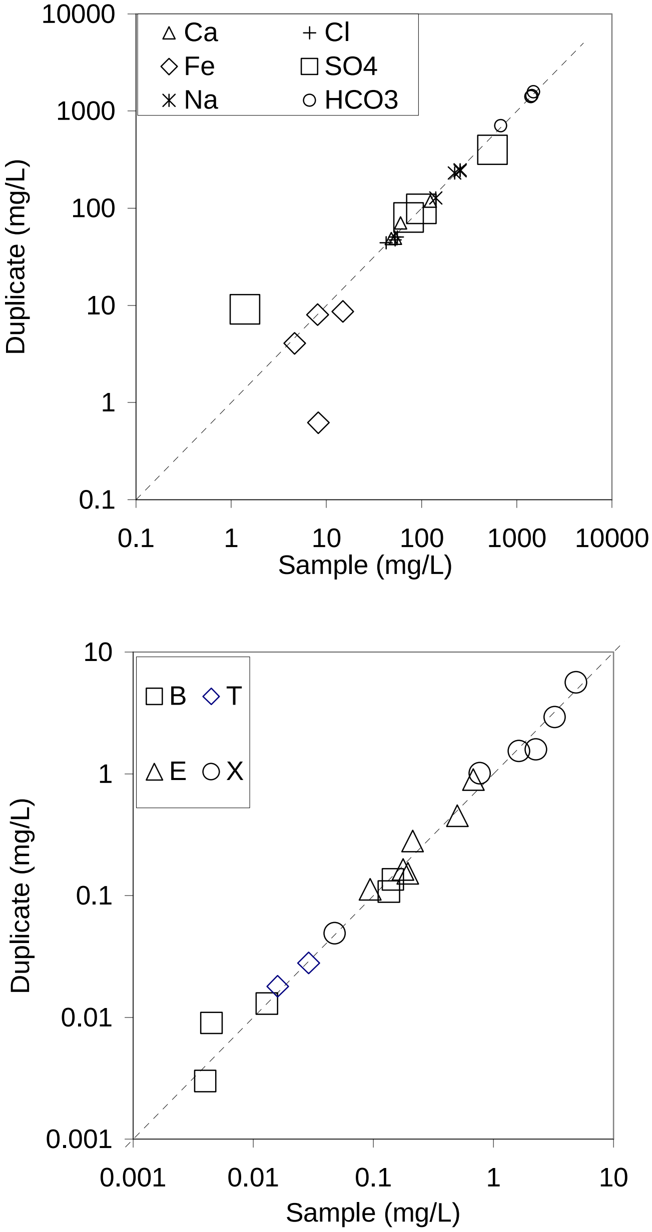


Figure 3-6 Cross-plots (log-scale) of selected analytes from duplicate samples at Site A. Symbol size includes error bar; dotted line shows the theoretical 1:1 ratio.

Data from seven pairs of duplicate samples with detectable BEX analyses (excluded pairs of mutually non-detectable analytes) ranged over four orders of magnitude. Regression analysis of the individual log-transformed B, E and X data (only two samples had detectable T) gave high r^2 values (>0.8, $p<0.05$, $n=7$) with slopes that did not differ significantly from 1.0.

Relative percent difference (RPD) was calculated for paired duplicate samples (C_1 and C_2) ($RPD=|C_1-C_2|/½ *(C_1+C_2)$). The RPD values ranged from 0 to 67%, with averages of 23% (B), 16% (E) and 18% (X). Analytical reports provided by Maxxam showed that internal lab-spike BTEX recoveries (target = 100%) ranged from 75 to 123 %, with mean|sd of 88%|12.1% (n=94, Site A) and 95%|11.1%, (n=60, Site B). These results were notably better than the lab's maximum acceptable RPD for blind lab duplicates (±40%, pers.comm., S. Raynard, Maxxam).

Five sets of three to nine samples (total = 28) were collected on different dates from P34, Site A. Each set used bailer (6 samples) and Waterra® (22 samples), with samples in each set typically separated in time by an hour. The analyses are cross-plotted for inorganic data (Figure 3.7) and hydrocarbon data (Figure 3-8). Confidence intervals (95%) for most inorganic species (full data set) were less than ±10% of the mean, with larger spreads noted for dissolved BEX (±10-20%), iron (±20%) and sulphate (±30%).

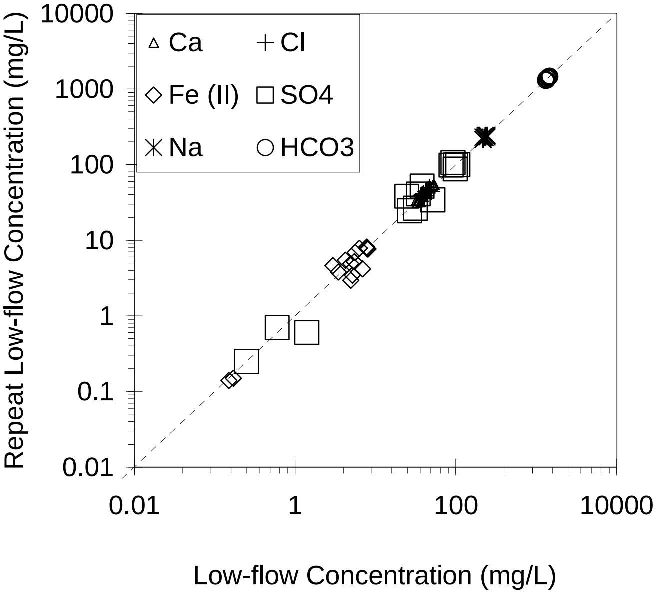


Figure 3-7 Cross-plots (log-scale) of selected inorganic analytes from replicate samples at Site A. Symbol size indicates error bar; dotted line shows the theoretical 1:1 ratio.

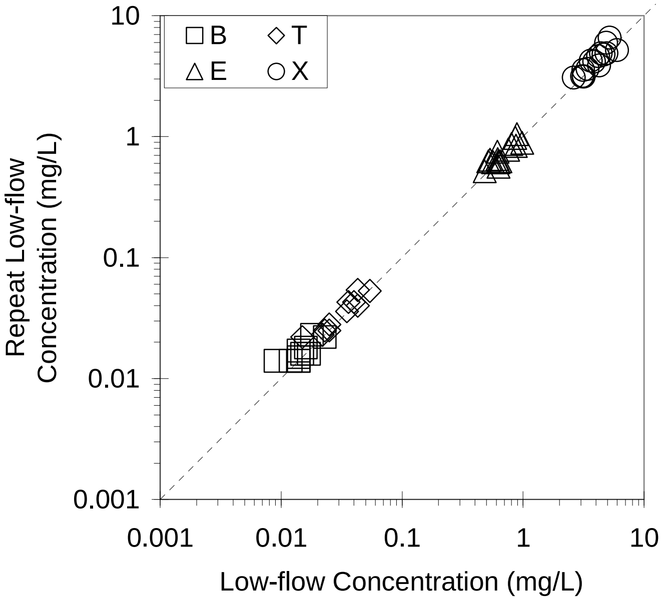


Figure 3-8 Cross-plots (log-scale) of selected PHCs from replicate samples at Site A. Symbol size includes 20% error; dotted line shows the theoretical 1:1 ratio.

Comparison between the plots shows three types of behaviour based on the clustering patterns of replicate samples. As examples, bicarbonate concentrations (large circles) cluster very tightly around 1,400 mg/L, dissolved hydrocarbons typically range over a factor of 2 to 3, while order of magnitude changes are noted for sulphate (large squares range from 0.25 mg/L to 100 mg/L) and iron (small diamonds ranges from 0.1 mg/L to 10 mg/L). The differences did not correlate with changes in water table elevations.

At Site B, there were 11 pairs of duplicate analytical sets, with data for selected inorganic and BEX analytes cross-plotted (log-log scale) in Figures 3-9 and 3-10. In general the pairs of duplicate analyses for most species plot along the theoretical line (1:1 slope), except iron (II) (all values <0.5 mg/L; data not shown) and some sulphate values at low concentrations. The hydrocarbon concentrations also appear to show reasonable agreement between duplicate samples over several orders of magnitude. Detailed checking showed that lower level concentrations had differences between duplicates up to a factor of two. Residual errors obtained from regression analyses (data not shown) did not identify any positive or negative bias between duplicate results. The RPD values ranged from 0 to 68%, with averages of 13% (B), 26% (E) and 12% (X).

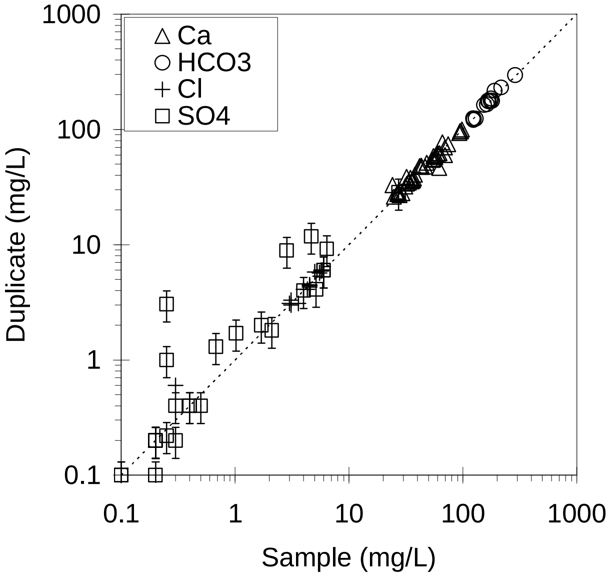


Figure 3-9 Cross-plot of selected analytes from duplicate samples at Site B. Symbol size includes 10% error; 30% error bar for SO_4; Dotted line shows theoretical 1:1 ratio.

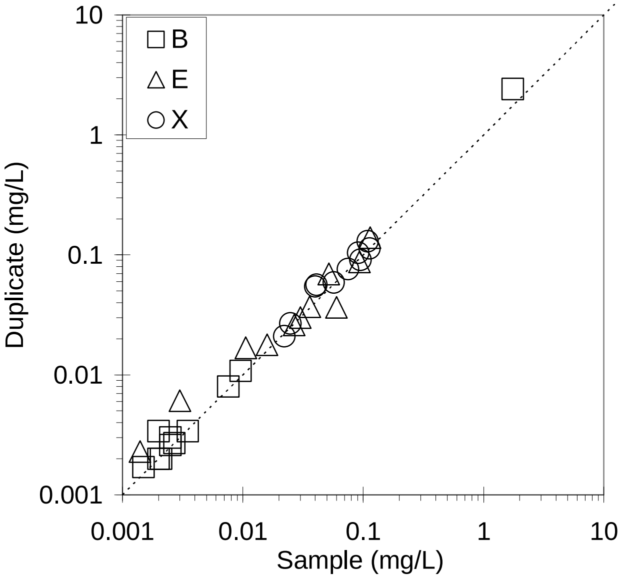


Figure 3-10 Cross-plot of selected analytes from duplicate samples at Site B. Symbol size includes 20% error; Dotted line shows the theoretical 1:1 ratio.

As at Site A, low level sulphate concentrations showed the poorest reproducibility, while hydrocarbons from replicate samples at various wells showed consistent values (plotted near the

1:1 line). Paired sample t-tests did not identify any significant differences ($p>0.05$) between hydrocarbon compounds (n=11 (B, T) and n=16 (E, X)).

In summary, most inorganic and BTEX analytes were consistent within any given sampling event, but not between events. Notable concentration variations between sampling events were seen for dissolved iron and sulphate. These two parameters can be sensitive indicators of redox-conditions and are used to interpret NA processes.

3.6.2 Site A

The results are reported in order for P34, then P35 and finally for downgradient wells that monitor the dissolved plume. Groundwater surface elevations measured manually at several wells in the P34 well cluster and data logger measurements are compiled with daily precipitation records (nearest Environment Canada weather station, within 10 km of the site) in Figure 3-11. A detailed review of data from the two multi-level wells (DP and ML-series) did not identify a consistent vertical gradient. Water levels measured using the data logger show notable variability not evident from the manual data and a close link with precipitation events. Water level increases of up to 0.8 m occurred as quickly as within two days of a precipitation event. The groundwater flow pattern remained relatively consistent, with a northwestward flow component.

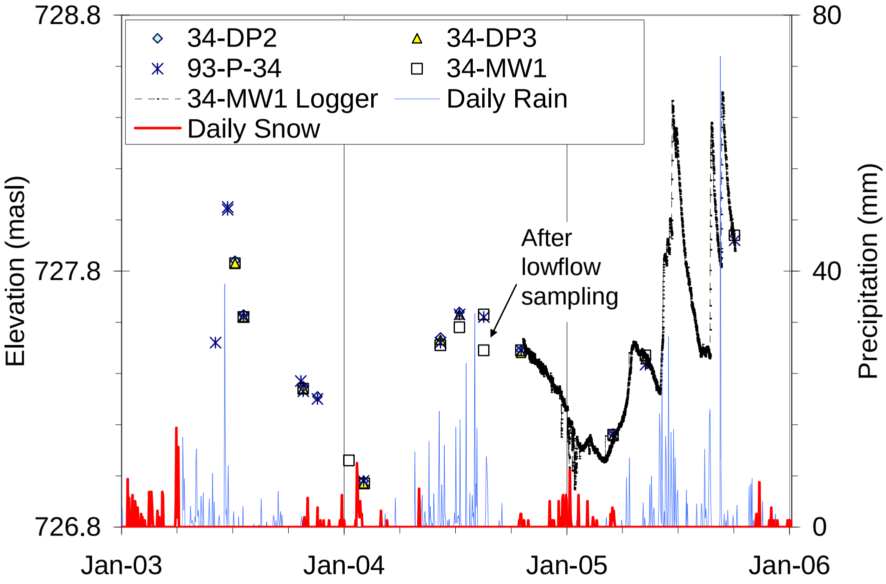


Figure 3-11 Daily precipitation, water table and hydraulic head (34-DP2 and DP3) elevations at P34 cluster, Site A; one low flow sampling event shown

3.6.2.1. P34 Cluster

The original design was to confirm vertical geochemical gradients using the ML-series and DP-series multilevel wells. Initial samples from the ML-series wells had notably higher sulphate (>400 mg/L) and sodium (>300 mg/L), with lower iron (<0.5 mg/L) and total BTEX (<1 mg/L) than either P34 or the equivalent DP-wells. Preliminary lab testing had determined that supernatant water in contact with bentonite pellets developed anomalously high concentrations of sulphate (1,720 mg/L) and sodium (783 mg/L). Although no obvious installation problems were encountered, concerns over possible influences from bentonite meant that the ML-samples were no longer considered. Analyses from direct push wells (DP-series) were therefore considered to best represent local geochemical conditions (least soil disruption during installation, least backfill materials, shortest sampling interval, no screen de-watering during sampling). The shallowest well, 34-DP1, typically had insufficient water to sample.

Means and standard deviations for selected analytes are summarized in Table 3-3, with plots of selected compounds summarized over time for chloride and calcium (Figures 3-12a and 12b), sulphate and iron (II) (Figures 3-13a and 13b), benzene and xylenes (Figure 3-14a and 14b). Plots for the same analytes from the P35 cluster are provided in Figures 3-15 to 3-17 using the same order. To avoid excessive clutter, error bars are provided only on the DP data points.

Table 3-3 Mean (Standard Deviation) For Selected Analytes: P34 Cluster Wells

Well|Sampler	Cl	Ca	SO_4	B	X
34-DP2 Low flow	32(17.6)	28(5.9)	1(0.7)	0.038(0.008)	5.42(0.092)
34-DP3 Low flow	60(5.1)	134(22.2)	371(107)	0.002(0.001)	0.22(0.445)
P34 Low Flow	46(4.6)	42(9.0)	47(49.1)	0.008(0.008)	4.14(1.094)
P34 Bail, Purge (historical)	55(47.2)	58(NM)	99(170.3)	0.138(0.171)	8.98(5.051)
P34 Bail, Purge (this study)	43(1.1)	48(0.5)	77(5.0)	0.013(0.012)	5.26(1.814)
P34 Bail No Purge	69(31.5)	41(8.9)	58(130.9)	0.024(0.012)	5.00(1.814)
MW1 Low Flow	57(NM)	61(NM)	111(NM)	0.008(NM)	2.50(NM)
MW1 Waterra®	72(12.3)	78(22.8)	171(124.1)	0.010(0.005)	2.96(1.464)
MW1 DDS	67(8.1)	71(17.4)	61(39.5)	0.009(0.002)	3.14(1.287)
MW2 Low Flow	48(NM)	61(NM)	105(NM)	0.009(NM)	3.51(NM)
MW2 Waterra®	57(5.2)	146(52.9)	551(257.7)	0.004(0.002)	1.34(1.292)

Notes: NM: insufficient data to calculate

The different chemical signatures of the middle (DP2) and deep (DP3) wells show several notable geochemical gradients. Shallower groundwater (DP2) typically has lower concentrations of major ions, higher concentrations of dissolved hydrocarbons, and NA indicator patterns (primarily enriched iron and depleted sulphate) consistent with greater bioactivity compared to the deeper well, DP3.

Chloride is generally conservative, thus these data were used to examine local data variability and possible evidence of in-well mixing. A plot of chloride concentrations (Figure 3-12a) suggests that external influences differentially affect the hydrochemistry from the various wells. Data in DP2 ranged from approximately 19-64 mg/L (n=6, mean=32 mg/L, sd=17.6 mg/L), while the deeper DP well (DP3) had a narrower concentration range (54-65 mg/L; n=6, mean=60 mg/L, sd=5.1 mg/L). Greater variability (range|mean|sd) was noted over time in samples from the original well in the cluster (P34: 35-153 mg/L|55|22.3). The two longer-screened wells had similar variability as DP2, but concentrations more like DP3 (MW1: 57-94 mg/L|69|11.0; and MW2:48-64 mg/L|56|5.6). All three wells are screened across the groundwater surface.

Calcium (Figure 3-12b) represents slightly reactive species that are not directly linked to biodegradation reactions. As with chloride, calcium analyses from DP2 (n=6; Ca: mean=28 mg/L, sd=5.9) and DP3 (n=6; Ca: mean=134; sd=22.2) tended to bracket results from the other three wells. In contrast to the chloride pattern, MW1 tended to have lower calcium (RPD=20-100%) compared to MW2.

Background sulphate concentrations at Site A are on the order of 1,000 mg/L. In general, decreased sulphate concentrations within plume wells compared to background areas is an indirect indicator of hydrocarbon biodegradation reactions. Sulphate concentrations from the P34 cluster are plotted using a log-scale to capture the four order of magnitude range of concentrations from the various wells (Figure 3-13a).

Results from DP2 (mean=1, sd=0.7) and DP3 (mean=371, sd=107) again tended to bracket data from other wells, where large variability between some results was evident. The MW2 Waterra® data were typically from double to almost an order of magnitude higher than equivalent MW1 Waterra® data. Extreme time-varying sulphate concentrations in P34 well are discussed in detail in Chapter 4.

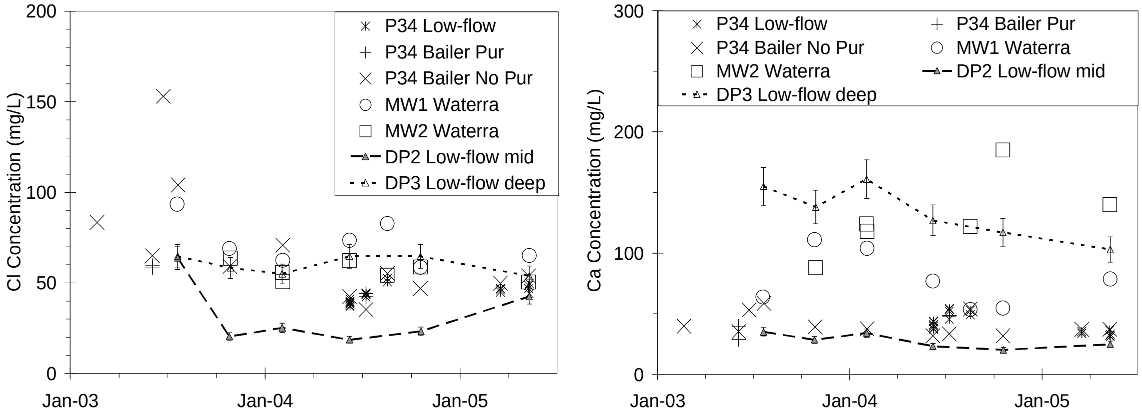


Figure 3-12 Chloride (a) and calcium (b) concentrations from selected monitoring wells and sampling strategies at P34 cluster: lines connect DP data to show data range for depth-discrete samples (0.7 m screens). Error bars (10%) shown for DP wells.

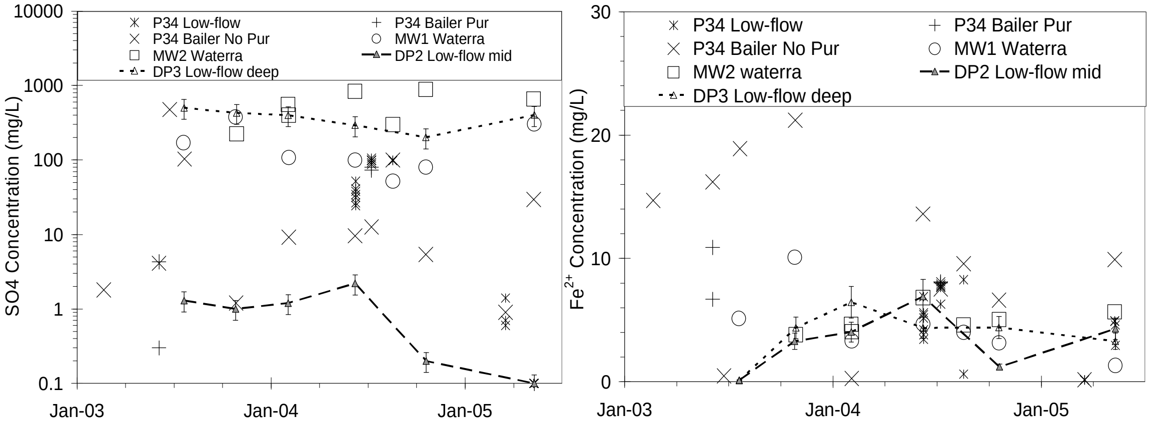


Figure 3-13 Sulphate (a) (log scale) and iron (II) (b) concentrations from selected monitoring wells and sampling strategies at P34 cluster: lines connect DP data to show data range for depth-discrete samples (0.7 m screen lengths). Error bars (30% SO_4, 20% Fe(II)) shown for DP wells.

Relative enrichment of dissolved iron (II) in plume wells compared to background conditions is another inorganic indicator of biodegradation. Background iron (II) at Site A is near the detection limit (0.1 mg/L). Concentrations measured in the various wells did not exhibit consistent patterns between wells, sampling types or dates (Figure 3-13b). Dissolved iron concentrations were typically from 1 to 7 mg/L, with a wider range in P34, from near the detection limit (0.1 mg/L) to 21 mg/L. Results from the DP-series and MW2 were similar, while MW1 showed a wider range.

Illustrative cases of dissolved hydrocarbon results versus time are summarized using data for benzene and total xylenes (Figures 3-14a and 3-14b) (ethylbenzene data not shown). Benzene and xylenes concentrations in the deeper DP3 well (means = 0.002 and 0.02 mg/L, respectively) were typically 1-2 orders of magnitude less than in the shallower DP 2 well (means = 0.038 and 5.42 mg/L, respectively), over the average 1 m depth separation. In contrast, measured concentrations from the other well and sampling method combinations (P34, MW1 or MW2 in Table 3-3) identified hydrocarbon presence within a factor of 2 to 5 (half an order of magnitude). These analyses represented inconsistent averages of the DP-results, yet captured hydrocarbon plume presence and character at an order of magnitude accuracy. Notably, the data themselves showed a similar range of variability over time.

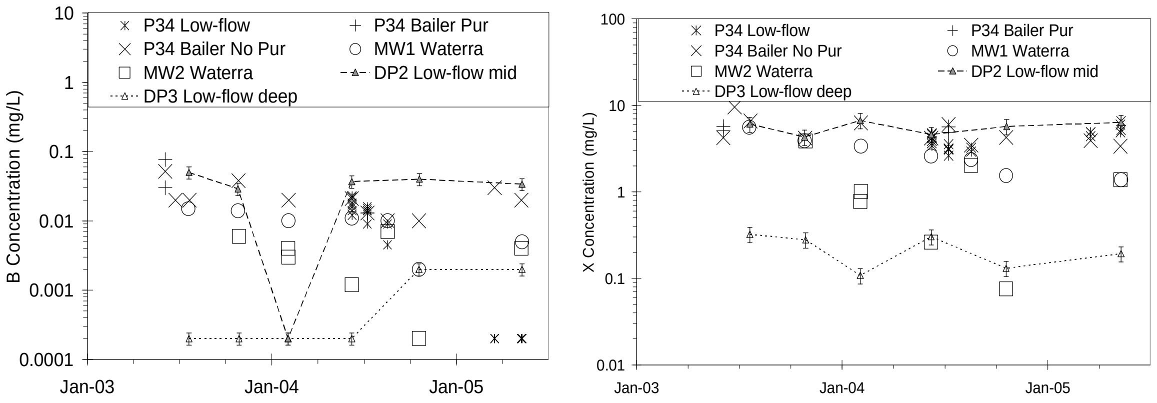


Figure 3-14 Benzene (a) and xylenes (b) concentrations (log scale) from selected monitoring wells at P34 cluster: lines connect DP data to show depth-discrete samples (0.7 m screen lengths); nondetect concentrations plotted at 0.0002 mg/L

3.6.2.2. P35 Cluster

Similar plots are shown for the P35 cluster (Figures 3-15 to 3-17) to compare variability at a location further downgradient from P34 cluster. These data provided a better opportunity to assess data variability, because all three DP wells typically contained sufficient water to sample, except in early 2005.

Chloride concentrations (Figure 3-15a) were more temporally stable than at P34 cluster. In contrast to P34 data, concentrations decreased with depth (DP-series). Mean values from MW1 and MW2 did not differ significantly (95 % confidence), but were lower than in P35.

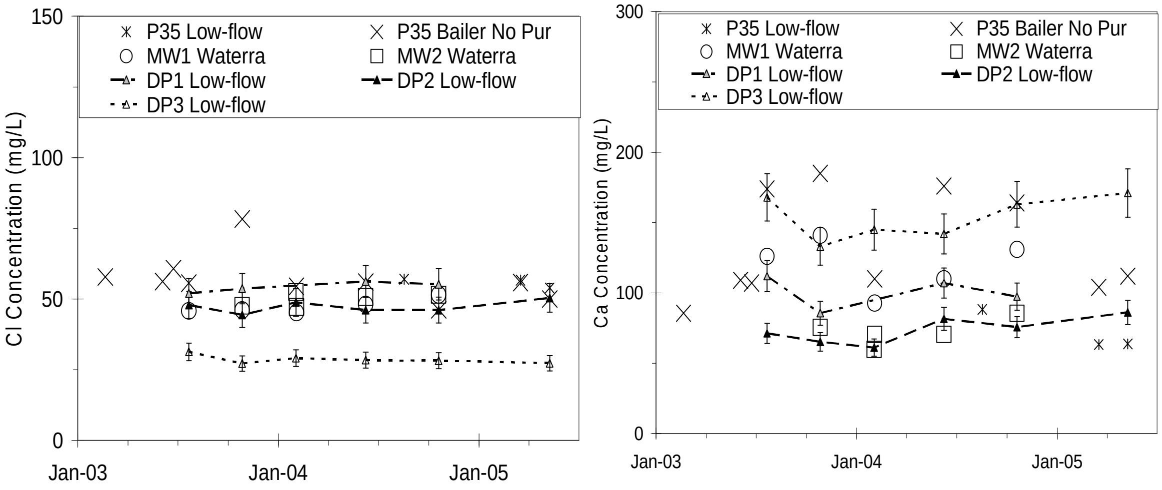


Figure 3-15 Chloride (a) and calcium (b) concentrations from selected monitoring wells at P35 cluster: lines connect DP data to show depth-discrete samples (0.7 m screen lengths)

Calcium concentrations (Figure 3-15b) showed wider concentration ranges with depth and between wells. Data from P35 varied inconsistently across the three concentration ranges indicated by DP1, DP2 and DP3 wells (respective means=100 mg/L, 74 mg/L and 154 mg/L). The longer-screened wells showed consistent differences, where MW2 (mean=72 mg/L) was very similar to DP2, while MW1 (mean=120 mg/L) tended to be approximately 40% larger.

Figure 3-16a shows how sulphate data in the deepest DP well (DP3 mean=300 mg/L) tended to be one or more orders of magnitude higher than the other samples from this cluster (typically <10 to <1 mg/L). Other than the first sample collected from MW1, samples from the longer-screen wells had sulphate concentrations near 10 mg/L or less.

The dissolved iron data (Figure 3-16b) showed a clear decrease in concentration with depth in the DP wells from DP1 (mean = 43 mg/L.) to DP2 (mean=12 mg/L) to DP3 (mean = 1.1 mg/L). In contrast, the other wells showed widespread variability, with most analyses being within the range established by DP1 and DP2. It is not clear why some analyses exceeded the range noted in the DP wells.

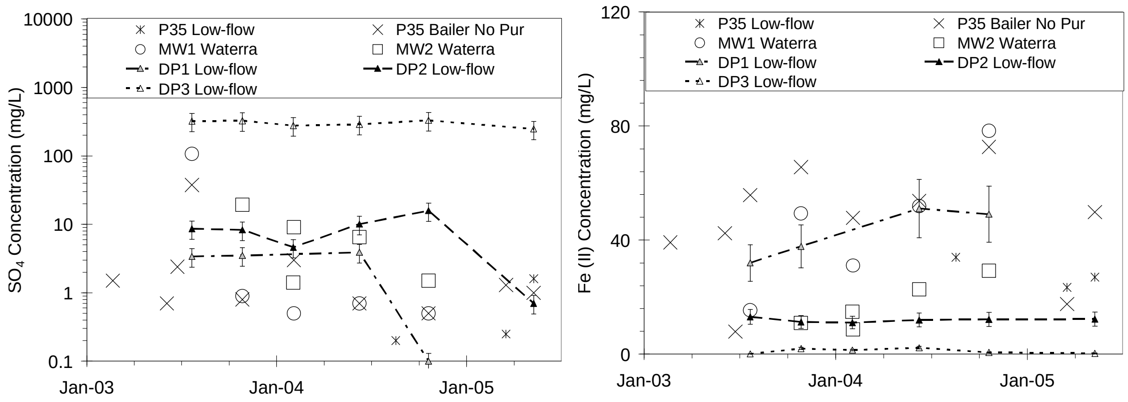


Figure 3-16 Sulphate (a, log-scale) and iron (II) (b) concentrations from selected monitoring wells at P35 cluster: lines connect DP data to show depth-discrete samples (0.7 m screen lengths); 30% error bars for sulphate and 20% for iron (II)

Benzene and xylenes concentrations decreased with depth in the DP wells (Figure 3-17a and 17b). The other wells (P35 and the longer-screened MW-series) all tended to give similar benzene concentrations, while the xylenes data tended to be lower in the MW wells compared to the original P35 well. Variable hydrocarbon concentrations were noted over time, possibly reflecting pulsed hydrocarbon inputs. This hypothesis is also consistent with a similar hydrocarbon spike having been noted closer to the fire training area (P34) in summer 2003.

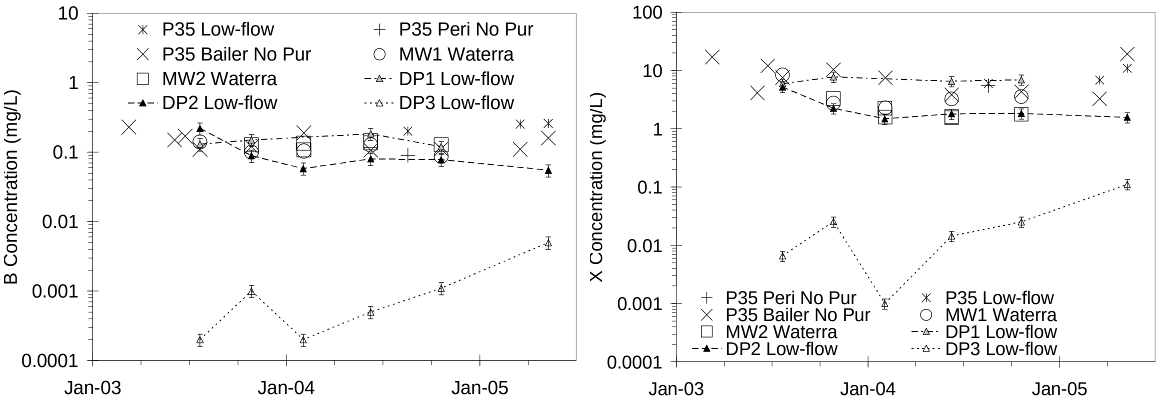


Figure 3-17 Benzene (a) and xylenes (b) concentrations from selected monitoring wells at P35 cluster: lines connect DP data to show depth-discrete samples (0.7 m screen lengths); 20% error bars shown only for DP data to reduce clutter; nondetect concentrations plotted at 0.0002 mg/L (benzene) and 0.001 mg/L (xylenes)

3.6.2.3. Concentrations at Downgradient Plume Delineation Wells

No temporal trends were evident over the two years of detailed monitoring in the near-source well clusters (P34 and P35); therefore, average values were considered appropriate for assessing spatial hydrochemical trends. Average concentrations measured in plume-monitoring wells (both along the groundwater flow direction and offset to the north) are plotted against downstream distance in Figure 3-18 (source area = 0). The data illustrate some general patterns typically expected from intrinsic biodegradation of PHCs (order of magnitude decreases in hydrocarbon and iron (II)) but highlight the confusing results regarding sulphate trends. Data from 3 m screened wells in the P34 cluster do not show sulphate depletion (at approximately 30 m downstream from the source) in contrast to evidence obtained from both similar wells at the P35 cluster. The minimal variation in chloride concentrations over the plume length indicated that dilution was apparently not significant at the plume spatial scale.

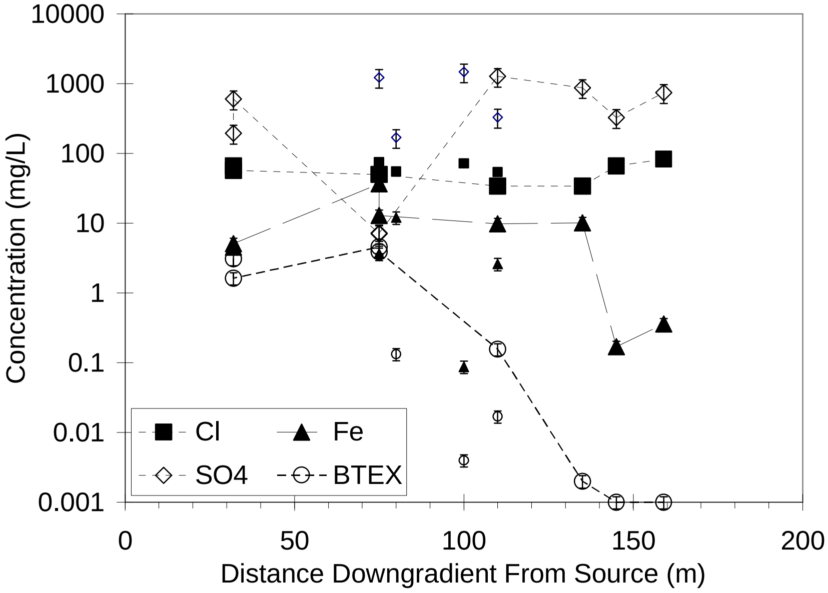


Figure 3-18 Two-year average concentrations of selected geochemical indicators sampled from 3 m screened wells. Distances projected as downgradient from the source, Site A. Small symbols show well data offset from plume centreline

Variability in results from the 3 m screened wells was compared using coefficients of variation (C_v) and ranges (Table 3-4). The results suggested several patterns that helped to identify the possibility of suspect data. The nonreactive chloride species had similar C_v values and ranges (approximate factor of 2) at all locations. Slightly reactive calcium had larger C_v and ranges in wells along the plume flow direction compared to offset wells. In contrast sulphate had notably inconsistent C_v and ranges between paired wells, but generally decreasing C_v with increasing distance. The iron (II) and hydrocarbon data had no consistent C_v trend with distance.

Table 3-4 (C_v | C_{range}) for 3 m screened wells with increasing distance from source at Site A

	Distance	**Ca**	**Cl**	**SO_4**	**Fe**	**B**	**X**
34-MW1	30 m	0.27|56	0.09|15	0.71|299	0.74|8.8	0.46|0.009	0.43|2.52
34-MW2	30 m	0.40|158	0.11|13	0.47|663	0.24|3.0	0.56|0.005	1.15|3.79
35-MW1	75 m	0.18|48	0.06|6.3	0.29|0.4	0.37|47	0.16|0.040	0.19|1.29
35-MW2	75 m	0.16|26	0.04|4.9	1.18|18	0.42|18	0.06|0.018	0.33|1.65
P-10	80 m[1]	0.14|57	0.06|5.8	0.56|232	0.18|5.8	0.23|0.0004	0.53|0.052
P7	75 m[2]	0.04|43	0.07|15	0.10|310	0.77|7.6	-	-
P-5	110 m	0.09|117	0.11|9.4	0.12|400	0.57|14.1	1.36|0.013	1.51|0.37
P-6	110 m[1]	0.08|45	0.08|11	0.09|82	0.54|3.6	-	1.54|0.019
P-8	100 m[2]	0.03|22	0.04|6.9	0.10|380	0.51|0.11	-	0.13|0.010
P-9	135 m	0.17|194	0.09|7.6	0.20|423	0.36|7.6	0.34|0.001	-

Notes:
1. Well offset north of plume centreline by 20 m
2. Well offset north of plume centreline by 40 m

In a general case, supporting data from shorter-screened wells are not available, thus plume interpretation must be based on groundwater samples from monitoring wells with longer screens (3 m). These results suggest that deeper insight about inconsistencies for interpreting natural attenuation of a PHC plume can be gained by using several data analysis tools (e.g., mean, sd, C_v and range) for multiple parameters. At this site, supportive data included decreasing BTEX and iron (II) concentrations with distance being accompanied by stable chloride concentrations, dven though sulphate data were inconsistent between paired wells at P34 cluster and between the two clusters (Figure 3-13a and 3-16a). Local-scale variability seen in the two well clusters between 3 m screened MW wells and the 0.7 m screened DP wells over time is discussed further in Section 3.7.2.1.

3.6.3 Site B

Water level logging at Site B showed evidence of two types of rapid seasonal water table increases (Figure 3-19). The first type occurred in March, when infiltration was likely limited by the frozen ground surface (snowfall records were unavailable from the nearby weather station). The notable increase in groundwater levels is interpreted to be due to a combined effect of melting snow and ground ice. Later during the summer, rainfall appears to have a rapid and transient influence, with both water level increases and decreases (order of 0.2 to 0.5 m) occurring over several days. At the research well cluster, the local maximum groundwater level varies between wells BH01 and DP2 over time (Figure 3-20). Data from the four DP-series wells completed over different intervals show that hydraulic head decreases with depth. The shallowest two points (DP1 and DP2) had similar hydraulic heads, although DP2 tended to be slightly higher than DP1 over time. Both locations had water surface elevations that were consistently higher than values measured in the next deepest well (DP3) and the deepest well (DP4).

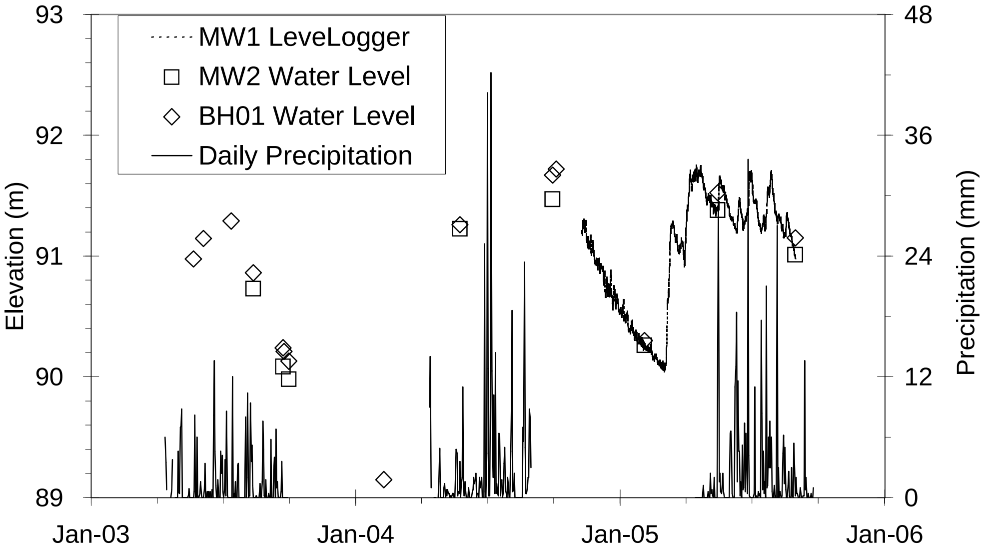


Figure 3-19 Rainfall (snowfall data not available) and water level data measured at Site B

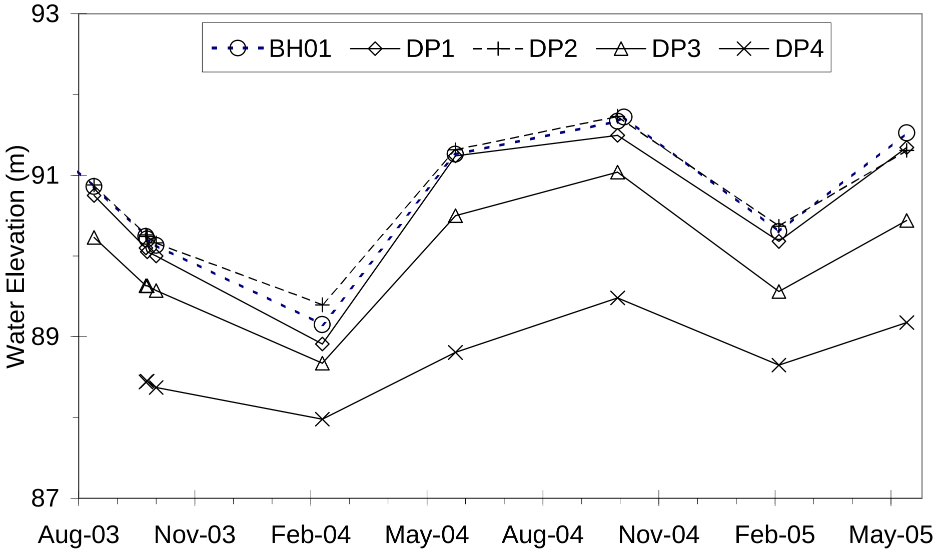


Figure 3-20 Vertical differences in water elevation in Site B research well cluster

3.6.3.1. BH1 Cluster

Monitoring data from this well cluster were assessed in a similar manner as for Site A, although groundwater concentrations for most ions were much lower than at Site A. Some wells at this site appeared to experience ‘well trauma’ following installation. Laboratory leachate testing identified the potential for bentonite (used as a borehole sealant during well construction) to cause high sulphate and sodium concentrations (Morin, in preparation). Notably higher concentrations of both analytes, measured in the first two sets of samples collected from both MW-series wells, decreased consistently and became similar to data from other wells in this area. Over this same time period, chloride and hydrocarbon concentrations did not show a similar pattern, thus in-well mixing was discounted as a potential cause. The ML-series installations were therefore not considered further in this work.

As at Site A, dissolved chloride concentrations showed almost no variability between any of the wells, sampling systems or purging protocols (Figure 3-21). Dissolved iron concentrations typically ranged from 2 to 10 mg/L (Figure 3-22), but no consistent patterns were identified. Dissolved sulphate concentrations in several wells were initially higher (>10 mg/L) during the first one or two rounds of sampling shortly after installation. Subsequent samples then dropped up to an order of magnitude (Figure 3-23). Analyses from all wells and methods then remained in a range from 0.1 to 5 mg/L. Dissolved hydrocarbon concentrations were typically quite similar between all wells. Including all data, benzene concentrations showed possible evidence of a decreasing trend (Figure 3-24), while xylenes (Figure 3-25) remained relatively stable.

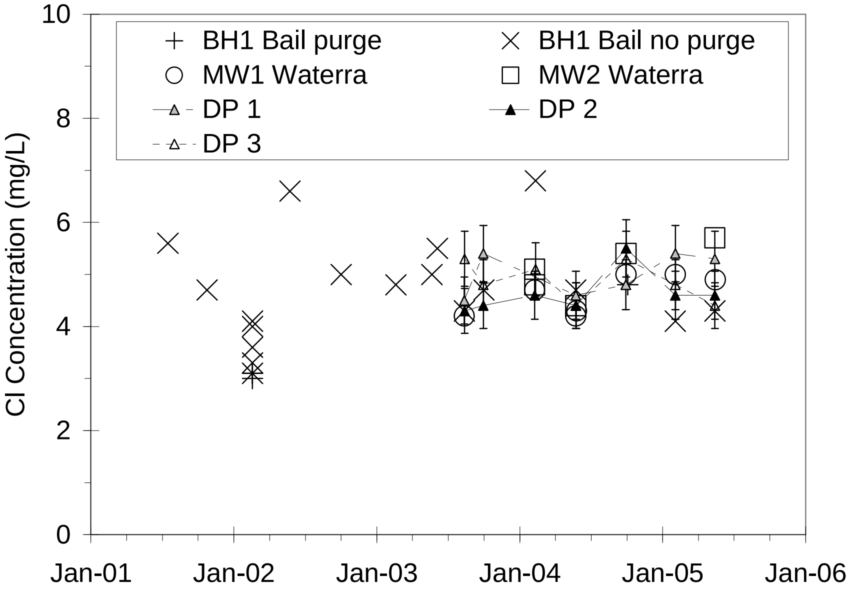


Figure 3-21 Chloride concentrations from selected monitoring wells at BH1 cluster: lines connect DP data to show depth-discrete samples (0.7 m screen lengths); 10% error bars shown for DP wells only

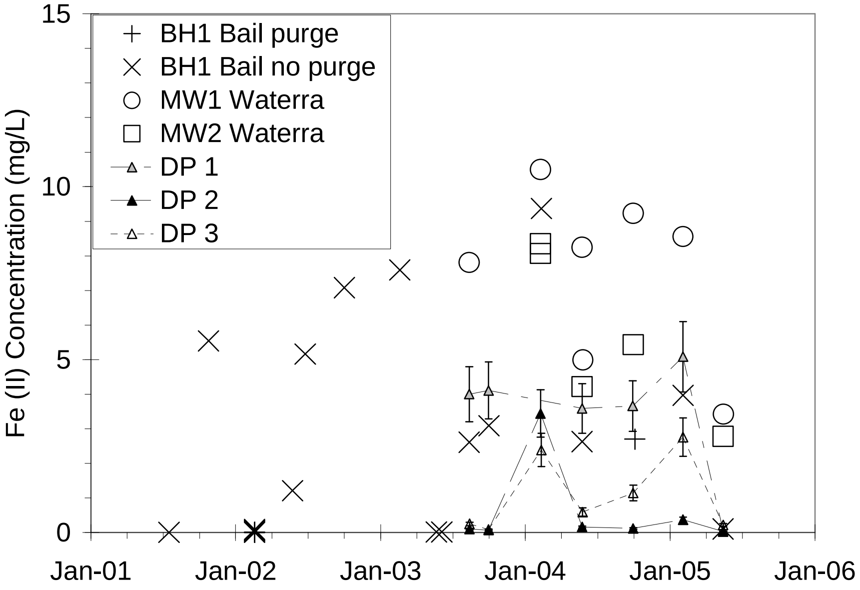


Figure 3-22 Iron(II) concentration from selected monitoring wells at BH1 cluster: lines connect DP data to show depth-discrete samples (0.7 m screen lengths); 20% error bars shown for DP wells only

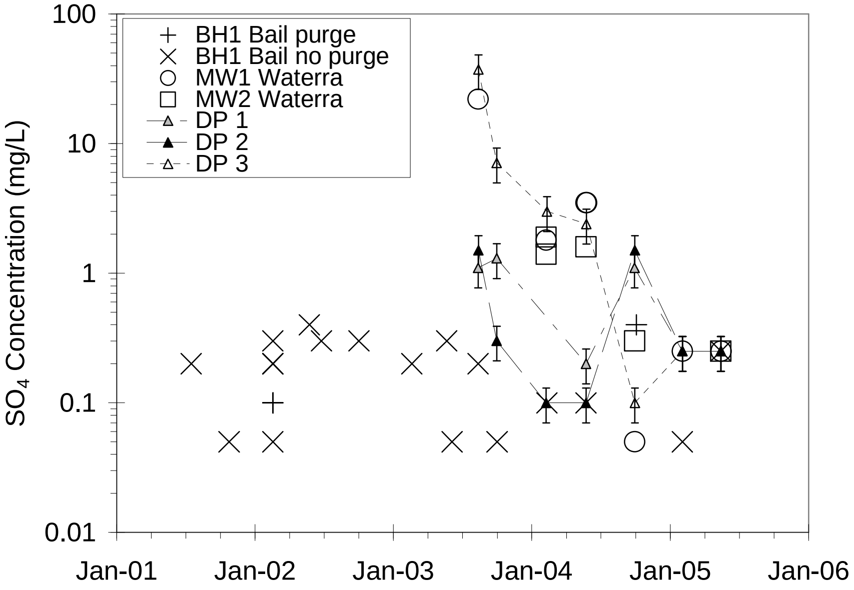


Figure 3-23 Sulphate concentrations from selected monitoring wells at BH1 cluster: lines connect DP data to show depth-discrete samples (0.7 m screen lengths); 30% error bars shown for DP wells only; nondetect concentrations plotted at 0.05 mg/L

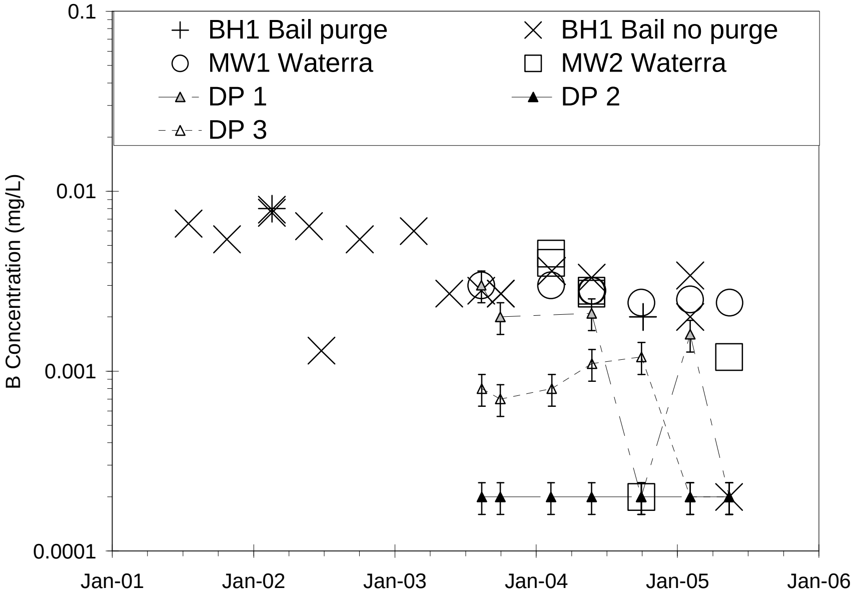


Figure 3-24 Benzene concentration from selected monitoring wells at BH1 cluster: lines connect DP data to show depth-discrete samples (0.7 m screen lengths); 20% error bars shown for DP wells only; nondetect concentrations plotted at 0.0002 mg/L

The three levels of shorter screen wells showed significant vertical variation with depth. The shallowest DP well typically had hydrocarbon concentrations that were approximately one order of magnitude higher than measured in the two deeper DP wells. Similarly, the shallow DP well also showed more evidence of biodegradation, based on TEAP concentrations.

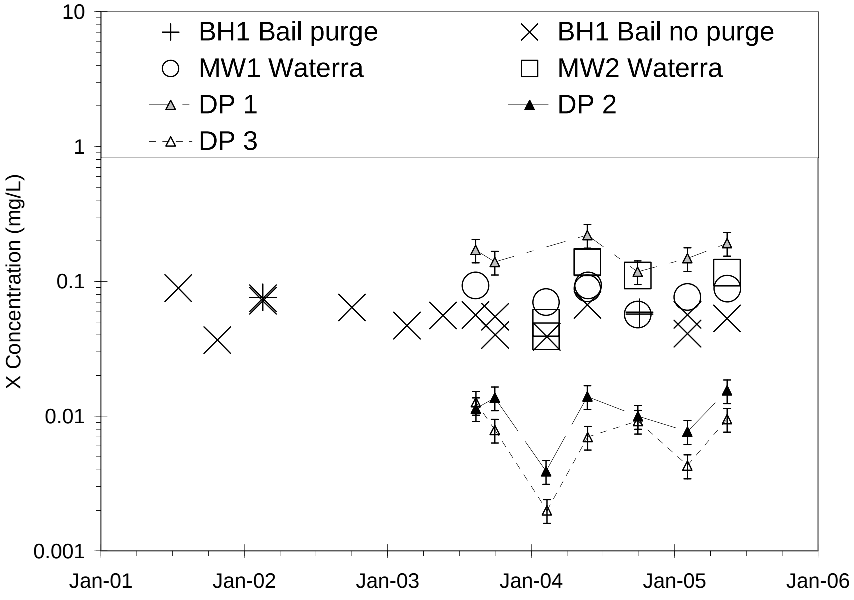


Figure 3-25 Total xylenes concentration from selected monitoring wells at BH1 cluster: lines connect DP data to show depth-discrete samples (0.7 m screen lengths); 20% error bars shown for DP wells only

The longer-screened wells (BH1, MW1 and MW2) had relatively minimal variation either between each other, or when compared to the shallowest DP-1 well. The various sampling methods also provided relatively similar results for inorganic and PHC analyses (except dissolved iron) when compared to samples from the original well, BH1. The relatively small concentration variations with depth at the BH1 cluster were not apparent from the DDS analyses (Figure 3-26).

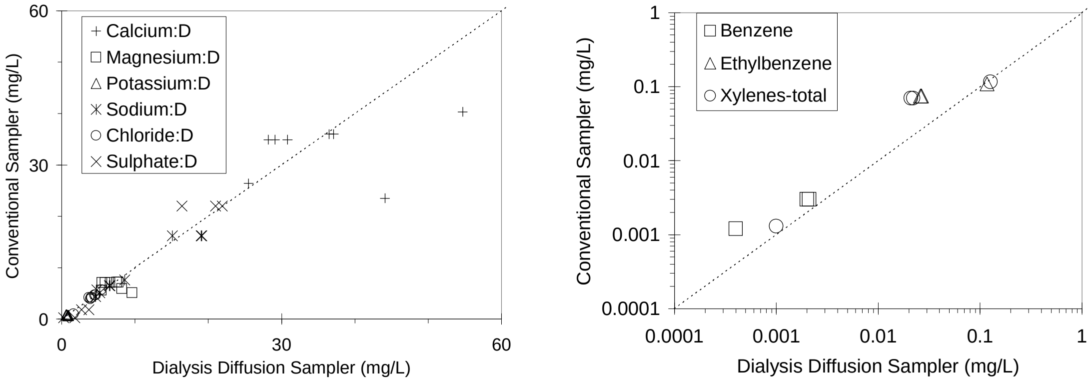


Figure 3-26 Paired analyses from conventional samples and DDS, BH1 cluster. Dotted line shows the theoretical 1:1 ratio.

3.6.3.2. Downgradient Plume Delineation Well Data

Geochemical concentrations measured along the groundwater flow path are consistent with the interpretation that the shallow plume is being attenuated over a short distance (Figure 3-27). The groundwater flow velocity at the site is on the order of 10 m/year. The relatively low hydrocarbon concentrations within the plume area decrease below the detection limit approximately 40 m downgradient of the source zone. This conclusion is based on groundwater samples collected from monitoring wells installed in the shallower groundwater-bearing zone, only. A confined hydrocarbon liquid layer was detected greater than 4 mbgs closer to the source. This layer appeared to be confined below the conventional or the three equivalent DP wells in the shallower aquifer system. PHC concentrations detected in the deepest well, DP4 (i.e., B=0.01-0.03 mg/L) where greater than any of the shallower wells. The DP4 well (5.2-6.1 mbgs) is completed below all of the conventional monitoring wells (~ 4.5 mbgs); implying that PHC detected in this well is from a deeper source, and not in-well mixing.

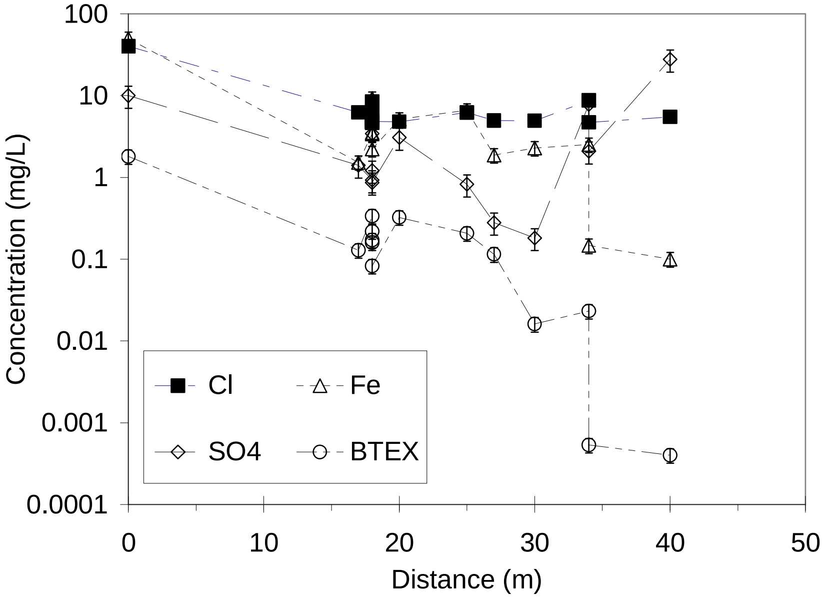


Figure 3-27 Two-year average concentrations of selected geochemical indicators sampled from 3 m screened wells. Distances projected as downgradient from the source, Site B; nondetect BTEX concentrations plotted at 0.0002 mg/L

Wells within the plume area showed depleted sulphate concentrations (from <0.1 to 1 mg/L) and enriched dissolved iron concentrations (1 to 10 mg/L) relative to background conditions (sulphate ~ 10 mg/L, dissolved iron <0.1 mg/L). Geochemical contrasts between wells within the plume and background wells were much less obvious than at Site A.

3.7 Discussion

Dissolved hydrocarbon data have been collected over the last decade by consultants for the site owners from selected wells (typically 3 m screens) at Sites A and B. Trend plots for BTEX gave conflicting evidence about PHC plume attenuation, as shown in selected plots for Site A (Figure 3-28) and Site B (Figure 3-29).

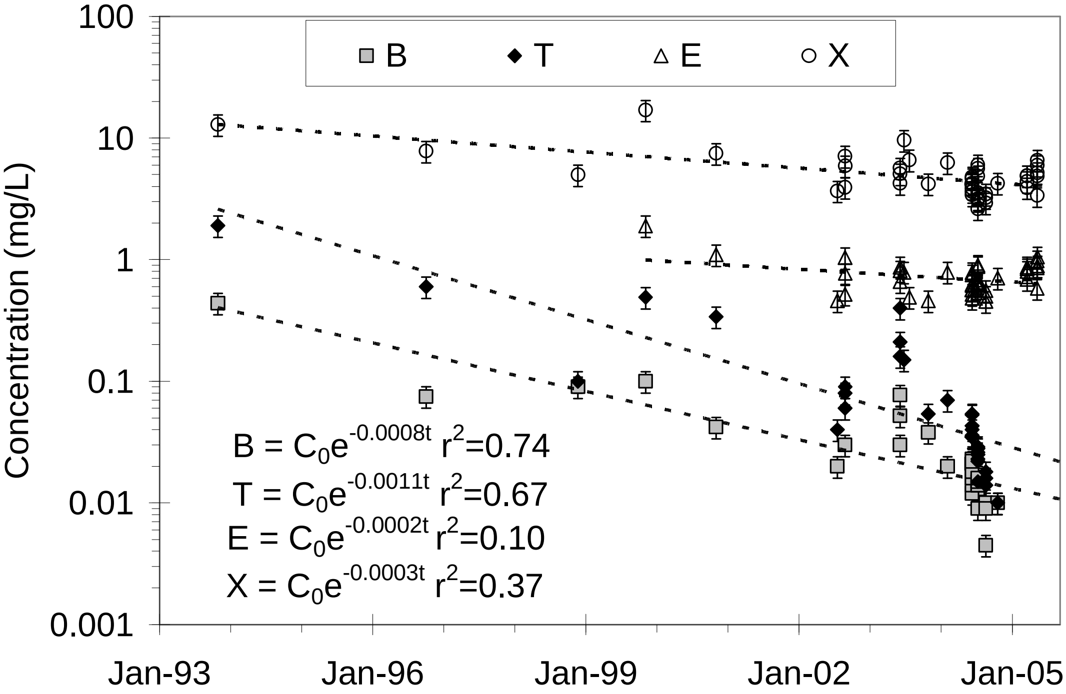


Figure 3-28 Temporal concentration trends for BTEX over time in P34, Site A; dashed lines follow exponential fit to the data with equations provided; suspected analytical problems with pre-1999 data for E

The apparent downward concentration trends interpreted by fitting a trend line to the log concentration vs. time data are not well supported by the more comprehensive seasonal data from the CORONA program (starting in 2002). A general downward trend is indicated for T, while B, E and X have no trend since 1999. The post-2002 data suggest that the plume is stable over time at this location, but with variability of almost an order of magnitude. Downward trends for dissolved hydrocarbons are unlikely to be seen until the source zone has been remediated.

A similar interpretation is made at Site B, where concentrations also vary rapidly by almost an order of magnitude (Figure 3-29). The extra data show that overall downward trends suggested by fitted lines to the data are weak, based on the moderate to low correlation coefficients.

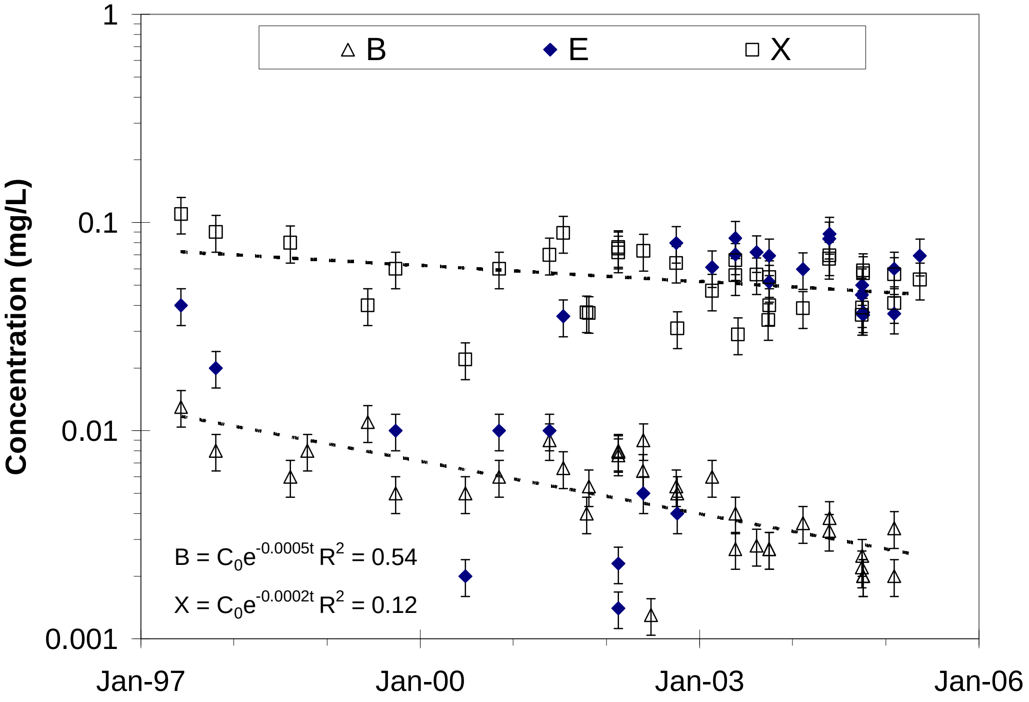


Figure 3-29 Temporal concentration trends for BEX over time in BH1, Site B; dashed lines follow exponential fit to the data with equations provided

The remainder of this paper considers scales of analytical variability related to use of differing sampling methods and well types. In particular, evidence of temporal variations raised a question about what is a 'representative' sample, and what analytical value (with associated uncertainty) is most appropriate for assessing NA at a given sampling location. Consideration was given to how existing groundwater analyses (commonly sampled after purging a 3 m screened well by bailer or Waterra®) might influence interpretation of natural attenuation, or if variability in groundwater monitoring data is sufficiently large that selection of the well and sampling method are of relatively minor consequence. The assessment considered well purging, well completion intervals and sampling methods.

3.7.1 Effect of Well Purging

Sampling from the research clusters at Site A showed up to order-of-magnitude, inconsistent sensitivity to purging for sulphate at P34. Sensitivity for other analytes was typically around a factor of two (Figures 3-30a and b). Testing at Site B identified a similar result, but at an order of magnitude lower concentrations (Figures 3-31a and b).

Some samples plotted notably off the theoretical 1:1 lines in Figures 3-30, 3-31 and 3-32, with pre-purge samples being biased low in sulphate and high in iron (II). Detailed review of the Site A data showed that data pairs with large sulphate differences came from plume wells that typically had depleted sulphate concentrations compared to background levels. The significance of these differences as related to NA assessment is discussed in more detail in Chapter 4. The same bias in sulphate and iron concentrations occurred at Site B, although the concentration scales (concentrations < 10 mg/L) were lower than at Site A.

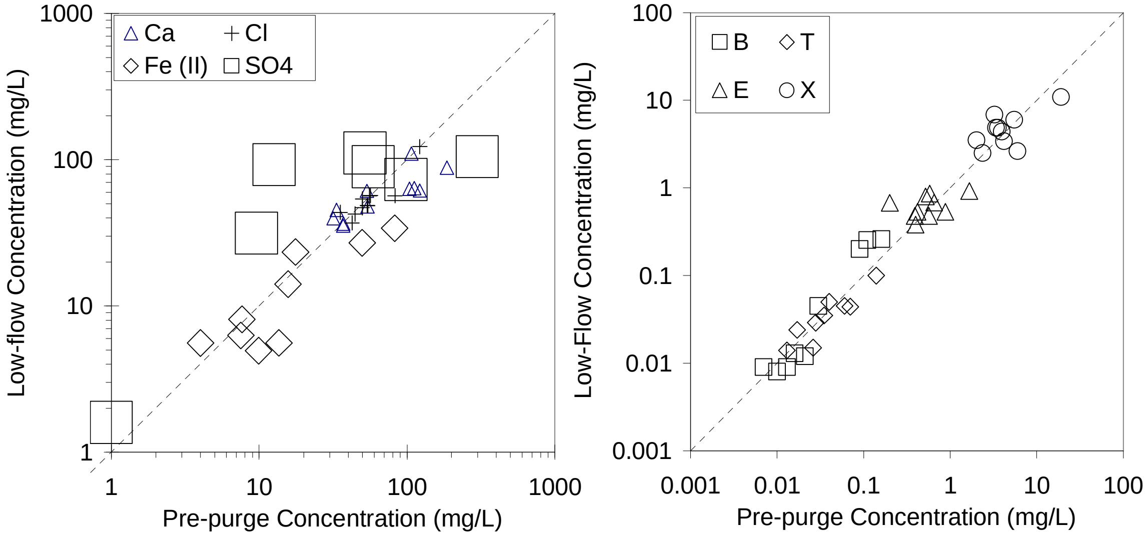


Figure 3-30 Cross plot of pre-purge vs. lowflow samples from Site A; (a) inorganic compounds; and (b) BTEX. Symbol size includes error bar; dotted line shows the theoretical 1:1 ratio.

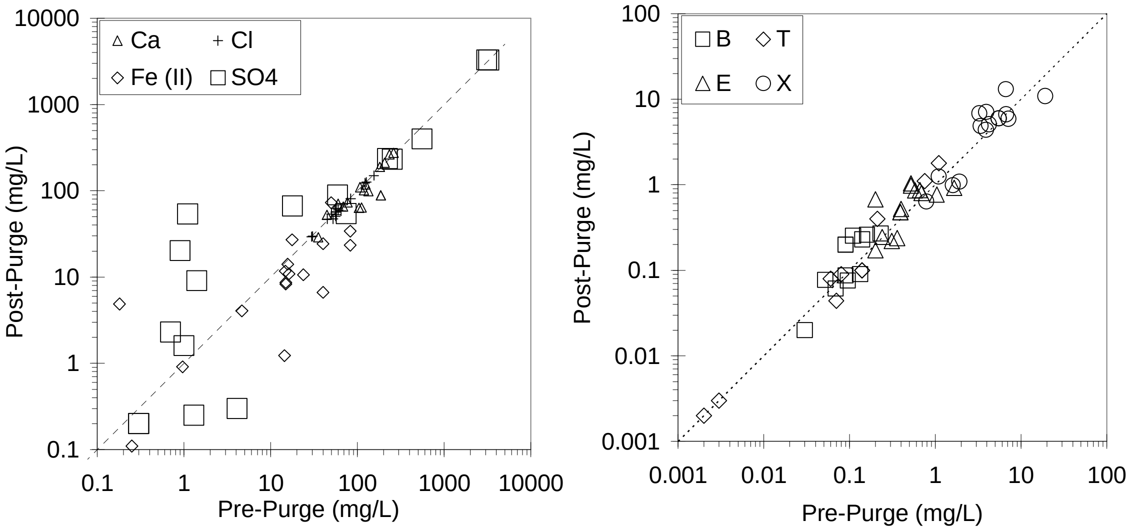


Figure 3-31 Cross plot of pre-purge vs. post-purge samples from Site A; (a) inorganic compounds; and (b) BTEX. Symbol size includes error bar; dotted line shows the theoretical 1:1 ratio.

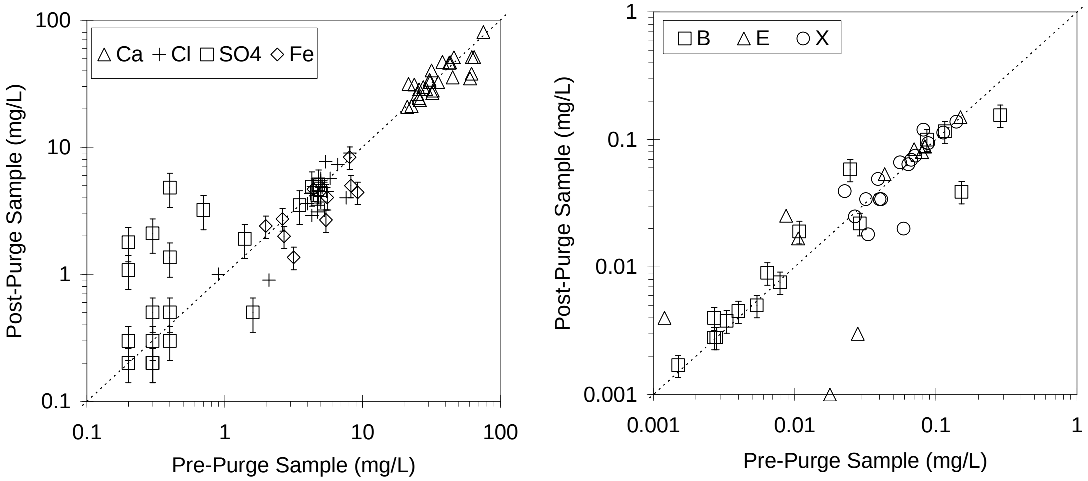


Figure 3-32 Cross plot of pre-purge vs. post-purge samples from Site B; (a) inorganic compounds error =10%, except 30% SO_4 and 20% Fe(II); and (b) BEX (20% error bar). Dotted line shows the theoretical 1:1 ratio.

Relative percent differences were calculated for major ions from paired duplicate samples (C_1 and C_2), and were typically within 20% at Sites A and B, respectively, except for manganese (59% and 34%), iron (II) (65% and 64%) and sulphate (68% and 81%). Average RPDs for BTEX analyses at Sites A and B ranged from 30-44% and 19 to 47%, respectively. These values are similar to the maximum acceptable variability reported by the lab for blind lab duplicates.

The PHC compounds at both sites generally plotted nearer the theoretical 1:1 line than iron (II) and sulphate. Correlation coefficients showed a stronger relationship between pre-purge and post-purge samples for BTEX at Site A (0.95, 0.96, 0.59, and 0.82, respectively) as compared to BEX (no toluene) at Site B (0.87, 0.88 and 0.82, respectively).

Differences between pre-purge and post-purge samples (inorganics: average RPD's <10%, except Fe(II) = 34%, SO_4 = 37%; PHCs: average RPD <20%); were on the same order as differences between consecutive samples from the longer-screened wells. Accordingly bias introduced to TEA interpretation by using pre-purge purge or post-purge samples would not be expected to be any more than already present within the monitoring data (i.e., Figures 3-21 and 3-30).

3.7.2 Effect of Well Types

The scale of sampling interval is well known to influence data interpretation, as discussed previously. At these sites, vertical differences between the DP wells (0.7 m screens) suggest that still finer-scaled sampling might identify greater vertical chemical differences, while samples from the MW wells (3 m screens) were more variable and inconsistent. The question was therefore whether other sampling methods using the longer-screened wells improve data interpretation regarding NA processes. Each site is considered separately.

3.7.2.1. Site A

Data plots for the P34 cluster (Figures 3-12 to 3-14) and P35 cluster (Figures 3-15 to 3-17) show notable, inconsistent variation for some of the selected analytes at the two locations. The DP wells (0.7 m screens) identified up to order of magnitude changes in analyte concentrations over a one metre change in depth. Given these steep geochemical gradients, it is not surprising that the longer-screened MW wells (3 m) could not capture these effects (mean and standard deviation) as summarized for several analytes in Table 3-5.

Unexplained variability was seen for some analytes in the DP wells, with order of magnitude variations seen over time in sulphate (P34 and P35 clusters) and benzene (P34 cluster). In contrast, analyses from MW1 (circles) and MW2 (squares) differed by a factor of two with no decreasing trend evident over the sampling period, and greater variability. The P34 data (crosses) also varied over almost an order of magnitude, but were generally similar to those from the shallower DP2 well.

Table 3-5 Mean (Standard Deviation) for Selected Analytes at Site A

Well (n)	Ca	Na	Cl	SO_4	Fe	B	X
34-DP2 (6)	27.6(5.97)	204(18.6)	32(17.6)	1.0(0.74)	3.3(2.41)	0.038(0.0078)	5.42 (0.913)
34-DP3 (6)	134(22.3)	260(22.6)	60(5.1)	371(107.0)	3.8(2.09)	0.002(0)	0.22(0.092)
93-P-34 (42)	42.5(8.52)	243(49.9)	55(23.8)	52.5(85.76)	8.4(8.85)	0.036(0.0705)	5.19(2.596)
34-MW1 (12)	74.0(19.79)	281(42.0)	69(11.0)	129(107.8)	4.3(2.43)	0.009(0.0037)	2.98(1.285)
34-MW2 (11)	122(54.0)	264(44.7)	64(17.4)	407(283.8)	4.2(1.75)	0.004(0.0028)	2.26(1.901)
35-DP1 (4)	101(11.6)	118(13.5)	54.3(1.83)	2.7(1.79)	42.5(9.13)	0.146(0.0282)	6.78(0.767)
35-DP2 (6)	73.5(9.56)	129(4.5)	47.3(2.17)	8.0(5.11)	12.0(0.73)	0.097(0.0619)	2.35(1.408)
35-DP3 (6)	154(15.7)	96.7(2.90)	28.6(1.51)	299(33.5)	1.1(0.91)	0.001(0.0018)	0.03(0.041)
93-P-35 918)	112(44.7)	135(8.7)	56.3(6.34)	3.4(8.63)	41.1(19.95)	0.165(0.0618)	8.05(4.191)
35-MW1 (8)	121(25.7)	131(19.4)	49.3(3.70)	18.7(38.16)	33.8(26.41)	0.121(0.0493)	4.54(2.591)
35-MW2 (10)	71.7(11.23)	139(11.2)	47.0(7.35)	22.3(36.49)	9.7(9.60)	0.147(0.0648)	2.94(1.386)

Mean values of selected analytes from wells at the P34 and P35 clusters were compared using a nonparametric test equivalent to analysis of variance (ANOVA) (Kruskal-Wallis, SYSTAT 11, p=0.05). This test is less influenced by outlying values. The results (Table 3-6) showed inconsistent differences between wells (significant at 95% confidence level) for most analytes, even between two essentially identical wells (34-MW1 and 34-MW2).

Table 3-6 Nonparametric Test of Equivalent Means from Well Clusters
(Kruskal-Wallis: SYSTAT 11, p=0.05)

Test	Ca	Mg	K	Na	Cl	HCO_3	SO_4	Fe	Mn	B	T	E	X
Site A P34 cluster													
P34 vs. MW1	-	y	-	-	y	y	-	y	-	-	-	-	-
P34 vs. MW2	-	-	-	y	y	y	-	y	-	-	-	-	-
MW1 vs. MW2	-	y	-	-	-	y	-	y	y	-	y	-	-
DP2 vs. P34	-	-	-	-	-	-	-	-	-	y	y	y	y
DP3 vs. P34	-	-	-	y	y	y	-	-	-	-	-	-	-
DP2 vs. MW1	-	-	-	-	-	-	-	y	-	-	-	-	-
DP2 vs. MW2	-	-	-	-	-	y	-	y	-	-	-	-	-
DP3 vs. MW1	-	y	y	y	-	y	-	y	-	y	y	-	-
DP3 vs. MW2	y	y	y	y	y	-	y	y	-	y	y	y	y
Site A P35 cluster													
P35 vs. MW1	y	y	-	y	-	y	y	y	-	y	y	y	-
P35 vs. MW2	-	-	y	y	-	-	y	-	y	y	NA	y	-
MW1 vs. MW2	-	-	y	y	y	-	-	-	-	-	NA	y	y
DP1 vs. P35	y	y	y	-	y	y	y	y	y	y	y	y	y
DP2 vs. P35	-	y	y	y	-	-	-	-	-	-	-	y	-
DP3 vs. P35	y	y	-	-	-	-	-	-	-	-	-	-	-

Notes: y: cannot reject null hypothesis that the two means are equal
-: reject the null hypothesis; means are unlikely to be equal at 95%confidence
NA: insufficient data to perform analysis

The inconsistent averaging effect of the increasing screen length is evident by comparing results from the short screens (0.7 m: DP series), intermediate screen (1.5 m: P-series) and long screens (3 m: MW-series). Differences between paired samples from the replicate MW-series wells highlight the qualitative nature of samples from these types of wells (Martin-Hayden and Robbins, 1991). These authors showed that mass balance effects dominated effects related to sampling methods.

Hydraulic conductivity values measured from slug tests conducted at P34 cluster in DP2, DP3 (0.7 m screens) and MW 2 (3 m screen) were all similar (~ $2x10^{-6}$ m/s), suggesting no obvious preferential groundwater flow zone within the interval covered by the nearby 3 m screen wells. In the absence of preferential flow layers, in-well mixing for the 3 m screen wells (MW-series) at both clusters was estimated using a linear combination of analyses from the DP wells (0.7 m screens). Limitations were caused by problems with the DP1 well and 0.5 m long extension of the MW wells compared to well DP3.

Mixing ratios were obtained using the Solver macro in EXCEL to minimize the squared error between the measured main ion data from MW-well samples and the corresponding linear combination of DP well analyses. Dissolved hydrocarbon and iron (II) concentrations were then calculated using the same linear combination from the DP data and compared to the MW analyses. Results for selected analytes from wells 34-MW1 and 34-MW2 are summarized in Table 3-7.

Table 3-7 Estimated Mixing of Discrete-depth Samples to Match Depth-averaged Samples

Paired Samples				Concentration Difference (Model-Field) (mg/L)				
Well	Sampler	fDP2	fDP3	Ca	Na	SO_4	Fe	X
34-MW1	Waterra®	0.07	0.93	18.9	53.4	18.4	-5.8	-3.3
34-MW2	Waterra®	0.42	0.58	4.2	-1.1	26.2	0.099	-1.9
34-MW1	Waterra®	0.34	0.66	13.5	-8.5	155.3	2.3	-1.0
34-MW2	Waterra®	0.21	0.79	16.2	8.2	-83.1	1.9	0.49
34-MW2	Waterra®	0.08	0.92	26.9	3.9	187.8	1.6	-0.14
34-MW1	Waterra®	0.04	0.96	45.8	38.2	181.0	-0.20	-2.1
34-MW2	Waterra®	0.00	1.00	119.0	-9.0	542.0	-2.5	0.041
34-MW1	Waterra®	0.19	0.81	44.3	48.9	84.2	0.65	-0.37
34-MW2	Waterra®	0.00	1.00	-68.0	3.0	685.0	-0.65	0.056
34-MW1	Waterra®	0.12	0.88	14.9	22.6	49.0	2.1	-0.43
34-MW2	Waterra®	0.00	1.00	-37.0	2.0	256.0	-2.4	1.2

Paired Samples		RPD (%)				
Well	**Sampler**	**Ca**	**Na**	**SO_4**	**Fe**	**X**
34-MW1	Waterra®	16%	18%	5%	81%	148%
34-MW2	Waterra®	5%	0%	11%	3%	65%
34-MW1	Waterra®	12%	3%	84%	51%	35%
34-MW2	Waterra®	13%	3%	23%	38%	39%
34-MW2	Waterra®	20%	2%	41%	29%	20%
34-MW1	Waterra®	46%	14%	95%	4%	138%
34-MW2	Waterra®	64%	4%	96%	44%	15%
34-MW1	Waterra®	58%	18%	69%	19%	28%
34-MW2	Waterra®	45%	1%	126%	14%	54%
34-MW1	Waterra®	17%	10%	15%	88%	37%
34-MW2	Waterra®	30%	1%	48%	53%	151%

Notes: fDP2, fDP3 = fraction of water estimated to derive from DP2 and DP3, respectively.

Simulations at the P34 cluster suggest that the longer-screened wells had a greater contribution from the deeper DP-series well. The MW data tended to overestimate calcium and sulphate concentrations (MW-1 only) but underestimate chloride, sodium, iron(II), and hydrocarbon concentrations. Using the relative RPD as a measure of acceptability (RPD<20% for inorganics, <40% for BTEX), the data suggest that the ability of the MW wells to capture hydrochemistry decreases with increasing analyte reactivity (e.g., adequate for chloride and sodium, poor for sulphate and iron). By extrapolation, greater vertical heterogeneity might be seen by using finer sampling intervals than the 0.75 m long DP wells.

The results given above combined with the inconsistent differences in mean/sd for replicate samples support previous findings of only qualitative results from 3 m screened wells. Therefore, benefits of using 3 m screens (ensure sufficient water to sample from the stained interval) have to be considered against the drawback of mixing/averaging vertical heterogeneity. The drawback is illustrated by notable differences even between samples collected from the two adjacent 3 m screened wells (MW1 and MW2, within one meter). The data do not enable differentiation of potential underlying causes such as lateral geochemical variability or local flow characteristics. Samples from MW1 were more consistent than from MW2 (even when using the same sampling methods in both wells).

Repeating the linear modelling at the P35 cluster identified most of the sampled groundwater as coming from either the shallow or intermediate depth DP wells (0.7 m screens). In contrast to the P34 cluster, samples from the 3 m screened wells at the P35 cluster wells tended to overestimate sulphate, iron, manganese, and calcium compared to the DP well results, but still captured hydrocarbon presence and TEAP patterns used for NA assessment. Further discussion on the use of different sampling techniques in the MW wells to capture depth-varying concentrations (e.g., highest hydrocarbon concentrations seen in shallow wells 34-DP2 and 35-DP1) is provided in section 3.7.3.

Closer investigation showed that the P34 and P35 clusters have similar mean values for the relatively nonreactive chloride and sodium ions. Mean values for TEX were also found not to be significantly different at the 95% confidence interval (n=11, p=0.14). The wells detected hydrocarbons, but gave inconsistent evidence of TEAPs (most notably sulphate) related to NA processes.

It is hypothesised that the reduced variability at the P35 cluster is related to the longer distance from the source and correspondingly greater travel time. Longer residence time would be associated with increased dispersive mixing, especially in the case of a time-varying source condition, coupled with longer bacterial and chemical acclimation periods that influence electron acceptor concentrations.

In summary, samples from the longer-screened wells (3 m) were incapable of capturing vertical chemical gradients identified by the DP-series. Varying inconsistency for analytes from the MW-series samples, both within and between wells separated by 1 m suggests that in-well mixing (e.g., due to infiltration, vertical hydraulic gradient, diffusion or thermal convective flow) can’t easily be characterized. Although samples from the longer-screened wells underestimated both the maximum and average hydrocarbon concentrations and the TEAP patterns used as evidence of IB activity, the data identified general characteristics (hydrocarbon presence and relevant TEAP patterns for NA assessment). Such wells may be adequate for assessing general patterns of PHC contamination and NA evidence, but not for characterizing trends and individual TEAPs.

3.7.2.2. Site B

Summary statistics to characterize the general variability of the data are provided in Table 3-8 for the BH01 Cluster wells, including the mean and standard deviation. Chemical changes with depth at this site were much smaller than at Site A, based on data from the DP wells, but differences still remained between depth-averaged chemical data from the longer-screened wells. Differences in PHC and TEA data between BH01 well and the two MW wells (3 m screens) included iron (high in MW1), sulphate (low in BH01) and xylenes (high in MW2). The exceptions noted above tended to be similar to the shallowest short screen well, DP1.

Table 3-8 Mean|Standard Deviation (mg/L) for Selected Analytes at Site B

	Cl	**Na**	**Ca**	**SO_4**	**Fe**	**B**	**X**
03-DP1	5.0|0.41	5.5|0.52	34.4|2.89	0.70|0.517	3.41|1.737	0.002|0.0006	0.165|0.0373
03-DP2	4.6|0.40	4.6|0.49	19.1|1.26	0.57|0.639	0.61|1.251		0.011|0.0041
03-DP3	4.9|0.38	19.2|17.99	25.0|5.26	7.2|13.50	1.06|1.095	0.001|0.0002	0.008|0|.0035
03-MW1	4.5|0.43	10.0|5.33	31.6|5.33	6.6|8.78	6.94|2.248	0.003|0.0005	0.071|0.0270
03-MW2	5.2|0.90	8.4|2,97	30.4|4.20	8.1|11.53	3.87|2.552	0.002|0.0015	0.101|0.0384
BH01	4.6|1.13	4.7|0.63	31.0|9.12	0.35|0.895	2.17|2.711	0.004|0.0022	0.052|0.0212

In-well mixing in the 3 m screened wells did not influence comparatively stable compounds (e.g., chloride, sodium and calcium), nor did it notably affect PHC detection. As was noted at Site A, differences between the MW-series results and depth-averaged data from the DP wells did affect interpretation of the TEAPs, most notably sulphate (resembled the DP-3 data). The longer-screened wells could assess general NA patterns, but not the specific TEAPs and trends.

As at Site A, mean concentrations at the BH1 cluster were compared using the Kruskal-Wallis nonparametric test (Table 3-9). The results were similar to Site A, where depth-discrete sampling was required in order to capture detailed plume behaviour (BTEX and TEA concentrations). Consistent patterns were not evident between concentrations from the discrete interval (DP-series) and longer-screened wells (MW-series), or even between the pair of adjacent longer-screened wells.

Table 3-9 Statistical Comparisons of Well Data Nonparametric Test of Equivalent Means (Kruskal-Wallis: SYSTAT 11, p=0.05)

Test	**Ca**	**Mg**	**K**	**Na**	**Cl**	**HCO_3**	**SO_4**	**Fe**	**Mn**	**B**	**T**	**E**	**X**
Site B BH01 cluster													
BH1 vs. MW1	-	y	-	-	y	-	-	-	-	y	y	y	-
BH1 vs. MW2	-	y	y	-	y	-	-	y	-	y	y	y	-
MW1 vs. MW2	y	y	-	y	-	y	y	-	-	y	y	-	-
DP1 vs. MW1	y	-	-	y	-	y	y	-	y	y	y	-	-
DP1 vs. MW2	y	-	-	-	y	y	y	y	-	y	y	-	-
DP2 vs. MW1	-	-	-	-	y	-	-	-	-	NA	y	-	-
DP2 vs. MW2	-	-	y	-	-	-	-	-	-	NA	y	-	-
DP3 vs. MW1	-	-	-	y	y	y	y	-	-	-	y	-	-
DP3 vs. MW2	-	-	-	y	y	y	y	-	-	y	y	-	-

Notes: y: cannot reject null hypothesis that the two means are equal
-: reject the null hypothesis; means are unlikely to be equal at 95%confidence
NA: insufficient data to perform analysis

3.7.3 Effect of Sampling Method

3.7.3.1. Site A

Several techniques were used in the longer-screen MW-series wells at the research clusters to see if depth-discrete samples could be collected from these wells. Results obtained using depth-discrete dialysis samplers (DDS) and BarCad pneumatic sampling system were cross-plotted against analyses collected from the same well and date using Waterra® inertial pump in the P34 and P35 clusters (Figures 3-33a and b). For these data pairs (n=5), iron (II) was the only compound with mean values that were significantly different between sampling methods (t-test, p=0.02; Waterra® samples were larger). In contrast, comparison of paired analyses collected from MW1 and 2 using the same sampling method (Waterra®) suggested that almost all compounds were significantly different (except iron (II) and xylenes).

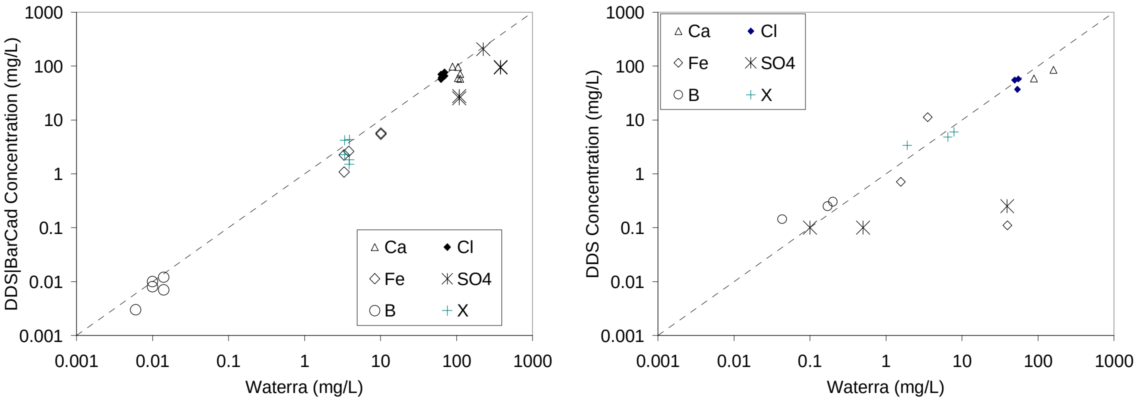


Figure 3-33 Cross plot of paired samples collected from 3 m screened wells at (a) P34 and (b) P35 clusters using Waterra and DDS or BarCad methods. Dotted line shows theoretical 1:1 ratio. Error bars shown by symbol size (10% Ca and Cl; 20% Fe(II), B and X; 30% SO_4)

The DDS samples were placed in the 3 m screened MW wells over approximately the same interval as DP2 and DP3. The DDS results did not match the depth-varying hydrochemical changes noted in the DP-series. Despite the several week equilibration periods, the DDS interval samplers in the MW wells (3 m screens) provided results more like the Waterra® inertial pumps. Specific inconsistencies included: chloride (both DDS were like deeper DP3), iron (both DDS results are similar but show no trend compared to DP wells), calcium (DDS averaged between DP wells), sulphate (both DDS similar to a log-normal average of DP wells) and the hydrocarbons (deeper DDS are similar to shallower DP). In summary mixing within the well appeared to dominate over flow through the well, at least over the sampling periods used here, thus the DDS approach could not be used in longer-screened wells to capture depth-specific variations.

A second test for assessing depth-varying concentrations involved comparing analyses from depth-discrete intervals collected using the direct-push hydro-punch-style method (only one visit) to samples from the corresponding DP wells. Most analytes were typically of the same order (RPD typically <30%). In contrast, hydro-punch samples were typically higher for dissolved sulphate (RPD= 36-99%), lower for BTEX (order of magnitude) and iron (2 orders of magnitude). Hydro-punch samples also typically had higher sulphate, lower BTEX and lower iron (II) concentrations than bailed samples from P34 and P35. The differences likely reflect bias due to aeration/vacuum-related losses while sampling with a peristaltic pump from the direct push pipe. Groundwater recharge was slow, making it hard to avoid drawing down the water level excessively while sampling. In summary, the hydro-punch samples would be poor for characterizing PHC presence and/or TEAP identification at this site.

3.7.3.2. Site B

Samples using various methods were collected from the 3 m screened wells in BH1 cluster. Results are compared between bailer or Waterra® samples and paired samples collected using either BarCad or DDS samplers. The paired data are plotted for selected analytes in Figure 3-34, using a log-log scale to capture the data range. The data show relative consistency in chloride and calcium, but less so for benzene, xylenes, iron (II) and sulphate.

Paired t-tests showed that mean values determined using the various sampling systems could not be differentiated for calcium, chloride, sulphate and xylenes ($n=8-11$, $p=0.05$), whereas mean values were significantly different for iron and benzene. Closer inspection of the data showed that the only consistent pattern was that BarCad analyses for sulphate were typically higher than the equivalent bailer/Waterra® samples. The higher variability in the sulphate data may be related to initially higher sulphate concentrations following well installation (during a period of geochemical equilibration) and not the sampling methods.

The linear mixing model used at Site A generally reproduced most parameters except those used to quantify NA (Table 3-10). Comparisons of simulated and measured data showed RPD values for ions were typically < 30%, PHC around 50% while iron and sulphate data typically exceeded

50 to 100%. Data from the longer-screened wells were adequate for drawing general conclusions about the PHC plume and TEAPs, but not quantitatively assessing NA.

Table 3-10 Estimated Mixing of Discrete-depth Samples to Match Depth-averaged Waterra® Samples

Paired Samples				**Concentration Difference (Model-Field) (mg/L)**				
Well	**fDP1r**	**fDP2**	**fDP3**	**Ca**	**Na**	**SO_4**	**Fe**	**BTEX**
MW1	0.88	0.00	0.12	-0.51	2.2	0.0	3.36	-0.162
MW2	0.32	0.00	0.68	-0.44	0.64	0.0	2.62	0.092
MW1	0.84	0.16	0.00	-0.12	-0.11	-1.11	6.1	0.083
MW2	0.46	0.04	0.50	-0.65	-0.38	-0.32	3.2	0.080
MW1	0.63	0.00	0.37	-2.34	6.72	2.48	2.52	-0.095
MW1	0.72	0.00	0.28	-3.63	2.58	2.69	5.5	-0.145
MW2	0.56	0.00	0.44	-0.99	-0.23	0.43	1.95	0.039

Paired Samples			**RPD (%)**		
Well	**Ca**	**Na**	**SO_4**	**Fe**	**BTEX**
MW1	2%	31%	0%	193%	63%
MW2	2%	9%	0%	178	51%
MW1	0%	2%	184%	100%	54%
MW2	3%	6%	70%	83%	49%
MW1	8%	60%	110%	68%	41%
MW1	12%	30%	125%	100%	59%
MW2	3%	3%	31%	60%	14%

Notes: fDP1, fDP2, fDP3 = fraction of water estimated to derive from DP1, DP2 and DP3, respectively.

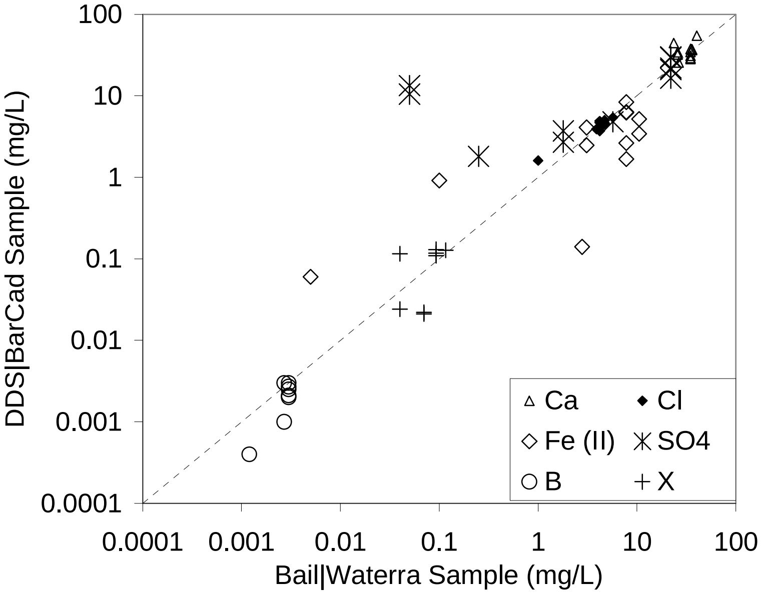


Figure 3-34 Cross plot of paired samples collected from 3 m screened wells at BH1 cluster using Waterra and DDS or BarCad methods. Dotted line shows the theoretical 1:1 ratio. Error bars shown by symbol size (10% Ca and Cl; 20% Fe(II), B and X; 30% SO_4)

3.7.4 Temporal Variability and Trend Assessment

As discussed in Section 3.6.2 and 3.6.3, differential changes in some analyte concentrations between replicate wells with 3 m screens confound NA interpretation more at Site A than Site B. The source of the variability is interpreted to be a combination of steep geochemical gradients (based on data from the short screen wells DP-series) coupled with complex mixing (based on differences between replicate MW-series samples). The question is therefore what data is worth gathering from monitoring wells with 3 m screens and how it can be interpreted.

Mean values for selected analyses from repeated low-flow purge samples from the P34 well (five separate sampling dates) were plotted along with historical analyses from the same well to give a visual assessment (Figures 3-35 and 3-36).

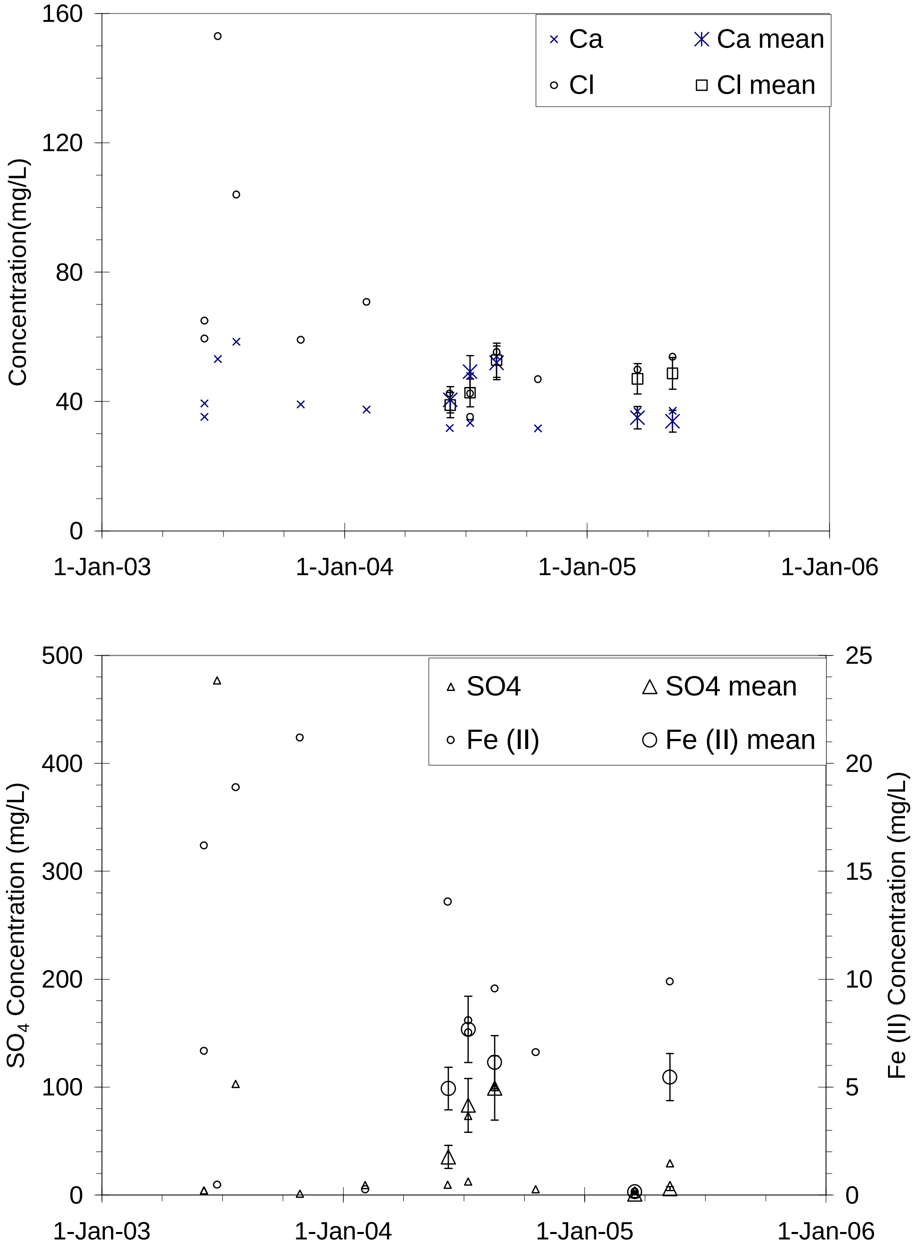


Figure 3-35 Historical variation compared to mean values of replicate samples for selected analytes sampled from well P34: a) Ca and Cl (10% error bar) and b) Fe(II) (20% error bar) and SO_4 (30% error bar)

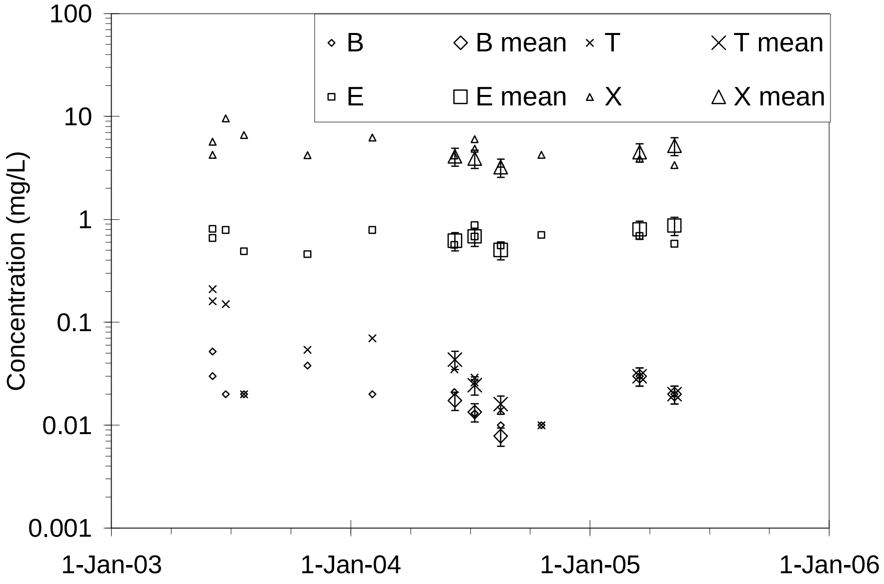


Figure 3-36 Historical variation compared to mean values of replicate samples for BTEX analytes sampled from well P34: (20% error bars)

The no-purge and purge samples for the selected major ions and BTEX (small symbols) were both very similar (RPD ≤ 40%) to the mean analyses from the low-flow purge samples (large hollow symbols, n=3-9), except for some sulphate and iron sets (inconsistent differences up to a factor of 2 to 4). Excluding the obvious extreme variability in the iron (II) and sulphate analyses, paired t-tests did not identify any significant differences (> 95% confidence) between mean values for the other analytes.

Temporal variability for Ca, Na and Cl within the five paired sets of purge and no-purge samples was typically within 10 %. In contrast, inclusion of the historical no-purge data showed differences ranged up to 300%. In particular, BTEX compounds showed greater variability, ranging from a factor of 3 (purge | non-purge data pairs) up to an order of magnitude over the longer term. Greater temporal variability was evident for the main TEAs (iron and sulphate); ranging from one order of magnitude (purge | no-purge pairs) up to two orders of magnitude when historical data were included.

3.8 NA Assessment with Varying Groundwater Data

Comparison of data from the 0.7 m and 3 m screened wells indicated that in-well mixing generated inconsistently variable results over time, making it difficult to interpret local TEAPs for

NA assessment, especially in 3 m screened wells. Variability tended to be greatest for the dominant TEAs (iron and sulphate), less for the main BTEX contaminants, and least for the relatively nonreactive main cations and chloride. At both sites, the 3 m-screened wells adequately identified an equivalent depth-average of PHC concentrations determined by the series of shorter screen (0.7 m) wells. The 3 m screened wells at Site A were less able to identify active TEAPs than at Site B, likely due to the much smaller variation in hydrochemistry with depth at Site B.

Despite the differing variability in analyses, comparison of data collected from similar types of wells installed across the Site A plume showed BTEX and TEA concentrations consistent with NA. In summary, the data from such wells appeared adequate for assessing attenuation of the target PHC contaminants. The data were far less useful for trying to assess dominant TEAPs or their relative role in supporting if NA meets site-specific management goals. The only way to interpret PHC plume changes (particularly expansion) is by seeing PHCs in downgradient wells.

The various combinations of sampling systems and well configurations were all able to identify dissolved hydrocarbon presence; however, only the DP-series of short-screen wells provided relatively consistent concentrations between visits. The inconsistent differences for inorganic analyses (nonreactive vs. TEAs) could only be resolved as general patterns. For a general case, these results indicated that the sampling method did not affect broad interpretation of NA as much as the well screen length. No sampling system in the 3 m screened wells was able to capture the depth-discrete results identified in the 0.7 m DP wells. Patterns of in-well mixing could not be identified, thus concentrations from those wells should be considered only as statistical means. Given observed order-of-magnitude variations, consideration should be given to log-transforming TEAs and PHC data before averaging. The TEAP data may then provide credibility for assigning PHC attenuation to biodegradation process(es) – a secondary requirement for NA assessment.

Despite the order-of-magnitude data variability in longer-screened wells at Site A, semi-annual monitoring in spring and fall still captured the general plume and NA character. More frequent sampling highlighted the variability. Shorter-screened wells were required to identify vertical spatial distribution and maximum concentrations. Neither factor was important at this site for assessing ecological risk (no surface discharge). In contrast to Site A, the decreased variability at Site B meant that the longer-screened wells gave adequate monitoring data for assessing both plume and TEA concentrations. In general, semi-annual monitoring from 3 m screened wells appeared adequate for assessing average contaminant concentrations, the key component for NA assessment. Variability from historical data helped to highlight the level of confidence that could be placed on trends in average concentrations.

Use of low-flow purging tended to give the most consistent data, compared to no-purge and DDS sampling; however, there was no obvious pattern between wells or analytes. No sampling approaches from the 3 m screen wells could capture the depth-varying concentration changes. Some insight regarding this heterogeneity could be gained by using two different sampling methods (repeat sampling from the same well). This approach helped to identify possible underlying influences when selecting ‘average’ contaminant and TEAP concentrations for NA assessment.

Quantitative assessment of dissolved PHC trends requires understanding of the original source; however, this information is often uncertain. As an example, the episodic hydrocarbon source (e.g., Site A), means spatio-temporal variation in PHC and TEA concentrations should be expected. True data variability could only be reduced by using frequent (quarterly) and detailed sampling of short-screen wells using minimal-disturbance sampling such as the low-flow approach. From a qualitative perspective, NA could still be addressed using the average data described previously.

Use of a data logger (with atmospheric compensation) to record daily water table fluctuations over a year identified much greater short-term variability in water levels than could otherwise be appreciated from semi-annual monitoring. Changes over several days were on the same order as seasonal ranges that had previously been estimated from semi-annual sampling. The changes generally correlated with local precipitation (good correlation at Site A) and also spring thaw (Site B). Infiltration and/or water table elevation variation has been shown to affect groundwater monitoring data at some sites (e.g., sulphate replenishment at Site A). Data loggers (preferably in at least one shallow and one deep monitoring well) combined with local precipitation data may help identify external influences on shallow groundwater chemistry changes that are otherwise not easily be identified from hydrochemical data.

3.9 Conclusions and Recommendations

Detailed site characterization and sampling results at two sites uncovered complexity regarding both spatial and temporal assessment of natural attenuation based on groundwater samples. Refinement of the vertical sampling intervals identified order of magnitude concentration changes within 1 m depth for some parameters. Repeated sampling using research well clusters in two areas at Site A and one area at Site B identified multiple types of variability in the monitoring data.

The influence of well purging was found to be relatively minor compared to the range of variability evident within and between the different wells within each research cluster. Replicate sample sets collected from various wells showed that the sampling technology also appeared to have a relatively minor influence on BTEX and electron acceptor concentrations used to assess natural attenuation of dissolved hydrocarbons. The use of discrete interval DDS samples within 3 m screened wells did not capture the depth variation, indicating that in-well mixing is a dominant mechanism.

Near the source area at one site, concentration data collected from two essentially identical wells with 3 m screens and separated laterally by 1 m showed inconsistently varying hydrochemical differences for more reactive analytes (up to an order of magnitude). The underlying cause was in-well mixing of groundwater from zones with steep geochemical gradients. This situation was identifiable (but not resolvable) by seeing large chemical differences between analyses from samples collected using differing methodologies. The variability within, and between, wells generally decreased with distance from the source.

The various sampling methodologies and purging protocols did not allow quantification of sampling-induced variability as it related to in-well mixing effects. By combining no-purge samples and either low-flow or DDS samplers in the long-screen wells (3 m: MW-series), the general chemical character and influence of depth-discrete variations were identifiable. Over the longer term, inherent complexity in monitoring data may be indicated by large historical fluctuations, but underlying factors could not be extracted. The data from 3 m screened wells were inadequate as input for quantitative modelling studies where depth-discrete variations may dominate a simulation. However, the data appear to be reasonable as order of magnitude values when modelling a problem to gain insight about attenuation time and space scales.

The 3 m screened wells were able to meet the primary objective of monitoring for NA, i.e., contaminant trend monitoring. These wells typically matched the average of concentrations measured in the depth-discrete samplers; hence identified the equivalent contaminant mass in the plume and average spatial plume behaviour. These wells underestimated maximum dissolved BTEX concentrations (typically by a factor of two to three), generating a possible drawback depending on the site conceptual model and ecological receptors. In contrast, the 3 m screens were typically inadequate for quantifying attenuation processes through identification of TEAPs

Temporal variability in analyses from 3 m screened wells tended to give confounding results over the short term (10's of months), apparently due to variable mixing of groundwater having different vertical distributions of PHC and TEA concentrations. These wells gave conflicting evidence regarding NA processes, despite capturing average hydrocarbon concentrations. Evidence from the research well clusters showed that the in-well mixing effect could not be determined from sampling the 3 m screened wells.

Use of shorter screened wells might be required in order to reduce analytical variability, refine a conceptual model and recognize potential influence of steep, fine-scale geochemical gradients (e.g., Site A), but not always (e.g., Site B). Sites requiring the more detailed approach may be recognizable by assessing variability in groundwater data collected using more than one sampling methodology. The level of monitoring effort should also be considered when developing the conceptual model underlying NA and setting plume management goals.

3.10 References

Aller, L., Bennett, T.W., Hackett, G., Petty, R.J., Lehr, J.H., Sedoris, H. and Nielsen, D.M., 1989. Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells. National Water Well Association, Dublin, OH, 398 pp.

Alvarez, P.J.J. and Illman, W.A., 2006. Bioremediation and Natural Attenuation: process fundamentals and mathematical models. John Wiley and Sons, Inc., 609 pp.

API, 1998. Evaluation of sampling and analytical methods for measuring indicators of intrinsic bioremediation. 5, American Petroleum Institute, Washington, DC.

Archfield, S.A. and LeBlanc, D.R., 2005. Comparison of Diffusion- and Pumped-Sampling Methods to Monitor Volatile Organic Compounds in Ground Water, Massachusetts Military Reservation, Cape Cod, Massachusetts, July 1999–December 2002. Scientific Investigations Report 2005-5010, USGS, Reston, Virginia.

Armstrong, J.E., Cross, K., M. and Biggar, K.W., 2002. Assessment of Monitored Natural Attenuation at Upstream Oil & Gas Facilities in Alberta – final report. 2001-0010, Canadian Association of Petroleum Producers (CAPP), Calgary.

Armstrong, J.E., Deutsch, C. and Biggar, K.W., 2003. Geostatistical assessment of cone penetrometer test data for soil characterization based on ultraviolet induced fluorescence, 56th Canadian Geotechnical Conference 4th Joint IAH-CNC/CGS Conference. CGS-IAH, Winnipeg, MB.

ASTM, 1998. Standard Guide for Remediation of Ground Water by Natural Attenuation at Petroleum Release Sites. E 1943 - 98, American Society for Testing and Materials.

ASTM, 2005. Standard Guide for Purging Methods for Wells Used for Ground-Water Quality Investigations, American Standard for Testing Materials, West Conshohocken, PA.

Baedecker, M.J., Cozzarelli, I.M., Eganhouse, R.P., Siegel, D.I. and Bennett, P.C., 1993. Crude oil in a shallow sand and gravel aquifer--Ill. Biogeochemical reactions and mass balance modeling in anoxic groundwater. Applied Geochemistry, 8(6): 569-586.

Barcelona, M.J. and Helfrich, J.A., 1986. Well construction and purging effects on ground-water samples. Environmental Science & Technology, 20(11): 1179-1184.

Barcelona, M.J., Helfrich, J.A. and Garske, E.E., 1988. Verification of sampling methods and selection of material for ground-water contamination studies. ASTM STP 963, American Society for Testing and Materials, Philadelphia.

Barcelona, M.J., Varljen, M.D., Puls, R.W. and Kaminski, D., 2005. Ground water purging and sampling methods: history vs. hysteria. Ground Water Monitoring & Remediation, 25(1): 52-62.

Barcelona, M.J., Wehrmann, H.A. and Varljen, M.D., 1994. Reproducible well-purging procedures and VOC stabilization criteria for groundwater sampling. Ground Water, 32(1): 12-22.

Barker, G.W., Raterman, K.T., Fisher, J.B., Corgan, J.M., Trent, G.L., Brown, D.R., Kemp, N. and Sublette, K.L., 1996. A case study of the natural attenuation of gas condensate hydrocarbons in soil and groundwater. Applied Biochemistry and Biotechnology, 57/58(8): 791-802.

Barker, J.F. and Dickhout, R., 1988. An evaluation of some systems for sampling gas-charged groundwater for volatile organic analysis. Ground Water Monitoring Review, 8(4): 112-120.

Barker, J.F., Patrick, G.C. and Major, D., 1987. Natural attenuation of aromatic hydrocarbons in shallow sand aquifer. Ground Water Monitoring Review., 7(1): 64-71.

Bekins, B.A., Cozzarelli, I.M., Godsy, E.M., Warren, E., Essaid, H.I. and Tuccillo, M.E., 2001a. Progression of natural attenuation processes at a crude oil spill site: II. Controls on spatial distribution of microbial populations. Journal of Contaminant Hydrology, 53(3-4): 387-406.

Bekins, B.A., Cozzarelli, I.M., Warren, E. and Godsy, E.M., 2001b. Microbial ecology of a crude oil contaminated aquifer. In: S.T.a.S. Oswald (Editor), Groundwater Quality: Natural and Enhanced Restoration of Groundwater Pollution. IAHS, Sheffield, UK, pp. 57-63.

Bekins, B.A., Warren, E. and Godsy, E.M., 1998. A comparison of zero-order, first-order, and Monod biotransformation models. Ground Water, 36(2): 261-268.

Beyer, C., Bauer, S. and Kolditz, O., 2006. Uncertainty assessment of contaminant plume length estimates in heterogeneous aquifers. Journal of Contaminant Hydrology, 87(1-2): 73-95.

Bockelmann, A., Ptak, T. and Teutsch, G., 2001. An analytical quantification of mass fluxes and natural attenuation rate constants at a former gasworks site. Journal of Contaminant Hydrology, 53(3-4): 429-453.

Bopp, S., Weiss, H. and Schirmer, K., 2005. Time-integrated monitoring of polycyclic aromatic hydrocarbons (PAHs) in groundwater using the Ceramic Dosimeter passive sampling device. Journal of Chromatography A, 1072(1): 137-147.

Borden, R.C., Hunt, M.J., Schafer, M.B. and Barlaz, M.A., 1997. Anaerobic Biodegradation of BTEX in Aquifer Material, National Risk Management Research Laboratory, Ada, OK, Washington, DC.

Brauner, J.S. and Widdowson, M.A., 2001. Numerical simulation of a natural attenuation experiment with a petroleum hydrocarbon NAPL source. Ground Water, 39(6): 939-952.

Byrnes, P.G., Briglia, J.E. and Bealer, L.J., 1996. Evaluation of well purging in ground-water sampling for BTEX and MTBE, Proceedings of the 1996 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation Conference. National Ground Water Association, pp. 221-236.

Chapelle, F.H., 1993. Ground-Water Microbiology & Geochemistry. John Wiley & Sons, Inc., New York, 424 pp.

Chapelle, F.H., Widdowson, M.A., Brauner, J.S., Mendez, E.I. and Casey, C.C., 2003. Methodology for estimating times of remediation associated with monitored natural attenuation. 03-4057, US Geological Survey, Columbia.

Christensen, O.F., Cassiani, G., Diggle, P.J., Ribeiro, J.P. and Andreotti, G., 2004. Statistical estimation of the relative efficiency of natural attenuation mechanisms in contaminated aquifers. Stochastic Environmental Research and Risk Assessment, 18(5): 339-350.

Church, P.E. and Granato, G.E., 1996. Bias in ground-water data caused by well-bore flow in long-screen wells. Ground Water, 34(2): 262-273.

Cilliers, P., 2005. Complexity, deconstruction and relativism. Theory, Culture & Society, 22(5): 255-267.

Cozzarelli, I.M., Bekins, B.A., Baedecker, M.J., Aiken, G.R., Eganhouse, R.P. and Tuccillo, M.E., 2001. Progression of natural attenuation processes at a crude-oil spill site - I. Geochemical evolution of the plume. Journal of Contaminant Hydrology, 53(3-4): 369-385.

Cozzarelli, I.M., Herman, J.S. and Baedecker, M.J., 1995. Fate of microbial metabolites of hydrocarbons in a coastal plain aquifer: the role of electron acceptors. Environmental Science & Technology, 29(2): 458-469.

Cozzarelli, I.M., Herman, J.S., Baedecker, M.J. and Fischer, J.M., 1999. Geochemical heterogeneity of a gasoline-contaminated aquifer. Journal of Contaminant Hydrology, 40(3): 261-284.

Davis, G.B., Barber, C., Power, T.R., Thierrin, J., Patterson, B.M., Rayner, J.L. and Wu, Q.L., 1999. The variability and intrinsic remediation of a BTEX plume in anaerobic sulphate-rich groundwater. Journal of Contaminant Hydrology, 36(3-4): 265-290.

Ehlke, T.A., Imbrigiotta, T.E. and Dale, J.M., 2004. Laboratory comparison of polyethylene and dialysis membrane diffusion samplers. Ground Water Monitoring & Remediation, 24(1): 53-59.

Elci, A., Molz III, F.J. and Waldrop, W.R., 2001. Implications of observed and simulated ambient flow in monitoring wells. Ground Water, 39(6): 853-862.

Elshahed, M.S., Gieg, L.M., McInerney, M.J. and Suflita, J.M., 2001. Signature metabolites attesting to the in situ attenuation of alkylbenzenes in anaerobic environments. Environmental Science & Technology, 25(4): 682-689.

Essaid, H.I., B.A, B., Godsy, E.M., Warren, E., M.J, B. and I.M, C., 1995. Simulation of aerobic and anaerobic biodegradation processes at a crude oil spill site. Water Resources Research, 31(12): 3309-3327.

Ghiorse, W.C. and Wilson, J.T., 1988. Microbial ecology of the terrestrial subsurface. Advances in Applied Microbiology, 33: 107-171.

Gibs, J., Brown, G.A., Turner, K.S., MacLeod, C.L., Jelinski, J.C. and Koehnlein, S.A., 1993. Effects of small-scale vertical variations in well-screen inflow rates and concentrations of organic compounds on the collection of representative groundwater quality samples. Ground Water, 31(2): 201-208.

Gibs, J. and Imbrigiotta, T.E., 1990. Well-purging criteria for sampling purgeable organic compounds. Ground Water, 28(1): 68-78.

Gieg, L.M., Kolhatkar, R.V., McInerney, M.J., Tanner, R.S., Harris, S.H.J., Sublette, K.L. and Suflita, J.M., 1999. Intrinsic bioremediation of petroleum hydrocarbons in a gas condensate-contaminated aquifer. Environmental Science & Technology, 33(15): 2550-2560.

Gieg, L.M. and Suflita, J.M., 2002. Detection of anaerobic metabolites of saturated and aromatic hydrocarbons in petroleum-contaminated aquifers. Environmental Science & Technology, 36(17): 3755-3762.

Guilbeault, M.A., 1999. Suspended DNAPL source zones in three sandy aquifers: plume anatomy, mass discharge and sampling scale considerations. M.Sc. Thesis, University of Waterloo, Waterloo, ON, 154 pp.

Gustavson, K.E. and Harkin, J.M., 2000. Comparison of sampling techniques and evaluation of semipermeable membrane devices (SPMDs) for monitoring polynuclear aromatic hydrocarbons (PAHs) in groundwater. Environmental Science & Technology, 34(20): 4445-4451.

Herzog, B.L., Chou, S.-F.J., Valkenburg, J.R. and Griffin, R.A., 1988. Changes in volatile organic chemical concentrations after purging slowly recovering wells. Ground Water Monitoring Review, 8(4): 93-99.

Herzog, B.L., Pennino, J. and Nielsen, G., 1991. Ground-water sampling. In: D.M. Nielsen (Editor), Practical Handbook of Ground-Water Monitoring. Lewis Publishing Inc., Chelsea, pp. 449-499.

Hutchins, S.R. and Acree, S.D., 2000. Ground water sampling bias observed in shallow, conventional wells. Ground Water Monitoring & Remediation, 20(1): 86-93.

Iwakun, O., Biggar, K.W., Armstrong, J.E., Donahue, R. and Sego, D., 2008. Evaluation of dialysis sampler's integrity in cold climate. Ground Water Monitoring & Remediation, 28(1): 50-56.

Iwakun, O., Biggar, K.W., Armstrong, J.E., Donahue, R. and Sego, D.C., 2005. Evaluation of a diffusion sampling system for MNA assessment, 58th Canadian Geotechnical Conference, Saskatoon, SK.

Jones, I., Lerner, D.N. and Baines, O.P., 1999. Multiport sock samplers: A low-cost technology for effective multilevel ground water sampling. Ground Water Monitoring & Remediation, 19(1): 134-142.

Kao, C.M. and Prosser, J., 2001. Evaluation of natural attenuation rate at a gasoline spill site. Journal of Hazardous Materials, 82(3): 275-289.

Kearl, P.M., Korte, N.E., Stites, M. and Baker, J., 1994. Field comparison of micropurging vs. traditional ground water sampling. Ground Water Monitoring & Remediation, 14(4): 183-190.

Keith, S.J., Wilson, L.G., Fitch, H.R. and Esposito, D.M., 1983. Sources of spatial-temporal variability in groundwater quality data and methods of control. Ground Water Monitoring Review, 3(2): 21-32.

Kennedy, L.G., Everett, J.W., Ware, K.J., Parsons, R. and Green, V., 1998. Iron and sulfur mineral analysis methods for natural attenuation assessments. Bioremediation Journal, 2(3&4): 259-276.

Kim, K., 2003. Long-term disturbance of ground water chemistry following well installation. Ground Water, 41(6): 780-789.

Kwon, M.J., Sanford, R.A., Park, J., Kirk, M.F. and Bethke, C.M., 2008. Microbiological response to well pumping. Ground Water, 46(2): 286-294.

Landmeyer, J.E., Chapelle, F.H., Petkewich, M.D. and Bradley, P.M., 1998. Assessment of natural attenuation of aromatic hydrocarbons in groundwater near a former manufactured-gas plant, South Carolina, USA. Environmental Geology, 34(4): 279-292.

Lee, J.Y., Cheon, J.Y., Lee, K.K., Lee, S.Y. and Lee, M.H., 2001a. Factors affecting the distribution of hydrocarbon contaminants and hydrogeochemical parameters in a shallow sand aquifer. Journal of Contaminant Hydrology, 50(1-2): 139-158.

Lee, J.Y., Cheon, J.Y., Lee, K.K., Lee, S.Y. and Lee, M.H., 2001b. Statistical evaluation of geochemical parameter distribution in a ground water system contaminated with petroleum hydrocarbons. Journal of Environmental Quality, 30(5): 1548-1563.

Lu, G.P., Clement, T.P., Zheng, C.M. and Wiedemeier, T.H., 1999. Natural attenuation of BTEX compounds: Model development and field-scale application. Ground Water, 37(5): 707-717.

Maier, U. and Grathwohl, P., 2006. Numerical experiments and field results on the size of steady state plumes. Journal of Contaminant Hydrology, 85(1-2): 33-52.

Martin, H., Patterson, B.M. and Davis, G.B., 2003. Field trial of contaminant groundwater monitoring: comparing time-integrating ceramic dosimeters and conventional water sampling. Environmental Science & Technology, 37(7): 1360-1364.

Martin-Hayden, J.M., 2000. Sample concentration response to laminar wellbore flow: Implications to ground water data variability. Ground Water, 38(1): 12-19.

Martin-Hayden, J.M. and Robbins, G.A., 1991. Mass balance evaluation of monitoring well purging: Part II, Field tests at a gasoline contamination site. Journal of Contaminant Hydrology, 8(3-4): 225-241.

Martin-Hayden, J.M. and Robbins, G.A., 1997. Plume distortion and apparent attenuation due to concentration averaging in monitoring wells. Ground Water, 35(2): 339-346.

McAlary, T.A. and Barker, J.F., 1987. Volatilization losses of organics during ground water sampling from low permeability materials. Ground Water Monitoring Review, 7(4): 63-68.

McGuire, T.M., Newell, C.J., Looney, B.B., Vangelas, K.M. and Sink, C.H., 2004. Historical analysis of monitored natural attenuation: A survey of 191 chlorinated solvent sites and 45 solvent plumes. Remediation: 99-112.

McLeish, K., Ryan, C. and Chu, A., 2007. Integrated sampling and analytical approach for common groundwater dissolved gases. Environmental Science & Technology, 41: 8388-8393.

McNab, W.W., 2001. A Monte Carlo simulation method for assessing biotransformation effects on groundwater fuel hydrocarbon plume lengths. Computers & Geosciences, 27(1): 31-42.

McNab, W.W. and Dooher, B.P., 1998. Uncertainty analyses of fuel hydrocarbon biodegradation signatures in ground water by probabilistic modeling. Ground Water, 36(4): 691-698.

Miralles-Wilhelm, F. and Gelhar, L.W., 2000. Stochastic analysis of oxygen-limited biodegradation in heterogeneous aquifers with transient microbial dynamics. Journal of Contaminant Hydrology, 42(1): 69-97.

Morgan, P., Lewis, S.T. and Watkinson, R.J., 1993. Biodegradation of benzene, toluene, ethylbenzene and xylenes in gas condensate ground water. Environmental Pollution, 82: 181-190.

Morin, D.M., in preparation. Critical analysis of monitoring technologies for monitored natural attenuation at upstream oil and gas sites in Alberta. M.Sc. Thesis, University of Alberta, Edmonton.

Newell, C.J., Lee, R.S. and Spextet, A.H., 2000. No-Purge Groundwater Sampling: An Approach for Long-Term Monitoring, American Petroleum Institute (API) Bulletin 12, pp. 1-10.

Nichols, E.M. and Roth, T.L., 2006. Downward solute plume migration: assessment, significance, and implications for characterization and monitoring of "diving plumes". American Petroleum Institute (API) Bulletin, 24: 1-29.

NRC, 1993. In Situ Bioremediation: When Does It Work. National Academy Press, Washington, DC.

NRC, 2000. Natural Attenuation for Groundwater Remediation. National Academy Press, Washington. DC, 274 pp.

Odermatt, J.R., 1999. Remediation by natural attenuation? Ground Water Monitoring & Remediation, 19(3): 58-60.

Parker, L.V. and Clark, C.H., 2002. Study of Five Discrete Interval-Type Groundwater Sampling Devices, US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, NH.

Pelayo, A.M. and Evangelista, F.S., 2003. A statistical F test for the natural attenuation of contaminants in groundwater. Environmental Monitoring and Assessment, 83(1): 47-70.

Pennino, J., 1988. There's no such thing as a representative ground water sample. Ground Water Monitoring Review, 8(3): 4-9.

Petersmeyer, C.W., 2006. Assessing Natural Attenuation of Petroleum Hydrocarbons Using Reactive Transport Modelling with Aqueous and Solid Phase Data. M.Sc. Thesis, University of British Columbia, Vancouver, 273 pp.

Poulsen, M. and Kueper, B.H., 1992. A field experiment to study the behaviour of tetrachloroethylene in unsaturated porous media. Environmental Science & Technology, 26(5): 889-895.

Powell, R.M. and Puls, R.W., 1993. Passive sampling of groundwater monitoring wells without purging: multilevel well chemistry and tracer disappearance. Journal of Contaminant Hydrology, 12(1): 51-77.

Prommer, H., Barry, D.A. and Davis, G.B., 1998. The effect of seasonal variability on intrinsic biodegradation of a BTEX plume, GQ'98. Groundwater Quality: Remediation and Protection. IAHS, Tubingen, Germany, pp. 213-244.

Prommer, H., Barry, D.A. and Davis, G.B., 2002. Modelling of physical and reactive processes during biodegradation of a hydrocarbon plume under transient groundwater flow conditions. Journal of Contaminant Hydrology, 59(1-2): 113-131.

Puls, R.W. and Barcelona, M.J., 1989. Ground water sampling for metals analyses. United States Environmental Protection Agency, Office of Research and Development, Ada, OK.

Puls, R.W. and Barcelona, M.J., 1995. Low-flow (minimal drawdown) groundwater sampling procedures. EPA/540/S-95/504, USEPA, Ada, OK.

Puls, R.W. and Paul, C.J., 1995. Low-flow purging and sampling of ground water monitoring wells with dedicated systems. Ground Water Monitoring Review, 15(1): 116-123.

Puls, R.W. and Paul, C.J., 1997. Multi-layer sampling in conventional monitoring wells for improved estimation of vertical contaminant distributions and mass. Journal of Contaminant Hydrology, 25(1-2): 85-111.

Remenda, V.H. and van der Kamp, G., 1997. Contamination from sand-bentonite seal in monitoring wells installed in aquitards. Ground Water, 35(1): 39-46.

Rice, D.W., Grose, R.D., Michaelsen, J.C., Dooher, B.P., MacQueen, D.H., Cullen, S.J., Kastenberg, W.E., Everett, L.G. and Marino, M.A., 1995. California Leaking Underground Fuel Tank (LUFT) Historical Cases Analyses. UCRL-AR-122207, Lawrence Livermore National Laboratory, Livermore.

Rifai, H.S., Newell, C.J., Gonzales, J.R. and Wilson, J.T., 2000. Modelling natural attenuation of fuels with Bioplume III. Journal of Environmental Engineering, 126(5): 428-438.

Rifai, H.S. and Rittaler, T., 2005. Modeling natural attenuation of benzene with analytical and numerical models. Biodegradation, 16: 291-304.

Rittmann, B.E., 2004. Definition, objectives and evaluation of natural attenuation. Biodegradation, 15: 349-357.

Robbins, G.A. and Martin-Hayden, J.M., 1991. Mass balance evaluation of monitoring well purging: Part I, Theoretical models and implications for representative sampling. Journal of Contaminant Hydrology, 8(3-4): 203-224.

Robin, M.J.L. and Gillham, R.W., 1987. Field evaluation of well purging procedures. Ground Water Monitoring Review, 7(4): 85-93.

Ronen, D., Margaritz, M. and Levy, I., 1986. A multi-layer sampler for the study of detailed hydrochemical profiles in groundwater. Water Research, 20(3): 311-315.

Rueter, P., Rabus, R., Wilkes, H., Aeckersberg, F., Rainey, F.A., Jannasch, H.W. and Widdel, F., 1994. Anaerobic oxidation of hydrocarbons in crude oil by new types of sulphate-reducing bacteria. Nature, 372: 455-458.

Salanitro, J.P., Wisniewski, H.L., Byers, D.L., Neaville, C.C. and Schroder, R.A., 1996. The potential and limits of aerobic and anaerobic BTEX biodegradation in aquifers, Third International Petroleum Environmental Conference, Albuquerque, NM, pp. 24-27.

Salanitro, J.P., Wisniewski, H.L., Byers, D.L., Neaville, C.C. and Schroder, R.A., 1997. Use of aerobic and anaerobic microcosms to assess BTEX biodegradation in aquifers. Ground Water Monitoring & Remediation, 17(3): 210-221.

Schaefer, W., 2001. Predicting natural attenuation of xylene in groundwater using a numerical model. Journal of Contaminant Hydrology, 52(1-4): 57-83.

Schirmer, M., Durrant, G.C., Molson, J.W. and Frind, E.O., 2001. Influence of transient flow on contaminant biodegradation. Ground Water, 39(2): 276-282.

Schirmer, M., Molson, J.W., Frind, E.O. and Barker, J.F., 2000. Biodegradation modelling of a dissolved gasoline plume applying independent laboratory and field parameters. Journal of Contaminant Hydrology, 46(3-4): 339-374.

Scholl, M.A., 2000. Effects of heterogeneity in aquifer permeability and biomass on biodegradation rate calculations - Results from numerical simulations. Ground Water, 38(5): 702-712.

Scholl, M.A., Cozzarelli, I.M. and Christenson, S.C., 2006. Recharge processes drive sulfate reduction in an alluvial aquifer contaminated with landfill leachate. Journal of Contaminant Hydrology, 86(3-4): 239-261.

Schreiber, M.E., Carey, G.R., Feinstein, D.T. and Bahr, J.M., 2004. Mechanisms of electron acceptor utilization: implications for simulating anaerobic biodegradation. Journal of Contaminant Hydrology, 73(1-4): 99-127.

Schuller, R.M., Gibb, J.P. and Griffin, R.A., 1981. Recommended sampling procedures for monitoring wells. Ground Water Monitoring Review, 1(2): 42-46.

SECOR, S.I.I., 1996. Final Report The California Groundwater Purging Study for Petroleum Hydrocarbons, Western States Petroleum Association, Glendale, CA.

Simoni, S.F., Schaefer, A., Harms, H. and Zehnder, A.J.B., 2001. Factors affecting mass transfer limited biodegradation in saturated porous media. Journal of Contaminant Hydrology, 50(1-2): 99-120.

Smets, B.F. and Pritchardy, P.H., 2003. Elucidating the microbial component of natural attenuation. Current Opinion in Biotechnology, 14(3): 283-288.

Suarez, M.P. and Rifai, H.S., 1999. Biodegradation rates for fuel hydrocarbons and chlorinated solvents in groundwater. Bioremediation Journal, 3(4): 337-362.

Thornton, S.F., Quigley, S., Spence, M.J., Banwart, S.A., Bottrell, S.H. and Lerner, D.N., 2001. Processes controlling the distribution and natural attenuation of dissolved phenolic compounds in a deep sandstone aquifer. Journal of Contaminant Hydrology, 53: 223-267.

Townsend, G.T., Prince, R.C. and Suflita, J.M., 2004. Anaerobic biodegradation of alicyclic constituents of gasoline and natural gas condensate by bacteria from an anoxic aquifer. FEMS Microbiology Reviews, 49: 129-135.

USEPA, 1999. Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites. OSWER Directive 9200.4-17P, Office of Solid Waste and Emergency Response Directive, Washington, DC.

van Breukelen, B.M., Griffioen, J., Roling, W.F.M. and van Verseveld, H.W., 2004. Reactive transport modelling of biogeochemical processes and carbon isotope geochemistry inside a landfill leachate plume. Journal of Contaminant Hydrology, 70(3-4): 249-269.

Van Stempvoort, D.R., Armstrong, J.E. and Mayer, B., 2007. Microbial reduction of sulfate injected to gas condensate plumes in cold groundwater. Journal of Contaminant Hydrology, 92(3-4): 184–207.

Varljen, M.D., 1997. No-purge sampling: here's the beef. Ground Water Monitoring Review, 17(3): 87-89.

Vroblesky, D.A., Petkewich, M.D. and Campbell, T.R., 2002. Field Tests of Diffusion Samplers for Inorganic Constituents in Wells and at a Ground-Water-Discharge Zone. 02-4031, U.S. Geological Survey, Columbia.

Wachter, T., Schaefer, D., Grandel, S. and Dahmke, A., 2005. Raeumliche and zeitliche Variabilitaet hydrochemischer Parameter am BTEX-kontaminierten Standort in Zeitz/Sachsen-Anhalt. Grundwasser, 10(4): 237-253.

Watson, I.A., Oswald, S.E., Banwart, S.A., Crouch, R.S. and Thornton, S.F., 2005. Modeling the dynamics of fermentation and respiratory processes in a groundwater plume of phenolic contaminants interpreted from laboratory- to field-scale. Environmental Science & Technology, 39(22): 8829-8839.

Watson, I.A., Oswald, S.E., Mayer, K.U., Wu, Y. and Banwart, S.A., 2003. Modeling kinetic processes controlling hydrogen and acetate concentrations in an aquifer-derived microcosm. Environmental Science & Technology, 37(17): 3910-3919.

Wiedemeier, T.H., Rifai, H.S., Newell, C.J. and Wilson, J.T., 1999. Natural attenuation of fuels and chlorinated solvents in the subsurface. John Wiley, New York, 617 pp.

Wilson, R.D., Thornton, S.F. and Mackay, D.M., 2004. Challenges in monitoring the natural attenuation of spatially variable plumes. Biodegradation, 15(6): 359-369.

Yeskis, D. and Zavala, B., 2002. Groundwater sampling guidelines for superfund and RCRA project managers. EPA 542-S-02-001, U.S. EPA, Chicago, IL.

4. IDENTIFYING EPISODIC SULPHATE REPLENISHMENT RELATED TO NATURAL ATTENUATION

4.1 Background

Natural attenuation (NA) of petroleum hydrocarbons (PHCs) has gained rapid support by site owners and managers since awareness first developed in the 1990’s. Natural attenuation is now well accepted as a cost-effective method for managing PHC contaminant situations. This approach relies on showing contaminant mass and/or concentrations are decreasing over time and space due to naturally occurring processes. For hydrocarbons, biodegradation is a key process because contaminant mass is destroyed. Empirical evidence of plume attenuation has supported process-based research showing that NA processes could limit dissolved contaminant migration. Accordingly, protocols were developed for NA implementation (ASTM, 1998; USEPA, 1999; Wiedemeier et al., 1995) with special focus on collecting good quality monitoring data to confirm plume attenuation.

Typically NA protocols use the multiple ‘line-of-evidence’ approach, based on site characterization and groundwater monitoring data. These data are used to demonstrate a reduction in contaminant concentrations over space and time, and characteristic patterns of biodegradation ‘indicators’ associated with electron-accepting processes. The patterns of indicators include depleted dissolved oxygen, nitrate and sulphate, and enriched dissolved iron, manganese and methane in plume wells compared to background wells. It is generally accepted that PHC-degrading bacteria are likely to be present (Chapelle, 1993), unless otherwise specifically proven. For a generic PHC-contaminated site, the questions must most likely addressed when considering if NA is appropriate are usually related to how big will the plume grow, how long will it take to remediate, and what is the chance/risk that the current view of NA might change.

Complex interactions between multiple processes underlying NA may complicate assessment of NA potential. In particular, it is important to relate interpretation of contaminant plume macro-behaviour (attenuation at the plume scale) with characteristic responses identified at the individual well scale (flow, transport and biogeochemical reactions). As an example, rates of attenuation based on temporal contaminant concentration changes at individual wells need to be related to the average contaminant plume attenuation rate (incorporating source dissolution, plume retardation, attenuation and groundwater flow velocity). If the attenuation rates estimated at individual wells decrease over time (e.g., see Chapter 5), then projected plume attenuation may be overestimated. Such effects may not be evident over months to years, but could become dominant over the plume lifetime (order of decades).

Process-specific research has investigated a number of complexities inherent within data sets comprising the conventional 'line of evidence' approach (Haack and Bekins, 2000; Lee et al., 2001b; Salanitro, 1993; Smets and Pritchardy, 2003). Microcosm studies have helped elucidate contaminant biodegradation pathways (Kropp et al., 2000; Lovley, 1991; Weiner and Lovley, 1998) or limiting/enhancing conditions (Allen-King et al., 1994; Beller et al., 1992; Weiner et al., 1998) but strictly apply only to the specific soil, water and environmental conditions tested (Davis et al., 2003). In situ microcosms have attempted to overcome this shortcoming (Baedecker et al., 1993; Mandelbaum et al., 1997), but again, really only apply at the given site. Soil sample analyses have been recommended to assess attenuation mechanisms based on mineralogy and/or bioavailability of electron acceptors (Kennedy et al., 2004; Schulmeister et al., 2004). However, as the sampling scale becomes finer, so do variations in influential parameters that form the basis of process-based descriptions of natural attenuation (Cozzarelli et al., 1999; Hurt et al., 2001; Roling et al., 2001; Smith et al., 1991).

Concentrations of dissolved contaminants and other chemical species have been shown to vary on very local scales (cm's) (Delin and Landon, 1996; Gibs et al., 1993; Ronen et al., 1987). Field sampling and/or modelling studies have also investigated the effects of additional complexity added by heterogeneous and/or nonlinear interactions between bacterial activity (Brockman and Murray, 1997; Li et al., 2001; Sandrin et al., 2004; Sandrin et al., 2001; Scholl, 2000), degradation rates (Bauer et al., 2006; Beyer et al., 2006; Davis et al., 2003), degradation processes (Wilson et al., 2004), mineralogy (Ulrich et al., 2003), geochemistry and hydrogeology (Julian et al., 2001; Lu et al., 1999; Maier and Grathwohl, 2006; Prommer et al., 1999; Schaefer, 2001; Zheng et al., 2002), and climate (precipitation, evapotranspiration and temperature) (Benner et al., 2002; Kaplan et al., 1991; Lee et al., 2001a; Scholl et al., 2006). Recognition of varying responses between multi-species contaminants and multiple biodegradation pathways adds yet more complexity through potential inhibition (Alvarez et al., 1991; van Bodegom et al., 2004; Wong et al., 2004) and/or enhancement (Alvarez and Vogel, 1991; Deeb and Alvarez-Cohen, 2000) and variable responses to individual terminal electron accepting processes (TEAPs) (Edwards et al., 1992). One proposed method for incorporating so much complexity is to estimate plume extents and/or lifetimes based on effective kinetic rates (LaViolette et al., 1999; Odermatt, 1997; Stenback et al., 2004; Suarez and Rifai, 2004).

In this study, detailed groundwater monitoring was conducted at research well clusters at two sites under CORONA (Consortium for Research on Natural Attenuation - University of Alberta) to examine how a variety of common monitoring well completions and sampling methods might influence data complexity (Chapter 3). The results showed that underlying complexities affecting hydrochemical data could be neglected at order-of-magnitude scale interpretations for PHCs, but not necessarily for TEAs, even when the monitoring data were collected over the same vertical interval. Data from multiple monitoring wells installed at the P34 research well cluster at Site A indicated that sulphate reduction was the key TEAP responsible for PHC plume attenuation; however, sequential sampling showed inconsistent sulphate variations both within and between sampling events. Such unexplained variations in the dominant TEAP could cast doubt on the NA conceptual model, especially regarding long-term projection of expected plume behaviour. This curious behaviour thus warranted closer examination.

The importance of sulphate reduction as a TEAP for PHC biodegradation has been reported by several researchers (Chapelle et al., 1996; Davis et al., 1999; Gieg et al., 1999). Sulphate was also identified as often being the most important TEAP associated with NA in a review of dissolved PHC plumes associated with oil and gas facilities in Alberta (Armstrong et al., 2001). Furthermore, injection of dissolved water enriched in sulphate has been evaluated as a way to enhance PHC biodegradation (Ulrich and Suflita, 2002; Van Stempvoort et al., 2007a; Weiner et al., 1998). Lastly, shallow groundwater in Alberta may be rich in sulphate due to weathering of sulphate and sulphide-rich sediments (Fennell and Bentley, 1998; Van Stempvoort et al., 2007b)

4.2 Purpose

Groundwater monitoring data collected for the CORONA program identified sulphate reduction as a main process responsible for natural attenuation of PHC contamination at a natural gas processing facility. Sequential sampling using no-purge and low-flow protocols identified notable and inconsistent variations in sulphate concentrations over very short time intervals in some wells, but not others. These data were examined to evaluate the role of sulphate reduction as an attenuation process at the site. Possible influences related to well construction and sampling protocols (method and purge amount) were considered, and the temporal changes examined to see if the data could be used to derive an estimate of the ‘effective’ attenuation rate, based on sulphate depletion. Recognition of characteristic patterns of sulphate replenishment could help design and implement better monitoring strategies to capture ‘average’ conditions. These conditions influence the conceptual model of NA, and its ability to predict future plume response.

4.3 Field Methods

4.3.1 Site Description

The site is adjacent to an active sweet gas (no hydrogen sulphide) processing facility located in southeast Alberta (Figure 4-1). Dissolved PHC contamination is interpreted to have resulted from accidental natural gas condensate releases from a nearby fire-fighting training facility. The training involves setting and extinguishing practice fires as part of the facility’s safety program. The facility was originally unlined, but has since been modified with installation of a subsurface liner. Site safety personnel identified ongoing potential for minor hydrocarbon releases as a result of runoff water during fire practice.

Three monitoring wells had been installed in the early 1990s to characterize groundwater and subsurface contamination conditions in this area. The groundwater flow velocity is estimated to be approximately 5 m /year. The soil in this area consists of fine silty sand to sandy silt, with the water table located approximately 1.5 to 2.5 m below ground surface (mbgs). Black-stained soil with a hydrocarbon odour was identified in two boreholes at the time (P34:1.5-3 mbgs and P35: 2.3-3.8 mbgs), but the plume’s approximate lateral extent was only coarsely delineated. Monitoring data identified the presence of elevated dissolved iron and depleted sulphate in the hydrocarbon-contaminated wells compared to wells with no hydrocarbon or staining. There are no nearby groundwater users or surface water bodies in the area. On this basis, the site was selected as part of the field program conducted under CORONA to study whether NA is a viable remediation strategy for the upstream oil and gas industry, and to help develop guidelines for the province and the industry.

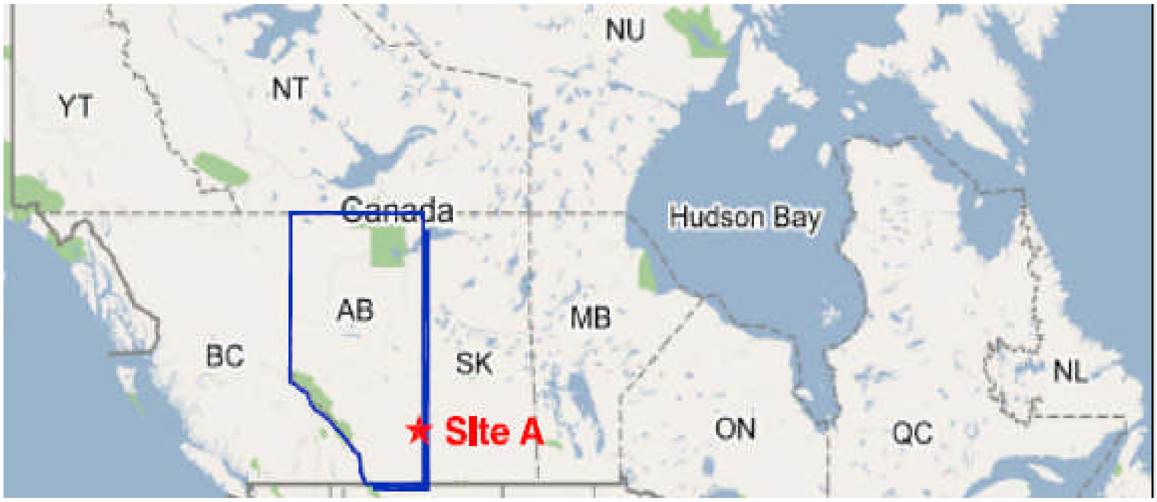


Figure 4-1 Site location

Two research well clusters were constructed adjacent to the two existing monitoring wells with detectable dissolved PHC: P34 (~40 m downgradient from source) and P35 (60 m further downgradient) (Figure 4-2). Other than sheen in P34, free phase PHC has never been detected in either well. The two clusters are shown in Figure 4-3 (Detail A for P35) and Figure 4-4 (Detail B for P34), where each cluster comprised (Figure 4-5):

- The original 1.5 m long screen, 0.05 m diameter PVC monitoring well;
- Two "conventional" wells (MW), each with a 3 m long screened section of 0.05 m diameter PVC pipe;
- Three direct push (DP) PVC wells (0.7 m long screen, 0.02 m diameter) completed at 1 m depth intervals near the top, middle and bottom of the adjacent 3 m long screen wells; and,
- Three multilevel sampling points (ML) using the Solinst model 403 CMT (continuous, 7 multichannel tubing, 0.04 m total diameter, 0.01 m per channel; 0.6 m sand-backfilled intervals) completed in a single borehole at similar levels as the direct push wells.

A series of six more "conventional" (3 m long screen wells: P5-P10, Figure 4-2) were also installed in July 2003 to refine hydrocarbon plume delineation downgradient of P35. A plan view and illustrative cross-section of the P34 research well cluster are shown in Figures 4-4 and 4-5, respectively. Data since 1996 show the historical groundwater surface ranged from 1.4 to 2.5 mbgs, but typically remained within the screened interval of the MW and P34 wells (>1.5 mbgs).

The new MW-series wells were installed using the solid stem auger method. Well installation details are summarized here. Clean quartz sand was placed around the 3 m long screened interval. The sand was overlain by an annular seal comprising approximately 0.3 to 0.5 m of bentonite pellets. The remainder of the annulus was filled to ground surface with bentonite chips that were hydrated with clean water.

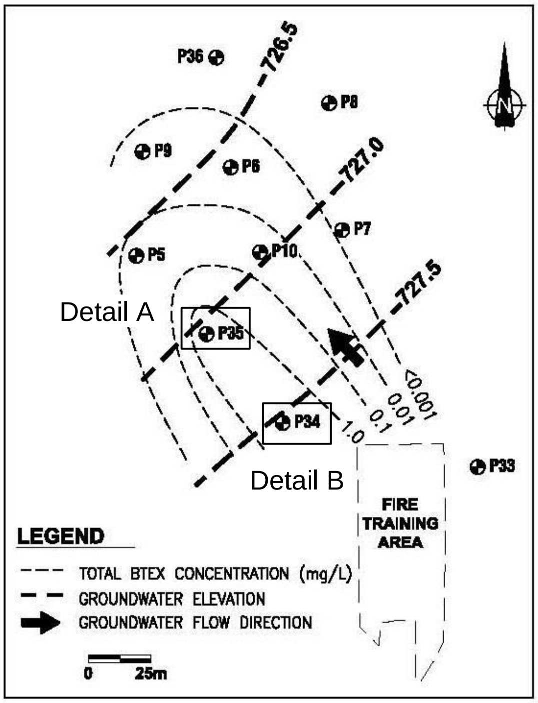


Figure 4-2 Research area site plan, including groundwater elevation and BTEX concentration contours

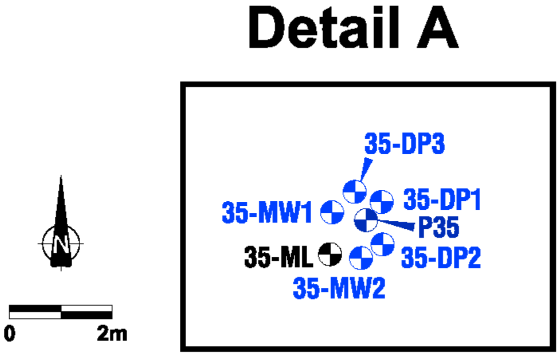


Figure 4-3 P35 research well cluster detail

The DP wells were installed using a direct push method. Steel drill rods (0.05 m diameter) equipped with a disposable steel tip were pushed to the desired depth. The well screen and riser were then lowered inside the drill rod, and the rods were withdrawn. Each well assembly comprised a well screen (PVC screen inside a 0.035 m O.D. stainless steel screen with pre-packed silica-sand filter, PrePak, GeoInsight) beneath a 0.1 m long expandable foam barrier and a 0.7 m long pre-packed bentonite powder seal (foam bridge and QuickSeal Sleeve, GeoInsight). After allowing time for the bentonite powder to expand, bentonite grout was mixed and poured down to fill the remaining annular space up to ground surface.

The multi-level well (ML-series: 0.01 m diameter, 7 channel MLS, Solinst, Waterloo, ON) was found to experience well trauma following installation, based on anomalously high sulphate and sodium concentrations. Data from these wells were therefore excluded from the study.

Monitoring data supporting interpretation of NA processes had been conducted for the site owner by consultants using conventional sampling methods and monitoring wells. Historical sampling typically used dedicated bailers to extract groundwater after purging up to three well casing volumes of standing groundwater.

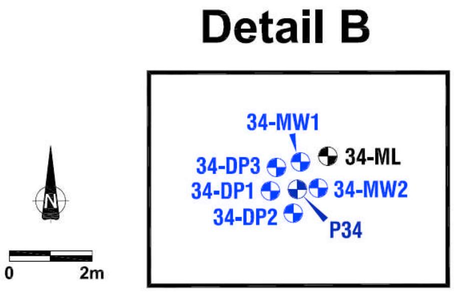


Figure 4-4 P34 research well cluster

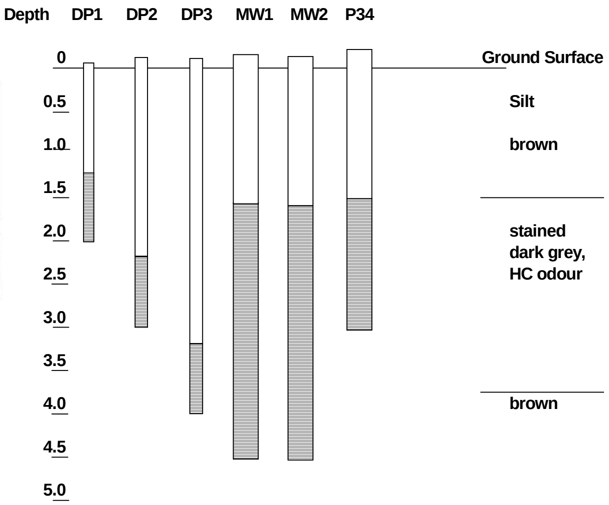


Figure 4-5 Schematic cross-section with well completion details; 34-ML left off due to 'well trauma' problems

Sampling Methodology

During the CORONA sampling program, a variety of sampling technologies were used to assess both their ease of use under typical field conditions, and data variability (seasonal, inter-well, and intra-well). Well names and completion depths/intervals are summarized along with the various methodologies used to collect groundwater samples in Table 4-1.

Depth to groundwater surface was measured in each well prior to sampling. A more detailed record of water table elevation and temperature was collected every two hours from October 2004 to August 2005 using a data logger installed in 34MW1, with barometric pressure compensation. Field measurements included pH and temperature (HI9024), electrical conductivity (HI9033), dissolved oxygen (OxyGuard Handy), oxidation-reduction potential (OxyGuard Handy pH) and dissolved sulphide (Hach). Downhole measurements were limited due to occasional hydrocarbon sheen presence.

Sampling protocols are discussed in more detail in Chapter 3, but involved collecting sequential samples from multiple wells using dedicated sampling equipment for each well. The groundwater surface was typically within the screened interval of the original P34 and 35 wells, the MW series of wells and the shallowest DP well. During sampling of the deeper DP-2 and DP-3 wells, care was taken to prevent drawing the water surface down to within the screened interval. Samples were identified according to the purging and sampling methodologies summarized in Table 4-1, and as follows:

Table 4-1 Summary Of Sampled Wells And Methods

Well Code	Sampling Method	Well Screen Type (depth mbgs)
P34[a] (original well)	Bailer, Waterra®, Low-flow purge	1.5 m screen (1.5-3.0)
34MW1[a]	Waterra®, Dialysis	3 m screen (1.5-4.6)
34MW2[a]	Waterra®, Dialysis, Low-flow purge	3 m screen (1.5-4.6)
34DP2[b] and 34DP3[b]	Low-flow purge	0.7 m screen intervals at various depths (2.3-3.0 and 3.3-4.0)
P35[a] (original well)	Bailer, Waterra®, Low-flow purge	1.5 m screen (1.5-3.0)
35MW1[a]	Waterra®, Dialysis	3 m screen (2.3-5.3)
35MW2[a]	Waterra®, Dialysis, Low-flow purge	3 m screen (2.4-5.4)
35DP1[b], 35DP2[b], 35DP3[b]	Low-flow purge	0.7 m screen intervals at various depths (2.2-2.9, 3.3-4.0 and 4.3-5.0)

Notes: a: 50 mm diameter PVC pipe with 0.25 mm slotted screen.
b: 20 mm diameter PVC pipe with 0.25 mm slotted screen inside 35 mm diameter stainless steel mesh pre-packed with silica sand.

Purging Protocols (P34, P35, MW-series):

- No-purge: rinse the sampling equipment with one volume (bailer or Waterra® tubing), then collect a sample from midpoint of the saturated interval of the well screen;
- Purge: remove 3 borehole volumes (or until well went dry), then sample recovering water;
- Post-purge: allow well to recover to static level after purging, and then sample (not DP wells).
- Low flow purge: use a peristaltic pump with dedicated tubing for each well to recover groundwater at a low flow rate (≤100 mL/min), ensuring minimal drawdown (0.1 to 0.3

m). Pumping was halted if drawdown approached 0.3 m (only happened at P35). Samples were collected either after pH, temperature and EC stabilized, or after each initial borehole volume was removed.

Purging protocol (DP-series)

A modified low flow purging method was required due to the small volume of these wells. A peristaltic pump with dedicated sampling tube for each well was used to remove standing water by slowly pumping from at least 0.3 m above the well screen. If drawdown occurred, pumping stopped to allow recovery in the well. A sample was then collected from the midpoint of the screened interval, while water level measurements ensured that the water level remained at least 0.3 m above the screen top.

Two tests were conducted at P34 to examine changes in measured concentrations by collecting low-flow samples hourly for four to six hours. Pump discharge was passed through a flow-through cell to monitor electrical conductivity, pH, temperature, dissolved oxygen and oxidation-reduction potential. The pumping rate corresponded to removing one pore volume of the well and saturated sand pack each hour.

Sampling visits were conducted approximately quarterly, although all methods could not be evaluated during each site visit. In particular, freezing conditions during winter and some fall visits hindered or prevented use of some technologies (e.g. rapid freezing during low-flow sampling in some wells), and/or field measurement equipment. Except as noted above, climatic effects were considered a random effect, because sampling plans did not change according to the weather. Additional information regarding the various sampling devices and protocols is provided in Chapter 3.

Data regarding local weather conditions (temperature and precipitation records) were obtained from the nearest Environment Canada weather station located approximately 27 km north of the site.

Analytical results for groundwater samples generally comprised:

- hydrocarbon contaminants (including target PHCs benzene, toluene, ethylbenzene and xylenes, BTEX and purgeable hydrocarbons: C_6-C_{10});

- geochemical indicators of NA (nitrate, dissolved iron and manganese and sulphate), and other major ions (calcium, magnesium, sodium, potassium, chloride and bicarbonate); and,
- general water quality indicators (hardness, alkalinity and mineralization expressed as total dissolved solids).

Site soil was used by several CORONA participants, including:

- in mesocosm experiments to examine enhanced hydrocarbon biodegradation through amendment with nutrients and/or electron acceptors (Fan et al., 2007);

- samples were analyzed for iron and sulphur-containing species to support geochemical modelling of plume behaviour (Petersmeyer, 2006); and,

- to help assess whether injection of sulphate-amended groundwater could enhance the rate and/or extent of hydrocarbon attenuation (Van Stempvoort et al., 2007a). The test involved injecting a 200 L slug of anoxic de-ionized water amended with 2000 mg/L sulphate and a bromide tracer followed by periodic sampling of the injection well and adjacent monitoring wells (within m's) for major ions and BTEX.

4.4 Results

There are several lines of evidence available that provide support for natural attenuation of the dissolved hydrocarbon plume at this site. Spatial data provide a clear indication that the average hydrocarbon concentrations decrease with distance from the source area, as shown in Figure 4-6. The figure also shows how the decrease in hydrocarbon concentrations is associated with a decrease in dissolved iron and an increase in dissolved sulphate. Near the source, the sulphate data show additional complexity, where the 3 m screen wells (MW-series) have one to two order of magnitude higher concentrations than the 1.5 m screened well (P34). This pattern was not noted further downgradient in the P35 cluster. In contrast, dissolved chloride concentrations are approximately constant along the plume, with no obvious trend.

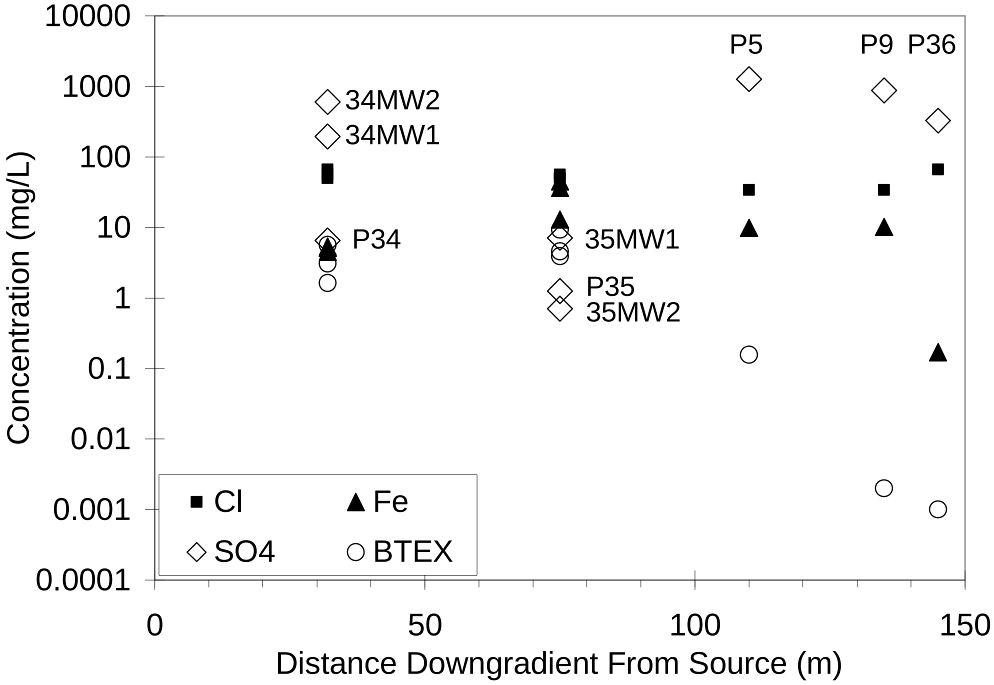


Figure 4-6 Spatial trends in NA indicators (autumn 2005); symbol sizes include error bars (Cl=10%, Fe, BTEX = 20%, SO_4=30%)

Dissolved PHC concentrations measured over time at P34 near the source (Figure 4-7; error bar = 20%) show a general decreasing trend in BTX compounds but increasing ethylbenzene over the twelve-year monitoring period (CORONA sampling from August 2002 to May 2005). Closer review suggests the appearance of possible spikes in 1999 and 2003 that may reflect the intermittent nature of the hydrocarbon source. However, confidence in these trends is reduced, based on the variability evident during the increased sampling density of the CORONA program. Scrutiny of the P34 data suggests that toluene and benzene concentrations decreased over time. The apparent decreases noted for ethylbenzene and total xylenes are considered suspect due to the low coefficients of correlation ($r^2 < 0.5$).

In contrast, data from well P35 show recent decreases only in toluene (Figure 4-8). However, direct comparisons between concentrations in the two wells must account for the travel time over the 40 m distance between locations (estimated at 8 years, based on an average unretarded groundwater flow velocity of 5 m/yr).

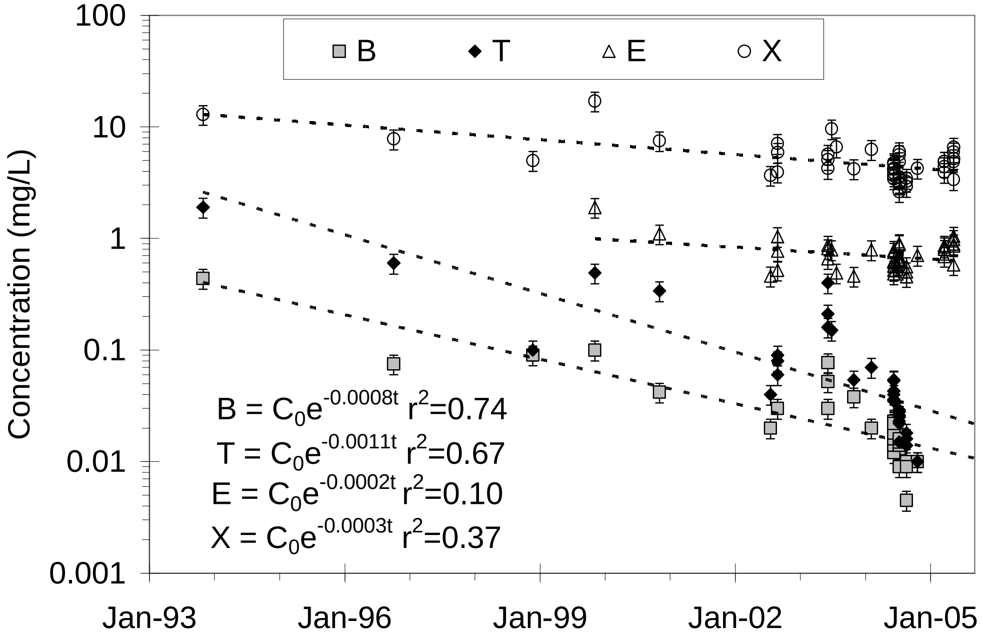


Figure 4-7 Temporal trends for BTEX at P34 (B, T in 2005 <0.04 mg/L)

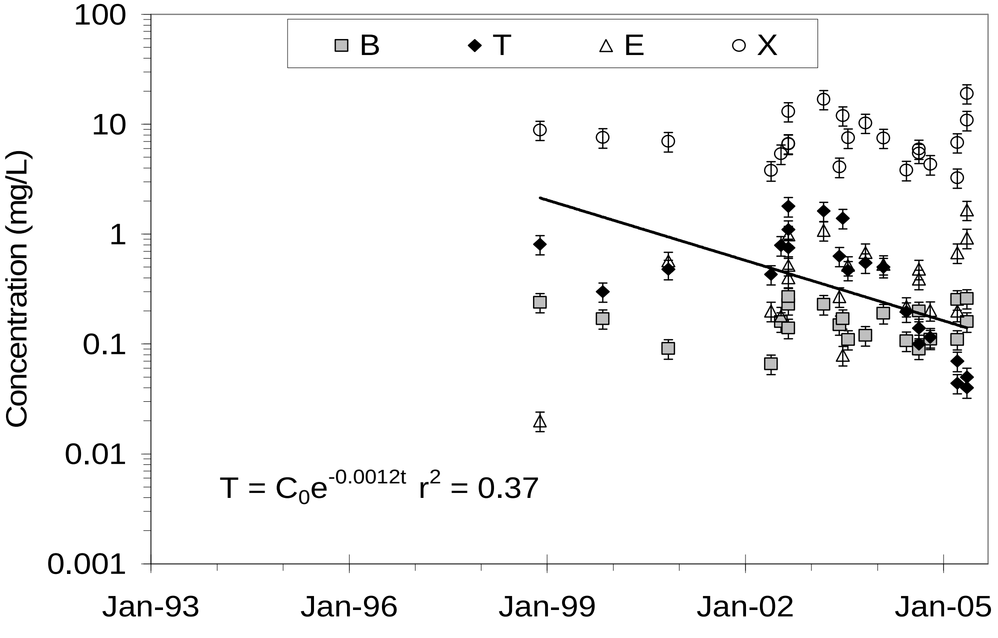


Figure 4-8 Dissolved hydrocarbon concentrations over time at P35 (40 m downgradient from P34); no trends noted for BEX.

Additional evidence of hydrocarbon biodegradation obtained for this site includes:

- detection of hydrocarbon biodegradation metabolites in selected water samples (Semple et al., 2007);
- enhanced hydrocarbon biodegradation in mesocosms amended with sulphate (Fan et al., 2007);
- soil sampling and reactive transport modelling to examine biodegradation processes (Petersmeyer, 2006); and,
- isotopic evidence collected during a nearby field demonstration of sulphate injection to enhance biodegradation supports hydrocarbon biodegradation (Van Stempvoort et al., 2007a)

The denser data sets collected at both P34 and P35 sites during the CORONA program were intended to examine issues related to variability associated with sampling methodologies and well installations, with overall results summarized in Chapter 3. During this program, intermittent variations were seen in some of the geochemical data used to assess NA processes, most notably in dissolved sulphate concentrations from summer 2004 to spring 2005. Multiple replicate samples had been collected to assess repeatability while assessing possible effects of no-purge sampling compared to using a low-flow purging protocol. Given that sulphate reduction was identified as a main attenuation process, these data are examined here in greater detail.

Main ion concentrations (mmol/L) and target dissolved hydrocarbons (μmol/L) measured at well P34 during the CORONA program are summarized in Figures 4-9a, b and c, respectively. Means, standard deviations (sd) and coefficients of variation (Cv = sd/mean) for the data are given in Table 4-2.

Table 4-2 Basic Statistics for Selected Analytes: Mean and Standard Deviation (mmol/L for ions; μmol/L for BTEX); Coefficient of Variation (C_v=mean/sd)

Analyte	**Na**	**Mg**	**Ca**	**HCO_3**	**Cl**	**SO_4**	**B**	**T**	**E**	**X**
mean	10.0	6.2	1.0	22.9	1.3	0.5	0.19	0.16	0.29	0.30
sd	0.54	0.40	0.20	1.00	0.19	0.42	0.059	0.044	0.138	0.139
C_v	0.054	0.065	0.020	0.044	0.146	0.84	0.311	0.275	0.476	0.463

These data suggest generally stable results for most of the major ions independent of the purging protocol or sampling method (bailer or peristaltic pump). In contrast, the sulphate data showed up to order of magnitude changes (both increases and decreases) both within single sampling sets (e.g., July 2004) and between sampling visits (e.g., June, July and August 2004). The Cv results show that sulphate had the greatest variability, followed by BTEX then the other main ions. Benzene and toluene results in 2005 were unavailable for plotting due to high detection limits (~0.5 μmol/L).

Closer inspection of the July 2004 data showed sulphate concentrations increased an order of magnitude from the no-purge (0.1 mmol/L) to subsequent post-purge samples (~1 mmol/L), while the May 2005 data showed the reverse pattern between the no-purge (0.3 mmol/L) and post-purge samples (0.003 mmol/L). Plots of sulphate concentrations against purge volumes removed (low flow purging; 1 borehole volume ~ 6 L) are shown in Figure 4-10 for three sampling dates. All pre-purge samples were collected using a dedicated bailer, as were the last two samples during the July 2004 program.

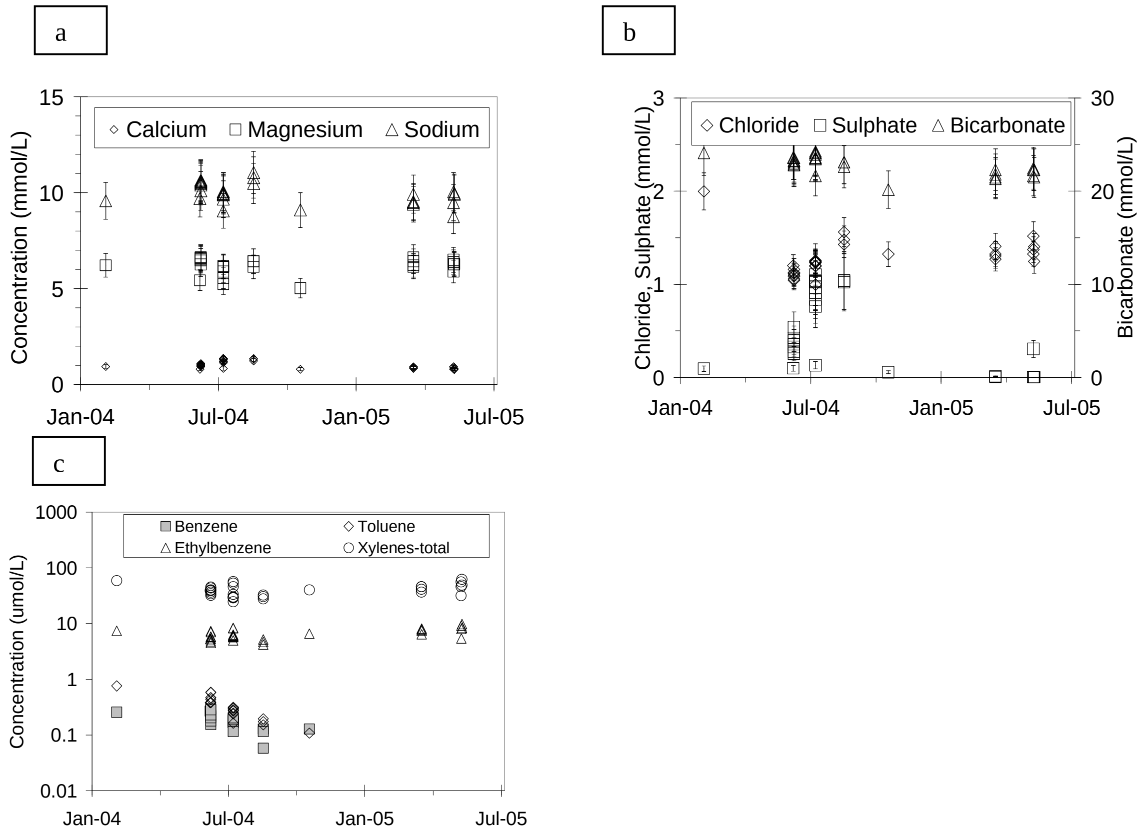


Figure 4-9 a) Major cations measured at P34 (10% error bar); b) Major anions measured at P34 (10% error bar, except sulphate (30%); and c) Individual BTEX compounds measured at P34 (20% error bar)

Possible seasonal influences due to water level fluctuations were also examined. Historical data measured at the site since 1996 showed a typical seasonal fluctuation on the order of 1 m, with a maximum historical variation of 2 m (Figure 4-11). Except for one data point in 2003, water levels remained within the black-stained soil interval noted during drilling. Soil extractions from near P34 (Petersmeyer, 2006) showed that the black-stained interval was notably enriched in sulphide and Fe(II) and depleted in Fe(III) compared to unstained soil above and below. The combination of results is used to infer that the plume has been anoxic for more than a decade.

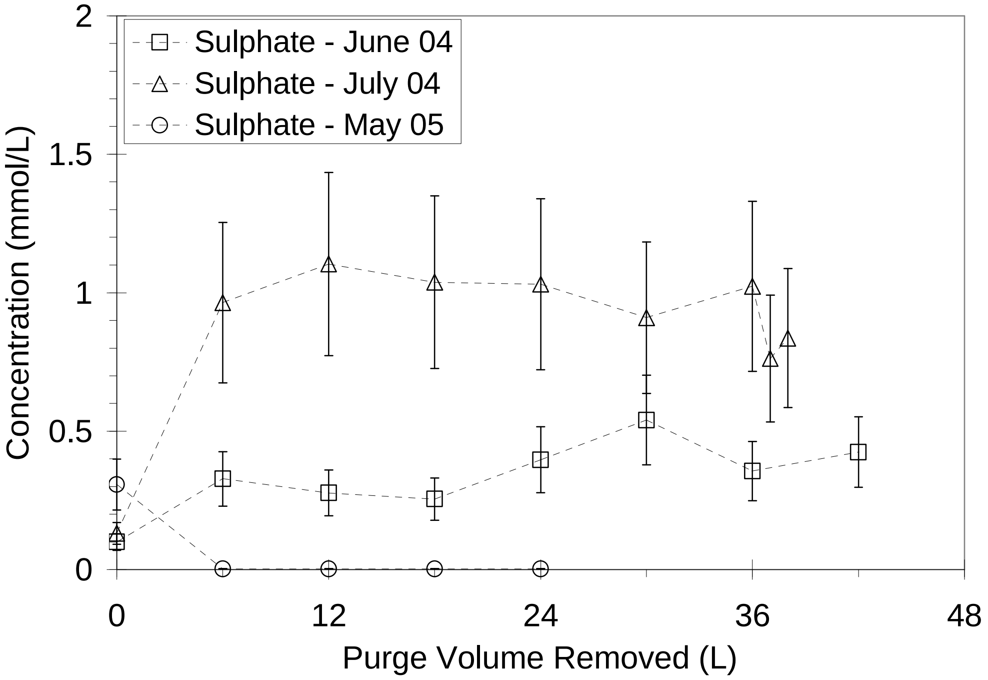


Figure 4-10 Sulphate concentrations for consecutive low-flow purge samples from P34 (1 borehole volume = 6 L)

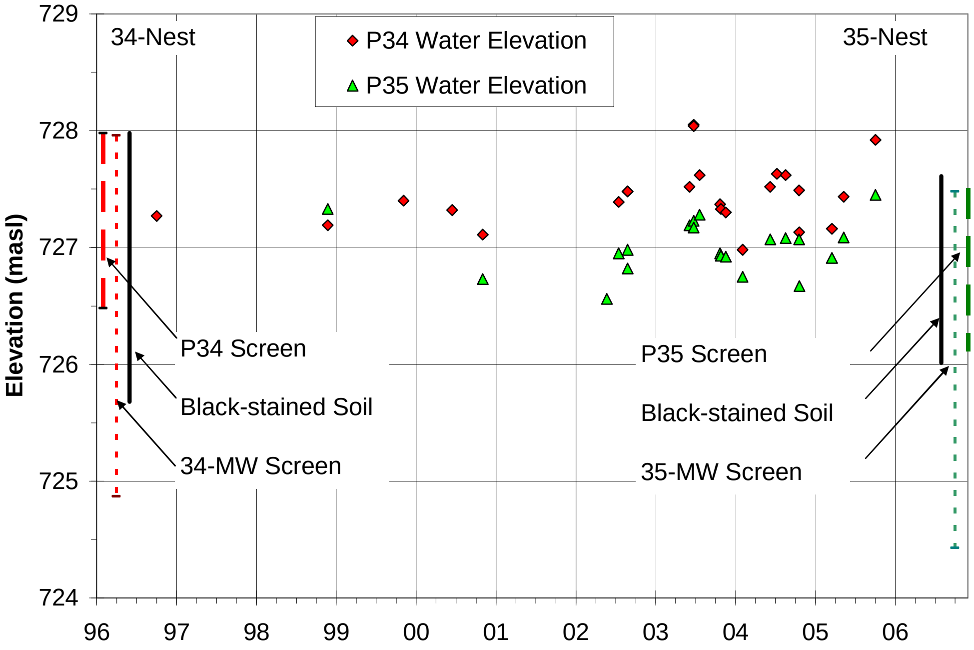


Figure 4-11 Historical groundwater elevations relative to soil staining and well screen intervals

Detailed water level data were obtained from August 2004 to October 2005 using a data logger installed in one well at the P34 cluster. These data are plotted along with manually-measured water levels for three other monitoring wells (varying completion intervals in the same cluster) in Figure 4-12, and the agreement is good. The apparent link between water level and precipitation data can be clearly seen from the greater detail available using the logger in 2005. These data show more frequent and larger amplitude oscillations in water table elevation than might be interpreted from the manual data (Figure 4-13). As an example, short-term increases of 0.5 to 1 m are evident over a few days, followed by similar order decreases over periods of weeks without rain (e.g., early September 2005).

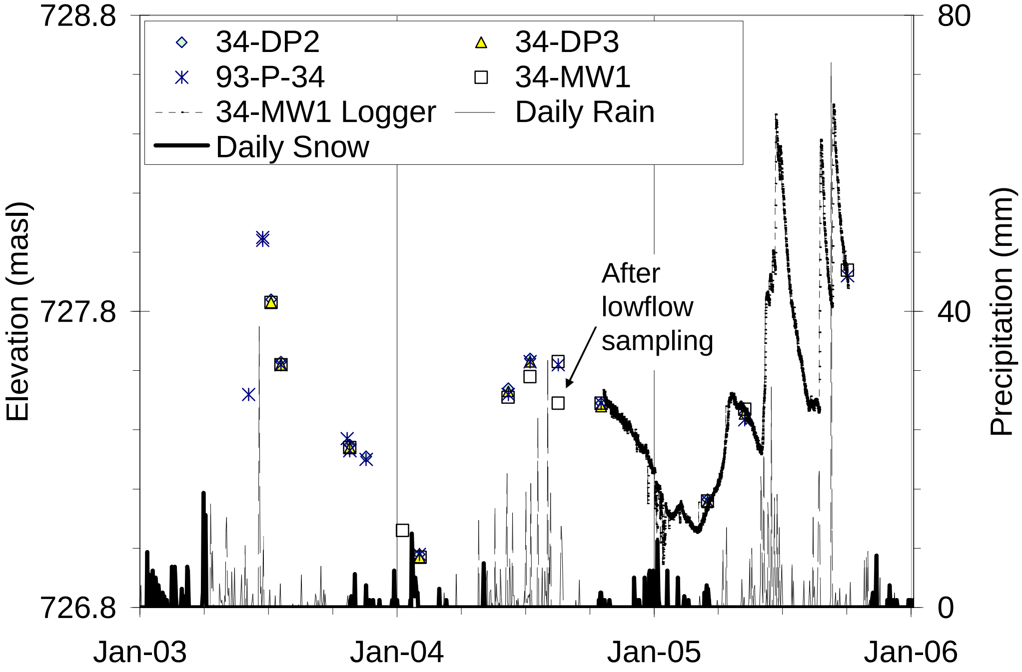


Figure 4-12 Groundwater level and precipitation record Site A, P34 Cluster

Water level changes have been shown to influence hydrochemistry (Lee et al., 2001b), thus, the geochemical data from summer 2004 were plotted together with precipitation and manual water elevation measurements in Figure 4-14. All of the analyses were obtained from the same monitoring well (P34), either as no-purge and post purge samples collected by bailer, or as low-flow samples collected by peristaltic pump. There was minimal water table change (< 0.15 m) during sampling, but a clear jump in dissolved sulphate concentrations was observed from no-purge (~10 mg/L) to low-flow sampling (30 to 100 mg/L) in June and July. In contrast, the August sulphate concentrations using both approaches were uniformly high (~ 100 mg/L) and the March 2005 data were all low (~1 mg/L). Data collected in May 2005 had a higher sulphate concentration in the no-purge sample (~30 mg/L), compared to subsequent low-flow purge samples (<1 mg/L).

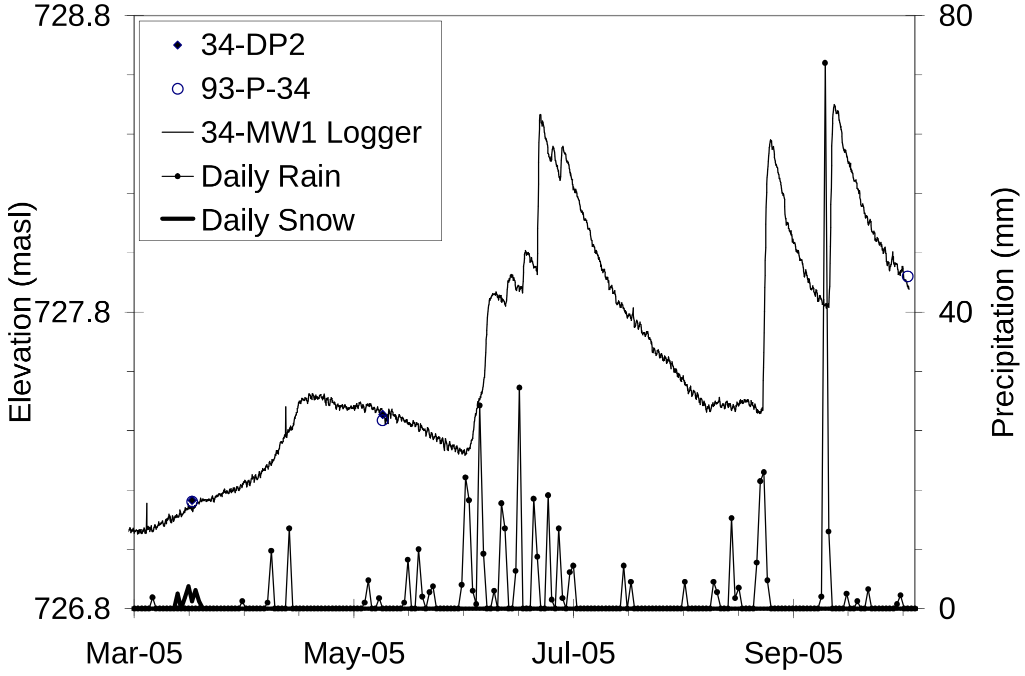


Figure 4-13 Groundwater level and precipitation record, 2005 detail, Site A, P34 Cluster

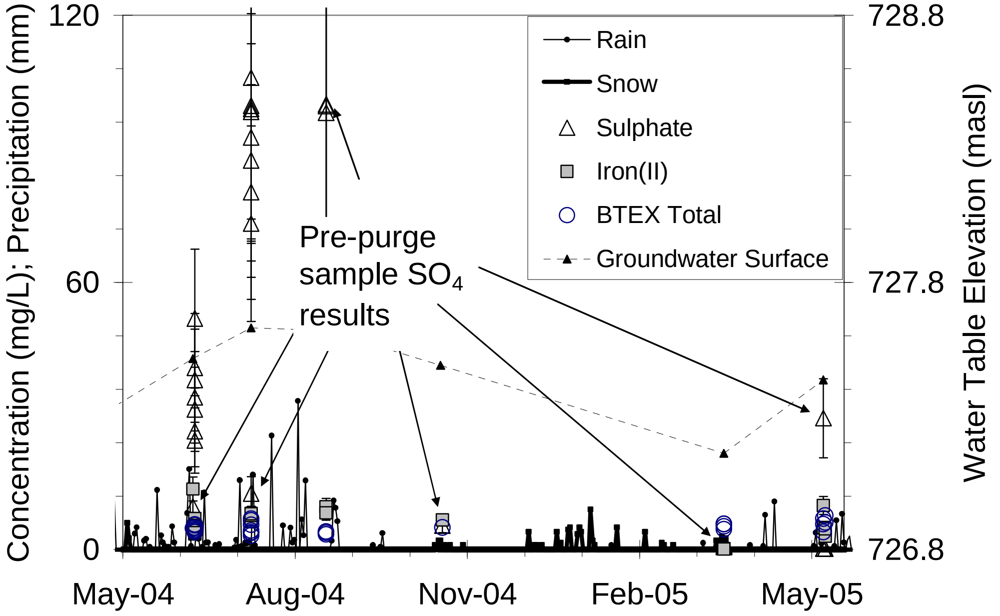


Figure 4-14 Dissolved sulphate, iron (II) and total BTEX concentrations and water table elevation during sequential sampling of well P34

In contrast to the order of magnitude variations noted in sulphate concentrations in P34, the other major ions, dissolved iron and BTEX concentrations showed only minor fluctuations.

Data at well P35 were also reviewed (Figure 4-15), and showed that in contrast to P34 results, dissolved iron concentrations were more sensitive than sulphate to the purging protocol. No-purge samples were approximately twice as high in two of three sampling events (no large difference in the other test). Based solely on manual measurements, the water table elevation showed the same general trend of being higher in summer.

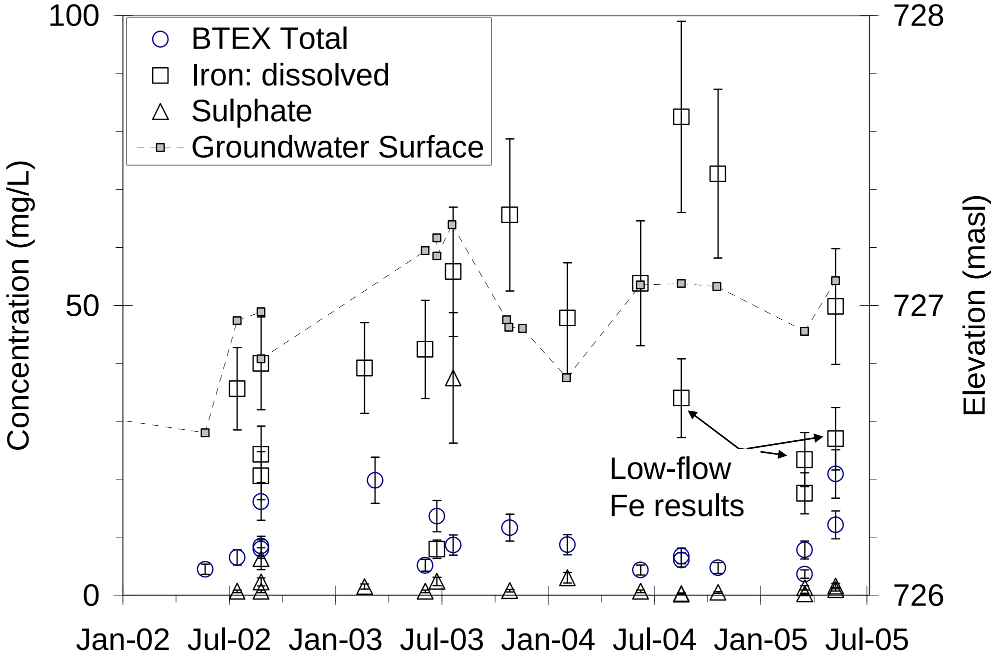


Figure 4-15 Seasonal variation of sulphate, iron(II) and BTEX concentrations relative to purging protocol in well P35

Over the longer term, most of the major ion and hydrocarbon analytical data were not notably influenced by the purging protocol. Other processes causing the irregular, short-term fluctuations in sulphate and iron noted at P34 and P35, respectively, were considered.

4.5 Discussion

4.5.1 Geochemical Complexity

The potential complexity associated with understanding how multiple possible interactions between contaminant(s) and environmental conditions might affect geochemical data has been previously reported (Davis et al., 2003; King and Barker, 1999; Lee et al., 2001b; Zheng et al., 2001). It seems logical, therefore, that interpretation of NA processes would vary according to how well the influential factors were recognized and assessed.

Controllable factors include how monitoring wells are constructed and groundwater samples are collected. Results presented in Chapter 3 showed that well screens up to 3 m long can adequately identify the order of magnitude of contamination, but that detailed understanding of geochemical conditions will require shorter screen wells. A similar interpretation was concluded from comparing monitoring data collected using a variety of sampling methods and purging protocols. The most important result was to avoid misinterpreting variability related to data collection with that due to environmental factors, especially given recent current interest in using no-purge sampling and/or diffusion-based sampling methods. A useful strategy would involve site-specific testing of no-purge samples against conventional sampling strategies (either three borehole volume purging or low-flow purging). Without such data, it may not be possible to understand and interpret a confusing dataset.

A comparison of groundwater analyses sampled using no-purge, low-flow purge and conventional purging at this site identified that only dissolved sulphate and, to a lesser extent, iron, gave significantly different results, and then only during some sampling events. Five possible causes were considered:

1. preferential chemical oxidation of reduced compounds within the well by atmospheric contact;
2. preferential chemical reduction of oxidized compounds within the well resulting from biofilm formation on the borehole sand pack material due to its greater porosity compared to the surrounding silty soil;
3. geochemical effects related to sampling;
4. geochemical effects related to seasonal influences; and,

5. in-well mixing of sampled groundwater compared to groundwater in the surrounding formation.

The first two causes were discarded because the impact on water chemistry was inconsistent between sampling visits. Either cause would be expected to result in a more consistent effect (e.g., for sulphate, in-well oxidation would lead to higher sulphate concentrations in no-purge vs. low-flow purge samples, while preferential reduction would lead to a lower sulphate concentration. Additionally, the field monitoring data (dissolved oxygen and iron) showed that conditions remained consistently anoxic over low-flow sampling periods of up to seven hours.

The third possible cause was based on an observed 0.5 pH unit increase (from 7.3 to 7.8, data not shown) noted between field data and laboratory analyses. Statistical testing showed a small but significant increase in field-measured pH values for the two largest sets of low-flow versus no-purge samples (0.1 to 0.2 units). Both sample sets showed notable sulphate concentration increases. Vacuum-induced de-gassing of volatile compounds by peristaltic pumps has been demonstrated to change their measured concentrations (Barker and Dickhout, 1988), and to affect redox-sensitive species (Parker, 1994). De-gassing of CO_2 formed as an end product of PHC biodegradation would increase the pH, possibly resulting in dissolution of sulphate-containing solid particles (e.g., increased pH decreases alkalinity, causing calcite to precipitate and gypsum to dissolve). However, these actions would have to occur rapidly within the peristaltic pump sampling tube, so are considered unlikely.

The fourth and fifth causes have been reported at other contaminated sites. Large variations in dissolved sulphate levels in groundwater near a municipal landfill were attributed to water table fluctuations causing oxidation of iron sulphides originally formed by anaerobic metabolism (Ulrich et al., 2003). Mixing attributed to precipitation infiltration has also been reported for a variety of species (Kaplan et al., 1991; Lee et al., 2001b). Likewise, the fifth cause, in-well mixing, has also been shown to affect a number of parameters, often in an unpredictable way (Martin-Hayden and Robbins, 1991). As shown in Chapter 3, data from the DP wells (0.7 m screens), P34 (1.5 m screen) and the two MW wells (3 m screens) showed how in-well mixing was influential. Accordingly, finer-scaled sampling (<30 cm) would be required to resolved these issues. Complex, groundwater sampling-induced changes and intermixing of water from zones dominated by different terminal electron accepting processes has been shown to occur in the field (Cozzarelli et al., 2001; Schulmeister et al., 2004) and through modelling (Schreiber et al., 2004).

Intermittent replenishment of sulphate by infiltration was interpreted to enhance hydrocarbon biodegradation at another PHC-contaminated site (Van Stempvoort et al., 2007b).

Complex links between precipitation, groundwater surface elevation, soil geochemistry and kinetic rates of biodegradation may help explain why no-purge and low flow samples sometimes differ notably. Conceptually oxygenated rainfall may dissolve soluble minerals during infiltration through the vadose zone. Once this infiltration reaches the black-stained soil (indicating a reducing environment), the small amount of oxygen is rapidly consumed. In contrast, sulphate is more slowly consumed by sulphate reducing bacteria during PHC biodegradation. At P34, the stained interval extends from approximately elevation 725.6 to 728 m above sea level (masl, Figure 4-11). As shown in Figure 4-13, the groundwater surface may temporarily rise above the stained layer following periods of high precipitation. During such periods, in-well mixing could result in enriched sulphate showing up in both no-purge and low-flow purge samples. Conversely, after long periods of no infiltration, both types of sample would likely have depleted sulphate.

The varying differences in sulphate concentrations in no-purge and low-flow purge samples likely depend on multiple processes that might occur during the intervening periods. Results might be estimated by comparing relevant reaction and transport rates, including:

- Water levels responded to precipitation events within two to three days (Figure 4-13), but not in winter (Figure 4-12);
- Water flow across the 0.15 m diameter borehole would take approximately 11 days (at a flow velocity of 5 m/year discounting borehole refraction);
- Estimated sulphate reduction rates are relatively slow; approximately 4 mg/L per day (Van Stempvoort et al., 2007a); and,
- In-well mixing unrelated to sampling is likely to occur on a similar time scale as infiltration.

Depending on the season, frequency and scale of rain events relative to monitoring visits, samples might show any combination of stable (low or high concentrations) or mixed concentration results (higher sulphate in either no-purge or post-purge samples). The concept of intermittent sulphate replenishment was used to estimate the rate of sulphate depletion, and correspondingly PHC biodegradation using concentrations from sets of consecutive samples collected in summer 2004.

The observed link between precipitation and water level data supports that sulphate increases noted in well P34 might relate to infiltration of surface water through the sulphate-rich unsaturated zone soil, as was shown elsewhere (Van Stempvoort et al., 2007b). Episodic sulphate replenishment at the site was also related to results obtained from two other research programs conducted at this site in association with CORONA:

1. A field trial of sulphate injection was conducted near well P34 to see if hydrocarbon biodegradation could be enhanced (Van Stempvoort et al., 2007a); and,
2. Reactive transport modelling of the plume based on soil and groundwater analyses to examine the rate and expected success of dissolved PHC attenuation (Petersmeyer, 2006).

Both programs analyzed sequential extractions of soil samples for iron and sulphur-containing minerals. The first study measured the absolute amounts and isotopic ratios ($\delta^{34}S$) of dissolved sulphate, total sedimentary sulphur, chromium reducible sulphur (CRS), and inorganic sulphate, while the second study used sequential extractions to characterize the iron and sulphur-containing minerals. Both studies showed that the blackened soil material was enriched in reduced inorganic sulphur and ferrous iron (1.3 and 2.95 mg/g, respectively), compared to zones above and below (reduced sulphur = 0.001 mg/g, and ferrous iron 0.01 to 0.07 mg/g). Abundant soluble sulphate was also measured in soil samples collected above and below the black-stained zone. These data show that sulphate replenishment could occur in P-34 (1.5 m screen extending to the top of the stained zone) by vertical infiltration. Also a well with a screen extending below the stained zone (e.g., MW1 or MW2) could have enough in-well mixing to give elevated sulphate concentrations. Stable isotope measurements of blackened soil showed preferential enrichment of ^{34}S in residual sulphate and ^{34}S-depleted sulphide (Van Stempvoort et al., 2007a). Similar results have been reported elsewhere as supporting evidence of sulphate-related biodegradation (Schroth et al., 2001; Spence et al., 2001).

The value of sequential extraction was underscored by the relative absence of crystalline iron and sulphur-containing minerals in three pairs of soil samples collected from within and below the black-stained interval (P34 and P35), and near the downgradient edge of the dissolved PHC plume (P8). Mineral identification by X-ray diffraction (XRD, University of Alberta Earth and Atmospheric Science) detected dominant crystalline minerals of feldspars, dolomite and clays. The only crystalline iron minerals were detected in soil samples collected from well P8, including pyrite (FeS_2) just below the groundwater surface and siderite ($FeCO_3$) in a zone of thin and disconnected layers of grey staining. Siderite precipitation has been shown in association with hydrocarbon biodegradation (Baedecker et al., 1993).

4.5.2 Sulphate Depletion Rate Assessment

Sulphate-related biodegradation of PHCs is interpreted to be a key attenuation process at this site. Groundwater monitoring showed that sulphate was depleted (as low as 1 mg/L) within the PHC plume area compared to background sulphate concentrations on the order of 1,000 to 2,000 mg/L. Mineral and isotope evidence linked sulphate reduction at the site directly to biological activity inferred to be hydrocarbon biodegradation (Van Stempvoort et al., 2007a). Sulphate reduction related to PHC biodegradation was also independently simulated using reactive transport modelling of the geochemical data for water (CORONA) and soil (Petersmeyer, 2006). Sulphate depletion rates derived from the sulphate injection test and numerical modelling effort were compared to rates identified by the no-purge and low-flow purge sampling program of the CORONA program. The purpose was to examine if these sampling methods could be combined to provide additional insight.

From June 2003 to May 2005 sulphate concentration changes at well P34 were evaluated between the last post-purge sample from one visit and the first (pre-purge) sample collected during the next sampling visit. The concentration changes between sequential visits ranged from +473 mg/L (June 5 to 25, 2003, sampled shortly after a large precipitation event) through -23 mg/L in 31 days (June 4 to July 4, 2004) to -374 mg/L in 28 days (June 25 to July 23, 2003). Apparent sulphate depletion rates (sulphate concentration decrease divided by intervening time period; NA for increases) are provided in Table 4-3. Considering only time intervals less than 100 days, rates ranged from approximately 0.7 to 13.4 mg/L/day.

Dissolved iron concentration changes over the same periods were typically less than 5 mg/L, while changes in dissolved oxygen, nitrate and manganese concentrations were minimal.

The sulphate injection test data were used to estimate sulphate depletion rates based on zero-order and first-order kinetics (Van Stempvoort et al., 2007a). The zero-order sulphate depletion rate (4 to 6 mg/L per day) assumes sulphate concentrations are not limiting, while the first-order rate constant (0.003 to 0.01 day $^{-1}$) considers a concentration limitation does exist. Upper limits of rates measured in laboratory mesocosms for individual hydrocarbons were 0.00093 day $^{-1}$ (B), 0.011 day $^{-1}$ (E) and 0.15 day $^{-1}$ (o-X) (Fan et al., 2007).

Table 4-3 Sulphate Depletion Rates from P34 Monitoring Data

Date Period	**Time (days)**	**Sulphate Concentration Change (start→end) (mg/L)**	**Effective Depletion Rate (mg/L/day)**	**Comment**
Jun 5-Jun 25/03	20	+473 (4→477)	NA	38 mm precip. 06/20
Jun 25-Jul 23/03	28	-374 (477→103)	13.4	Minimal precip.
Jul 23-Oct 28/03	97	-102 (103→1)	1.1	Minimal precip.
Jun 9-Jul 9/04	30	-23 (35→12)	0.7	16 mm precip. 07/03
Jul 9-Aug 18/04	40	+2 (97→99)	NA	26 mm precip. 07/20 33 mm precip. 08/03
Aug 18-Oct 19/04	62	-94 (99→5)	1.5	Minimal precip.
Oct 19/04-Mar 18/05	150	-4.5 (5.4→0.9)	0.03	Minimal precip.
Mar 18-May 10/05	53	+28 (0.9→29.5)	NA	Minimal precip., spring melt

The magnitude of sulphate concentration depletion over a given time period for a zero-order reaction is the rate multiplied by the time. For a first-order reaction, the corresponding decrease in sulphate is estimated by:

$$C_0 - C_t = C_0 (1-e^{-\lambda t})$$

where: C_0 is the starting concentration (M/L^3), C_t is the concentration after time interval, t (T) and λ is the first-order rate constant (T^{-1}).

The numerical simulation approach used MIN3P, a reactive transport model, (Mayer et al., 2002) to simulate geochemical changes associated with mineral and dissolved species, where PHC biodegradation was assumed to follow Monod kinetics (Petersmeyer, 2006). The model incorporated both water and soil geochemical data, using iron and sulphur mineral data obtained from sequential extractions of soil samples from wells at P34, P35, P10, P6 P8 and P36 (Figure 4-2).

Two combinations of boundary conditions were used to examine possible influences. The base case used upper and lower domain boundaries set as no-flow, with horizontal groundwater flow forced by constant head upstream and downstream boundaries set to give an average groundwater flow velocity of approximately 5 m/year. Zero-flux Neumann transport boundaries were used everywhere, except on the upstream end (Cauchy concentration-dependent flux). A second simulation was performed using a recharge flow and concentration-dependent flux along the upper boundary. The fitted sulphate depletion rate that matched field-measured sulphate data in the PHC plume was 0.99 mg/L/day ($1.2x10^{-10}$ mole/L/s).

The sulphate injection test showed that sulphate depletion occurred relatively quickly, presumably contributing to enhanced NA behaviour. Numerical modelling of the PHC plume also required that sulphate replenishment occur in order to reproduce observed plume behaviour. The amounts of sulphate depletion estimated from the sulphate amendment test and numerical simulation over the same time interval as the field-measured data are compared in Table 4-4.

Table 4-4 Comparison of Field-Measured Sulphate Depletion to Estimates Based on Rates from Amendment test and Numerical Modelling

Date Period	Time (days)	Measured Sulphate Concentration Decrease (mg/L)	Push Pull Zero Order (mg/L)	Push Pull First Order (mg/L)	Model (mg/L)
Jun 25-Jul 23/03	28	374	112-168	38-116	28
Jul 23-Oct 28/03	97	102	388-582	26-64	96
Jun 9-Jul 9/04	30	22	120-180	3-9	30
Aug 18-Oct 19/04	62	94	248-372	17-46	61

Sulphate depletion rates derived from plume modelling were more similar to measured results than values derived using the amendment test results, except from June-July 2003. The larger starting concentration measured in June 2003 was likely related to the preceding precipitation event (38 mm). This condition is more like the zero-order reaction at the start of the amendment test. In summary, the method of sequentially collecting no-purge followed by low-flow purge samples appeared to offer a simple and efficient means to estimate an average sulphate consumption rate. In the absence of measurable PHC depletion rates (e.g., for a stable plume where the PHC source has not been removed) or other significant TEAPs, this approach may offer insight regarding estimation of an effective PHC attenuation rate.

4.5.3 Remediation Time Frame

Determination of an appropriate effective attenuation rate enables estimation of the extent of a dissolved PHC plume (for a continuous source), or the time to reach a specified clean-up goal (if the source has been controlled or eliminated). A commonly-used approach is to combine all attenuation mechanisms into one effective (empirical) parameter described by a first-order model. The attenuation rate is given by the slope of a straight line fitted to a plot of concentration (logarithmic units) over time. This empirical approach has several limitations that require consideration. Sampling-induced and/or in-well averaging (especially in well screens ≥ 3 m long) mean that groundwater analyses often cannot capture fine spatial or temporal details (Bekins et al., 2001) regarding geochemical processes. Care is required when interpreting PHC degradation based solely on anaerobic TEAs in groundwater samples (Salanitro et al., 1997). Lastly, the wide variety of potential environmental influences (hydraulic, microbiological, geochemical) mean that 'true' reasons for changes in groundwater chemistry may be very difficult to discern.

The historical data for dissolved BTEX concentrations from well P34 were plotted, along with a least squares best fit straight line. The data were all weighted equally to capture the uncertainty between the series of multi-sample groups obtained from CORONA. The data suggest that benzene, toluene and xylenes generally appear to decrease, but show intermittent concentration increases. In contrast, ethylbenzene appeared to show a large, sudden concentration increase in 1999, but then stabilized and mimicked the general patterns of the other three compounds. Given the consistency within the CORONA data for all BTEX analytes, it is inferred (but irresolvable) that the early ethylbenzene data were anomalously low. Accordingly, these data were not considered further.

For all compounds, the increased sampling for CORONA identified greater variation than had been seen in the previous data. Nevertheless, the data provide a method for estimating a time scale for PHC plume attenuation. The first-order attenuation rate derived using this approach ranged from 0.0003 day^{-1} (xylenes) to 0.0011 day^{-1} (toluene) (Figure 4-7). These rates are much lower than the sulphate depletion rates determined above, and highlight the care required in trying to compare TEA utilization to target PHC degradation. Complicating factors include: presence of other organic compounds besides the target compounds of concern (meaning there may not be stoichiometric balance between TEA utilization and substrate depletion), temporary depletion of available TEAs (e.g., sulphate in this case), and complicated interactions between TEAs (e.g., iron and sulphur minerals).

Current drinking water criteria for dissolved BTEX compounds in Alberta groundwater range from 0.3 mg/L (xylenes) to 0.0024 mg/L (toluene). Using these guidelines as generic remediation targets and assuming both source control and no change in attenuation rate, groundwater at well P34 will take from 3 years (benzene) to approximately 20 years (xylenes).

4.6 Conclusions and Implications

Historical groundwater monitoring results at the research site had been interpreted to show that a dissolved hydrocarbon plume was attenuating under natural conditions. Two research monitoring well clusters (six wells per cluster) and six other monitoring wells were installed within the hydrocarbon-contaminated groundwater plume at the site. Groundwater and soil samples from selected wells were used to examine possible influences related to sampling on interpretation of plume attenuation.

This paper focussed on using the results from a series of sampling programs conducted at one research cluster to examine temporal variability in analytes used for NA assessment. As expected for the unconfined silty sand unit, water level data logger identified a qualitative link with precipitation, but the magnitude and frequency of changes were notably greater than had previously been identified. The use of no-purge and low-flow sampling methods identified geochemical differences (mainly sulphate) between the two sets of samples for consecutive sampling events within one month.

Sulphate was the only analyte sensitive (order of magnitude variation) to the use of no-purge and low flow purge sampling methodologies. The observed variation in sulphate values differed between visits and purging protocols. This sensitivity could be explained by a combination of sulphate replenishment via groundwater recharge and precipitation coupled with sulphate reduction. In contrast, the dissolved BTEX concentrations typically varied within a factor of two or less between and within sampling events (for no-purge and low-flow methods). Other than for sulphate concentrations, purging was generally interpreted as playing an unimportant role.

The temporal changes in sulphate concentrations suggested that infiltration of precipitation provided a fresh input of sulphate. Results of research activities conducted by others around the same time (a sulphate injection test) showed that sulphate replenishment enhanced NA behaviour. Accordingly, the data supported the idea that episodic replenishment of sulphate via infiltration may significantly influence local biodegradation rates. Additional supporting evidence was provided by numerical modelling of the PHC plume that required sulphate replenishment in order to reproduce observed plume behaviour. The model was based on soil and groundwater analyses showing sulphate depletion in soil and water within the hydrocarbon-contaminated zone, with associated enrichment of reduced sulphur and iron.

Using conventional monitoring data, the plume attenuation rate was estimated to be very slow. In contrast, the episodic sulphate-rich infiltrating water identified by sequential pairs of no-purge and post-purge sampling events provided evidence that the local attenuation rate may be notably higher. At this site, insight was gained only through multiple no-purge and post-purge sampling events conducted monthly. A similar sequential combination of sampling protocols may assist in identifying other cases where electron acceptors are subject to episodic replenishment after having appeared to be depleted.

4.7 References

Allen-King, R.M., Barker, J.F., Gillham, R.W. and Jensen, B.K., 1994. Substrate- and nutrient-limited toluene biotransformation in sandy soil. Environmental Toxicology and Chemistry, 13(5): 693-705.

Alvarez, P.J.J., Anid, P.J. and Vogel, T.M., 1991. Kinetics of aerobic biodegradation of benzene and toluene in sandy aquifer material. Biodegradation, 2: 43-51.

Alvarez, P.J.J. and Vogel, T.M., 1991. Substrate interactions of benzene, toluene and para-xylene during microbial degradation by pure cultures and mixed culture aquifer slurries. Applied and Environmental Microbiology, 57(10): 2981-2985.

Armstrong, J.E., Cross, K., M. and Biggar, K.W., 2001. Assessment of monitored natural attenuation at Alberta oil and gas facilities, CORONA, Calgary.

ASTM, 1998. Standard Guide for Remediation of Ground Water by Natural Attenuation at Petroleum Release Sites. E 1943 - 98, American Society for Testing and Materials.

Baedecker, M.J., Cozzarelli, I.M., Eganhouse, R.P., Siegel, D.I. and Bennett, P.C., 1993. Crude oil in a shallow sand and gravel aquifer--Ill. Biogeochemical reactions and mass balance modeling in anoxic groundwater. Applied Geochemistry, 8(6): 569-586.

Barker, J.F. and Dickhout, R., 1988. An evaluation of some systems for sampling gas-charged groundwater for volatile organic analysis. Ground Water Monitoring Review, 8(4): 112-120.

Bauer, S., Beyer, C. and Kolditz, O., 2006. Assessing measurement uncertainty of first-order degradation rates in heterogeneous aquifers. Water Resources Research, 42(W01420, doi:10.1029/2004WR003878): 14.

Bekins, B.A., Cozzarelli, I.M., Godsy, E.M., Warren, E., Essaid, H.I. and Tuccillo, M.E., 2001. Progression of natural attenuation processes at a crude oil spill site: II. Controls on spatial distribution of microbial populations. Journal of Contaminant Hydrology, 53(3-4): 387-406.

Beller, H.R., Grbic-Galic, D. and Reinhard, M., 1992. Microbial degradation of toluene under sulfate-reducing conditions and the influence of iron on the process. Applied and Environmental Microbiology, 58(3): 786-793.

Benner, S.G., Blowes, D.W., Ptacek, C.J. and Mayer, K.U., 2002. Rates of sulfate reduction and metal sulfide precipitation in a permeable reactive barrier. Applied Geochemistry, 17(3): 301-320.

Beyer, C., Bauer, S. and Kolditz, O., 2006. Uncertainty assessment of contaminant plume length estimates in heterogeneous aquifers. Journal of Contaminant Hydrology, 87(1-2): 73-95.

Brockman, F.J. and Murray, C.J., 1997. Subsurface microbiological heterogeneity: current knowledge, descriptive approaches and applications. FEMS Microbiology Reviews, 20(3, 4): 231-247.

Chapelle, F.H., 1993. Ground-Water Microbiology & Geochemistry. John Wiley & Sons, Inc., New York, 424 pp.

Chapelle, F.H., Bradley, P.M., Lovley, D.R. and Vroblesky, D.A., 1996. Measuring rates of biodegradation in a contaminated aquifer using field and laboratory methods. Ground Water, 34(4): 691-698.

Cozzarelli, I.M., Bekins, B.A., Baedecker, M.J., Aiken, G.R., Eganhouse, R.P. and Tuccillo, M.E., 2001. Progression of natural attenuation processes at a crude-oil spill site - I. Geochemical evolution of the plume. Journal of Contaminant Hydrology, 53(3-4): 369-385.

Cozzarelli, I.M., Herman, J.S., Baedecker, M.J. and Fischer, J.M., 1999. Geochemical heterogeneity of a gasoline-contaminated aquifer. Journal of Contaminant Hydrology, 40(3): 261-284.

Davis, C., Cort, T., Dai, D., Illangasekare, T.H. and Munakata-Marr, J., 2003. Effects of heterogeneity and experimental scale on the biodegradation of diesel. Biodegradation, 14: 373-384.

Davis, G.B., Barber, C., Power, T.R., Thierrin, J., Patterson, B.M., Rayner, J.L. and Wu, Q.L., 1999. The variability and intrinsic remediation of a BTEX plume in anaerobic sulphate-rich groundwater. Journal of Contaminant Hydrology, 36(3-4): 265-290.

Deeb, R.A. and Alvarez-Cohen, L., 2000. Aerobic transformation of gasoline aromatics in multicomponent mixtures. Bioremediation Journal, 4(2): 171-179.

Delin, G.N. and Landon, M.K., 1996. Multiport well design for sampling of ground water at closely spaced vertical intervals. Ground Water, 34(6): 1098-1104.

Edwards, E.A., Wills, L.E., Reinhard, M. and Grbic-Galic, D., 1992. Anaerobic degradation of toluene and xylene by aquifer microoganisms under sulfate-reducing conditions. Applied and Environmental Microbiology, 58(3): 794-800.

Fan, X., Guigard, S., Foght, J., Semple, K.M. and Biggar, K.W., 2007. Enhancement of anaerobic biodegradation of petroleum hydrocarbons in groundwater: laboratory mesocosm studies, Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates. University of Alberta, Edmonton, pp. 12-20.

Fennell, J. and Bentley, L.R., 1998. Distribution of sulfate and organic carbon in a prairie till setting: Natural versus industrial sources. Water Resources Research, 34(7): 1781-1794.

Gibs, J., Brown, G.A., Turner, K.S., MacLeod, C.L., Jelinski, J.C. and Koehnlein, S.A., 1993. Effects of small-scale vertical variations in well-screen inflow rates and concentrations of organic compounds on the collection of representative groundwater quality samples. Ground Water, 31(2): 201-208.

Gieg, L.M., Kolhatkar, R.V., McInerney, M.J., Tanner, R.S., Harris, S.H.J., Sublette, K.L. and Suflita, J.M., 1999. Intrinsic bioremediation of petroleum hydrocarbons in a gas condensate-contaminated aquifer. Environmental Science & Technology, 33(15): 2550-2560.

Haack, S.K. and Bekins, B.A., 2000. Microbial populations in contaminant plumes. Hydrogeology Journal, 8(1): 63-76.

Hurt, K.L., Beck, F.P. and Wilson, J.T., 2001. Implications of subsurface heterogeneity at a potential monitored natural attenuation site. Ground Water Monitoring & Remediation, 21(3): 59-63.

Julian, H.E., Boggs, J.M., Zheng, C.M. and Feehley, C.E., 2001. Numerical simulation of a natural gradient tracer experiment for the natural attenuation study: Flow and physical transport. Ground Water, 39(4): 534-545.

Kaplan, E., Banerjee, S., Ronen, D., Margaritz, M., Machlin, A., Sosnow, M. and Koglin, E., 1991. Multilayer sampling in the water-table region of a sandy aquifer. Ground Water, 29(2): 191-198.

Kennedy, L., Everett, J.W. and Gonzales, J., 2004. Aqueous and mineral intrinsic bioremediation assessment: natural attenuation. Journal of Environmental Engineering, 130(9): 942-950.

King, M.W.G. and Barker, J.F., 1999. Migration and natural fate of a coal tar creosote plume 1. Overview and plume development. Journal of Contaminant Hydrology, 39(3-4): 249-279.

Kropp, K.G., Davidova, I.A. and Suflita, J.M., 2000. Anaerobic oxidation of *n*-dodecane by an addition reaction in a sulfate-reducing bacterial enrichment culture. Applied and Environmental Microbiology, 66(12): 5393-5398.

LaViolette, R.A., Watwood, M.E., Ginn, T.R. and Stoner, D.L., 1999. Spatial disorder and degradation kinetics in intrinsic biodegradation schemes. The Journal of Physical Chemistry. A, Molecules, Spectroscopy, Kinetics, Environment & General Theory, 103(23): 4480-4484.

Lee, C.H., Lee, J.Y., Cheon, J.Y. and Lee, K.K., 2001a. Attenuation of petroleum hydrocarbons in smear zones: A case study. Journal of Environmental Engineering, 127(7): 639-647.

Lee, J.Y., Cheon, J.Y., Lee, K.K., Lee, S.Y. and Lee, M.H., 2001b. Factors affecting the distribution of hydrocarbon contaminants and hydrogeochemical parameters in a shallow sand aquifer. Journal of Contaminant Hydrology, 50(1-2): 139-158.

Li, L., Yolcubal, I., Sandrin, S., Hu, M.Q. and Brusseau, M.L., 2001. Biodegradation during contaminant transport in porous media: 3. Apparent condition-dependency of growth-related coefficients. Journal of Contaminant Hydrology, 50(3-4): 209-223.

Lovley, D.R., 1991. Dissimilatory Fe(III) and Mn(IV) reduction. Microbiological Reviews, 55(2): 259-287.

Lu, G.P., Clement, T.P., Zheng, C.M. and Wiedemeier, T.H., 1999. Natural attenuation of BTEX compounds: Model development and field-scale application. Ground Water, 37(5): 707-717.

Maier, U. and Grathwohl, P., 2006. Numerical experiments and field results on the size of steady state plumes. Journal of Contaminant Hydrology, 85(1-2): 33-52.

Mandelbaum, R.T., Shati, M.R. and Ronen, D., 1997. In situ microcosms in aquifer bioremediation studies. FEMS Microbiology Reviews, 20: 489-502.

Martin-Hayden, J.M. and Robbins, G.A., 1991. Mass balance evaluation of monitoring well purging: Part II, Field tests at a gasoline contamination site. Journal of Contaminant Hydrology, 8(3-4): 225-241.

Mayer, K.U., Frind, E.O. and Blowes, D.W., 2002. A numerical model for the investigation of reactive transport in variably saturated media using a generalized formulation for kinetically controlled reactions. Water Resources Research, 38(9): 1174-1194.

Odermatt, J.R., 1997. Simulations of intrinsic biodegradation using a non-linear modification of first-order reaction kinetics. Journal of Soil Contamination, 6(5): 495-508.

Parker, L.V., 1994. The effects of ground water sampling devices on water quality: a literature review. Ground Water Monitoring Review, 14(2): 130-141.

Petersmeyer, C.W., 2006. Assessing Natural Attenuation of Petroleum Hydrocarbons Using Reactive Transport Modelling with Aqueous and Solid Phase Data. M.Sc. Thesis, University of British Columbia, Vancouver, 273 pp.

Prommer, H., Davis, G.B. and Barry, D.A., 1999. Geochemical changes during biodegradation of petroleum hydrocarbons: field investigations and biogeochemical modelling. Organic Geochemistry, 30(6): 423-435.

Roling, W.F.M., van Breukelen, B.M., Braster, M., Lin, B. and van Verseveld, H.W., 2001. Relationships between microbial community structure and hydrochemistry in a landfill leachate-polluted aquifer. Applied and Environmental Microbiology, 67(10): 4619-4629.

Ronen, D., Magaritz, M., Gvirtzman, H. and Garnerc, W., 1987. Microscale chemical heterogeneity in groundwater. Journal of Hydrology, 92(1-2): 173-178.

Salanitro, J.P., 1993. The role of bioattenuation in the management of aromatic hydrocarbon plumes in aquifers. Ground Water Monitoring and Remediation, 13(4): 150-161.

Salanitro, J.P., Wisniewski, H.L., Byers, D.L., Neaville, C.C. and Schroder, R.A., 1997. Use of aerobic and anaerobic microcosms to assess BTEX biodegradation in aquifers. Ground Water Monitoring & Remediation, 17(3): 210-221.

Sandrin, S.K., Brusseau, M.L., Piatt, J.J., Bodour, A.A., Blanford, W.J. and Nelson, N.T., 2004. Spatial variability of in situ microbial activity: biotracer tests. Ground Water, 42(3): 374-383.

Sandrin, S.K., Jordan, F.L., Maier, R.M. and Brusseau, M.L., 2001. Biodegradation during contaminant transport in porous media: 4. Impact of microbial lag and bacterial cell growth. Journal of Contaminant Hydrology, 50(3-4): 225-242.

Schaefer, W., 2001. Predicting natural attenuation of xylene in groundwater using a numerical model. Journal of Contaminant Hydrology, 52(1-4): 57-83.

Scholl, M.A., 2000. Effects of heterogeneity in aquifer permeability and biomass on biodegradation rate calculations - Results from numerical simulations. Ground Water, 38(5): 702-712.

Scholl, M.A., Cozzarelli, I.M. and Christenson, S.C., 2006. Recharge processes drive sulfate reduction in an alluvial aquifer contaminated with landfill leachate. Journal of Contaminant Hydrology, 86(3-4): 239-261.

Schreiber, M.E., Carey, G.R., Feinstein, D.T. and Bahr, J.M., 2004. Mechanisms of electron acceptor utilization: implications for simulating anaerobic biodegradation. Journal of Contaminant Hydrology, 73(1-4): 99-127.

Schroth, M.H., Kleikemper, J., Bolliger, C., Bernasconi, S.M. and Zeyer, J., 2001. In situ assessment of microbial sulfate reduction in a petroleum-contaminated aquifer using push-pull tests and stable sulfur isotope analyses. Journal of Contaminant Hydrology, 51(3-4): 179-195.

Schulmeister, M.K., Healey, J.M., Butler, J., James J. and McCall, G.W., 2004. Direct-push geochemical profiling for assessment of inorganic chemical heterogeneity in aquifers. Journal of Contaminant Hydrology, 69(3-4): 215-232.

Semple, K.M., Fan, X., Foght, J., Guigard, S.E. and Biggar, K.W., 2007. Detecting anaerobic hydrocarbon biodegradation "signature metabolites" in a two-year laboratory study of petroleum-contaminated groundwater and sediment., Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, Edmonton, AB, pp. 21-25.

Smets, B.F. and Pritchardy, P.H., 2003. Elucidating the microbial component of natural attenuation. Current Opinion in Biotechnology, 14(3): 283-288.

Smith, R.L., Harvey, R.W. and LeBlanc, D.R., 1991. Importance of closely spaced vertical sampling in delineating chemical and microbiological gradients in groundwater studies. Journal of Contaminant Hydrology, 7(3): 285-300.

Spence, M.J., Bottrell, S.H., Thornton, S.F. and Lerner, D.N., 2001. Isotopic modelling of the significance of bacterial sulphate reduction for phenol attenuation in a contaminated aquifer. Journal of Contaminant Hydrology, 53(3-4): 285-304.

Stenback, G.A., Ong, S.K., Rogers, S.W. and Kjartanson, B.H., 2004. Impact of transverse and longitudinal dispersion on first-order degradation rate constant estimation. Journal of Contaminant Hydrology, 73(1-4): 3-14.

Suarez, M.P. and Rifai, H.S., 2004. Modeling natural attenuation of total BTEX and benzene plumes with different kinetics. Ground Water Monitoring & Remediation, 24(3): 53-68.

Ulrich, G.A., Breit, G.N., Cozzarelli, I.M. and Suflita, J.M., 2003. Sources of sulfate supporting anaerobic metabolism in a contaminated aquifer. Environmental Science & Technology, 37(6): 1093-1099.

Ulrich, G.A. and Suflita, J.M., 2002. Enhancement of Microbial Sulfate Reduction for the Remediation of Hydrocarbon Contaminated Aquifers - a Laboratory and Field-Scale Project – Final Report Executive Summary. EPA Agreement Number: R827015–01– 0, University of Oklahoma, Tulsa.

USEPA, 1999. Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites. OSWER Directive 9200.4-17P, Office of Solid Waste and Emergency Response Directive, Washington, DC.

van Bodegom, P.M., Scholten, J.C.M. and Stams, A.J.M., 2004. Direct inhibition of methanogenesis by ferric iron. FEMS Microbiology Ecology, 49: 261-268.

Van Stempvoort, D.R., Armstrong, J.E. and Mayer, B., 2007a. Microbial reduction of sulfate injected to gas condensate plumes in cold groundwater. Journal of Contaminant Hydrology, 92(3-4): 184–207.

Van Stempvoort, D.R., Armstrong, J.E. and Mayer, B., 2007b. Seasonal recharge and replenishment of sulfate associated with biodegradation of a hydrocarbon plume. Ground Water Monitoring & Remediation, 27(4): 110-121.

Weiner, J.M., Lauck, T.S. and Lovley, D.R., 1998. Enhanced anaerobic benzene degradation with the addition of sulfate. Bioremediation Journal, 2(3&4): 159-173.

Weiner, J.M. and Lovley, D.R., 1998. Rapid benzene degradation in methanogenic sediments from a petroleum-contaminated aquifer. Applied and Environmental Microbiology, 64(5): 1937-1939.

Wiedemeier, T.H., Wilson, J.T., Kampbell, D.H., Miller, R.N. and Hansen, J.E., 1995. Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater (Volume I and II), AFCEE, Technology Transfer Division, Brooks Air Force Base, San Antonio, Texas.

Wilson, R.D., Thornton, S.F. and Mackay, D.M., 2004. Challenges in monitoring the natural attenuation of spatially variable plumes. Biodegradation, 15(6): 359-369.

Wong, D., Suflita, J.M., McKinley, J.P. and Krumholz, L.R., 2004. Impact of clay minerals on sulfate-reducing activity in aquifers. Microbial Ecology, 47: 80-86.

Zheng, Z., Breedveld, G.D. and Aagaard, P., 2001. Biodegradation of soluble aromatic compounds of jet fuel under anaerobic conditions: laboratory batch experiments. Applied Microbiology and Biotechnology, 57(4): 572-578.

Zheng, Z.P., Aagaard, P. and Breedveld, G.D., 2002. Sorption and anaerobic biodegradation of soluble aromatic compounds during groundwater transport. 2. Computer modeling. Environmental Geology, 41(8): 933-941.

5. USE OF DECISION ANALYSIS TOOLS TO EXAMINE PROJECTED TIMESCALES FOR NATURAL ATTENUATION

5.1 Introduction

5.1.1 Natural Attenuation

Natural attenuation (NA) refers to the reduction of a contaminant mass or concentration by a series of naturally occurring physical, chemical, and biological processes. For petroleum hydrocarbons (PHC), biodegradation is the only process that destroys contaminant mass. Increasing experience with NA field sites has led to suggestions that the definition should change to include only biodegradation and strong contaminant immobilization (Rittmann, 2004). Other naturally occurring processes (e.g., diffusion, sorption and volatilization) dilute the mass over a larger area or between phases.

Monitored natural attenuation (MNA) refers to a strategy whereby the contaminant source is controlled or removed and site data are collected over regular intervals to demonstrate that natural attenuation processes are reducing contaminant concentrations. The obvious key component of MNA is establishing source control, preventing ongoing contaminant release. A secondary component is concerned with estimating how long NA will take to achieve established remediation goals; hence, how long monitoring will be required. While the site owner typically has control over issues related to source control, definition of an acceptable time frame for clean-up by NA will often depend on the subjective viewpoints of all stakeholders. Assuming agreement can be reached for these components, MNA represents an alternative approach to plume remediation that could be used either as stand-alone strategy, or in combination with conventional engineered remediation techniques. Details of this strategy are provided in several guide documents (ASTM, 1998; USEPA, 1999).

The key element of the strategy is the ongoing collection of monitoring data to confirm that natural attenuation is occurring. The first main decision related to NA is therefore based on judging whether the attenuation will be sufficient. If NA is an effective strategy, then monitoring effort (costs) will typically be much less than active, engineered remediation. However, if NA does not result in adequate PHC plume reduction, contingency measures will be required at some future point. In this case, the original decision to rely on NA meant that the money spent on monitoring was wasted, and possibly there may be an increased requirement for active remediation if additional plume growth occurred. It is therefore noteworthy that sites have been closed using the assumption that NA is effective (Johnson, 2002), and that post-closure investigations confirming NA effectiveness were not done once the monitoring wells have been removed.

5.1.2 Demonstration Case

A case example is used to show how Decision Analysis can be applied when considering whether natural attenuation could manage a plume of PHC-contaminated groundwater. Facility infrastructure in the areas of the hydrocarbon source and resulting downgradient groundwater plume precludes excavation until after active operations cease. Strictly speaking, excavation therefore does not represent an appropriate contingency plan. However, excavation is a common contingent plan, so it was retained for this generic illustration of benefits obtained using Decision Analysis. Relevant features provided by this case included:

- source removal was ongoing;
- hydrochemical monitoring indicated that the dissolved hydrocarbon plume was attenuating;
- no immediate sensitive environmental receptors were identified near the release area;
- source area excavation was not practicable;
- the groundwater plume remained on-site, thus no other stakeholders were involved; and,
- regulators were willing to accept this strategy on a trial basis.

Details of the site-specific conditions are provided in Section 5.2.

5.1.3 Decision Analysis

Decision analysis describes a methodology for using probabilistic tools to examine and integrate all aspects of a given problem to arrive at a decision. The methodology gets all stakeholders to participate and to identify what are the key factors or uncertainties, and how they affect the situation. In this manner, decision makers minimize the effects of supposition or bias, and decisions can be made based on a clear and logical review of uncertainties, concerns, expectations and assumptions (Skinner, 2001). Any chosen course of action is thus based on an understanding of the state of knowledge related to the decision, including the decision to reduce the identified level(s) of uncertainty.

The value of incorporating probability into decision-making processes is well known when considering how uncertainty in input values affects potential outcomes (and costs) (Whitman, 1984). The benefits of this approach for identifying sensitive inputs increase, particularly when the severity of potential negative outcomes increases. This point is particularly relevant early in a project when far-reaching decisions may be required. A simplified example would be the decision of whether to rely on natural attenuation or a more active remediation approach: should the contaminated material be excavated immediately upon release/detection (short-term, high cost, disruptive), or left in place with the concept that it will attenuate naturally (long-term, lower cost, non-intrusive)? Typically, the decision process will start with minimal to no data from which NA effectiveness can be assessed (uncertainty, reliance on expert opinion). While suitable data are collected, the zone of contamination may grow, increasing the cost if excavation is subsequently selected.

There are many variations of the decision analysis process both in the public and private domain but most follow the same general flow. An example of the typical steps required is summarized below, with additional comments provided to clarify or illustrate the steps. This paper examines how the last three steps can be used to examine and quantify uncertainties associated with projecting possible NA behaviour based on existing site monitoring data. A case study illustrating application of the initial steps to compare alternative approaches, including NA, is provided elsewhere (Armstrong et al., 2004).

1. Define the problem statement,
2. Raise and categorize all actual and potential issues,
3. Develop strategy alternatives,
4. Build the model and quantify the uncertainties,
5. Perform sensitivity analysis to identify ‘dominating’ factors,
6. Run probabilistic analysis to assess the possible range of outcomes,
7. Develop insights and examine possible hybrid solutions,
8. Make a decision.

Step 1 – Define the problem statement

This step appears to be self-evident, but may require considerable effort for a multi-disciplinary team, or a contentious issue. The importance of the problem statement cannot be underestimated. While it may be difficult to solve a stated problem, it is practically impossible to solve a poorly-stated problem.

Step 2 – Raise and categorize the issues, using a three-step process

i. Identify issues, where an issue is a concern/problem making it difficult to decide today;
ii. Categorize the issues into facts (known data or background information), uncertainties (a potential outcome about which one has no control) and decisions (a choice that may be controlled); and,
iii. Further categorize decisions into: policy decisions, strategic decisions, or tactical decisions.

Facts are generally clear. Uncertainties can be grouped into two categories: chance uncertainties (e.g., will natural attenuation work), and range uncertainties (e.g., how much contaminant mass is present). Policy decisions have already been made, and may also be called "assumptions" or "givens". Strategy decisions represent the current focus (how to remediate the site), while tactical decisions are those decisions that can be made later after a strategy is selected (should additional confirmatory plume data be collected in the future).

Step 3 – Develop strategy alternatives

This step involves selecting combinations of strategic decisions (step 2) to create a few distinctly different strategies that will be evaluated, and try to identify the key problem drivers.

Step 4 – Build the model and collect the uncertainties

This step involves building the calculation model and incorporating reasonable inputs for range uncertainties (e.g., high, median, low) to examine the associated range of outputs for each alternative.

Step 5 – Perform sensitivity analysis

The sensitivity analysis identifies which range uncertainties cause the biggest output fluctuation. Once identified, these uncertainties can either be included into a probabilistic analysis (decision trees) or, suggest where effort might be expended to reduce the uncertainty range (e.g., drill more boreholes to provide better spatial monitoring coverage).

Step 6 – Run probabilistic analysis

Chance variables are handled in probabilistic analysis through decision trees that reflect the order in which decisions are made and uncertainties are resolved.

Step 7 – Develop insights and look for hybrid solutions

The analysis is reviewed for evidence of other, compelling alternatives that combine the best pieces of specific strategies or mitigate specific uncertainties. During this step, it is extremely important to consider the probability of making errors in judgment. The two main errors to consider, Type 1 and Type 2, are illustrated using 4 monitoring points collected in the first year of monitoring that show a weak downward trend. The null hypothesis is that there is no trend. A Type 1 error (reject a true null hypothesis) is illustrated by interpreting the data points as indicating attenuation when the concentration change is actually seasonal (e.g., due to changing groundwater elevation). In contrast, a Type 2 error (accept a false null hypothesis as true) might be to excavate the spill area because the data do not support interpretation of NA.

Step 8 – Make decisions

The final step is to make decisions, based on the ‘shape’ of the range of outcomes that result from inclusion of input uncertainty.

This description of steps to making a decision glosses over a difficult component in Step 4, where expert input is required to identify appropriate ranges of inputs. Depending on the decision structure, there may be no single expert who can provide guidance (e.g., if the decision required specific input related to global warming), or the expert may be perceived as being ‘biased’ (e.g. site owner’s consultant). The former case may require multiple trials to examine the sensitivity of the decision to this input, while the latter case is easily addressed by requesting confirmation from an independent expert.

Experts from multiple fields are sometimes required to gain insight regarding uncertainty ranges for each decision element. However, one should never forget that each expert input represents a value judgement (interpretation, not knowledge), and therefore includes some level of uncertainty. If the decision were easy, effort to improve understanding of the decision components would not be required.

A simple case (small area, biodegradable PHC contaminant, source removal) was selected for this research to examine the influence of complexities inherent in natural attenuation monitoring data. In a more general case, external complexities such as changing land use, ownership, and regulatory environment could dominate the decision analysis steps.

5.1.4 Problem Statement

Monitoring data from many sites have been interpreted as showing that NA will likely control plume expansion, but few cases are available to show the longer-term performance where complete plume dissipation may be achieved. To examine this problem, data were taken from a field site where PHC contamination was being attenuated (following hydrocarbon source removal). This paper uses decision analysis techniques to re-examine the decision to rely on NA, compared to the alternative strategy of excavating and landfilling the hydrocarbon-contaminated zone. The analysis compared changes in the interpreted effectiveness of NA as monitoring data were compiled over time. Using these data, it was also possible to assess changes in the level of confidence associated with predicting the project lifespan. The case uses assumed fixed costs for the two remediation alternatives (NA and excavation), but cost variability could readily be included, as shown for a different case (Armstrong et al., 2004).

5.2 Methodology

5.2.1 Site Description

The site is located in central Alberta (Figure 5-1). Several cubic metres of natural gas condensate were accidentally released as a result of a pump malfunction. The condensate was observed to pool on the ground surface, before infiltrating into surficial fill (variably comprising silt to gravel material with 0.3 to 1.0 m thickness) and the underlying clayey to sandy silt. Emergency response measures led to the recovery of approximately half of the estimated release volume via liquid pumping from shallow excavations. Subsequent site characterization to assess potential environmental impact was conducted in two phases. Three monitoring wells were installed shortly after the release to characterize soil in the immediate area. Additional wells were installed to delineate the extent of hydrocarbon presence (both free phase liquid and dissolved components), and to provide access points for hydrocarbon liquid recovery.

Site investigation work characterized the extent of soil and groundwater contamination, and identified a zone of liquid hydrocarbon surrounded by a dissolved hydrocarbon groundwater plume. The contaminated area is congested with above- and below-ground facilities, so excavation was considered impractical. In situ remediation activities were initiated in the release area (source) via soil vapour extraction (SVE) alone, and in combination with liquid recovery. Following two summer's operation, free phase hydrocarbon was no longer detected in any wells.

The PHC groundwater plume was initially observed to migrate southeastward, at a rate approaching the local average groundwater flow velocity (estimated at <10 m/year). Within two years of the release, however, hydrochemical analyses indicated that dissolved hydrocarbon concentrations were generally decreasing. The inorganic geochemical data illustrated some of the characteristic geochemical patterns indicative of intrinsic biodegradation, including differentially enriched iron and depleted sulphate within plume-monitoring wells compared to nearby monitoring wells with no dissolved hydrocarbons. Based on these monitoring data, MNA was selected as the remediation approach.

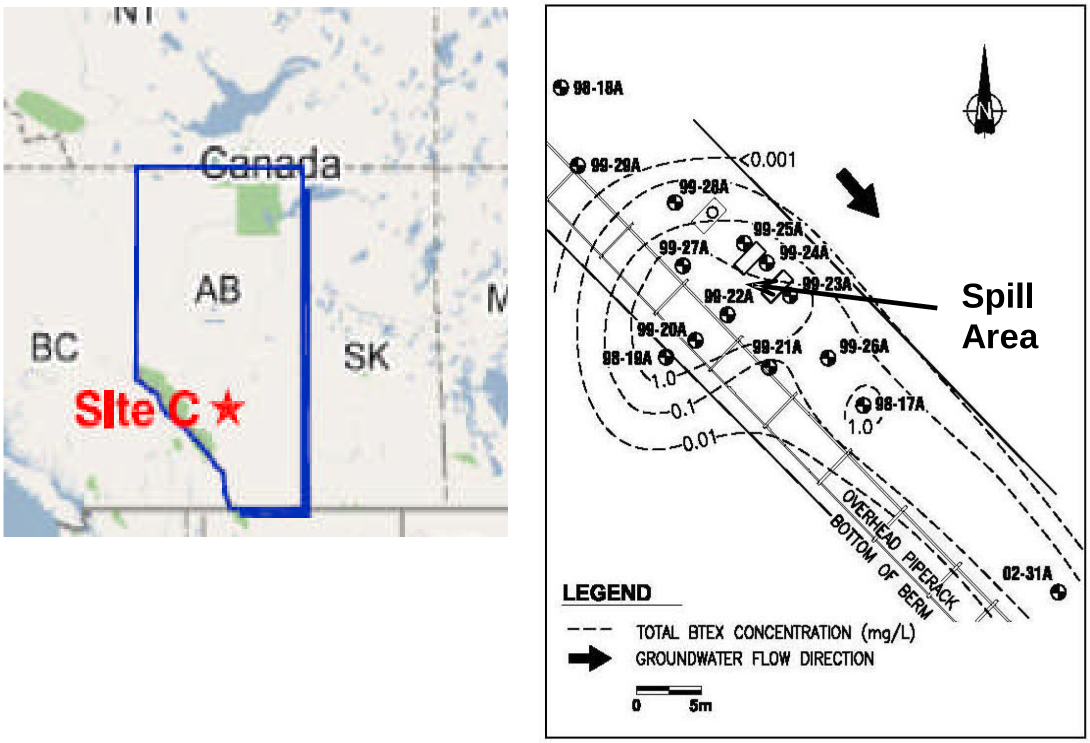


Figure 5-1 Site location, monitoring wells, groundwater flow direction and BTEX plume concentrations

5.2.2 Methodology

Monitoring data collected during the first two years indicated that natural attenuation processes appeared to be active, including:

- decreasing trends in hydrocarbon concentrations over time and space;
- characteristic dissolved iron enrichment and depletion of oxygen and sulphate in within-plume wells compared to background wells.

The groundwater sampling program was increased from semi-annually to quarterly for 13 of the 14 wells (99-22 was damaged), with an analytical schedule comprising main ions, PHC target compounds of benzene, toluene, ethylbenzene and xylenes (BTEX), and other general water quality parameters (pH, electrical conductivity, hardness, alkalinity and mineralization expressed as total dissolved solids, or TDS). Samples were collected using a conventional protocol, involving use of dedicated bailers or Waterra tubing installed in each well, and a pre-sampling purge volume of up to three borehole volumes of standing water

5.3 Data Analysis

Basic data analysis involved assessing temporal and spatial trends in concentrations of dissolved hydrocarbons and geochemical indicators of natural attenuation. For this paper, the focus is on the hydrocarbon trends over time. Example data plots for two of the BTEX compounds at one of the twelve monitoring well are provided in Figure 5-2.

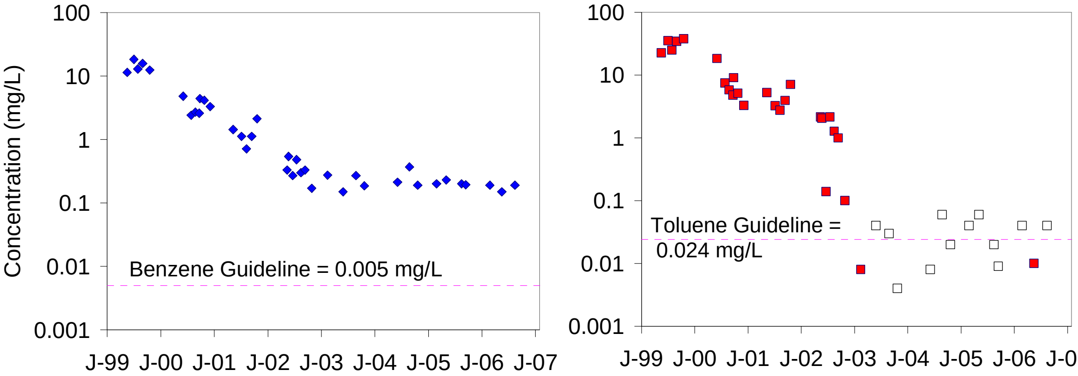


Figure 5-2 Sample monitoring well data set for Well 98-19A: benzene and toluene (hollow symbols show analyses below method detection limit)

The data were evaluated using the MAROS V2.0 software (monitoring and remediation optimization system) (Aziz et al., 2003). This program helps evaluate spatial and temporal trends in site monitoring data. Analysis was repeated as each year's monitoring results were added to the data set (4 measurements per year) over 6 years, from 1999 to 2005. Both the parametric and nonparametric methods provided in MAROS were used, with both methods giving similar results. Accordingly, only the parametric results are reviewed to examine how the addition of data modifies the estimated attenuation rates derived using this approach.

The parametric method assumes a first order attenuation reaction, and involves fitting a least-squares linear regression to a plot of natural logarithm of concentration versus time for the *n* samples. The underlying equation is $C=C_0\ e^{-kt}$, characterized by a rate constant, k (T^{-1}). The attenuation rate constant is the slope of the fitted straight line, where a negative rate constant indicates a downward trend. Further details regarding the calculation are provided below in Section 5.4. The parametric approach is sensitive to the magnitude of concentration changes, where sudden or varying changes reduce confidence in the fitted slope and inferred trend. Trends were considered at each well for each of benzene, toluene, ethylbenzene and total xylenes (BTEX).

5.4 Results

Results are presented for the monitoring data, followed by the decision tools. Within MAROS, trends for each data set (increasing or decreasing) are classified using a decision matrix based on the coefficient of variation (C_v = standard deviation/mean) and confidence in trend (based on a t-test with null hypothesis that the slope is zero). Guidelines are provided in Table 5.1 for how trends are assigned according to the MAROS manual. The total trend types (for all wells and all BTEX compounds) are summarized in Table 5-2. The total number of annual results increased in 2002 (one well added), and again in 2003 (one more well added) as sufficient analyses were collected to classify trends.

Table 5-1 Guidelines Used to Assign Trends in MAROS

Confidence in Trend	**Ln Slope>0**	**Ln Slope<0**
< 90%	No Trend	C_v<1 Stable C_v >1 No Trend
90% to 95%	Probably Increasing	Probably Decreasing
>95%	Increasing	Decreasing

Illustrative plots to show the range of possible cases are shown in Figures 5-3 and 5-4.

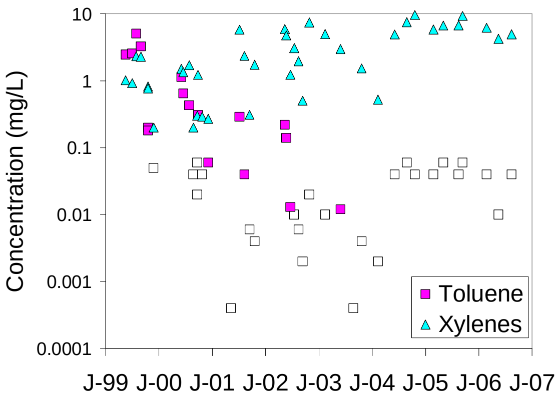


Figure 5-3 Trends at 98-17A: for T (decrease) and X (increase); hollow symbol = compound not detected

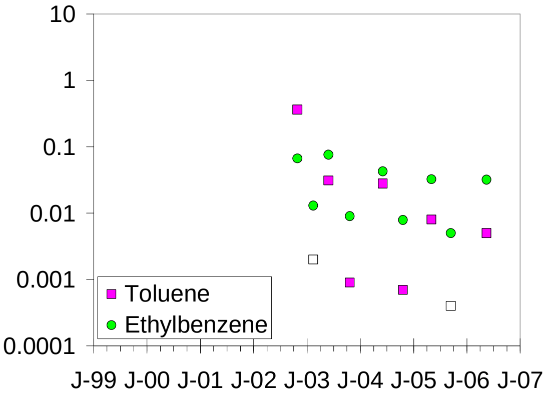


Figure 5-4 Trends at 02-31A for E (no trend) and T (decrease); hollow symbol = compound not detected

The data were analyzed using the complete set of detectable concentrations from the first monitoring visit until the end of each successive year. The laboratory detection limits varied between years, thus all non-detects were filtered out. This approach was considered to provide a conservative bias, compared to a common approach of considering non-detects at one half of the detection limit (Farnham et al., 2002). Results are summarized in Table 5-2, showing the number of wells and individual BTEX compounds that indicated a particular trend in a given year.

Table 5-2 Number of Monitoring Well/BTEX Sets Showing Specified Trends over Time

Trend Year	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Decreasing Concentration	15	20	31	33	40	42	43
Increasing Concentration	0	0	1	1	2	2	2
Not analyzed	24	8	4	4	0	0	0
No trend	3	5	5	10	8	3	3
Probably decreasing	2	6	5	1	0	3	2
Stable Concentration	0	5	2	3	2	2	2
Grand total	44	44	48	52	52	52	52

The table illustrates the effect of adding analyses over time at each well. In general, the number of trends classified as 'Decreasing' became larger, providing general support that NA was reducing PHC contamination. However, the interpretation that NA is effective has some uncertainty, given that the number of wells judged to be 'Increasing', 'Stable' or as having 'No trend' remained relatively stable, and the results derive mainly from two downgradient wells. As shown in Table 5-2, the number of wells judged as having a 'Stable' trend remained similar in contrast to those classified as 'No trend', based on the C_v.

For each individual BTEX compound at each well, semi log plots of concentration versus time data were developed. The plots were updated as each year's data was compiled. The fitted slopes (rate constant, k) for each analyte were then averaged for the number of wells monitored each year (between 11 and 13) (Table 5-3). The averaging also included values for any wells with inferred stable or upward trends, but did not include wells for which no trend was assigned (a slope is not meaningful for these cases). These data show no notable changes in attenuation rate constants, although ethylbenzene and toluene tend to show decreasing rates (less negative constant), while xylenes tend to show an increasing rate constant.

Table 5-3 Average Attenuation First Order Rate Constants (day $^{-1}$) from BTEX Data Updated Over Time

Year	Benzene	Ethylbenzene	Toluene	Xylenes
2000	-0.0018	-0.0015	-0.0042	-0.0013
2001	-0.0022	-0.0034	-0.0051	-0.0012
2002	-0.0027	-0.0017	-0.0044	-0.0015
2003	-0.0022	-0.0008	-0.0045	-0.0018
2004	-0.0031	-0.0019	-0.0041	-0.0020
2005	-0.0025	-0.0013	-0.0035	-0.0020
2006	-0.0024	-0.0013	-0.0031	-0.0020

An example plot of the decreasing slope (i.e., slower attenuation rate) over time at a single monitoring well is provided in Figure 5-5.

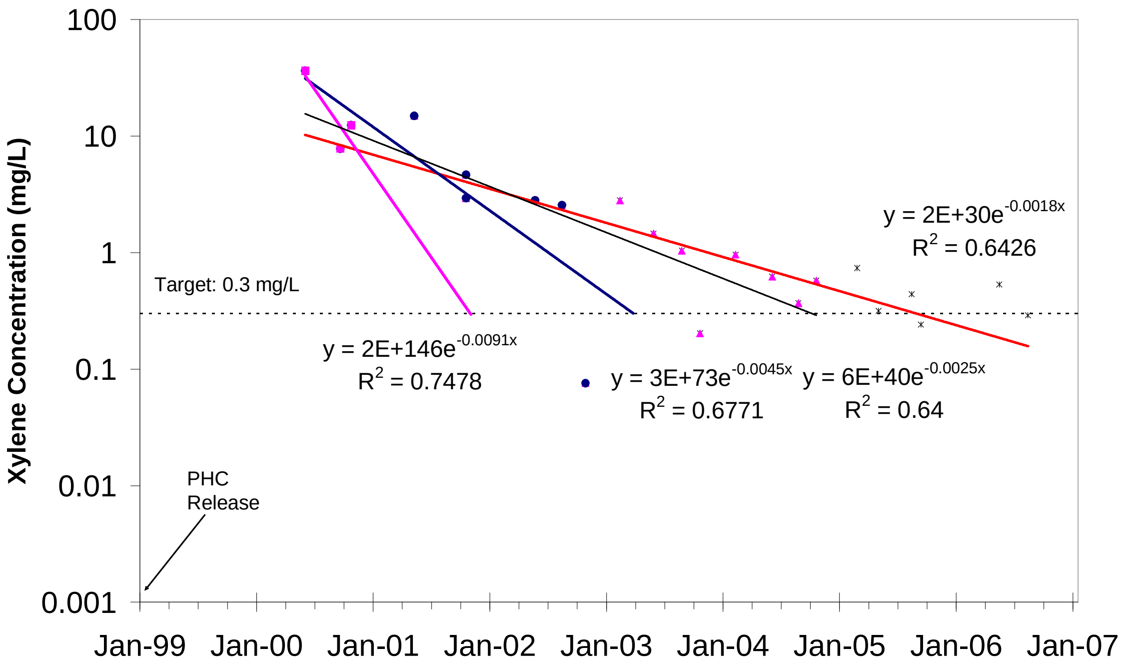


Figure 5-5 Example of apparent attenuation rate decrease over time (99-26A)

A ‘Confidence in Trend’ value was calculated for each well using the t-test, as described above. This value reflects the statistical confidence that the interpreted trend is not zero. Using the numbers of wells with assigned trends provided in Table 5-2, the level of confidence in the interpreted plume responses from 2000 to 2006 are summarized in Table 5-4.

Table 5-4 Average Measure of Confidence in Interpreted Trends for Individual Compounds

	Benzene	**Ethylbenzene**	**Toluene**	**Xylenes**
2000	43%	41%	45%	42%
2001	74%	76%	79%	67%
2002	89%	79%	91%	82%
2003	88%	72%	90%	90%
2004	98%	89%	98%	96%
2005	99%	94%	99%	97%
2006	99%	96%	99%	96%

Further confirmatory evidence of natural attenuation is provided by changes in average annual concentrations and masses for each component. To provide context, historical maximum concentrations recorded and calculated masses at the site when free phase hydrocarbon had been present are included in Table 5-5. The data show clear indications of decreasing concentrations as time proceeds, but at a decreasing rate. The average annual BTEX concentrations show a decrease of approximately 60 to 70 % from 2000 to 2004, and an average decrease of approximately 90% from the historical maximum concentrations.

The total dissolved PHC mass remaining in the groundwater plume was also calculated for each year using the Delaunay method provided in MAROS. The method uses Delaunay triangulation to divide the areal extent of the total groundwater plume into sub-areas that are assigned to each monitoring well. Assuming that the groundwater plume has a constant plume thickness and porosity, the total dissolved PHC plume mass (excluding residual hydrocarbon liquid, if any) can be estimated by multiplying the concentration at each monitoring well by its appropriate sub-area.

Table 5-5 Annual Values of Average BTEX Concentration and Mass

Concentration (mg/L) | Mass (g) **Historical Maximum**	**Benzene** **21 (1998)**	**Ethylbenzene** **2.7 (2003)**	**Toluene** **47 (1998)**	**Xylenes** **51 (2000)**
2000	4.39 | 57.7	0.472 | 2.2	9.91 | 19.7	13.13 | 75.0
2001	3.19 | 7.9	0.275 | 0.3	6.76 | 15.9	11.18 | 78.5
2002	2.20 | 8.6	0.183 | 1.6	4.13 | 5.8	6.90 | 70.3
2003	1.73 | 10.4	0.195 | 2.9	3.24 | 1.2	5.80 | 47.8
2004	1.50 | 5.0	0.170 | 2.5	2.75 | 0.5	4.96 | 35.0
2005	1.29 | 2.7	0.152 | 1.6	2.35 | 0.3	4.34 | 22.6
2006	1.17 | 1.7	0.140 | 0.7	2.12 | 0.3	4.02 | 17.5

Changes in estimated plume mass over time are shown in Figure 5-6, and show a general decrease over time, except for ethylbenzene (circles). Trend lines are fitted for BTX, and suggest that toluene (squares) is most readily attenuated, while xylenes (triangles) are the most recalcitrant.

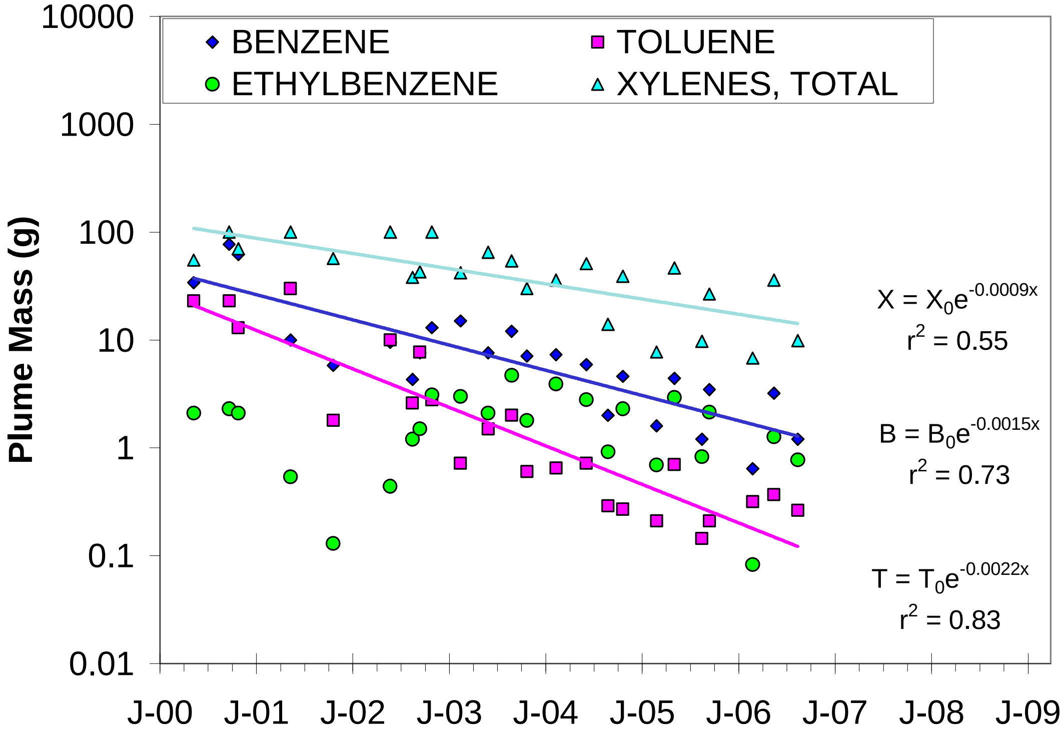


Figure 5-6 Change in dissolved BTEX mass estimated by MAROS over the monitoring period, and fitted trend lines for BTX (no trend for E)

The slopes of the log transformed concentration vs. time plots were derived from linear regression of measured data; thus, results of forward projection should be considered with caution. As shown in Figure 5-5, the slopes (attenuation rates) may not remain constant over time. Nevertheless these values provide a means to forward-estimate the time required to reach BTEX remediation goals, such as the Canadian drinking water guidelines. Assuming full cleanup required concentration reductions of three orders of magnitude from the first available data set (2000), the remediation timeframe was estimated to range from approximately 5 years (k = -0.004 day $^{-1}$) to 15 years (k = -0.0013 day $^{-1}$). Using the minimum average value, the longest cleanup time could be up to 24 years (k = -0.0008 day $^{-1}$; 2003). After 5 years of monitoring (2004), the average attenuation rates remained on the same order of magnitude (k = -0.0019 day $^{-1}$ to -0.0041 day $^{-1}$), but the average concentrations had only decreased approximately half an order of magnitude. Using these new values, the remediation timeframe remained on the order of 5 years. The marginal differences in rates of change of each of the BTEX concentrations, their attenuation rates and likely, their corresponding remediation goals, show how these contaminants need to be considered individually.

The historical monitoring data were re-evaluated by assigning each of the monitoring well locations into 6 zones to look at possible spatial effects. The source is central. Two wells are located upstream (generally non-detect) and are both used to show both no growth in that direction. Overall flow is to the southeast, but some local component of radial outward flow is present. Wells are classified as:

- SOURCE: three wells located near the source, previously had liquid PHC;
- DS PLUME: two wells located downstream (southeast) of the source area;
- N PLUME: two wells located radially northward from the source;
- S PLUME: two wells located radially southward from the source area;
- W PLUME: two wells located radially westward from the source area; and,
- US PLUME: two wells located at the upgradient edge of the source area.

The monitoring well data were analyzed separately for each of these groups using the same approach as described previously for Table 5-3. The average attenuation rates are summarized below for benzene in Table 5-6, where missing values indicate there were insufficient data for analysis. Previous results obtained by combining all data to give a single average are included in the lumped column. Minor differences are noted for these lumped values because the wells classified at the upstream edge of the plume (US PLUME) were removed to be consistent.

Table 5-6 Average Benzene Attenuation First Order Rate Constants (Day $^{-1}$) By Plume Zone

Zone/ Year	**Source**	**DS Plume**	**N Plume**	**S Plume**	**W Plume**	**Lumped**[1]
2000		-0.0015		-0.0060	-0.0036	-0.0022
2001	-0.0025	-0.0046		-0.0029	-0.0037	-0.0027
2002	-0.0021	-0.0018	-0.0033	-0.0033	-0.0036	-0.0028
2003	-0.0016	-0.0030	-0.0013	-0.0024	-0.0032	-0.0023
2004	-0.0021	-0.0020	-0.0014	-0.0025	-0.0026	-0.0021
2005	-0.0025	-0.0015	-0.0012	-0.0027	-0.0023	-0.0020
2006	-0.0031	-0.0012	-0.0010	-0.0028	-0.0020	-0.0020

Note: 1. Re-calculated excluding the US PLUME wells

This grouping indicates that the attenuation rates are variable within the plume. The average attenuation rate appears to be increasing (rate constant becomes more negative) within the source area, but stable or even slowing over time (values are less negative) in the rest of the plume. By comparing the lumped benzene rate constant changes, it appears that natural attenuation of the PHC plume in some parts of the plume may take longer than others. The constants appear to be of similar magnitude (0.002 ± 0.001); however, it is important to recognize the exponential influence. As an example, decreasing the rate constant (k = -0.002 day $^{-1}$) by a factor of 2 in the first order equation ($C=C_0 e^{kt}$) for a concentration reduction of one order of magnitude ($C=0.1C_0$) corresponds to double the clean up time.

5.5 Decision Analysis

The data review presented above provides evidence for typical patterns that may be observed when relying on NA as a remediation strategy. Attenuation rates may vary for individual contaminants, and across different parts of a contaminated site. Moreover, interpreted attenuation rates may vary temporally, making it difficult to predict the time to reach established remediation targets. However, these data were clearly not available when the decision had to be made to select NA as the remediation strategy.

In this section, the data summarized above are used to provide a means for re-evaluating the decision to select NA in the context of a decision analysis framework. Time is turned back to the start of the project to see how decision analysis might have helped when choosing a remediation strategy. The project is thus started using the initial assumptions entered into the decision model, but it is re-calibrated over time using updated results to examine the model for insight that might apply to other similar cases. In this way, the effects of uncertainty may be captured and provide guidance for how uncertainty can be managed with decision analysis.

At the start of the project, decisions regarding the applicability and performance of site remediation using natural attenuation depend heavily on “expert judgment”. The expert has to predict project success, and re-interpret this projection using new data as the project progresses. Thus, the NA monitoring results described previously provide a means to re-examine the monitoring data over the project lifespan compared to the initial assessment provided as expert judgment.

Shortly after the release, in situ remediation methods (liquid pumping and SVE) were used to recover as much of the liquid PHC as possible, given that excavation was not possible. Reliance on NA was subsequently proposed, based on the initial monitoring data. For this research program, a decision model was developed to examine the choice between NA and active remediation, using a hypothetical contingency plan of excavation. As noted in Section 5.1.2, this site provided suitable conditions for NA as a remedial strategy because there were no other site–related environmental issues driving a need for more aggressive remediation at the time.

A decision tree was constructed for the initial decision of choosing between NA and excavation, where the decision metric was lowest expected cost (ECost in $CAD, undiscounted in nominal terms). For comparison purposes, plume excavation was estimated to cost approximately 250K$ using then-current rates for excavation, hauling, landfill disposal and backfilling (assuming it was feasible). Each groundwater monitoring visit to support MNA was estimated to cost approximately 7 K$, based on unit rates for sampling, analyses and reporting. Costs were inflated annually at 2.5% undiscounted. Groundwater monitoring requirements were assumed to decrease over time as data trends became evident: quarterly sampling for two years and annual sampling thereafter.

The go-forward position in the base case is modeled in the decision tree shown in Figure 5-7. Given the small impacted area and spill volume, an original estimate assumed a 15% chance that the dissolved PHC groundwater plume would naturally attenuate completely within 7 years (97.2K$), 50% chance of taking 15 years (171.9K$) and a 35 % chance of taking 30 years (358.1K$). Based on these values, the expected cost of MNA is calculated below:

Cost = K$97.2*0.15+K$171.9*0.5+K$358.1*.35) = 225.8 K$

which is less than the excavation strategy (250K$). Expected cost (225.8 K$) is an estimate of the average cost for a large number of sites, each having similar conditions. It is important to note that the remediation cost at any single site could be higher or lower, as represented by the probabilities and costs in the decision tree.

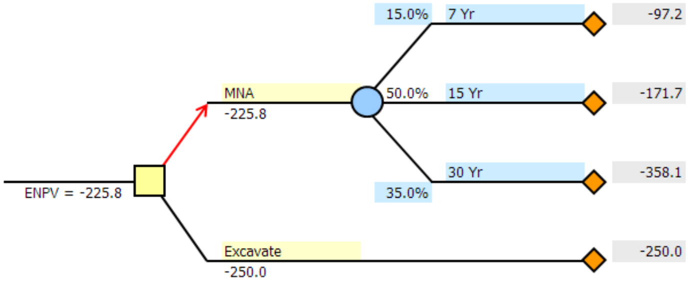


Figure 5-7 Base case decision tree giving estimated costs and likelihoods

Based on minimizing cost, a probabilistic decision process using these input values would always select MNA as the lower expected cost option. However, it is important to recognize that for this case (one specific realization), there is an estimated 35% chance that the remediation will take 30 years and cost more than excavating the contaminated soil. Conversely, if the decision were made to excavate, there is a 65% chance that NA would have cost less.

Expert opinion initially tends to provide a broad distribution of potential outcomes that reflects uncertainty about the 'state of nature', or site-specific conditions. As more monitoring data are collected, the distribution of uncertainty in potential outcomes is expected to narrow. However, an expert must also consider data variability when interpreting the range of expected outcomes. For the site being studied, the value of the 'updated information' is assessed regarding the decision to rely on natural attenuation.

For a general case, a reasonable alternative might be to try NA monitoring for two years. If these data suggest the program would take excessively long (here, set at 30 years), then excavation would be immediately carried out. The decision tree was revised to illustrate this approach (Figure 5-8). The new tree shows that the expected project cost with the two-year pilot remains the same as the base case, because the monitoring data was not reliable enough to change the decision, even when it was interpreted that NA would take 30 years. There remains a 2.7% and 35.4% chance that the NA profile has been misinterpreted and that the actual NA profile will end up being 7 or 15 years, respectively. The method for calculating these changes is shown below. Note that the excavation cost increased to 307.6K$ to include the cost of the two-year MNA pilot plus inflation.

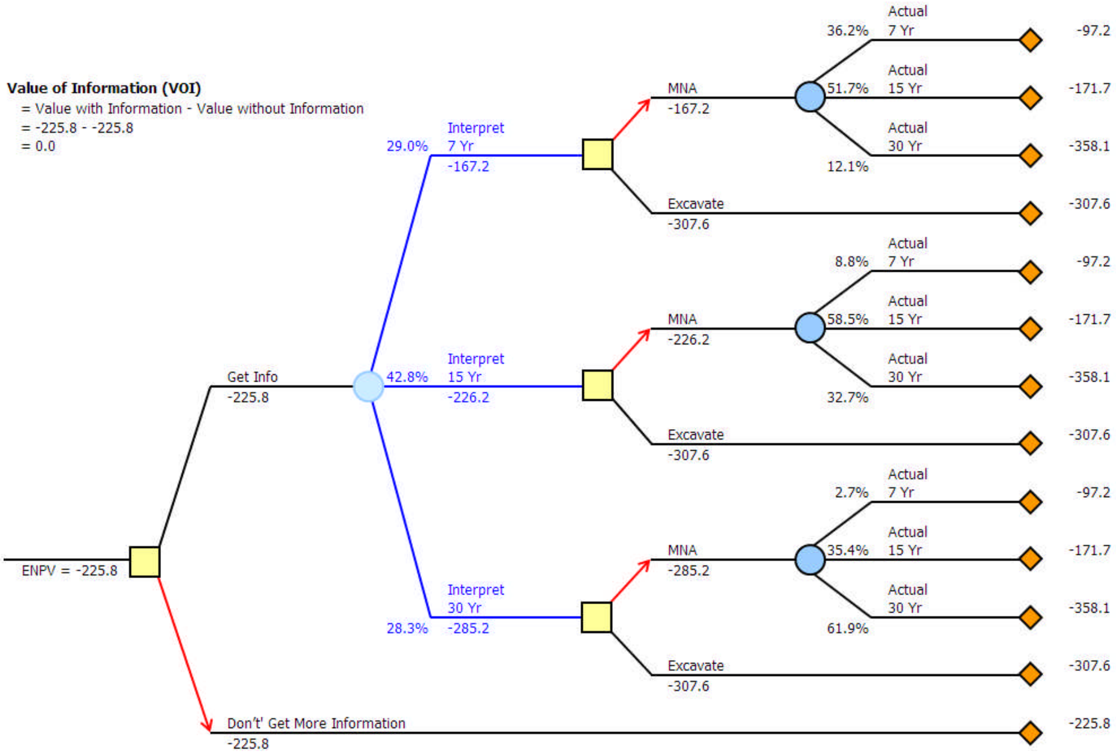
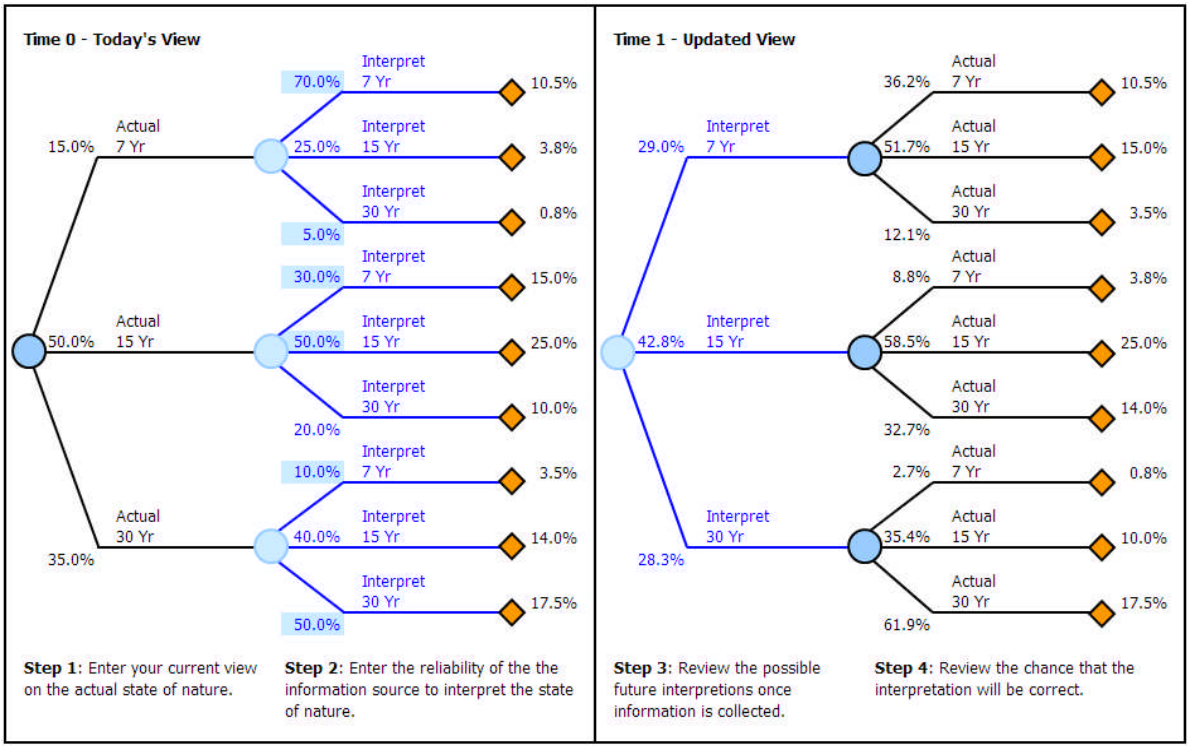


Figure 5-8 Base case with two year MNA pilot test decision tree (figure shows only top branch of decision tree in Figure 5-7)

The probabilities on the tree in Figure 5-8 are derived from an estimated reliability to interpret the outcome correctly using the limited information available from a two year pilot test (i.e., two years of monitoring), as shown in Figure 5-9. The left side tree in Figure 5-9 shows the expert's estimated reliability at predicting the true state of nature (i.e., the reliability of collecting and interpreting data correctly), based on two years of monitoring from the pilot study. Consider first conditions where the actual remediation by NA took 7 years. If a project took 7 years, two years of data would enable correct identification of the 7 year remediation timeframe in an estimated 70% of cases. There remains a 25% chance of mis-identifying it as a 15-year project, but only 5% chance of predicting a 30-year project. Recalling from Figure 5-7 that the expert expects only 15% of all similar projects to take 7 years, values for tree branches (left side) for an actual 7-year project (15 % of cases) are:

- 70% chance of correctly identifying actual 7 year project = 0.7*0.15 = 10.5% of all cases.
- 25% chance of misidentifying actual 7 year project as a 15 yr project =0.25*0.15 = 3.75%
- 5% chance of misidentifying actual 7 year project as a 30 yr project = 0.05*0.15 = 0.75%

The left tree represents the expected reliability of the prediction (Time 0).



Step 1: Enter your current view on the actual state of nature.

Step 2: Enter the reliability of the the information source to interpret the state of nature.

Step 3: Review the possible future interpretions once information is collected.

Step 4: Review the chance that the interpretation will be correct.

Figure 5-9 Decision tree modification using Bayes Law (interpret 7 year project after 2 years of monitoring) values rounded to 1 decimal place.

The underlying logic is that if NA occurs in 7 years (the stated fact), then significant levels of degradation should be evident within 2 years. The expert is asked: "Given that the true state of nature is that the contaminant at this site will remediate in 7 years using NA, how likely is it that you would correctly predict 7 years after collecting 2 years of monitoring data? How often might you predict NA to require 15 years or 30 years?" Similarly, consider the case where NA would actually take 30 years to remediate the site. Correct prediction of 30 years is estimated to occur only 50% of the time with only 2 years of data showing slow degradation rates. Given minimal evidence of degradation in two years, it was considered likely that a 15-year project would be interpreted 40% of the time (to account for project optimism), and a 7-year project 10% of the time (to consider inexperience or misrepresentative data).

The right side tree in Figure 5-9 shows the updated view of the project after the data have been collected. The difference between the trees is that the actual state of nature (left side) is never known, but has to be interpreted (right side). The two trees are related via Bayes Law, by reversing the conditional probabilities of the left hand tree from 'Given actual conditions, how likely might it be interpreted?' to the site situation in the right hand tree 'Given the interpretation, how likely might it be the actual case?' The source of the values is illustrated using the interpreted 7 year project as an example.

A project interpreted to take 7 years could actually be a 7, 15 or 30 year project. From the left tree, these values correspond to:

- actual 7 year project interpreted as a 7 year project (0.70*0.15 = 10.5%);
- actual 15 year project misinterpreted as a 7 year project (0.50*0.30 = 15%); and,
- actual 30 year project misinterpreted as a 7 year project (0.10 * 0.35 = 3.5%)

After adding these probabilities, the 7 year project would be interpreted 29% of the time (10.5% + 15% + 3.5%), even though the expert originally expected only 15% of cases to actually remediate within 7 years. Using the same data, a site interpreted to take 7 years would actually be remediated in 7 years in only 36.2% of the cases (10.5/29), with 51.7% of those cases taking 15 years (15/29) and 12.1% of the cases actually taking 30 years (3.5/29).

These results illustrate the two types of errors to evaluate when considering the reliability of an expert's assessment. A Type I error occurs when a true null hypothesis is incorrectly rejected (Davis, 2002), say, keep on sampling after remediation guidelines have been met. In contrast, a

Type II error occurs when a false alternate hypothesis is incorrectly accepted (say, stop sampling although contamination remains). To paraphrase, a Type 1 error provides a measure of conservatism, as in the case where a 15 year project is interpreted, but it will only take 7 years. A Type II error is likely to be more problematic for environmental considerations, where natural attenuation will actually take 15 years to remediate a site, but is interpreted (and budgeted) as only taking 7 years. While the data provided in this example are not strictly relevant for assessing Type I and II errors (based on one dataset), it is still informative to compare the error magnitudes based on the conditional probabilities provided in the right hand tree of Figure 5-9. The interpreted and actual results would be expected to match up in 53% of cases (10.5+25+17.5). A Type I error would be expected in 14.6% of cases (3.8+10+0.8), while a Type II error would occur in 32.5% of cases (15+3.5+14). These results suggest an initial tendency to overestimate the effectiveness of natural attenuation.

Using the right hand tree in Figure 5-9, the first 2 years of data indicate that the actual state of nature (15% chance that NA would occur in 7 years) would be overestimated, with a 29% chance of predicting a 7 year project. This unintuitive result is driven by the false positive interpretations that could be characterized as over-optimism. Furthermore, even when the data support interpretation of a 7-year program (strong evidence of attenuation), it will actually be correct in 36.2% of the cases, given these expert inputs. More interestingly from a decision perspective, interpretation of a 7 year MNA program based on the first two years of data, will have an extreme downside (defined as a 30 year program) with a probability of 12.1%. By simplifying the cost levels to consider only the three cases of 7, 15 and 30 years, the data suggest there is a 12.1% chance that NA remediation costs will exceed that of excavation. For a specific case, there is clearly a cross-over point between 15 years and 30 years when monitoring starts to become the more expensive option.

Returning to the case history data, the first two years of monitoring data (2000) suggested that a threefold order of magnitude drop in concentration would take approximately 7 years ($C/C_0=0.001$, $k=0.0036$ day $^{-1}$, $t=\ln(C/C_0)/k$, $t=5$ years, plus 2 years monitoring). A detailed review showed that 14 of 44 combinations of well & contaminant had >95% confidence limits on the attenuation rates (data not shown). The estimated time of 7 years may be optimistic for general plume behaviour, but is used here to illustrate how new data are incorporated.

The first 2 years of data initially indicate that this particular site may be on the 7-year branch of the original base case decision tree and reliability estimate (Figure 5-8). Values from the branch for Interpret 7 Year (top branch, right hand of Figure 5-9) were introduced to reflect the updated view of actual conditions. These values showed that the updated probability of a 7-year project has increased to 36.2%; the 15-year project remains essentially constant (51.7%) and the 30-year project decreases to 12.1%. This new tree is shown in the left side of Figure 5-10, along with an updated version of the reliability interview. In this case, the same questions as before were repeated, but assuming that 4 year's worth of data were available (Figure 5-10). As shown in the left side of Figure 5-10, after 4 years of data were available, an actual 7-year project would be recognized in 90% of cases, with only 10% of cases actually taking longer (5% at 15 years and 5% at 30 years). This change is somewhat intuitive, because interpretation of a 7-year program based on 4 years of data should be more dependable compared to when the project started (with no data).

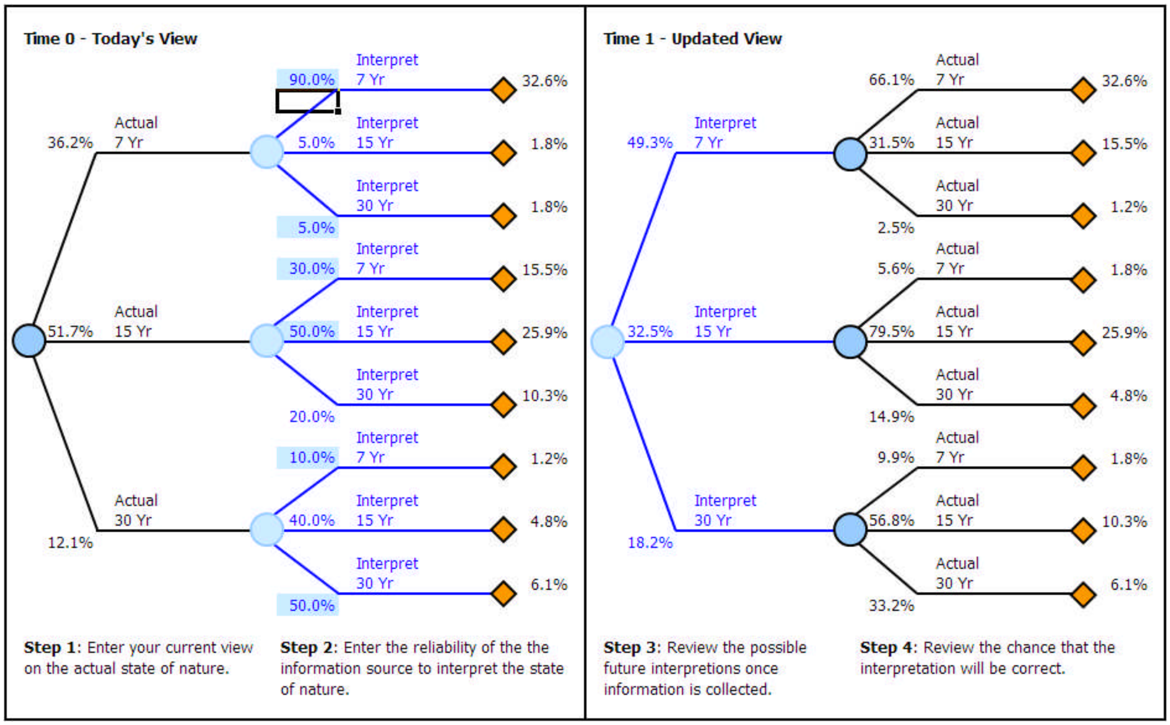
The remainder of the tree was then populated as before, and the Bayes Law reversal was done for the conditional probabilities. The right hand side of the tree in Figure 5-10 shows that a project interpreted to require 7 years would have a 66.1% probability of finishing in that time frame. The probabilities for the interpreted 15 year and 30 year projects have also increased (79.5% and 33.2%, respectively). At this point, the interpreted and actual results would be expected to match up in 64.6% of cases (32.6+25.9+6.1), a Type I error would be expected in 13.9% of cases (1.8+1.8+10.3), while a Type II error would occur in 21.5% of cases (15.5+1.2+4.8).

In contrast, attenuation rates derived from 4 years of field data indicated that the projected remediation time frame had increased to approximately 11 years ($k=-0.0025$ day^{-1}; $t=7$ years + 4 years monitoring). The updated (but conservative) view is therefore that the project may now take 15 years to reach the endpoint, where confidence in this interpretation has increased to 79.5% (right hand tree, Figure 5-11).

The decision tree calculations were again repeated using the middle branch from the right hand tree in Figure 5-11 (Interpret 15 Year) and updated insight gained from 6 years of monitoring (2004). As before, the input probabilities (left hand tree, Figure 5-11) reflect the updated view of the true state of nature.

The left hand tree in Figure 5-10 shows that the reliability estimates become extremely high for the 7-year project (98%) because the project should be almost complete. The estimates also increase higher for the two other possible outcomes (80% for the 15 and 30 year projects), as the elapsed time becomes an increasing fraction of estimated project life.

Based on the most recent available monitoring data at that time (2004), the attenuation rates suggest the project lifespan may be more like 12 years ($k=-0.0016\ day^{-1}$).



Step 1: Enter your current view on the actual state of nature.

Step 2: Enter the reliability of the the information source to interpret the state of nature.

Step 3: Review the possible future interpretions once information is collected.

Step 4: Review the chance that the interpretation will be correct.

Figure 5-10 Updated decision tree (interpret 15 year project after 4 years of monitoring)

Based on the available data at this time, the project is considered most likely to require 15 years to achieve remediation goals. Based on the initial cost estimates, the expected cost of the 15 year NA monitoring program will be on the order of 170$K, giving an approximate savings of $80K compared to immediate excavation. From a full cost perspective, the NA program did not include source removal activities, but neither did it include consideration of a notable reduction in monitoring effort as data become available.

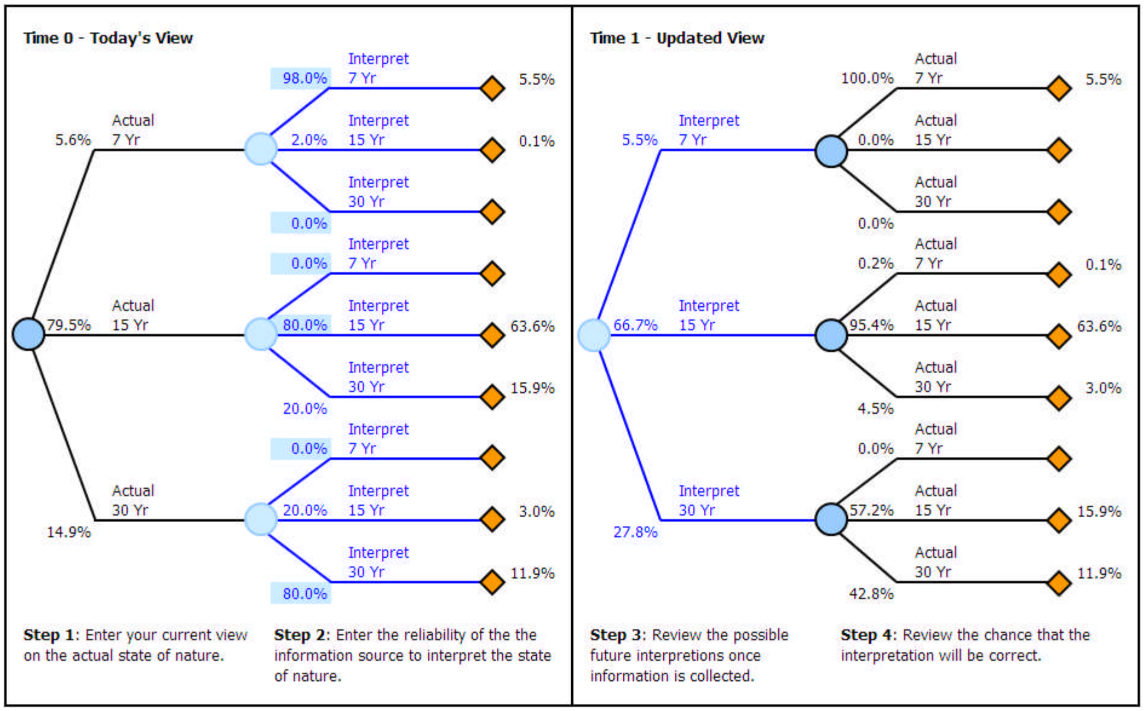


Figure 5-11 Updated decision tree (interpret 15 year project after 6 years of monitoring)

Replacing the updated interpretation shown in Figure 5-10 into the original expected project cost calculation, the total expected project cost has not changed significantly from K$225 (Figure 5-7) to K$220, as shown below:

Cost = K$97.2*0.055+K$171.9*0.667+K$358.1*.278) = 219.6 K$

5.6 Discussion

It is accepted that most projects have some level of uncertainty as to how they will proceed, but it is not always appreciated that this fact is not changed by a conscious decision of whether to consider or ignore the uncertainty. When trying to estimate future results, there is a range of potential outcomes that can often not be constrained. Given the complexity inherent in natural attenuation processes, it may never be possible to characterize all of the active processes and their relative influences. This approach for trying to analyze the embedded uncertainty is really an attempt to recognize and highlight the ranges of uncertainty. In this way it may be possible to choose a path that increases the odds of making a "reasonably" accurate prediction of what will happen. By using expert input, this approach also tries to capture 'professional judgment and experience' in a quantitative manner.

The probabilistic basis for the decision analysis is also intended to provide decision makers with a better understanding of the ranges of outcomes and their associated probability. These tools can also be used to assess sensitivity, where decision makers can see the effect of changing the various inputs. It is important to note that the probability values apply to expected outcomes for a number of similar sites. Each individual site is only one realization from the range of outcomes, thus the decision-maker is gaining insight regarding the range of possible outcomes and their associated likelihood of occurring when using this strategy to decide what should be done.

The comparison of interpretations made after adding each set of two additional years' monitoring shows how the predicted outcome may change. In this case, the attenuation rates decreased, suggesting a longer time frame was required to reach the clean up goal (arbitrarily set at three order of magnitude decrease in dissolved hydrocarbon concentrations). However, the associated level of confidence in the interpretation of attenuation trends increased. Despite the increased confidence, further changes may still yet be identified in the future. As an example, complete exhaustion of a terminal electron acceptor or inhibition of biodegradation due to another process could alter the underlying assumptions of attenuation behaviour. Similarly, the assumption that first-order kinetics describes attenuation may prove to be unrealistic over the specified three order of magnitude decrease in concentrations.

Several other topics to consider are identified, but are beyond the scope of this paper. The original metric used for making the decision about remediation methods was expected cost. Incorporation of other potentially influential factors may change the decision in non-obvious ways. Examples of such factors include liability minimization, inclusion of time-value of money, and external factors such as cleanup time, regulatory change, alternate land use, and asset liquidation.

The decision analysis work presented here could also be used to examine implications of changing how NA is tracked. As an example, this project is assumed to use a consistent monitoring schedule. The combination of increased confidence in both monitoring data and project lifespan at later stages of the project could be used to justify changing the monitoring program. Depending on the local regulatory regime, the data may provide the necessary support to decrease the monitoring frequency, analytical schedule and/or number of wells tested. If approved, these modifications would clearly lead to a further reduction in total project cost.

5.7 Conclusions

A combination of soil vapour extraction and groundwater monitoring was used to control the source area of a natural gas condensate release where excavation was not an option. Based on early monitoring data supporting the interpretation that the dissolved PHC plume was attenuating naturally, a monitored natural attenuation program was implemented. While NA appears to continue, recent data suggested that the average attenuation rate was decreasing (longer-than-expected remediation timeframe).

A hypothetical review of this case was conducted (assuming that excavation had been an option), to examine the original decision to rely on NA. A decision tree was constructed (NA vs. excavation) to examine how collection of new monitoring data affected project cost between expected and actual attenuation behaviour.

Monitoring data showed that the average attenuation time period to achieve remediation objectives (based on an assumed first-order reaction) was underestimated by the early time data, leading to an underestimated expected project cost. Even after 6 years of monitoring, the chance of underestimating the clean-up time remained significant (47%), largely because of the apparent decrease in attenuation rate over the early time interval.

The results suggest that interpreting NA response from the first two years of monitoring data may not be conservative, especially for estimating a clean-up time frame. The monitoring data set also show varying attenuation behaviour of individual PHC compounds and locations, but that a lumped approach (averaged response of compounds in all plume wells) was adequate for classifying attenuation behaviour, at least on a scaling basis (say, decades). Estimation of an expected remediation timeframe is complicated by the different remediation targets set for each of the BTEX compounds. In this case study, the expected remediation time frames for the various BTEX compounds appeared to be within approximately a factor of two.

The MAROS software was intuitive, easy to use, and provided valuable insight regarding PHC attenuation in both individual monitoring wells and the overall plume. Although not seen for this case study, the software would be limited when addressing more complex geology/hydrogeology. Care is required to ensure appropriate monitoring data are used and avoid possible complexity related to the kind of data variability seen in Chapter 3.

Surprisingly, for the set of costing assumptions used here, the unexpected changes in attenuation response had little effect on the total expected cost of the project and the original decision to rely on NA. It is apparent that different basic assumptions could change this conclusion.

5.8 References

Armstrong, J.E., Burkholder, M.K. and Biggar, K.W., 2004. Applying decision analysis to site remediation, Canadian International Petroleum Conference, Calgary, AB.

ASTM, 1998. Standard Guide for Remediation of Ground Water by Natural Attenuation at Petroleum Release Sites. E 1943 - 98, American Society for Testing and Materials.

Aziz, J.J., Newell, C.J., Ling, M., Rifai, H.S. and Gonzales, J.R., 2003. Monitoring and Remediation Optimization System (MAROS) Software V 2.0: User's Guide GSI 2236. Air Force Center for Environmental Excellence, U.S.A., pp. 306.

Davis, J.C., 2002. Statistics and Data Analysis in Geology. John Wiley & Sons, New York, 638 pp.

Farnham, I.M., Singh, A.K., Stetzenbach, K.J. and Johannesson, K.H., 2002. Treatment of nondetects in multivariate analysis of groundwater geochemistry data. Chemometrics and Intelligent Laboratory Systems, 60(1): 265-281.

Johnson, P.C., 2002. Editorial/ Risk-based, quota-based, or fund-based LUST closures? (career-limiting editorial #1, the final episode ...). Ground Water Monitoring and Remediation, 23(4): 4.

Rittmann, B.E., 2004. Definition, objectives and evaluation of natural attenuation. Biodegradation, 15: 349-357.

Skinner, D.C., 2001. Introduction to Decision Analysis. Probabilistic Publishing, Gainesville, FL, 369 pp.

USEPA, 1999. Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites. OSWER Directive 9200.4-17P, Office of Solid Waste and Emergency Response Directive, Washington, DC.

Whitman, R.V., 1984. Evaluating calculated risk in geotechnical engineering. Journal of Geotechnical Engineering, 110(2): 145-188.

6. CONCLUSIONS

6.1 Overview

Reliance on natural attenuation (NA) to manage contaminated groundwater requires developing a site conceptual model that describes how the contaminants are cleaned up before affecting any nearby receptors. Elements of the conceptual model include contaminant distribution, fate and transport behaviour, attenuation mechanisms and potentially sensitive receptors that might be affected if the plume continues to migrate. Monitoring is then conducted to show that contaminants continue to attenuate as proposed in the model. Detailed research into individual NA processes has identified extreme complexity, such that models may not be able to provide predictive behaviour from a process perspective. Nevertheless numerous field-based assessments have provided sufficient evidence for regulators to accept that dissolved contaminant plumes in groundwater do attenuate naturally.

This research program focussed on two main topics that commonly generate underlying uncertainty related to NA assessment. The first topic addressed how best to sample groundwater and incorporate uncertainty issues related to NA assessment. The second topic considered how to incorporate changes in NA understanding, based on monitoring data, when deciding whether or not NA may provide an appropriate remediation alternative for any given case.

6.2 Sampling

A large component of the uncertainty in many NA data sets is due to the combined influences of well completion details and sampling methods used to characterize contaminant situations. During initial site characterization, there are trade-offs between using longer screened wells (to ensure that any zone within the soil profile containing contaminated groundwater is sampled) and shorter screened wells (to limit in-well mixing when sampling groundwater only from within or outside the contaminated zone). This research focused on how to interpret NA processes using groundwater data obtained using several sampling methods from monitoring wells with different screen lengths.

The research presented in Chapters 3 to 5 examined several issues related to collecting and interpreting groundwater samples for characterizing natural attenuation of dissolved hydrocarbon contamination. The research involved groundwater sampling for dissolved hydrocarbon contaminants and inorganic geochemical analytes representing terminal electron acceptors (TEAs, including nitrite+nitrate, sulphate, dissolved iron and dissolved manganese). Other TEAs were either field-measured (i.e., dissolved oxygen via a downhole probe) or not considered in this work (dissolved methane). It cannot be stressed enough that conditions at every site may require re-assessment, especially factors that relate to local geologic and contaminant considerations.

Measurable thicknesses of free phase liquid hydrocarbon were not present in either of the shallow, unconfined aquifers studied in this program (Sites A and B), but the original source PHC located upgradient had not been fully remediated. Dissolved hydrocarbon concentrations were typically dependent on combined influences of contaminant thickness and water table fluctuations. Accordingly the most consistent analyses were obtained for samples collected from short-screen wells (0.7 m) installed just below the water table.

Most major ions and dissolved hydrocarbon analyses for samples collected over the two years of monitoring from each of the 0.7 m discrete-interval samplers (DP-series) typically ranged within a factor of two, indicating notable temporal stability within these individual wells. In contrast, the major TEAs (dissolved iron and sulphate) showed variability of up to half an order of magnitude within each well. Between individual DP-series wells (midpoints separated vertically by approximately 1 m), many analytes differed by up to an order of magnitude. Sample heterogeneity should be expected if sampling over vertical intervals greater than 1.5 m.

Results from slightly longer screened wells (approximately 1.5 m) gave similar order of magnitude estimates of BTEX compounds, but had greater ranges and temporal changes in main ions, TEAs and BTEX. The greater variability was likely due to the longer mixing zone, but may have included some influence from recharging precipitation and/or increased oxidation of shallow groundwater. These wells still appeared able to play a useful role for monitoring PHC plumes, especially at sites where seasonal water table elevations exceed approximately 1.5 m. The increased variability should be taken as a cautionary indicator when trying to interpret changes over time. A complicating factor that could not be assessed at Site A may have been that the original source was episodic, thus it is unclear how the variability might relate to the intermittent presence of free-phase hydrocarbon.

At Site A, samples collected from ‘conventional’ 3 m long screened wells across the same interval as the DP-series of wells showed much greater analytical variability over time, complicating interpretation of natural attenuation behaviour. Analyses from these wells typically ranged over one to two orders of magnitude during the same two-year period. The variability problem appeared to be greater near the hydrocarbon source where chemical variation with depth was greater. Despite problems with assessing how to address this variability at each well, time-averaged data from the longer 3 m screened wells appeared adequate for identifying 'plume-scale' contaminant presence and geochemical trends consistent with natural attenuation. These interpretations were based on apparent decreases in variability with increasing distance from the source. The large variability, especially in TEA concentrations, reduced confidence in drawing more detailed process-related inferences about NA performance.

The variability problem within the 3m screened wells at Site A could not be resolved by using quasi depth-specific sampling methods (e.g. DDS samplers) compared to low flow-sampling or more integrating methods (e.g., bottom-loading bailer or Waterra). Based on limited data, the dialysis membrane diffusion samplers appeared to give similar order of magnitude results as the conventional methods. Individual DDS analyses inconsistently varied both within pairs in the same well, and between pumped samples from the longer-screened wells by a factor of 2 to half order of magnitude.

A linear mixing model was used to examine how analyses from the shorter- and longer-screen wells might be related, but no consistent pattern was identified. It is interpreted that the net mixing effect within a longer-screened well is a combination of influences related to groundwater flow, chemical mixing and local hydrochemical variability.

In general, the different groundwater sampling methodologies tested (bailer, Waterra, low-flow purge with peristaltic or DDS) did not appear to influence data variability any more than was already interpreted as being due to mixing within the longer 3 m screens. Data collected using the DDS approach were similar to results from conventional purging, but offered a potential to save sampling time. Comparisons between samples collected using three types of purging protocol (no-purge, low-flow purge and conventional purge) also did not lead to consistent differences between samples, particularly when compared to the greater temporal variability. The sampling data indicated no clear preference for any of the sampling methods

One exception, apparently related to seasonal influence, was observed at Site A, where differences in sulphate concentrations were seen between no-purge and low-flow purge samples collected from well P34 near the contaminant source. The results were interpreted as showing temporal variations in sulphate reduction. Although the data were not definitive, the differences appeared to be related mostly to the rate of infiltration of sulphate-rich water compared to rate of sulphate reduction. These differences (observable only in shorter-screened wells completed across the water table) provided a simple means to estimate the rate of sulphate depletion (and presumably hydrocarbon degradation). Other research involving laboratory mesocosms, field sulphate injection and numerical simulation had supported sulphate amendment to enhance hydrocarbon biodegradation.

6.3 NA Performance

The relevance of sampling-induced variability is most likely to be problematic when trying to do forward-projection of attenuation behaviour based on current hydrochemical evidence. By controlling variability in sampling results through better well completion and sampling programs, and understanding the magnitude of temporal concentration variation, confidence can be increased in the processes underlying the conceptual model. Recognition of underlying variability sources is critical when trying to use historical data for NA assessment.

Natural attenuation is a complex process where some degree of uncertainty must be accepted when trying to project future attenuation behaviour. This uncertainty may comprise a general component (e.g., analytical and sampling variability up to a factor of two), and a site-specific component that relates to the local hydrogeology and contaminant situation (e.g., Site A had much greater variability than Site B due to steep hydrochemical gradients). The generic conceptual model of NA needs to be combined with a local assessment of uncertainty ranges for the monitoring data. As examples, Sites A and B (no source remediation at either Site) had notably different NA responses, where Site A monitoring data had much greater data ranges and variability.

Site C has undergone source remediation, and is currently being monitored to examine NA performance. The data were re-examined to see how ongoing sampling fits the original projected attenuation behaviour. Using an alternative hypothetical choice of excavating the contaminated area (not actually possible due to pipe infrastructure), use of decision trees and reliability assessments were illustrated. The case shows the influence of updated monitoring information on the original range of expected outcomes through re-calibration of the decision tree.

In combination with source removal, NA appeared to be managing the plume. NA assessment based on the first two years of data (termed early monitoring data) tended to be optimistic. As additional monitoring information became available, the average attenuation rate generally decreased but still indicated that NA could continue to manage the dissolved hydrocarbon plume. At this site, the decrease in attenuation rate (approximately by a factor of two) was noted after four years, and effectively doubled the time for remediation. Early-time quarterly sampling identified variability.

7. FUTURE DIRECTIONS

The research results presented in these papers relate to assessing natural attenuation of hydrocarbon contaminants at upstream oil and gas facilities. All three cases were selected where there was no apparent or immediate concern about PHC plumes affecting third party stakeholders or ecological receptors. In a general case, NA assessment may require additional site characterization and analysis effort than was conducted here to explain the relative contributions of factors causing variability in monitoring data. Without a credible explanation, it is foreseeable that external stakeholders (particularly landowners or potential receptors) might not accept arguments supporting NA effectiveness. It is therefore suggested that additional sites where NA is being proposed, implement additional confirmatory studies to examine temporal variability; its impact on interpretation of site behaviour; and, whether the variability can be better controlled or constrained. Repetition of these types of studies will improve understanding of 'typical' data variability, and assessment of contributions through temporal changes or sampling protocols.

A key finding of this research was recognition of the site-specific nature of variability in groundwater analyses relative to well construction details and sampling protocol. Given multiple potential causes, careful consideration is required when trying to assess data variability. As an example, seasonal and precipitation-related variations were interpreted at Site A using the detailed data set, but these influences might not have been predicted. Communicating an accurate understanding of how this data variability affects NA interpretation to regulators and non-technical stakeholders will require technical insight and teaching skill.

Development of NA guidelines was originally based on the concept of site remediation. The data from the three research sites suggest that NA may be able to achieve site remediation, but only when hydrocarbon sources have been removed. If the hydrocarbon source remains, NA might control/manage a contaminated groundwater plume, but the project may last decades. Avoidance of problems associated with NA not meeting expectations will require raising awareness about NA's role as a long-term plume management strategy.

Data collected during the research showed that monitoring wells with conventional 3m long screens may complicate detailed interpretation of NA, especially if the site has a strong vertical chemical gradient (a likely case). While such wells may still serve a purpose for site characterization, reliance on NA may require installation of replacement wells with shorter screens. This situation is hard to assess; thus, site owners, consultants and regulators need to increase their awareness of variability associated with the well completion length.

When making a decision to rely on natural attenuation, it is important to consider a variety of potentially influential metrics. While cost is an obvious factor, others such as liability minimization, time-value of money, regulatory changes, modified land use, and asset liquidation may be influential. Given the underlying reliance on natural processes (site owner commitment only to monitoring), decisions will be increasingly likely to require both scientific input and inclusion of complex interactions related to political and social issues. Research and insight is required to understand how such interactions occur, especially given their unpredictable nature and underlying probabilistic character. This type of research is likely to be very challenging, possibly requiring a need to incorporate post-normal science concepts developed in the social sciences rather than in environmental sciences.

APPENDIX I

CORONA-RELATED PUBLICATIONS LIST

JAMES ARMSTRONG

Department of Civil and Environmental Engineering
University of Alberta

Graduate Supervisor: Dr. K.W. Biggar

CONSORTIUM FOR RESEARCH ON NATURAL ATTENUATION **SEPTEMBER 2008**

Refereed Journal Articles

Cross, K.M., K.W. Biggar, K. Semple, J. Foght, S.E. Guigard and J.E. Armstrong, 2006. Natural attenuation of invert diesel fuel contaminating cold groundwater in a bedrock formation. Journal of Environmental Engineering & Science, Vol. 5, no. 1, pp. 13-27.

Ulrich, A, S.E. Guigard, J.M. Foght, K. Semple, K. Pooley, J.E. Armstrong and K.W. Biggar, 2008. Effect of salt on aerobic biodegradation of petroleum hydrocarbons in contaminated groundwater. Biodegradation. Published online:
http://www.springerlink.com/content/p0g7267815511h70

McLeish, K.L., M.C. Ryan, and A. Chu, 2007. Integrated sampling and analytical approach for common groundwater dissolved gases. Environmental Science & Technology. 41:8388-8393

Van Stempvoort, Dale R., J.E. Armstrong and B. Mayer, 2007. Microbial reduction of sulfate injected to gas condensate plumes in cold groundwater. Journal of Contaminant Hydrology, **92**, pp. 184-207.

Van Stempvoort, Dale R., J.E. Armstrong and B. Mayer, 2007. Seasonal recharge and replenishment of sulfate associated with biodegradation of a hydrocarbon plume. Ground Water Monitoring & Remediation **27**, pp. 110-121

Theses

Armstrong, James E., 2008. Variability in groundwater monitoring data used to assess natural attenuation of hydrocarbon contamination at upstream oil and gas facilities. Doctor of Philosophy thesis. Unpublished. University of Alberta, Edmonton, AB.

Cross, Katherine M., 2002. Natural attenuation at upstream oil and gas sites. Master of Science thesis. Unpublished. University of Alberta, Edmonton, AB.

Fan, Xiaoying, 2008. Enhancement of Anaerobic Biodegradation of Petroleum Hydrocarbons in Groundwater: Laboratory Mesocosm Studies. Doctor of Philosophy thesis. Unpublished. University of Alberta, Edmonton, AB.

Iwakun, Olumide, 2006. Use of dialysis sampler for monitored natural attenuation assessment. M.Sc. thesis. Unpublished. University of Alberta, Edmonton, AB. 158 pp.

Morin, Dean, 2008.

Petersmeyer, Chad W., 2006. Assessing natural attenuation of petroleum hydrocarbons using reactive transport modelling with aqueous and solid phase data. Master of Science thesis. Unpublished. University of British Columbia, Vancouver, BC, 273 pp.

Conference Proceedings

Hosseini, A.H., Deutsch, C.V., Biggar, K.W. and Mendoza, C., 2008. Uncertainty in spatial distribution of residual NAPL and its downstream impacts. Proceedings, 61st Annual Canadian Geotechnical Conference and 7th Joint CGS/IAH-CNC Groundwater Specialty Conference, September 21 – 24, 2008, Edmonton, AB.

Hosseini, A.H., Biggar, K.W., Deutsch, C.V. and Mendoza C., 2008. Uncertainty in measured biodegradation rate constant for heterogeneous aquifers. Proceedings, 61st Annual Canadian Geotechnical Conference and 7th Joint CGS/IAH-CNC Groundwater Specialty Conference, September 21 – 24, 2008, Edmonton, AB.

Fan, X., Guigard, S., Foght, J., Semple, K.M. and Biggar, K.W., 2007. Enhancement of anaerobic biodegradation of petroleum hydrocarbons in groundwater: laboratory Mesocosm studies. Proceedings, Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, May 7-8, 2007, Edmonton, AB.

Hosseini, A.H. 2007. A distance function based algorithm to quantify uncertainty in areal limits. Proceedings, 9th Annual CCG Meeting, September 27-28, 2007, Edmonton, AB.

Hosseini, A.H. Data integration for characterization of spatial distribution of residual hydrocarbon. 9th Annual CCG Meeting, September 27-28, 2007, Edmonton, AB.

Semple, K., Fan, X., Foght, J., Guigard, S., and Biggar, K.W, 2007. Detecting anaerobic hydrocarbon biodegradation “signature metabolites” in a two-year laboratory study of petroleum-contaminated groundwater and sediment. Proceedings, Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates. May 7-8, 2007, Edmonton, AB.

Van Stempvoort, D. R., Armstrong, J.E., and Biggar, K.W. 2007. Groundwater recharge as a mechanism to replenish sulfate for bioremediation of hydrocarbon plumes. Proceedings, 60th Canadian Geotechnical Conference 8th Joint IAH-CNC/CGS Conference, Ottawa, ON.

Alostaz, M., Biggar, K.W., Donahue, R., and Hall, G. 2006. Using fluorescence emission-excitation matrices (eems) and parallel factor analysis (parafac) for characterizing soil petroleum contaminants. Proceedings, 59th Canadian Geotechnical Conference and the 7th Joint CGS/IAH-CNC Groundwater Specialty Conference, October 1-4, 2006. Vancouver, BC.

Fan, X., Guigard, S., Foght, J. Semple, K., and Biggar, K.W. 2006. A mesocosm study of enhanced anaerobic biodegradation of petroleum hydrocarbons in groundwater from a flare pit site. Proceedings, 59th Canadian Geotechnical Conference and the 7th Joint CGS/IAH-CNC Groundwater Specialty Conference, October 1-4, 2006. Vancouver, BC.

Hosseini, A., Biggar, K.W., Deutsch, C.V., and Mendoza, C.A., 2006. Geostatistical analysis of CPT-UVIF data for development of a site conceptual model. Proceedings, National Groundwater Association Annual Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, November 6-8, 2006. Houston, Texas.

Ulrich, A.C., Biggar, K.W., Armstrong, J.E., van Stempvoort, D., Tappenden, K., and Rogers, P. 2006. Impact of cold temperatures on biodegradation rates. Proceedings, 59th Canadian Geotechnical Conference and the 7th Joint CGS/IAH-CNC Groundwater Specialty Conference, October 1-4, 2006. Vancouver, BC.

Armstrong, J.E. and Biggar, K.W., 2005. Sampling methods and monitoring data variability: influence on MNA assessment. Presentation at: Remediation Technologies Symposium (RemTech) 2005 (ESAA), October 19-21, 2005. Banff, AB.

Armstrong, J.E., Biggar, K.W. and Burkholder, M.K., 2005. Decision analysis of expert input related to cost evaluation of natural attenuation. Proceedings of 58th Canadian Geotechnical Conference and 6th joint IAH-CNC/CGS Conference, September 18-21, 2005, Saskatoon, SK.

Fan, X., Guigard, S.E., Foght, J., Semple, K., Biggar, K.W., 2005. A mesocosm study of enhanced anaerobic degradation of petroleum hydrocarbons in groundwater. Proceedings, Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, May 8-10, 2005, Edmonton, AB.

Foght, J., Semple, K., Pooley K., Guigard, S.E., and Biggar, K., 2005. Effect of salt on aerobic biodegradation of petroleum hydrocarbons in contaminated groundwater. Proceedings, Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, May 7-10, 2005, Edmonton, AB.

Iwakun, O., Biggar, K.W., Armstrong, J.E., Donahue, R., and Sego, D.C., 2005. Evaluation of a diffusion sampling system for MNA assessment. Proceedings, 58th Canadian Geotechnical Conference and 6th joint IAH-CNC/CGS Conference, September 18-21, 2005, Saskatoon, SK.

McLeish, K. Ryan, C., Armstrong, J. and Chu, A., 2004. Application of passive gas diffusion sampling to MNA, Proceedings of the 2005 Geological Society of America Conference, November 6 – 11, 2004, Denver, CO.

Van Stempvoort, Dale R., J.E. Armstrong, K.W. Biggar, O. Iwakun, and G. Bickerton, 2005. Research on bioremediation of petroleum hydrocarbons in groundwater in cold climates: limitations or opportunities? Presentation at: Remediation Technologies Symposium (RemTech) 2005 (ESAA), October 19-21, 2005. Banff, AB.

Armstrong, J.E., Burkholder, M.K., and Biggar, K.W., 2004. Applying decision analysis to site remediation. Paper 2004-137. Proceedings, Petroleum Society's 5th Canadian International Petroleum Conference, June 8-10, 2004 Calgary, AB.

Armstrong, J.E., Biggar, K.W., Morin, D.M. and McLeish, K., 2004. Sampling-method-induced variability and its influence on interpretation of natural attenuation of hydrocarbons, proceedings of 57th Canadian Geotechnical Conference, 5th Joint IAH-CNC/CGS conference, October 25-27, 2004, Quebec City, QC.

Burkholder, M.K., Armstrong, J.E., and Biggar, K.W., 2004. A case study using the decision analysis process to select a remediation strategy for an upstream oil and gas facility. Proceedings of: Remediation Technologies Symposium (RemTech) 2004 (ESAA), October 14-15, 2004, Banff, AB.

Armstrong, J.E., Deutsch, C., and Biggar, K.W., 2003. Geostatistical assessment of cone penetrometer test data for soil characterization based on ultraviolet induced fluorescence, proceedings of 56th Canadian Geotechnical conference, 4th joint IAH-CNC/CGS conference, September 29-October 1, 2003, Winnipeg, MB.

Armstrong, J.E. and Biggar, K.W., 2003. Natural attenuation as remedial strategy for the upstream industry, presentation at Canadian International Petroleum conference, June 10-12, 2003, Calgary, AB.

Biggar, K.W., Woeller, D., Murphy, S. and Armstrong, J.E., 2003. Ultraviolet induced fluorescence cone penetration testing for characterization at hydrocarbon contaminated sites. Proceedings: Remediation Technologies Symposium (RemTech) 2003 (ESAA), October 15-17, 2003, Banff, AB.

Cross, K.M., Biggar, K.W., Semple, K., Foght, J., Guigard, S., and Armstrong, J.E., 2003. Intrinsic bioremediation of invert diesel fuel contaminating groundwater in a bedrock formation. Proceedings: 2003 third biennial workshop on Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, May 5-6, 2003, Edmonton, AB.

Cross, K.M., Biggar, K.W., Semple, K., Foght, J., Guigard, S.E., and Armstrong, J.E., 2003. Biodegradation of weathered diesel fuel in groundwater in anaerobic and aerobic microcosms to assess natural attenuation of total extractable hydrocarbon range petroleum hydrocarbons. Proceedings: 2003 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation, August 20-22, 2003. Costa Mesa, CA.

Biggar, K.W., Woeller, D., Murphy, S., and Armstrong, J.E., 2003. UVIF-CPT characterization at upstream oil and gas facilities. Proceedings, Vancouver Geotechnical Society annual symposium, Geotechnical Engineering for Geoenvironmental Applications, 22 May, 2003, Vancouver, B.C. pp. 31-37.

Armstrong, J.E., Biggar, K.W., Staudt, W.J., Moore, B.J. and Cross, K.M., 2002. Monitored natural attenuation at upstream oil and gas sites in Alberta. Western Environment Business, Vol. 3, issue 2: 16-18

Biggar, K.W., Armstrong, J.E., Cross, K.M., Foght, J., Guigard, S., 2002. Natural attenuation of diesel range petroleum hydrocarbons deep in fractured bedrock at cold temperatures, abstract and presentation; European Conference on Natural Attenuation, October 15-17, 2002, Heidelberg, Germany.

Epp, T., Armstrong, J.E., and Biggar, K.W., 2002. Guideline development for use of monitored natural attenuation at contaminated sites in Alberta. Proceedings of: European Conference on Natural Attenuation, October 15-17, 2002, Heidelberg, Germany, pp. 64-67.

Epp, T., Armstrong, J.E., and Biggar, K.W., 2002. Guideline development for use of monitored natural attenuation at contaminated sites in Alberta. Proceedings of: Remediation Technologies Symposium (RemTech) 2002 (ESAA), October 16-18, 2002 Banff, AB.

Van Stempvoort, D.R., Armstrong, J.E., and Mayer, B., 2002. Bacterial sulfate reduction in biodegradation of hydrocarbons in low-temperature, high-sulfate groundwater, western Canada, proceedings of 2002 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation, 19th annual Conference and Exposition (NGWA/API), November 6-8, 2002, Atlanta, GA.

Van Stempvoort, D.R., Armstrong, J.E., and Biggar, K.W., 2002. Significance of sulfate reduction in bioremediation of hydrocarbons in groundwater. Proceedings of 55th Canadian Geotechnical and 3rd joint IAH-CNC/CGS Conference, "Ground and Water: Theory to Practice", October 21-24, 2002, Niagara Falls, ON.

Armstrong, J.E., Biggar, K.W., Cross, K.M., Moore, B.J. and Staudt, W.J., 2001. Natural attenuation assessment at upstream oil and gas sites in Alberta. Proceedings of 6th Canadian/American Conference on Hydrogeology. July 9-10, 2001. Banff, AB.

Armstrong, J.E., Greene, E.A., Cross, K.M., Moore, B.J. and Staudt, W.J., 2001. Biological activity assessment to support monitored natural attenuation at upstream oil and gas sites in Alberta Canada. Proceedings of 54th Canadian Geotechnical Conference, September 16-19, 2001, Calgary, AB.

Cross, K.M., Armstrong, J.E., and Biggar, K.W., 2001. Characterization of monitored natural attenuation at upstream oil and gas sites in western Canada. Proceedings of 54th Canadian Geotechnical Conference, September 16-19, 2001, Calgary, AB.

Cross, K.M., Biggar, K.W., Semple, K., Foght, J., Guigard, S.E., and Armstrong, J.E., 2001. Monitored natural attenuation of diesel fuel contaminating groundwater in a bedrock formation. Proceedings of 54th Canadian Geotechnical Conference, September 16-19, 2001, Calgary, AB.

APPENDIX II

RESEARCH SITE DESCRIPTION SUMMARY

JAMES ARMSTRONG

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF ALBERTA

GRADUATE SUPERVISOR: DR. K.W. BIGGAR

CONSORTIUM FOR RESEARCH ON NATURAL ATTENUATION **SEPTEMBER 2008**

GENERAL SITE DESCRIPTION

BACKGROUND

Three demonstration sites were identified as candidate MNA sites for the detailed sampling program based on a monitoring data review performed as the first stage of the CORONA program (Armstrong et al. 2001). A fourth site was subsequently added to provide appropriate monitoring data for assessing longer term projections of NA effectiveness as a remediation strategy. One of the original sites was subsequently deemed inappropriate. Site access became problematic, delaying site characterization by months. When limited site access was granted, the first round of additional site characterization activities identified complexity not interpreted from the original conceptual model of the contaminant situation. The goal of CORONA was to examine process and sampling effects; thus this additional complexity made the site inappropriate. Site locations are summarized in Table AII-1 with approximate locations for the three sites used in this work shown in Figure AII-1. Site details and local site plans are provided in the following sections, along with generic descriptions of sampling-related issues.

Table AII-1 Sites Selected for CORONA Research Program

Site Name	Original Plume Wells	Added Plume Wells
Site A (originally Site 3)	3	2 well clusters+6 wells
Site B (originally Site 1)	4	1 well cluster+18 wells
Site C (originally Site 4)	14	No installations
Site D (originally Site 2)	2	6 wells

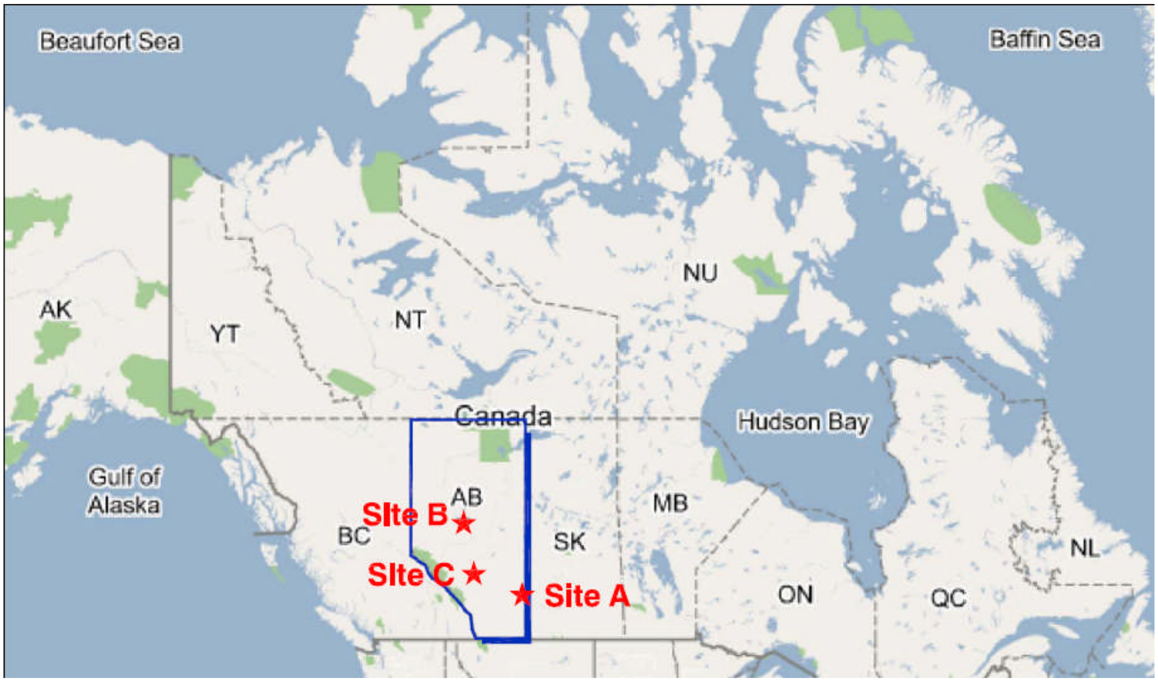


Figure AII-1 Site locations used in CORONA research

SITE A CONDITIONS SUMMARY

SITE DESCRIPTION

Site A is located in southeast Alberta. The shallow surficial unconsolidated material at the site generally consists of laminated and very fine silty sands. With increasing depth, this material grades into varved silts (~5 m depth) and eventually to varved clays at approximately 10 m depth. These lower deposits are lacustrine in origin; the upper fine silty sand is likely of aeolian origin. Grain size analyses of the upper fine silty sand classify the texture as predominantly on the boundary between coarse silt and fine sand. The groundwater surface is located approximately 2 to 3.5 m below ground surface (mbgs). There are multiple potential sources of the natural gas condensate, but the main source is likely to have been the Fire Training area. No free phase hydrocarbon is present in the research area, but apparent thicknesses up to approximately 1 m have been measured further upgradient. The research area is shown in Figure AII-2.

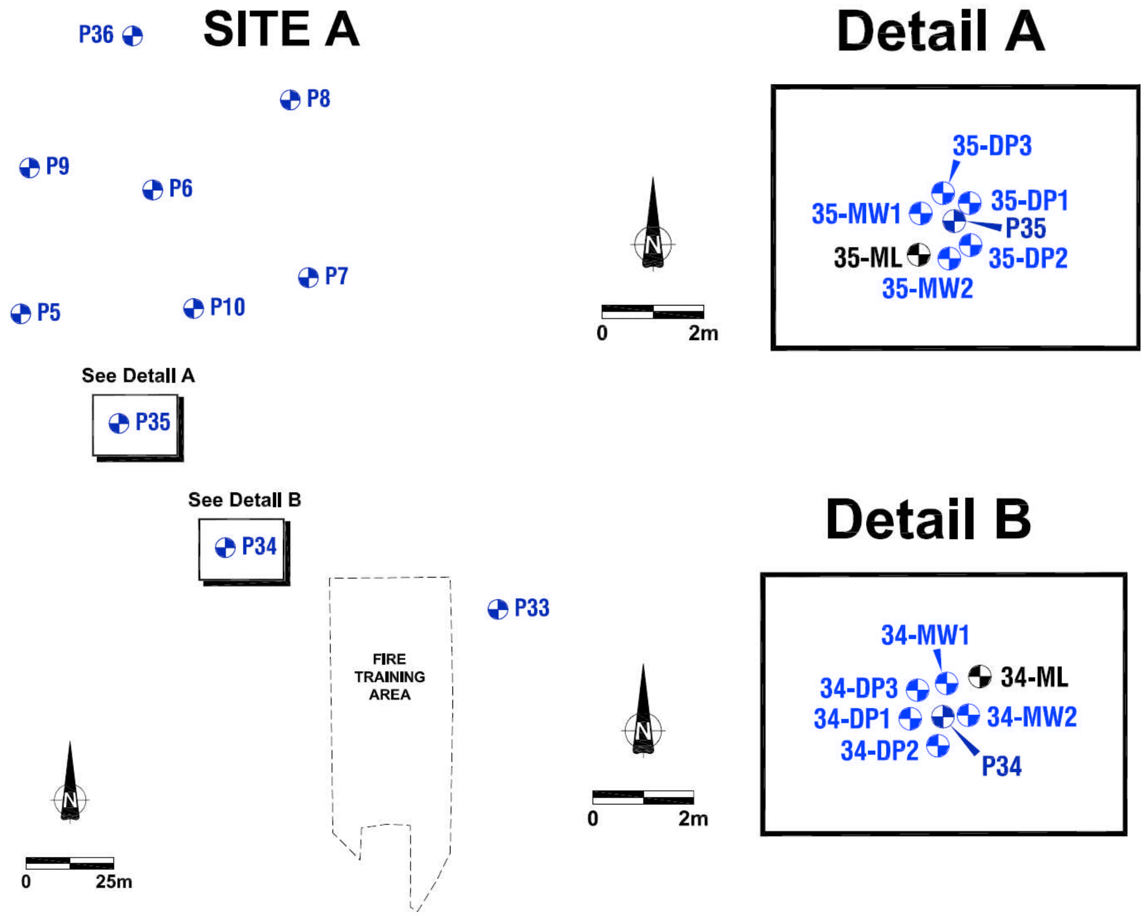


Figure AII-2 Site A wells and research well cluster details

Conventional monitoring wells (3 m screens, 0.05 m diameter PVC pipe) were installed downgradient of the zone of known hydrocarbon impact. Clusters of closely spaced monitoring wells were also installed adjacent to conventional monitoring wells P34 and P35. Each cluster comprised two conventional wells (MW-series; 3 m screened intervals, 0.05 m diameter), three direct push wells (DP-series; 0.75 m screened intervals, 0.025 m diameter), and a multi-level well (ML-series; effective screened intervals of 0.6 m, 0.01 m diameter). Completion depths were intended to provide comparisons between the various wells over similar monitoring intervals. The direct push screens and multi-level wells were installed approximately near the top, middle and bottom of the 3 m long screened intervals. A closely spaced network of one injection well and 6 monitoring wells (0.7 m long screened sections) were installed approximately 15 m upgradient of the CORONA research area (not shown, located between Fire Training area and P34). This well network was used for a related project directed by Environment Canada personnel (Van Stempvoort et al. 2007) that looked at the utility of injecting sulphate-laden water to enhance anaerobic hydrocarbon biodegradation based on sulphate reduction. The monitoring network comprised 9 locations (3 existed prior to CORONA inception).

The ultraviolet induced fluorescence (UVIF) method used in conjunction with cone penetrometer testing (CPT) was found to be unreliable for hydrocarbon liquid identification at this site. Test CPT-UVIF holes advanced adjacent to monitoring wells known to contain free hydrocarbon had variable signals, generally characterized by very low UVIF response. At one location, a second borehole was advanced using a conventional auger rig near the monitoring well. The soil log confirmed the hydrocarbon presence identified in the original monitoring well, but not clearly seen in the CPT-UVIF log. This result was a catalyst for a spin-off research program currently being conducted at U of A to improve the ability of the UVIF method to identify hydrocarbon presence using a series of fluorescence-inducing light emitting diode (LED) sources. The research has since determined that the excitation wavelength of the UVIF LED was too high to generate fluorescence in gas condensate.

FLOW CONDITIONS

Hydraulic conductivity (K) values were measured using slug tests at the monitoring wells throughout the plume area downgradient of the local source. It is recognized that K values from slug tests are indicator values only, given the extremely local zone of testing influence. Nevertheless, values measured for a number of monitoring wells completed throughout the plume area showed a relatively limited range over one order of magnitude (2×10^{-6} to 2×10^{-7} m/s). Based on local geologic considerations (fining downward sequence), K values would be expected to decrease with depth. Furthermore, a generally decreasing trend in averaged K values is interpreted spatially from the source area ($1.7\text{x}10^{-6}$ m/s, n=4) to the downgradient plume area ($3.4\text{x}10^{-7}$ m/s, n=3). Vertical changes in K were assessed at the two research well clusters, and ranged from negligible at the 34-cluster to an apparent two order of magnitude decrease with depth at the P35-cluster.

Seasonal fluctuations in the groundwater flow direction and hydraulic gradient were evident within the plume area, but the overall groundwater flow pattern was consistently toward the northwest. The two sets of depth-discrete sampling points at each cluster indicated a slight (DP-series) to nonexistent (ML-series) downward vertical groundwater flow component. Differences between the DP-series wells are on the order of 1-2 cm, near the measurement error. Seasonal shifts in the groundwater flow pattern can affect contaminant distribution and interpretation of natural attenuation behaviour (Lee et al. 2001, Schirmer et al. 2001).

The link between precipitation and water level fluctuations is shown in Figure AII-3. Detailed seasonal water table fluctuations were examined by recording water levels every 2 hours for one year in one of the longer screen wells at the P34-series cluster. Precipitation data were obtained from an Environmental Canada weather station approximately 30 km north of the site (http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html). Based on historical data, the annual variation was noted to be approximately 0.5 to 1 m, with the annual minimum typically occurring in late winter to early spring (February-March). The logged data showed a larger annual range (1.5 m), and a series of intermittent, episodic water table increases (amplitude up to 1 m) during summer and early fall. The data suggest precipitation caused the rapid recharge events (e.g., 1 m water table rise in 2 days), followed by longer intervals of dissipation (e.g., 0.5 m water table drop in 16 days). Preferential infiltration features (gopher holes) were observed at this site, but their potential influence is not known. A detailed spatial assessment of water table changes would be required to assess this possibility.

Seasonal fluctuations of the groundwater surface in both the P-34 and P-35 well clusters generally remained within the black-stained soil interval noted when the boreholes were drilled. It is inferred that the blackened interval indicates the historical water table fluctuation. Mineral analyses conducted on black-stained soil was found to be notably enriched in ferrous and sulphide minerals compared to soil from above the stained interval (Van Stempvoort et al. 2007).

The 2005 precipitation and water level data were reviewed for evidence of infiltration-based reaction (Figure AII-4). Early in June 2005, a series of precipitation events followed closely on each other for three weeks. During that time, the water surface elevation in 34-MW1 rose rapidly (approximately 1.1 m). After precipitation essentially stopped in early July, the water table dropped approximately 0.86 m over 41 days. Two similar pulsed increases were then observed in August (rise 0.91m in 3 days, drop of 0.55 m in 16 days, rise 0.66 m in 1 day, drop 0.62 m in 21 days).

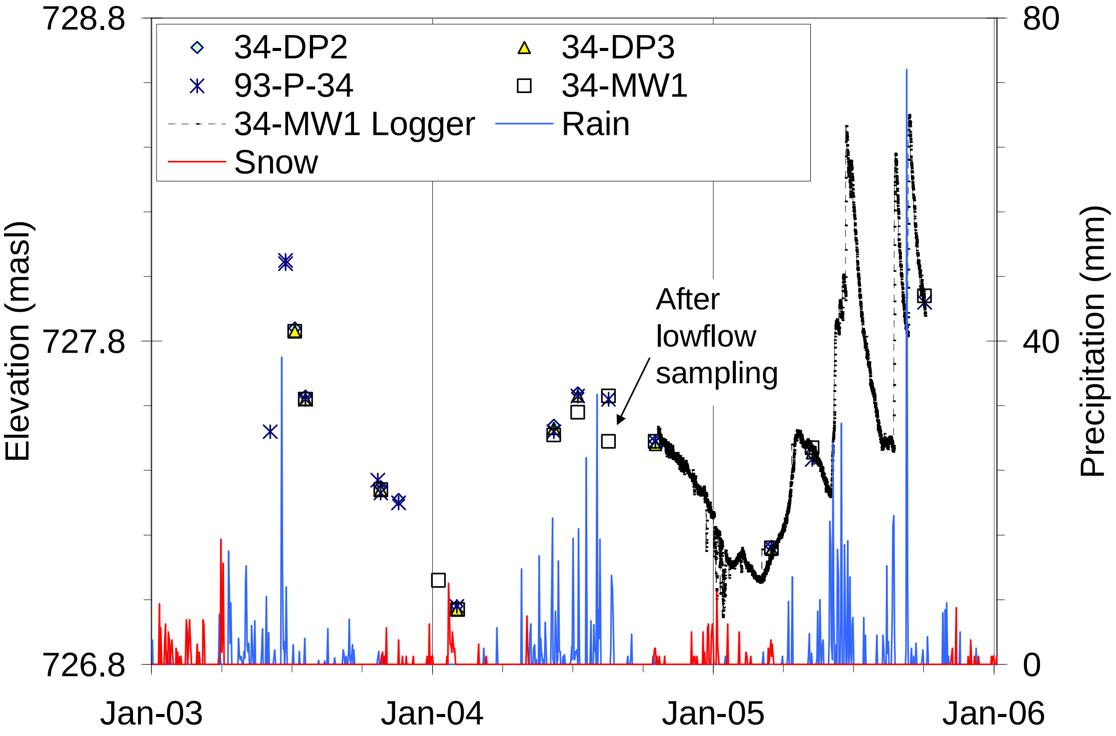


Figure AII-3 Precipitation and water level data (manual points and data logger curve): P34 cluster

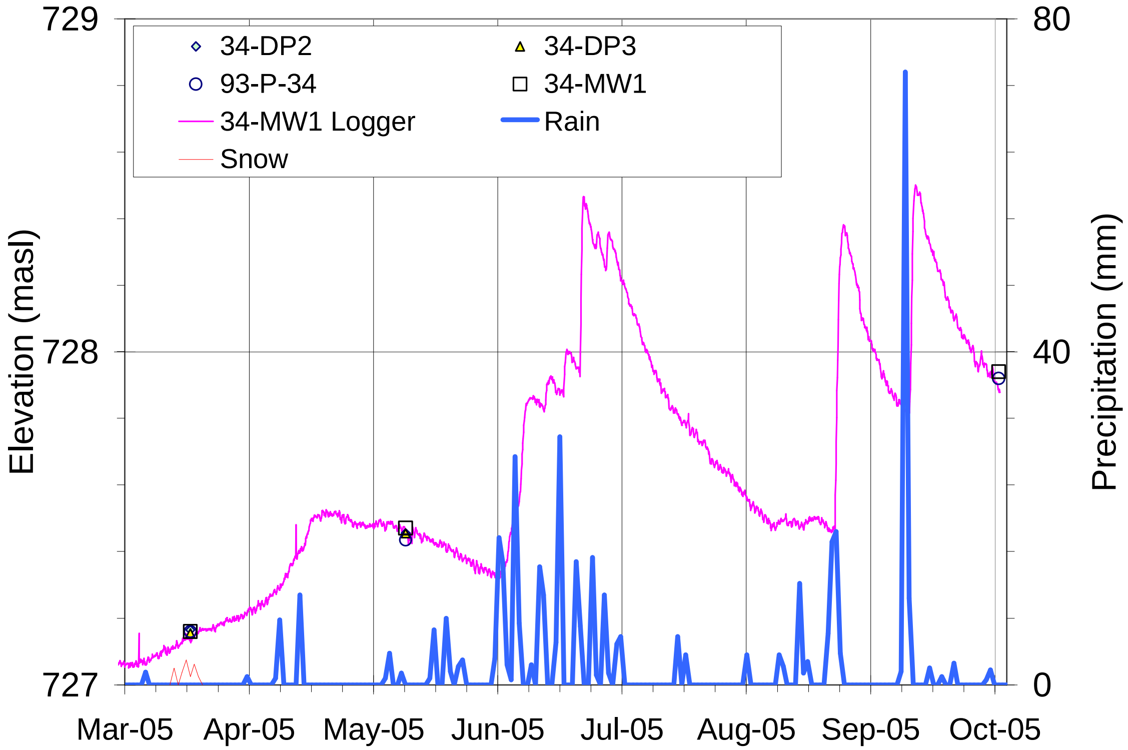


Figure AII-4 Detail of water level and precipitation data: P34 cluster

CLIMATIC CONDITIONS

Weather data were obtained from Environment Canada records for a nearby weather station (approximately 30 km north of the site). A plot of available mean daily precipitation and temperature data in 2003 to 2005 is presented in Figure AII-5. These data show relatively large variations in mean precipitation intensity and time-varying temperatures over the recorded period. From 2003 to 2005, the total precipitation reported as rain was 218 mm, 290 mm and 454 mm, respectively. The last snow after winter may vary from March to May, with the first snow generally seen in October or November. At this site, late spring snow falls may sometimes play a major role as a source of recharge water. As noted in 2003 and 2004, mean temperatures exceeded 0 ^{o}C for several weeks prior to the spring snow, thus rapid infiltration may have occurred during the subsequent melt.

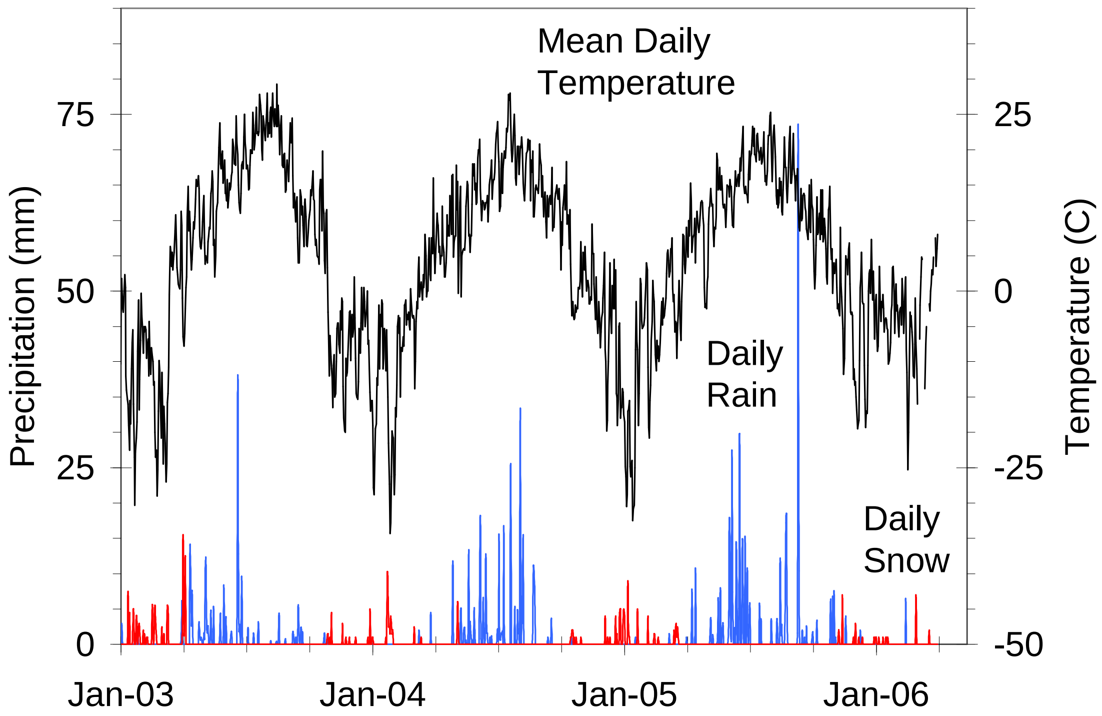


Figure AII-5 Daily precipitation and temperature: weather station near Site A

CONTAMINANT DESCRIPTION

The inferred contaminant source was the Fire Training area. In this location, free phase natural gas condensate produced at the facility was used to set artificial fires to provide practice for facility staff in working with realistic situations. It is understood that the Fire Training area was initially unlined, thus unburned condensate may have been able to enter the subsurface. A sample of the condensate was collected from a monitoring well installed in a nearby part of the site where a tank leak had occurred, and submitted for hydrocarbon characterization. The analysis is provided in Appendix III. This sample was considered to represent a reasonable surrogate for hydrocarbon released in association with fire training activities.

NATURAL ATTENUATION CHARACTERIZATION

Site characterization activities had already identified apparent hydrocarbon contamination, based on black soil staining, odour, and field-measured explosimeter readings. Based on the spatial pattern of soil staining, average groundwater flow direction and nearby facilities, it is possible that hydrocarbon identified near the Fire Training area may also include some proportion from further upgradient to the east. In general, the hydrocarbon source was the same natural gas condensate, thus plume co-mingling likely does not complicate general site understanding, but does increase the source mass function. Site conditions relevant to NA assessment are summarized in Figures AII-6a (groundwater and total BTEX concentrations, June 2004) and AII-6b (dissolved iron and sulphate concentrations).

The soil in this area was classified as varying thicknesses of silty sand through sandy clay, generally grading finer with depth. Analytical results from two monitoring wells (0.05m diameter PVC, screened from 2 to 3 mbgs) located downgradient from the main source showed evidence of hydrocarbon contamination, based mainly on target BTEX compounds. The limited inorganic analyses showed evidence of sulphate depletion (< 1 mg/L) and iron enrichment (40 mg/L) relative to background conditions (700-2,000 mg/L and <0.1-0.4 mg/L, respectively) measured in downgradient monitoring wells with no measurable hydrocarbon compounds. Within the plume wells, a possible downward trend in BTX compounds was evident, but ethylbenzene concentrations were variable. The Fire Training area and upstream source area have not been remediated.

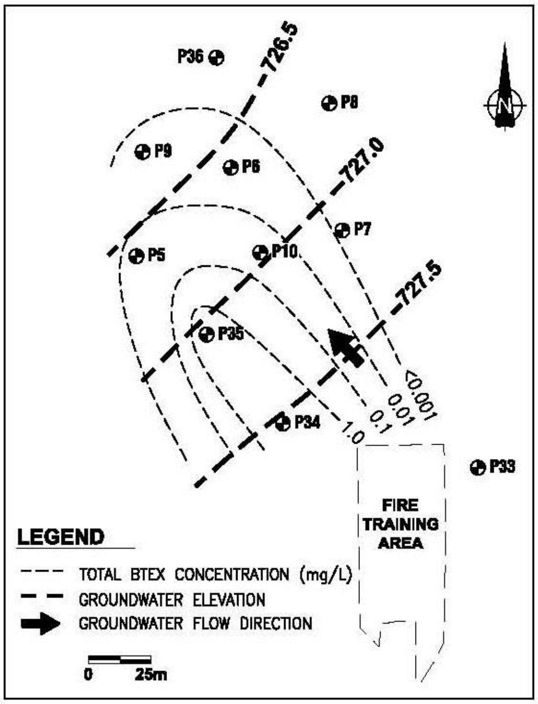


Figure AII-6a Groundwater surface elevations and dissolved BTEX concentrations (mg/L)

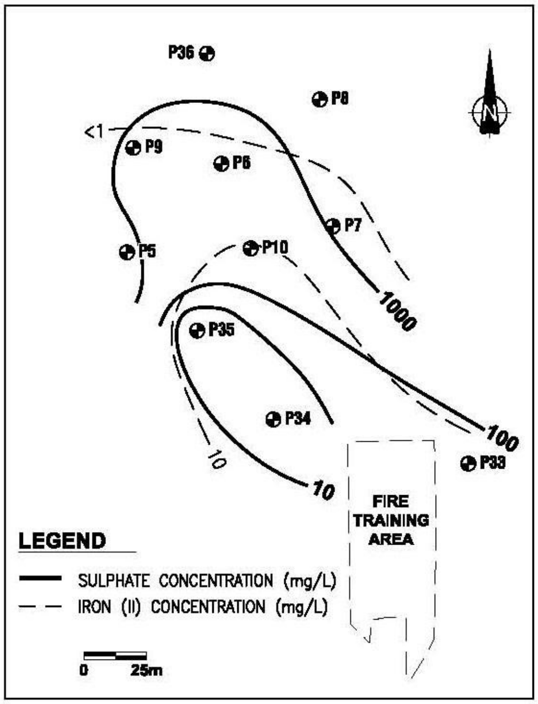


Figure AII-6b Iron (II) and sulphate concentrations (mg/L)

During installation of the additional monitoring wells, soil samples were collected for grain size and mineralogical characterization. The soil in the new boreholes was generally characterized as a surficial silt layer overlying silty fine-grained sand and silt and clay. Limited grain size analyses confirmed the general characterization of these soil units.

Soil samples from two depths at three locations were submitted for X-ray diffraction analysis (XRD, Department of Earth and Atmospheric Sciences, University of Alberta) to characterize crystalline mineral composition: P34 cluster (2.4-3.0 and 4.3-4.9 mbgs); P35 cluster (2.7-3.0 and 4.6 mbgs) and 03-8 (2.0-2.3 mbgs and 3.0-3.7 mbgs). This analysis does not provide information on amorphous minerals, but mineral extractions were subsequently conducted to assess amorphous mineral phases relevant to NA assessment (Petersmeyer 2006). The XRD results showed generally similar mineral phases in all locations, comprising quartz and various feldspar and clay minerals. Dolomite ($CaMg(CaCO_3)_2$) was also generally present, with calcite ($CaCO_3$)

reported only in the deeper samples from P8 and P35. Crystalline pyrite (FeS_2) and siderite ($FeCO_3$) were only detected at 03-8, in the shallow sample (above the thin, grey-stained interval) and deeper sample (containing the thin, grey-stained interval), respectively. As noted by others who sampled this site (Petersmeyer 2006, Van Stempvoort et al. 2007), amorphous minerals likely dominate geochemical reactions related to biodegradation.

Groundwater samples were collected from ten monitoring wells throughout the plume and submitted to HydroQual Laboratories for a battery of indicator tests intended to identify biodegradation potential. Results are provided in Appendix III, and summarized in Table AII-2, according to well position relative to the plume geometry.

Table AII-2 Biological Evidence of Natural Attenuation

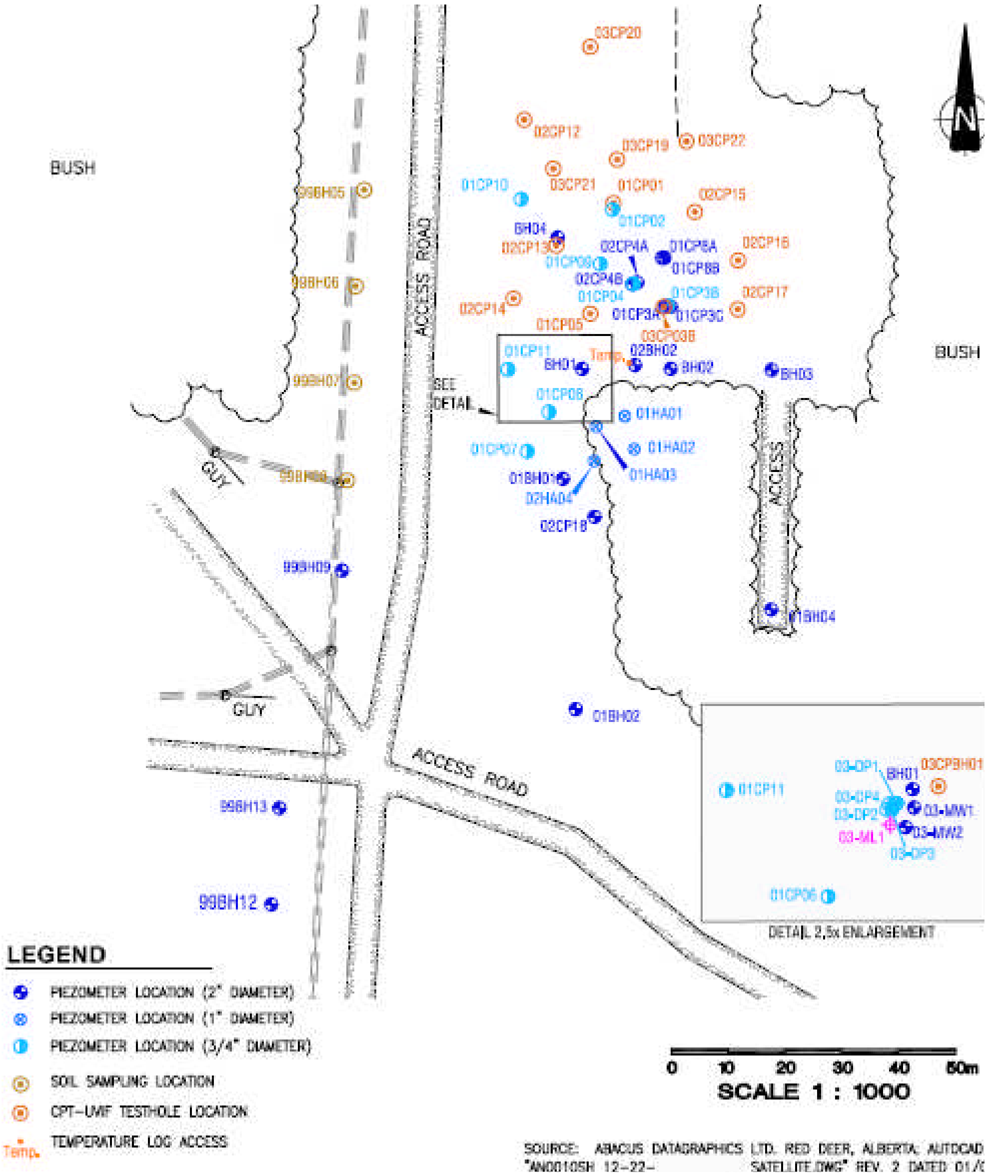
Locations	Wells	SRB (log cfu/mL)	Aerobic (log cfu/mL)	BIOLOG Response Aerobic/Anaerobic
Plume Core	P34, P35&35MW2	10^5	10^4	11, 17 & 17 / 7, 19 & 15
Plume Path	P10, P6	10^4	10^3, 10^2	1 / 0
Plume End	P8	10^3	10^3	2 / 0
Plume Sides	P5, P7, P9	10^2, 10^3, 10^3	10^3	1, 4, 1 / 5, 5, 1

The results showed equally high numbers of iron-related bacteria in all well samples. In contrast, the highest estimated populations of sulphate-reducing bacteria were reported for the samples from the central part of the plume, with elevated values reported for wells within the plume. Samples from wells at the plume end and sides had yet another order of magnitude lower numbers. The highest BIOLOG diversity response (most number of substrates) was reported for the plume core wells.

SITE B CONDITIONS SUMMARY

SITE DESCRIPTION

Site B is located in west central Alberta. Shallow soil comprises interbedded layers of sand or silty clay till overlying fractured siltstone (typically > 4 mbgs in the research well cluster). The site has a topographic slope to the south away from the original source area (former flare pit). The flare pit was excavated, but some hydrocarbon-contaminated soil was left in place. Due to the topography, depth to groundwater varies from more than 6 m below ground surface (mbgs) near the source to less than 1 mbgs at the plume's distal end. The research area is shown in Figure AII-7.



SOURCE: ABACUS DATAGRAPHICS LTD. RED DEER, ALBERTA; AUTOCAD "AN00105H 12-22- SATELLITE.DWG" REV. 2 DATED 01/(

Figure AII-7 Site B wells and research well cluster details

Additional detailed site characterization was conducted at Site B to improve the then-current understanding of site conditions. The first phase used CPT-UVIF to provide objective information regarding fine-scale (0.05 to 0.2 m) variations in soil properties. When combined with UVIF, the results were especially insightful at Site B. The UVIF data identified a heterogeneous and unpredictable distribution of liquid hydrocarbon southwest and south of the former flare pit. Most notably, hydrocarbon was identified in a deeper water-bearing zone below an existing monitoring well that had routinely been sampled and shown to be uncontaminated. UVIF data showed limited hydrocarbon impact to the southwest, and a more continuous zone of impact extending south of the flare pit below the shallow water-bearing zone.

Drilling was conducted to install additional monitoring wells and provide a relatively dense monitoring network, at least compared to what is commonly available at contaminated sites in Alberta. The extra wells improved characterization of local groundwater flow patterns and contaminant distribution.

At Site B, wells were installed within selected CPT holes, typically using 1.0 m long screened intervals and 0.02 m diameter pipe. Conventional 3 m long, 0.05 m diameter wells were also installed in selected locations relative to zones of suspected free phase hydrocarbon. Due to access restrictions in a heavily-treed area at the south end of the plume, four shallow monitoring wells (1 m screened interval, 0.025 m diameter) were installed using a hand auger. A sealed borehole was installed to 5 mbgs and filled with vegetable oil prior to installation of a thermistor series for logging subsurface temperatures (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 mbgs).

A cluster of closely-spaced monitoring wells was installed beside an existing conventional monitoring well that had been used to monitor site conditions. The cluster comprised two conventional wells (MW-series; 3 m screened intervals, 0.05 m diameter), four direct push wells (DP-series; 0.75 m screened intervals, 0.025 m diameter), and a multi-level well (ML-series; effective screened intervals of 0.6 m, 0.01 m diameter). Completion depths were intended to provide comparisons between the various wells over similar monitoring intervals. The direct push screens and multi-level wells were installed approximately near the top, middle and bottom of the 3 m long screened intervals.

FLOW CONDITIONS

Hydraulic conductivity (K) values were measured using slug tests at the monitoring wells throughout the plume area downgradient of the local source. It is recognized that K values from slug tests are indicator values only, given the extremely local zone of testing influence. The measured values showed quite a large range (1.3×10^{-9} m/s to 1.6×10^{-6} m/s). Even within the immediate area of the research well cluster, measured K values also showed a relatively large range (3.2×10^{-8} m/s to 1.2×10^{-6} m/s), with the lower values tending to be measured in the deeper wells.

An average K value for the plume area was estimated, using the common assumption that the individual measurements follow a log-normal distribution (Freeze and Cherry 1979). The average value, 1.6×10^{-7} m/s is within the range typically expected for fine-grained silt soils. The data did not show any clear spatial trends, consistent with the general model of heterogeneous soil types derived from a geostatistical review of the CPT logs (Armstrong et al. 2003).

Groundwater levels were measured over four different depth intervals at the research well cluster (shallowest in DP-1 to deepest in DP-4), and are shown in Figure AII-8. According to these data, there is a small component of upward groundwater flow between the two shallowest direct push wells (water surface elevations are higher in DP-2 than DP-1). In contrast, groundwater surface elevations consistently decrease from DP-2 through to DP-4, indicating a downward vertical component of groundwater flow. This observation suggests that monitoring wells completed over more than one of these would likely be subject to flow-induced mixing. The data show that the longer screened well, BH01, tends to have a groundwater surface level between the two shallowest discrete interval wells (DP1 and DP2).

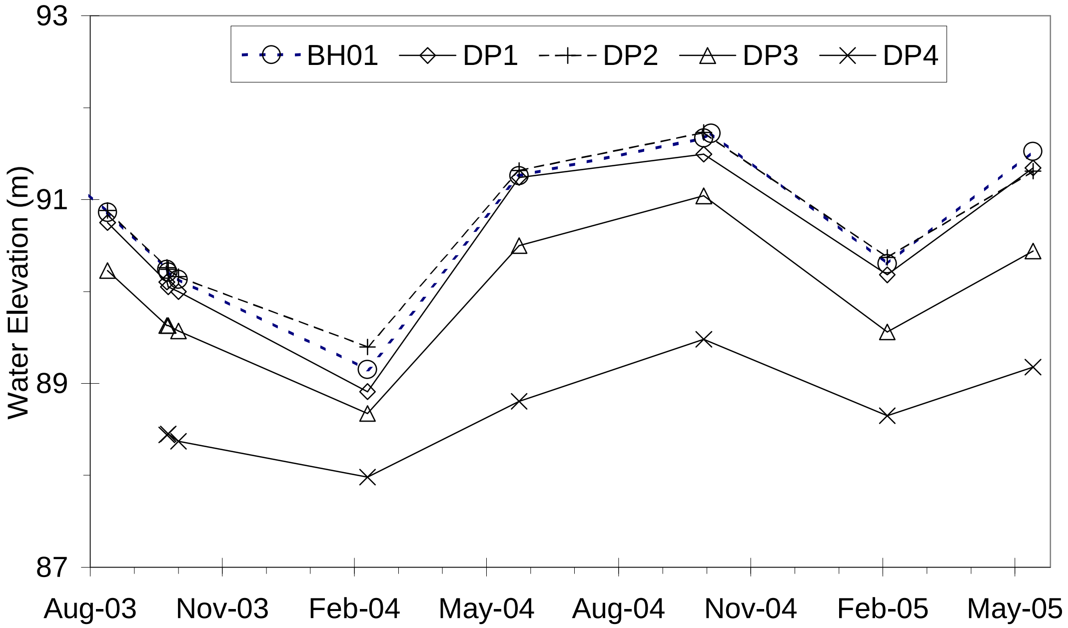


Figure AII-8 Vertical distribution of water levels in MH1 research cluster

Historical groundwater surface elevation data measured near the MH1 research well cluster show that the annual groundwater fluctuation was typically on the order of 1.5 to 2 m, being lowest in winter and highest in fall (Figure AII-9). Seasonal variations in groundwater surface elevations were assessed in more detail by installing a data logger in one of the research well clusters. These results show a slightly larger range, but also a much more active variation in groundwater surface elevations than evident in the discrete data.

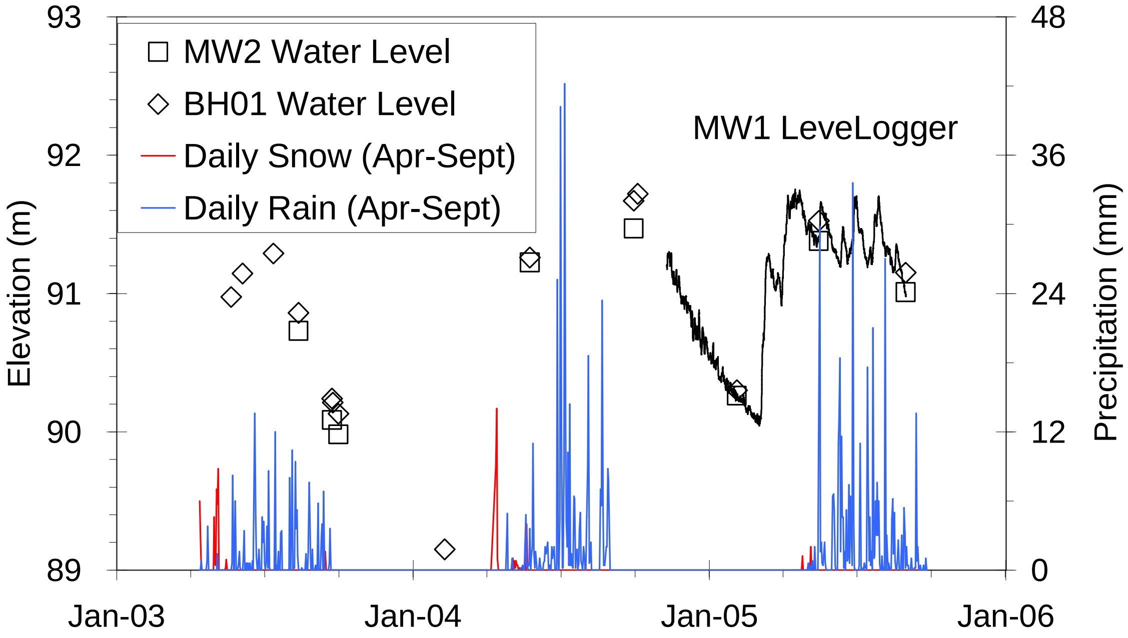


Figure AII-9 Seasonal groundwater surface elevations and precipitation at Site B research cluster area

A detailed review of the groundwater surface elevations showed two interesting features relevant to collecting monitoring data for NA assessment (Figure AII-10). The largest increase in water table elevation occurred in March, while surface and shallow subsurface temperatures were still below the freezing point. Secondly, a series of smaller water table oscillations (on the order of 0.25 to 0.4m) were noted throughout the summer. These features typically involved a relatively rapid rise in the groundwater surface, followed by a slower decrease. The smaller oscillations noted during the summer likely reflect the influence of precipitation events.

One possible cause of the rapid water table fluctuation noted around April could be the melting of an ice plug that built up in the borehole. An ice plug was still evident in the monitoring well with the data logger in May 2005. This plug may have been related to the lower water table elevation inferred from the manual water level measurement. Furthermore rapid melting of such a feature could result in a relatively rapid water table increase. Subsurface temperature logging showed that shallow temperatures changed from below freezing to above freezing around this time.

It is interpreted that the two increases in water level elevation noted in March and April correspond to two melting processes. The first melt causing the larger increase noted in March 2005 corresponds to melting of snow and ice at ground surface. This increase is not due to ground ice melting, as indicated by the surface and shallow subsurface (0.5 m below ground surface) remaining below freezing at that time. The second increase (April) corresponds to melting of ice present in the subsurface. Notably, ice was still evident in the monitoring well in May, up to a month after the second main melt period. Depending on the contaminant distribution relative to the groundwater surface, such rapid water level changes might influence the apparent groundwater chemistry, if samples were collected during these recharge events.

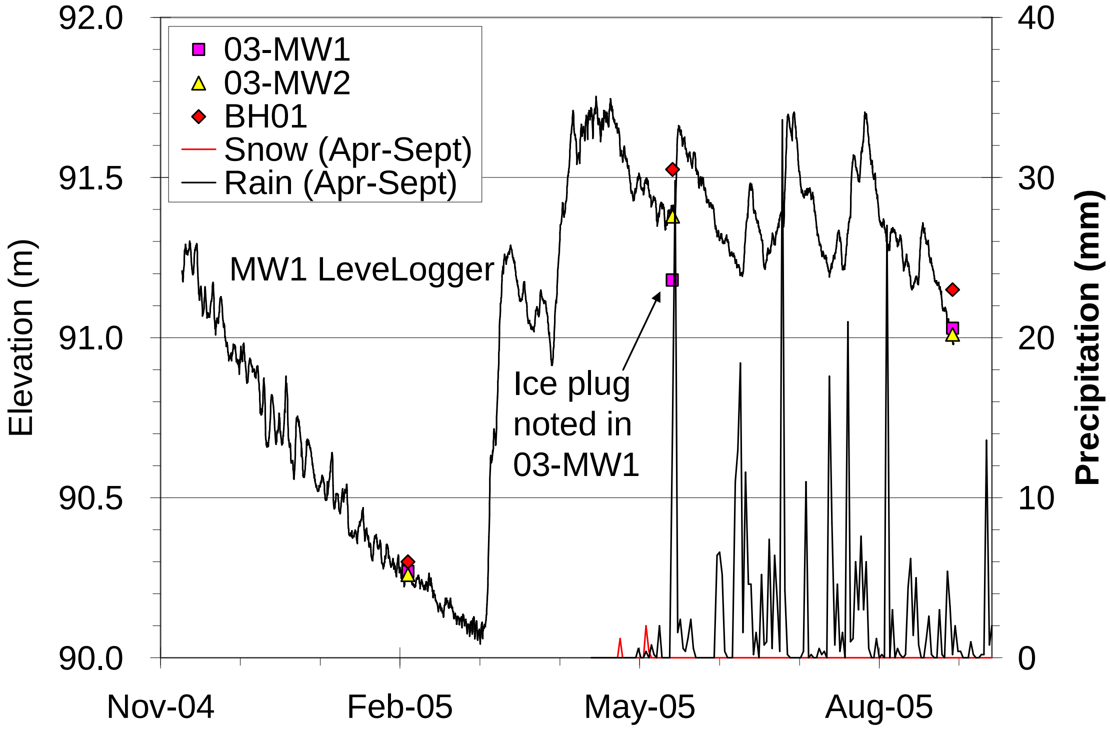


Figure AII-10 Annual groundwater surface elevation at Site B

CLIMATIC CONDITIONS

Weather data were obtained from Environment Canada records for a nearby weather station. Plots of available mean daily precipitation and temperature data from April to September in 2003 to 2005, and recorded snow falls are presented in Figures AII-11 and AII-12, respectively. The data show relatively large variations in mean precipitation intensity and time-varying temperatures over the recorded period. No information was found regarding either precipitation or temperature during winter months, thus the figures are cropped. From 2003 to 2005, the total precipitation reported as rain was 188 mm, 369 mm and 390 mm, respectively. The last snow after winter is generally recorded in May, with the first snow seen as early as September (2004 data not available for September).

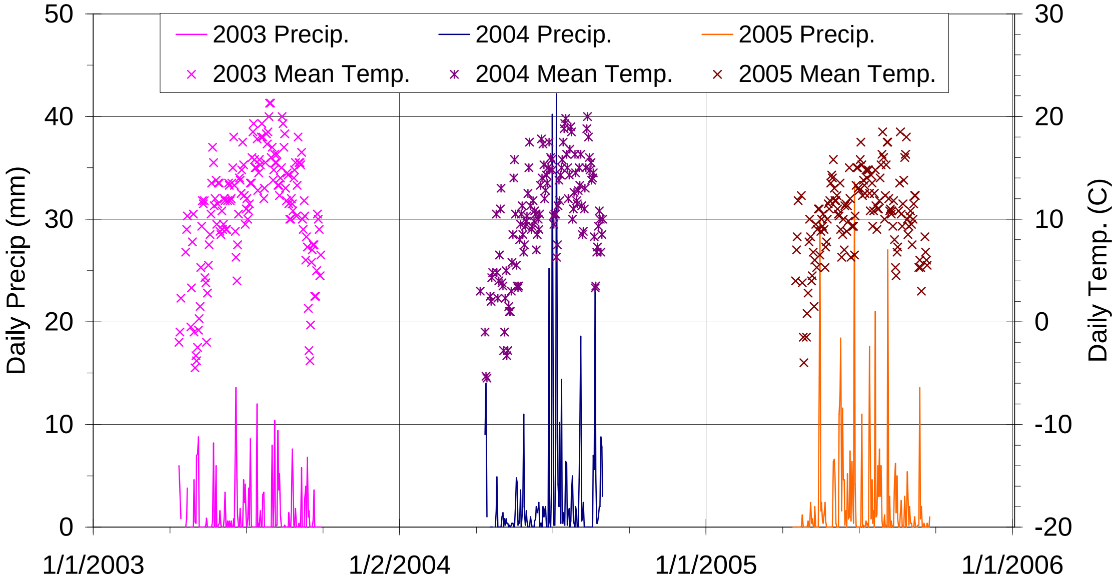


Figure AII-11 Daily precipitation and temperature at Site B

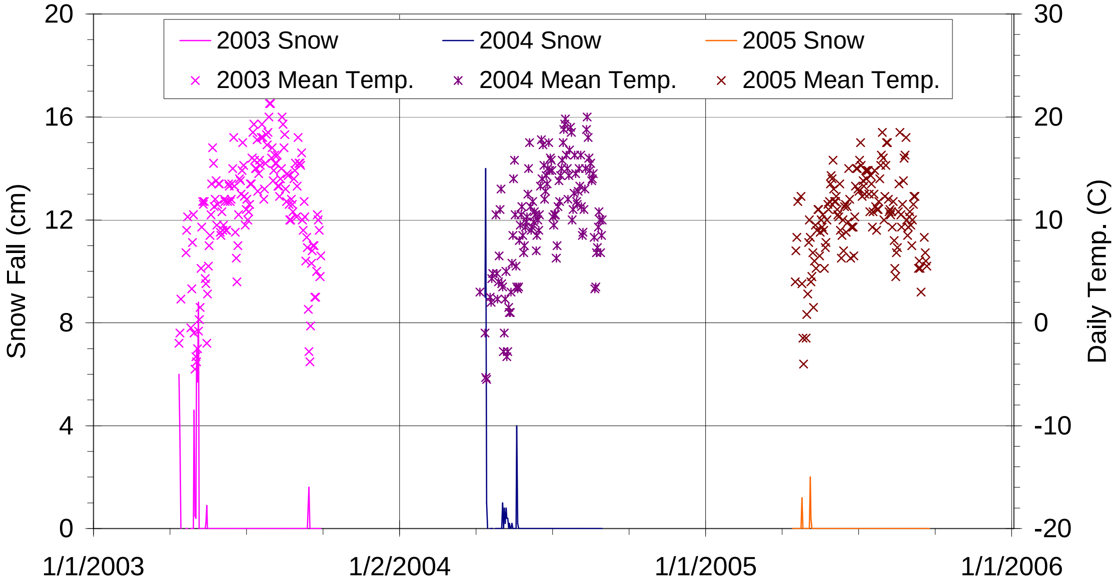


Figure AII-12 Daily snowfall and temperature at Site B

Subsurface temperatures obtained from the data logger system are provided in Figure AII-13

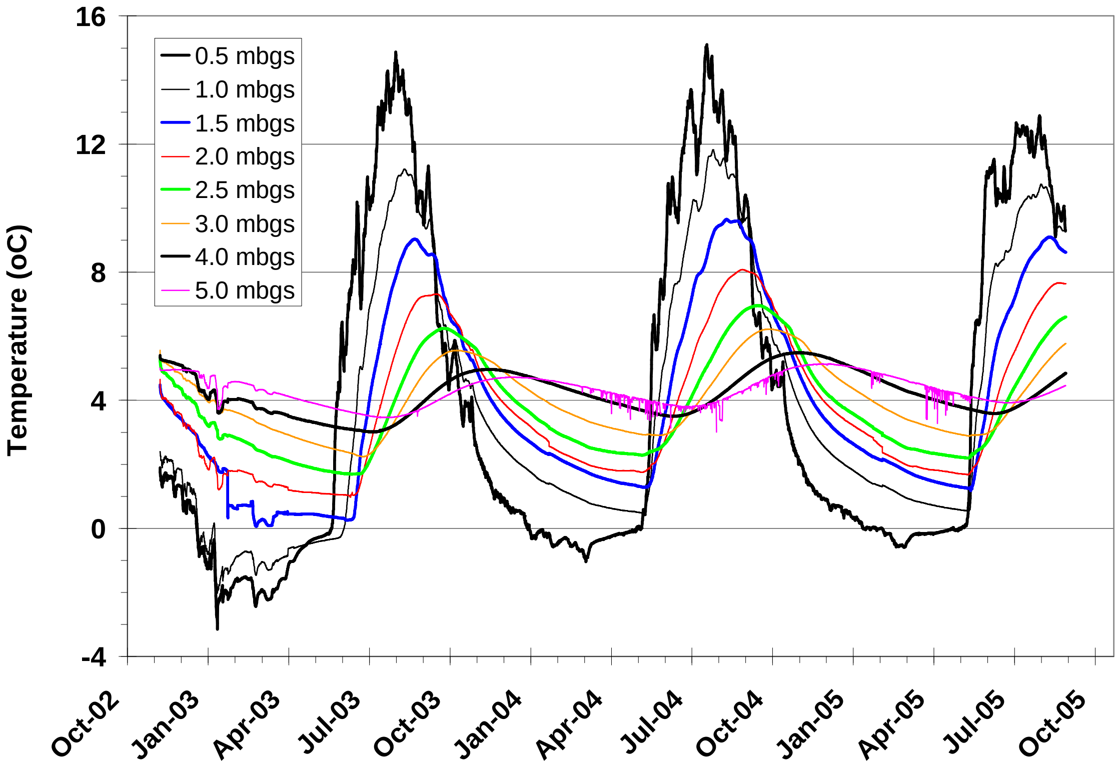


Figure AII-13 Subsurface temperature range with depth at Site B

CONTAMINANT DESCRIPTION

The inferred contaminant source was the former Flare Pit. The majority of the former flare pit source material had been excavated and disposed elsewhere. Residual contamination beyond the reach of the excavation equipment was left in place. A sample of the free phase hydrocarbon liquid that had accumulated in a deeper monitoring well installed near the former flare pit was collected and submitted for hydrocarbon characterization. The analysis is provided in Appendix III. This sample was considered to represent a reasonable surrogate for hydrocarbon released from the flare pit.

NATURAL ATTENUATION CHARACTERIZATION

Historical chemical analyses identified dissolved hydrocarbon contamination in two monitoring wells installed by others (BH1 and BH2: 0.05m diameter PVC, screened from 0.8 to 3.9 mbgs) downslope from the former flare pit. Hydrocarbon contamination was identified using both integrated hydrocarbon range analyses (purgeable hydrocarbons: C_3-C_{10} and extractable hydrocarbons: C_{11}-C_{30}) as well as the target BTEX compounds. Other results included evidence of sulphate depletion (<1 mg/L) and iron enrichment (5 mg/L) relative to background conditions (40 mg/L and <0.1 mg/L, respectively) measured in delineation wells located outside the plume (lateral and downgradient locations). Within the plume wells, possible downward trends in BX compounds and the extractable hydrocarbon fraction were evident (toluene and ethylbenzene were not often detected). Analyses had also shown the presence of hydrocarbon-degrading bacteria, as well as both sulphate-reducing and iron-related bacteria. Site conditions relevant to NA assessment are summarized in Figures AII-14a (groundwater and total BTEX concentrations, June 2004) and AII-14b (dissolved iron and sulphate concentrations).

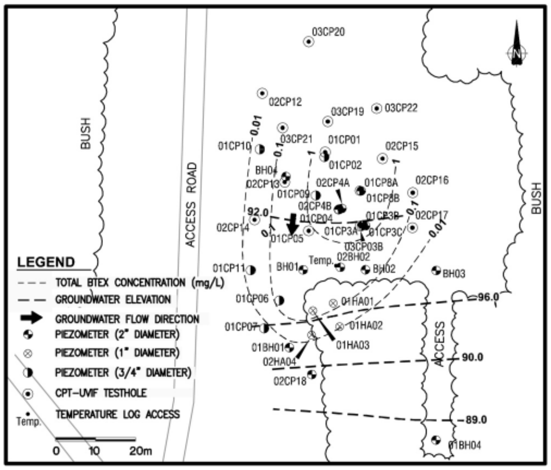


Figure AII-14a Groundwater surface elevations and dissolved BTEX concentrations (mg/L)

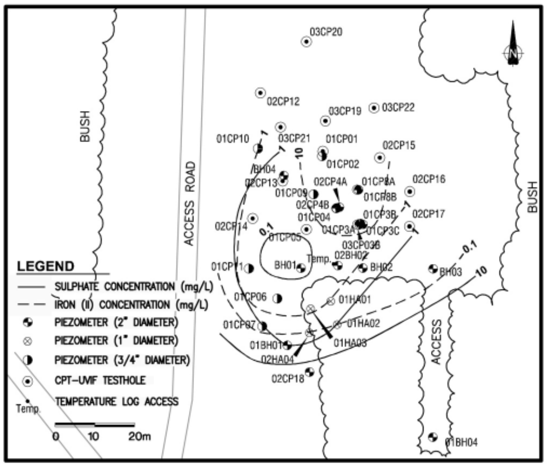


Figure AII-14b Iron (II) and sulphate concentrations (mg/L)

During installation of additional monitoring wells for CORONA, soil samples were collected for mineralogical characterization. Soil samples from two depths at the research well cluster (BH1) were submitted for X-Ray diffraction analysis (XRD, Department of Earth and Atmospheric Sciences, University of Alberta): 2.1-2.4 and 4.3-469 mbgs. This analysis does not provide information on amorphous minerals. The XRD results showed similar crystalline mineral phases in all locations, comprising quartz and various feldspar and clay minerals. Amorphous minerals likely dominate geochemical reactions related to biodegradation.

Groundwater samples were collected from six monitoring wells throughout the plume and submitted to HydroQual Laboratories for a battery of indicator tests intended to identify biodegradation potential. Results are summarized in Table AII-3, according to well position relative to the plume geometry.

Table AII-3 Biological Evidence of Natural Attenuation

Locations	Wells	IRB (log cfu/mL)	Aerobic (log cfu/mL)	BIOLOG Response Aerobic/Anaerobic
Plume	BH1, MW1	10^1, 10^4	10^2, 10^2	1, 2/ 6, 17
Plume Path	BH2, 01CP6	10^3, 10^3	10^3, 10^2	4, 1/ 16, 21
Plume End	01BH01	10^4	10^3	1 / 6
Plume Sides	BH4	10^4	10^3	1 / 18

The results showed equally high numbers of sulphate-reducing bacteria (10^4) in all well samples, except 01CP6 (10^1). These data should only be considered as indicative, being based on one round of water samples.

SITE C CONDITIONS SUMMARY

Site C is located in southwest Alberta. Borehole logs indicate the soil is generally sandy to silty to the maximum depth investigated (3.8 mbgs). In one area (99-28A), gravel fill associated with an underground tank was identified. The groundwater surface is typically around 0.5 to 1.5 mbgs, but can approach ground surface following precipitation. Local surface drainage is toward this area, thus surface ponding has been observed on occasion. A valve problem led to a condensate release (estimated at several m^3). Spill response involved using a vacuum truck to pump free phase hydrocarbon out of shallow collection holes excavated in the area. Following this program, a series of wells were installed to determine the extent of hydrocarbon impact, and then to provide access for soil vapour extraction (alone, and then in association with groundwater recovery).

A relatively dense network of wells already exists at Site C, so additional drilling was not conducted (Figure AII-15). Fourteen wells located in the vicinity of the spill area. Drill locations are restricted to the selected areas by a variety of operating site features such as aboveground and underground pipelines, an elevated roadway and a lined tank farm.

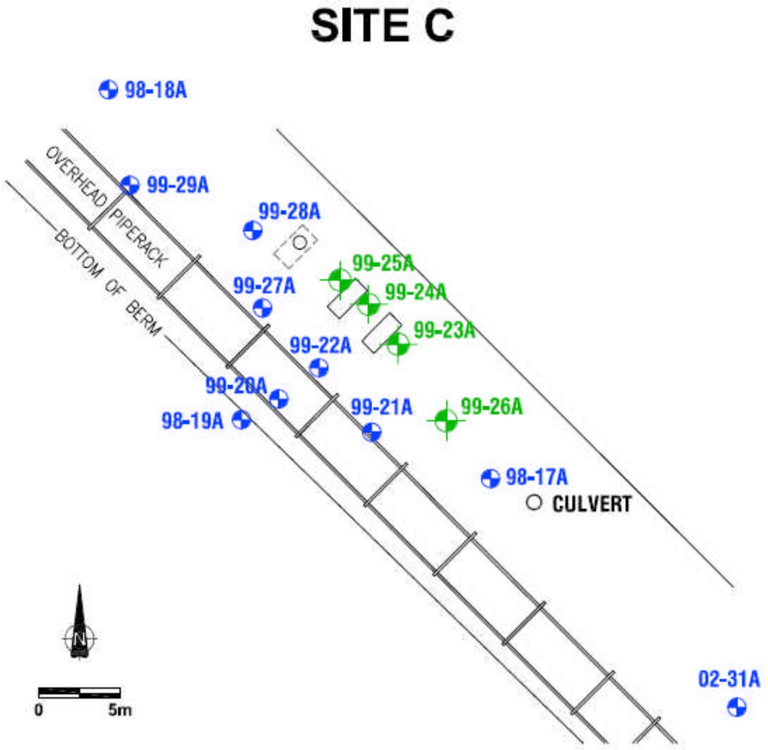


Figure AII-15 Site plan and monitoring wells at Site C

NATURAL ATTENUATION CHARACTERIZATION

Site characterization activities following the condensate release identified apparent hydrocarbon contamination. Site conditions relevant to NA assessment are summarized in Figures AII-16a (groundwater and total BTEX concentrations, June 2004) and 16b (dissolved iron and sulphate concentrations).

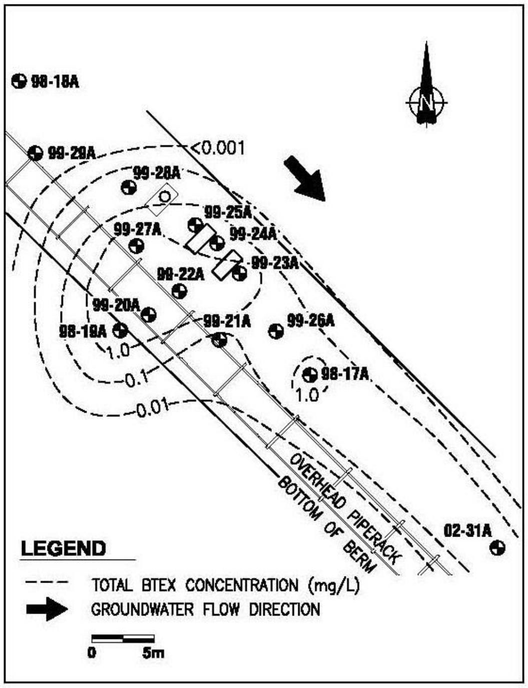


Figure AII-16a Groundwater surface elevations and dissolved BTEX concentrations (mg/L)

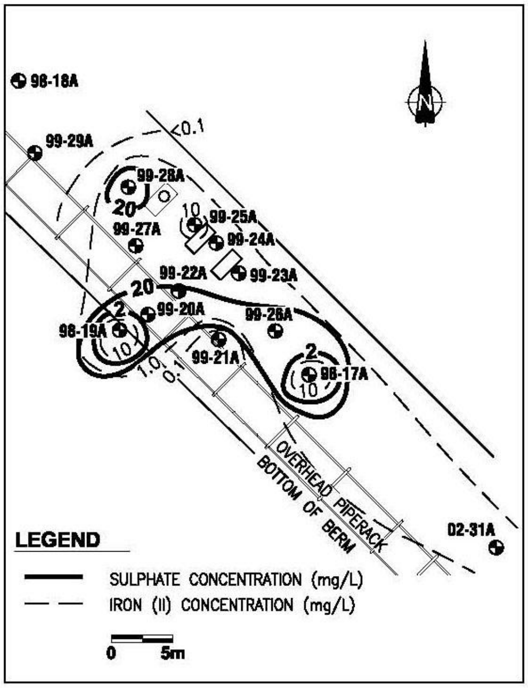


Figure AII-16b Iron(II) and sulphate concentrations (mg/L)

SITE D

Trials using the CPT-UVIF method at Site D showed that the direct push drill rods could not penetrate far enough into shallow bedrock to use the UVIF module in the contaminated interval. As a result, additional characterization was conducted using a series of conventional monitoring wells (0.05 m diameter, 1.5 m long screens). These wells were installed throughout the area north and east of the known hydrocarbon contamination in two phases. The first phase (6 wells) showed that the groundwater flow pattern was more complex than had originally been indicated. Groundwater flows north from the site, but then develops a strong eastward component, possibly as a result of a preferential flow influence related to underlying bedrock. A second phase of drilling confirmed this general flow pattern, and indicated a complex interaction between the inferred source area and dissolved hydrocarbon plume. Given the additional complexity of the flow system, the decision was made to focus effort on the other sites where flow conditions were more consistent.

ADDITIONAL CHARACTERIZATION DATA

Free phase hydrocarbon samples were collected at all three sites and analyzed by a commercial laboratory (Maxxam Analytics Inc., or Maxxam) for hydrocarbon composition (specific compounds and by boiling point for each successive carbon number). The analyses provide a measure of the theoretical hydrocarbon source composition, although some weathering has likely occurred.

Limited soil samples were collected from one location at Site A and analyzed by National Water Research Institute (NWRI) for selected soil quality indicators. These data (one location) showed concentration spikes in reduced sulphur and iron in the zone of hydrocarbon contamination compared to soil outside this interval. Further sampling is planned to examine spatial trends associated with iron- and sulphur-related mineral presence.

TEMPORAL VARIABILITY

Groundwater levels and samples are being collected quarterly to investigate both seasonal and temporal trends. Seasonal groundwater surface elevations indicate an annual fluctuation of approximately 1 to 2 m. Recharge is expected to be relatively slow at three of the sites, due to fine grained soil types (Sites B and D) or relatively arid climate (Site A). In contrast, Site C may have faster recharge due to its location within a local depression which appears to capture local surface water runoff.

Preliminary groundwater monitoring data collected at Site B suggested a seasonal temperature-induced change in dissolved TEA response. Therefore, a thermistor string (0.5 m intervals to 3 mbgs, then 1 m intervals to 5 mbgs) was installed in a sealed, dedicated well filled with vegetable oil to record the vertical distribution of subsurface temperatures. Quarterly sampling at Sites A and D did not show any similar temperature-induced variation in geochemical response, so subsurface temperatures were not continuously logged.

GROUNDWATER SAMPLING OVERVIEW

For all sampling methods, water was sampled from within the screened interval, thus stagnant water from above the screened interval was not sampled. Efforts were also made to avoid groundwater aeration and contact with atmospheric gas by minimizing drawdown during sampling. Effort was also made to minimize turbulence during sample decanting into laboratory-supplied bottles. Water surface elevation measurements taken before and after sampling, suggested that the net drawdown was typically on the order of 5 to 10 cm after bailing the 0.05 m diameter monitoring wells. An exception was made for samples collected after aggressive purging, where the goal was to examine the effect of allowing atmospheric air contact.

Groundwater samples were collected for laboratory analysis of main ions (calcium, magnesium, sodium, potassium, bicarbonate, carbonate, chloride and sulphate), general water quality indicators (pH, electrical conductivity, alkalinity, mineralization as total dissolved solids, hardness), nitrite and nitrate, dissolved iron and manganese (field filtered with 0.45 um cartridge filters and acidified with 1.25 mL of 1:1 HNO_3 supplied by the laboratory) and target hydrocarbons BTEX (benzene, toluene, ethylbenzene, and xylenes) and petroleum hydrocarbon, fraction F1 (C_6 to C_{10} – BTEX). Other analyses collected intermittently include sulphide, total extractable hydrocarbons (C_{11}-C_{30+}), polycyclic aromatic hydrocarbons (PAHs), and free phase hydrocarbon liquid composition.

Field-measured water quality indicators were collected during some sampling visits, but typically not in winter due to extremely cold conditions. Field-measured indicators included dissolved oxygen, pH, electrical conductivity (EC), oxidation-reduction potential (ORP) and temperature.

SAMPLING METHODS

Illustrative photographs for selected well completions and/or sampling methodologies are provided below. It is assumed that the reader is already familiar with use of conventional sampling methods such as dedicated bailer and Waterra® inertial pump.

P34 Cluster

ML-well showing hand-sewn pre-pack frac-sand and bentonite pellet sleeves

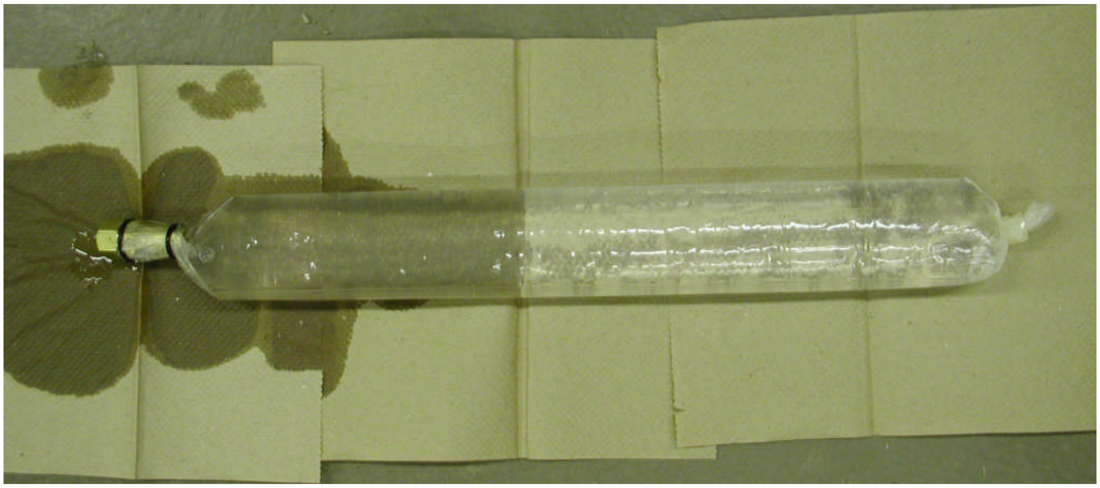
DP-pre-pack well screen, foam seal and paper wrapped bentonite seal to be placed inside driven steel pipe

DP Disposable Tip Detail for driven steel pipe

Groundwater Sampling: Site A, P35 cluster

BarCad Sampler showing ceramic screen and pneumatic packer

BarCad Sampling Method with Compressed Argon: P34 cluster


Prepared DDS Sampler


DDS sample being decanted into sample bottle

Low-flow sampling from P34 well

REFERENCES

Armstrong, J. E., K. Cross, M., and K. W. Biggar. 2001. Assessment of monitored natural attenuation at Alberta oil and gas facilities. CORONA, Calgary.

Armstrong, J. E., C. Deutsch, and K. W. Biggar. 2003. Geostatistical assessment of cone penetrometer test data for soil characterization based on ultraviolet induced fluorescence. *in* 56th Canadian Geotechnical Conference 4th Joint IAH-CNC/CGS Conference. CGS-IAH, Winnipeg, MB.

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Lee, J. Y., J. Y. Cheon, K. K. Lee, S. Y. Lee, and M. H. Lee. 2001. Factors affecting the distribution of hydrocarbon contaminants and hydrogeochemical parameters in a shallow sand aquifer. Journal of Contaminant Hydrology **50**:139-158.

Petersmeyer, C. W. 2006. Assessing Natural Attenuation of Petroleum Hydrocarbons Using Reactive Transport Modelling with Aqueous and Solid Phase Data. M.Sc. University of British Columbia, Vancouver.

Schirmer, M., G. C. Durrant, J. W. Molson, and E. O. Frind. 2001. Influence of transient flow on contaminant biodegradation. Ground Water **39**:276-282.

Van Stempvoort, D. R., J. E. Armstrong, and B. Mayer. 2007. Microbial reduction of sulfate injected to gas condensate plumes in cold groundwater. Journal of Contaminant Hydrology **92**:184–207.

APPENDIX III

ANALYTICAL DATA

JAMES ARMSTRONG

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF ALBERTA

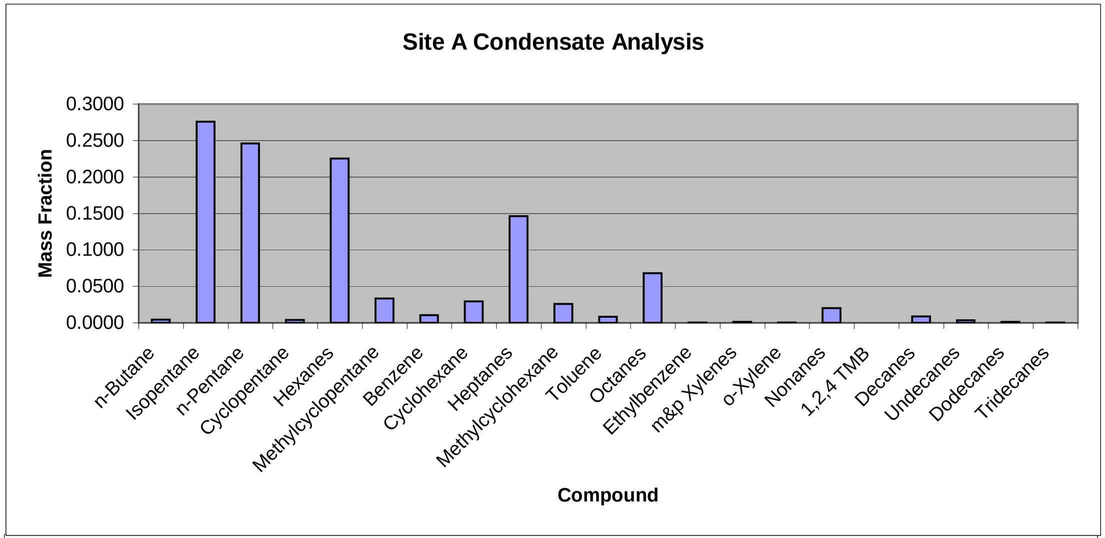
GRADUATE SUPERVISOR: DR. K.W. BIGGAR

CONSORTIUM FOR RESEARCH ON NATURAL ATTENUATION SEPTEMBER 2008

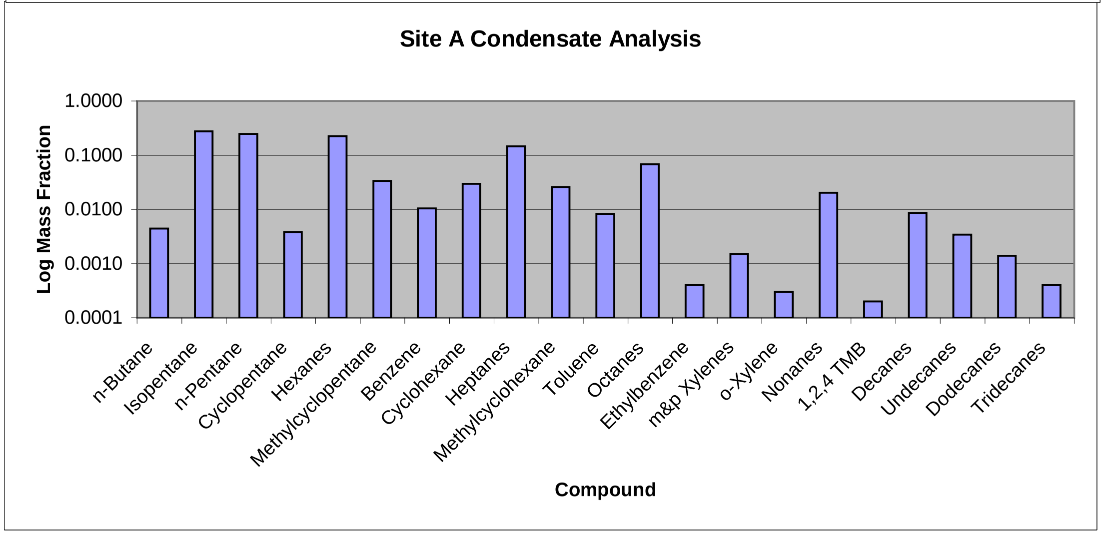
Table 1
Site A Condensate Analysis

Site A Condensate Analysis July 2004

	Mass Fraction	Mole Fraction
Propoane	<0.0001	<0.0001
Isobutane	TRACE	TRACE
n-Butane	0.0044	0.0060
Isopentane	0.2759	0.3077
n-Pentane	0.2460	0.2743
Cyclopentane	0.0038	0.0036
Hexanes	0.2254	0.2104
Methylcyclopentane	0.0333	0.0317
Benzene	0.0104	0.0107
Cyclohexane	0.0296	0.0282
Heptanes	0.1462	0.1285
Methylcyclohexane	0.0260	0.0212
Toluene	0.0083	0.0072
Octanes	0.0680	0.0523
Ethylbenzene	0.0004	0.0003
m&p Xylenes	0.0015	0.0011
o-Xylene	0.0003	0.0002
Nonanes	0.0203	0.0131
1,2,4 TMB	0.0002	0.0001
Decanes	0.0086	0.0050
Undecanes	0.0034	0.0018
Dodecanes	0.0014	0.0007
Tridecanes	0.0004	0.0002
Tetradecanes	TRACE	TRACE



Site A Condensate Analysis



Site A Condensate Analysis

Table 2

Site A Monitoring Well Installation Details, Datum/Groundwater Surface Elevations And Hydraulic Conductivities

Monitoring Station	Ground Elevation	Stick-Up PVC Pipe	Datum Elevation (top of PVC casing)	Depth of Piezo (below ground)	Depth Interval of Sand (below ground)	Date	Depth To Water Below Datum	Depth To Product Below Datum	Apparent Condensate Thickness	Groundwater Surface Elevation	Hydraulic Conductivity	Lithology
	(masl)	*(m)*	*(masl)*	*(m)*	*(m)*	*(d-m-y)*	*(m)*	*(m)*	*(m)*	*(masl)*	*(m/s)*	
93-P-33	729.75	0.91	730.66	N/M	N/M	3-Oct-96	3.00	---	---	727.66	5.3E-06	Silt
						24-Nov-98	3.09	---	---	727.57		
						6-Nov-99	2.33	---	---	728.33		
						16-Jun-00	2.83	---	---	727.83		
						2-Nov-00	3.17	---	---	727.49		
						17-Jul-02	3.03	---	---	727.63		
						26-Aug-02	2.99	---	---	727.67		
						27-Aug-02	2.94	2.92	0.015	727.74		
						28-Aug-02	2.95	2.94	0.001	727.72		
						5-Jun-03	2.80	2.77	0.030	727.88		
						25-Jun-03	2.67	---	---	727.99		
						21-Jul-03	2.72	---	---	727.94		
						27-Oct-03	3.06	---	---	727.61		
						28-Oct-03	3.08	3.06	0.025	727.60		
93-P-34	729.48	0.89	730.37	5.20	2.00 - 5.20	3-Oct-96	3.10	---	---	727.27	N/M	Silt
						24-Nov-98	3.18	---	---	727.19		
						6-Nov-99	2.97	---	---	727.40		
						15-Jun-00	3.05	---	---	727.32		
						2-Nov-00	3.26	---	---	727.11		
						17-Jul-02	2.98	---	---	727.39		
						26-Aug-02	2.90	---	---	727.48		
						27-Aug-02	2.89	---	---	727.48		
						5-Jun-03	2.85	---	---	727.52		
						25-Jun-03	2.32	---	---	728.05		
						25-Jun-03	2.33	---	---	728.04		
						21-Jul-03	2.76	---	---	727.62		
						23-Oct-03	3.00	---	---	727.37		
						27-Oct-03	3.04	---	---	727.33		
						19-Nov-03	3.07	---	---	727.30		
						3-Feb-04	3.40	---	---	726.98		
						8-Jun-04	2.86	---	---	727.52		
						18-Aug-04	2.75	---	---	727.62		
(Low Flow)						18-Aug-04	2.84	---	---	727.54		
						18-Oct-04	2.88	---	---	727.49		
(Post-Purge)						19-Oct-04	3.24	---	---	727.13		
						18-Mar-05	3.21	---	---	727.16		
						10-May-05	2.94	---	---	727.44		
93-P-35	729.71	0.90	730.61	5.30	2.20 - 5.30	24-Nov-98	3.28	---	---	727.33	N/M	Silty sand
						2-Nov-00	3.88	---	---	726.73		
						23-May-02	4.05	---	---	726.56		
						17-Jul-02	3.73	---	---	726.95		
						27-Aug-02	3.70	---	---	726.98		
						27-Aug-02	3.86	---	---	726.82		
						5-Jun-03	3.49	---	---	727.19		
						25-Jun-03	3.45	---	---	727.23		
						25-Jun-03	3.44	---	---	727.17		
						21-Jul-03	3.40	---	---	727.28		

Table 2

Site A Monitoring Well Installation Details, Datum/Groundwater Surface Elevations And Hydraulic Conductivities

Monitoring Station	Ground Elevation	Stick-Up PVC Pipe	Datum Elevation (top of PVC casing)	Depth of Piezo (below ground)	Depth Interval of Sand (below ground)	Date	Depth To Water Below Datum	Depth To Product Below Datum	Apparent Condensate Thickness	Groundwater Surface Elevation	Hydraulic Conductivity	Lithology
	(masl)	*(m)*	*(masl)*	*(m)*	*(m)*	*(d-m-y)*	*(m)*	*(m)*	*(m)*	*(masl)*	*(m/s)*	
						23-Oct-03	3.66	---	---	726.95		
						27-Oct-03	3.69	---	---	726.93		
						19-Nov-03	3.69	---	---	726.92		
						3-Feb-04	3.86	---	---	726.75		
						9-Jun-04	3.54	---	---	727.07		
						18-Aug-04	3.54	---	---	727.08		
(Low Flow)						18-Aug-04	3.94	---	---	726.67		
						18-Oct-04	3.55	---	---	727.07		
(Post-Purge)						20-Oct-04	3.94	---	---	726.67		
						18-Mar-05	3.70	---	---	726.91		
						10-May-05	3.53	---	---	727.09		
93-P-36	728.78	0.85	729.62	N/M	N/M	3-Oct-96	4.22	---	---	725.40	N/M	
						24-Nov-98	3.93	---	---	725.69		
						16-Jun-00	3.45	---	---	726.17		
						2-Nov-00	Dry	---	---	N/M		
						23-Oct-01	Dry	---	---	N/M		
						23-May-02	Dry	---	---	N/M		
						17-Jul-02	3.57	---	---	726.05		
						12-Nov-02	3.37	---	---	726.25		
						23-Jun-03	2.97	---	---	726.65		
						25-Jun-03	2.97	---	---	726.65		
						21-Jul-03	3.22	---	---	726.40		
						23-Oct-03	3.76	---	---	725.86		
						10-Jun-04	3.15	---	---	726.47		
						6-Oct-04	3.35	---	---	726.27		
						18-Oct-04	3.34	---	---	726.28		
						18-Mar-05	3.36	---	---	726.27		
						10-May-05	3.09	---	---	726.54		
34-MW1	729.47	0.72	730.19	4.61	1.52 - 4.61	7-Jul-03	2.37	---	---	727.83	N/M	Silt
						21-Jul-03	2.57	---	---	727.62		
						27-Oct-03	2.86	---	---	727.34		
						10-Jan-04	3.14	---	---	727.06		
						4-Feb-04	3.22	---	---	726.97		
						8-Jun-04	2.68	---	---	727.51		
						18-Aug-04	2.56	---	---	727.63		
(Low Flow)						18-Aug-04	2.70	---	---	727.49		
						18-Oct-04	2.71	---	---	727.49		
(Post-Purge)						19-Oct-04	2.86	---	---	727.33		
						18-Mar-05	3.03	---	---	727.16		
						10-May-05	2.72	---	---	727.47		
34-MW2	729.50	0.74	730.24	4.64	1.52 - 4.64	7-Jul-03	2.43	---	---	727.82	2.0E-06	Silt
						21-Jul-03	2.63	---	---	727.61		
						27-Oct-03	2.91	---	---	727.33		
						19-Nov-03	2.95	---	---	727.30		
						3-Feb-04	3.27	---	---	726.97		
						8-Jun-04	2.75	---	---	727.50		

Table 2

Site A Monitoring Well Installation Details, Datum/Groundwater Surface Elevations And Hydraulic Conductivities

Monitoring Station	Ground Elevation	Stick-Up PVC Pipe	Datum Elevation (top of PVC casing)	Depth of Piezo (below ground)	Depth Interval of Sand (below ground)	Date	Depth To Water Below Datum	Depth To Product Below Datum	Apparent Condensate Thickness	Groundwater Surface Elevation	Hydraulic Conductivity	Lithology
	(masl)	*(m)*	*(masl)*	*(m)*	*(m)*	*(d-m-y)*	*(m)*	*(m)*	*(m)*	*(masl)*	*(m/s)*	
						18-Aug-04	2.62	---	---	727.63		
(Low Flow)						18-Aug-04	2.75	---	---	727.49		
						18-Oct-04	2.76	---	---	727.48		
(Post-Purge)						19-Oct-04	3.16	---	---	727.08		
						18-Mar-05	3.08	---	---	727.16		
						10-May-05	2.77	---	---	727.48		
34-DP1	729.52	0.57	730.09	2.00	1.24 - 2.00	7-Jul-03	2.26	---	---	727.83	N/M	Silt
						21-Jul-03	2.35	---	---	727.75		
						27-Oct-03	>2.57	---	---	<727.52		
						19-Nov-03	>2.57	---	---	<727.52		
						3-Feb-04	>2.57	---	---	<727.52		
						8-Jun-04	>2.57	---	---	<727.52		
						18-Oct-04	2.56	---	---	727.53		
						18-Mar-05	>2.57	---	---	<727.52		
						10-May-05	>2.57	---	---	<727.52		
34-DP2	729.51	0.62	730.13	3.00	2.24 - 3.00	7-Jul-03	2.30	---	---	727.84	1.9E-06	Silt
						21-Jul-03	2.50	---	---	727.63		
						27-Oct-03	2.78	---	---	727.35		
						19-Nov-03	2.83	---	---	727.31		
						3-Feb-04	3.15	---	---	726.98		
						8-Jun-04	2.60	---	---	727.54		
						18-Oct-04	2.64	---	---	727.49		
						18-Mar-05	2.97	---	---	727.17		
						10-May-05	2.68	---	---	727.46		
34-DP3	729.46	0.58	730.04	4.00	3.24 - 4.00	7-Jul-03	2.22	---	---	727.83	1.1E-06	Silt
						21-Jul-03	2.42	---	---	727.62		
						27-Oct-03	2.71	---	---	727.34		
						19-Nov-03	3.39	---	---	726.66		
						3-Feb-04	3.07	---	---	726.97		
						8-Jun-04	2.51	---	---	727.53		
						18-Oct-04	2.56	---	---	727.48		
						18-Mar-05	2.89	---	---	727.16		
						10-May-05	2.59	---	---	727.46		
34-ML1	729.45	0.72	730.17	1.86	1.45 - 2.08	7-Jul-03	2.56	---	---	727.62	N/M	Silt
						21-Jul-03	2.38	---	---	727.80		
						27-Oct-03	>2.58	---	---	<727.59		
						3-Feb-04	>2.58	---	---	<727.59		
						8-Jun-04	2.44	---	---	727.73		
						18-Oct-04	2.46	---	---	727.72		
34-ML5	729.45	0.72	730.17	3.83	3.50 - 4.10	7-Jul-03	2.56	---	---	727.62	N/M	Silt
						21-Jul-03	2.38	---	---	727.80		
						27-Oct-03	2.64	---	---	727.53		
						3-Feb-04	3.00	---	---	727.17		
						8-Jun-04	2.44	---	---	727.74		
						18-Oct-04	2.48	---	---	727.69		

Table 2

Site A Monitoring Well Installation Details, Datum/Groundwater Surface Elevations And Hydraulic Conductivities

Monitoring Station	Ground Elevation	Stick-Up PVC Pipe	Datum Elevation (top of PVC casing)	Depth of Piezo (below ground)	Depth Interval of Sand (below ground)	Date	Depth To Water Below Datum	Depth To Product Below Datum	Apparent Condensate Thickness	Groundwater Surface Elevation	Hydraulic Conductivity	Lithology
	(masl)	*(m)*	*(masl)*	*(m)*	*(m)*	*(d-m-y)*	*(m)*	*(m)*	*(m)*	*(masl)*	*(m/s)*	
34-ML6	729.45	0.72	730.17	2.83	2.59 - 3.10	7-Jul-03	2.56	---	---	727.62	N/M	Silt
						21-Jul-03	2.38	---	---	727.80		
						27-Oct-03	2.64	---	---	727.53		
						3-Feb-04	3.00	---	---	727.18		
						8-Jun-04	2.44	---	---	727.73		
						18-Oct-04	2.50	---	---	727.68		
34-ML7	729.45	0.72	730.17	4.57	4.47 - 4.60	7-Jul-03	2.56	---	---	727.62	N/M	Silt
						21-Jul-03	2.38	---	---	727.80		
						27-Oct-03	2.64	---	---	727.53		
						3-Feb-04	3.00	---	---	727.17		
						8-Jun-04	2.46	---	---	727.72		
						18-Oct-04	2.48	---	---	727.69		
35-MW1	729.58	0.79	730.37	5.33	2.23 - 5.28	7-Jul-03	3.18	---	---	727.19	N/M	Sand, silt
						21-Jul-03	3.15	---	---	727.22		
						27-Oct-03	3.46	---	---	726.92		
						10-Jan-04	3.57	---	---	726.81		
						3-Feb-04	N/M	---	---	N/M		
						9-Jun-04	2.92	---	---	727.46		
						18-Oct-04	3.31	---	---	727.07		
						18-Mar-05	3.54	---	---	726.83		
						10-May-05	3.29	---	---	727.08		
35-MW2	729.57	0.74	730.31	5.33	2.24 - 5.35	7-Jul-03	3.05	---	---	727.26	5.5E-07	Sand, silt
						21-Jul-03	3.08	---	---	727.23		
						27-Oct-03	3.38	---	---	726.94		
						3-Feb-04	3.56	---	---	726.75		
(DDS)						3-Feb-04	3.28	---	---	727.04		
						9-Jun-04	3.22	---	---	727.09		
						18-Oct-04	3.23	---	---	727.09		
						18-Mar-05	3.47	---	---	726.84		
						10-May-05	3.21	---	---	727.10		
35-DP1	729.57	0.61	730.18	2.91	2.15 - 2.91	7-Jul-03	2.97	---	---	727.22	N/M	Sand, silt
						21-Jul-03	2.95	---	---	727.23		
						27-Oct-03	3.25	---	---	726.93		
						19-Nov-03	3.27	---	---	726.91		
						3-Feb-04	3.43	---	---	726.75		
						9-Jun-04	3.11	---	---	727.07		
						18-Aug-04	2.40	---	---	727.79		
						18-Oct-04	3.12	---	---	727.07		
						18-Mar-05	3.34	---	---	726.85		
						10-May-05	3.09	---	---	727.09		
35-DP2	729.59	0.53	730.12	4.01	3.25 - 4.01	7-Jul-03	2.89	---	---	727.23	2.6E-06	Sand, silt
						21-Jul-03	2.89	---	---	727.23		
						23-Oct-03	3.20	---	---	726.92		
						19-Nov-03	3.21	---	---	726.92		
						3-Feb-04	3.37	---	---	726.75		

Table 2

Site A Monitoring Well Installation Details, Datum/Groundwater Surface Elevations And Hydraulic Conductivities

Monitoring Station	Ground Elevation	Stick-Up PVC Pipe	Datum Elevation (top of PVC casing)	Depth of Piezo (below ground)	Depth Interval of Sand (below ground)	Date	Depth To Water Below Datum	Depth To Product Below Datum	Apparent Condensate Thickness	Groundwater Surface Elevation	Hydraulic Conductivity	Lithology
	(masl)	*(m)*	*(masl)*	*(m)*	*(m)*	*(d-m-y)*	*(m)*	*(m)*	*(m)*	*(masl)*	*(m/s)*	
						9-Jun-04	3.05	---	---	727.07		
						18-Aug-04	2.50	---	---	727.62		
						18-Oct-04	3.05	---	---	727.07		
						18-Mar-05	3.29	---	---	726.83		
						10-May-05	3.03	---	---	727.09		
35-DP3	729.59	0.77	730.36	4.99	4.23 - 4.99	7-Jul-03	3.36	---	---	727.00	5.3E-08	Silt
						21-Jul-03	3.15	---	---	727.21		
						27-Oct-03	3.45	---	---	726.91		
						19-Nov-03	3.47	---	---	726.89		
						3-Feb-04	3.63	---	---	726.73		
						9-Jun-04	3.31	---	---	727.05		
						18-Aug-04	2.42	---	---	727.94		
						18-Oct-04	3.32	---	---	727.05		
(Post-Purge)						20-Oct-04	4.80	---	---	725.56		
						18-Mar-05	3.55	---	---	726.81		
						10-May-05	3.29	---	---	727.07		
35-ML1	729.61	0.37	729.98	3.09	2.59 - 3.30	21-Jul-03	2.78	---	---	727.20	N/M	
						27-Oct-03	3.06	---	---	726.93		
						3-Feb-04	3.23	---	---	726.75		
						9-Jun-04	2.91	---	---	727.08		
						18-Oct-04	2.90	---	---	727.08		
35-ML2	729.61	0.37	729.98	4.07	3.70 - 4.30	21-Jul-03	2.78	---	---	727.20	N/M	
						27-Oct-03	3.06	---	---	726.92		
						3-Feb-04	3.24	---	---	726.75		
						9-Jun-04	2.90	---	---	727.08		
						18-Oct-04	2.92	---	---	727.07		
35-ML3	729.61	0.37	729.98	5.07	4.71 - 5.16	21-Jul-03	2.76	---	---	727.22	N/M	
						27-Oct-03	3.06	---	---	726.92		
						3-Feb-04	3.24	---	---	726.74		
						9-Jun-04	2.90	---	---	727.08		
						18-Oct-04	2.92	---	---	727.07		
35-ML7	729.61	0.37	729.98	6.21	5.87 - 6.21	21-Jul-03	2.77	---	---	727.21	N/M	
						27-Oct-03	3.06	---	---	726.92		
						3-Feb-04	3.27	---	---	726.71		
						9-Jun-04	2.92	---	---	727.06		
						18-Oct-04	2.93	---	---	727.05		
03-P-05	729.33	0.77	730.10	4.68	1.52 - 4.68	7-Jul-03	3.19	---	---	726.92	1.4E-06	Silty sand, silt
						21-Jul-03	3.29	---	---	726.81		
						27-Oct-03	3.69	---	---	726.42		
						19-Nov-03	3.68	---	---	726.42		
						3-Feb-04	3.83	---	---	726.27		
						9-Jun-04	3.39	---	---	726.72		
						18-Oct-04	3.48	---	---	726.63		
(Post-Purge)						20-Oct-04	3.82	---	---	726.28		
						18-Mar-05	3.59	---	---	726.51		

Table 2

Site A Monitoring Well Installation Details, Datum/Groundwater Surface Elevations And Hydraulic Conductivities

Monitoring Station	Ground Elevation	Stick-Up PVC Pipe	Datum Elevation (top of PVC casing)	Depth of Piezo (below ground)	Depth Interval of Sand (below ground)	Date	Depth To Water Below Datum	Depth To Product Below Datum	Apparent Condensate Thickness	Groundwater Surface Elevation	Hydraulic Conductivity	Lithology
	(masl)	*(m)*	*(masl)*	*(m)*	*(m)*	*(d-m-y)*	*(m)*	*(m)*	*(m)*	*(masl)*	*(m/s)*	
						10-May-05	3.34	---	---	726.76		
03-P-06	729.56	0.75	730.31	4.65	1.52 - 4.65	7-Jul-03	3.55	---	---	726.77	2.9E-06	Silty sand, silt
						21-Jul-03	3.55	---	---	726.76		
						27-Oct-03	3.89	---	---	726.42		
						19-Nov-03	3.88	---	---	726.43		
						6-Feb-04	4.00	---	---	726.31		
						9-Jun-04	3.69	---	---	726.62		
						18-Oct-04	3.71	---	---	726.60		
(Post-Purge)						20-Oct-04	3.86	---	---	726.45		
						18-Mar-05	3.87	---	---	726.44		
						10-May-05	3.64	---	---	726.67		
03-P-07	729.48	0.77	730.25	4.34	1.22 - 4.34	7-Jul-03	2.86	---	---	727.39	1.1E-06	Silty sand, silt
						21-Jul-03	2.93	---	---	727.33		
						27-Oct-03	3.25	---	---	727.01		
						19-Nov-03	3.21	---	---	727.04		
						3-Feb-04	3.50	---	---	726.75		
						9-Jun-04	3.11	---	---	727.14		
						18-Oct-04	3.11	---	---	727.15		
(Post-Purge)						20-Oct-04	3.56	---	---	726.69		
						18-Mar-05	3.38	---	---	726.88		
						10-May-05	3.06	---	---	727.20		
03-P-08	729.62	0.72	730.34	4.90	1.66 - 4.90	7-Jul-03	3.49	---	---	726.86	3.8E-07	Silty sand, silt
						21-Jul-03	3.47	---	---	726.87		
						27-Oct-03	3.80	---	---	726.54		
						19-Nov-03	3.81	---	---	726.53		
						3-Feb-04	3.96	---	---	726.38		
						9-Jun-04	3.66	---	---	726.68		
						18-Oct-04	3.64	---	---	726.70		
(Post-Purge)						20-Oct-04	4.14	---	---	726.20		
						18-Mar-05	2.82	---	---	727.53		
						10-May-05	3.56	---	---	726.78		
03-P-09	728.68	0.79	729.47	4.27	1.07 - 4.27	7-Jul-03	2.81	---	---	726.67	4.1E-07	Silt
						21-Jul-03	3.05	---	---	726.42		
						27-Oct-03	3.45	---	---	726.03		
						19-Nov-03	3.41	---	---	726.06		
						3-Feb-04	3.60	---	---	725.87		
						9-Jun-04	3.65	---	---	725.82		
						18-Oct-04	3.16	---	---	726.32		
(Post-Purge)						20-Oct-04	3.66	---	---	726.47		
						18-Mar-05	3.20	---	---	726.28		
						10-May-05	2.91	---	---	726.56		
03-P-10	729.48	0.74	730.22	4.65	1.45 - 4.65	7-Jul-03	3.01	---	---	727.21	2.5E-07	Silty sand, silt
						21-Jul-03	3.06	---	---	727.16		
						27-Oct-03	3.36	---	---	726.86		
						19-Nov-03	3.37	---	---	726.85		

Table 2

Site A Monitoring Well Installation Details, Datum/Groundwater Surface Elevations And Hydraulic Conductivities

Monitoring Station	Ground Elevation *(masl)*	Stick-Up PVC Pipe *(m)*	Datum Elevation (top of PVC casing) *(masl)*	Depth of Piezo (below ground) *(m)*	Depth Interval of Sand (below ground) *(m)*	Date *(d-m-y)*	Depth To Water Below Datum *(m)*	Depth To Product Below Datum *(m)*	Apparent Condensate Thickness *(m)*	Groundwater Surface Elevation *(masl)*	Hydraulic Conductivity *(m/s)*	Lithology
						3-Feb-04	3.54	---	---	726.68		
						9-Jun-04	3.26	---	---	726.96		
						18-Oct-04	3.23	---	---	727.00		
(Post-Purge)						20-Oct-04	3.75	---	---	726.47		
						18-Mar-05	3.42	---	---	726.81		
						10-May-05	3.19	---	---	727.03		

NOTES:

1. Data may be entered to the nearest mm, but are reported above to the nearest cm.
Apparent rounding errors may occasionally occur in calculated fields (e.g., Groundwater Surface Elevation).
2. Where free product is present, Groundwater Surface Elevation is calculated as
Groundwater Surface = Datum Elevation - Depth to Water + Product Specific Density * Product Thickness.
3. N/M - Denotes not measured.

Table 3

Site A Water Quality: Field Measured Parameters

Monitoring Station	Notes	Date *(d-m-y)*	Time *(hh:mm)*	Temp *(°C)*	Electrical Conductivity *(µS/cm)*	pH *(unit)*	Eh *(mV)*	DO *(mg/L)*	***Comments***
Corona									
93-P-33		24-Nov-1998		10.9	2,510	7.09	---	---	
93-P-33		06-Nov-1999		10.1	2,470	7.02	---	---	
93-P-33		16-Jun-2000		7.3	2,540	---	---	---	*H/C sheen and odour, pH probe malfunction*
93-P-33		02-Nov-2000		10.2	2,420	6.85	---	---	
93-P-33		17-Jul-2002		---	---	---	---	---	*Not sampled, strong odour, free product*
93-P-33		26-Aug-2002	16:35	---	---	---	---	---	*Not sampled, free product*
93-P-33		27-Aug-2002	11:15	---	---	---	---	---	*Not sampled, free product*
93-P-33		05-Jun-2003		---	---	---	-171	0.3	*Samples may contain free product*
93-P-33		23-Oct-2003		8.7	3,160	7.51	---	---	
93-P-34		24-Nov-1998		9.2	2,140	7.41	---	---	
93-P-34		06-Nov-1999		10.3	2,210	7.39	---	---	
93-P-34		15-Jun-2000		8.4	1,890	---	---	---	*H/C sheen and odour, pH probe malfunction*
93-P-34		02-Nov-2000		10.9	2,150	7.02	---	---	
93-P-34		26-Aug-2002	15:50	12.1	---	6.92	---	---	*Hydrocarbon sheen, black precipitate*
93-P-34		27-Aug-2002	10:35	14.0	---	7.32	---	---	
93-P-34		05-Jun-2003		---	---	---	-125	0.2	*Hydrocarbon sheen*
93-P-34		25-Jun-2003		8.9	3,530	7.49	---	---	*Strong hydrocarbon odour/sheen*
93-P-34		08-Jun-2004		8.6	1,840	7.36	---	0.2	*Hydrocarbon odour/sheen, black precipitates*
93-P-34	**(Low-Flow)**	18-Aug-2004		11.8	1,560	---	-120	0.4	*Low Flow Purge Sampling*
93-P-34	**(Post-Purge)**	19-Oct-2004	16:00	7.7	1,735	7.35	---	---	*Sulphide: <0.1 mg/L*
93-P-34		20-Oct-2004	10:00	9.3	---	---	-57	0.6	
93-P-35		24-Nov-1998		11.3	1,623	6.98	---	---	
93-P-35		02-Nov-2000		10.2	1,209	6.57	---	---	*Strong H/C sheen and odour*
93-P-35		23-May-2002		7.0	1,330	6.88	---	---	*Some H/C sheen and odour*
93-P-35		27-Aug-2002	09:05	14.2	---	6.55	---	---	*Hydrocarbon odour*
93-P-35		27-Aug-2002	16:20	13.3	---	7.08	---	---	*Hydrocarbon sheen*
93-P-35		05-Jun-2003		---	---	---	-132	0.3	
93-P-35		25-Jun-2003		10.0	1,030	7.34	---	---	*Strong hydrocarbon odour*
93-P-35		09-Jun-2004		8.5	1,836	7.11	---	---	*Pulled DDS sampler - was submerged*
93-P-35	**(Low-Flow)**	18-Aug-2004		15.5	1,040	---	-150	1.0	
93-P-35	**(Post-Purge)**	20-Oct-2004	09:30	---	1,790	---	---	---	*Sediment present. Hydrocarbon sheen*
93-P-36		24-Nov-1998		10.1	1,587	6.74	---	---	
93-P-36		06-Nov-1999		13.4	1,013	7.19	---	---	*Well plugged with sediment*
93-P-36		16-Jun-2000		9.6	1,578	---	---	---	*pH probe malfunction*
93-P-36		02-Nov-2000		---	---	---	---	---	*Dry @ 3.70m*
93-P-36		23-Oct-2001		---	---	---	---	---	*Dry @ 3.70m*
93-P-36		23-May-2002		---	---	---	---	---	*Dry @ 3.70m*
93-P-36		17-Jul-2002		---	---	---	---	---	*Not sampled*
93-P-36		12-Nov-2002		6.1	1,704	7.33	---	---	*Silty*
93-P-36		23-Jun-2003		7.6	2,340	7.30	---	---	
93-P-36		23-Oct-2003		---	---	---	---	---	*Insufficient water for field params*
93-P-36		10-Jun-2004		7.5	1,555	7.25	---	---	
93-P-36		06-Oct-2004		9.0	1,679	7.09	---	---	
93-P-36		20-Oct-2004		9.7	---	---	137	1.4	
34-MW1		08-Jun-2004		8.3	2,400	7.13	---	---	*Hydrocarbon odour, black precipitate*
34-MW1	**(Low-Flow)**	18-Aug-2004		12.8	1,660	---	-100	0.8	*Low Flow Purge Sampling*
34-MW1	**(Post-Purge)**	19-Oct-2004	14:45	8.6	2,320	7.27	---	---	*Sulphide: 0.7mg/L Iron: 2.5mg/L Black staining*
34-MW1		20-Oct-2004		9.0	---	---	-99	0.5	
34-MW2		08-Jun-2004		8.4	3,020	7.15	---	---	*Hydrocarbon odour, black precipitate*
34-MW2	**(Low-Flow)**	18-Aug-2004		15.5	1,040	---	-150	1.0	*Low Flow Purge Sampling*
34-MW2	**(Post-Purge)**	19-Oct-2004	15:45	9.1	2,660	7.33	---	---	*Sulphide: 0.3mg/L Iron: 4.5mg/L Hydrocarbon odour*
34-MW2		20-Oct-2004		9.1	---	---	-52	0.4	
34-DP1		08-Jun-2004		---	---	---	---	---	*Dry @ 2.475*
34-DP2		08-Jun-2004		14.8	1,363	7.36	---	---	
34-DP2		20-Oct-2004		5.7	1,361	7.62	---	---	*Hydrocarbon odour*
34-DP3		08-Jun-2004		10.7	2,450	7.45	---	---	
34-DP3		20-Oct-2004		8.1	2,410	7.48	---	---	*Sulphide: <0.1mg/L*
34-ML5		08-Jun-2004		8.4	2,680	7.16	---	---	
34-ML5		20-Oct-2004		6.9	2,620	7.13	---	---	*Sulphide: 0.2mg/L Black precipitate*
34-ML6		08-Jun-2004		11.9	2,680	7.76	---	---	
34-ML6		20-Oct-2004		---	1,738	---	---	---	*Slight hydrocarbon odour*
34-ML7		20-Oct-2004		---	3,370	---	---	---	*Sulphide: 0.25mg/L*

Table 3

Site A Water Quality: Field Measured Parameters

Monitoring Station	Notes	Date *(d-m-y)*	Time *(hh:mm)*	Temp *(°C)*	Electrical Conductivity *(µS/cm)*	pH *(unit)*	Eh *(mV)*	DO *(mg/L)*	***Comments***
35-MW1		09-Jun-2004		8.7	1,453	6.93	---	---	*Black precipitate, Hydrocarbon odour*
35-MW1		20-Oct-2004		9.5	1,647	---	-38	0.5	*Sulphide: <0.1mg/L Black sediment, hydrocarbon odour*
35-MW2		09-Jun-2004		9.5	1,150	7.10	---	---	
35-MW2		20-Oct-2004		---	1,215	---	-18	0.4	*Black sediment, hydrocarbon odour*
35-DP1		09-Jun-2004		---	---	---	---	---	*Insufficient water for field parameters*
35-DP1		20-Oct-2004		---	---	---	---	---	*Possible reddish sediment*
35-DP2		09-Jun-2004		9.6	1,204	7.27	---	---	
35-DP2		20-Oct-2004		---	1,220	---	---	---	*Slight hydrocarbon odour*
35-DP3		09-Jun-2004		11.3	1,475	7.12	---	---	
35-DP3	**(Post-Purge)**	20-Oct-2004	11:00	---	---	---	---	---	*No odour/sheen*
35-ML1		09-Jun-2004		11.4	1,347	6.87	---	---	*Clear*
35-ML2		09-Jun-2004		11.1	1,314	7.09	---	---	*Sulphide: <0.1mg/L Clear*
35-ML3		09-Jun-2004		9.8	2,420	7.45	---	---	
35-ML3		20-Oct-2004		---	---	---	---	---	*Sulphide: 0.2mg/L Clear*
35-ML7		09-Jun-2004		10.8	1,650	7.27	---	---	*Possible hydrocarbon odour*
03-P-05		08-Jun-2004		5.9	---	---	---	2.0	
03-P-05		09-Jun-2004		7.3	2,490	6.74	---	---	
03-P-05		20-Oct-2004		9.0	---	---	32	0.5	
03-P-05	**(Post-Purge)**	20-Oct-2004	13:30	---	2,710	---	---	---	*Black sediment*
03-P-06		08-Jun-2004		6.1	---	---	---	0.4	
03-P-06		09-Jun-2004		7.2	1,562	6.96	---	---	
03-P-06		20-Oct-2004		9.1	---	---	72	0.6	
03-P-06	**(Post-Purge)**	20-Oct-2004		---	1,660	---	---	---	
03-P-07		08-Jun-2004		7.6	---	---	---	0.4	
03-P-07		09-Jun-2004		7.1	2,810	7.23	---	---	
03-P-07		20-Oct-2004		9.4	---	---	32	0.9	*Sulphide: <0.1mg/L*
03-P-08	**03-P-08**	08-Jun-2004		7.1	---	---	---	1.3	
03-P-08		09-Jun-2004		7.6	3,420	6.95	---	---	
03-P-08		20-Oct-2004		10.1	---	---	162	1.1	
03-P-08	**(Post-Purge)**	20-Oct-2004		---	---	---	---	3.0	
03-P-09		08-Jun-2004		5.2	---	---	---	0.7	
03-P-09		09-Jun-2004		6.9	2,730	6.97	---	---	
03-P-09		20-Oct-2004		9.3	---	---	36	2.7	
03-P-09	**(Post-Purge)**	20-Oct-2004	13:00	---	2,800	---	---	---	
03-P-10		08-Jun-2004		7.1	---	---	---	0.3	
03-P-10		09-Jun-2004		7.4	1,687	7.11	---	---	
03-P-10		20-Oct-2004		9.1	---	---	-18	0.5	
03-P-10	**(Post-Purge)**	20-Oct-2004	12:30	---	---	---	---	1.5	*Sulphide: <0.1mg/L*

NOTES: ***1. Electrical conductivity values standardized to 25°C.***

Table 4

Site A Water Quality: Parameter Concentrations

Monitoring Station	Date (d-m-y)	EC (us/cm)	pH (units)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Chloride:D (mg/L)	Sulphate:D (mg/L)	Ion Balance (balance)	TDS-calculated (mg/L)	Tot Hard as $CaCO_3$ (mg/L)	Tot Alk as $CaCO_3$ (mg/L)	NO_2+NO_3 as N (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	Sulphide (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylenes-total (mg/L)	PHC F_1 (C_6-C_{10})-BTEX (mg/L)	TPH (C_3-C_{10}) (mg/L)
93-P-33	29-Oct-93	---	---	---	---	---	---	---	114	134	---	1,910	---	---	---	---	---	---	<0.001	<0.001	0.006086	0.7049	---	---
	3-Oct-96	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.06	0.15	<0.0029	(0.160 - 0.163)	---	0.79
	23-Nov-98	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.091	<0.002	0.155	0.333	---	0.9
	5-Nov-99	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.16	<0.0005	0.2	0.4	---	0.84
	16-Jun-00	---	7.3	---	---	---	---	---	128	1.9	---	2,970	---	---	---	---	---	---	---	---	---	---	---	---
	2-Nov-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.067	0.0019	0.11	0.18	---	0.6
	17-Jul-02	2,550	7.65	125	51.1	1.3	378	1,610	14.1	0.6	1.01	1,370	520	1,320	0.113	0.16	4.41	---	0.14	<0.01	0.38	1.9	---	5.1
(Pre-Purge)	26-Aug-02	2,380	7.5	119	56.2	2.5	505	1,630	155	0.9	1.05	1,670	530	1,330	(0.005)	23.8	5.07	---	0.133	<0.009	0.359	1.91	---	5.8
(Post-Purge)	26-Aug-02	2,190	7.4	102	44.2	2.8	476	1,490	150	20.3	1.02	1,540	440	1,220	<0.003	10.6	3.84	---	0.09	<0.004	0.239	1.09	---	3.7
(Post-Recovery)	27-Aug-02	2,250	7.4	---	48.3	3.2	523	1,480	334	32.3	0.94	1,790	470	1,210	(0.005)	9.61	4.18	---	0.087	<0.006	0.245	1.25	---	4
	21-Feb-03	2,240	7.5	107	43.4	1.9	445	1,410	143	0.3	1.05	1,460	440	1,150	<0.003	19.4	3.74	---	---	---	---	---	---	---
	11-Mar-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.12	<0.02	0.55	3.05	1.2	---
(Pre-Purge)	5-Jun-03	2,460	7.62	68.5	30.4	1.5	499	1,490	127	17.8	0.97	1,480	300	1,220	0.015	0.25	2.86	1.9	0.095	(0.002)	0.31	1.6	15	---
(Post-Purge)	5-Jun-03	2,340	7.66	65.6	31.7	2.2	462	1,360	126	66.8	0.96	1,430	290	1,110	0.082	0.11	2.57	<0.01	0.076	(0.002)	0.22	0.99	2	---
(Pre-Purge)	9-Jun-04	2,260	7.88	107	41.9	2.9	434	1,400	122	59.1	1.02	1,480	440	1,150	<0.003	15.7	3.78	---	0.069	(0.003)	0.2	0.785	0.5	1.6
(Post-Purge)	9-Jun-04	2,300	7.84	110	41.6	2.9	450	1,380	123	89.6	1.04	1,520	450	1,130	<0.003	14.1	3.75	---	0.061	(0.003)	0.171	0.64	0.4	1.3
(Post-Recovery)	9-Jun-04	2,270	7.9	114	42.9	3.1	437	1,350	117	106	1.04	1,500	460	1,100	<0.003	13.3	3.79	---	0.0458	(0.0013)	0.114	0.416	0.3	0.9
93-P-34	29-Oct-93	---	---	---	---	---	---	---	104	296	---	1,980	---	---	---	---	---	---	0.4391	1.909	0.02598	12.92	---	---
	3-Oct-96	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.15	0.6	<0.15	(7.80 - 7.95)	---	11
	23-Nov-98	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.09	0.1	<0.03	4.99	---	5.2
	5-Nov-99	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.1	0.49	1.9	17	---	25
	15-Jun-00	---	7.5	---	---	---	---	---	50.5	1.6	---	1,180	---	---	---	---	---	---	---	---	---	---	---	---
	2-Nov-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.042	0.34	1.1	7.5	---	14
	17-Jul-02	2,650	7.49	57.7	226	1.6	246	1,860	9.8	0.5	1.05	1,500	1,100	1,520	0.051	42.3	0.41	---	0.02	0.04	0.46	3.67	---	6.3
(Pre-Purge)	26-Aug-02	2,330	7.33	44.4	178	1.5	254	1,780	83.6	1.1	0.89	1,480	850	1,460	0.028	40	0.305	---	(0.03)	0.06	0.52	3.93	---	7.2
(Post-Purge)	26-Aug-02	2,390	7.71	52.6	185	2.6	248	1,800	81.1	53.9	0.87	1,520	890	1,470	(0.005)	6.64	0.126	---	<0.04	0.08	1.04	7.11	---	12.8
(Post-Recovery)	27-Aug-02	2,180	7.55	40.7	181	2.9	253	1,690	89.7	12.7	0.92	1,410	850	1,380	0.007	4.41	0.109	---	<0.04	0.09	0.77	5.91	---	10.1
	21-Feb-03	1,940	7.79	39.8	168	2	240	1,340	83.4	1.8	1.08	1,210	790	1,100	<0.003	14.7	0.094	---	---	---	---	---	---	---
(Pre-Purge)	5-Jun-03	2,160	7.73	35.3	139	1.7	232	1,520	65	4.1	0.87	1,240	660	1,240	0.18	16.2	0.16	3.3	0.052	0.21	0.66	4.24	11.8	---
(Post-Purge)	5-Jun-03	2,010	7.86	28.8	123	0.7	215	1,420	58.3	0.3	0.84	1,130	580	1,160	(0.003)	10.9	0.064	<0.01	0.077	0.4	0.87	5.09	5.6	---
(Post-Recovery)	5-Jun-03	2,030	7.95	39.4	138	1.2	234	1,440	59.5	4.3	0.93	1,190	660	1,180	(0.003)	6.68	0.236	2.2	0.03	0.16	0.81	5.68	9.3	---
	25-Jun-03	3,410	7.6	53.1	213	2.8	477	1,820	153	477	0.93	2,270	1,010	1,490	0.06	0.48	0.11	7.28	<0.04	0.15	0.79	9.6	34	---
	23-Jul-03	2,770	7.57	58.5	194	3	430	1,950	104	103	1.02	1,870	940	1,600	(0.005)	18.9	1.11	<0.01	<0.04	<0.04	0.49	6.6	9.4	---
	28-Oct-03	2,010	7.76	39.1	155	2.1	262	1,520	59.1	1.2	1.01	1,290	740	1,250	<0.003	21.2	0.336	---	0.038	0.054	0.459	4.2	5.2	---
	4-Feb-04	1,760	7.84	37.5	151	1.8	220	1,470	70.8	9.2	0.91	1,210	710	1,200	<0.003	0.27	0.079	---	<0.04	(0.07)	0.79	6.27	2.2	8.1
	8-Jun-04	1,910	7.84	31.8	132	1.2	223	1,440	42.5	9.6	0.91	1,160	620	1,180	(0.005)	13.6	0.213	---	0.021	0.035	0.566	4.18	0.7	---
Low Flow1	9-Jun-04	1,860	7.89	39.7	159	1.4	244	1,390	37	31.5	1.06	1,200	750	1,140	<0.003	5.59	0.24	---	(0.012)	0.035	0.481	3.41	0.9	---
Low Flow3	9-Jun-04	1,880	7.9	37.4	157	1.4	245	1,400	38.9	26.6	1.04	1,200	740	1,150	<0.003	6.91	0.185	---	(0.014)	0.036	0.517	3.63	0.9	---
Low Flow4	9-Jun-04	1,860	8	38	152	1.4	232	1,390	37.5	24.5	1.01	1,170	720	1,140	<0.003	4.2	0.18	---	(0.017)	0.043	0.627	4.25	1.3	---
Low Flow5	9-Jun-04	1,910	7.98	43.8	160	1.5	243	1,420	39.5	38.1	1.04	1,230	770	1,160	<0.003	5.44	0.232	---	(0.016)	0.04	0.565	3.87	1	---
Low Flow6	9-Jun-04	1,950	8	43.2	161	1.6	242	1,440	41.1	51.9	1.01	1,250	770	1,180	<0.003	5.17	0.234	---	0.018	0.043	0.613	4.18	2.1	---
Low Flow7	9-Jun-04	1,910	7.95	41.1	157	1.6	239	1,410	38.5	34.2	1.02	1,210	750	1,160	<0.003	3.44	0.197	---	0.023	0.054	0.751	4.63	2.8	---
Low Flow8	9-Jun-04	1,940	7.98	40.8	161	2.2	241	1,420	39.9	40.8	1.03	1,230	770	1,160	<0.003	3.81	0.162	---	0.022	0.053	0.782	4.78	3.1	---
	9-Jul-04	1,700	8.26	33.4	127	1.5	208	1,320	35.3	12.6	0.94	1,070	610	1,080	0.026	7.53	0.182	---	(0.013)	0.026	0.879	6.01	3.2	---
Low Flow1	9-Jul-04	1,930	8.18	45.4	143	1.7	227	1,430	43.7	92.6	0.91	1,260	700	1,170	<0.003	6.3	0.436	---	(0.009)	0.015	0.533	2.62	3	---
Low Flow2	9-Jul-04	1,950	8.22	52	150	1.8	228	1,430	43.8	106	0.93	1,300	750	1,180	<0.003	7.79	0.44	---	0.014	0.022	0.647	3.08	3.6	---
Low Flow3	9-Jul-04	1,960	8	53.6	149	1.8	228	1,470	44.1	99.7	0.92	1,310	750	1,200	<0.003	8.1	0.502	---	0.014	0.023	0.625	3.16	3.4	---
Low Flow4	9-Jul-04	1,970	8.02	54	149	1.8	229	1,470	42.3	99	0.92	1,310	750	1,210	<0.003	7.7	0.531	---	0.014	0.025	0.627	3.17	3.5	---
Low Flow6	9-Jul-04	1,950	8.03	54.2	149	1.9	231	1,480	43.9	87.4	0.93	1,300	750	1,210	<0.003	7.93	0.54	---	0.015	0.025	0.614	3.14	3.8	---
Low Flow7	9-Jul-04	1,940	8.01	54	149	1.9	229	1,460	44.5	98.3	0.93	1,300	750	1,200	<0.003	7.64	0.546	---	0.016	0.028	0.654	3.56	3.5	---
(Post-Purge)	9-Jul-04	1,880	8.05	47.9	135	1.7	222	1,440	42.5	73.2	0.9	1,240	680	1,180	<0.003	8.1	0.483	---	(0.013)	0.029	0.682	4.88	2.7	---
(Post-Purge, New Bailer)	9-Jul-04	1,900	8.06	48.6	149	1.9	231	1,440	44.1	80.3	0.94	1,270	740	1,180	<0.003	8.01	0.44	---	(0.013)	0.028	0.9	5.64	3.9	---
	18-Aug-04	2,130	7.88	53.9	156	2.3	241	1,380	55.3	100	1.01	1,300	780	1,130	(0.004)	9.57	0.615	---	(0.010)	(0.014)	0.558	3.46	0.4	---
Low Flow1	18-Aug-04	2,170	7.82	52.9	156	2.2	254	1,410	52.4	99.6	1.01	1,320	780	1,160	0.011	8.27	0.565	---	<0.009	(0.016)	0.5	3.24	0.4	---
Low Flow2	18-Aug-04	2,170	7.84	49.2	149	2	248	1,410	50.6	98.1	0.96	1,290	740	1,160	<0.003	0.62	0.516	---	(0.009)	0.018	0.454	2.93	0.3	---
	19-Oct-04	1,800	8.03	31.7	122	1.9	209	1,230	46.9	5.4	0.97	1,030	580	1,010	<0.003	6.62	0.186	---	(0.010)	(0.010)	0.706	4.25	3.3	---
(Pre-Purge)	18-Mar-05	1,760	7.79	37.0	161	1.7	228	1,360	49.9	(0.9)	1.05	1,150	750	1,120	<0.003	0.17	0.097	(34)	<0.06	<0.06	0.69	3.9	0.8	---
Low Flow1	18-Mar-05	1,750	7.82	35.4	156	1.5	219	1,330	47.0	1.4	1.04	1,120	730	1,090	0.011	0.17	0.071	<30	<0.09	<0.09	0.80	4.4	(0.6)	---
Low Flow2	18-Mar-05	1,720	7.75	33.8	151	1.4	218	1,310	46.2	(0.6)	1.04	1,090	710	1,070	(0.004)	0.15	0.073	<0.01	<0.09	<0.09	0.87	4.9	(0.8)	---
Low Flow3	18-Mar-05	1,710	7.77	33.8	149	1.4	216	1,300	45.0	(0.7)	1.03	1,090	700	1,070	0.028	0.14	0.072	<0.01	<0.09	<0.09	0.84	4.9	(0.9)	---
(Pre-Purge)	10-May-05	1,930	7.70	37.1	143	1.3	201	1,360	53.8	29.5	0.93	1,150	680	1,120	0.005	9.90	0.313	<0.005	<0.04	<0.04	0.58	3.37	3.7	---
Low Flow1	10-May-05	1,930	7.93	36.5	158	1.6	218	1,370	48.7	<0.5	1.03	1,140	740	1,120	<0.003	4.94	0.111	<0.005	<0.04	<0.04	0.86	4.87	0.9	---
Low Flow2	10-May-05	1,840	7.90	32.0	155	1.6	231	1,320	47.0	<0.5	1.08	1,120	720	1,080	<0.003	4.91	0.071	<0.005	<0.04	<0.04	0.98	5.97	1.0	---
Low Flow3	11-May-05	1,890	7.97	33.0	152	1.3	229	1,360	49.8	<0.5	1.03	1,140	710	1,110	<0.003	2.95	0.127	<0.005	<0.04	<0.04	0.89	5.19	1.4	---
Low Flow4	11-May-05	1,840	7.91	31.1	153	1.5	228	1,310	44.1	<0.5	1.06	1,110	710	1,080	<0.003	4.61	0.077	<0.005	<0.04	<0.04	1.05	6.58	1.1	---
93-P-35	23-Nov-98	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.24	0.81	<0.04	8.89	---	12.6

Table 4

Site A Water Quality: Parameter Concentrations

Monitoring Station	Date	EC	pH	Calcium:D	Magnesium:D	Potassium:D	Sodium:D	Bicarbonate	Chloride:D	Sulphate:D	Ion Balance	TDS-calculated	Tot Hard as $CaCO_3$	Tot Alk as $CaCO_3$	NO_2+NO_3 as N	Iron:D	Manganese:D	Sulphide	Benzene	Toluene	Ethylbenzene	Xylenes-total	PHC F_1 (C_6-C_{10})-BTEX	TPH (C_3-C_{10})
	(d-m-y)	*(us/cm)*	*(units)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(balance)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*
	5-Nov-99	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.17	0.3	<0.0005	7.6	---	14
	2-Nov-00	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.091	0.48	0.57	7	---	26
	23-May-02	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.066	0.43	0.2	3.8	4.9	10
	17-Jul-02	1,270	7.2	74.3	53.7	2	141	780	54.9	0.7	1	748	410	639	0.132	35.6	1.18	---	0.16	0.79	0.18	5.4	---	9.1
	27-Aug-02	1,270	6.95	76.9	57.5	2.2	146	875	56.9	0.7	0.94	812	430	717	0.038	40	1.72	---	0.14	0.75	0.4	6.7	---	13.7
(Post-Purge)	27-Aug-02	1,180	7.23	73.6	53.8	2.7	134	792	52.9	2.3	0.96	734	410	649	0.091	24.3	0.915	---	0.23	1.1	0.52	6.65	---	12.6
(Post-Recovery)	27-Aug-02	1,150	7.3	63.4	49.3	2.8	139	757	53	6.3	0.95	708	360	621	0.035	20.6	0.833	---	0.27	1.79	0.98	13.1	---	31.1
	21-Feb-03	1,310	7.25	85.6	59.6	1.7	132	853	57.8	1.5	0.96	798	460	699	<0.003	39.2	1.62	---	---	---	---	---	---	---
	11-Mar-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.23	1.63	1.08	16.9	2.9	---
	5-Jun-03	1,580	7.17	109	60	1.6	135	1,020	56.2	0.7	0.89	907	520	834	<0.003	42.4	2.18	<0.01	0.15	0.63	0.27	4.1	10.9	---
	25-Jun-03	1,430	7.1	107	75.9	2.3	136	986	60.7	2.4	0.98	869	580	808	0.09	7.94	1.25	5.19	0.17	1.4	0.079	12	<0.1	---
	23-Jul-03	1,640	7.55	174	63.4	1.6	111	932	55.6	37.5	1.07	961	700	764	<0.003	55.8	3.04	<0.01	0.11	0.47	0.52	7.55	8.4	---
	28-Oct-03	1,910	7.78	185	82.9	3.4	137	1,250	78.3	0.8	1.08	1,170	800	1,030	0.02	65.6	3.81	---	0.12	0.55	0.68	10.3	75.5	---
	4-Feb-04	1,180	7.19	110	56.3	1.8	126	862	54.5	3	1.1	825	510	706	0.019	47.8	1.81	---	0.19	0.5	0.53	7.5	2.9	10.8
	9-Jun-04	2,760	7.44	176	70.8	2.6	134	1,720	56	0.7	0.75	1,340	730	1,410	0.027	53.8	2.38	---	0.107	0.197	0.22	3.83	1.1	5.7
Low Flow1	18-Aug-04	1,280	7.43	88.2	47	1.7	139	773	57	0.2	1.09	748	410	633	<0.003	34	1.28	---	0.2	0.1	0.48	5.98	0.9	---
	18-Aug-04	1,860	7.06	186	70.5	2.3	143	1,190	56.6	0.3	1.15	1,130	760	973	0.023	82.5	2.54	---	0.09	0.14	0.39	5.48	1.5	---
	20-Oct-04	1,620	7.3	164	58.5	2.2	138	1,010	46.2	0.5	1.21	983	650	830	0.066	72.7	2.3	---	0.111	0.115	0.202	4.31	2.4	---
(Pre-Purge)	18-Mar-05	1,340	7.23	104	52.9	1.8	148	901	55.8	1.3	1.02	826	480	738	0.014	17.6	1.52	(48)	0.11	0.07	0.20	3.26	0.8	---
Low Flow1	18-Mar-05	1,110	7.44	63.4	39.0	1.3	125	672	56.7	<0.5	1.01	640	320	551	(0.003)	23.4	0.952	<0.01	0.254	0.044	0.677	6.83	4.1	---
(Pre-Purge)	10-May-05	1,400	7.26	112	46.5	1.6	127	870	50.0	1.0	1.07	818	470	713	0.021	49.8	1.76	<0.005	0.16	<0.08	1.66	19.1	233	---
Low Flow1	10-May-05	1,270	7.38	63.9	41.8	1.3	132	763	53.9	1.6	0.95	699	330	626	0.24	27.0	1.01	<0.005	0.26	0.05	0.92	10.9	68.1	---
93-P-36	29-Oct-93	---	---	---	---	---	---	---	29.8	1,120	---	1,850	---	---	---	---	---	---	<0.001	<0.001	0.00201	0.07421	---	---
	25-Oct-94	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.001	<0.001	<0.001	---	---	---
	19-Oct-95	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.001	<0.001	<0.001	<0.001	---	<0.03
	3-Oct-96	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.0009	<0.0009	<0.0009	<0.0018	---	0.8
	15-Oct-97	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.0004	<0.0004	<0.0004	<0.0008	---	0.16
	23-Nov-98	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.0004	<0.0004	<0.0004	<0.0012	---	<0.1
	5-Nov-99	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.0015	<0.0005	0.0044	0.0087	---	0.35
	16-Jun-00	---	7.2	---	---	---	---	---	39.2	162	---	850	---	---	---	---	---	---	---	---	---	---	---	---
	17-Jul-02	1,710	7.72	153	110	3.7	38.4	853	66	216	0.91	1,010	830	699	0.179	0.05	0.018	---	---	---	---	---	---	---
	12-Nov-02	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.0005	<0.0005	<0.0005	<0.0005	<0.1	<0.1
	23-Jun-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.0005	<0.0005	<0.0005	<0.0005	<0.1	<0.1
	11-May-05	1,730	7.60	173	113	4.1	39.5	792	63.6	326	0.92	1,110	900	649	0.226	0.17	2.01	---	<0.0004	<0.0004	<0.0004	<0.0008	<0.1	---
34-MW1	21-Jul-03	829	8.02	63.8	183	3.9	359	469	93.5	171	2.44	1,120	910	385	0.505	5.13	2.18	<0.01	<0.03	0.14	0.47	5.57	3.2	---
	27-Oct-03	2,770	7.75	111	219	4.9	327	1,840	69	379	0.96	2,030	1,200	1,510	<0.003	10.1	3.59	---	0.014	<0.007	0.564	3.9	4.9	---
DDS-mid	19-Nov-03	1,930	7.32	58	144	2.6	238	1,340	65.1	93.2	0.98	1,270	740	1,100	0.115	5.4	2.33	---	(0.007)	<0.006	0.155	1.81	0.9	---
DDS-deep	19-Nov-03	2,270	7.4	71.4	183	3.1	286	1,700	76.3	96.3	0.98	1,560	930	1,390	0.021	5.72	2.47	---	(0.012)	<0.009	0.444	4.29	1.7	---
	4-Feb-04	2,150	7.54	104	185	3	253	1,850	62.5	108	0.92	1,630	1,000	1,520	0.01	3.32	2.46	---	<0.02	<0.02	0.56	3.38	1.7	4.8
DDS-mid	4-Feb-04	1,540	7.8	59.1	142	2.3	211	1,240	57.1	25.2	1.07	1,110	730	1,010	(0.005)	2.23	1.59	---	0.008	<0.004	0.322	2.26	1.1	3.3
DDS-deep	4-Feb-04	2,110	7.89	95.5	198	3.2	279	1,910	69.7	27.6	0.99	1,620	1,100	1,570	0.008	1.08	2.16	---	(0.010)	<0.009	0.638	4.19	1.8	5.8
	8-Jun-04	2,590	7.7	76.9	191	2.7	287	1,880	73.5	99.9	0.92	1,660	980	1,540	0.008	4.68	2.34	---	(0.011)	<0.006	0.426	2.6	0.7	---
	18-Aug-04	2,440	7.89	53.5	149	2.9	323	1,660	82.8	52	0.96	1,480	750	1,360	<0.003	4.01	1.53	---	(0.010)	(0.013)	0.398	2.37	0.3	---
Low Flow1	18-Aug-04	2,310	7.87	61.2	162	2.5	274	1,500	56.8	111	1.01	1,410	820	1,230	(0.004)	5.58	1.06	---	(0.008)	0.014	0.381	2.5	0.2	---
	19-Oct-04	2,450	7.87	54.7	134	3.1	294	1,650	58.6	80.3	0.88	1,440	690	1,350	<0.003	3.16	1.32	---	<0.004	<0.004	0.671	1.54	6.3	---
	11-May-05	2,470	7.73	78.6	169	2.5	241	1,540	65.2	304	0.85	1,620	890	1,260	<0.003	1.33	1.12	9	0.005	<0.002	0.349	1.38	0.4	---
34-MW2 BarCad shal	22-Jul-03	2,660	7.88	76.8	186	5	378	1,790	105	140	1.02	1,780	960	1,460	0.59	5.09	2.92	<0.01	<0.03	0.08	0.58	5.56	3.1	---
BarCad deep	23-Jul-03	2,590	7.91	77.3	187	4.5	293	1,750	87.4	166	0.93	1,680	960	1,440	<0.003	3.53	1.87	<0.01	<0.03	(0.05)	0.59	4.94	3.6	---
	29-Oct-03	2,410	7.94	88	193	4.4	254	1,670	63.6	224	0.94	1,650	1,000	1,370	<0.003	3.82	1.48	---	(0.006)	0.022	0.75	3.86	8.6	---
BarCad deep	29-Oct-03	2,340	7.96	97.4	213	4.2	290	1,620	61.3	205	1.02	1,640	1,100	1,330	0.017	2.61	1.87	---	0.003	0.003	0.403	1.51	7.6	---
	3-Feb-04	2,270	7.58	124	201	3.8	254	1,500	55.8	556	0.9	1,940	1,100	1,230	<0.003	4.65	1.61	---	0.004	<0.002	0.213	0.771	0.8	1.6
	4-Feb-04	2,220	7.56	118	191	4	243	1,580	50.7	399	0.91	1,790	1,100	1,290	(0.005)	4.06	1.43	---	(0.003)	<0.002	0.281	1.01	2.6	3.5
	8-Jun-04	3,050	7.79	246	230	6.4	260	1,440	62.3	835	1.01	2,360	1,600	1,180	<0.003	6.82	2.69	---	0.0012	(0.0006)	0.0982	0.262	(0.1)	---
34-HydroPunch mid	8-Jun-04	1,740	8.43	31	132	5.7	222	1,240	28.7	6.5	0.97	1,080	620	1,090	0.075	(0.01)	0.101	---	<0.02	0.25	0.47	4.11	4.7	10.1
34-HydroPunch deep	8-Jun-04	2,500	7.95	136	189	9.7	238	1,410	68.6	420	0.97	1,760	1,100	1,160	<0.003	(0.01)	0.349	---	<0.0009	0.0053	0.0061	0.0388	0.2	0.3
	18-Aug-04	2,340	7.99	122	176	4	230	1,300	54.2	299	1.06	1,530	1,000	1,070	0.01	4.61	1.13	---	(0.007)	0.017	0.42	2.02	0.4	---
Low Flow1	18-Aug-04	2,140	7.93	61.6	141	2.4	222	1,330	48.4	105	0.96	1,240	730	1,090	<0.003	0.14	0.534	---	(0.009)	0.024	0.532	3.51	0.4	---
	19-Oct-04	3,130	7.86	185	193	6.1	256	1,270	58.8	887	0.9	2,220	1,300	1,040	<0.003	5.05	1.53	---	<0.0004	<0.0004	0.0309	0.0754	0.2	---
	10-May-05	2,650	7.67	140	193	3.5	221	1,300	50.5	658	0.90	1,910	1,100	1,060	<0.003	5.67	1.01	0.087	0.004	0.002	0.338	1.38	0.7	---
unfiltered	10-May-05	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.005	---	---	---	---	---	---
34-DP2	22-Jul-03	1,960	7.8	35	155	1.4	230	1,410	63.8	1.3	0.98	1,180	730	1,160	0.015	0.13	0.129	<0.01	(0.05)	0.26	0.75	6.09	3	---
	27-Oct-03	1,680	8.15	28.4	137	2.2	218	1,360	20.4	1	0.98	1,080	630	1,110	<0.003	3.29	0.056	---	0.029	0.2	0.577	4.31	0.8	---
	3-Feb-04	1,560	7.93	34	131	1.2	211	1,310	25.2	1.2	0.98	1,050	630	1,080	0.007	4.03	0.066	---	<0.2	(0.3)	0.6	---	2	9
	8-Jun-04	1,520	8.23	23.2	113	1	197	1,180	18.6	2.2	0.97	941	520	965	(0.003)	6.91	0.064	---	0.037	0.184	0.535	4.6	1.9	7.4
	20-Oct-04	1,500	8.15	20.2	104	1.3	184	1,050	23.3	0.2	0.99	849	480	859	<0.003	1.2	0.041	---	(0.04)	0.16	0.7	5.71	2	---

Table 4

Site A Water Quality: Parameter Concentrations

Monitoring Station	Date	EC	pH	Calcium:D	Magnesium:D	Potassium:D	Sodium:D	Bicarbonate	Chloride:D	Sulphate:D	Ion Balance	TDS-calculated	Tot Hard as $CaCO_3$	Tot Alk as $CaCO_3$	NO_2+NO_3 as N	Iron:D	Manganese:D	Sulphide	Benzene	Toluene	Ethylbenzene	Xylenes-total	PHC F_1 (C_6-C_{10})-BTEX	TPH (C_3-C_{10})
	(d-m-y)	*(us/cm)*	*(units)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(balance)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*
	11-May-05	1,650	7.87	24.8	122	1.0	185	1,180	42.5	<0.5	0.95	960	570	966	0.003	4.30	0.056	0.039	0.034	0.175	0.873	6.37	0.7	---
34-DP3	22-Jul-03	2,850	8.02	155	241	5.5	288	1,740	64.7	503	0.99	2,110	1,400	1,420	0.084	0.11	0.931	<0.01	<0.002	<0.002	0.181	0.323	0.5	---
	29-Oct-03	2,720	8.04	138	236	4.9	278	1,800	58.3	429	0.97	2,040	1,300	1,480	<0.003	4.37	0.644	---	<0.0006	0.0025	0.187	0.279	0.2	---
	3-Feb-04	2,360	7.78	161	213	4.3	262	1,720	55	400	0.98	1,950	1,300	1,410	<0.003	6.45	0.977	---	<0.002	<0.002	0.209	0.108	0.3	0.6
	8-Jun-04	2,590	8.14	127	190	4	251	1,700	64.6	293	0.93	1,770	1,100	1,390	0.007	4.37	0.78	---	<0.001	0.004	0.211	0.303	0.3	0.9
	19-Oct-04	2,560	8.07	117	170	4.3	259	1,610	64.6	202	0.97	1,610	990	1,320	<0.003	4.4	0.786	---	0.002	0.003	0.0836	0.131	0.4	---
	11-May-05	2,520	7.83	103	173	2.8	223	1,450	53.9	402	0.87	1,680	970	1,190	0.006	3.29	0.428	0.017	0.002	0.007	0.402	0.193	1.0	---
34-ML1	23-Jul-03	2,290	7.98	85.9	52	5.2	494	904	69.4	524	1.09	1,680	430	741	0.276	0.05	0.463	<0.01	<0.02	0.07	0.36	3.4	2.1	---
34-ML5	23-Jul-03	3,140	7.63	232	213	8.4	280	1,380	70.3	1,030	0.9	2,520	1,500	1,130	0.035	0.58	3.33	<0.01	<0.006	(0.011)	0.053	0.47	0.3	---
	27-Oct-03	2,870	7.77	227	207	8	295	1,520	53.8	648	1.04	2,200	1,400	1,250	<0.003	7.66	4.3	---	0.0018	<0.0004	0.107	0.174	0.9	---
	3-Feb-04	2,360	7.4	206	191	6.2	288	1,670	57.6	450	1.02	2,040	1,300	1,370	<0.003	7.62	3.76	---	(0.001)	<0.001	0.078	0.144	0.8	0.9
	8-Jun-04	2,820	7.82	174	181	5.7	271	1,590	60.3	540	0.92	2,020	1,200	1,300	<0.003	5.95	3.1	---	(0.0005)	<0.0004	0.0315	0.0677	<0.1	---
	20-Oct-04	2,690	7.79	158	181	5.8	261	1,350	59	509	1	1,840	1,100	1,100	<0.003	4.71	2.6	---	0.0017	0.0016	0.059	0.198	(0.1)	---
34-ML6	23-Jul-03	2,750	7.83	97.5	224	6.1	341	1,580	94.9	427	1.02	1,970	1,200	1,290	<0.003	0.31	2.14	<0.01	<0.009	0.018	0.097	0.81	0.6	---
	28-Oct-03	2,380	8	69.7	184	3.9	281	1,800	113	3.1	0.95	1,550	930	1,470	<0.003	7.31	1.33	---	(0.005)	<0.003	0.355	1.97	1	---
	3-Feb-04	1,990	7.98	73.6	171	2.8	269	1,700	92.3	(0.1)	0.98	1,450	890	1,390	0.007	5.02	1.08	---	0.005	<0.002	0.238	1.19	0.3	1.6
	8-Jun-04	2,090	8.15	53.5	141	2.3	240	1,550	72.1	0.7	0.91	1,280	710	1,270	0.047	5.77	0.682	---	(0.004)	<0.004	0.264	1.26	0.3	---
	20-Oct-04	1,870	8.14	46.7	125	2.6	225	1,270	58.4	0.5	1.01	1,090	630	1,040	<0.003	7.5	0.516	---	0.004	(0.003)	0.316	1.64	2.7	---
34-ML7	23-Jul-03	3,590	7.63	364	304	29.2	374	1,200	84.6	1,590	1.09	3,340	2,200	981	<0.003	2.02	3.98	<0.01	<0.002	0.006	0.025	0.226	0.3	---
	28-Oct-03	3,460	7.82	329	248	20.9	337	1,400	67.9	1,280	1.01	2,970	1,800	1,150	0.01	1.4	4.46	---	0.0019	0.0064	0.0238	0.156	<0.1	---
	3-Feb-04	2,910	7.46	331	237	15.6	361	1,410	65.8	1,250	1.03	2,960	1,800	1,150	0.107	1.57	4.65	---	0.0017	<0.0004	0.0261	0.119	<0.1	0.2
	8-Jun-04	3,430	7.89	296	234	12.8	301	1,390	64.4	1,160	0.98	2,760	1,700	1,140	0.03	6.44	3.64	---	0.0011	<0.0004	0.0249	0.0611	<0.1	---
	20-Oct-04	3,500	7.78	280	224	13	300	1,220	61	1,190	0.99	2,670	1,600	996	0.022	5.69	3.08	---	0.0008	0.0009	0.0296	0.0582	<0.1	---
35-MW1	23-Jul-03	1,490	7.17	126	57.8	4.5	131	889	45.8	107	0.93	929	550	728	<0.003	15.4	4.37	<0.01	0.14	0.87	0.32	8.35	3.6	---
	28-Oct-03	1,730	7.9	141	72	3.6	139	1,150	46.1	0.9	1.03	1,020	650	944	<0.003	49.4	4.51	---	0.1	0.057	0.196	2.74	5.7	---
	4-Feb-04	1,180	7.25	92.8	51.3	2.6	119	820	45.2	0.5	1.04	748	440	672	<0.003	31.1	2.12	---	0.104	<0.009	0.224	2.27	0.6	2.9
	9-Jun-04	1,470	7.08	110	65.2	2.7	122	1,000	48	0.7	1.02	894	540	820	(0.005)	51.9	2.23	---	0.127	0.136	0.28	3.23	1.1	5
	20-Oct-04	2,020	7.58	131	69.8	2.8	125	1,180	51.5	0.5	0.99	1,040	620	970	0.01	78.3	2.19	---	0.087	0.198	0.188	3.56	2.7	---
DDS	18-Mar-05	---	---	---	---	---	---	---	55.0	(0.5)	---	---	---	---	---	1.56	0.711	---	0.2	0.3	0.7	7.8	<0.7	---
DDS	10-May-05	1,260	7.84	88.3	51.7	1.5	111	747	49.3	<0.5	1.10	709	430	612	0.04	39.4	1.14	---	0.17	0.23	0.51	6.49	0.2	---
35-MW2 BarCad shal	23-Jul-03	1,080	7.64	58.1	37.2	3.3	152	575	36.3	89.3	1.03	661	300	471	0.049	0.41	1.29	<0.01	0.09	0.126	0.171	3.38	2	---
BarCad deep	23-Jul-03	1,130	7.67	66	38.5	3.4	147	595	37.7	100	1	688	320	487	0.011	1.51	1.8	<0.01	0.085	0.112	0.185	3.29	2.1	---
35-MW2	28-Oct-03	1,210	7.8	75.6	45.7	3.1	144	772	47.6	19.4	0.99	728	380	633	<0.003	10.9	2.06	---	0.128	<0.004	0.386	3.28	1.8	---
BarCad deep	28-Oct-03	1,170	7.79	87	45.5	2.9	147	756	44.8	17.3	1.06	726	400	620	0.012	6.37	2.53	---	0.106	<0.004	0.26	2.33	0.6	---
	3-Feb-04	1,030	7.46	59.9	42.8	2.3	141	679	52.5	1.4	1.05	650	330	557	(0.003)	14.9	0.932	---	0.135	<0.009	0.194	2.26	1.4	3.4
	4-Feb-04	1,030	7.33	70.6	44.9	2.7	127	708	47.2	9.1	1	660	360	581	(0.003)	8.66	1.27	---	0.108	<0.004	0.153	1.59	1.1	2.7
	9-Jun-04	1,130	7.32	70.5	46.6	2	130	727	50.7	6.5	1.03	687	370	596	<0.003	22.7	1.18	---	0.146	<0.004	0.177	1.63	2.2	4.2
(Duplicate)	9-Jun-04	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.136	<0.004	0.164	1.54	3	4.9
	20-Oct-04	1,280	7.67	85.5	46.9	2.5	129	792	51.5	1.5	1.03	738	410	649	<0.003	29.3	1.93	---	0.128	<0.004	0.17	1.77	7	---
DDS	18-Mar-05	---	---	---	---	---	---	---	57.4	<0.5	---	---	---	---	---	0.71	0.382	---	0.303	(0.005)	0.819	5.98	6.7	---
DDS	10-May-05	1,180	8.17	58.9	41.7	1.3	123	686	54.7	<0.5	0.92	618	320	563	0.051	0.11	0.488	---	0.25	<0.04	0.47	4.83	<0.2	---
35-DP1	23-Jul-03	1,350	7.36	112	60.2	2.1	117	885	52	3.4	0.98	816	530	726	0.048	32	1.58	<0.01	0.13	0.93	0.29	5.92	2.8	---
	28-Oct-03	1,300	7.86	85.6	48	1.6	99.6	812	53.7	3.5	0.94	730	410	666	<0.003	37.8	1.17	---	0.15	1.19	0.48	7.75	1.2	---
	9-Jun-04	1,440	7.63	107	60.3	1.6	126	880	56.2	3.9	1.1	840	520	721	0.028	51.1	1.26	---	0.184	0.769	0.478	6.53	4.5	12.7
	20-Oct-04	1,640	7.99	97.4	54.3	1.6	130	952	55.2	<0.1	0.98	857	470	781	<0.003	49.1	1.1	---	0.12	0.6	0.36	6.92	1.6	---
35-DP2	23-Jul-03	1,130	7.81	71.3	57.1	2.1	131	703	47.9	8.6	1.08	678	410	576	0.012	13.1	0.512	<0.01	0.22	0.16	0.62	5.17	2.6	---
	28-Oct-03	1,160	7.9	65.2	51.9	2.2	134	770	44.4	8.3	0.98	697	380	631	0.009	11.3	0.479	---	0.089	<0.004	0.371	2.23	1	---
	3-Feb-04	1,040	7.71	61.2	48.5	1.9	132	728	48.8	4.6	0.99	667	350	597	0.053	11.1	0.405	---	0.058	<0.004	0.323	1.48	1.5	2.8
	9-Jun-04	1,250	7.84	81.6	61.5	2.1	129	838	46.1	10.1	1	755	460	687	<0.003	12	0.81	---	0.08	0.008	0.314	1.8	0.7	3
	20-Oct-04	1,340	7.97	75.7	55.7	2.2	129	841	46.1	15.8	0.94	751	420	690	<0.003	12.2	0.649	---	0.078	0.013	0.26	1.83	0.7	---
	10-May-05	1,230	7.74	86.2	60.5	2.0	121	761	50.4	0.7	1.08	708	460	624	<0.003	12.3	0.722	<0.005	0.055	<0.004	0.305	1.57	0.4	---
35-DP3	23-Jul-03	1,410	7.92	168	62.7	6.1	99.3	601	31.3	323	1.03	988	680	493	0.231	0.1	1.06	<0.01	<0.0004	<0.0004	<0.0004	0.0066	<0.1	---
	28-Oct-03	1,410	7.97	133	60.9	4.8	96.1	617	27.2	327	0.91	956	580	505	0.012	1.97	0.739	---	0.001	0.0033	0.0032	0.0255	<0.1	---
	3-Feb-04	1,260	7.74	145	57.7	5	92.3	635	29.1	278	0.95	922	600	520	0.017	1.44	0.796	---	<0.0004	<0.0004	<0.0004	<0.0008	<0.1	<0.1
	9-Jun-04	1,410	7.96	142	58.4	4.1	100	656	28.4	290	0.94	949	600	537	<0.003	2.27	0.795	---	(0.0005)	0.001	0.0019	0.0144	<0.1	<0.1
	20-Oct-04	1,510	8.03	163	59.7	5	94.7	614	28.2	331	0.97	985	650	503	0.044	0.59	0.814	---	0.0011	0.0026	0.0035	0.0253	<0.1	---
	10-May-05	1,360	7.71	171	62.2	4.9	97.5	623	27.3	247	1.12	918	680	511	0.069	0.30	0.925	---	0.0050	0.0012	0.0110	0.111	<0.1	---
35-HydroPunch shal	8-Jun-04	1,230	8.06	51.7	38.1	2.1	128	712	51.5	3.2	0.86	625	290	583	0.035	0.03	0.338	---	0.029	0.108	0.056	0.632	0.3	1.2
35-HydroPunch mid	8-Jun-04	1,450	8.13	98.4	78.2	4.5	136	981	40.3	28.9	0.98	870	570	804	<0.003	(0.01)	0.319	---	0.0025	0.0096	0.0223	0.155	0.2	0.4
35-HydroPunch deep	8-Jun-04	2,120	8.02	149	80	8.7	113	556	30.3	466	0.97	1,120	700	455	0.14	<0.01	0.488	---	---	---	---	---	---	---
35-ML1	23-Jul-03	1,320	7.72	95.7	40.1	3.6	151	760	52.3	71.9	0.96	794	400	623	0.067	2.74	2.59	<0.01	0.142	0.559	0.249	3.57	1.6	---
	28-Oct-03	1,500	7.78	116	58.2	3.2	169	1,070	54.4	1.1	0.98	950	530	873	0.006	17.2	6.64	---	0.141	(0.003)	0.292	2.81	0.8	---

Table 4

Site A Water Quality: Parameter Concentrations

Monitoring Station	Date (d-m-y)	EC (us/cm)	pH (units)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Chloride:D (mg/L)	Sulphate:D (mg/L)	Ion Balance (balance)	TDS-calculated (mg/L)	Tot Hard as $CaCO_3$ (mg/L)	Tot Alk as $CaCO_3$ (mg/L)	NO_2+NO_3 as N (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	Sulphide (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylenes-total (mg/L)	PHC F_1 (C_6-C_{10})-BTEX (mg/L)	TPH (C_3-C_{10}) (mg/L)
	4-Feb-04	1,490	7.9	136	66.9	3	173	1,140	60.5	1.4	1.03	1,030	610	932	0.036	27.8	6.74	---	---	---	---	---	---	---
	9-Jun-04	1,370	7.73	92	49.8	2.4	140	908	59.4	0.7	0.96	826	430	744	<0.003	30.7	4.16	---	0.222	(0.009)	0.535	4.33	3.5	8.8
	20-Oct-04	---	---	---	---	---	---	---	---	---	---	---	---	---	---	32	3.84	---	0.18	<0.006	0.484	3.38	6.6	---
35-ML2	23-Jul-03	1,630	7.95	59.8	40.3	3.2	260	867	25.1	172	0.95	995	320	711	0.571	4.7	0.559	<0.01	0.0117	0.0052	0.0185	0.147	0.8	---
	28-Oct-03	1,330	7.94	66.4	48.4	3.3	200	919	41.1	16.6	0.99	837	360	753	(0.003)	8.22	0.731	---	0.0105	0.0015	0.0234	0.131	3.5	---
	4-Feb-04	1,200	7.7	74.2	51.3	3.1	187	876	42.7	7	1.05	807	400	718	0.03	10.4	0.861	---	0.035	0.002	0.042	0.33	0.5	0.8
	9-Jun-04	1,310	7.95	74.5	53.5	2.9	165	895	42.6	6.4	0.98	796	410	734	<0.003	9.81	0.893	---	0.0276	0.0018	0.0369	0.344	0.2	0.6
	20-Oct-04	1,340	8.02	84	57.2	3.1	138	862	42.5	4.6	0.99	764	450	706	0.024	9.35	0.929	---	0.0407	0.0025	0.0737	0.539	0.6	---
35-ML3	23-Jul-03	3,510	8.08	96.1	30.6	6.4	778	657	46.6	1,360	1	2,690	370	539	10.9	0.03	0.781	<0.01	0.0044	0.0069	0.0036	0.0624	0.2	---
	29-Oct-03	3,280	8.16	57.7	20.4	6.4	722	845	35.6	1,140	0.93	2,400	230	692	0.134	0.44	1.06	---	0.0058	0.0031	0.0157	0.0897	0.4	---
	4-Feb-04	2,670	7.92	48	15.1	5.1	717	887	34.9	946	0.99	2,210	180	727	(0.004)	2.43	0.888	---	0.014	(0.001)	0.012	0.101	<0.1	0.2
	9-Jun-04	2,780	8.21	62.4	19.5	5.2	557	894	32.7	571	1.06	1,690	240	733	<0.003	1.94	0.902	---	0.0086	0.0038	0.0147	0.0792	<0.1	0.2
	20-Oct-04	2,550	8.21	41.2	13.7	5.1	610	814	30.8	642	1.08	1,740	160	667	0.018	0.88	0.613	---	0.0107	0.0016	0.0135	0.0981	<0.1	---
35-ML7	23-Jul-03	1,460	7.73	111	43	4.6	164	634	44.2	276	0.94	958	450	520	0.166	0.95	2.14	<0.01	0.011	0.022	0.01	0.158	0.3	---
	29-Oct-03	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	0.0701	0.0018	0.0336	0.132	0.3	---
	29-Oct-03	1,480	7.85	116	49.5	5.5	168	902	48.4	112	0.95	951	490	739	(0.004)	5.25	3.13	---	---	---	---	---	---	---
	4-Feb-04	1,520	7.45	133	51.6	4.3	199	924	45.4	209	0.96	1,110	540	757	0.017	5.56	4.65	---	0.0306	<0.0004	0.015	0.0359	<0.1	0.2
	9-Jun-04	1,850	8.11	126	47.7	5.8	235	727	35.4	457	0.92	1,270	510	596	0.008	4.05	3.66	---	0.017	0.0019	0.024	0.0743	<0.1	0.2
	20-Oct-04	1,980	7.88	129	40.3	5.3	271	584	28.2	586	0.97	1,360	490	479	0.014	7	3.55	---	0.007	0.0012	0.01	0.029	<0.1	---
03-P-05	22-Jul-03	1,910	7.25	292	108	5.2	90.8	1,080	39.2	305	1.1	1,380	1,200	881	0.044	5.9	3.73	<0.01	0.036	0.014	0.445	2.15	<0.1	---
	28-Oct-03	2,620	7.5	541	153	4	112	884	37.6	1,300	1.06	2,610	2,000	724	<0.003	19.3	3.55	---	0.0141	<0.0006	0.184	0.381	16.6	---
	4-Feb-04	2,590	7.33	591	156	5	124	887	35.4	1,490	1.04	2,850	2,100	727	0.007	9.93	1.7	---	0.0033	<0.0004	0.0271	0.0845	0.4	0.5
	9-Jun-04	2,730	7.5	495	118	4.5	106	877	34.8	1,290	0.93	2,490	1,700	718	<0.003	5.18	1.44	---	(0.0007)	<0.0004	0.01	0.0177	(0.1)	---
	20-Oct-04	2,920	7.6	485	127	4.7	109	843	32.4	1,170	1.02	2,350	1,700	691	<0.003	7.91	1.89	---	(0.0007)	<0.0004	0.0104	0.0136	0.3	---
	10-May-05	2,820	7.29	474	124	4.5	104	852	28.2	1,090	1.04	2,250	1,700	698	<0.003	6.84	2.49	---	<0.0004	<0.0004	0.0081	0.0243	1.1	---
03-P-06	22-Jul-03	1,520	7.69	209	69.8	4.6	54.1	750	50.9	292	0.94	1,050	810	615	(0.005)	0.08	0.355	<0.01	<0.0004	<0.0004	0.0036	0.008	0.5	---
	28-Oct-03	1,690	7.64	259	80.9	3.4	58	909	48.9	290	1	1,200	980	745	<0.003	5	4.42	---	<0.0004	<0.0004	0.0575	0.0195	2.6	---
	4-Feb-04	1,560	7.47	274	81.2	3.6	60.7	871	49.8	319	1.04	1,220	1,000	714	(0.004)	2.1	3.34	---	<0.0004	<0.0004	0.0049	0.0017	0.2	0.2
	9-Jun-04	1,620	7.65	234	80.1	4.5	59.2	794	59.7	334	0.97	1,170	910	651	<0.003	1.42	1.92	---	<0.0004	<0.0004	(0.0005)	0.0016	<0.1	---
	20-Oct-04	1,730	7.73	237	82.3	5.3	60.3	755	54.3	329	1.03	1,140	930	619	<0.003	1.88	1.82	---	<0.0004	<0.0004	(0.0006)	(0.0008)	<0.1	---
(duplicate)	20-Oct-04	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.0004	<0.0004	(0.0006)	<0.0012	<0.1	---
	10-May-05	1,770	7.55	229	85.0	4.6	62.1	758	55.3	372	0.98	1,190	920	621	<0.003	2.66	0.973	---	<0.0004	<0.0004	<0.0004	<0.0008	1.6	---
03-P-07	22-Jul-03	2,790	7.68	458	92.8	13.7	192	583	68	1,420	0.96	2,530	1,500	478	0.029	0.17	3.53	<0.01	<0.0004	<0.0004	<0.0004	0.002	(0.1)	---
	28-Oct-03	2,770	7.7	400	95.2	11.8	208	654	66.4	1,250	0.96	2,360	1,400	536	<0.003	2.69	3.31	---	<0.0004	<0.0004	<0.0004	<0.0012	<0.1	---
	4-Feb-04	2,480	7.64	432	106	13.6	252	685	77.6	1,290	1.03	2,510	1,500	561	<0.003	0.27	3.19	---	<0.0004	<0.0004	<0.0004	<0.0008	<0.1	<0.1
	9-Jun-04	2,930	7.67	443	104	12.7	234	726	75.1	1,350	0.98	2,590	1,500	595	0.013	3.04	2.89	---	<0.0004	<0.0004	<0.0004	<0.0008	<0.1	---
	20-Oct-04	3,110	7.73	414	93.9	12.7	221	752	76.1	1,200	0.98	2,400	1,400	616	<0.003	7.89	2.7	---	<0.0004	<0.0004	<0.0004	<0.0008	<0.1	---
	10-May-05	2,890	7.47	427	92.9	11.1	206	863	81.3	1,040	1.01	2,290	1,400	707	0.003	4.34	2.58	---	<0.0004	<0.0004	<0.0004	<0.0008	<0.1	---
03-P-08	22-Jul-03	3,230	7.6	351	162	10.9	277	1,050	79.6	1,320	0.92	2,720	1,500	862	0.104	0.11	0.706	<0.01	<0.0004	<0.0004	<0.0004	<0.0008	<0.1	---
	28-Oct-03	3,320	7.61	334	169	8.7	441	1,100	69.9	1,320	1.05	2,890	1,500	897	0.019	(0.01)	0.973	---	<0.0004	<0.0004	<0.0004	<0.0012	<0.1	---
	4-Feb-04	2,900	7.4	346	178	8	405	1,050	73.2	1,410	1.03	2,940	1,600	860	0.016	0.12	1.15	---	<0.0004	<0.0004	<0.0004	<0.0008	<0.1	<0.1
	9-Jun-04	3,530	7.55	335	181	7.8	416	1,050	73.2	1,700	0.91	3,230	1,600	860	0.07	0.12	1.56	---	<0.0004	<0.0004	<0.0004	<0.0008	<0.1	---
	20-Oct-04	3,800	7.56	324	167	7.9	446	1,030	74.5	1,450	1.01	2,980	1,500	840	<0.003	0.1	2.08	---	<0.0004	<0.0004	0.0016	0.0101	<0.1	---
	11-May-05	3,680	7.50	346	184	7.5	409	1,000	67.6	1,470	1.03	2,980	1,600	820	<0.003	0.10	1.50	<0.005	<0.0004	<0.0004	0.0008	0.0084	<0.1	--- ---
03-P-09	22-Jul-03	2,620	7.47	345	162	9.9	104	1,420	36.3	691	0.92	2,050	1,500	1,160	0.059	0.11	4.46	<0.01	<0.0004	<0.0004	<0.0004	<0.0008	<0.1	---
	28-Oct-03	2,720	7.63	444	188	6	113	1,340	32.6	868	1.05	2,330	1,900	1,100	<0.003	8.7	7.36	---	0.001	<0.0004	0.0022	<0.0012	<0.1	---
	4-Feb-04	2,620	7.24	542	174	4.9	106	1,390	36.5	1,150	0.97	2,710	2,100	1,140	(0.004)	7.13	6.59	---	(0.0005)	<0.0004	<0.0004	<0.0008	<0.1	<0.1
	9-Jun-04	2,790	7.41	398	163	5.5	144	1,230	36	899	1	2,270	1,700	1,010	0.006	6.7	5.64	---	(0.0007)	<0.0004	0.0026	<0.0008	<0.1	---
	20-Oct-04	2,780	7.46	348	130	4.7	107	1,260	33.7	727	0.91	1,990	1,400	1,030	<0.003	14.3	3.96	---	<0.0004	<0.0004	0.0011	<0.0008	<0.1	---
	10-May-05	2,790	7.22	406	143	4.0	97.6	1,380	29.3	731	0.95	2,110	1,600	1,130	<0.003	13.8	4.38	---	<0.0004	<0.0004	0.0004	<0.0008	0.1	---
03-P-10	22-Jul-03	1,690	7.81	147	99.3	6.5	119	863	52.5	285	0.97	1,140	770	708	(0.003)	0.09	0.948	<0.01	<0.0004	<0.0004	0.0158	0.0385	0.5	---
	28-Oct-03	1,590	7.85	140	99.8	3.7	119	1,060	49.7	93.8	1	1,040	760	866	0.291	8.94	1.65	---	0.0008	<0.0004	0.122	0.0721	2.3	---
	4-Feb-04	1,460	7.47	113	96.6	2.5	114	1,060	56.3	72.9	0.93	989	680	867	(0.005)	13.5	0.799	---	(0.0007)	<0.0004	0.0941	0.0477	0.3	0.4
(Duplicate)	4-Feb-04	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	<0.001	<0.001	0.113	0.049	0.4	0.5
	9-Jun-04	1,750	7.82	152	118	3.7	126	1,070	57.7	152	1.04	1,150	870	880	<0.003	11.6	0.839	---	(0.0005)	<0.0004	0.0608	0.02	(0.1)	---
	20-Oct-04	1,950	7.76	142	127	3.2	118	1,080	55.5	221	0.98	1,210	880	882	<0.003	14.7	0.794	---	(0.0006)	<0.0004	0.0881	0.0219	0.2	---
	10-May-05	2,010	7.65	170	141	2.3	98.4	1,090	54.5	305	0.96	1,320	1,000	893	0.005	11.5	0.595	<0.005	0.0009	<0.0004	0.0924	0.0408	0.1	---

NOTES: *1. --- in detail data row(s) denotes parameter not analyzed.*

Table 5

Site A Mixing Model Output: P34 Cluster

Well	Err/Mod	Sampler	Purge	34-DP1	34-DP2	34-DP3	Date	EC	pH	Ca (meq/L)	Mg (meq/L)	K (meq/L)	Na (meq/L)	HCO3 (meq/L)	Cl (meq/L)	SO4 (meq/L)	Fe (meq/L)	Mn (meq/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	HCO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	Fe (mg/L)	Mn (mg/L)	B (mg/L)	T (mg/L)	E (mg/L)	X (mg/L)	TDS (mg/L)
34-HP-2	**field**	**directpush**	**mid**				**8-Jun-04**	**1740**	**8.43**	**1.55**	**10.86**	**0.15**	**9.66**	**20.32**	**0.81**	**0.14**	**0.000**	**0.004**	**31.0**	**132**	**5.7**	**222.0**	**1240**	**28.7**	**6.5**	**0.01**	**0.10**	**<0.02**	**0.25**	**0.47**	**4.11**	**1080**
34-HP-2	model	directpush	mid	0	87%	13%	8-Jun-04			1.83	10.12	0.04	8.87	20.45	0.69	0.83	0.236	0.006	36.7	123.0	1.4	204.0	1247.4	24.6	39.9	6.58	0.16	NA	0.161	0.493	4.043	1048
34-HP-2	err^2	directpush	mid				8-Jun-04			0.080	0.551	0.012	0.613	0.015	0.014	0.483	0.055	0.000	5.7	-9.0	-4.3	-18.0	7.4	-4.1	33.4	6.57	0.06	NA	-0.089	0.023	-0.067	-32
34-HP-2	RPD	directpush	mid				8-Jun-04												17%	-7%	-122%	-8%	1%	-16%	144%	199%	43%	NA	-44%	5%	-2%	-3%
34-HP-3	**field**	**directpush**	**deep**				**8-Jun-04**	**2500**	**7.95**	**6.79**	**15.55**	**0.25**	**10.35**	**23.11**	**1.94**	**8.74**	**0.000**	**0.013**	**136.0**	**189**	**9.7**	**238.0**	**1410**	**68.6**	**420**	**0.01**	**0.35**	**<0.0009**	**0.0053**	**0.0061**	**0.0388**	**1760**
34-HP-3	model	directpush	deep	0	13%	87%	8-Jun-04			5.66	14.81	0.09	10.61	26.76	1.65	5.31	0.168	0.025	113.5	180.0	3.6	244.0	1632.3	58.6	255.2	4.70	0.69	NA	0.027	0.253	0.862	1662
34-HP-3	err^2	directpush	deep				8-Jun-04			1.261	0.551	0.024	0.068	13.280	0.079	11.776	0.028	0.000	-22.5	-9.0	-6.1	6.0	222.3	-10.0	-164.8	4.69	0.34	NA	0.022	0.247	0.823	-98
34-HP-3	RPD	directpush	deep				8-Jun-04												-18%	-5%	-92%	2%	15%	-16%	-49%	199%	65%	NA	135%	191%	183%	-6%
34-MW1	**field**	**waterra**	**no purge**				**27-Oct-03**	**2770**	**7.75**	**5.54**	**18.02**	**0.13**	**14.22**	**30.16**	**1.95**	**7.89**	**0.362**	**0.131**	**111.0**	**219**	**4.9**	**327.0**	**1840**	**69.0**	**379**	**10.10**	**3.59**	**0.014**	**<0.007**	**0.564**	**3.9**	**2030**
34-MW1	model	waterra	no purge	0	7%	93%	27-Oct-03			6.48	18.81	0.12	11.90	28.97	1.57	8.27	0.154	0.022	129.9	228.7	4.7	273.6	1767.5	55.5	397.4	4.29	0.60	NA	0.017	0.216	0.577	1969
34-MW1	err^2	waterra	no purge				27-Oct-03			0.889	0.634	0.000	5.403	1.413	0.145	0.146	0.043	0.012	18.9	9.7	-0.2	-53.4	-72.5	-13.5	18.4	-5.81	-2.99	NA	NA	-0.348	-3.323	-61
34-MW1	RPD	waterra	no purge				27-Oct-03												16%	4%	-4%	-18%	-4%	-22%	5%	-81%	-143%	NA	NA	-89%	-148%	-3%
34-MW1	**field**	**waterra**	**no purge**				**4-Feb-04**	**2150**	**7.54**	**5.19**	**15.22**	**0.08**	**11.00**	**30.32**	**1.76**	**2.25**	**0.119**	**0.090**	**104.0**	**185**	**3.0**	**253.0**	**1850**	**62.5**	**108**	**3.32**	**2.46**	**<0.02**	**<0.02**	**0.56**	**3.38**	**1630**
34-MW1	model	waterra	no purge	0	34%	66%	4-Feb-04			5.86	15.21	0.08	10.64	25.89	1.26	5.48	0.201	0.024	117.5	184.9	3.2	244.5	1579.5	44.8	263.3	5.62	0.66	NA	NA	0.343	2.368	1641
34-MW1	err^2	waterra	no purge				4-Feb-04			0.451	0.000	0.000	0.136	19.664	0.250	10.452	0.007	0.004	13.5	-0.1	0.2	-8.5	-270.5	-17.7	155.3	2.30	-1.80	NA	NA	-0.217	-1.012	11
34-MW1	RPD	waterra	no purge				4-Feb-04												12%	0%	8%	-3%	-16%	-33%	84%	51%	-115%	NA	NA	-48%	-35%	1%
34-MW1	**field**	**waterra**	**no purge**				**8-Jun-04**	**2590**	**7.7**	**3.84**	**15.71**	**0.07**	**12.48**	**30.81**	**2.07**	**2.08**	**0.168**	**0.085**	**76.9**	**191**	**2.7**	**287.0**	**1880**	**73.5**	**99.9**	**4.68**	**2.34**	**0.011**	**<0.006**	**0.426**	**2.6**	**1660**
34-MW1	model	waterra	no purge	0	4%	96%	8-Jun-04			6.12	15.37	0.10	10.82	27.51	1.77	5.85	0.160	0.027	122.7	186.8	3.9	248.8	1678.4	62.7	280.9	4.48	0.75	NA	0.011	0.224	0.481	1736
34-MW1	err^2	waterra	no purge				8-Jun-04			5.221	0.119	0.001	2.767	10.918	0.093	14.203	0.000	0.003	45.8	-4.2	1.2	-38.2	-201.6	-10.8	181.0	-0.20	-1.59	NA	NA	-0.202	-2.119	76
34-MW1	RPD	waterra	no purge				8-Jun-04												46%	-2%	36%	-14%	-11%	-16%	95%	-4%	-103%	NA	NA	-62%	-138%	4%
34-MW1	**field**	**waterra**	**no purge**				**19-Oct-04**	**2450**	**7.87**	**2.73**	**11.02**	**0.08**	**12.79**	**27.04**	**1.65**	**1.67**	**0.113**	**0.048**	**54.7**	**134**	**3.1**	**294.0**	**1650**	**58.6**	**80.3**	**3.16**	**1.32**	**<0.004**	**<0.004**	**0.671**	**1.54**	**1440**
34-MW1	model	waterra	no purge	0	19%	81%	19-Oct-04			4.94	12.98	0.10	10.66	24.68	1.61	3.43	0.136	0.024	99.0	157.7	3.7	245.1	1506.0	56.9	164.5	3.81	0.65	0.009	0.032	0.198	1.167	1469
34-MW1	err^2	waterra	no purge				19-Oct-04			4.892	3.816	0.000	4.529	5.569	0.002	3.075	0.001	0.001	44.3	23.7	0.6	-48.9	-144.0	-1.7	84.2	0.65	-0.67	NA	NA	-0.473	-0.373	29
34-MW1	RPD	waterra	no purge				19-Oct-04												58%	16%	19%	-18%	-9%	-3%	69%	19%	-68%	NA	NA	-109%	-28%	2%
34-MW1	**field**	**waterra**	**no purge**				**11-May-05**	**2470**	**7.73**	**3.92**	**13.90**	**0.06**	**10.48**	**25.24**	**1.84**	**6.33**	**0.048**	**0.041**	**78.6**	**169**	**2.5**	**241.0**	**1540**	**65.2**	**304**	**1.33**	**1.12**	**0.005**	**<0.002**	**0.349**	**1.38**	**1620**
34-MW1	model	waterra	no purge	0	12%	88%	11-May-05			4.66	13.72	0.07	9.50	23.23	1.48	7.35	0.122	0.014	93.5	166.8	2.6	218.4	1417.1	52.5	353.0	3.41	0.38	0.006	0.027	0.459	0.946	1592
34-MW1	err^2	waterra	no purge				11-May-05			0.550	0.033	0.000	0.969	4.060	0.128	1.041	0.006	0.001	14.9	-2.2	0.1	-22.6	-122.9	-12.7	49.0	2.08	-0.74	0.001	NA	0.110	-0.434	-28
34-MW1	RPD	waterra	no purge				11-May-05												17%	-1%	3%	-10%	-8%	-22%	15%	88%	-98%	17%	NA	27%	-37%	-2%
34-MW1B	**field**	**dialysis**	**mid**				**19-Nov-03**	**1930**	**7.32**	**2.89**	**11.85**	**0.07**	**10.35**	**21.96**	**1.84**	**1.94**	**0.193**	**0.085**	**58.0**	**144**	**2.6**	**238.0**	**1340**	**65.1**	**93.2**	**5.40**	**2.33**	**0.007**	**<0.006**	**0.155**	**1.81**	**1,270**
34-MW1B	model	dialysis	mid	0	87%	13%	19-Nov-03			2.14	12.35	0.07	9.83	23.24	0.72	1.20	0.123	0.005	42.9	150.1	2.6	225.9	1418.1	25.4	57.5	3.43	0.13	NA	0.174	0.525	3.777	1207
34-MW1B	err^2	dialysis	mid				19-Nov-03			0.569	0.250	0.000	0.276	1.640	1.254	0.551	0.005	0.006	-15.1	6.1	0.0	-12.1	78.1	-39.7	-35.7	-1.97	-2.20	NA	NA	0.370	1.967	-63
34-MW1B	RPD	dialysis	mid				19-Nov-03												-30%	4%	-2%	-5%	6%	-88%	-47%	-45%	-178%	NA	NA	109%	70%	-5%
34-MW1B	**field**	**dialysis**	**mid**				**4-Feb-04**	**1540**	**7.8**	**2.95**	**11.68**	**0.06**	**9.18**	**20.32**	**1.61**	**0.52**	**0.080**	**0.058**	**59.1**	**142**	**2.3**	**211.0**	**1240**	**57.1**	**25.2**	**2.23**	**1.59**	**0.008**	**<0.004**	**0.322**	**2.26**	**1110**
34-MW1B	model	dialysis	mid	0	95%	5%	4-Feb-04			2.04	11.15	0.04	9.30	21.84	0.76	0.48	0.149	0.004	40.9	135.5	1.4	213.8	1332.4	26.8	23.0	4.16	0.12	NA	NA	0.579	6.339	1099
34-MW1B	err^2	dialysis	mid				4-Feb-04			0.820	0.287	0.001	0.015	2.295	0.729	0.002	0.005	0.003	-18.2	-6.5	-0.9	2.8	92.4	-30.3	-2.2	1.93	-1.47	NA	NA	0.257	4.079	-11
34-MW1B	RPD	dialysis	mid				4-Feb-04												-36%	-5%	-51%	1%	7%	-72%	-9%	60%	-173%	NA	NA	57%	95%	-1%
34-MW1C	**field**	**dialysis**	**deep**				**19-Nov-03**	**2270**	**7.4**	**3.56**	**15.06**	**0.08**	**12.44**	**27.86**	**2.15**	**2.00**	**0.205**	**0.090**	**71.4**	**183**	**3.1**	**286.0**	**1700**	**76.3**	**96.3**	**5.72**	**2.47**	**0.012**	**<0.009**	**0.444**	**4.29**	**1,560**
34-MW1C	model	dialysis	deep	0	53%	47%	19-Nov-03			3.97	15.07	0.09	10.70	25.65	1.07	4.17	0.136	0.012	79.5	183.2	3.5	246.0	1565.1	38.1	200.5	3.79	0.33	NA	0.108	0.395	2.431	1528
34-MW1C	err^2	dialysis	deep				19-Nov-03			0.163	0.000	0.000	3.032	4.888	1.163	4.707	0.005	0.006	8.1	0.2	0.4	-40.0	-134.9	-38.2	104.2	-1.93	-2.14	NA	NA	-0.049	-1.859	-32
34-MW1C	RPD	dialysis	deep				19-Nov-03												11%	0%	11%	-15%	-8%	-67%	70%	-41%	-153%	NA	NA	-12%	-55%	-2%
34-MW1C	**field**	**dialysis**	**deep**				**4-Feb-04**	**2110**	**7.89**	**4.77**	**16.29**	**0.08**	**12.14**	**31.31**	**1.97**	**0.57**	**0.039**	**0.079**	**95.5**	**198**	**3.2**	**279.0**	**1910**	**69.7**	**27.6**	**1.08**	**2.16**	**0.010**	**<0.009**	**0.638**	**4.19**	**1620**
34-MW1C	model	dialysis	deep	0	34%	66%	4-Feb-04			5.86	15.21	0.08	10.63	25.89	1.26	5.48	0.201	0.024	117.4	184.9	3.2	244.5	1579.3	44.8	263.1	5.62	0.66	NA	NA	0.343	2.370	1641
34-MW1C	err^2	dialysis	deep				4-Feb-04			1.196	1.169	0.000	2.252	29.382	0.494	24.044	0.026	0.003	21.9	-13.1	0.0	-34.5	-330.7	-24.9	235.5	4.54	-1.50	NA	NA	-0.295	-1.820	21
34-MW1C	RPD	dialysis	deep				4-Feb-04												21%	-7%	1%	-13%	-19%	-44%	162%	136%	-106%	NA	NA	-60%	-55%	1%
34-MW2	**field**	**waterra**	**no purge**				**29-Oct-03**	**2410**	**7.94**	**4.39**	**15.88**	**0.11**	**11.05**	**27.37**	**1.79**	**4.66**	**0.137**	**0.054**	**88.0**	**193**	**4.4**	**254.0**	**1670**	**63.6**	**224**	**3.82**	**1.48**	**0.006**	**0.022**	**0.75**	**3.86**	**1,650**
34-MW2	model	waterra	no purge	0	42%	58%	29-Oct-03			4.60	16.01	0.10	11.00	26.49	1.20	5.21	0.140	0.015	92.2	194.6	3.8	252.9	1616.2	42.5	250.2	3.92	0.40	NA	0.085	0.350	1.963	1639
34-MW2	err^2	waterra	no purge				29-Oct-03			0.044	0.018	0.000	0.002	0.777	0.355	0.298	0.000	0.002	4.2	1.6	-0.6	-1.1	-53.8	-21.1	26.2	0.10	-1.08	NA	0.063	-0.400	-1.897	-11
34-MW2	RPD	waterra	no purge				29-Oct-03												5%	1%	-15%	0%	-3%	-40%	11%	3%	-115%	NA	118%	-73%	-65%	-1%
34-MW2	**field**	**waterra**	**no purge**				**3-Feb-04**	**2270**	**7.58**	**6.19**	**16.54**	**0.10**	**11.05**	**24.59**	**1.57**	**11.57**	**0.167**	**0.059**	**124.0**	**201**	**3.8**	**254.0**	**1500**	**55.8**	**556**	**4.65**	**1.61**	**0.004**	**<0.002**	**0.213**	**0.771**	**1940**
34-MW2	model	waterra	no purge	0	8%	92%	3-Feb-04			7.53	16.99	0.10	11.22	27.66	1.48	7.66	0.224	0.033	150.9	206.5	4.1	257.9	1687.3	52.6	368.2	6.26	0.90	NA	NA	0.240	0.634	1878
34-MW2	err^2	waterra	no purge				3-Feb-04			1.798	0.202	0.000	0.029	9.424	0.008	15.287	0.003	0.001	26.9	5.5	0.3	3.9	187.3	-3.2	-187.8	1.61	-0.71	NA	NA	0.027	-0.137	-62
34-MW2	RPD	waterra	no purge				3-Feb-04												20%	3%	6%	2%	12%	-6%	-41%	29%	-56%	NA	NA	12%	-20%	-3%
34-MW2	**field**	**waterra**	**no purge**				**4-Feb-04**	**2220**	**7.56**	**5.89**	**15.71**	**0.10**	**10.57**	**25.90**	**1.43**	**8.31**	**0.145**	**0.052**	**118.0**	**191**	**4.0**	**243.0**	**1580**	**50.7**	**399**	**4.06**	**1.43**	**0.003**	**<0.002**	**0.281**	**1.01**	**1790**
34-MW2	model	waterra	no purge	0	21%	79%	4-Feb-04			6.70	16.10	0.09	10.93	26.77	1.37	6.58	0.213	0.029	134.2	195.7	3.6	251.2	1633.5	48.7	315.9	5.94	0.78	NA	NA	0.291	1.499	1760
34-MW2	err^2	waterra	no purge				4-Feb-04			0.654	0.149	0.000	0.128	0.769	0.003	2.996	0.005	0.001	16.2	4.7	-0.4	8.2	53.5	-2.0	-83.1	1.88	-0.65	NA	NA	0.010	0.489	-30
34-MW2	RPD	waterra	no purge				4-Feb-04												13%	2%	-9%	3%	3%	-4%	-23%	38%	-58%	NA	NA	4%	39%	-2%
34-MW2	**field**	**waterra**	**no purge**				**8-Jun-04**	**3050**	**7.79**	**12.28**	**18.92**	**0.16**	**11.31**	**23.60**	**1.76**	**17.38**	**0.244**	**0.098**	**246.0**	**230**	**6.4**	**260.0**	**1440**	**62.3**	**835**	**6.82**	**2.69**	**0.001**	**0.0006**	**0.0982**	**0.262**	**2360**
34-MW2	model	waterra	no purge	0	0%	100%	8-Jun-04			6.34	15.63	0.10	10.92	27.86	1.82	6.10	0.156	0.028	127.0	190.0	4.0	251.0	1700.0	64.6	293.0	4.37	0.78	NA	0.004	0.211	0.303	1770
34-MW2	err^2	waterra	no purge				8-Jun-04			35.261	10.830	0.004	0.153	18.161	0.004	127.316	0.008	0.005	-119.0	-40.0	-2.4	-9.0	260.0	2.3	-542.0	-2.45	-1.91	NA	0.003	0.113	0.041	-590
34-MW2	RPD	waterra	no purge				8-Jun-04												-64%	-19%	-46%	-4%	17%	4%	-96%	-44%	-110%	NA	148%	73%	15%	-29%
34-MW2	**field**	**waterra**	**no purge**				**19-Oct-04**	**3130**	**7.86**	**9.23**	**15.88**	**0.16**	**11.14**	**20.82**	**1.66**	**18.47**	**0.181**	**0.056**	**185.0**	**193**	**6.1**	**256.0**	**1270**	**58.8**	**887**	**5.05**	**1.53**	**<0.0004**	**<0.0004**	**0.0309**	**0.0754**	**2220**
34-MW2	model	waterra	no purge	0	0%	100%	19-Oct-04			5.84	13.99	0.11	11.27	26.39	1.82	4.21	0.158	0.029	117.0	170.0	4.3	259.0	1610.0	64.6	202.0	4.40	0.79	0.002	0.003	0.084	0.131	1610
34-MW2	err^2	waterra	no purge				19-Oct-04			11.514	3.581	0.002	0.017	31.057	0.027	203.360	0.001	0.001	-68.0	-23.0	-1.8	3.0	340.0	5.8	-685.0	-0.65	-0.74	NA	NA	0.053	0.056	-610
34-MW2	RPD	waterra	no purge				19-Oct-04												-45%	-13%	-35%	1%	24%	9%	-126%	-14%	-64%	NA	NA	92%	54%	-32%
34-MW2	**field**	**waterra**	**no purge**				**10-May-05**	**2650**	**7.67**	**6.99**	**15.88**	**0.09**	**9.61**	**21.31**	**1.42**	**13.70**	**0.203**	**0.037**	**140.0**	**193**	**3.5**	**221.0**	**1300**	**50.5**	**658**	**5.67**	**1.01**	**0.004**	**0.002**	**0.338**	**1.38**	**1910**
34-MW2	model	waterra	no purge	0	0%	100%	10-May-05			5.14	14.23	0.07	9.70	23.77	1.52	8.37	0.118	0.016	103.0	173.0	2.8	223.0	1450.0	53.9	402.0	3.29	0.43	0.002	0.007	0.402	0.193	1680
34-MW2	err^2	waterra	no purge				10-May-05			3.409	2.707	0.000	0.008	6.045	0.009	28.403	0.007	0.000	-37.0	-20.0	-0.7	2.0	150.0	3.4	-256.0	-2.38	-0.58	-0.002	0.005	0.064	-1.187	-230
34-MW2	RPD	waterra	no purge				10-May-05												-30%	-11%	-22%	1%	11%	7%	-48%	-53%	-81%	-67%	111%	17%	-151%	-13%
34-MW2C	**field**	**BarCad**	**deep**				**29-Oct-03**	**2340**	**7.96**	**4.86**	**17.52**	**0.11**	**12.61**	**26.55**	**1.73**	**4.27**	**0.093**	**0.068**	**97.4**	**213**	**4.2**	**290.0**	**1620**	**61.3**	**205**	**2.61**	**1.87**	**0.003**	**0.003**	**0.403**	**1.51**	**1,640**
34-MW2C	model	BarCad	deep	0	37%	63%	29-Oct-03			4.85	16.38	0.10	11.12	26.81	1.25	5.61	0.142	0.015	97.1	199.1	3.9	255.6	1635.9	44.2	269.4	3.97	0.42	NA	0.076	0.332	1.782	1682
34-MW2C	err^2	BarCad	deep				29-Oct-03			0.000	1.312	0.000	2.236	0.068	0.234	1.796	0.002	0.003	-0.3	-13.9	-0.3	-34.4	15.9	-17.1	64.4	1.36	-1.45	NA	0.073	-0.071	0.272	42
34-MW2C	RPD	BarCad	deep				29-Oct-03												0%	-7%	-8%	-13%	1%	-32%	27%	41%	-126%	NA	185%	-19%	17%	3%
93-P-34	**field**	**waterra**	**no purge**				**21-Jul-03**	**2770**	**7.57**	**3.18**	**15.06**	**0.10**	**15.62**	**7.69**	**2.64**	**3.56**	**0.184**	**0.079**	**63.8**	**183**	**3.9**	**359.0**	**469**	**93.5**	**171**	**5.13**	**2.18**	**<0.03**	**0.14**	**0.47**	**5.57**	**1120**
93-P-34	model	waterra	no purge	0	100%	0%	21-Jul-03			1.75	12.75	0.04	10.00	23.11	1.80	0.03	0.005	0.005	35.0	155.0	1.4	230.0	1410.0	63.8	1.3	0.13	0.13	NA	NA	0.750	6.090	1180
93-P-34	err^2	waterra	no purge				21-Jul-03			2.065	5.306	0.004	31.485	237.891	0.702	12.481	0.032	0.006	-28.8	-28.0	-2.5	-129.0	941.0	-29.7	-169.7	-5.00	-2.05	NA	NA	0.280	0.520	60
93-P-34	RPD	waterra	no purge				21-Jul-03												-58%	-17%	-94%	-44%	100%	-38%	-197%	-190%	-178%	NA	NA	46%	9%	5%

Table 5

Site A Mixing Model Output: P34 Cluster

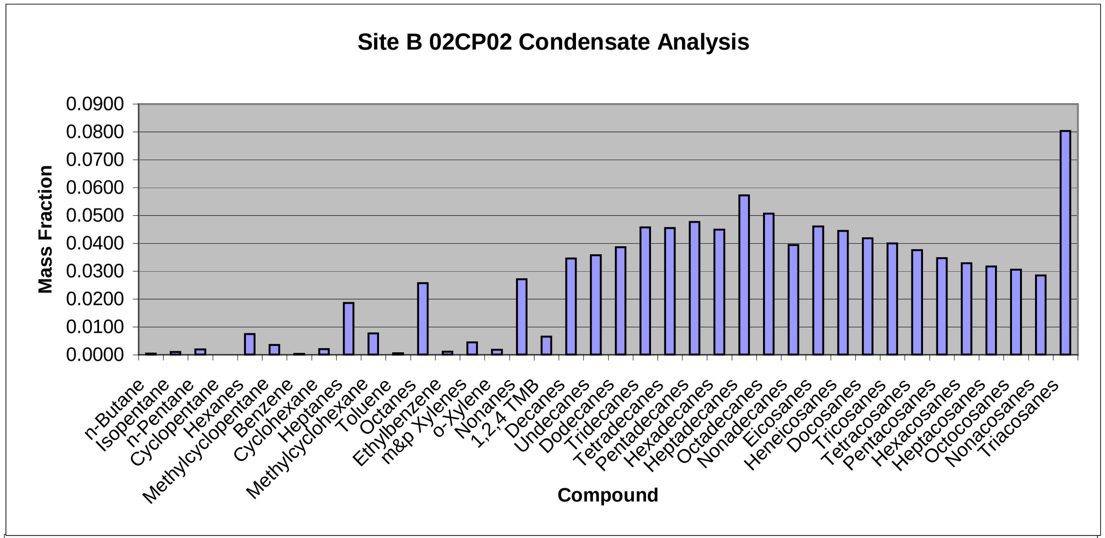
Well	Err/Mod	Sampler	Purge	34-DP1	34-DP2	34-DP3	Date	EC	pH	Ca (meq/L)	Mg (meq/L)	K (meq/L)	Na (meq/L)	HCO3 (meq/L)	Cl (meq/L)	SO4 (meq/L)	Fe (meq/L)	Mn (meq/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	HCO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	Fe (mg/L)	Mn (mg/L)	B (mg/L)	T (mg/L)	E (mg/L)	X (mg/L)	TDS (mg/L)
93-P-34	field	BadCad	shallow				22-Jul-03	2770	7.57	3.83	15.30	0.13	16.44	29.34	2.96	2.91	0.182	0.106	76.8	186	5.0	378.0	1790	105.0	140	5.09	2.92	<0.03	0.08	0.58	5.56	1780
93-P-34	model	BadCad	shallow	0	52%	48%	22-Jul-03			4.62	16.15	0.09	11.21	25.71	1.81	5.04	0.004	0.019	92.6	196.3	3.4	257.8	1568.3	64.2	242.0	0.12	0.51	NA	NA	0.477	3.323	1626
93-P-34	err^2	BadCad	shallow				22-Jul-03			0.620	0.713	0.002	27.322	13.200	1.323	4.511	0.032	0.008	15.8	10.3	-1.6	-120.2	-221.7	-40.8	102.0	-4.97	-2.41	NA	NA	-0.103	-2.237	-154
93-P-34	RPD	BadCad	shallow				22-Jul-03												19%	5%	-39%	-38%	-13%	-48%	53%	-191%	-140%	NA	NA	-19%	-50%	-9%
93-P-34	field	BadCad	deep				23-Jul-03	2770	7.57	3.86	15.38	0.12	12.74	28.68	2.47	3.46	0.126	0.068	77.3	187	4.5	293.0	1750	87.4	166	3.53	1.87	<0.03	0.05	0.59	4.94	1680
93-P-34	model	BadCad	deep	0	55%	45%	23-Jul-03			4.45	15.95	0.08	11.14	25.55	1.81	4.74	0.004	0.018	89.2	193.8	3.3	256.2	1559.0	64.2	227.9	0.12	0.49	NA	NA	0.493	3.486	1600
93-P-34	err^2	BadCad	deep				23-Jul-03			0.352	0.317	0.001	2.563	9.797	0.428	1.659	0.015	0.003	11.9	6.8	-1.2	-36.8	-191.0	-23.2	61.9	-3.41	-1.38	NA	NA	-0.097	-1.454	-80
93-P-34	RPD	BadCad	deep				23-Jul-03												14%	4%	-32%	-13%	-12%	-31%	31%	-187%	-117%	NA	NA	-18%	-35%	-5%
93-P-34	field	bailer	no purge				23-Jul-03	2770	7.57	2.92	15.96	0.08	18.70	31.96	2.93	2.14	0.677	0.040	58.5	194	3.0	430.0	1950	104.0	103	18.90	1.11	<0.04	<0.04	0.49	6.60	1870
93-P-34	model	bailer	no purge	0	47%	53%	23-Jul-03			4.91	16.49	0.09	11.34	25.96	1.81	5.54	0.004	0.020	98.3	200.4	3.6	260.6	1584.1	64.3	266.0	0.12	0.55	NA	NA	0.450	3.047	1671
93-P-34	err^2	bailer	no purge				23-Jul-03			3.947	0.275	0.000	54.292	35.965	1.256	11.517	0.452	0.000	39.8	6.4	0.6	-169.4	-365.9	-39.7	163.0	-18.78	-0.56	NA	NA	-0.040	-3.553	-199
93-P-34	RPD	bailer	no purge				23-Jul-03												51%	3%	17%	-49%	-21%	-47%	88%	-197%	-67%	NA	NA	-9%	-74%	-11%
93-P-34	field	bailer	no purge				28-Oct-03	2010	7.76	1.95	12.75	0.05	11.40	24.91	1.67	0.02	0.759	0.012	39.1	155	2.1	262.0	1520	59.1	1.2	21.20	0.34	0.038	0.054	0.459	4.2	1290
93-P-34	model	bailer	no purge	0	83%	17%	28-Oct-03			2.35	12.66	0.07	9.93	23.52	0.76	1.54	0.124	0.006	47.1	153.8	2.7	228.2	1434.9	26.8	73.8	3.47	0.16	NA	0.166	0.511	3.624	1243
93-P-34	err^2	bailer	no purge				28-Oct-03			0.157	0.009	0.000	2.160	1.947	0.828	2.286	0.403	0.000	8.0	-1.2	0.6	-33.8	-85.1	-32.3	72.6	-17.73	-0.18	NA	0.112	0.052	-0.576	-47
93-P-34	RPD	bailer	no purge				28-Oct-03												18%	-1%	24%	-14%	-6%	-75%	194%	-144%	-73%	NA	102%	11%	-15%	-4%
93-P-34	field	bailer	no purge				4-Feb-04	1760	7.84	1.87	12.42	0.05	9.57	24.09	2.00	0.19	0.010	0.003	37.5	151	1.8	220.0	1470	70.8	9.2	0.27	0.08	<0.04	0.07	0.79	6.27	1,210
93-P-34	model	bailer	no purge	0	84%	16%	4-Feb-04			2.72	11.87	0.04	9.54	22.56	0.85	1.37	0.158	0.008	54.5	144.2	1.7	219.2	1376.2	30.0	65.6	4.42	0.21	NA	NA	0.537	5.636	1195
93-P-34	err^2	bailer	no purge				4-Feb-04			0.720	0.309	0.000	0.001	2.364	1.324	1.378	0.022	0.000	17.0	-6.8	-0.1	-0.8	-93.8	-40.8	56.4	4.15	0.13	NA	NA	-0.253	-0.634	-15
93-P-34	RPD	bailer	no purge				4-Feb-04												37%	-5%	-6%	0%	-7%	-81%	151%	177%	92%	NA	NA	-38%	-11%	-1%
93-P-34	field	waterra	no purge				8-Jun-04	1910	7.84	1.59	10.86	0.03	9.70	23.60	1.20	0.20	0.487	0.008	31.8	132	1.2	223.0	1440	42.5	9.6	13.60	0.21	0.021	0.035	0.566	4.18	1160
93-P-34	model	waterra	no purge	0	71%	29%	8-Jun-04			2.65	11.12	0.05	9.25	21.80	0.90	1.79	0.221	0.010	53.1	135.2	1.9	212.6	1330.0	31.9	86.1	6.18	0.27	NA	0.132	0.442	3.361	1180
93-P-34	err^2	waterra	no purge				8-Jun-04			1.134	0.070	0.000	0.206	3.252	0.090	2.534	0.071	0.000	21.3	3.2	0.7	-10.4	-110.0	-10.6	76.5	-7.42	0.06	NA	0.097	-0.124	-0.819	20
93-P-34	RPD	waterra	no purge				8-Jun-04												50%	2%	43%	-5%	-8%	-29%	160%	-75%	24%	NA	116%	-25%	-22%	2%
93-P-34	field	bailer	no purge				19-Oct-04	1800	8.03	1.58	10.04	0.05	9.09	20.16	1.32	0.11	0.237	0.007	31.7	122	1.9	209.0	1230	46.9	5.4	6.62	0.19	0.010	0.01	0.706	4.25	1030
93-P-34	model	bailer	no purge	0	74%	26%	19-Oct-04			2.24	9.95	0.05	8.84	19.56	0.96	1.08	0.072	0.008	45.0	120.9	2.1	203.2	1193.3	33.9	51.9	2.02	0.23	0.030	0.120	0.542	4.282	1044
93-P-34	err^2	bailer	no purge				19-Oct-04			0.439	0.008	0.000	0.064	0.361	0.135	0.935	0.027	0.000	13.3	-1.1	0.2	-5.8	-36.7	-13.0	46.5	-4.60	0.05	0.020	0.110	-0.164	0.032	14
93-P-34	RPD	bailer	no purge				19-Oct-04												35%	-1%	8%	-3%	-3%	-32%	162%	-107%	22%	101%	169%	-26%	1%	1%
93-P-34	field	bailer	no purge				10-May-05	1930	7.7	1.85	11.76	0.03	8.74	22.29	1.52	0.61	0.355	0.011	37.1	143	1.3	201.0	1360	53.8	29.5	9.90	0.31	<0.04	<0.04	0.58	3.37	1150
93-P-34	model	bailer	no purge	0	77%	23%	10-May-05			2.14	11.01	0.04	8.43	20.37	1.27	1.95	0.146	0.005	42.9	133.8	1.4	193.8	1242.6	45.1	93.5	4.07	0.14	0.027	0.136	0.764	4.937	1127
93-P-34	err^2	bailer	no purge				10-May-05			0.085	0.569	0.000	0.098	3.700	0.060	1.773	0.044	0.000	5.8	-9.2	0.1	-7.2	-117.4	-8.7	64.0	-5.83	-0.17	NA	NA	0.184	1.567	-23
93-P-34	RPD	bailer	no purge				10-May-05												15%	-7%	9%	-4%	-9%	-17%	104%	-84%	-75%	NA	NA	27%	38%	-2%
93-P-34A1	field	peristaltic	shallow 6L				9-Jun-04	1860	7.89	1.98	13.08	0.04	10.61	22.78	1.04	0.66	0.200	0.009	39.7	159	1.4	244.0	1390	37.0	31.5	5.59	0.24	0.012	0.035	0.481	3.41	1200
93-P-34A1	model	peristaltic	shallow 6L	0	64%	36%	9-Jun-04			3.04	11.60	0.05	9.42	22.44	1.00	2.25	0.214	0.012	61.0	141.0	2.1	216.6	1369.2	35.3	108.0	5.99	0.32	NA	0.119	0.417	3.037	1243
93-P-34A1	err^2	peristaltic	shallow 6L				9-Jun-04			1.126	2.190	0.000	1.416	0.116	0.002	2.536	0.000	0.000	21.3	-18.0	0.7	-27.4	-20.8	-1.7	76.5	0.40	0.08	NA	0.084	-0.064	-0.373	43
93-P-34A1	RPD	peristaltic	shallow 6L				9-Jun-04												42%	-12%	40%	-12%	-2%	-5%	110%	7%	30%	NA	109%	-14%	-12%	3%
93-P-34B1	field	peristaltic	mid 12L				9-Jun-04	1880	7.9	1.87	12.92	0.04	10.66	22.95	1.10	0.55	0.247	0.007	37.4	157	1.4	245.0	1400	38.9	26.6	6.91	0.19	0.014	0.036	0.517	3.63	1200
93-P-34B1	model	peristaltic	mid 12L	0	64%	36%	9-Jun-04			3.02	11.58	0.05	9.41	22.41	0.99	2.23	0.215	0.012	60.6	140.7	2.1	216.4	1367.2	35.2	106.9	6.00	0.32	NA	0.119	0.418	3.053	1240
93-P-34B1	err^2	peristaltic	mid 12L				9-Jun-04			1.337	1.793	0.000	1.543	0.288	0.011	2.795	0.001	0.000	23.2	-16.3	0.7	-28.6	-32.8	-3.7	80.3	-0.91	0.14	NA	0.083	-0.099	-0.577	40
93-P-34B1	RPD	peristaltic	mid 12L				9-Jun-04												47%	-11%	39%	-12%	-2%	-10%	120%	-14%	54%	NA	107%	-21%	-17%	3%
93-P-34B2	field	peristaltic	mid 18L				9-Jun-04	1860	8	1.90	12.51	0.04	10.09	22.78	1.06	0.51	0.150	0.007	38.0	152	1.4	232.0	1390	37.5	24.5	4.20	0.18	0.017	0.043	0.627	4.25	1170
93-P-34B2	model	peristaltic	mid 18L	0	67%	33%	9-Jun-04			2.87	11.39	0.05	9.34	22.15	0.95	2.04	0.217	0.011	57.5	138.4	2.0	214.8	1351.7	33.8	98.2	6.07	0.30	NA	0.125	0.428	3.181	1215
93-P-34B2	err^2	peristaltic	mid 18L				9-Jun-04			0.944	1.248	0.000	0.558	0.395	0.011	2.354	0.004	0.000	19.5	-13.6	0.6	-17.2	-38.3	-3.7	73.7	1.87	0.12	NA	0.082	-0.199	-1.069	45
93-P-34B2	RPD	peristaltic	mid 18L				9-Jun-04												41%	-9%	35%	-8%	-3%	-10%	120%	36%	50%	NA	97%	-38%	-29%	4%
93-P-34B3	field	peristaltic	mid 24L				9-Jun-04	1910	7.98	2.19	13.16	0.04	10.57	23.27	1.11	0.79	0.195	0.008	43.8	160	1.5	243.0	1420	39.5	38.1	5.44	0.23	0.016	0.04	0.565	3.87	1230
93-P-34B3	model	peristaltic	mid 24L	0	60%	40%	9-Jun-04			3.23	11.83	0.06	9.51	22.75	1.04	2.47	0.211	0.013	64.7	143.8	2.2	218.6	1387.9	37.0	118.4	5.89	0.35	NA	0.112	0.405	2.882	1272
93-P-34B3	err^2	peristaltic	mid 24L				9-Jun-04			1.087	1.781	0.000	1.128	0.277	0.005	2.798	0.000	0.000	20.9	-16.2	0.7	-24.4	-32.1	-2.5	80.3	0.45	0.12	NA	0.072	-0.160	-0.988	42
93-P-34B3	RPD	peristaltic	mid 24L				9-Jun-04												39%	-11%	38%	-11%	-2%	-7%	103%	8%	41%	NA	95%	-33%	-29%	3%
93-P-34C1	field	peristaltic	deep 30L				9-Jun-04	1950	8	2.16	13.25	0.04	10.53	23.60	1.16	1.08	0.185	0.009	43.2	161	1.6	242.0	1440	41.1	51.9	5.17	0.23	0.018	0.043	0.613	4.18	1250
93-P-34C1	model	peristaltic	deep 30L	0	57%	43%	9-Jun-04			3.37	12.00	0.06	9.57	22.97	1.08	2.63	0.209	0.013	67.4	145.8	2.3	220.0	1401.6	38.2	126.1	5.83	0.37	NA	0.107	0.397	2.769	1294
93-P-34C1	err^2	peristaltic	deep 30L				9-Jun-04			1.463	1.560	0.000	0.914	0.395	0.007	2.389	0.001	0.000	24.2	-15.2	0.7	-22.0	-38.4	-2.9	74.2	0.66	0.14	NA	0.064	-0.216	-1.411	44
93-P-34C1	RPD	peristaltic	deep 30L				9-Jun-04												44%	-10%	35%	-10%	-3%	-7%	83%	12%	45%	NA	86%	-43%	-41%	3%
93-P-34C1	field	peristaltic	deep 6L				10-May-05	1930	7.93	1.82	13.00	0.04	9.48	22.46	1.37	0.01	0.177	0.004	36.5	158	1.6	218.0	1370	48.7	0.3	4.94	0.11	<0.04	<0.04	0.86	4.87	1140
93-P-34C1	model	peristaltic	deep 6L	0	75%	25%	10-May-05			2.20	11.07	0.04	8.46	20.43	1.28	2.07	0.145	0.005	44.1	134.6	1.4	194.4	1246.7	45.3	99.5	4.05	0.15	0.026	0.134	0.757	4.845	1138
93-P-34C1	err^2	peristaltic	deep 6L				10-May-05			0.144	3.708	0.000	1.055	4.086	0.009	4.265	0.001	0.000	7.6	-23.4	-0.2	-23.6	-123.3	-3.4	99.2	-0.89	0.04	NA	NA	-0.103	-0.025	-2
93-P-34C1	RPD	peristaltic	deep 6L				10-May-05												19%	-16%	-10%	-11%	-9%	-7%	199%	-20%	28%	NA	NA	-13%	-1%	0%
93-P-34C2	field	peristaltic	deep 36L				9-Jun-04	1910	7.95	2.05	12.92	0.04	10.40	23.11	1.09	0.71	0.123	0.007	41.1	157	1.6	239.0	1410	38.5	34.2	3.44	0.20	0.023	0.054	0.751	4.63	1210
93-P-34C2	model	peristaltic	deep 36L	0	63%	37%	9-Jun-04			3.10	11.67	0.05	9.45	22.53	1.01	2.31	0.213	0.012	62.1	141.9	2.1	217.2	1374.8	35.8	111.2	5.96	0.33	NA	0.117	0.414	2.990	1252
93-P-34C2	err^2	peristaltic	deep 36L				9-Jun-04			1.097	1.553	0.000	0.896	0.332	0.006	2.567	0.008	0.000	21.0	-15.1	0.5	-21.8	-35.2	-2.7	77.0	2.52	0.14	NA	0.063	-0.337	-1.640	42
93-P-34C2	RPD	peristaltic	deep 36L				9-Jun-04												41%	-10%	28%	-10%	-3%	-7%	106%	54%	51%	NA	73%	-58%	-43%	3%
93-P-34C2	field	peristaltic	deep 12L				10-May-05	1840	7.9	1.60	12.75	0.04	10.05	21.64	1.33	0.01	0.176	0.003	32.0	155	1.6	231.0	1320	47.0	0.3	4.91	0.07	<0.04	<0.04	0.98	5.97	1120
93-P-34C2	model	peristaltic	deep 12L	0	79%	21%	10-May-05			2.06	10.92	0.04	8.39	20.27	1.27	1.76	0.146	0.005	41.2	132.7	1.4	193.0	1236.7	44.9	84.6	4.09	0.13	0.027	0.140	0.774	5.073	1111
93-P-34C2	err^2	peristaltic	deep 12L				10-May-05			0.212	3.362	0.000	2.735	1.864	0.004	3.086	0.001	0.000	9.2	-22.3	-0.2	-38.0	-83.3	-2.1	84.4	-0.82	0.06	NA	NA	-0.206	-0.897	-9
93-P-34C2	RPD	peristaltic	deep 12L				10-May-05												25%	-15%	-15%	-18%	-7%	-5%	199%	-18%	62%	NA	NA	-23%	-16%	-1%
93-P-34C3	field	peristaltic	deep 42L				9-Jun-04	1940	7.98	2.04	13.25	0.06	10.48	23.27	1.13	0.85	0.136	0.006	40.8	161	2.2	241.0	1420	39.9	40.8	3.81	0.16	0.022	0.053	0.782	4.78	1230
93-P-34C3	model	peristaltic	deep 42L	0	60%	40%	9-Jun-04			3.23	11.83	0.06	9.51	22.74	1.04	2.46	0.211	0.013	64.6	143.7	2.2	218.6	1387.6	37.0	118.3	5.90	0.35	NA	0.112	0.406	2.885	1272
93-P-34C3	err^2	peristaltic	deep 42L				9-Jun-04			1.415	2.017	0.000	0.953	0.282	0.007	2.602	0.006	0.000	23.8	-17.3	0.0	-22.4	-32.4	-2.9	77.5	2.09	0.19	NA	0.059	-0.376	-1.895	42
93-P-34C3	RPD	peristaltic	deep 42L				9-Jun-04												45%	-11%	0%	-10%	-2%	-8%	97%	43%	73%	NA	72%	-63%	-49%	3%
93-P-34C3	field	peristaltic	deep 18L				11-May-05	1890	7.97	1.65	12.51	0.03	9.96	22.29	1.40	0.01	0.106	0.005	33.0	152	1.3	229.0	1360	49.8	0.3	2.95	0.13	<0.04	<0.04	0.89	5.19	1140
93-P-34C3	model	peristaltic	deep 18L	0	77%	23%	11-May-05			2.12	10.98	0.04	8.42	20.34	1.27	1.89	0.146	0.005	42.4	133.5	1.4	193.6	1240.9	45.1	90.9	4.07	0.14	0.027	0.137	0.767	4.977	1122
93-P-34C3	err^2	peristaltic	deep 18L				11-May-05			0.222	2.316	0.000	2.375	3.811	0.018	3.558	0.002	0.000	9.4	-18.5	0.1	-35.4	-119.1	-4.7	90.6	1.12	0.01	NA	NA	-0.123	-0.213	-18
93-P-34C3	RPD	peristaltic	deep 18L				11-May-05												25%	-13%	8%	-17%	-9%	-10%	199%	32%	10%	NA	NA	-15%	-4%	-2%
93-P-34C4	field	peristaltic	deep 24L				11-May-05	1840	7.91	1.55	12.59	0.04	9.92	21.47	1.24	0.01	0.165	0.003	31.1	153	1.5	228.0	1310	44.1	0.3	4.61	0.08	<0.04	<0.04	1.05	6.58	1110
93-P-34C4	model	peristaltic	deep 24L	0	80%	20%	11-May-05			2.00	10.86	0.03	8.37	20.21	1.26	1.64	0.147	0.005	40.1	132.0	1.4	192.4	1232.8	44.7	78.7	4.10	0.13	0.028	0.142	0.781	5.163	1101
93-P-34C4	err^2	peristaltic	deep 24L				11-May-05			0.201	2.995	0.000	2.395	1.603	0.000	2.671	0.000	0.000	9.0	-21.0	-0.1	-35.6	-77.2	0.6	78.5	-0.51	0.05	NA	NA	-0.269	-1.417	-9
93-P-34C4	RPD	peristaltic	deep 24L				11-May-05												25%	-15%	-10%	-17%	-6%	1%	199%	-12%	50%	NA	NA	-29%	-24%	-1%

Table 6

Site B Condensate Analysis

Site B 02CP02 Condensate Analysis November 2001

	Mass Fraction	Mole Fraction
Propane		
Isobutane	0.0001	0.0004
n-Butane	0.0005	0.0021
Isopentane	0.0010	0.0034
n-Pentane	0.0019	0.0064
Cyclopentane		
Hexanes	0.0075	0.0207
Methylcyclopentane	0.0036	0.0085
Benzene	0.0003	0.0007
Cyclohexane	0.0021	0.0050
Heptanes	0.0186	0.0370
Methylcyclohexane	0.0077	0.0158
Toluene	0.0006	0.0012
Octanes	0.0258	0.0459
Ethylbenzene	0.0012	0.0023
m&p Xylenes	0.0045	0.0085
o-Xylene	0.0018	0.0034
Nonanes	0.0271	0.0432
1,2,4 TMB	0.0066	0.0107
Decanes	0.0346	0.0503
Undecanes	0.0358	0.0482
Dodecanes	0.0386	0.0484
Tridecanes	0.0458	0.0541
Tetradecanes	0.0455	0.0508
Pentadecanes	0.0477	0.0506
Hexadecanes	0.0450	0.0456
Heptadecanes	0.0572	0.0548
Octadecanes	0.0507	0.0456
Nonadecanes	0.0394	0.0336
Eicosanes	0.0461	0.0364
Heneicosanes	0.0445	0.0335
Docosanes	0.0418	0.0309
Tricosanes	0.0400	0.0286
Tetracosanes	0.0376	0.0260
Pentacosanes	0.0347	0.0233
Hexacosanes	0.0329	0.0214
Heptacosanes	0.0317	0.0201
Octocosanes	0.0306	0.0188
Nonacosanes	0.0285	0.0171
Triacosanes	0.0804	0.0467
	1.0000	1.0000



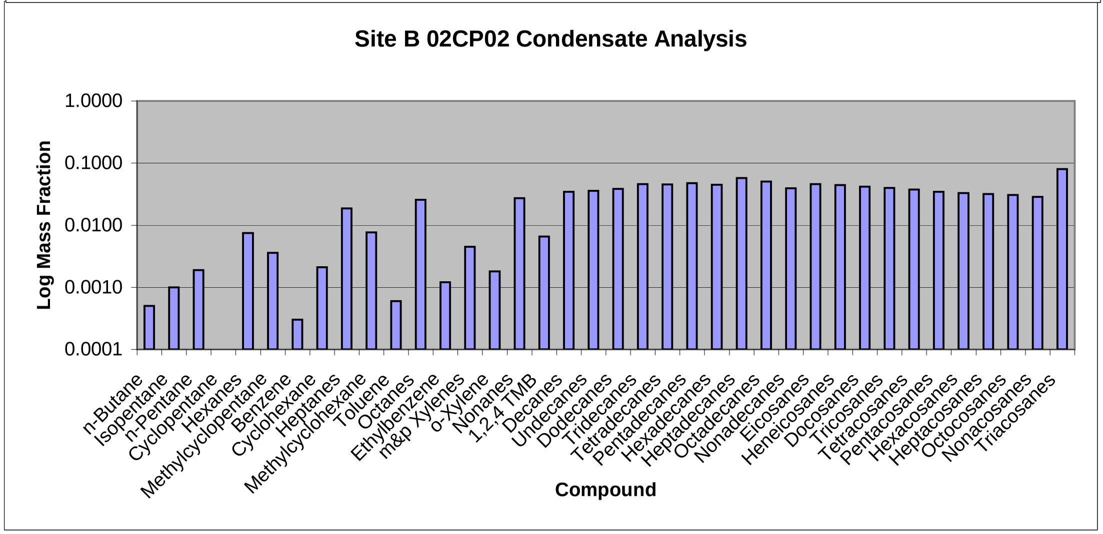
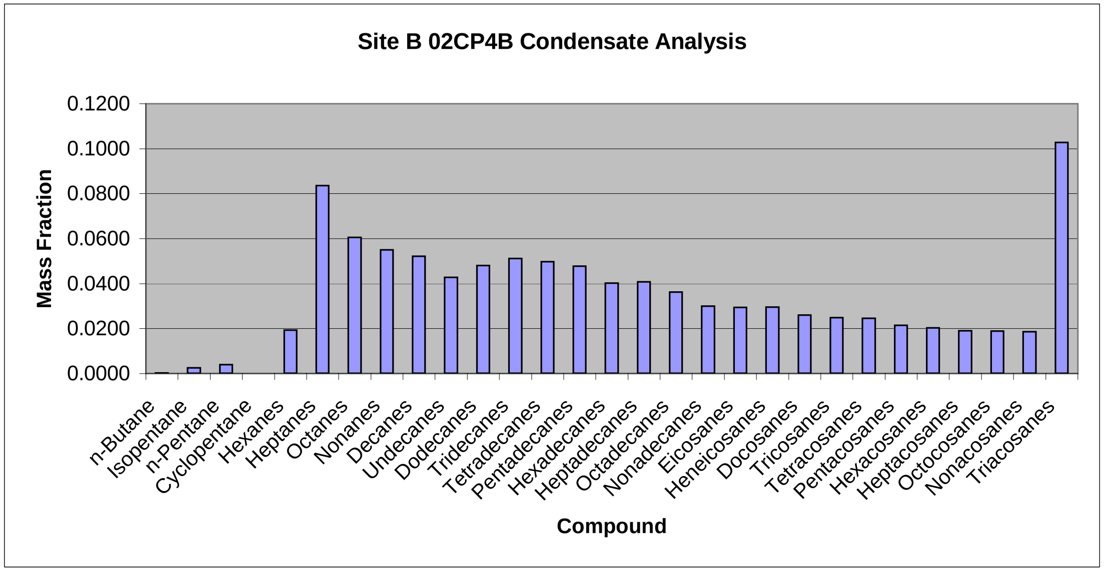


Table 6
Site B Condensate Analysis

Site B 02CP4B Condensate Analysis June 2003

	Mass Fraction	Mole Fraction
Propane		
Isobutane	trace	
n-Butane	0.0003	0.0009
Isopentane	0.0025	0.0061
n-Pentane	0.0040	0.0096
Cyclopentane		
Hexanes	0.0193	0.0389
Heptanes	0.0836	0.1496
Octanes	0.0605	0.0934
Nonanes	0.0550	0.0768
Decanes	0.0522	0.0662
Undecanes	0.0428	0.0500
Dodecanes	0.0481	0.0523
Tridecanes	0.0512	0.0524
Tetradecanes	0.0497	0.0481
Pentadecanes	0.0478	0.0440
Hexadecanes	0.0402	0.0353
Heptadecanes	0.0408	0.0336
Octadecanes	0.0362	0.0282
Nonadecanes	0.0300	0.0222
Eicosanes	0.0295	0.0202
Heneicosanes	0.0296	0.0193
Docosanes	0.0260	0.0166
Tricosanes	0.0249	0.0154
Tetracosanes	0.0246	0.0147
Pentacosanes	0.0215	0.0125
Hexacosanes	0.0203	0.0115
Heptacosanes	0.0191	0.0105
Octocosanes	0.0189	0.0101
Nonacosanes	0.0186	0.0096
Triacosanes	0.1028	0.0520
Total	1.0000	1.0000
Specific Coumpounds		
Methylcyclopentane	0.0082	0.0171
Benzene		
Cyclohexane	0.0045	0.0092
Methylcyclohexane	0.0200	0.0355
Toluene	0.0001	0.0002
Ethylbenzene	0.0011	0.0018
m&p Xylenes	0.0009	0.0014
o-Xylene	0.0008	0.0014
1,2,4 TMB	0.0017	0.0025
SubTotal	0.0373	0.0691



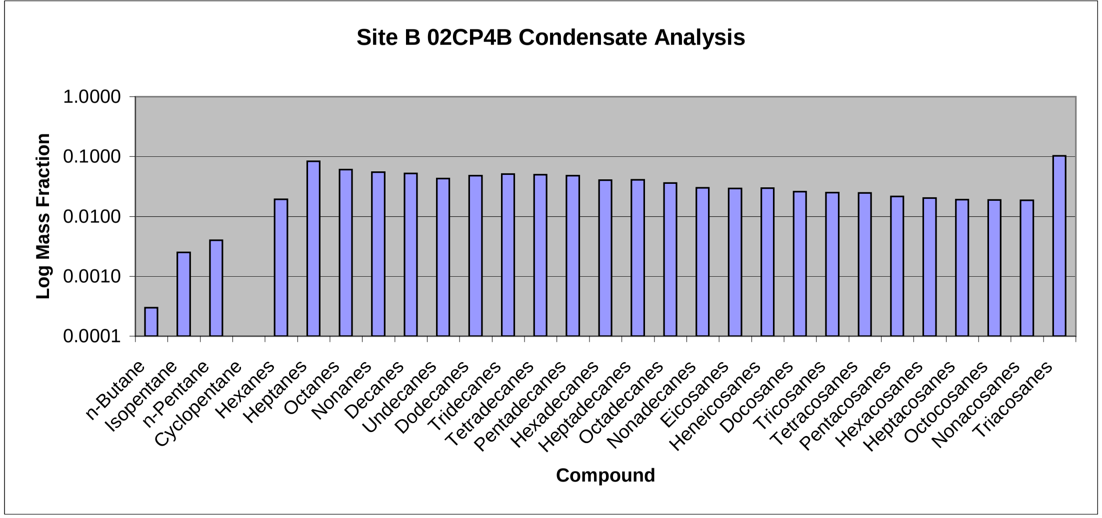
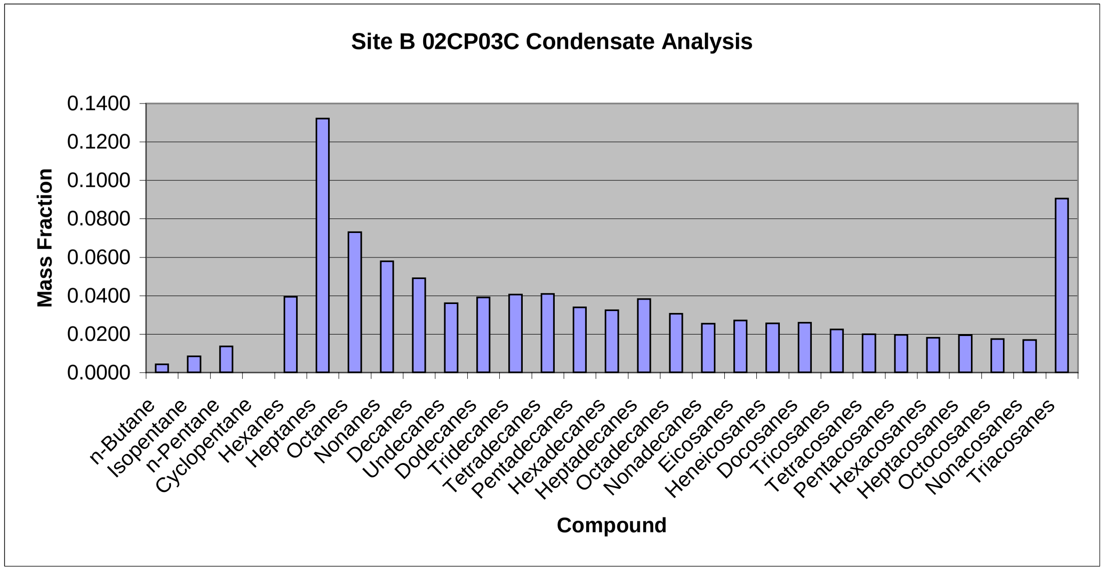


Table 6

Site B Condensate Analysis

Site B 02CP3C Condensate Analysis February 2004

	Mass Fraction	Mole Fraction
Propane	0.0002	0.0006
Isobutane	0.0007	0.0019
n-Butane	0.0044	0.0118
Isopentane	0.0085	0.0183
n-Pentane	0.0136	0.0294
Cyclopentane		
Hexanes	0.0394	0.0712
Heptanes	0.1321	0.2130
Octanes	0.0730	0.1008
Nonanes	0.0579	0.0731
Decanes	0.0491	0.0557
Undecanes	0.0362	0.0378
Dodecanes	0.0391	0.0380
Tridecanes	0.0407	0.0373
Tetradecanes	0.041	0.0355
Pentadecanes	0.0339	0.0279
Hexadecanes	0.0325	0.0255
Heptadecanes	0.0383	0.0282
Octadecanes	0.0306	0.0213
Nonadecanes	0.0255	0.0169
Eicosanes	0.0271	0.0166
Heneicosanes	0.0256	0.0149
Docosanes	0.0260	0.0149
Tricosanes	0.0225	0.0125
Tetracosanes	0.0199	0.0107
Pentacosanes	0.0197	0.0102
Hexacosanes	0.0182	0.0092
Heptacosanes	0.0194	0.0095
Octocosanes	0.0175	0.0084
Nonacosanes	0.0169	0.0079
Triacosanes	0.0905	0.0410
Total	1.0000	1.0000
Specific Compounds		
Methylcyclopentane	0.0167	0.0309
Benzene	0.0004	0.0008
Cyclohexane	0.0082	0.0152
Methylcyclohexane	0.0277	0.0439
Toluene	0.0005	0.0008
Ethylbenzene	0.0029	0.0042
m&p Xylenes	0.0031	0.0046
o-Xylene	0.0006	0.0009
1,2,4 TMB	0.0024	0.0030
SubTotal	0.0625	0.1043



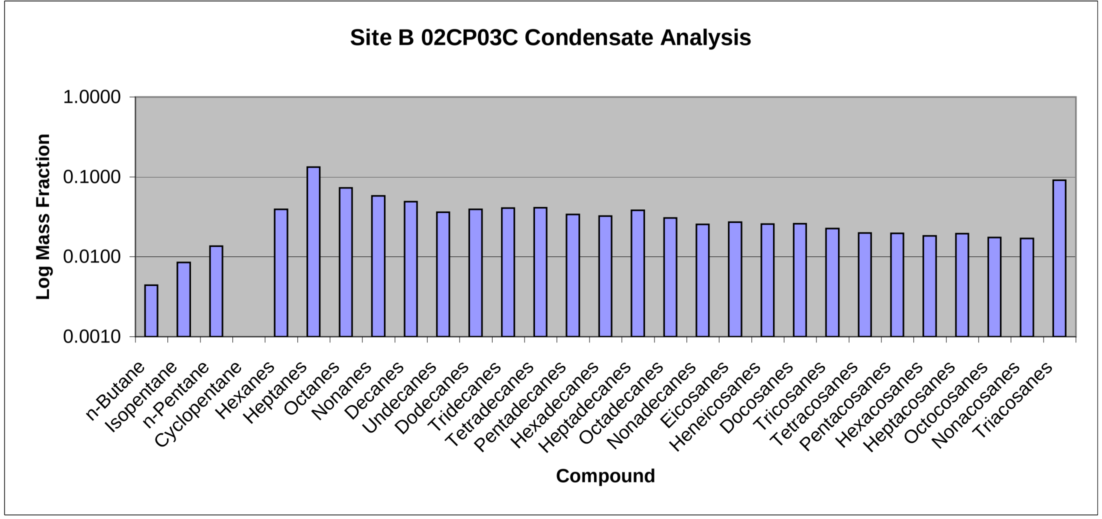


Table 7

Site B Monitoring Well Installation Details, Datum/Groundwater Surface Elevations And Hydraulic Conductivities

Monitoring Station	Ground Elevation	Stick-Up PVC Pipe	Datum Elevation (top of PVC casing)	Depth of Piezo (below ground)	Depth Interval of Sand (below ground)	Date	Depth To Water Below Datum	Depth To Product Below Datum	Apparent Condensate Thickness	Groundwater Surface Elevation	Hydraulic Conductivity	Lithology
	(masl)	*(m)*	*(masl)*	*(m)*	*(m)*	*(d-m-y)*	*(m)*	*(m)*	*(m)*	*(masl)*	*(m/s)*	
BH01	92.10	0.82	92.92	3.52	0.60 - 3.52	5-Jun-97	0.93	---	---	91.99	6.0E-06	
						7-Jun-97	1.01	---	---	91.91		
						8-Jun-97	N/M	---	---	N/M		
						23-Oct-97	1.79	---	---	91.13		
						11-Aug-98	2.27	---	---	90.65		
						17-Oct-98	3.04	---	---	89.88		
						20-Jan-99	3.58	---	---	89.34		
						11-Jun-99	1.50	---	---	91.42		
						28-Sep-99	2.70	---	---	90.22		
						22-Dec-99	3.46	---	---	89.46		
						28-May-00	1.89	---	---	91.03		
						27-Oct-00	1.83	---	---	91.09		
						24-May-01	2.82	---	---	90.10		
						16-Jul-01	1.37	---	---	91.56		
						11-Oct-01	2.44	---	---	90.48		
						25-Oct-01	2.54	---	---	90.38		
						18-Feb-02	3.26	---	---	89.67		
						18-Feb-02	3.36	---	---	89.56		
						19-Feb-02	3.28	---	---	89.64		
						24-May-02	2.76	---	---	90.17		
						27-May-02	2.77	---	---	90.16		
						25-Jun-02	2.40	---	---	90.52		
						3-Oct-02	2.61	---	---	90.31		
						5-Oct-02	2.61	---	---	90.31		
						7-Nov-02	2.26	---	---	90.67		
						23-May-03	1.95	---	---	90.98		
						31-May-03	1.86	---	---	91.06		
						6-Jun-03	1.78	---	---	91.15		
						14-Jul-03	1.63	---	---	91.30		
						14-Aug-03	2.06	---	---	90.86		
						24-Sep-03	2.68	---	---	90.24		
						25-Sep-03	2.71	---	---	90.21		
						27-Sep-03	2.76	---	---	90.16		
						2-Oct-03	2.79	---	---	90.13		
						10-Feb-04	3.77	---	---	89.15		
						25-May-04	1.66	---	---	91.26		
						30-Sep-04	1.25	---	---	91.67		
						5-Oct-04	1.20	---	---	91.72		
						4-Feb-05	2.62	---	---	90.30		
03-MW1	91.86	0.62	92.48	4.83	1.52 - 4.83	14-Aug-03	1.77	---	---	90.71	1.2E-06	
						25-Sep-03	2.44	---	---	90.04		
						2-Oct-03	N/M	---	---	N/M		
						10-Feb-04	N/M	---	---	N/M		
						25-May-04	1.25	---	---	91.24		
						30-Sep-04	0.99	---	---	91.49		
						4-Feb-05	2.21	---	---	90.27		
03-MW2	91.72	0.76	92.48	4.27	1.14 - 4.27	14-Aug-03	1.75	---	---	90.73	3.6E-07	
						24-Sep-03	2.40	---	---	90.09		
						2-Oct-03	2.50	---	---	89.98		
						10-Feb-04	3.98	---	---	88.50		
						25-May-04	1.26	---	---	91.23		
						30-Sep-04	1.01	---	---	91.47		
						4-Feb-05	2.22	---	---	90.26		
03-DP1	91.92	0.61	92.53	3.01	2.10 - 3.01	14-Aug-03	1.78	---	---	90.75	3.5E-06	
						24-Sep-03	2.43	---	---	90.10		
						25-Sep-03	2.48	---	---	90.05		
						2-Oct-03	2.53	---	---	90.00		
						10-Feb-04	>3.62	---	---	<88.91		
						25-May-04	1.29	---	---	91.24		
						30-Sep-04	1.04	---	---	91.50		
						4-Feb-05	2.35	---	---	90.18		
03-DP2	91.95	0.29	92.24	3.67	2.76 - 3.67	14-Aug-03	1.36	---	---	90.88	2.3E-07	
						24-Sep-03	1.98	---	---	90.26		
						25-Sep-03	2.00	---	---	90.24		
						2-Oct-03	2.08	---	---	90.16		
						10-Feb-04	2.85	---	---	89.40		
						25-May-04	0.93	---	---	91.32		
						30-Sep-04	0.51	---	---	91.73		
						4-Feb-05	1.87	---	---	90.37		
03-DP3	91.96	0.61	92.57	4.73	3.82 - 4.73	14-Aug-03	2.34	---	---	90.23	5.5E-08	
						24-Sep-03	2.94	---	---	89.63		
						25-Sep-03	2.94	---	---	89.63		
						2-Oct-03	3.00	---	---	89.57		
						10-Feb-04	3.90	---	---	88.67		
						25-May-04	2.07	---	---	90.50		
						30-Sep-04	1.53	---	---	91.04		
						4-Feb-05	3.01	---	---	89.56		
03-DP4	91.97	0.64	92.61	6.15	5.24 - 6.15	14-Aug-03	3.88	---	---	88.73	6.3E-07	
						24-Sep-03	4.17	---	---	88.44		
						25-Sep-03	4.16	---	---	88.45		
						2-Oct-03	4.24	---	---	88.37		
						10-Feb-04	4.63	---	---	87.98		
						25-May-04	3.81	---	---	88.81		
						30-Sep-04	3.13	---	---	89.48		
						4-Feb-05	3.96	---	---	88.65		

<u>**NOTES:**</u>

1. Data may be entered to the nearest mm, but are reported above to the nearest cm.
Apparent rounding errors may occasionally occur in calculated fields (e.g., Groundwater Surface Elevation).
2. Where free product is present, Groundwater Surface Elevation is calculated as
Groundwater Surface = Datum Elevation - Depth to Water + Product Specific Density * Product Thickness.
3. N/M - Denotes not measured.

Table 8

Site B Water Quality: Field Measured Parameters

Monitoring Station	Date *(d-m-y)*	Temp *(°C)*	Electrical Conductivity *(µS/cm)*	pH *(unit)*	Eh *(mV)*	DO *(mg/L)*	*Comments*
BH01	25-Oct-01	5.2	379	6.13	---	---	*Bio-log samples*
	27-May-02	12.8	223	6.16	62	3.5	
	3-Oct-02	---	---	---	---	---	*Water level only*
	23-May-03	3.8	---	---	35	0.2	
	10-Feb-04	3.4	286	6.20	---	---	*Sheen*
	25-May-04	4.2	---	---	---	0.2	
	25-May-04	5.6	189	5.83	---	---	*Pre-purge*
(Post-Purge)	26-May-04	5.4	189	5.86	---	---	*Sample after pumping 200L of water*
	30-Sep-04	5.5	186	5.78	---	---	*100ml/52sec. sample location 3.6 below casing*
	1-Oct-04	4.5	---	---	139	0.4	
	5-Oct-04	6.3	154	6.07	---	2.2	
	16-May-05	3.9	158	5.54	---	---	
03-MW1	2-Oct-03	---	---	---	---	---	*DDS at 1.86m*
	10-Feb-04	1.7	273	6.22	---	---	*Sheen*
	25-May-04	3.3	---	---	---	0.2	
	25-May-04	4.6	243	5.96	---	---	*Sheen*
	30-Sep-04	6.2	210	6.05	---	---	*Waterra*
	1-Oct-04	6.9	202	6.04	---	---	*Peristaltic Pump, sample location 3.63m below casing*
	1-Oct-04	6.3	---	---	30	0.8	
	16-May-05	4.0	242	5.70	---	---	
03-MW2	2-Oct-03	6.2	289	6.09	-245		
	10-Feb-04	3.2	295	6.25	---	---	*Sheen*
	10-Feb-04	2.8	275	6.18	---	---	*Sheen*
	25-May-04	5.1	237	5.97	---	---	
	30-Sep-04	6.2	184	5.80	---	---	*Waterra*
	1-Oct-04	7.5	181	5.88	---	---	*Peristalitic Pump, sample location 3.6m below casing*
	1-Oct-04	6.6	---	---	20	0.5	
	16-May-05	---	---	---	---	---	
03-ML1-1	3-Oct-03	10.9	333	6.05	---	---	
	25-May-04	5.3	275	5.83	---	---	*No drawdown*
	30-Sep-04	6.5	291	5.95	---	---	*Sulphides <0.1mg/L*
03-ML1-2	10-Feb-04	2.4	716	6.29	---	---	
	26-May-04	5.1	719	6.11	---	---	
	30-Sep-04	---	---	---	---	---	*Water level only*
03-ML1-3	3-Oct-03	8.0	400	6.06	---	---	
	10-Feb-04	2.8	837	6.25	---	---	*Sheen*
	25-May-04	7.7	393	5.99	---	---	*Sheen. Double-checked EC calibration*
	30-Sep-04	7.5	347	6.22	---	---	
03-ML1-7	3-Oct-03	5.9	480	6.22	-112	---	
	10-Feb-04	3.3	451	6.20	---	---	
	25-May-04	6.7	376	6.03	---	---	
	30-Sep-04	6.8	325	6.81	---	---	
03-DP1	2-Oct-03	10.9	306	6.14	---	---	
	10-Feb-04	---	---	---	---	---	*Dry @ 3.04m*
	25-May-04	6.5	316	5.98	---	---	
	30-Sep-04	5.5	260	5.98	---	---	*Sulphides <0.1mg/L, sample rate: 150ml/min. Max drawdown is 1.1m*
	1-Oct-04	5.0	---	---	103	0.3	
	16-May-05	5.1	228	5.92	---	---	
03-DP2	2-Oct-03	9.6	163	5.96	---	---	
	10-Feb-04	2.1	159	6.12	---	---	
	25-May-04	7.2	153	5.95	---	---	
	30-Sep-04	4.3	132	5.87	---	---	
	16-May-05	9.2	147	5.99	---	---	
03-DP3	2-Oct-03	---	---	---	---	---	*insufficient water for field parameters*
	10-Feb-04	---	---	---	---	---	*Water level only*
	26-May-04	6.4	197	5.91	---	---	
	30-Sep-04	---	---	---	---	---	*Sulphides <0.1mg/L*
	16-May-05	---	---	---	---	---	*insufficient water for field parameters*
03-DP4	2-Oct-03	---	---	---	---	---	*insufficient water for field parameters*
	10-Feb-04	2.0	545	6.85	---	---	
	25-May-04	7.7	608	6.55	---	---	
	30-Sep-04	7.2	585	6.50	---	---	*Sulphides <0.1mg/L*
	1-Oct-04	10.8	---	---	58	0.6	
	16-May-05	7.7	609	6.20	---	---	

NOTES:

1. ***Electrical conductivity values standardized to 25°C.***
2. ***Eh values have been corrected using a standard Zobell's solution.***

Table 9

Site B Water Quality: Parameter Concentrations

Station	Not CORONA	Method	Purge/depth	Notes	Date (d-m-y)	EC (uS/cm)	pH (units)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Chloride:D (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO2+NO3 as N (mg/L)	Sulphide (mg/L)	PHC F1 (C6-C10)-BTEX (mg/L)	TPH (C3-C10) (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylenes-total (mg/L)	TDS-calculated (mg/L)	Tot Alk as CaCO3 (mg/L)
01BH01	x	bailer	purge		17-Jul-01	186	6.62	27.2	4.6	0.5	3.9	106	5.5	1.7	<0.01	0.152	<0.003			<0.1	<0.0004	<0.0004	<0.0004	<0.0012	95.8	87.2
01BH01	x	bailer	purge		31-Jul-01	196	6.34	33.4	5.24	0.7	3.7		5	2.29	0.048	0.244	<0.006	0.004		<0.01	<0.001	<0.001	<0.001	<0.001		
01BH01	x	bailer	purge		16-Oct-01	324	6.53	66.4	6.04	0.8	3.9		3.4	1.63	0.25	0.233	<0.006	0.004		<0.01	<0.001	<0.001	<0.001	<0.001		
01BH01	x	bailer	purge		27-May-02	268	6.59	43.4	7.71	0.7	4.7	166	5	4.68	<0.003	0.196	<0.006		<0.01		<0.001	<0.001	<0.001	<0.001	148	136
01BH01	x	bailer	purge	**(duplicate)**	27-May-02									15.7				0.066								
01BH01	x	bailer	purge		7-Oct-02	198	6.27	26.9	5.7	0.2	2.8	108	6.6	1.7	0.03	0.145	0.123		<0.01		<0.001	<0.001	<0.001	<0.001	97	88
01BH01	x	bailer	purge	**(duplicate)**	7-Oct-02									2				<0.003								
01BH01	x	bailer	purge		2-Jun-03	200	6.34	32.2	6.7	0.8	4.2	125	4.1	2	0.02	0.155		<0.005	<0.01		<0.001	<0.001	<0.001	<0.001	111	102
01BH01	x	bailer	purge		29-Sep-03	265	6.52	39.9	10	0.9	4.3	166	4	1.1	<0.01	0.15			<0.01		<0.001	<0.001	<0.001	<0.001	142	136
01BH01		bailer	no purge		10-Feb-04	281	6.74	45.3	10.3	0.7	4.2	197	5.6	0.9	0.18	0.246	<0.003		<0.1	<0.1	0.0016	<0.0004	<0.0004	<0.0012	164	161
01BH01		bailer	no purge		25-May-04	159	6.59	18.5	4.3	0.8	5.1	94.2	4.8	3	0.06	0.127	0.042		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	83	77.2
01BH01		bailer	purge		5-Oct-04	186.00	6.46	27.4	5.3	0.8	4.8	111	4.6	0.9	0.09	0.231	<0.2		0.03		<0.001	<0.001	<0.001	<0.001	98	91
01BH01		bailer	no purge		16-May-05	178	6.6	23.5	5.1	0.7	4.4	106	3.9	0.25	0.1	0.194	0.025		<0.1		0.0013	<0.0004	<0.0004	0.0013	90	87.2
01BH01		dialysis	deep		16-May-05	339	7.15	44.1	9.6	0.8	4.6	239	3.9	1.8	0.91	0.313	0.155		<0.1		<0.0009	<0.0009	<0.0009	<0.002	184	196
01BH02		bailer	no purge		17-Jul-01	599	7.46	113	9.9	2.5	5.6	386	6.3	8.2	<0.01	1.04	0.003			<0.1	<0.0004	<0.0004	<0.0004	<0.0012	337	316
01BH02	x	bailer	purge		31-Jul-01	442	6.96	87.4	7.85	2.1	5.2		6.2	11.4	0.276	1.08	0.252	0.003		<0.01	<0.001	<0.001	<0.001	<0.001		
01BH02	x	bailer	purge		16-Oct-01	475	6.88	105	5.43	1.8	5.1		3.9	8.02	0.099	1.25	0.015	0.005		<0.01	<0.001	<0.001	<0.001	<0.001		
01BH02	x	bailer	purge		27-May-02	468	6.9	77.5	7.49	2	23.2	294	5.7	16.9	<0.003	0.0434	<0.006		<0.01		<0.001	<0.001	<0.001	<0.001	277	241
01BH02	x	bailer	purge	**(duplicate)**	27-May-02									25.5				0.103								
01BH02	x	bailer	purge		7-Oct-02	581	6.69	112	8.1	2.3	6.9	393	8.3	6.4	<0.01	0.727	<0.006		<0.01		<0.001	<0.001	<0.001	<0.001	337	322
01BH02	x	bailer	purge	**(duplicate)**	7-Oct-02									9.2				0.005								
01BH02	x	bailer	purge		2-Jun-03	546		105	6.8	2.5	2.5	386	4.5	8.5	<0.01	0.506		<0.005	<0.01		<0.001	<0.001	<0.001	<0.001	328	317
01BH02	x	bailer	purge	**(duplicate)**	2-Jun-03				10.2																	
01BH02	x	bailer	purge		29-Sep-03	731	6.86	140	16.8	3.4	7.1	498	4.9	7.6	<0.01	0.708			<0.01		<0.001	<0.001	<0.001	<0.001	424	408
01BH02		bailer	purge		5-Oct-04	631	7.25	102	11.7	2.5	5.6	425	6.2	6.4	0.33	0.544	<0.2		<0.01		<0.001	<0.001	<0.001	<0.001	343	348
01BH04		bailer	no purge		17-Jul-01	501	7.43	97.5	7.9	1.4	2.9	322	1	8.3	<0.01	0.743	<0.003								278	264
01BH04	x	bailer	purge		31-Jul-01	362	6.89	73.5	6.03	1	3.1		0.9	6.6	0.024	0.746	<0.006	0.005		<0.01	<0.001	<0.001	<0.001	<0.001		
01BH04	x	bailer	purge		16-Oct-01	330	6.91	69.5	6.73	0.8	2.6		<0.5	5.15	0.004	0.714	<0.006	<0.005		<0.01	<0.001	<0.001	<0.001	<0.001		
01BH04	x	bailer	purge	**(duplicate)**	16-Oct-01	329	7.05	59.9	6.26	0.7	2.6		0.6	4.1	0.497	0.71	<0.006			<0.01	<0.001	<0.001	<0.001	<0.001		
01BH04	x	bailer	purge		27-May-02	388	6.89	71	5.7	1.1	4.5	258	<0.5	10.3	<0.003	0.484	0.023		<0.01		<0.001	<0.001	<0.001	<0.001	219	211
01BH04	x	bailer	purge	**(duplicate)**	27-May-02									19				0.007								
01BH04	x	bailer	purge		7-Oct-02	616	6.89	124	8.5	1.4	4.2	390	<0.5	27.3	<0.01	0.441	0.086		<0.01		<0.001	<0.001	<0.001	<0.001	357	320
01BH04	x	bailer	purge	**(duplicate)**	7-Oct-02									28.4				<0.003								
01BH04	x	bailer	purge		2-Jun-03	295	7.07	62.1	3.6	1	4	208	<0.5	6.1	0.03	0.036		<0.005	<0.01		<0.001	<0.001	<0.001	<0.001	179	170
01BH04	x	bailer	purge		29-Sep-03	260	6.85	45.6	7.5	0.7	2.6	168	<0.5	6.2	<0.01	0.449			<0.01		<0.001	<0.001	<0.001	<0.001	145	137
01BH04		bailer	no purge		10-Feb-04	174	6.99	28.7	4.9	0.5	2.3	115	<0.5	2.7	0.33	0.482	<0.003		<0.1	<0.1	<0.0004	<0.0004	<0.0004	<0.0012	97	94.6
01BH04		bailer	no purge		25-May-04	229	7.29	45.8	6.4	0.7	3.8	155	0.3	4.6	0.2	0.853	<0.003		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	139	127
01BH04		bailer	purge		5-Oct-04	294	7.27	46.8	7.7	0.6	2.4	198	<0.5	6	0.2	0.702	<0.2		<0.01		<0.001	<0.001	<0.001	<0.001	161	162
01BH04		bailer	no purge		17-May-05	233	6.96	37.5	7	0.5	2.6	153	0.6	3.5	<0.01	0.736	0.032		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	128	125
01CP02		bailer	no purge		26-Jun-02	370	6.43	49.5	10.8	0.8	25.6	173	43.8	1.5	3.26	1.04	<0.003			3.2	0.0704	<0.0004	<0.0004	0.0106	221	141
01CP03A		bailer	no purge	**(raw sample)**	26-Oct-01	1030	7.33	153	26.8		53.2	599	45.5	15.3	0.07	3.69	0.009			4.4	0.375	<0.004	0.035	0.059	595	491
01CP03A		bailer	no purge	**(filtered/preserved)**	26-Oct-01			122	19.5		41.3				0.1	2.77										
01CP03A		bailer	no purge		19-Feb-02															1.4	0.215	<0.001	0.022	<0.003		
01CP03A		bailer	no purge		3-Oct-02	1060	7.15	182	29.5	4.7	49	685	41.9	30.9	13.3	5.98	0.09		0.3		0.138	<0.001	0.025	0.011	694	562
01CP03A		bailer	no purge		30-Sep-04	776	7.68	76.9	10.7	2	70.3	443	34.6	15.4	0.17	1.31	<0.003		<0.1		0.0196	<0.0004	0.0046	0.0039	429	363
01CP03B		bailer	no purge		17-Jul-01	431	6.47	36	8.4	1.3	40.3	159	53.6	6.8	<0.01	0.679	<0.003			4.1	0.236	<0.003	0.009	0.033	225	130
01CP03B		bailer	no purge	**(filtered/preserved)**	26-Oct-01			29.5	7.1		26				0.75	0.585										
01CP03B		bailer	no purge		25-May-02															0.2	0.0078	<0.0009	<0.0009	<0.0029		
01CP03B		bailer	no purge		3-Oct-02	384	6.64	46.1	10.4	2	27.3	185	38.7	1	4.66	0.873	0.1		0.8		0.122	<0.0009	0.0429	0.021	223	152
01CP04		waterra	no purge		17-Jul-01	757	6.44	88.9	23.9	3	13.1	153	164	1.2	<0.01	1.6	<0.003			2.3	1.45	<0.02	0.06	<0.06	371	125
01CP04		waterra	no purge	**(raw sample)**	26-Oct-01	853	6.83	99.3	27.3		14	104	221	0.7	<0.01	2.08	0.013			4	1.14	<0.01	<0.01	<0.03	419	85
01CP04		waterra	no purge	**(filtered/preserved)**	26-Oct-01			94.8	26.4		13.2				0.11	1.91										
01CP04		waterra	no purge		25-May-02	648	6.5	53.6	14.8	2.7	10.1	142	145	0.5	0.09	1.18	<0.003			1.2	0.682	<0.0009	0.0067	0.003	298	116
01CP04		waterra	no purge		4-Oct-02	525	6.46	69.1	17.9	3.1	12.9	107	113	1.8	0.14	1.54	0.095		0.2		0.559	<0.007	0.018	<0.01	272	87.8
01CP06		waterra	no purge		17-Jul-01	227	6.25	34.2	7.2	0.3	6.6	139	5.6	0.4	<0.01	0.71	<0.003			12.6	<0.002	<0.002	0.003	0.097	123	114
01CP06		waterra	no purge	**(raw sample)**	25-Oct-01	238	6.71	33.9	7.5		5.1	144	4.9	0.1	0.02	0.719	0.013			10.1	<0.003	<0.003	<0.003	0.06	124	118
01CP06		waterra	no purge	**(filtered/preserved)**	25-Oct-01			30.5	6.6		4.9				3.78	0.726										
01CP06		waterra	no purge	**(Pre-Purge)**	18-Feb-02	236	6.36	32.1	6.5	<0.3	4.4	149	4.8	0.2	<0.01	0.768	0.01								122	122
01CP06		waterra	dry purge	**(Post-Purge)**	18-Feb-02	203	6.32	26.6	5.5	<0.3	4.3	125	4.5	0.2	<0.01	0.586	0.02								104	103
01CP06		waterra	dry purge	**(duplicate Post-Purge)**	18-Feb-02	200	6.27	27.5	5.6	<0.3	4.3	123	4.3	0.2	<0.01	0.617	0.009			4.3	0.0015	<0.0004	0.0106	0.113	103	101
01CP06		waterra	dry purge	**(duplicate Post-Purge)**	18-Feb-02	203	6.31	28	5.7	<0.3	4.3	125	4.1	0.2	<0.01	0.631	0.01								105	102
01CP06		waterra	purge	**(Post-recovery)**	18-Feb-02	214	6.38	29.4	6.1	<0.3	4.5	130	4.5	0.2	0.24	0.66	0.02								110	107
01CP06		waterra	purge	**(duplicate Post-recovery)**	18-Feb-02	203	6.33	27.9	5.8	<0.3	4.7	124	4.5	0.2	<0.01	0.627	0.007			4.5	0.0017	<0.0004	0.0168	0.113	105	102

Table 9

Site B Water Quality: Parameter Concentrations

Station	Not CORONA	Method	Purge/depth	Notes	Date (d-m-y)	EC (uS/cm)	pH (units)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Chloride:D (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO2+NO3 as N (mg/L)	Sulphide (mg/L)	PHC F1 (C6-C10)-BTEX (mg/L)	TPH (C3-C10) (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylenes-total (mg/L)	TDS-calculated (mg/L)	Tot Alk as CaCO3 (mg/L)
01CP06		waterra	purge	**(duplicate Post-recovery)**	18-Feb-02	198	6.29	27	5.6	<0.3	4.3	121	4.4	0.1	<0.01	0.609	0.006								102	99.1
01CP06		waterra	no purge		25-May-02	191	6.42	26.9	5.6	1.2	5.9	117	5.3	0.2	2.76	0.581	<0.003			4.1	0.0025	<0.0004	0.003	0.0908	106	95.8
01CP06		waterra	no purge	**(duplicate)**	25-May-02															4.2	0.0026	<0.0004	0.0061	0.104		
01CP06		waterra	no purge		3-Oct-02	235	6.42	31.5	6.6	0.6	5.2	148	4.6	0.3	3.69	0.726	0.004		2.3		0.0008	<0.0004	0.0389	0.0941	126	121
01CP06		waterra	no purge		20-Feb-03	220	6.45	28.2	5.8	0.4	4.9	134	4.6	0.2	0.01	0.673	<0.003								111	110
01CP06		waterra	no purge		23-May-03	195	6.32	26.3	5.7	0.4	4.5	126	4.5	0.2	0.01	0.54	0.01	<0.01	1.6	2.5	0.0007	<0.0004	0.0072	0.0485	104	103
01CP06		waterra	no purge		14-Aug-03	212	6.32	24.5	5.3	0.4	4.5	120	4.3	0.4	2.82	0.562	0.015	<0.01	1.9		0.0006	<0.0004	0.0467	0.0752	102	98.3
01CP06		waterra	no purge		2-Oct-03	196	6.42	27.9	5.5	0.5	4.7	121	5.7	<0.1	3.27	0.595	<0.003		3.2		<0.0004	<0.0004	0.0317	0.0796	108	99.4
01CP06		waterra	no purge		10-Feb-04	220	6.39	30	6.1	0.4	4.7	148	4.7	<0.1	3.39	0.607	<0.003		2.6	3.4	<0.002	<0.002	0.022	0.081	123	121
01CP06		waterra	no purge		25-May-04	202	6.48	29.3	5.8	0.4	5.1	129	4.9	0.3	1.49	0.585	0.006		2		0.0007	<0.0004	0.0625	0.0902	111	106
01CP06		waterra	no purge		30-Sep-04	195	6.77	25.1	5.4	0.5	4.8	117	5.4	<0.1	0.06	0.526	<0.003		1.7		<0.0004	0.0005	0.0461	0.0738	99	96
01CP06		waterra	no purge		4-Feb-05	199	6.38	27	5.4	0.4	4.4	127	5.1	<0.5	2.83	0.597	0.003		0.7		<0.002	<0.002	0.043	0.055	108	104
01CP06		waterra	no purge		16-May-05	199	6.62	27.6	6	<0.3	4.7	120	4.7	1.2	<0.01	0.587	<0.003		2.9		<0.0004	<0.0004	0.0935	0.117	104	98
01CP07		waterra	dry purge		17-Jul-01	125	6.21	14.2	2.4	0.4	8	56	11	5.4	0.05	0.731	0.003			<0.1	<0.0004	<0.0004	<0.0004	<0.0012	69.9	45.9
01CP07		waterra	dry purge	**(raw sample)**	25-Oct-01	212	6.58	29.9	5.4		6	118	6.8	1.2	0.01	0.835	0.067			<0.1	<0.0004	<0.0004	<0.0004	<0.0012	109	96.9
01CP07		waterra	dry purge	**(filtered/preserved)**	25-Oct-01			31.2	5.4		5.9				1.44	1.06										
01CP07		waterra	dry purge		25-May-02	129	6.22	22.8	4.9	0.7	5.3	61.1	7.9	5.9	7.42	0.801	0.275			<0.1	<0.0004	<0.0004	<0.0004	<0.0012	87	50.1
01CP07		waterra	dry purge		3-Oct-02	162	6.45	22.1	4.2	1	8.3	85.3	6	4.9	2.45	0.731	0.005		<0.1		0.0006	<0.0004	<0.0004	<0.0008	91.7	69.9
01CP07		waterra	dry purge		6-Jun-03	108	6.2	12.4	2.4	0.8	6.6	53.7	6.9	6.7	2.93	0.251	0.007		<0.1						65.4	44
01CP07		waterra	dry purge		14-Aug-03	142	6.2	12.5	2.3	0.7	7	70.1	5.1	2.4	0.56	0.395	0.01		0.2		0.0009	<0.0004	<0.0004	<0.0008	65.3	57.4
01CP07		waterra	dry purge		2-Oct-03	163	6.37	22.5	3.9	0.7	5.9	95.5	5.8	0.6	1.2	0.636	<0.003		0.5		0.0016	<0.0004	<0.0004	<0.0012	88.1	78.2
01CP07		waterra	dry purge		26-May-04	23.3	6.39	7.2	1.3	0.5	5.3	15	3.1	3.8	0.59	0.205	<0.003		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	29	12.3
01CP07		waterra	dry purge		1-Oct-04	153	6.61	12.5	2.3	1.2	8.4	73.6	4.9	0.9	0.46	0.551	0.045		<0.1		<0.0004	<0.0004	<0.0004	<0.0012	68	60.3
01CP07		waterra	no purge		16-May-05	80.4	6.19	7.4	1.2	1.2	5.8	46.8	3	1.5	0.12	0.121	0.022		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	43	38.3
01CP08A		bailer	no purge		26-Jun-02	969	7.12	158	23.3	3.1	35.4	592	48.5	49.8	0.77	3.54	0.005			1.1	0.0854	<0.0004	<0.0004	<0.0012	614	485
01CP08B		bailer	no purge		17-Jul-01	15900	6.73	1460	496	25.7	1170	440	5520	11.2	<0.01	23.5	<0.003			3	1.49	0.55	<0.02	0.96	8920	361
01CP08B		bailer	no purge		26-Oct-01	17200	6.95	1640	351		1430	443	6330	2.3	0.15	18.1	0.006			6.5	1.93	1	<0.02	1.29	10000	363
01CP08B		bailer	no purge		25-May-02	17500	6.74	1840	426	20.5	1450	458	7050	1.4	3.02	18.7	<0.003			5	1.24	0.46	0.02	1.2	11000	376
01CP08B		bailer	no purge		26-Jun-02	25000	7.41	665	82.6	11.7	3970	1180	7210	<0.1	0.53	5.31	<0.003			10.5	1.02	0.44	0.05	1.14	12500	963
01CP08B		bailer	no purge		4-Oct-02	11600	6.74	1820	396	23.2	1540	452	6360	0.4	1.9	24.7	0.56		0.7		1.23	0.3	0.05	1.32	10400	371
01CP08B		bailer	no purge		10-Feb-04	9900	6.6	1570	367	18.5	1540	466	6270	<0.1	27.7	24.5	0.015		1.4	3.3	1.02	0.061	0.074	0.569	10100	382
01CP08B		bailer	no purge		26-May-04	14800	6.48	1780	373	21	1530	1820	6320	1.4	34	29	0.23		0.4		0.686	0.062	0.017	0.775	11000	1500
01CP08B		bailer	no purge		1-Oct-04	13400	6.9	977	199	12.1	1500	548	4950	0.9	65.7	26.4	<0.003		2.6		0.22	0.026	0.003	0.296	8000	449
01CP09		waterra	no purge		17-Jul-01	763	6.89	92.4	27.7	4	10.8	221	133	3	<0.01	2.17	<0.003			1.6	1.29	<0.01	0.04	<0.03	382	181
01CP09		waterra	no purge		26-Oct-01	717	7.1	77.3	24.1		9.4	226	106	0.7	<0.01	1.61	0.034			22.2	1.94	<0.02	0.29	0.26	334	186
01CP09		waterra	no purge		25-May-02	1100	7.26	145	37	4.7	10.9	396	161	0.3	0.13	2.57	<0.003			4.7	1.04	<0.006	<0.006	0.02	556	325
01CP09		waterra	no purge		4-Oct-02	953	6.79	115	31.8	4.5	13.9	350	142	1.1	0.87	2.32	0.07								484	287
01CP09		waterra	no purge		23-May-03	910	6.63	100	29.1	3.5	9	222	157	0.3	1.2	2.05	0.012		0.3	0.7	0.133	<0.002	0.016	0.014	412	182
01CP09		waterra	no purge		2-Oct-03	802	6.83	82.8	23.2	3.6	9.4	252	103	1.3	3.7	1.74	0.003		<0.1		0.83	<0.01	0.05	0.04	352	206
01CP09		waterra	no purge		10-Feb-04	871	6.9	118	32.6	4.4	10.2	295	145	0.1	0.02	2.1	<0.003		0.5	1.7	0.924	<0.006	0.052	0.04	457	242
01CP09		waterra	no purge		26-May-04	719	6.53	88.6	24.3	3.2	10.7	212	129	<0.1	2	1.77	<0.003		0.1		0.495	<0.002	0.014	0.017	363	174
01CP09		waterra	no purge		1-Oct-04	660	6.87	67.3	20.7	3	9.2	177	105	0.3	0.21	1.48	<0.003		1.1		1.08	<0.006	0.063	0.05	295	145
01CP10		waterra	dry purge		17-Jul-01	463	7.02	51.3	12.3	1.9	29.6	278	6.9	1.8	16	1.58	<0.003			1.9	<0.0009	<0.0009	<0.0009	0.192	258	228
01CP10		waterra	dry purge	**(raw sample)**	26-Oct-01	490	7.02	50.8	13.5		24.7	299	3.3	0.5	15.8	0.654	0.007			3.7	<0.004	<0.004	<0.004	0.186	258	245
01CP10		waterra	dry purge	**(filtered/preserved)**	26-Oct-01			49.8	11.1		24				20.6	0.946										
01CP10		waterra	dry purge		25-May-02	404	6.87	46.2	10	1.6	24.3	249	6.4	0.7	16.6	0.644	<0.003			2.5	<0.002	<0.002	<0.002	0.075	229	204
01CP10		waterra	dry purge		23-May-03	432	6.88	45.5	10	1.5	13.1	208	5.9	11.3	15.3	0.62	3.75		3.7	3.9	<0.002	<0.002	0.004	0.033	222	170
01CP10		waterra	dry purge		2-Oct-03	333	6.93	38	10	1.9	16.3	196	5.2	1.3	32.6	0.959	<0.003		5.5		<0.0004	<0.0004	0.0125	0.101	203	161
01CP10		waterra	dry purge		10-Feb-04	213	6.55	25.1	5.8	1.4	9.8	130	3.9	1.2	0.06	0.706	0.099		0.5	0.6	<0.0009	<0.0009	0.0078	0.0517	112	106
01CP10		waterra	dry purge		26-May-04	412	6.52	49.1	11.8	1.9	19.4	270	10.7	9	17.1	1.16	1.61		0.3		0.0009	0.0009	0.0084	0.0616	260	221
01CP10		waterra	dry purge		1-Oct-04	363	6.85	37.3	8.5	1.7	18.2	216	5.3	2.8	1.06	1.34	<0.003		0.7		0.0014	0.0011	0.0094	0.0622	183	177
01CP11		waterra	no purge		17-Jul-01															3	0.0021	<0.0006	0.0019	0.014		
01CP11		waterra	no purge	**(raw sample)**	25-Oct-01	216	6.94	27.4	4.7		4.8	108	5.8	0.1	0.08	0.711	0.027			2.7	<0.0009	<0.0009	<0.0009	0.007	97.8	88.5
01CP11		waterra	no purge	**(filtered/preserved)**	25-Oct-01			27.8	4.6		4.8				4.24	0.738										
01CP11		waterra	no purge		25-May-02	174	6.33	24.4	3.9	1.5	5.2	102	5.5	0.1	1.7	0.712	<0.003			3.3	<0.0004	<0.0004	<0.0004	0.0139	93	83.3
01CP11		waterra	no purge		3-Oct-02	188	6.53	27.6	4.6	1.3	5.2	110	5.7	0.7	4.74	0.788	0.005		2		<0.0004	<0.0004	0.0147	0.0188	105	90.5
01CP11		waterra	no purge		23-May-03	193	6.53	23.4	3.8	0.8	4.3	104	4.7	0.2	0.06	0.654	<0.003		1.3	1.6	<0.0009	<0.0009	0.0066	0.009	88.9	85.1
01CP11		waterra	no purge		2-Oct-03	161	6.46	22.3	3.3	0.9	4.4	97.6	3.8	<0.1	3.21	0.615	<0.003		5.9		<0.0004	<0.0004	0.0089	0.0108	86.5	80
01CP11		waterra	no purge		10-Feb-04	191	6.73	28.4	4.3	0.9	4.5	124	3.9	0.2	4.61	0.82	<0.003		1.5	1.6	<0.0009	<0.0009	0.0036	0.005	109	102
01CP11		waterra	no purge		26-May-04	185	6.28	29	4.8	0.8	5	102	5.8	<0.1	1.8	0.757	<0.003		<0.1		<0.0004	<0.0004	0.0093	0.0117	98	83.6
01CP11		waterra	no purge		30-Sep-04	181	6.78	20.5	3.3	0.9	4.3	90	5.4	<0.1	0.2	0.596	<0.003		3.5		<0.0004	<0.0004	0.0055	0.0069	79	73.8
01CP11		waterra	no purge		16-May-05	140	6.44	20.8	3.4	0.6	4.1	84.4	3.7	<0.5	0.01	0.602	<0.003		4.6		<0.002	<0.002	0.005	0.006	75	69.2
01HA01		bailer	no purge		17-Jul-01	445	6.74	71.6	9.5	0.8	11.1	282	6.5	3.4	<0.01	1.56	<0.003			10.5	0.039	<0.006	<0.006	0.31	243	231

Table 9

Site B Water Quality: Parameter Concentrations

Station	Not CORONA	Method	Purge/depth	Notes	Date (d-m-y)	EC (uS/cm)	pH (units)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Chloride:D (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO2+NO3 as N (mg/L)	Sulphide (mg/L)	PHC F1 (C6-C10)-BTEX (mg/L)	TPH (C3-C10) (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylenes-total (mg/L)	TDS-calculated (mg/L)	Tot Alk as CaCO3 (mg/L)
01HA01		bailer	no purge	**(raw sample)**	26-Oct-01	520	7.19	84.2	13.5		9.5	338	8	1.6	0.19	2.16	0.057			10.9	0.033	<0.009	0.029	0.31	287	277
01HA01		bailer	no purge	**(filtered/preserved)**	26-Oct-01			80.8	12.6		9.4				5.94	2.09										
01HA01		bailer	no purge		25-May-02	148	6.81	18.6	3.7	1.3	9.9	89.4	2.1	3	4.59	0.492	<0.003			2.4	0.0015	<0.0004	0.0004	0.041	87.7	73.3
01HA01		bailer	no purge		3-Oct-02	579	7.22	93.5	16.3	1.6	18.3	381	4.4	13.4	3.28	2.36	0.005		3.1		0.012	<0.0009	0.0714	0.167	341	312
01HA01		bailer	no purge		23-May-03	575	6.84	85.9	13.3	0.8	17.7	383	4.1	3	0.02	2.06	0.036		2.1	3	0.0154	<0.0004	0.0741	0.131	315	314
01HA01		bailer	no purge		14-Aug-03	533	6.82	79.4	14.1	0.9	15	324	4.1	1.2	9.77	2.32	<0.003	<0.01	2.4		0.02	<0.002	0.129	0.186	286	265
01HA01		bailer	no purge		2-Oct-03	350	6.93	52.3	7.7	0.8	7.4	230	5.7	0.3	10.7	1.32	<0.003		3.9		0.019	<0.001	0.12	0.229	199	188
01HA01		bailer	no purge		25-May-04	262	6.55	36	5.7	0.6	10.6	167	3.8	4.7	1.49	0.724	0.011		<0.1		0.018	<0.0004	0.119	0.177	146	137
01HA01		bailer	no purge		30-Sep-04	209	6.68	27.9	5	0.5	5.9	129	5.1	0.5	0.01	0.618	0.02		1.6		0.0093	0.0005	0.152	0.185	109	105
01HA01		bailer	no purge		4-Feb-05	525	6.84	92.4	15	0.8	10.7	357	4.4	0.7	15.6	2.18	0.018		1.5		0.014	<0.002	0.145	0.177	318	293
01HA01		bailer	no purge		16-May-05	277	6.75	42.5	7.3	0.5	7.2	174	4.4	2	0.03	1.02	0.012		5.4		0.016	<0.002	0.274	0.341	150	142
01HA02		bailer	no purge		17-Jul-01	571	7.25	98.7	15.4	1.2	8.2	373	6.1	2.6	<0.01	1.36	<0.003			1.4	0.001	<0.0004	<0.0004	<0.0012	317	306
01HA02		bailer	no purge		26-Oct-01															<0.1	<0.0004	<0.0004	<0.0004	<0.0012		
01HA02		bailer	no purge		25-May-02	492	7.04	79.6	13.3	1.3	6.3	322	6.6	3	0.46	1.79	0.007			<0.1	<0.0004	<0.0004	<0.0004	<0.0012	271	264
01HA02		bailer	no purge		3-Oct-02	506	7.23	80.5	15.1	1.7	13.2	340	5.3	2.3	1.57	1.81	<0.003		0.1		0.0024	<0.0004	0.0015	0.0035	289	279
01HA02		bailer	no purge		23-May-03	367	7.07	46.9	9.3	0.6	17.5	224	7.1	6.5	<0.01	0.99	0.048		0.2	0.3	0.0007	<0.0004	0.0007	0.004	199	183
01HA02		bailer	no purge		14-Aug-03	468	7.08	65.7	13.2	0.7	9.4	289	5.2	0.9	0.41	1.79	0.011	<0.01	0.2		0.004	<0.0004	0.0021	0.0018	240	237
01HA02		bailer	no purge		25-May-04	246	7.12	20.7	4.1	0.4	27.1	134	9	11.3	0.18	0.305	<0.003		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	139	109
01HA02		bailer	no purge		30-Sep-04	421	7.24	45.6	10.5	1.4	24.8	255	6.3	1.5	6.07	0.905	0.018		<0.1		0.0022	<0.0004	0.0015	0.0027	223	209
01HA02		bailer	no purge		17-May-05	297	7.05	32.5	6.6	0.6	23.1	180	4.9	4.5	0.03	0.756	0.149		<0.1		<0.0004	<0.0004	<0.0004	0.001	162	148
01HA03		bailer	no purge		17-Jul-01	289	6.66	45.7	7.7	0.5	5.9	179	6.3	0.6	<0.01	0.991	<0.003			6.6	0.006	<0.0007	0.0209	0.182	156	147
01HA03		bailer	no purge	**(raw sample)**	26-Oct-01	346	7.16	54.8	9.4		5.9	213	6.7	0.6	0.1	1.41	0.014			10.3	0.006	<0.002	0.005	0.158	185	175
01HA03		bailer	no purge	**(filtered/preserved)**	26-Oct-01			47.4	8.7		5.8				4.14	1.39										
01HA03		bailer	no purge		25-May-02	339	6.72	63.2	14.1	1.7	6.3	219	5.2	0.9	18.1	2.01	<0.003			4.1	0.0034	<0.0004	<0.0004	0.0783	219	179
01HA03		bailer	no purge		3-Oct-02	243	6.82	31.7	5.5	1.4	12.9	140	10.8	2	1.2	0.731	0.003		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	135	115
01HA03		bailer	no purge		6-Jun-03																					116
01HA03		bailer	no purge		14-Aug-03	208	6.56	23.8	4.8	0.6	6.2	110	7.6	0.7	3.59	1.02	0.004	<0.01	1.1		0.001	<0.0004	0.0167	0.0407	102	90.3
01HA03		bailer	no purge		2-Oct-03	299	6.91	42.5	7.3	0.8	6.8	194	5.5	0.1	9.1	1.54	0.006		3.6		0.003	<0.001	0.085	0.156	169	159
01HA03		bailer	no purge		25-May-04	221	6.49	36.5	7.6	1.1	13.8	144	4.6	0.1	4.34	1.4	<0.003		<0.1		0.0049	<0.0004	0.126	0.265	140	118
01HA03		bailer	no purge		30-Sep-04	228	6.79	25.7	5.5	0.5	4.1	124	5.2	0.4	4.54	0.97	<0.003		1.6		0.0019	<0.0004	0.0725	0.114	108	102
01HA03		bailer	no purge		4-Feb-05	225	6.5	36.3	6.7	0.5	5.2	149	5.3	<0.5	7.97	1.21	0.009		1.1		<0.002	<0.002	0.055	0.081	136	122
01HA03		bailer	no purge		16-May-05	191	6.4	25.1	5.4	0.4	4.9	115	4.8	2	<0.01	0.921	0.013		2.8		0.0028	<0.0004	0.161	0.216	100	94
02BH02B		waterra	no purge		4-Oct-02	398	6.65	50.2	12.6	2.7	21	265	8.1	3.5	0.09	0.719	0.106		2.9		0.0714	<0.0009	0.0741	0.064	230	218
02BH02B		waterra	no purge		7-Nov-02	572	7.06	66.5	17.4	3	20.3	325	12.5	30.9	0.07	0.78	0.151		0.7		0.204	<0.002	0.009	0.013	312	266
02BH02B		waterra	no purge		23-May-03	577	7.28	78.8	21	2.1	12.3	335	11.2	25.7	0.02	0.634	0.663		<0.1	0.3	0.222	<0.002	<0.002	<0.006	320	275
02BH02B		waterra	no purge		14-Aug-03	515	7.03	58.7	16.3	1.9	19.4	264	11.4	35	0.01	0.183	0.623	<0.01	<0.1		0.225	<0.002	<0.002	<0.004	276	217
02BH02B		waterra	no purge		3-Oct-03	526	7.77	68	18.9	1.9	16.2	297	11.8	33.3	0.02	0.203	0.455		<0.1		0.131	<0.002	<0.002	<0.006	298	244
02BH02B		waterra	no purge		10-Feb-04	492	7.12	64.5	16.8	1.9	16.5	274	12	29.5	0.05	0.217	0.41		<0.1	0.3	0.185	<0.0009	<0.0009	<0.0029	278	224
02BH02B		waterra	no purge		25-May-04	481	7.21	61.7	15.5	1.7	16.4	279	10.8	27.9	0.11	0.294	0.37		<0.1		0.0913	<0.0009	<0.0009	<0.002	273	228
02BH02B		waterra	no purge		16-May-05	488	7.34	61.6	17.5	1.7	16.9	287	9	15.3	<0.01	0.096	0.115		<0.1		0.0704	<0.0004	<0.0004	<0.0008	264	235
02CP03A		bailer	no purge		2-Oct-03	1320	7.1	198	31.6	3.9	57.4	671	65.9	106	4.42	5.23	<0.003		1		0.136	<0.0004	0.0549	0.0285	802	550
02CP03A		bailer	no purge		26-May-04	1120	7.31	169	24.6	3.3	43.7	572	71.4	94	0.41	2.64	<0.003		0.3		0.0816	<0.0004	0.0244	0.0166	690	469
02CP03B		waterra	no purge		2-Oct-03	471	6.59	50.4	11.3	1.6	27.1	192	51.9	1	8.2	0.984	<0.003		1.5		0.183	<0.001	0.065	0.029	247	157
02CP03B		waterra	no purge		26-May-04	443	6.14	35	7.8	1.2	25	128	74.5	5.1	2.48	0.644	<0.003		0.3		0.0481	<0.0004	0.0105	0.0052	215	105
02CP03B		waterra	no purge		1-Oct-04	451	6.64	43.7	10.2	1.3	24.1	152	63.4	4.3	5.98	0.883	0.025		0.1		0.0719	<0.0004	0.0072	0.0028	229	124
02CP03C		bailer	no purge		4-Oct-02	904	6.7	129	39.7	4.2	13.9	615	32.2	1	60.9	5.67	0.08		2		1.13	<0.004	0.303	0.213	589	504
02CP03C		bailer	no purge		7-Nov-02	784	6.66	90.6	26.3	5.9	16.1	463	37.6	4	16.1	4.73	<0.003		1.4		1.33	<0.02	0.27	0.2	429	379
02CP03C		bailer	no purge		23-May-03	1010	6.85	119	36	2.7	11.3	634	33.8	0.2	12.7	5.29	<0.003		1.2	5.5	1.13	<0.007	0.269	0.21	533	520
02CP03C		bailer	no purge		2-Oct-03	607	6.45	69.9	18.7	3.1	17.4	249	53.3	29.9	18.7	1.71	<0.003		3.1		1.33	<0.01	0.35	0.3	335	204
02CP03C		bailer	no purge		10-Feb-04	930	6.81	120	33.4	2.8	12.8	632	37.7	1.1	89.3	4.22	<0.003		1.8	5.9	1.61	<0.009	0.344	0.22	612	518
02CP03C		bailer	no purge		26-May-04	950	6.69	110	29.8	2.4	10.5	620	40.1	1.5	81.2	3.71	<0.003		5.8		1.94	<0.009	0.46	0.41	585	508
02CP03C		bailer	no purge		30-Sep-04	590	6.9	53.6	14.4	2.6	17.7	289	38.1	12.6	27.7	1.14	<0.003		0.7		1.53	<0.009	0.302	0.27	310	237
02CP04A		bailer	no purge		2-Oct-03	765	6.21	92.8	21.5	2.2	13.9	132	156	19.4	2.61	2.33	0.008		<0.1		1.13	<0.01	0.11	0.05	376	108
02CP04A		bailer	no purge		10-Feb-04	666	6.13	82.2	20.3	2.4	11.9	176	122	11.3	8.95	1.98	<0.003		1.4	3.5	1.42	<0.009	0.111	0.06	348	145
02CP04A		bailer	no purge		26-May-04	690	6.06	81.2	18.2	1.6	12.2	121	147	8.2	0.15	1.4	<0.003		0.5		0.42	<0.001	0.049	0.079	329	99.2
02CP04A		bailer	no purge		1-Oct-04	854	6.54	92.4	22.6	1.9	24.4	126	202	11	5.1	2.06	<0.003		0.6		0.591	<0.004	0.077	0.112	423	103
02CP04B		waterra	no purge		4-Oct-02	1060	6.53	143	47.6	5.6	15	420	146	47.6	27	10.7	<0.003		3		2.47	<0.002	0.07	0.094	648	344
02CP04B		waterra	no purge		7-Nov-02	1210	6.59	117	39.3	5.3	18.1	421	171	50	26.2	10	<0.003		0.7		3.12	<0.04	0.06	0.08	644	345
02CP04B		waterra	no purge		23-May-03	1340	6.85	144	46.4	4	11.7	538	152	56.3	27.5	12.4	<0.003		1.7	4.2	1.75	<0.02	0.03	<0.06	720	441
02CP04B		waterra	no purge	**(duplicate)**	23-May-03														1	4.2	2.41	<0.02	0.03	<0.06		
02CP04B		waterra	no purge		2-Oct-03	1310	6.72	148	50.7	4.3	12.5	489	167	58.6	97.3	12.6	<0.003		1.7		3.62	<0.04	0.09	0.08	792	401
02CP04B		waterra	no purge		10-Feb-04	1130	6.82	119	38	3.7	12.4	584	115	20	57.2	8.22	<0.003		1.7	5.3	2.8	<0.02	0.16	0.15	661	479
02CP04B		waterra	no purge		26-May-04	1280	6.7	136	44.6	3.8	12.8	594	135	51.1	88.1	11.5	<0.003		0.6		2.66	<0.009	0.123	0.12	776	487

Table 9

Site B Water Quality: Parameter Concentrations

Station	Not CORONA	Method	Purge/depth	Notes	Date (d-m-y)	EC (uS/cm)	pH (units)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Chloride:D (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO2+NO3 as N (mg/L)	Sulphide (mg/L)	PHC F1 (C6-C10)-BTEX (mg/L)	TPH (C3-C10) (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylenes-total (mg/L)	TDS-calculated (mg/L)	Tot Alk as CaCO3 (mg/L)
02CP04B		waterra	no purge		1-Oct-04	1220	6.83	132	43.2	4.1	19.2	418	160	62.3	56.5	8.26	<0.003		1.1		2.36	<0.02	0.13	0.13	692	343
02CP18		waterra	no purge		7-Nov-02	290	6.9	2.9	0.6	2.3	53.8	107	11.3	31.8	0.14	0.06	1.16		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	161	87.9
02CP18		waterra	no purge		23-May-03	162	6.45	13.1	2.9	1.1	13.5	41.5	5.2	35.7	<0.01	0.186	0.281		<0.1	<0.1	<0.0004	<0.0004	<0.0004	<0.0012	93.5	34
02CP18		waterra	no purge		2-Oct-03	149	6.51	12.2	2.9	1	7.1	40.8	5	30.6	0.07	0.089	0.122		<0.1		<0.0004	<0.0004	<0.0004	<0.0012	79.5	33.5
02CP18		waterra	no purge		25-May-04	117	6.34	12	2.5	0.6	8.2	29.1	5.1	25.5	0.02	0.015	0.087		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	69	23.9
02CP18		waterra	no purge		1-Oct-04	134	6.65	11.7	2.6	0.8	8.5	41.8	4.4	24.6	<0.01	0.02	0.064		<0.1		<0.0004	<0.0004	<0.0004	<0.0012	73	34.2
02CP18		waterra	no purge		4-Feb-05	121	6.25	12.5	2.8	0.7	7.6	45.4	3.8	18.3	0.36	0.016	0.093		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	69	37.2
02CP18		waterra	no purge		16-May-05	128	6.33	12	2.7	0.4	8.5	47.4	3.7	<20	<0.01	0.01	0.072		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	69	38.9
02HA04		bailer	no purge		26-Jun-02	420	6.58	30.3	6.4	2.6	80	157	9.5	62.3	5.92	0.746	3.8			8.2	0.0066	<0.0004	<0.0004	0.01	292	129
02HA04		bailer	no purge		3-Oct-02	221	6.25	24.4	5	1.1	16.6	92.7	9.4	22.1	2.53	0.446	0.329		1.2		0.003	<0.0004	0.0122	0.0208	129	76
02HA04		bailer	no purge		23-May-03	208	6.42	16.8	3.3	0.5	18.7	91.6	12.5	13.9	0.02	0.321	0.022		0.1	0.2	<0.0004	<0.0004	0.0007	<0.0012	111	75.1
02HA04		bailer	no purge		14-Aug-03	192	6.4	15.6	3.2	0.4	17.4	87.6	7.5	9.7	2.55	0.261	0.012	<0.01	0.3		<0.0004	<0.0004	0.0006	0.0013	99.8	71.8
02HA04		bailer	no purge		2-Oct-03	213	6.57	29.7	5.4	0.8	6.6	127	6	0.6	6.99	0.742	<0.003		<0.1		0.0077	<0.0004	0.0212	0.0458	119	104
02HA04		bailer	no purge		25-May-04	149	6.52	18.2	4	0.8	20.6	66.5	9.2	8.9	0.17	0.16	0.011		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	95	54.5
02HA04		bailer	no purge		30-Sep-04	181	6.69	13.1	2.7	0.4	14.4	81.7	9.2	2.4	0.06	0.214	<0.003		<0.1		<0.0004	<0.0004	<0.0004	<0.0012	83	66.9
02HA04		bailer	no purge		4-Feb-05	135	6.29	15.6	3	0.3	7.7	70.9	8.7	2.2	1.98	0.278	0.083		0.4		0.0032	<0.0004	0.0005	0.0055	75	58.1
02HA04		bailer	no purge		16-May-05	179	6.37	15.3	3.1	<0.3	18.1	96.6	6.4	2.4	<0.01	0.261	0.003		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	93	79.2
03-DP1		peristaltic	no purge		14-Aug-03	263	6.37	33.7	7.3	0.5	5.7	147	4.5	1.1	4	1.03	0.009	<0.01	2.6		0.003	<0.002	0.19	0.171	130	121
03-DP1		peristaltic	no purge		2-Oct-03	264	6.46	37.8	7.7	0.6	5.9	172	5.4	1.3	4.11	1.1	0.013		2.7		0.002	<0.002	0.154	0.139	148	141
03-DP1		peristaltic	no purge		25-May-04	257	6.67	36.6	7.5	0.4	5.3	166	4.6	0.2	3.59	1.11	<0.003		2.5		0.0021	<0.0009	0.214	0.22	141	136
03-DP1		peristaltic	low flow		30-Sep-04	227	6.88	29.5	6.3	0.4	4.5	145	4.8	1.1	3.66	0.936	<0.003		1.4		<0.0004	0.0005	0.112	0.118	123	119
03-DP1		peristaltic	no purge		4-Feb-05	243	6.5	35	7.2	0.5	5.6	162	5.4	<0.5	5.08	1.07	<0.003		2		0.0016	<0.0009	0.16	0.148	140	133
03-DP1		peristaltic	no purge		16-May-05	244	6.53	33.6	7.5	0.3	5.8	153	5.3	<0.5	0.04	1.04	<0.003		2.6		<0.0004	<0.0004	0.191	0.192	129	125
03-DP2		peristaltic	no purge		15-Aug-03	164	6.41	19.9	4.4	1.2	5.4	89.9	4.3	1.5	0.1	0.435	0.007	<0.01	1.2		<0.0004	<0.0004	0.0065	0.0114	81.5	73.7
03-DP2		peristaltic	no purge		2-Oct-03	151	6.7	20	4.1	1.2	4.6	90.8	4.4	0.3	0.07	0.397	0.003		1.6		<0.0004	<0.0004	0.0116	0.0137	79.7	74.4
03-DP2		peristaltic	no purge		10-Feb-04	148	6.75	18.6	3.9	1.1	5.2	90	4.6	0.1	3.44	0.391	0.003		0.8	1	<0.0004	<0.0004	0.0054	0.0039	82	73.8
03-DP2		peristaltic	no purge		25-May-04	157	6.55	20.9	4.3	1	4.1	96.2	4.4	0.1	0.16	0.427	<0.003		2		<0.0004	<0.0004	0.0146	0.014	83	78.9
03-DP2		peristaltic	no purge		1-Oct-04	151	6.82	18.5	4.1	1.1	4.5	89.1	5.5	1.5	0.12	0.403	0.017		1.1		<0.0004	0.0005	0.0104	0.01	80	73
03-DP2		peristaltic	no purge		4-Feb-05	134	6.54	17.2	3.8	1	4.5	82.5	4.6	<0.5	0.37	0.373	0.008		1.6		<0.0004	<0.0004	0.004	0.0077	73	67.6
03-DP2		peristaltic	no purge		16-May-05	147	6.47	18.3	4.2	0.8	4.2	86.9	4.6	<0.5	0.03	0.402	<0.003		2.2		<0.0004	<0.0004	0.0136	0.0155	75	71.2
03-DP3		peristaltic	no purge		15-Aug-03	532	6.82	36.3	7.9	2.1	56.5	279	5.3	37.3	0.25	0.646	0.009		1		0.0008	<0.0004	0.0053	0.0127	283	228
03-DP3		peristaltic	no purge		2-Oct-03	286	6.95	26.7	5.5	1.8	28.3	179	4.8	7.1	0.09	0.391	<0.003		0.2		0.0007	<0.0004	0.0075	0.0079	163	147
03-DP3		peristaltic	no purge		12-Feb-04	205	7.15	22	4.7	1.6	14.4	125	5.1	3	2.39	0.435	0.021		0.5	0.6	0.0008	<0.0004	0.005	0.002	115	102
03-DP3		peristaltic	no purge		26-May-04	198	6.81	22	4.6	1.3	12.2	121	4.4	2.4	0.59	0.394	0.041		0.4		0.0011	<0.0004	0.0101	0.007	108	99.4
03-DP3		peristaltic	no purge		1-Oct-04	198	7.26	22.9	5.2	1.3	9.1	121	5.3	0.1	1.14	0.513	<0.003		0.6		0.0012	0.0006	0.0183	0.0092	105	98.9
03-DP3		peristaltic	no purge		4-Feb-05	181	6.61	21.6	4.7	1.1	6.7	111	4.8	<0.5	2.76	0.475	<0.003		0.8		<0.0004	<0.0004	0.005	0.0043	97	91
03-DP3		peristaltic	no purge		16-May-05	190	6.62	23.7	5.5	1.1	7.5	111	4.4	<0.5	0.22	0.528	<0.003		0.9		<0.0004	<0.0004	0.0101	0.0095	98	90.9
03-DP4		peristaltic	no purge		15-Aug-03	681	7.29	101	28	2.4	7	455	4.4	3	0.03	0.646	0.032	<0.01	<0.1		0.0187	<0.0004	<0.0004	<0.0008	371	373
03-DP4		peristaltic	no purge		2-Oct-03	670	7.54	102	24.8	2.3	7.5	442	4.8	16.6	0.05	1.13	<0.003		<0.1		0.0241	<0.0004	0.0014	0.0016	377	363
03-DP4		peristaltic	no purge		10-Feb-04	571	7.38	90.5	22.8	2.1	7.6	405	5	10	0.37	0.654	0.003		<0.1	<0.1	0.0198	<0.0004	<0.0004	<0.0012	338	332
03-DP4		peristaltic	no purge		25-May-04	635	7.44	104	24.1	2	6.5	454	4.1	3.7	0.11	0.608	<0.003		<0.1		0.0111	<0.0004	<0.0004	<0.0008	368	372
03-DP4		peristaltic	low flow		1-Oct-04	649	7.71	95.1	25.2	2.1	6.7	448	5.1	2	0.37	0.732	0.01		<0.1		0.0018	0.0009	<0.0004	<0.0012	358	367
03-DP4		peristaltic	no purge		4-Feb-05	559	7.16	78.7	20.7	1.9	8.5	378	5	1.9	1.32	0.651	0.011		<0.1		0.0034	<0.0004	<0.0004	<0.0008	305	310
03-DP4		peristaltic	no purge		16-May-05	636	7.28	93.7	25.1	1.9	8.3	423	4.4	2.1	0.01	0.654	0.004		<0.1		0.0011	<0.0004	0.0013	0.006	344	347
03-ML1-1		peristaltic	no purge		14-Aug-03	310	6.29	33.1	7.1	1.6	24.4	137	4.9	38.1	0.68	1.76	0.063	<0.01	1.3		0.002	<0.002	0.094	0.082	179	112
03-ML1-1		peristaltic	no purge		2-Oct-03	327	6.54	35.1	7.1	1.3	25	153	5.7	46	5.54	2.03	<0.003		1.9		0.003	<0.002	0.115	0.103	203	126
03-ML1-1		peristaltic	no purge		25-May-04	304	6.4	35.1	6.8	1	13.2	165	4.9	27.1	9.27	1.62	<0.003		2.2		0.002	<0.0004	0.0515	0.0835	180	135
03-ML1-1		peristaltic	no purge		30-Sep-04	269	6.82	26.4	5.5	0.8	8.6	166	5.8	2.3	21.4	1.29	<0.003		1.3		<0.0004	0.0006	0.0688	0.0785	154	136
03-ML1-2		peristaltic	no purge		14-Aug-03	1140	6.6	61.9	12.9	3.4	167	181	9.3	410	0.11	2.75	1.58	<0.01	0.3		0.0027	<0.0004	0.0185	0.0159	763	149
03-ML1-2		peristaltic	no purge		2-Oct-03	868	7.55	73.5	14.8	3.3	82.8	178	9.4	306	0.77	3.34	0.005		0.8		0.0052	<0.0004	0.0254	0.0251	581	146
03-ML1-2		peristaltic	no purge		10-Feb-04	741	6.51	88.1	17.6	2.4	44.6	177	8.6	257	8.16	4.48	<0.003		0.9	1.2	0.0098	<0.0004	0.0399	0.0352	518	145
03-ML1-2		peristaltic	no purge		25-May-04	701	6.88	93.9	18.8	2.2	33.2	172	7.2	240	10	4.31	0.018		0.8		0.0088	<0.0004	0.0242	0.0243	494	141
03-ML1-2		peristaltic	no purge		1-Oct-04	739	6.98	82.1	17.2	1.9	30.2	174	7.7	238	11.6	3.32	<0.003		0.4		0.0116	0.0004	0.0261	0.0182	478	142
03-ML1-3		peristaltic	no purge		14-Aug-03	397	6.52	32.5	8.1	2.5	44.1	171	6.2	62	<0.01	1.37	0.195	<0.01	0.9		0.015	<0.0004	0.0171	0.0293	242	140
03-ML1-3		peristaltic	no purge		2-Oct-03	462	6.69	44.3	9.6	2.5	38	165	6.3	92.9	0.16	1.65	<0.003		0.8		0.0233	<0.0004	0.0116	0.0161	277	135
03-ML1-3		peristaltic	no purge		10-Feb-04										3.5	3.13			0.5	0.6	0.0099	<0.0004	0.0098	0.0124		
03-ML1-3		peristaltic	no purge		25-May-04	376	6.69	43.1	9.3	1.8	25.5	170	5.4	61.9	2.23	1.27	0.01		0.1		0.0284	<0.0004	0.0021	0.0022	234	139
03-ML1-3		peristaltic	no purge		1-Oct-04	453	6.88	41.2	9.7	1.8	33.7	174	6.5	84.3	5.05	1.04	<0.003		<0.1		0.0261	0.0007	0.0012	0.0011	269	142
03-ML1-7		peristaltic	no purge		14-Aug-03	498	6.49	39.5	9.2	2.4	58	162	6	106	0.01	1.46	0.556	0.4	0.5		0.0191	<0.0004	0.0082	0.017	305	133
03-ML1-7		peristaltic	no purge		3-Oct-03	447	6.7	40.4	9	2.1	36	164	5.9	86.6	0.16	1.47	0.006		0.1		0.0315	<0.0004	0.002	0.0029	262	134
03-ML1-7		peristaltic	no purge		10-Feb-04	434	6.57	48.4	10.7	2.1	33.3	164	5.8	89	2.13	1.75	<0.003		0.3	0.4	0.0334	<0.0004	0.0049	0.0054	274	135
03-ML1-7		peristaltic	no purge		25-May-04	367	6.66	37.8	8.4	1.6	28.4	179	5	50.9	4.28	1.3	0.015		<0.1		0.0313	<0.0004	0.0016	0.0022	226	147
03-ML1-7		peristaltic	no purge		1-Oct-04	364	6.89	32.9	7.6	1.5	33.2	171	6	47	5.44	1.04	0.033		<0.1		0.0493	0.0006	<0.0004	<0.0012	219	140

Table 9

Site B Water Quality: Parameter Concentrations

Station	Not CORONA	Method	Purge/depth	Notes	Date (d-m-y)	EC (uS/cm)	pH (units)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Chloride:D (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO2+NO3 as N (mg/L)	Sulphide (mg/L)	PHC F1 (C6-C10)-BTEX (mg/L)	TPH (C3-C10) (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylenes-total (mg/L)	TDS-calculated (mg/L)	Tot Alk as CaCO3 (mg/L)
03-MW1		waterra	no purge		14-Aug-03	278	6.36	34.9	7.1	0.8	16.2	149	4.2	22	7.81	1.03	<0.003	<0.01	23.8		0.003	<0.0009	0.103	0.093	167	122
03-MW1		dialysis	deep		28-Aug-03	263	6.98	29.1	5.9	0.6	19	140	3.7	21	6.33	0.901	0.041		1.2						156	115
03-MW1		dialysis	mid		28-Aug-03	273	7.04	30.8	6.6	0.6	15.1	136	4	21.9	8.35	0.986	0.029		1.5						155	112
03-MW1		dialysis	shallow		28-Aug-03	274	7.04	28.2	5.5	0.7	19.1	141	4.1	16.4	6.19	0.853	0.012		1.6						151	116
03-MW1		dialysis	deep		24-Oct-03	222	7.37	33.5	6.7	0.5	5	146	4.4	0.6	9.08	1.07	0.003		1.9		0.0034	<0.0009	0.0876	0.091	133	119
03-MW1		dialysis	mid		24-Oct-03	224	7.38	33.3	6.7	0.5	4.9	147	4.5	0.5	8.4	1.13	0.005		1.9		0.0035	<0.0009	0.0933	0.095	132	120
03-MW1		dialysis	deep		10-Feb-04	246	6.74	36.5	7.5	0.9	6.5	164	4.6	2.7	5.18	0.667	<0.003		2	2.3	0.0021	<0.0004	0.0267	0.0221	145	134
03-MW1		dialysis	mid		10-Feb-04		7.4	37.1	7.7	0.9	6.6	162	4.5	3.7	3.41	0.575			1.6	1.8	0.002	<0.0009	0.026	0.021		133
03-MW1		waterra	no purge		10-Feb-04	285	6.54	36	7.2	0.7	6.5	180	4.7	1.8	10.5	1.06	<0.003		13.9	14.7	0.003	<0.002	0.075	0.07	157	147
03-MW1		waterra	no purge		25-May-04	261	6.69	28.9	5.7	0.5	9.8	169	4.2	3.5	8.25	1.11	<0.003		2		0.0028	<0.0004	0.0832	0.0885	145	138
03-MW1		waterra	purge		27-May-04	258	6.76	28.8	5.6	0.6	14.6	165	4.3	3.5	4.99	0.886	<0.003		2		0.0028	<0.0004	0.0886	0.0933	145	135
03-MW1		peristaltic	low flow		1-Oct-04	225	6.91	29.7	6.6	0.5	4.9	144	5.3	0.2	4.42	1.19	0.0015		1		0.002	0.0004	0.0486	0.0533	123	118
03-MW1		waterra	no purge		1-Oct-04	217	6.71	27.6	6.1	0.5	4.4	136	5	0.05	9.23	1.1	0.0015		1.2		0.0024	0.0006	0.0532	0.0567	121	111
03-MW1		waterra	no purge		4-Feb-05	251	6.55	28.3	5.9	0.4	9.2	172	5	<0.5	8.56	1.11	<0.003		2.1		0.0025	<0.0004	0.0852	0.0764	143	141
03-MW1		waterra	no purge		17-May-05	234	6.67	31.9	7	0.4	8.2	150	4.9	<0.5	3.42	1.3	0.003		2.3		0.0024	<0.0004	0.0867	0.0884	131	123
03-MW2		BarCad	shallow		14-Aug-03	302	6.42	37.6	6.9	1.1	11.3	150	4.7	29.4	1.67	1.77	0.007	<0.01	1.6		0.0027	<0.0009	0.124	0.117	168	123
03-MW2		BarCad	deep		15-Aug-03	296	6.45	34.4	7	1.4	16.1	133	4.9	29.9	2.64	1.79	0.006	<0.01	2.1		0.0025	<0.0009	0.114	0.109	163	109
03-MW2		BarCad	deep	**(duplicate)**	15-Aug-03														2.6		0.003	<0.002	0.139	0.13		
03-MW2		BarCad	deep		3-Oct-03	262	6.52	34.2	7	1.5	8.3	157	5	13.3	4.08	1.64	0.062		3.5		0.003	<0.002	0.127	0.115	153	129
03-MW2		BarCad	shallow		3-Oct-03	248	7.51	32	7.1	1.3	7.2	148	4.6	10.5	2.48	1.55	<0.003		0.3		<0.002	<0.002	0.027	0.024	139	121
03-MW2		waterra	no purge		10-Feb-04	228	6.53	30.9	6.3	1	6.5	152	5.1	1.4	8.07	1.57	0.004		3	3.5	0.004	<0.0009	0.0435	0.039	136	125
03-MW2		waterra	purge		10-Feb-04	258	6.7	32.5	6.6	1	6.5	173	4.8	1.9	8.35	1.63	<0.003		3.1	3.5	0.0045	<0.0009	0.0535	0.049	149	142
03-MW2		waterra	no purge		25-May-04	232	6.72	29.2	5.6	0.6	8.1	150	4.4	1.6	4.22	1.5	<0.003		1.9		0.0027	<0.0004	0.149	0.14	129	123
03-MW2		waterra	purge		25-May-04														2		0.0028	<0.0004	0.15	0.138		
03-MW2		peristaltic	low flow		1-Oct-04	207	6.96	26.2	5.6	0.6	5.7	129	7.7	0.5	2.67	1.36	0.0015		1.4		0.0002	0.0008	0.0924	0.105	114	106
03-MW2		waterra	no purge		1-Oct-04	214	6.8	25.1	5.5	0.6	6.4	132	5.4	0.3	5.43	1.38	0.0015		1.5		0.0002	0.0005	0.0905	0.11	115	108
03-MW2		dialysis	deep		16-May-05	245	8.1	25.5	5.4	0.8	8.6	157	5.4	<0.5	0.14	1.27	0.092		2.4		<0.0009	<0.0009	0.117	0.127	125	129
03-MW2		waterra	no purge		16-May-05	<400	6.56	26.4	5.6	0.6	7.6	126	5.7	<0.5	2.78	1.39	<0.003		2.7		0.0012	<0.0004	0.109	0.116	112	103
04CP2		waterra	no purge		1-Oct-04	3000	8.07	27.6	4.1	9.5	674	1630	214	23.5	14.2	2.96	0.006		0.6		1.48	0.159	0.116	0.876	1770	1340
99BH09	x	bailer	purge		28-Sep-99	430	7.62	62.2	9.17	2.56	23.5		2.3	10.8	0.02	0.01	0.68			0.03	<0.001	<0.001	<0.001	<0.001		
99BH09	x	bailer	purge	**(duplicate)**	28-Sep-99			62.3	9.22	2.6	23.5															
99BH09	x	bailer	purge		28-Jun-00	245	7.72	48.6	5.28	1.3	3.7		3.9	1.44	0.095	0.0163				<0.01	<0.001	<0.001	<0.001	<0.001		
99BH09	x	bailer	purge		5-Nov-00	240	7.13	35.5	3.59	0.8	2.6		2	1.05			0.09			0.1	<0.001	<0.001	<0.001	<0.001		
99BH09	x	bailer	purge		24-May-01	380	7.52	69.7	9.88	1.6	5.9		<0.5	5			0.33			<0.01	<0.001	<0.001	<0.001	<0.001		
99BH09	x	bailer	purge	**(duplicate)**	24-May-01			69.7																		
99BH09	x	bailer	purge		16-Oct-01	314	7.29	59.6	4.37	1	3.5		<0.5	3.58	0.042	0.0085	0.154			<0.01	<0.001	<0.001	<0.001	<0.001		
99BH09	x	bailer	purge		27-May-02	150	7.35	27.5	3.08	0.7	2.3	93	1.7	3.75	<0.003	0.0068	0.1		<0.01		<0.001	<0.001	<0.001	<0.001	85	76
99BH09	x	bailer	purge		7-Oct-02	326	7.48	50.8	7.7	1.2	5.7	211	1.7	2.9	0.02	<0.005	0.224		<0.01		<0.001	<0.001	<0.001	<0.001	174	173
99BH09	x	bailer	purge		2-Jun-03	166	7.23	29.9	3.3	0.8	2.3	108	<0.5	4.5	<0.01	<0.005			<0.01		<0.001	<0.001	<0.001	<0.001	94	88
99BH09	x	bailer	purge		29-Sep-03	318	7.46	56.8	7.7	1.4	4.2	212	<0.5	3.1	<0.01	0.007			<0.01		<0.001	<0.001	<0.001	<0.001	178	174
99BH09		bailer	purge		5-Oct-04	166	7.23	31.3	4.3	0.7	1.8	106	0.8	2.1	0.27	0.031	<0.2		0.01		<0.001	<0.001	<0.001	<0.001	93	87
99BH12	x	bailer	purge		28-Sep-99	550	7.4	93.1	11.7	1.98	6.37		13.9	2.84	0.01	0.03	0.06	0.01		<0.01	<0.001	<0.001	<0.001	<0.001		
99BH12	x	bailer	purge	**(duplicate)**	28-Sep-99			93.3	11.8	2	6.4			8.9												
99BH12	x	bailer	purge		28-Jun-00	494	7.41	104	12.3	1.6	6.6		8.3	3.2	0.099	0.015				<0.01	<0.001	<0.001	<0.001	<0.001		
99BH12	x	bailer	purge		5-Nov-00	370	7.47	65.9	7.84	1.1	6.3		1	1.87			0.18			<0.1	<0.001	<0.001	<0.001	<0.001		
99BH12	x	bailer	purge		24-May-01	420	7.6	74.8	9.61	1.3	6		9.9	5.61			0.22			<0.01	<0.001	<0.001	<0.001	<0.001		
99BH12	x	bailer	purge		16-Oct-01	400	7.27	72.7	8.97	1.2	9.5		1.1	3.32	0.036	0.0049	0.041			<0.01	<0.001	<0.001	<0.001	<0.001		
99BH12	x	bailer	purge		27-May-02	345	7.5	64.8	7.74	1.2	9.2	227	3.6	5.35	<0.003	0.0042	0.012		<0.01		<0.001	<0.001	<0.001	<0.001	204	186
99BH12	x	bailer	purge		7-Oct-02	225	7.09	28	4	0.7	14.6	119	11.5	4.1	0.11	<0.005	<0.006		<0.01		<0.001	<0.001	<0.001	<0.001	122	98
99BH12	x	bailer	purge		2-Jun-03	318	7.57	54	6.8	0.9	10	197	11.8	5.3	<0.01	<0.005			<0.01		<0.001	<0.001	<0.001	<0.001	186	161
99BH12	x	bailer	purge		29-Sep-03	364	7.66	58.9	8	1.2	10.8	215	7.8	4	<0.01	0.006			<0.01		<0.001	<0.001	<0.001	<0.001	197	176
99BH12		bailer	purge		5-Oct-04	393	7.68	70.5	8.6	0.8	7.8	269	3.4	0.9	0.03	<0.005	<0.2		<0.01		<0.001	<0.001	<0.001	<0.001	224	221
99BH13	x	bailer	purge		28-Sep-99	550	7.45	96.1	15.3	4	8.18		8.6	4.66	0.02	0.53	0.05	0.01		0.06	<0.001	<0.001	<0.001	<0.001		
99BH13	x	bailer	purge	**(duplicate)**	28-Sep-99			96.3	15.4	4.01	8.2			11.8												
99BH13	x	bailer	purge		28-Jun-00	560	7.51	99.4	14.8	2.2	18		51.5	3.12	0.083	0.0186				<0.01	<0.001	<0.001	<0.001	<0.001		
99BH13	x	bailer	purge		5-Nov-00	810	7.03	142	20.6	2.5	16.6		33	2.69			0.01			<0.1	<0.001	<0.001	<0.001	<0.001		
99BH13	x	bailer	purge		24-May-01	690	8.01	124	19.7	2.3	16.7		41.9	13.1			0.19			<0.01	<0.001	<0.001	<0.001	<0.001		
99BH13	x	bailer	purge		16-Oct-01	605	7.11	109	15.3	1.9	13.7		18.8	4.29	0.005	0.035	0.075			<0.01	<0.001	<0.001	<0.001	<0.001		
99BH13	x	bailer	purge		27-May-02	518	7.37	89.8	13	1.8	15	285	34	8.74	<0.003	0.0008	0.072		<0.01		<0.001	<0.001	<0.001	0.002	303	234
99BH13	x	bailer	purge		7-Oct-02	391	7.14	50.7	7.6	1	21.5	214	14.9	12	0.01	<0.005	0.137		<0.01		<0.001	<0.001	<0.001	<0.001	213	175
99BH13	x	bailer	purge		29-Sep-03	658	7.33	108	17.9	1.9	12.8	423	15	3	<0.01	0.006			<0.01		<0.001	<0.001	<0.001	<0.001	367	347
99BH13		bailer	purge		5-Oct-04	433	7.57	74	9.4	0.9	9.6	277	7.7	4.8	<0.01	<0.005	<0.2		<0.01		<0.001	<0.001	<0.001	<0.001	243	227
BH01	x	bailer	purge		8-Jun-97	1790	6.17	24.8	4.92	<0.60	4.9		3	0.4	2.14	0.77	<0.05			7.51	0.013	<0.001	0.04	0.11		

Table 9

Site B Water Quality: Parameter Concentrations

Station	Not CORONA	Method	Purge/depth	Notes	Date (d-m-y)	EC (uS/cm)	pH (units)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Chloride:D (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO2+NO3 as N (mg/L)	Sulphide (mg/L)	PHC F1 (C6-C10)-BTEX (mg/L)	TPH (C3-C10) (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylenes-total (mg/L)	TDS-calculated (mg/L)	Tot Alk as CaCO3 (mg/L)
BH01	x	bailer	purge	**(duplicate)**	8-Jun-97			26	5.2	<0.60	4.93															
BH01	x	bailer	purge		23-Oct-97															10.9	0.008	<0.001	0.02	0.09		
BH01	x	bailer	purge		11-Aug-98	304	6.29	54.5	7.68	1	5.1		3.5	0.3	1.14	1.32	0.05			10.6	0.006	<0.001	<0.001	0.08		
BH01	x	bailer	purge	**(duplicate)**	11-Aug-98			54.5	7.7	1	5.1															
BH01	x	bailer	purge		17-Oct-98	350	6.37	60.4	8.14	0.9	4.8		4.1	<1.60	0.71	1.37	0.14			18.7	0.008	<0.001	<0.001	<0.001		
BH01	x	bailer	purge	**(duplicate)**	17-Oct-98			61.5	8.58	1.03	5.57															
BH01	x	bailer	purge		11-Jun-99	270	6.16	26.7	5.63	0.8	5		10	5	2.75	0.77	<0.05			3.47	0.011	<0.001	<0.001	0.04		
BH01	x	bailer	purge	**(duplicate)**	11-Jun-99			28.5	6.5	3.08	6.8															
BH01	x	bailer	purge		28-Sep-99	230	6.8	32	6	1	4.7		5	1	1.56	0.99	0.39			6.14	0.005	<0.001	0.01	0.06		
BH01	x	bailer	purge	**(duplicate)**	28-Sep-99			38.7	7.52	1	6															
BH01	x	bailer	purge		28-Jun-00	291	6.31	52.3	8.25	0.8	5.6		4.6	0.285	0.755	1.24				2.66	0.005	<0.001	0.002	0.022		
BH01	x	bailer	purge		7-Nov-00	240	6.28	31.2	6.57	0.7	4.5		3.7	<0.5	3.88	0.8	0.22	<0.003		3.8	0.006	0.001	0.01	0.06		
BH01	x	bailer	purge	**(duplicate)**	7-Nov-00			32.1	6.76	0.8	4.6			0.22												
BH01	x	bailer	purge		24-May-01	270	6.25	0.5	7.64	0.6	4.5		5.4	1.02	3.44	1.04	<0.006	<0.003		4.23	0.009	<0.001	0.01	0.07		
BH01	x	bailer	purge	**(duplicate)**	24-May-01			39.3	8.64	0.6	4.9			1.7												
BH01		bailer	no purge		17-Jul-01	206	6.48	27.3	6.4	0.5	4.4	123	5.6	0.2	0.005	0.828	<0.003			6.4	0.0066	<0.0009	0.0354	0.089	106	101
BH01	x	bailer	purge		31-Jul-01	196	6.34	33.4	5.24	0.7	3.7		5	2.29	0.112	0.216	<0.006	0.004		<0.01	<0.001	<0.001	<0.001	<0.001		
BH01	x	bailer	purge		16-Oct-01	205	6.14	27.9	6.38	0.7	4.4		3.1	0.68	4.01	0.811	<0.006	0.014		3.04	0.004	<0.001	<0.001	0.037		
BH01		bailer	no purge	**(raw sample)**	25-Oct-01	228	6.83	32.4	8.1		4.7	138	4.7	0.05			0.003			4.4	0.0054	<0.0004	<0.0004	0.0367	119	113
BH01		bailer	no purge	**(filtered/preserved)**	25-Oct-01										5.54	1.06										
BH01		bailer	no purge	**(Pre-Purge)**	18-Feb-02	279	6.42	35.5	9.4	0.6	4.7	181	4	0.3	0.09	1.29	<0.003								145	148
BH01		bailer	no purge	**(duplicate Pre-Purge)**	18-Feb-02	273	6.41	35.3	9.1	0.6	4.8	177	4.1	0.2	0.06	1.26	<0.003			4.3	0.0079	<0.0004	<0.0004	0.0717	142	145
BH01		bailer	dry purge	**(Post-Purge)**	18-Feb-02	244	6.37	32.4	7.1	1.1	5.8	154	3.6	0.2	0.005	1.11	<0.003								127	126
BH01		bailer	dry purge	**(duplicate Post-Purge)**	18-Feb-02	260	6.39	33.8	7.6	0.7	4.6	163	3.1	0.2	0.03	1.18	<0.003			4.5	0.0076	<0.0004	0.0014	0.0749	131	134
BH01		bailer	dry purge	**(duplicate Post-Purge)**	18-Feb-02	259	6.39	35.7	8	0.6	4.7	165	3.3	0.05	0.05	1.24	<0.003								135	135
BH01		bailer	recovery	**(Post-recovery)**	18-Feb-02	275	6.38	36.5	8.7	0.5	4.6	175	3	0.1	0.01	1.31	<0.003			4	0.008	<0.0004	0.0023	0.0761	141	144
BH01		bailer	recovery	**(duplicate Post-recovery)**	18-Feb-02	272	6.38	36	8.5	0.5	4.5	177	3.1	0.1	0.005	1.27	<0.003								141	145
BH01		bailer	recovery	**(duplicate Post-recovery)**	18-Feb-02	263	6.38	36.3	8.3	0.5	4.6	169	3.1	0.1	0.005	1.3	<0.003								138	139
BH01		bailer	no purge		25-May-02	229	6.33	31.7	7.8	1.4	5.7	140	6.6	0.4	1.21	0.917	<0.003			1.3	0.0064	<0.0004	<0.0004	<0.0012	125	115
BH01	x	bailer	purge		27-May-02	272	6.08	40.2	9.52	0.8	5	171	7.3	1.36	0.0015	1.19	<0.006		3.92		0.009	<0.001	0.005	0.073	148	140
BH01	x	bailer	purge	**(duplicate)**	27-May-02									14				0.01								
BH01		bailer	no purge		26-Jun-02	436	6.63	63.9	11.4	0.7	5.3	289	7.5	0.3	5.16	1.5	<0.003			0.1	0.0013	<0.0004	<0.0004	<0.0012	238	237
BH01		bailer	no purge		3-Oct-02	260	6.42	38.1	8.7	1.1	5.3	162	5	0.3	7.08	1.16	0.007		2.8		0.0054	<0.0009	0.0797	0.064	146	133
BH01	x	bailer	purge		7-Oct-02	326	6.23	46.9	9.8	0.7	4.6	210	3.7	2.1	0.02	1.26	<0.006		1.48		0.005	<0.001	0.004	0.031	171	173
BH01	x	bailer	purge	**(duplicate)**	7-Oct-02									1.8				0.007								
BH01		bailer	no purge		20-Feb-03	269	6.38	35.5	8.3	1	5.6	166	4.8	0.2	7.59	1.15	0.016		1.9	2.5	0.006	<0.002	0.061	0.047	146	136
BH01		bailer	no purge	**(Pre-Purge)**	23-May-03	198	6.4	25.6	5.9	0.7	4.3	119	5	0.3	0.02	0.729	0.01		3	4	0.0027	<0.0004	0.0702	0.0559	101	97.6
BH01		bailer	purge	**(Post-Purge)**	23-May-03	191	6.38	24.4	5.5	0.7	4.2	115	4.9	0.2	0.02	0.776	<0.003		3.3	4.3	0.004	<0.0009	0.0842	0.066	97	94
BH01	x	bailer	purge		2-Jun-03	203	6.15	31.1	6.8	1	5.1	128	4.5	0.4	0.04	0.756		<0.005	2.54		<0.001	<0.001	<0.001	0.029	112	105
BH01		bailer	no purge		6-Jun-03	194	7.17	23.8	5.7	0.7	4.3	115	5.5	0.05	0.02	0.724	0.011								97.1	94.1
BH01		bailer	no purge		14-Aug-03	200	6.36	26.3	6.2	0.8	4.7	120	4.3	0.2	2.61	0.759	0.019	<0.01	2.7		0.0028	<0.0004	0.072	0.0563	105	98.4
BH01	x	bailer	purge		29-Sep-03	208	6.2	28.6	7.6	0.9	4.7	125	3.5	0.05	0.02	0.543			2.15		<0.001	<0.001	<0.001	0.034	107	103
BH01		bailer	no purge		3-Oct-03	193	6.52	25.7	5.7	0.8	4.5	120	4.7	0.05	3.09	0.72	0.003		2.1		0.0027	<0.0008	0.0518	0.04	104	98.3
BH01		bailer	no purge	**(duplicate)**	3-Oct-03														<0.1		0.0027	<0.0004	0.0694	0.0546		
BH01		bailer	no purge		12-Feb-04	302	6.69	43.4	9.6	0.9	5.7	198	6.8	0.1	9.37	1.26	<0.003		5.6	6.4	0.0036	<0.0004	0.0597	0.0388	174	162
BH01		bailer	no purge		25-May-04	189	6.35	26.1	6.4	0.8	6	121	4.7	0.1	2.63	0.737	<0.003		2.7		0.0033	<0.0004	0.0836	0.067	107	99.5
BH01		peristaltic	200 L	**(Post-Purge)**	26-May-04	181	6.65	23.5	5.2	0.7	4.3	112	4.2	0.05	2.73	0.678	<0.003		<0.1		0.0038	<0.0004	0.0882	0.0695	96	91.8
BH01		waterra	no purge		30-Sep-04	171	6.67	21.1	4.9	0.8	4.4	103	5.1	4.8	1.99	0.638	0.009		1.3		0.0022	0.0002	0.045	0.036	94	84.2
BH01		peristaltic	low flow		1-Oct-04	167	6.85	20.8	5	0.7	3.3	100	5.1	0.05	2.4	0.633	0.0015		1.3		0.0025	0.0007	0.05	0.0391	87	82.3
BH01		bailer	purge	**(duplicate)**	5-Oct-04														4.95		0.002	<0.001	0.037	0.059		
BH01		bailer	purge		5-Oct-04	170	6.29	22.7	5.2	0.7	4.4	102	4.8	0.4	2.7	0.706	<0.2		5.56		0.002	<0.001	0.036	0.057	88	84
BH01		bailer	no purge		4-Feb-05	164	6.43	23.5	5.5	0.7	4	105	4.1	<0.5	3.97	0.767	0.007	<0.01	1.2		0.002	<0.002	0.06	0.041	94	86
BH01		bailer	no purge	**(duplicate)**	4-Feb-05														3.3		0.0034	<0.0004	0.0365	0.0565		
BH01		bailer	no purge		16-May-05	159	6.64	20.8	4.9	0.4	4	93.2	4.3	<0.5	0.1	0.625	<0.003		2.6		<0.0004	<0.0004	0.0692	0.0532	81	76.4
BH02	x	bailer	purge		8-Jun-97	380	6.34	64.7	9.9	1.36	8.4		14	1.6			<0.05			1.73	0.23	<0.001	0.01	0.02		
BH02	x	bailer	purge		23-Oct-97															1.29	0.1	<0.001	0.01	0.03		
BH02	x	bailer	purge		11-Aug-98	398	6.41	74.2	9.3	1.3	8.3		9.8	0.7	0.42	0.84	0.05			1.34	0.12	<0.001	<0.001	0.02		
BH02	x	bailer	purge	**(duplicate)**	11-Aug-98			74.2	9.33	1.3	8.3															
BH02	x	bailer	purge		17-Oct-98	510	6.56	94.4	11.7	1.3	8.2		8.7	<1.60	0.53	1.21	<0.05			0.54	0.15	<0.001	<0.001	<0.001		
BH02	x	bailer	purge	**(duplicate)**	17-Oct-98			96.8	11.8	1.31	8.82															
BH02	x	bailer	purge		11-Jun-99	410	6.34	46.5	8.22	0.88	8		10	6	0.52	0.69	<0.05	0		1.48	0.05	<0.001	0.02	0.03		
BH02	x	bailer	purge	**(duplicate)**	11-Jun-99			47.5	9.4	1.1	11.8			6												
BH02	x	bailer	purge		28-Sep-99	380	7	62	7.42	1.1	6.5		7	<0.5	0.24	0.7	0.16	0.01		1.17	0.01	<0.001	<0.001	0		

Table 9

Site B Water Quality: Parameter Concentrations

Station	Not CORONA	Method	Purge/depth	Notes	Date (d-m-y)	EC (uS/cm)	pH (units)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Chloride:D (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO2+NO3 as N (mg/L)	Sulphide (mg/L)	PHC F1 (C6-C10)-BTEX (mg/L)	TPH (C3-C10) (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylenes-total (mg/L)	TDS-calculated (mg/L)	Tot Alk as CaCO3 (mg/L)
BH02	x	bailer	purge	**(duplicate)**	28-Sep-99			46.3	8	3	8			1												
BH02	x	bailer	purge		28-Jun-00	477	6.51	90.9	11.8	0.9	13.7		9.9	1.56	0.066	1.05				0.52	0.002	<0.001	<0.001	0.002		
BH02	x	bailer	purge		5-Nov-00	380	6.43	46.9	9.78	1	7.1		3.4	0.45			0.31			0.54	0.02	0	0.03	0.05		
BH02	x	bailer	purge		24-May-01	340	6.3	55.4	9.94	0.7	9		4	1.71	0.01	0.96	<0.006			3.52	0.11	0.01	0.04	0.12		
BH02	x	bailer	purge	**(duplicate)**	24-May-01			55.4	9.94	0.7	9															
BH02		bailer	no purge		17-Jul-01	271	6.56	37.9	8.6	0.8	7	166	7	0.2	<0.01	0.722	<0.003								144	136
BH02	x	bailer	purge		31-Jul-01	442	6.96	87.4	7.85	2.1	5.2		6.2	11.4	0.013	1.08	0.252	0.003		<0.01	<0.001	<0.001	<0.001	<0.001		
BH02	x	bailer	purge		16-Oct-01	330	6.3	51.1	11.9	0.9	7.4		3.2	1.08	4.68	0.948	<0.006			1.93	0.1	<0.001	0.004	0.034		
BH02		bailer	no purge	**(raw sample)**	25-Oct-01	422	7.06	64.7	14.4		8.2	269	5.3	0.2	0.03	1.12	0.006			1.8	0.0865	<0.0009	0.0012	0.032	227	220
BH02		bailer	no purge	**(filtered/preserved)**	25-Oct-01			29	7		4.7				4.41	0.88										
BH02		bailer	no purge	**(Pre-Purge)**	18-Feb-02	447	6.56	60.4	12.6	0.7	8.9	288	5	0.2	0.03	1.61	0.016								231	236
BH02		bailer	no purge	**(duplicate Pre-Purge)**	18-Feb-02	456	6.57	61.8	12.6	0.8	8.9	296	5.8	<0.1	<0.01	1.65	<0.003			4.3	0.286	<0.002	<0.002	0.059	237	243
BH02		bailer	dry purge	**(Post-Purge)**	18-Feb-02	268	6.32	34.7	7.4	0.9	7.4	166	5.5	0.3	0.01	0.871	<0.003								139	136
BH02		bailer	dry purge	**(duplicate Post-Purge)**	18-Feb-02	284	6.38	37.9	7.6	0.9	7.3	177	5.7	0.4	<0.01	0.884	0.006			1.7	0.155	<0.0009	<0.0009	0.02	148	145
BH02		bailer	dry purge	**(duplicate Post-Purge)**	18-Feb-02	293	6.39	40.5	8	0.9	7.5	185	6	0.4	<0.01	0.952	0.004								155	152
BH02		bailer	recovery	**(Post-recovery)**	18-Feb-02	304	6.44	41.7	8.4	0.8	7.7	190	5.7	0.5	<0.01	0.988	<0.003								159	156
BH02		bailer	recovery	**(duplicate Post-recovery)**	18-Feb-02	345	6.52	48.1	9.5	0.8	7.8	217	5.9	0.4	<0.01	1.16	<0.003			1.4	0.0885	<0.0009	<0.0009	0.006	180	178
BH02		bailer	recovery	**(duplicate Post-recovery)**	18-Feb-02	366	6.6	51.4	10.1	0.8	8	231	6	0.4	<0.01	1.25	0.006								192	189
BH02		bailer	no purge		25-May-02	319	6.41	46	9.2	0.7	8.9	195	8.1	0.2	1.5	0.861	<0.003			2.3	0.116	<0.0004	<0.0004	0.0817	171	159
BH02	x	bailer	purge		27-May-02	347	6.18	51	10.5	0.9	10.3	221	9	1.79	<0.003	1.02	0.036		2.14		0.116	<0.001	0.058	0.119	193	182
BH02		bailer	no purge		26-Jun-02	447	6.72	75.9	13.9	0.5	11.5	299	8.4	0.2	1.94	1.18	<0.003			5.5	0.0549	<0.0004	<0.0004	0.0194	261	245
BH02		bailer	no purge		3-Oct-02	415	6.57	62.1	13.8	1.8	12.6	264	7.6	0.7	7.38	1.24	0.004		0.7		0.152	<0.001	0.028	0.041	237	217
BH02	x	bailer	purge		7-Oct-02	370	6.44	51.1	8.5	4	11.9	230	4	3.2	<0.01	0.555	<0.006		0.86		0.039	<0.001	0.003	0.034	196	189
BH02		bailer	no purge		20-Feb-03	402	6.55	51.9	12.6	1.1	8.5	251	7.1	0.2	0.12	1.11	0.011		0.5	1.1	0.141	<0.0009	0.0243	0.036	206	206
BH02		bailer	no purge	**(Pre-Purge)**	23-May-03	199	6.99	21.6	4.2	1	15.1	119	5	1.6	0.01	0.006	0.005		<0.1	<0.1	<0.0004	<0.0004	<0.0004	<0.0012	107	97.4
BH02		bailer	no purge	**(Post-Purge)**	23-May-03	248	6.66	31.5	7.1	1	8.3	154	5.7	0.5	0.02	0.433	<0.003		0.6	1	0.0239	<0.0004	0.0161	0.0249	130	126
BH02	x	bailer	purge		2-Jun-03	226	6.54	29.1	4.6	0.9	19.8	151	3.7	3.5	0.02	0.021			<0.01		<0.001	<0.001	<0.001	<0.001	136	124
BH02		bailer	no purge		14-Aug-03	229	6.69	25.4	4.7	1.6	3.3	138	2.4	0.9	0.07	0.213	0.014	<0.01	0.2		0.0038	<0.0004	0.0021	0.0056	106	113
BH02	x	bailer	purge		29-Sep-03	326	6.27	46.1	13.1	1.2	7.6	206	4.1	0.3	0.17	0.677			0.94		0.022	<0.001	<0.001	0.018	174	169
BH02		bailer	no purge		2-Oct-03	305	6.62	42.5	10.6	1.1	8.1	200	5	0.3	3.04	0.755	0.004		1.2		0.0289	<0.0004	0.014	0.0331	170	164
BH02		bailer	no purge		12-Feb-04	363	6.75	56.2	13.4	1.1	9.1	266	6.5	0.2	9.8	1.25	<0.003		0.8	1.2	0.0981	<0.0009	0.0038	0.022	228	218
BH02		bailer	no purge		25-May-04	311	6.56	45.1	10.2	1	7.7	212	4.4	0.4	3.17	0.75	0.012		0.5		0.0247	0.0001	0.0087	0.0226	177	174
BH02		bailer	purge		25-May-04	265	6.8	35.4	7.5	1	7.1	172	4.9	0.3	1.36	0.729	0.003		0.8		0.0582	0.0001	0.0252	0.0394	143	141
BH02		bailer	no purge		1-Oct-04	246	6.74	30.7	7.7	1.1	6.2	157	4.3	0.4	0.08	0.732	0.018		0.6		0.0108	<0.0004	0.0178	0.0268	129	129
BH02		bailer	no purge	**(duplicate)**	1-Oct-04														0.6		0.0096	0.0005	0.0159	0.0248		
BH02		bailer	purge		5-Oct-04	244	6.33	33.9	8.6	1	6.4	156	2.9	0.5	2.39	0.79	<0.2		2.72		0.019	<0.001	0.001	0.025	130	128
BH02		bailer	no purge		4-Feb-05	299	6.63	46.6	13	1	7.2	218	4.8	<0.5	7.25	1.06	0.021		0.8		0.0469	<0.0004	0.0121	0.0146	188	178
BH02		bailer	no purge		16-May-05	226	6.47	29.3	7.4	0.8	6.3	142	4.4	<0.5	0.44	0.686	<0.003		2		0.0098	<0.0004	0.0491	0.0579	119	116
BH03	x	bailer	purge		8-Jun-97	310	6.55	55.1	7.85	1.29	6.86		6.1	8.3	0.01	0.06	0.16			0.03	0	<0.001	<0.001	<0.001		
BH03	x	bailer	purge	**(duplicate)**	8-Jun-97			58.8	8	1.29	6.9															
BH03	x	bailer	purge		23-Oct-97															0.01	<0.001	<0.001	<0.001	<0.001		
BH03	x	bailer	purge		11-Aug-98	335	6.52	64.4	7.6	1.06	5.5		5.3	8.4			0.05			<0.01	<0.001	<0.001	<0.001	<0.001		
BH03	x	bailer	purge		17-Oct-98	510	6.77	98.2	11.6	1.25	5.4		5.3	2.37	0.41	0.02	0.06			<0.01	<0.001	<0.001	<0.001	<0.001		
BH03	x	bailer	purge	**(duplicate)**	17-Oct-98			100	11.7	1.3	5.75															
BH03	x	bailer	purge		11-Jun-99	460	6.6	58.2	8.14	0.75	11.4		8	15	0.01	0	<0.05			<0.01	<0.001	<0.001	<0.001	<0.001		
BH03	x	bailer	purge	**(duplicate)**	11-Jun-99			60	9.6	0.9	14.2															
BH03	x	bailer	purge		28-Sep-99	410	7	66	8	0.8	5.8		3	7	0.08	0.01	0.26			<0.01	<0.001	<0.001	<0.001	<0.001		
BH03	x	bailer	purge	**(duplicate)**	28-Sep-99			77.1	9.03	1	7															
BH03	x	bailer	purge		28-Jun-00	279	7.27	44.9	5.39	0.7	16.1		4.2	4.98	0.674	0.028				<0.01	<0.001	<0.001	<0.001	<0.001		
BH03	x	bailer	purge		5-Nov-00	420	6.96	71.5	8.49	0.6	4.8		0.6	2.12			0.24			<0.1	<0.001	0	<0.001	<0.001		
BH03	x	bailer	purge		24-May-01	330	7.1	57.4	7.47	0.6	9.8		1.6	6.56	0.01	0.01	0.04			<0.01	<0.001	<0.001	<0.001	<0.001		
BH03	x	bailer	purge	**(duplicate)**	24-May-01			57.4	7.47	0.6	9.8															
BH03		bailer	no purge		17-Jul-01	321	7.25	50.5	6.8	0.6	11	199	2.2	6.3	<0.01	<0.004	0.004								175	163
BH03	x	bailer	purge		16-Oct-01	388	6.83	75.9	9.81	0.7	6.2		1.7	6.15	0.013	0.0072	0.023			<0.01	<0.001	<0.001	<0.001	<0.001		
BH03	x	bailer	purge		27-May-02	328	6.54	53.2	8.79	0.7	6.3	211	1.8	6.11	<0.003	0.0166	0.04		<0.01		<0.001	<0.001	<0.001	<0.001	181	173
BH03	x	bailer	purge		7-Oct-02	344	6.82	52	7.5	2	11.3	220	1.6	5.3	<0.01	0.02	<0.006		<0.01		<0.001	<0.001	<0.001	<0.001	188	181
BH03	x	bailer	purge		2-Jun-03	354	6.73	65.5	9.4	1.6	5.9	251	1.2	4.8	<0.01	0.017			<0.01		<0.001	<0.001	<0.001	<0.001	212	206
BH03	x	bailer	purge		29-Sep-03	352	6.91	80.7	12.3	1.4	6.6	312	0.9	5.1	0.005	0.12			<0.01		<0.001	<0.001	<0.001	<0.001	261	256
BH03		bailer	no purge		2-Oct-03	462	7.23	75.4	10.5	1.2	6.5	301	2.1	4.8	0.02	0.012	0.035		<0.1		<0.0004	<0.0004	<0.0004	<0.0012	249	247
BH03		bailer	no purge		12-Feb-04	385	6.96	74	10.6	1.1	6	284	2.6	4.2	0.04	0.159	<0.003		<0.1	<0.1	<0.0004	<0.0004	<0.0004	<0.0012	239	233
BH03		bailer	no purge		25-May-04	195	7.47	22.9	3.1	0.7	10	129	0.4	5.3	0.02	0.006	0.026		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	106	105
BH03		bailer	no purge		30-Sep-04	293	7.62	43.3	6.4	0.9	7.1	191	0.9	4.3	0.01	0.005	0.026		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	157	156
BH03		bailer	purge		5-Oct-04	271	6.82	46.6	7.4	0.8	6.1	175	1	4.9	0.07	0.015	<0.2		0.03		<0.001	<0.001	<0.001	<0.001	153	144

Table 9

Site B Water Quality: Parameter Concentrations

Station	Not CORONA	Method	Purge/depth	Notes	Date (d-m-y)	EC (uS/cm)	pH (units)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Chloride:D (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO2+NO3 as N (mg/L)	Sulphide (mg/L)	PHC F1 (C6-C10)-BTEX (mg/L)	TPH (C3-C10) (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylenes-total (mg/L)	TDS-calculated (mg/L)	Tot Alk as CaCO3 (mg/L)
BH03		bailer	no purge		16-May-05	257	6.99	40.3	5.9	0.7	5.1	167	1	5.7	<0.01	<0.004	0.04		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	141	136
BH03		dialysis	deep		16-May-05	388	7.32	54.7	8.2	0.9	5.2	254	1.6	4.8	0.06	0.017	0.031		<0.1		<0.0009	<0.0009	<0.0009	<0.002	200	208
BH04	x	bailer	purge		8-Jun-97	480	6.9	58.3	8.9	2.57	38.2		11.4	8.3			0.08			<0.01	<0.001	<0.001	<0.001	<0.001		
BH04	x	bailer	purge		23-Oct-97																0	<0.001	<0.001	<0.001		
BH04	x	bailer	purge		11-Aug-98	405	6.9	71.9	5.4	2.2	20		1.9	5.8			0.11			<0.01	<0.001	<0.001	<0.001	<0.001		
BH04	x	bailer	purge		17-Oct-98	290	6.85	37.1	3.88	2.62	23.2		5.8	3.16	7.55	0.86	0.56			<0.01	<0.001	<0.001	<0.001	<0.001		
BH04	x	bailer	purge	**(duplicate)**	17-Oct-98			37.5	3.89	2.8	25															
BH04	x	bailer	purge		11-Jun-99	260	7.23	33.4	3.57	1.1	6.5		6	6	0.14	0.05	0.14	<0.003		<0.01	<0.001	<0.001	<0.001	<0.001		
BH04	x	bailer	purge	**(duplicate)**	11-Jun-99			34.5	4.4	1.2	8.5			6												
BH04	x	bailer	purge		28-Sep-99	300	7.5	43	3	1.7	13.7		4	4	0.5	0.06	0.4	0		<0.01	<0.001	<0.001	<0.001	<0.001		
BH04	x	bailer	purge	**(duplicate)**	28-Sep-99			48.5	4.63	2	15			4												
BH04	x	bailer	purge		28-Jun-00	211	7	35.4	3.58	1.4	10.1		3.2	1.36	1.49	0.0583				<0.01	<0.001	<0.001	<0.001	<0.001		
BH04	x	bailer	purge		5-Nov-00	260	7.18	43.8	4.85	1	6		2.6	0.68	0.05	<0.001	0.25	<0.03		<0.1	<0.001	<0.001	<0.001	<0.001		
BH04	x	bailer	purge	**(duplicate)**	5-Nov-00			47.1	4.96	1.1	6.1			1.3												
BH04	x	bailer	purge		24-May-01	210	6.77	24.1	3.3	1.4	9.6		0.8	<0.5	0.06	0.01	1.44	<0.03		<0.01	<0.001	<0.001	<0.001	<0.001		
BH04	x	bailer	purge	**(duplicate)**	24-May-01			32.9	4.76					3.05												
BH04	x	bailer	purge		31-Jul-01	362	6.89	73.5	6.03	1	3.1		0.9	6.6	0.016	0.751	<0.006	0.01		<0.01	<0.001	<0.001	<0.001	<0.001		
BH04	x	bailer	purge		16-Oct-01	405	6.92	77.5	5.4	1.4	17		6	3.49	0.007	0.0999	1.02	0.006		<0.01	<0.001	<0.001	<0.001	<0.001		
BH04	x	bailer	purge		27-May-02	421	7.1	75.6	8.61	1.2	4.9	208	3.4	3.53	<0.003	0.0066	14.1		<0.01		<0.001	<0.001	<0.001	<0.001	199	170
BH04	x	bailer	purge	**(duplicate)**	27-May-02									15.3				0.018								
BH04	x	bailer	purge		7-Oct-02	395	7.32	54	7.6	1.4	10	238	4.1	2.9	<0.01	<0.005	18		<0.01		<0.001	<0.001	<0.001	<0.001	197	195
BH04	x	bailer	purge		2-Jun-03	415	6.98	79.6	9	1.3	4	282	2.3	2.9	<0.01	0.008		<0.005	<0.01		<0.001	<0.001	<0.001	<0.001	238	231
BH04	x	bailer	purge		29-Sep-03	373	7.01	66.8	7.1	1.5	7.4	238	2.9	1.8	<0.01	0.016			<0.01		<0.001	<0.001	<0.001	<0.001	205	196
BH04		bailer	no purge		25-May-04	482	7.25	53.2	7.5	1.3	21.5	267	11	4.7	0.13	0.357	11.8		<0.1		<0.0004	<0.0004	0.0005	<0.0008	283	219
BH04		bailer	purge		5-Oct-04	616	7.05	80	9.5	2.1	47.5	364	23.1	11.2	0.18	2.03	<0.2		0.03		0.001	<0.001	<0.001	<0.001	352	298
BH04		bailer	no purge		17-May-05	367	7.52	61.7	7.4	1.3	11.6	239	3.5	3	<0.01	0.031	0.608		<0.1		<0.0004	<0.0004	<0.0004	<0.0008	209	196

Table 10

Site B Mixing Model Output

Well	Err/Mod	Sampler	Purge	fDP1	fDP2	fDP3	Date	Caeqm (meq/L)	Mgeqm (meq/L)	Keqm (meq/L)	Naeqm (meq/L)	HCO3eqm (meq/L)	Cleqm (meq/L)	SO4eqm (meq/L)	Feeqm (meq/L)	Mneqm (meq/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	HCO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	Fe (mg/L)	Mn (mg/L)	BTEX (mg/L)	TDS (mg/L)
03-MW1	**field**	**waterra**	**no purge**	**0.57**	**0.24**	**0.19**	**8/14/03**	**1.742**	**0.584**	**0.020**	**0.705**	**2.442**	**0.118**	**0.458**	**0.280**	**0.037**	**34.9**	**7.1**	**0.8**	**16.2**	**149.0**	**4.2**	**22.0**	**7.81**	**1.03**	**0.199**	**167.0**
03-MW1	model	waterra	no purge	0.57	0.24	0.19	8/14/03	1.541	0.553	0.025	0.665	2.596	0.130	0.168	0.084	0.030	30.9	6.7	1.0	15.3	158.4	4.6	8.1	2.35	0.81	0.215	147.4
03-MW1	err^2	waterra	no purge	0.57	0.24	0.19	8/14/03	0.040	0.001	0.000	0.002	0.024	0.000	0.084	0.196	0.008	4.0	0.4	-0.2	0.9	-9.4	-0.4	13.9	5.46	0.22	-0.016	19.6
03-MW1	rpd	waterra	no purge	0.57	0.24	0.19	8/14/03										-12%	-6%	19%	-6%	6%	9%	-93%	-108%	-23%	8%	
03-MW2	**field**	**BarCad**	**shallow**	**0.81**	**0.07**	**0.12**	**8/14/03**	**1.876**	**0.568**	**0.028**	**0.492**	**2.458**	**0.133**	**0.612**	**0.060**	**0.064**	**37.6**	**6.9**	**1.1**	**11.3**	**150.0**	**4.7**	**29.4**	**1.67**	**1.77**	**0.244**	**168.0**
03-MW2	model	BarCad	shallow	0.81	0.07	0.12	8/14/03	1.651	0.590	0.019	0.521	2.614	0.129	0.117	0.117	0.034	33.1	7.2	0.7	12.0	159.5	4.6	5.6	3.27	0.94	0.297	145.7
03-MW2	err^2	BarCad	shallow	0.81	0.07	0.12	8/14/03	0.051	0.001	0.000	0.001	0.024	0.000	0.245	-0.057	0.030	4.5	-0.3	0.4	-0.7	-9.5	0.1	23.8	-1.60	0.83	-0.054	22.3
03-MW2	rpd	BarCad	shallow	0.81	0.07	0.12	8/14/03										-13%	4%	-38%	6%	6%	-2%	-136%	65%	-61%	20%	
BH01	**field**	**bailer**	**no purge**	**0.51**	**0.49**	**0.00**	**8/14/03**	**1.312**	**0.510**	**0.020**	**0.204**	**1.967**	**0.121**	**0.004**	**0.093**	**0.028**	**26.3**	**6.2**	**0.8**	**4.7**	**120.0**	**4.3**	**0.2**	**2.61**	**0.76**	**0.131**	**105.0**
BH01	model	bailer	no purge	0.51	0.49	0.00	8/14/03	1.344	0.484	0.022	0.242	1.950	0.124	0.027	0.075	0.027	26.9	5.9	0.8	5.6	119.0	4.4	1.3	2.09	0.74	0.194	106.2
BH01	err^2	bailer	no purge	0.51	0.49	0.00	8/14/03	0.001	0.001	0.000	0.001	0.000	0.000	0.001	0.019	0.001	-0.6	0.3	0.0	-0.9	1.0	-0.1	-1.1	0.52	0.02	-0.063	-1.2
BH01	rpd	bailer	no purge	0.51	0.49	0.00	8/14/03										2%	-5%	5%	17%	-1%	2%	147%	-22%	-3%	39%	
03-MW2	**field**	**BarCad**	**deep**	**0.40**	**0.42**	**0.18**	**8/15/03**	**1.717**	**0.576**	**0.036**	**0.700**	**2.180**	**0.138**	**0.622**	**0.095**	**0.065**	**34.4**	**7.0**	**1.4**	**16.1**	**133.0**	**4.9**	**29.9**	**2.64**	**1.79**	**0.226**	**163.0**
03-MW2	model	BarCad	deep	0.40	0.42	0.18	8/15/03	1.417	0.510	0.028	0.647	2.413	0.129	0.164	0.060	0.026	28.4	6.2	1.1	14.9	147.3	4.6	7.9	1.68	0.71	0.156	137.7
03-MW2	err^2	BarCad	deep	0.40	0.42	0.18	8/15/03	0.090	0.004	0.000	0.003	0.055	0.000	0.210	0.034	0.039	6.0	0.8	0.3	1.2	-14.3	0.3	22.0	0.96	1.08	0.070	25.3
03-MW2	rpd	BarCad	deep	0.40	0.42	0.18	8/15/03										-19%	-12%	-25%	-8%	10%	-7%	-116%	-44%	-86%	-36%	
03-MW1	**field**	**dialysis**	**deep**	**0.15**	**0.59**	**0.25**	**8/28/03**	**1.452**	**0.485**	**0.015**	**0.826**	**2.294**	**0.104**	**0.437**	**0.227**	**0.033**	**29.1**	**5.9**	**0.6**	**19.0**	**140.0**	**3.7**	**21.0**	**6.33**	**0.90**	**---**	**156.0**
03-MW1	model	dialysis	deep	0.15	0.59	0.25	8/28/03	1.306	0.472	0.034	0.802	2.404	0.129	0.219	0.026	0.021	26.2	5.7	1.3	18.4	146.7	4.6	10.5	0.73	0.58	0.071	140.1
03-MW1	err^2	dialysis	deep	0.15	0.59	0.25	8/28/03	0.021	0.000	0.000	0.001	0.012	0.001	0.047	0.200	0.012	2.9	0.2	-0.7	0.6	-6.7	-0.9	10.5	5.60	0.32	-0.071	15.9
03-MW1	rpd	dialysis	deep	0.15	0.59	0.25	8/28/03										-11%	-3%	75%	-3%	5%	21%	-66%	-158%	-43%		
03-MW1	**field**	**dialysis**	**mid**	**0.34**	**0.48**	**0.18**	**8/28/03**	**1.537**	**0.543**	**0.015**	**0.657**	**2.229**	**0.113**	**0.456**	**0.299**	**0.036**	**30.8**	**6.6**	**0.6**	**15.1**	**136.0**	**4.0**	**21.9**	**8.35**	**0.99**	**---**	**155.0**
03-MW1	model	dialysis	mid	0.34	0.48	0.18	8/28/03	1.377	0.496	0.029	0.642	2.356	0.128	0.163	0.052	0.025	27.6	6.0	1.1	14.8	143.8	4.5	7.9	1.46	0.68	0.137	134.7
03-MW1	err^2	dialysis	mid	0.34	0.48	0.18	8/28/03	0.025	0.002	0.000	0.000	0.016	0.000	0.086	0.247	0.011	3.2	0.6	-0.5	0.3	-7.8	-0.5	14.0	6.89	0.31	-0.137	20.3
03-MW1	rpd	dialysis	mid	0.34	0.48	0.18	8/28/03										-11%	-9%	61%	-2%	6%	13%	-94%	-140%	-37%		
03-MW1	**field**	**dialysis**	**shallow**	**0.14**	**0.61**	**0.25**	**8/28/03**	**1.407**	**0.452**	**0.018**	**0.831**	**2.311**	**0.116**	**0.341**	**0.222**	**0.031**	**28.2**	**5.5**	**0.7**	**19.1**	**141.0**	**4.1**	**16.4**	**6.19**	**0.85**	**---**	**151.0**
03-MW1	model	dialysis	shallow	0.14	0.61	0.25	8/28/03	1.295	0.468	0.034	0.802	2.389	0.129	0.220	0.024	0.021	26.0	5.7	1.3	18.4	145.8	4.6	10.5	0.67	0.57	0.065	139.3
03-MW1	err^2	dialysis	shallow	0.14	0.61	0.25	8/28/03	0.013	0.000	0.000	0.001	0.006	0.000	0.015	0.198	0.010	2.2	-0.2	-0.6	0.7	-4.8	-0.5	5.9	5.52	0.28	-0.065	11.7
03-MW1	rpd	dialysis	shallow	0.14	0.61	0.25	8/28/03										-8%	3%	62%	-4%	3%	11%	-43%	-161%	-40%		
BH01	**field**	**bailer**	**purge**	**0.46**	**0.54**	**0.00**	**9/29/03**	**1.427**	**0.625**	**0.023**	**0.204**	**2.049**	**0.099**	**0.001**	**0.001**	**0.020**	**28.6**	**7.6**	**0.9**	**4.7**	**125.0**	**3.5**	**0.1**	**0.02**	**0.54**	**0.034**	**107.0**
BH01	model	bailer	purge	0.46	0.54	0.00	9/29/03	1.404	0.473	0.024	0.226	2.096	0.137	0.016	0.069	0.026	28.1	5.7	0.9	5.2	127.9	4.9	0.8	1.92	0.72	0.149	110.9
BH01	err^2	bailer	purge	0.46	0.54	0.00	9/29/03	0.001	0.023	0.000	0.000	0.002	0.001	0.000	-0.068	-0.006	0.5	1.9	0.0	-0.5	-2.9	-1.4	-0.7	-1.90	-0.18	-0.115	-3.9
BH01	rpd	bailer	purge	0.46	0.54	0.00	9/29/03										-2%	-28%	3%	10%	2%	32%	175%	196%	28%	125%	
03-MW2	**field**	**BarCad**	**deep**	**0.71**	**0.17**	**0.12**	**10/3/03**	**1.707**	**0.576**	**0.038**	**0.361**	**2.573**	**0.141**	**0.277**	**0.146**	**0.060**	**34.2**	**7.0**	**1.5**	**8.3**	**157.0**	**5.0**	**13.3**	**4.08**	**1.64**	**0.245**	**153.0**
03-MW2	model	BarCad	deep	0.71	0.17	0.12	10/3/03	1.668	0.561	0.022	0.363	2.605	0.145	0.038	0.105	0.033	33.4	6.8	0.8	8.3	159.0	5.2	1.8	2.94	0.90	0.216	138.1
03-MW2	err^2	BarCad	deep	0.71	0.17	0.12	10/3/03	0.001	0.000	0.000	0.000	0.001	0.000	0.057	0.041	0.027	0.8	0.2	0.7	0.0	-2.0	-0.2	11.5	1.14	0.74	0.029	14.9
03-MW2	rpd	BarCad	deep	0.71	0.17	0.12	10/3/03										-2%	-3%	-56%	1%	1%	3%	-152%	-32%	-59%	-13%	
03-MW2	**field**	**BarCad**	**shallow**	**0.63**	**0.29**	**0.08**	**10/3/03**	**1.597**	**0.584**	**0.033**	**0.313**	**2.426**	**0.130**	**0.219**	**0.089**	**0.056**	**32.0**	**7.1**	**1.3**	**7.2**	**148.0**	**4.6**	**10.5**	**2.48**	**1.55**	**0.051**	**139.0**
03-MW2	model	BarCad	shallow	0.63	0.29	0.08	10/3/03	1.586	0.534	0.022	0.319	2.446	0.143	0.031	0.094	0.031	31.8	6.5	0.9	7.3	149.2	5.1	1.5	2.62	0.84	0.195	129.6
03-MW2	err^2	BarCad	shallow	0.63	0.29	0.08	10/3/03	0.000	0.003	0.000	0.000	0.000	0.000	0.035	-0.005	0.026	0.2	0.6	0.4	-0.1	-1.2	-0.5	9.0	-0.14	0.71	-0.144	9.4
03-MW2	rpd	BarCad	shallow	0.63	0.29	0.08	10/3/03										-1%	-9%	-40%	2%	1%	10%	-151%	6%	-59%	117%	
BH01	**field**	**bailer**	**no purge**	**0.35**	**0.65**	**0.00**	**10/3/03**	**1.282**	**0.469**	**0.020**	**0.196**	**1.967**	**0.133**	**0.001**	**0.111**	**0.026**	**25.7**	**5.7**	**0.8**	**4.5**	**120.0**	**4.7**	**0.1**	**3.09**	**0.72**	**0.095**	**104.0**
BH01	model	bailer	no purge	0.35	0.65	0.00	10/3/03	1.309	0.441	0.025	0.220	1.954	0.134	0.014	0.053	0.023	26.2	5.4	1.0	5.1	119.2	4.8	0.7	1.48	0.64	0.120	103.6
BH01	err^2	bailer	no purge	0.35	0.65	0.00	10/3/03	0.001	0.001	0.000	0.001	0.000	0.000	0.000	0.057	0.003	-0.5	0.3	-0.2	-0.6	0.8	-0.1	-0.6	1.61	0.08	-0.025	0.4
BH01	rpd	bailer	no purge	0.35	0.65	0.00	10/3/03										2%	-6%	21%	12%	-1%	1%	171%	-70%	-11%	24%	
03-MW1	**field**	**dialysis**	**deep**	**0.70**	**0.30**	**0.00**	**10/24/03**	**1.672**	**0.551**	**0.013**	**0.217**	**2.393**	**0.124**	**0.012**	**0.325**	**0.039**	**33.5**	**6.7**	**0.5**	**5.0**	**146.0**	**4.4**	**0.6**	**9.08**	**1.07**	**0.182**	**133.0**
03-MW1	model	dialysis	deep	0.70	0.30	0.00	10/24/03	1.623	0.546	0.020	0.240	2.425	0.144	0.021	0.104	0.032	32.5	6.6	0.8	5.5	148.0	5.1	1.0	2.91	0.89	0.215	127.8
03-MW1	err^2	dialysis	deep	0.70	0.30	0.00	10/24/03	0.002	0.000	0.000	0.001	0.001	0.000	0.000	0.221	0.006	1.0	0.1	-0.3	-0.5	-2.0	-0.7	-0.4	6.17	0.18	-0.033	5.2
03-MW1	rpd	dialysis	deep	0.70	0.30	0.00	10/24/03										-3%	-1%	43%	10%	1%	15%	50%	-103%	-18%	17%	
03-MW1	**field**	**dialysis**	**mid**	**0.71**	**0.29**	**0.00**	**10/24/03**	**1.662**	**0.551**	**0.013**	**0.213**	**2.409**	**0.127**	**0.010**	**0.301**	**0.041**	**33.3**	**6.7**	**0.5**	**4.9**	**147.0**	**4.5**	**0.5**	**8.40**	**1.13**	**0.192**	**132.0**
03-MW1	model	dialysis	mid	0.71	0.29	0.00	10/24/03	1.628	0.547	0.020	0.240	2.431	0.144	0.021	0.105	0.033	32.6	6.7	0.8	5.5	148.3	5.1	1.0	2.93	0.90	0.216	128.1
03-MW1	err^2	dialysis	mid	0.71	0.29	0.00	10/24/03	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.196	0.009	0.7	0.0	-0.3	-0.6	-1.3	-0.6	-0.5	5.47	0.23	-0.025	3.9
03-MW1	rpd	dialysis	mid	0.71	0.29	0.00	10/24/03										-2%	-1%	43%	12%	1%	13%	67%	-96%	-23%	12%	
03-MW1	**field**	**waterra**	**no purge**	**0.72**	**0.00**	**0.28**	**5/25/04**	**1.442**	**0.469**	**0.013**	**0.426**	**2.770**	**0.118**	**0.073**	**0.295**	**0.040**	**28.9**	**5.7**	**0.5**	**9.8**	**169.0**	**4.2**	**3.5**	**8.25**	**1.11**	**0.175**	**145.0**
03-MW1	model	waterra	no purge	0.72	0.00	0.28	5/25/04	1.623	0.551	0.017	0.314	2.515	0.128	0.017	0.099	0.033	32.5	6.7	0.7	7.2	153.5	4.5	0.8	2.75	0.91	0.320	131.8
03-MW1	err^2	waterra	no purge	0.72	0.00	0.28	5/25/04	0.033	0.007	0.000	0.013	0.065	0.000	0.003	0.197	0.007	-3.6	-1.0	-0.2	2.6	15.5	-0.3	2.7	5.50	0.20	-0.145	13.2
03-MW1	rpd	waterra	no purge	0.72	0.00	0.28	5/25/04										12%	16%	26%	-30%	-10%	8%	-125%	-100%	-20%	59%	
03-MW2	**field**	**waterra**	**no purge**	**0.56**	**0.00**	**0.44**	**5/25/04**	**1.457**	**0.461**	**0.015**	**0.352**	**2.458**	**0.124**	**0.033**	**0.151**	**0.055**	**29.2**	**5.6**	**0.6**	**8.1**	**150.0**	**4.4**	**1.6**	**4.22**	**1.50**	**0.292**	**129.0**
03-MW2	model	waterra	no purge	0.56	0.00	0.44	5/25/04	1.506	0.512	0.020	0.362	2.397	0.127	0.024	0.081	0.029	30.2	6.2	0.8	8.3	146.2	4.5	1.2	2.27	0.80	0.253	126.5
03-MW2	err^2	waterra	no purge	0.56	0.00	0.44	5/25/04	0.002	0.003	0.000	0.000	0.004	0.000	0.000	0.070	0.026	-1.0	-0.6	-0.2	-0.2	3.8	-0.1	0.4	1.95	0.70	0.039	2.5
03-MW2	rpd	waterra	no purge	0.56	0.00	0.44	5/25/04										3%	11%	28%	3%	-3%	3%	-31%	-60%	-61%	-14%	
BH01	**field**	**bailer**	**no purge**	**0.32**	**0.54**	**0.14**	**5/25/04**	**1.302**	**0.527**	**0.020**	**0.261**	**1.983**	**0.133**	**0.002**	**0.094**	**0.027**	**26.1**	**6.4**	**0.8**	**6.0**	**121.0**	**4.7**	**0.1**	**2.63**	**0.74**	**0.154**	**107.0**
BH01	model	bailer	no purge	0.32	0.54	0.14	5/25/04	1.304	0.442	0.022	0.243	2.002	0.126	0.009	0.048	0.023	26.1	5.4	0.8	5.6	122.2	4.5	0.4	1.33	0.64	0.159	105.2
BH01	err^2	bailer	no purge	0.32	0.54	0.14	5/25/04	0.000	0.007	0.000	0.000	0.000	0.000	0.000	0.047	0.003	0.0	1.0	0.0	0.4	-1.2	0.2	-0.3	1.30	0.09	-0.005	1.8
BH01	rpd	bailer	no purge	0.32	0.54	0.14	5/25/04										0%	-17%	6%	-7%	1%	-5%	127%	-66%	-14%	3%	
BH01	**field**	**peristaltic**	**200 L**	**0.20**	**0.76**	**0.04**	**5/26/04**	**1.173**	**0.428**	**0.018**	**0.187**	**1.836**	**0.118**	**0.001**	**0.098**	**0.025**	**23.5**	**5.2**	**0.7**	**4.3**	**112.0**	**4.2**	**0.1**	**2.73**	**0.68**	**0.162**	**96.0**
BH01	model	peristaltic	200 L	0.20	0.76	0.04	5/26/04	1.201	0.407	0.023	0.201	1.820	0.125	0.004	0.031	0.020	24.1	5.0	0.9	4.6	111.0	4.4	0.2	0.86	0.56	0.110	95.5
BH01	err^2	peristaltic	200 L	0.20	0.76	0.04	5/26/04	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.067	0.004	-0.6	0.2	-0.2	-0.3	1.0	-0.2	-0.2	1.87	0.12	0.052	0.5
BH01	rpd	peristaltic	200 L	0.20	0.76	0.04	5/26/04										2%	-5%	24%	7%	-1%	6%	121%	-104%	-19%	-38%	
03-MW1	**field**	**waterra**	**purge**	**0.63**	**0.00**	**0.37**	**5/27/04**	**1.437**	**0.461**	**0.015**	**0.635**	**2.704**	**0.121**	**0.073**	**0.179**	**0.032**	**28.8**	**5.6**	**0.6**	**14.6**	**165.0**	**4.3**	**3.5**	**4.99**	**0.89**	**0.185**	**145.0**
03-MW1	model	waterra	purge	0.63	0.00	0.37	5/27/04	1.554	0.528	0.019	0.343	2.445	0.128	0.021	0.088	0.031	31.1	6.4	0.7	7.9	149.2	4.5	1.0	2.47	0.84	0.280	128.7
03-MW1	err^2	waterra	purge	0.63	0.00	0.37	5/27/04	0.014	0.005	0.000	0.085	0.067	0.000	0.003	0.090	0.002	-2.3	-0.8	-0.1	6.7	15.8	-0.2	2.5	2.52	0.04	-0.095	16.3

Table 10

Site B Mixing Model Output

Well	Err/Mod	Sampler	Purge	fDP1	fDP2	fDP3	Date	Caeqm (meq/L)	Mgeqm (meq/L)	Keqm (meq/L)	Naeqm (meq/L)	HCO3eqm (meq/L)	Cleqm (meq/L)	SO4eqm (meq/L)	Feeqm (meq/L)	Mneqm (meq/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	HCO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	Fe (mg/L)	Mn (mg/L)	BTEX (mg/L)	TDS (mg/L)
03-MW1	rpd	waterra	purge	0.63	0.00	0.37	5/27/04										8%	14%	20%	-60%	-10%	5%	-110%	-68%	-5%	41%	
BH01	**field**	**waterra**	**no purge**	**0.25**	**0.75**	**0.00**	**9/30/04**	**1.053**	**0.403**	**0.020**	**0.191**	**1.688**	**0.144**	**0.100**	**0.071**	**0.023**	**21.1**	**4.9**	**0.8**	**4.4**	**103.0**	**5.1**	**4.8**	**1.99**	**0.64**	**0.083**	**94.0**
BH01	model	waterra	no purge	0.25	0.75	0.00	9/30/04	1.059	0.382	0.024	0.196	1.688	0.150	0.029	0.036	0.019	21.2	4.6	0.9	4.5	103.0	5.3	1.4	1.00	0.54	0.073	90.7
BH01	err^2	waterra	no purge	0.25	0.75	0.00	9/30/04	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.035	0.004	-0.1	0.3	-0.1	-0.1	0.0	-0.2	3.4	0.99	0.10	0.010	3.3
BH01	rpd	waterra	no purge	0.25	0.75	0.00	9/30/04										1%	-5%	15%	2%	0%	4%	-110%	-66%	-17%	-13%	
03-MW1	**field**	**peristaltic**	**low flow**	**0.98**	**0.00**	**0.02**	**10/1/04**	**1.482**	**0.543**	**0.013**	**0.213**	**2.360**	**0.150**	**0.004**	**0.158**	**0.043**	**29.7**	**6.6**	**0.5**	**4.9**	**144.0**	**5.3**	**0.2**	**4.42**	**1.19**	**0.104**	**123.0**
03-MW1	model	peristaltic	low flow	0.98	0.00	0.02	10/1/04	1.467	0.517	0.011	0.199	2.370	0.136	0.023	0.130	0.034	29.4	6.3	0.4	4.6	144.6	4.8	1.1	3.62	0.93	0.227	122.7
03-MW1	err^2	peristaltic	low flow	0.98	0.00	0.02	10/1/04	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.029	0.009	0.3	0.3	0.1	0.3	-0.6	0.5	-0.9	0.80	0.26	-0.123	0.3
03-MW1	rpd	peristaltic	low flow	0.98	0.00	0.02	10/1/04										-1%	-5%	-19%	-7%	0%	-10%	138%	-20%	-25%	74%	
03-MW1	**field**	**waterra**	**no purge**	**0.84**	**0.16**	**0.00**	**10/1/04**	**1.377**	**0.502**	**0.013**	**0.191**	**2.229**	**0.141**	**0.001**	**0.331**	**0.040**	**27.6**	**6.1**	**0.5**	**4.4**	**136.0**	**5.0**	**0.1**	**9.23**	**1.10**	**0.113**	**121.0**
03-MW1	model	waterra	no purge	0.84	0.16	0.00	10/1/04	1.383	0.489	0.013	0.196	2.228	0.139	0.024	0.110	0.031	27.7	5.9	0.5	4.5	136.0	4.9	1.2	3.09	0.85	0.196	116.0
03-MW1	err^2	waterra	no purge	0.84	0.16	0.00	10/1/04	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.220	0.009	-0.1	0.2	0.0	-0.1	0.0	0.1	-1.1	6.14	0.25	-0.083	5.0
03-MW1	rpd	waterra	no purge	0.84	0.16	0.00	10/1/04										0%	-3%	3%	2%	0%	-2%	184%	-100%	-26%	54%	
03-MW2	**field**	**peristaltic**	**low flow**	**0.58**	**0.17**	**0.25**	**10/1/04**	**1.307**	**0.461**	**0.015**	**0.248**	**2.114**	**0.217**	**0.010**	**0.096**	**0.050**	**26.2**	**5.6**	**0.6**	**5.7**	**129.0**	**7.7**	**0.5**	**2.67**	**1.36**	**0.198**	**114.0**
03-MW2	model	peristaltic	low flow	0.58	0.17	0.25	10/1/04	1.295	0.464	0.019	0.245	2.119	0.142	0.019	0.087	0.027	26.0	5.6	0.7	5.6	129.3	5.0	0.9	2.42	0.74	0.144	111.1
03-MW2	err^2	peristaltic	low flow	0.58	0.17	0.25	10/1/04	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.009	0.023	0.2	0.0	-0.1	0.1	-0.3	2.7	-0.4	0.25	0.62	0.054	2.9
03-MW2	rpd	peristaltic	low flow	0.58	0.17	0.25	10/1/04										-1%	1%	22%	-1%	0%	-42%	59%	-10%	-59%	-32%	
03-MW2	**field**	**waterra**	**no purge**	**0.46**	**0.04**	**0.50**	**10/1/04**	**1.252**	**0.452**	**0.015**	**0.278**	**2.163**	**0.152**	**0.006**	**0.194**	**0.050**	**25.1**	**5.5**	**0.6**	**6.4**	**132.0**	**5.4**	**0.3**	**5.43**	**1.38**	**0.201**	**115.0**
03-MW2	model	waterra	no purge	0.46	0.04	0.50	10/1/04	1.285	0.466	0.022	0.295	2.141	0.143	0.013	0.081	0.026	25.7	5.7	0.9	6.8	130.7	5.1	0.6	2.26	0.70	0.122	112.2
03-MW2	err^2	waterra	no purge	0.46	0.04	0.50	10/1/04	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.114	0.025	-0.6	-0.2	-0.3	-0.4	1.3	0.3	-0.3	3.17	0.68	0.080	2.8
03-MW2	rpd	waterra	no purge	0.46	0.04	0.50	10/1/04										3%	3%	37%	6%	-1%	-6%	70%	-83%	-65%	-49%	
BH01	**field**	**peristaltic**	**low flow**	**0.21**	**0.79**	**0.00**	**10/1/04**	**1.038**	**0.411**	**0.018**	**0.144**	**1.639**	**0.144**	**0.001**	**0.086**	**0.023**	**20.8**	**5.0**	**0.7**	**3.3**	**100.0**	**5.1**	**0.1**	**2.40**	**0.63**	**0.092**	**87.0**
BH01	model	peristaltic	low flow	0.21	0.79	0.00	10/1/04	1.036	0.374	0.024	0.196	1.648	0.151	0.030	0.030	0.019	20.8	4.6	1.0	4.5	100.6	5.4	1.4	0.85	0.51	0.064	88.8
BH01	err^2	peristaltic	low flow	0.21	0.79	0.00	10/1/04	0.000	0.001	0.000	0.003	0.000	0.000	0.001	0.056	0.004	0.0	0.4	-0.3	-1.2	-0.6	-0.3	-1.4	1.55	0.12	0.028	-1.8
BH01	rpd	peristaltic	low flow	0.21	0.79	0.00	10/1/04										0%	-9%	31%	31%	1%	5%	186%	-96%	-21%	-36%	
03-MW1	**field**	**waterra**	**no purge**	**0.90**	**0.00**	**0.10**	**2/4/05**	**1.412**	**0.485**	**0.010**	**0.400**	**2.819**	**0.141**	**0.001**	**0.307**	**0.040**	**28.3**	**5.9**	**0.4**	**9.2**	**172.0**	**5.0**	**0.1**	**8.56**	**1.11**	**0.164**	**143.0**
03-MW1	model	waterra	no purge	0.90	0.00	0.10	2/4/05	1.681	0.572	0.014	0.248	2.574	0.151	0.001	0.174	0.037	33.7	7.0	0.6	5.7	157.0	5.3	0.1	4.85	1.01	0.280	135.8
03-MW1	err^2	waterra	no purge	0.90	0.00	0.10	2/4/05	0.072	0.008	0.000	0.023	0.060	0.000	0.000	0.133	0.004	-5.4	-1.1	-0.2	3.5	15.0	-0.3	0.0	3.71	0.10	-0.116	7.2
03-MW1	rpd	waterra	no purge	0.90	0.00	0.10	2/4/05										17%	16%	33%	-47%	-9%	7%	0%	-55%	-9%	52%	
BH01	**field**	**bailer**	**no purge**	**0.31**	**0.69**	**0.00**	**2/4/05**	**1.173**	**0.452**	**0.018**	**0.174**	**1.721**	**0.116**	**0.001**	**0.142**	**0.028**	**23.5**	**5.5**	**0.7**	**4.0**	**105.0**	**4.1**	**0.1**	**3.97**	**0.77**	**0.103**	**94.0**
BH01	model	bailer	no purge	0.31	0.69	0.00	2/4/05	1.134	0.400	0.022	0.211	1.757	0.137	0.001	0.066	0.021	22.7	4.9	0.8	4.8	107.2	4.8	0.1	1.83	0.59	0.104	93.8
BH01	err^2	bailer	no purge	0.31	0.69	0.00	2/4/05	0.001	0.003	0.000	0.001	0.001	0.000	0.000	0.077	0.006	0.8	0.6	-0.1	-0.8	-2.2	-0.7	0.0	2.14	0.18	-0.001	0.2
BH01	rpd	bailer	no purge	0.31	0.69	0.00	2/4/05										-3%	-12%	19%	19%	2%	17%	0%	-74%	-26%	1%	
03-MW2	**field**	**dialysis**	**deep**	**0.74**	**0.00**	**0.26**	**5/16/05**	**1.272**	**0.444**	**0.020**	**0.374**	**2.573**	**0.152**	**0.001**	**0.005**	**0.046**	**25.5**	**5.4**	**0.8**	**8.6**	**157.0**	**5.4**	**0.1**	**0.14**	**1.27**	**0.244**	**125.0**
03-MW2	model	dialysis	deep	0.74	0.00	0.26	5/16/05	1.550	0.575	0.013	0.271	2.332	0.143	0.001	0.003	0.033	31.1	7.0	0.5	6.2	142.3	5.1	0.1	0.09	0.91	0.290	121.1
03-MW2	err^2	dialysis	deep	0.74	0.00	0.26	5/16/05	0.077	0.017	0.000	0.011	0.058	0.000	0.000	0.002	0.013	-5.6	-1.6	0.3	2.4	14.7	0.3	0.0	0.05	0.36	-0.046	3.9
03-MW2	rpd	dialysis	deep	0.74	0.00	0.26	5/16/05										20%	26%	-45%	-32%	-10%	-6%	0%	-48%	-33%	17%	
03-MW2	**field**	**waterra**	**no purge**	**0.32**	**0.00**	**0.68**	**5/16/05**	**1.317**	**0.461**	**0.015**	**0.331**	**2.065**	**0.161**	**0.001**	**0.100**	**0.051**	**26.4**	**5.6**	**0.6**	**7.6**	**126.0**	**5.7**	**0.1**	**2.78**	**1.39**	**0.226**	**112.0**
03-MW2	model	waterra	no purge	0.32	0.00	0.68	5/16/05	1.339	0.505	0.022	0.303	2.037	0.132	0.001	0.006	0.025	26.8	6.1	0.8	7.0	124.3	4.7	0.1	0.16	0.69	0.135	107.8
03-MW2	err^2	waterra	no purge	0.32	0.00	0.68	5/16/05	0.000	0.002	0.000	0.001	0.001	0.001	0.000	0.094	0.025	-0.4	-0.5	-0.2	0.6	1.7	1.0	0.0	2.62	0.70	0.092	4.2
03-MW2	rpd	waterra	no purge	0.32	0.00	0.68	5/16/05										2%	9%	34%	-9%	-1%	-20%	0%	-178%	-67%	-51%	
BH01	**field**	**bailer**	**no purge**	**0.12**	**0.88**	**0.00**	**5/16/05**	**1.038**	**0.403**	**0.010**	**0.174**	**1.528**	**0.121**	**0.001**	**0.004**	**0.023**	**20.8**	**4.9**	**0.4**	**4.0**	**93.2**	**4.3**	**0.1**	**0.10**	**0.63**	**0.122**	**81.0**
BH01	model	bailer	no purge	0.12	0.88	0.00	5/16/05	1.006	0.378	0.019	0.191	1.555	0.132	0.001	0.001	0.017	20.2	4.6	0.7	4.4	94.9	4.7	0.1	0.03	0.48	0.072	81.5
BH01	err^2	bailer	no purge	0.12	0.88	0.00	5/16/05	0.001	0.001	0.000	0.000	0.001	0.000	0.000	0.002	0.005	0.6	0.3	-0.3	-0.4	-1.7	-0.4	0.0	0.07	0.15	0.050	-0.5
BH01	rpd	bailer	no purge	0.12	0.88	0.00	5/16/05										-3%	-6%	60%	9%	2%	9%	0%	-105%	-26%	-52%	
03-MW1	**field**	**waterra**	**no purge**	**0.88**	**0.00**	**0.12**	**5/17/05**	**1.592**	**0.576**	**0.010**	**0.357**	**2.459**	**0.138**	**0.001**	**0.122**	**0.047**	**31.9**	**7.0**	**0.4**	**8.2**	**150.0**	**4.9**	**0.1**	**3.42**	**1.30**	**0.178**	**131.0**
03-MW1	model	waterra	no purge	0.88	0.00	0.12	5/17/05	1.617	0.597	0.010	0.261	2.425	0.146	0.001	0.002	0.036	32.4	7.3	0.4	6.0	147.9	5.2	0.1	0.06	0.98	0.339	125.3
03-MW1	err^2	waterra	no purge	0.88	0.00	0.12	5/17/05	0.001	0.000	0.000	0.009	0.001	0.000	0.000	0.120	0.012	-0.5	-0.3	0.0	2.2	2.1	-0.3	0.0	3.36	0.32	-0.162	5.7
03-MW1	rpd	waterra	no purge	0.88	0.00	0.12	5/17/05										2%	4%	-1%	-31%	-1%	6%	0%	-193%	-28%	63%	

Notes: 1. --- denotes not analyzed

Table 11

Site C Water Quality: Parameter Concentrations

Monitoring Station	Date (d-m-y)	EC (us/cm)	pH	Tot Hard as $CaCO_3$ (mg/L)	Tot Alk as $CaCO_3$ (mg/L)	PP Alk. as $CaCO_3$ (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO_2+NO_3 as N (mg/L)	TDS-calculated (mg/L)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Chloride:D (mg/L)	Ion Balance (balance)
98-17A	18-May-99	994	---	380	475	<0.1	92	<0.01	1.36	(0.003)	590	102	30.8	2.1	67.6	580	<0.5	10.7	0.91
	19-Oct-99	852	---	---	---	---	8.5	---	---	---	580	---	---	---	---	---	---	9.6	---
	09-May-00	943	---	490	529	<0.1	55.6	0.03	2.48	0.031	611	128	42	1.6	56.4	646	<0.5	9.9	1.02
	20-Sep-00	980	---	---	---	---	12.9	---	---	<0.003	681	---	---	---	---	---	---	10.3	---
	13-Jun-01	936	---	520	565	<0.1	16.2	0.09	1.42	0.007	559	133	46.5	1.2	13.1	689	<0.5	7.8	0.94
	19-Oct-01	1,020	---	560	591	<0.5	4.7	<0.01	2.32	0.021	581	145	48.8	1.5	16.2	721	<0.5	7.6	0.99
	23-May-02	972	---	560	565	<0.5	19	6.62	1.47	(0.004)	592	149	45.8	1.5	19.1	690	<0.5	10	1.01
	15-Aug-02	982	---	540	586	<0.5	11.5	10.2	1.72	0.006	596	146	42.4	1.6	19.7	715	<0.5	11.1	0.95
	28-Oct-02	1,020	---	520	578	<0.5	16	9.58	1.57	<0.003	583	141	41.1	1.5	17.8	705	<0.5	8.1	0.93
	13-Feb-03	935	---	520	561	<0.5	13.8	16.5	2.75	<0.003	586	149	37.2	1.3	20.4	684	<0.5	8.4	0.97
	29-May-03	1,030	---	540	564	<0.5	18.2	0.07	2.46	<0.003	581	147	41.4	1.2	22.4	689	<0.5	9.9	0.98
	26-Aug-03	928	---	530	549	<0.5	27.6	14.5	2.86	0.086	594	148	40.1	1.5	19.1	669	<0.5	10.4	1.02
	22-Oct-03	986	---	520	614	<0.5	1.7	14.8	2.94	<0.003	599	142	39.8	1.4	19.2	749	<0.5	8.7	0.94
	10-Feb-04	991	---	590	636	<0.5	4.8	0.04	2.93	<0.003	633	162	44.1	1.4	25.1	776	<0.5	10.9	0.98
	04-Jun-04	1,030	---	540	618	<0.5	10.4	16.8	2.03	<0.003	627	149	39.8	1.3	27.7	753	<0.5	8.6	0.98
	25-Aug-04	989	---	500	565	<0.5	0.8	21.1	2.23	<0.003	563	141	35.5	1.4	15.6	690	<0.5	6.7	0.99
	20-Oct-04	820	---	360	457	<0.5	0.4	18.2	1.74	<0.003	440	104	25.4	1.2	10.3	558	<0.5	4.3	0.91
	25-Feb-05	904	---	440	498	<0.5	14.7	23.2	2.23	0.007	542	125	30.4	1.3	39.1	608	<0.5	6.4	1.08
	03-May-05	779	---	350	377	<0.5	18	14.7	1.81	<0.003	426	100	24.2	1	23.6	460	<0.5	16.4	1.02
	15-Aug-05	722	---	330	408	<0.5	0.8	18	1.82	<0.003	411	95.9	22.8	1.3	13.5	498	<0.5	11.9	0.93
	13-Sep-05	674	---	310	380	<0.5	0.6	15.8	1.68	0.008	379	89.3	21	1.3	13	464	<0.5	7.6	0.94
	24-Feb-06	724	---	340	394	<0.5	<0.5	0.06	2	0.017	386	99.9	22.5	1.1	18.6	480	<0.5	5.4	0.96
	15-May-06	755	7.92	260	432	<0.5	0.6	11.9	1.51	0.008	398	76.1	17.3	0.8	25.1	527	<0.5	5.3	---
	14-Aug-06	808	---	360	467	<0.5	<0.5	16.4	2.3	<0.003	458	104	23.3	1.5	23.8	570	<0.5	5.4	0.93
98-18A	18-May-99	833	---	430	421	<0.1	66	<0.01	0.074	0.038	488	124	29.8	1.1	9.7	514	<0.5	5.3	0.91
	19-Oct-99	919	---	---	---	---	22.6	---	---	---	634	---	---	---	---	---	---	7.3	---
	09-May-00	752	---	440	379	<0.1	67.5	(0.01)	0.026	0.041	478	124	31.8	1	17.6	462	<0.5	8.5	1.04
	20-Sep-00	883	---	---	---	---	43.5	---	---	<0.003	605	---	---	---	---	---	---	8.2	---
	13-Jun-01	940	---	540	539	<0.1	35.9	<0.01	0.369	0.323	570	155	36.7	1.2	7.8	658	<0.5	7.5	0.95
	19-Oct-01	1,000	---	590	559	<0.5	25.7	<0.01	0.915	0.049	587	169	41.3	<0.3	6.9	681	<0.5	7.9	1.02
	23-May-02	961	---	560	508	<0.5	51.6	<0.01	0.062	1.36	581	157	39.9	1.3	9.6	620	<0.5	10.2	1
	15-Aug-02	991	---	550	543	<0.5	51.8	0.03	0.025	0.657	600	161	36.9	1.6	7.7	663	<0.5	12.2	0.93
	28-Oct-02	1,030	---	560	545	<0.5	45.5	0.08	0.1	0.925	599	162	36.6	1.3	9.6	664	<0.5	13.1	0.94
	13-Feb-03	976	---	590	568	<0.5	27.4	0.02	0.173	0.336	601	170	39.4	1.2	7.2	693	<0.5	13.3	0.98
	29-May-03	979	---	530	507	<0.5	33.2	0.05	(0.005)	0.521	548	150	38.2	1.1	6.9	619	<0.5	11.5	0.98
	26-Aug-03	805	---	510	427	<0.5	45.7	0.09	0.28	0.006	507	150	32.1	1.7	10.6	521	<0.5	10.4	1.09
	22-Oct-03	1,000	---	560	573	<0.5	41.5	0.03	(0.007)	0.229	606	163	38	1.2	7.5	699	<0.5	10.9	0.92
	10-Feb-04	961	---	610	573	<0.5	27.7	0.03	0.015	0.077	609	177	40.1	1.2	6.7	699	<0.5	11.8	1.01
	04-Jun-04	985	---	530	519	<0.5	61.1	0.03	<0.004	1.84	597	155	34.2	1.3	11.4	633	<0.5	13.6	0.91
	25-Aug-04	1,010	---	520	504	<0.5	56.2	0.03	0.016	1.07	575	152	34.1	1.5	10.6	614	<0.5	13.2	0.93
	20-Oct-04	995	---	530	477	<0.5	55.8	0.16	0.133	2.4	581	154	35.5	10.1	14.7	582	<0.5	14.2	1.02
	25-Feb-05	1,030	---	560	582	<0.5	28.6	0.03	0.025	0.242	596	160	38.7	0.9	5.9	710	<0.5	11.7	0.91
	03-May-05	1,090	---	580	582	<0.5	25.4	0.04	0.021	0.443	598	160	42.4	1.2	7.3	710	<0.5	10	0.95
	15-Aug-05	1,030	---	590	572	<0.5	40.5	<0.01	<0.004	0.648	618	167	42.2	1.5	8.7	697	<0.5	12.3	0.96
	13-Sep-05	999	---	580	533	<0.5	52.4	<0.01	0.006	0.907	610	168	38.1	1.7	12.6	650	<0.5	12.7	1

Table 11

Site C Water Quality: Parameter Concentrations

Monitoring Station	Date (d-m-y)	EC (us/cm)	pH	Tot Hard as $CaCO_3$ (mg/L)	Tot Alk as $CaCO_3$ (mg/L)	PP Alk. as $CaCO_3$ (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO_2+NO_3 as N (mg/L)	TDS-calculated (mg/L)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Chloride:D (mg/L)	Ion Balance (balance)
	24-Feb-06	1,080	---	570	582	<0.5	30.8	0.04	0.008	0.455	604	164	38.5	1	7.5	710	<0.5	11.4	0.93
	16-May-06	990	7.97	470	535	<0.5	39.1	<0.01	<0.004	0.643	553	134	33.9	1.1	10.5	653	<0.5	11.1	---
	14-Aug-06	1,100	---	530	584	<0.5	49.8	0.03	0.008	0.104	614	152	35.5	1.7	12.4	712	<0.5	12	0.85
98-19A	18-May-99	661	---	260	278	<0.1	61.1	<0.01	1.61	0.094	375	76.6	17.6	1	41.7	339	<0.5	9.4	1
	19-Oct-99	1,150	---	---	---	---	136	---	---	---	805	---	---	---	---	---	---	11.7	---
	09-May-00	840	---	410	393	<0.1	52	0.03	2.79	0.05	493	114	30.1	0.7	46.1	479	<0.5	14.3	1.09
	20-Sep-00	965	---	---	---	---	3	---	---	0.017	671	---	---	---	---	---	---	6.7	---
	13-Jun-01	731	---	390	380	<0.1	0.7	0.58	2.26	(0.005)	393	117	23.8	1	9.8	463	<0.5	10.7	1.04
	19-Oct-01	907	---	430	514	<0.5	1.8	7.93	2.97	0.019	518	122	31.4	(0.5)	33.6	627	<0.5	9.9	0.96
	23-May-02	729	---	380	377	<0.5	20	11.5	2.08	<0.003	438	111	25.9	1.1	17.7	460	<0.5	22.6	0.99
	15-Aug-02	740	---	370	397	<0.5	1.7	12.8	2.13	<0.003	424	109	24.2	1.8	16.9	485	<0.5	16.7	0.97
	28-Oct-02	883	---	470	483	<0.5	13	20.9	2.51	<0.003	517	135	31.4	2.1	8	589	<0.5	14.3	0.94
	13-Feb-03	803	---	430	469	<0.5	1.8	17.5	2.27	0.006	482	126	28.3	1.7	10.7	572	<0.5	13.1	0.93
	29-May-03	574	---	290	302	<0.5	0.5	0.08	1.47	<0.003	301	83.2	19.2	1	7.4	369	<0.5	6.6	0.97
	26-Aug-03	570	---	300	314	<0.5	0.5	13.9	1.62	0.021	330	87.8	20.2	1.6	8.4	384	<0.5	7.2	1.07
	22-Oct-03	754	---	420	445	<0.5	0.8	19.1	2.2	(0.003)	458	121	28.2	1.9	9.5	543	<0.5	8.2	1.04
	04-Jun-04	763	---	410	443	<0.5	0.6	21	2.02	<0.003	453	119	27.2	1.7	8.5	541	<0.5	7.4	1.03
	25-Aug-04	721	---	360	397	<0.5	0.4	17.8	1.74	0.008	402	104	23.7	1.8	8.7	485	<0.5	5.4	1.01
	20-Oct-04	729	---	350	396	<0.5	0.8	15.3	1.72	4.58	418	103	22.9	1.7	8.2	484	<0.5	5.8	0.95
	25-Feb-05	772	---	390	431	<0.5	(0.9)	17.9	1.85	<0.003	439	115	26.1	1.6	8.3	526	<0.5	8.9	1
	03-May-05	678	---	330	326	<0.5	3.7	15.6	1.5	0.009	361	95.7	21.1	1.6	7.5	398	<0.5	18.4	1.05
	15-Aug-05	651	---	300	359	<0.5	0.8	15.2	1.44	<0.003	364	88.4	19.7	1.9	9	438	<0.5	12.4	0.93
	13-Sep-05	651	---	290	359	<0.5	<0.5	13.6	1.4	0.009	355	85.7	18.7	2	8.5	437	<0.5	10.4	0.9
	24-Feb-06	640	---	320	345	<0.5	<0.5	0.08	1.49	0.005	341	94.5	21.4	1	7.7	421	<0.5	7.4	0.96
	16-May-06	525	8	280	287	<0.5	1.7	12	1.26	0.007	304	82.3	17.5	1.8	9.3	351	<0.5	5.4	---
	14-Aug-06	610	---	290	343	<0.5	<0.5	9.19	1.31	0.167	336	84.7	18.8	2.1	8.7	419	<0.5	4.9	0.93
99-20A	19-Oct-01	880	---	550	505	<0.5	2	<0.01	2.04	0.031	514	141	47.2	<0.3	11	616	<0.5	7.8	1.1
	23-May-02	874	---	530	487	<0.5	17.9	13.5	2.15	<0.003	543	143	41.8	1.8	13.8	594	<0.5	16.9	1.06
	15-Aug-02	870	---	470	510	<0.5	0.9	15.1	2.02	<0.003	514	128	36.6	1.6	10.9	623	<0.5	13	0.94
	28-Oct-02	904	---	480	511	<0.5	1.6	12.4	2	0.007	513	127	39.5	1.8	10.5	623	<0.5	12.1	0.95
	13-Feb-03	884	---	520	525	<0.5	2.4	9.94	2.04	(0.004)	539	148	37.4	1.5	10.4	641	<0.5	12.7	1
	29-May-03	854	---	430	462	<0.5	7.2	0.1	1.72	<0.003	461	123	31	1.2	12	563	<0.5	7.7	0.96
	26-Aug-03	785	---	450	459	<0.5	0.7	13	1.94	0.009	473	126	33.9	1.5	9.6	560	<0.5	10.5	1.05
	22-Oct-03	804	---	450	484	<0.5	1	9.67	1.78	<0.003	480	123	34.5	1.5	9.6	590	<0.5	8.7	0.98
	10-Feb-04	806	---	470	487	<0.5	1.3	0.05	1.89	<0.003	483	129	36.2	1.6	9.6	594	<0.5	10.7	0.98
	04-Jun-04	890	---	500	525	<0.5	2.4	15.2	1.97	<0.003	535	141	35.4	1.6	10	641	<0.5	11.7	1.01
	25-Aug-04	809	---	380	436	<0.5	10	9.6	1.44	<0.003	440	106	27.6	1.6	14.6	532	<0.5	6.9	0.94
	20-Oct-04	706	---	360	384	<0.5	1.5	8.75	1.53	<0.003	388	102	26	1.4	10.8	469	<0.5	5	1.03
	25-Feb-05	670	---	360	372	<0.5	1.6	10.6	1.48	<0.003	379	96.2	28	1.4	10.3	454	<0.5	5.9	1.04
	03-May-05	720	---	350	340	<0.5	25.3	6.62	1.34	0.021	389	98	25.1	1.2	12.5	415	<0.5	15.1	1
	15-Aug-05	672	---	340	373	<0.5	6.1	5.61	1.36	0.003	385	95.9	23.8	1.3	16.8	455	<0.5	10.7	0.98
	13-Sep-05	626	---	310	345	<0.5	1.5	8.95	1.36	0.011	351	86.6	22.9	1.6	11.2	422	<0.5	9.7	0.98
	24-Feb-06	699	---	350	367	<0.5	12.1	0.03	1.42	0.004	375	98.1	25.4	1.2	9.3	447	<0.5	7.6	0.95
	16-May-06	614	7.97	300	334	<0.5	7.7	7.48	1.23	0.008	340	85.1	20.4	1.3	11.4	408	<0.5	5.2	---
	14-Aug-06	610	---	280	329	<0.5	11.7	6.95	1.09	0.029	334	78.5	20.4	1.7	12.1	401	<0.5	4.2	0.92

Table 11

Site C Water Quality: Parameter Concentrations

Monitoring Station	Date (d-m-y)	EC (us/cm)	pH	Tot Hard as $CaCO_3$ (mg/L)	Tot Alk as $CaCO_3$ (mg/L)	PP Alk. as $CaCO_3$ (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO_2+NO_3 as N (mg/L)	TDS-calculated (mg/L)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Chloride:D (mg/L)	Ion Balance (balance)
99-21A	19-Oct-01	907	---	490	525	<0.5	0.4	9.14	3.36	0.033	522	142	32.7	1.4	10.4	640	<0.5	7.6	0.96
	23-May-02	486	---	250	214	<0.5	41.8	(0.01)	0.417	0.704	293	75.9	14.2	4.2	11.7	261	<0.5	13	1
	15-Aug-02	833	---	460	469	<0.5	14.1	7.77	2.6	0.107	497	139	27.3	3.8	11.8	572	<0.5	8.8	0.99
	28-Oct-02	557	---	270	223	<0.5	51.5	0.22	0.232	6.51	330	84.6	14.4	2.9	7.9	272	<0.5	5.5	0.95
	13-Feb-03	809	---	450	470	<0.5	5.9	12.2	1.95	0.055	490	134	28.1	2	12.7	573	<0.5	10.6	0.98
	29-May-03	508	---	220	218	<0.5	24.3	0.03	0.212	0.036	268	68.5	11.8	3.7	11.2	266	<0.5	16.7	0.93
	26-Aug-03	721	---	420	402	<0.5	12.5	8.4	1.7	0.013	442	134	21.1	3.1	11.2	491	<0.5	8.6	1.09
	22-Oct-03	754	---	410	432	<0.5	21	3.95	1.78	0.027	450	129	20.3	2.4	8.1	527	<0.5	3.9	0.95
	04-Jun-04	578	---	310	287	<0.5	39.1	0.05	0.603	0.923	342	99.7	14.2	2.5	6.7	350	<0.5	2.8	0.97
	25-Aug-04	415	---	190	182	<0.5	23.7	<0.01	0.012	1.93	223	60.2	10.3	3.2	5.4	222	<0.5	2.5	0.96
	20-Oct-04	506	---	280	240	<0.5	22.8	0.05	0.6	0.918	285	89.2	14.1	2.3	5.7	293	<0.5	2	1.1
	25-Feb-05	733	---	390	385	<0.5	27.5	0.03	0.846	0.401	418	125	19.9	2.1	7.2	469	<0.5	3.2	0.98
	03-May-05	570	---	280	248	<0.5	35.4	0.01	0.054	0.341	306	86.6	14.8	2.7	6.5	302	<0.5	10.4	0.98
	15-Aug-05	322	---	160	163	<0.5	15.8	0.02	<0.004	0.72	185	49.8	8.4	2.5	4.9	199	<0.5	2.8	0.93
	13-Sep-05	328	---	170	166	<0.5	12.6	0.03	0.006	0.568	185	52.2	9.4	2.6	4.6	202	<0.5	1.6	1
	24-Feb-06	561	---	280	291	<0.5	8.6	0.02	<0.004	0.17	297	89	14.4	2.3	3.9	355	<0.5	3.2	0.96
	16-May-06	654	7.98	350	338	<0.5	29.3	0.02	0.209	0.481	377	114	15.8	2.6	7.3	413	<0.5	3	---
	14-Aug-06	307	---	140	140	<0.5	17.7	0.02	<0.004	1.06	168	44.3	7.6	2.3	4.8	170	<0.5	2.7	0.94
99-23A	19-Oct-01	926	---	480	530	<0.5	3.2	6.6	2.37	0.03	514	139	31.6	<0.3	8.6	647	<0.5	4.2	0.92
	23-May-02	601	---	300	262	<0.5	54.8	0.15	1	0.138	379	91.4	16.5	6	34.3	319	<0.5	17.5	1.1
	15-Aug-02	1,060	---	520	595	<0.5	27.4	5.62	2.98	0.02	622	154	33.1	3.4	23.5	727	<0.5	15.1	0.89
	28-Oct-02	500	---	210	210	<0.5	39.5	1.62	0.768	3.97	291	62.8	13.9	3.2	19.4	256	<0.5	5.9	0.95
	13-Feb-03	1,180	---	650	721	<0.5	1.3	13.8	3.43	0.682	715	176	50.1	3.4	20.4	879	<0.5	11.4	0.94
	29-May-03	540	---	220	239	<0.5	26.6	0.26	0.757	0.072	290	67.2	13	4.5	20.7	292	<0.5	13	0.95
	26-Aug-03	978	---	560	609	<0.5	2.6	12	2.77	(0.005)	614	163	37.2	3.5	17.9	744	<0.5	8.7	1
	22-Oct-03	1,050	---	550	656	<0.5	2.6	14.5	2.97	0.546	639	161	37	2.7	16	800	<0.5	7.1	0.92
	10-Feb-04	1,200	---	740	794	<0.5	0.2	0.54	3.95	<0.003	772	203	56.3	3	18.1	969	<0.5	10.9	0.97
	04-Jun-04	549	---	280	278	<0.5	33.4	2.28	0.864	0.814	328	86.8	16	3.3	10.1	339	<0.5	4.3	0.97
	25-Aug-04	608	---	290	297	<0.5	28.8	5.88	0.765	0.037	340	88.1	16.5	4.1	14.3	362	<0.5	3.2	1.01
	20-Oct-04	464	---	210	220	<0.5	21.6	1.6	0.292	0.715	249	66.3	11.5	3.3	7.9	269	<0.5	1.5	0.96
	25-Feb-05	751	---	410	409	<0.5	15.8	5.35	1.94	0.008	436	127	23.4	2.7	10.5	499	<0.5	3.9	1.04
	03-May-05	639	---	290	266	<0.5	48.3	1.41	0.385	0.086	346	91.2	15.8	4.7	10.2	324	<0.5	14	0.96
	15-Aug-05	454	---	230	236	<0.5	17.2	0.02	0.519	0.024	258	72.2	11.6	3.8	7.7	288	<0.5	2.8	0.97
	13-Sep-05	612	---	280	341	<0.5	6.5	2.86	0.785	0.02	335	88.7	14	4.3	10.5	416	<0.5	2.9	0.89
	24-Feb-06	868	---	440	473	<0.5	2.7	0.09	1.98	0.011	464	129	27.7	2.9	9.5	577	<0.5	6.5	0.95
	16-May-06	820	7.84	440	407	<0.5	61.8	6.75	1.84	0.016	498	140	22.5	3.1	13.4	496	<0.5	4.2	---
	14-Aug-06	470	---	240	242	<0.5	14.7	2.35	0.445	0.282	266	75.6	12.5	3.3	7.9	295	<0.5	2.4	1.02
99-24A	19-Oct-01	1,050	---	610	613	<0.5	1.4	3.74	3.3	0.03	618	146	59.6	<0.3	31.3	748	<0.5	5.3	1.09
	23-May-02	944	---	430	534	<0.5	27.4	0.26	1.68	0.034	561	108	38.5	1.5	48.6	652	<0.5	14.2	0.92
	15-Aug-02	1,010	---	480	600	<0.5	5.7	3.4	2.13	<0.003	577	122	41.4	1.7	31.4	732	<0.5	9.5	0.88
	28-Oct-02	1,060	---	530	616	<0.5	10.2	5.36	2.59	0.008	613	131	49.8	2	33.9	751	<0.5	8.2	0.95
	13-Feb-03	975	---	510	585	<0.5	12.1	3.18	2.98	<0.003	586	127	48.1	1.8	32	714	<0.5	8.1	0.96
	29-May-03	1,010	---	480	559	<0.5	14.6	0.08	2.67	<0.003	560	121	44.4	1.5	33.2	682	<0.5	7.7	0.95
	26-Aug-03	946	---	550	598	<0.5	2.6	6.73	3.25	0.016	608	138	50.1	1.9	38.8	730	<0.5	8	1.06

Table 11

Site C Water Quality: Parameter Concentrations

Monitoring Station	Date (d-m-y)	EC (us/cm)	pH	Tot Hard as $CaCO_3$ (mg/L)	Tot Alk as $CaCO_3$ (mg/L)	PP Alk. as $CaCO_3$ (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO_2+NO_3 as N (mg/L)	TDS-calculated (mg/L)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Chloride:D (mg/L)	Ion Balance (balance)
	22-Oct-03	1,040	---	580	653	<0.5	3.7	4.32	3.03	0.006	640	145	52.5	1.6	31.8	796	<0.5	6.9	0.99
	10-Feb-04	1,010	---	610	662	<0.5	0.8	0.06	3.25	<0.003	640	142	61.6	1.9	24.3	808	<0.5	8.3	0.99
	04-Jun-04	959	---	490	558	<0.5	23.5	2.45	2.17	0.046	578	122	46	2.2	36.1	681	<0.5	8.2	0.98
	25-Aug-04	882	---	360	457	<0.5	34.4	1.29	1.77	0.014	488	92.5	32	1.7	43.3	558	<0.5	6.3	0.92
	20-Oct-04	828	---	340	435	<0.5	24.9	0.64	1.71	0.026	450	88.7	28.3	1.5	39	531	<0.5	4.4	0.91
	25-Feb-05	928	---	450	519	<0.5	21.3	1.1	2.13	<0.003	533	113	41.9	1.6	33.9	633	<0.5	6.4	0.97
	03-May-05	754	---	330	330	<0.5	48.2	0.25	1.27	0.01	415	85.2	27.9	2.2	34.5	403	<0.5	17.5	1
	15-Aug-05	868	---	420	469	<0.5	30	0.01	2	0.019	505	110	35.6	1.8	32	572	<0.5	12.1	0.95
	13-Sep-05	756	---	330	409	<0.5	27.4	0.34	1.46	0.052	430	90.6	26.2	2.1	29.9	498	<0.5	6.4	0.9
	24-Feb-06	823	---	380	437	<0.5	15.3	0.04	1.95	0.024	439	96.4	35	1.6	21	533	<0.5	5.6	0.94
	16-May-06	600	8.06	290	304	<0.5	30.2	0.18	0.696	0.233	342	75	23.8	1.8	22.4	371	<0.5	5	---
	14-Aug-06	747	---	270	386	<0.5	36.4	0.08	0.818	0.164	432	70	22.1	2.4	63.7	471	<0.5	4.8	0.95
99-25A	19-Oct-01	1,140	---	690	679	<0.5	0.4	0.42	4.12	0.033	668	167	66.5	<0.3	17.4	829	<0.5	4.6	1.06
	23-May-02	1,060	---	550	599	<0.5	26.2	2.48	2.74	0.04	667	147	44.9	1.8	62.9	731	<0.5	19.8	1.06
	15-Aug-02	1,130	---	600	699	<0.5	0.7	8.81	3.26	<0.003	673	151	54.3	1.9	22.5	853	<0.5	10.2	0.91
	28-Oct-02	1,230	---	640	727	<0.5	11.6	3.78	3.26	0.007	714	164	54.9	2	30.2	887	<0.5	7.2	0.94
	13-Feb-03	1,220	---	700	765	<0.5	3.3	13.5	3.68	0.01	753	178	61.4	1.7	25	934	<0.5	7.3	0.97
	29-May-03	1,210	---	600	683	<0.5	8.2	0.74	3.2	<0.003	670	162	48.2	1.4	28.7	833	<0.5	8	0.95
	26-Aug-03	1,110	---	660	730	<0.5	0.5	16.2	3.74	0.009	723	174	55.3	1.7	25.2	891	<0.5	8.6	1.01
	22-Oct-03	1,180	---	620	752	<0.5	0.9	11.3	3.35	0.008	707	162	51.9	1.6	21.2	918	<0.5	3.5	0.9
	10-Feb-04	1,090	---	660	725	<0.5	1.8	0.06	2.94	<0.003	700	168	59.6	1.6	22.7	884	<0.5	9	0.97
	04-Jun-04	1,150	---	610	625	<0.5	78.8	6.83	2.36	0.017	732	165	47.6	1.9	45.7	762	<0.5	9.5	1
	25-Aug-04	1,290	---	600	684	<0.5	61.4	10.2	3.4	<0.003	755	164	47.4	1.8	46.5	834	<0.5	10.1	0.95
	20-Oct-04	1,320	---	630	718	<0.5	40.6	12.5	3.52	<0.003	760	171	48.3	1.8	42.4	876	<0.5	8.1	0.96
	25-Feb-05	1,210	---	620	699	<0.5	26.5	13.2	2.92	0.009	723	161	54.3	1.6	33.3	853	<0.5	10.9	0.97
	03-May-05	958	---	420	439	<0.5	61.9	2.84	2	0.006	535	118	29.1	2.2	37.3	536	<0.5	17.9	0.95
	15-Aug-05	964	---	470	525	<0.5	44.8	0.04	2.26	<0.003	575	134	32	2.2	34.6	641	<0.5	10.8	0.93
	13-Sep-05	973	---	520	533	<0.5	36.2	7.99	2.61	<0.003	595	152	33.4	2.9	29.9	650	<0.5	9.3	1.03
	24-Feb-06	1,030	---	490	559	<0.5	17.4	0.08	2.44	0.014	556	134	37.5	1.7	18.7	682	<0.5	8.6	0.9
	16-May-06	769	7.86	390	371	<0.5	61.7	4.97	1.46	0.006	455	111	26	2.1	18.4	453	<0.5	6.7	---
	14-Aug-06	727	---	390	342	<0.5	55.5	1.55	1.11	0.438	426	114	25.2	2.7	15	417	<0.5	4.1	1.05
99-26A	19-Oct-01	1,210	---	580	708	<0.5	1.1	11.2	3.5	0.045	673	157	46.3	2.9	19.4	864	<0.5	6.1	0.9
	23-May-02	1,050	---	590	567	<0.5	58.7	5.54	3.39	<0.003	664	182	33.9	2.1	27.6	691	<0.5	11	1.02
	15-Aug-02	985	---	520	584	<0.5	15.6	13.4	3.4	0.018	593	159	31	2	10.9	712	<0.5	7.1	0.9
	28-Oct-02	635	---	310	316	<0.5	35.3	3.83	1.49	1.66	370	95.6	17.8	1.7	12.7	386	<0.5	4.7	0.94
	13-Feb-03	889	---	510	532	<0.5	10.1	15.5	3.03	<0.003	547	149	32.9	1.4	9.8	649	<0.5	6	0.96
	29-May-03	830	---	440	404	<0.5	33.6	0.25	3.41	<0.003	464	138	22.3	1.6	8.4	494	<0.5	13.7	1
	26-Aug-03	988	---	570	623	<0.5	0.4	23.4	4.03	0.018	635	179	30.9	2.2	11.1	761	<0.5	9.4	1.01
	22-Oct-03	1,020	---	530	634	<0.5	0.5	22.6	3.79	0.02	618	165	28.3	1.8	9.4	773	<0.5	6.6	0.92
	10-Feb-04	961	---	600	601	<0.5	19.2	0.15	3.82	0.006	618	177	37.5	1.8	9.7	734	<0.5	8.4	0.98
	04-Jun-04	858	---	480	479	<0.5	35.9	6.84	2.4	0.21	529	149	26.7	1.9	11.7	585	<0.5	5.3	1
	25-Aug-04	720	---	350	379	<0.5	15.7	4.9	2.25	0.044	395	111	18.9	1.9	10.3	462	<0.5	3	0.97
	20-Oct-04	748	---	350	392	<0.5	17.8	4.52	2.53	0.247	404	110	18.8	1.7	9.8	478	<0.5	3.2	0.92
	25-Feb-05	905	---	500	517	<0.5	6.7	9.91	3.3	0.009	527	149	31.1	1.5	8.9	631	<0.5	6.1	1.01
	03-May-05	700	---	330	317	<0.5	40	4.23	1.99	0.008	383	104	17.9	1.5	9.5	387	<0.5	13	0.97

Table 11

Site C Water Quality: Parameter Concentrations

Monitoring Station	Date (d-m-y)	EC (us/cm)	pH	Tot Hard as $CaCO_3$ (mg/L)	Tot Alk as $CaCO_3$ (mg/L)	PP Alk. as $CaCO_3$ (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO_2+NO_3 as N (mg/L)	TDS-calculated (mg/L)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Chloride:D (mg/L)	Ion Balance (balance)
	15-Aug-05	585	---	310	321	<0.5	12	<0.01	1.84	0.052	332	97.9	15	1.7	6.6	392	<0.5	3.9	0.95
	13-Sep-05	546	---	270	301	<0.5	7	4.22	1.74	0.019	307	85.6	13.8	2.2	8.5	368	<0.5	2.4	0.96
	24-Feb-06	779	---	390	419	<0.5	7.3	0.03	2.34	0.003	416	120	22.4	1.5	5.8	511	<0.5	5.1	0.94
	16-May-06	659	7.89	350	355	<0.5	14.2	5.63	2.06	0.017	375	109	17.7	1.9	7.7	433	<0.5	3.3	---
	14-Aug-06	592	---	300	314	<0.5	16.1	1.88	1.47	0.275	333	94.1	14.9	2.2	10	384	<0.5	2.6	0.96
99-27A	19-Oct-01	1,020	---	510	580	<0.5	0.2	14.2	4.21	0.044	575	147	34	1	20.1	708	<0.5	6	0.94
	23-May-02	848	---	450	405	<0.5	51.1	5.85	2.88	<0.003	523	137	27.5	2	29.5	494	<0.5	24.5	1.06
	15-Aug-02	680	---	320	354	<0.5	28.1	1.32	1.88	0.513	388	96.3	19.9	1.7	19.1	432	<0.5	4.7	0.93
	28-Oct-02	867	---	450	492	<0.5	0.9	17.1	3.44	(0.005)	503	135	27.7	1.6	12.9	601	<0.5	9.2	0.95
	13-Feb-03	892	---	490	533	<0.5	0.3	19.2	3.75	0.045	550	146	30.7	1.1	21	650	<0.5	7.4	0.99
	29-May-03	716	---	330	337	<0.5	20.5	0.35	1.48	<0.003	389	102	18	1.9	23	411	<0.5	19.1	0.99
	26-Aug-03	900	---	520	558	<0.5	0.4	19	3.68	0.017	575	157	32.4	1.5	19.7	681	<0.5	6.9	1.06
	22-Oct-03	920	---	460	563	<0.5	2.6	12.3	2.91	(0.004)	544	137	28.4	1.3	16.9	687	<0.5	4.8	0.91
	10-Feb-04	861	---	500	539	<0.5	0.8	0.15	3.31	(0.003)	531	146	32.4	1.1	16.7	658	<0.5	7.7	0.97
	04-Jun-04	581	---	300	276	<0.5	51.3	3	0.95	1.08	354	93.8	16.4	1.9	12.1	337	<0.5	4.2	0.99
	25-Aug-04	711	---	340	356	<0.5	30.7	3.36	1.44	<0.003	396	106	17.9	2.4	17.6	434	<0.5	3	0.98
	20-Oct-04	718	---	330	391	<0.5	2.9	3.53	1.74	0.008	384	105	17.3	1.6	13.9	478	<0.5	3.2	0.93
	25-Feb-05	792	---	400	399	<0.5	48.4	14.8	1.48	<0.003	465	123	23.3	2	7.2	487	<0.5	5	0.98
	03-May-05	657	---	410	323	<0.5	15.1	<0.01	<0.004	0.021	377	122	26.6	1.7	7.8	394	<0.5	10.1	1.23
	15-Aug-05	564	---	250	313	<0.5	9.1	1.76	0.856	0.004	316	77.5	12.7	2	20.3	382	<0.5	3.9	0.9
	13-Sep-05	567	---	300	308	<0.5	9.1	3.88	1.38	0.005	332	91.4	16.5	2.2	19.2	376	<0.5	3.7	1.08
	24-Feb-06	909	---	460	496	<0.5	<0.5	0.06	2.77	0.007	487	139	26.5	1.3	12.8	606	<0.5	7	0.96
	15-May-06	667	7.88	350	363	<0.5	14.9	6.35	1.91	0.003	384	108	19	1.5	11.5	442	<0.5	3.4	---
	14-Aug-06	661	---	320	367	<0.5	<0.5	5.46	1.55	0.029	366	98.3	17.3	2	16.5	448	<0.5	4.8	0.98
99-28A	19-Oct-01	878	---	520	487	<0.5	12.1	23.2	2.45	0.041	530	151	33.9	<0.3	8.4	594	<0.5	7.1	1.05
	23-May-02	776	---	420	303	<0.5	77.9	3.67	2.17	<0.003	471	131	23.4	3.8	18.2	370	<0.5	28.9	1.1
	15-Aug-02	786	---	450	438	<0.5	16.7	0.23	1.82	(0.004)	470	131	30.6	3.1	10	534	<0.5	13.3	1.01
	28-Oct-02	634	---	350	301	<0.5	41.2	0.02	1.1	0.03	378	108	20.3	2.7	13.1	367	<0.5	10.3	1.08
	13-Feb-03	788	---	420	449	<0.5	13.2	30.2	1.14	<0.003	489	127	26.4	2.8	10.8	547	<0.5	8.9	0.95
	29-May-03	600	---	270	294	<0.5	17.5	0.06	1.1	<0.003	314	84.5	15.4	2.2	10.1	359	<0.5	7	0.93
	26-Aug-03	885	---	480	538	<0.5	5.6	11	1.7	0.008	537	146	27.1	3.2	9.9	656	<0.5	9.1	0.94
	22-Oct-03	905	---	460	513	<0.5	37.2	16.2	1.75	(0.004)	547	143	25.6	2.6	9.1	626	<0.5	3.6	0.93
	10-Feb-04	827	---	480	443	<0.5	67.1	0.09	1.05	(0.003)	524	135	33.7	2.6	9.9	541	<0.5	8.2	0.95
	04-Jun-04	795	---	450	433	<0.5	35.4	11.8	1.49	0.015	495	140	23.6	2.7	14.5	529	<0.5	5	1.06
	25-Aug-04	416	---	220	197	<0.5	17.8	7.74	0.461	0.351	237	65.1	12.9	1.9	8.1	240	<0.5	2.9	1.13
	20-Oct-04	600	---	280	314	<0.5	9.2	6.08	1.01	<0.003	320	88.2	14.5	1.7	6.7	384	<0.5	3.7	0.93
	25-Feb-05	915	---	490	525	<0.5	<0.5	17.9	3.12	(0.003)	536	147	30.5	1.4	15.4	640	<0.5	6.1	1.05
	03-May-05	841	---	430	431	<0.5	12.3	9.18	1.55	0.004	461	128	26.4	5.9	9.7	525	<0.5	9.6	1.03
	15-Aug-05	491	---	260	271	<0.5	5.2	3.18	0.852	0.014	281	82.5	13.7	2.8	5.9	331	<0.5	4.1	1.01
	13-Sep-05	320	---	160	161	<0.5	12.1	1.09	0.183	0.113	178	48.8	9.7	1.8	4.6	197	<0.5	2.6	0.99
	24-Feb-06	572	---	290	289	<0.5	14.1	0.04	0.806	0.005	301	85.2	18.2	1.9	3.9	353	<0.5	3.6	0.97
	16-May-06	661	7.98	330	348	<0.5	21.9	2.61	1.1	0.012	370	102	17.2	2.7	7.3	424	<0.5	6.5	---
	14-Aug-06	386	---	180	189	<0.5	16.1	1.71	0.333	0.166	208	54.6	9.8	1.9	5.7	231	<0.5	3.2	0.92

Table 11

Site C Water Quality: Parameter Concentrations

Monitoring Station	Date (d-m-y)	EC (us/cm)	pH	Tot Hard as $CaCO_3$ (mg/L)	Tot Alk as $CaCO_3$ (mg/L)	PP Alk. as $CaCO_3$ (mg/L)	Sulphate:D (mg/L)	Iron:D (mg/L)	Manganese:D (mg/L)	NO_2+NO_3 as N (mg/L)	TDS-calculated (mg/L)	Calcium:D (mg/L)	Magnesium:D (mg/L)	Potassium:D (mg/L)	Sodium:D (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Chloride:D (mg/L)	Ion Balance (balance)
99-29A	19-Oct-01	918	---	560	496	<0.5	32.9	0.06	0.318	0.123	553	161	37.4	<0.3	17.4	605	<0.5	5.9	1.1
	23-May-02	652	---	350	329	<0.5	32.2	0.03	(0.006)	4.41	393	101	23.3	2.1	11	402	<0.5	6	0.97
	15-Aug-02	919	---	510	512	<0.5	35.6	0.05	0.015	1.86	555	149	33.4	3.1	11.5	624	<0.5	6.3	0.96
	28-Oct-02	594	---	280	286	<0.5	28.2	0.27	0.011	4.42	331	80.7	19.7	1.5	5.7	349	<0.5	3.2	0.88
	13-Feb-03	860	---	510	468	<0.5	40.3	0.07	0.03	0.098	526	150	32.3	1.7	9.9	571	<0.5	11.3	1.01
	29-May-03	685	---	320	326	<0.5	33.6	0.05	(0.007)	1.32	366	92.9	21.6	1.5	8.2	398	<0.5	6.2	0.91
	26-Aug-03	920	---	580	570	<0.5	1.9	0.03	0.377	0.031	568	167	40.3	1.3	6.6	696	<0.5	8.6	1.02
	22-Oct-03	936	---	550	522	<0.5	45.6	<0.01	0.028	0.416	580	160	35.7	1.8	13.9	637	<0.5	8.3	0.99
	10-Feb-04	887	---	530	509	<0.5	42.3	0.03	0.042	0.061	567	158	33.2	1.4	14.8	621	<0.5	12.3	0.99
	04-Jun-04	816	---	460	419	<0.5	38.5	0.03	0.047	5.09	496	136	29.4	2.2	8	511	<0.5	7.9	0.98
	25-Aug-04	625	---	330	295	<0.5	31.5	0.02	0.055	3.29	353	96.6	21.1	1.9	6.9	360	<0.5	3.5	1
	20-Oct-04	624	---	310	299	<0.5	28.7	<0.01	0.018	1.38	340	93.3	19.8	1.3	5.9	365	<0.5	5.1	0.96
	25-Feb-05	903	---	500	456	<0.5	47.6	0.96	0.346	0.022	529	145	32.1	1.4	11	556	<0.5	16	0.99
	03-May-05	754	---	310	365	<0.5	28	2.71	1.1	1.94	401	97.8	16.6	1.8	17.8	445	<0.5	7.3	0.87
	15-Aug-05	588	---	290	309	<0.5	27	0.02	0.005	0.342	332	85.1	18.7	1.5	8.7	377	<0.5	4.2	0.9
	13-Sep-05	440	---	210	225	<0.5	18.8	0.02	0.016	0.667	243	61.6	14.7	1.4	7	274	<0.5	1.7	0.93
	24-Feb-06	846	---	440	428	<0.5	37.7	0.04	0.076	0.149	476	132	27.6	1.2	8.9	522	<0.5	11.1	0.96
	16-May-06	825	8.07	340	432	<0.5	33.6	<0.01	0.12	0.896	440	101	21.7	1.3	9.7	528	<0.5	9.8	---
	07-Aug-06	767	---	390	407	<0.5	26.8	0.02	0.005	0.924	432	116	24.7	1.8	8.6	497	<0.5	5.5	0.93
02-31A	28-Oct-02	987	---	360	544	<0.5	27	0.06	0.628	0.419	573	98.7	27.1	4.2	77.4	664	<0.5	9.4	0.91
	13-Feb-03	990	---	480	546	<0.5	48.1	0.66	1.15	(0.003)	611	136	34.4	1.8	51.5	666	<0.5	9.9	0.98
	29-May-03	969	---	430	487	<0.5	51.4	0.05	1.11	<0.003	597	123	30.6	1.4	45.7	594	<0.5	7.3	0.87
	22-Oct-03	923	---	430	531	<0.5	38.2	1.9	0.843	(0.004)	561	121	30.9	1.5	41.5	648	<0.5	6.6	0.91
	04-Jun-04	907	---	440	523	<0.5	24.3	2.01	0.862	0.029	547	125	32.2	1.4	40.2	639	<0.5	7.4	0.96
	20-Oct-04	1,050	---	440	553	<0.5	37.3	1.78	0.766	(0.004)	595	124	30.7	1.5	59	675	<0.5	7.9	0.94
	03-May-05	976	---	440	521	<0.5	14.3	1.35	0.923	0.011	530	118	34	1.2	39.5	636	<0.5	7.8	0.96
	13-Sep-05	1,010	---	450	573	<0.5	25.9	1.21	0.901	0.008	598	123	33.3	2	58.2	700	<0.5	9.1	0.94
	16-May-06	918	7.93	310	527	<0.5	9.7	1.63	0.732	0.006	469	85.1	22.5	0.8	22.9	642	<0.5	7.4	---

NOTES: *1. --- in detail data row(s) denotes parameter not analyzed.*

Table 12

Site C Water Quality: Dissolved Hydrocarbons

Monitoring Station	Date (d-m-y)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylene-m&p (mg/L)	Xylene-o (mg/L)	Xylenes-total (mg/L)	PHC F_1 (C_6-C_{10}) (mg/L)	PHC F_1 (C_6-C_{10})-BTEX (mg/L)	TPH (C_3-C_{10}) (mg/L)
98-17A	18-Dec-98	0.0022	<0.0009	<0.0009	<0.002	0.0031	(0.0031	---	---	(0.1)
	18-May-99	2.62	2.46	-0.07	0.74	0.28	1.02	---	---	6.5
	02-Jul-99	5.61	2.56	<0.08	0.6	0.32	0.92	---	---	14.2
	29-Jul-99	6.38	5.07	<0.06	1.5	0.83	2.33	---	---	13.9
	31-Aug-99	5.22	3.28	<0.04	1.38	0.91	2.29	---	---	21.6
	19-Oct-99	5.42	0.2	0.07	0.63	0.19	0.82	---	---	6.6
	19-Oct-99	5.68	0.18	0.06	0.59	0.18	0.77	---	---	6.7
	26-Nov-99	3.61	<0.05	<0.05	0.2	<0.05	(0.20	---	---	3.8
	02-Jun-00	3.58	1.13	<0.05	0.9	0.61	1.51	---	---	7.6
	16-Jun-00	3.38	0.65	<0.05	0.9	0.45	1.35	---	---	7.3
	27-Jul-00	3.02	0.43	<0.04	1.31	0.4	1.71	---	---	5.2
	24-Aug-00	2.65	<0.04	<0.04	0.2	<0.04	(0.20	---	---	2.9
	20-Sep-00	2.18	<0.06	<0.06	0.3	<0.06	(0.30	---	---	4.9
	20-Sep-00	1.63	<0.02	<0.02	<0.04	(0.02)	(0.02	---	---	3
	25-Sep-00	2.66	0.31	<0.04	0.97	0.26	1.23	---	---	4.2
	24-Oct-00	1.52	<0.04	<0.04	0.21	0.08	0.29	---	---	4.8
	04-Dec-00	2.54	-0.06	<0.04	(0.14)	0.13	0.27	---	---	5.5
	10-May-01	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	0.2
	06-Jul-01	1.01	0.29	<0.03	4.13	1.66	5.79	---	---	9
	09-Aug-01	0.61	0.04	<0.01	1.59	0.76	2.35	---	---	3.8
	13-Sep-01	0.279	<0.006	<0.006	0.29	0.02	0.31	---	---	1.5
	19-Oct-01	<0.004	<0.004	<0.004	1.37	0.356	1.73	---	---	2.9
	13-May-02	0.29	0.22	0.13	4.27	1.64	5.91	8.2	<6	10.2
	23-May-02	0.18	0.14	0.03	---	---	4.75	---	2	7.1
	20-Jun-02	0.039	0.013	<0.006	0.75	0.476	1.23	---	---	4.1
	16-Jul-02	0.27	<0.01	0.06	---	---	3.07	---	1.5	5.6
	15-Aug-02	0.35	<0.006	0.117	---	---	1.96	---	0.3	3.4
	12-Sep-02	0.059	<0.002	0.018	---	---	0.503	---	0.2	0.9
	28-Oct-02	0.28	<0.02	0.18	---	---	7.42	---	1.4	9.8
	13-Feb-03	0.17	<0.01	0.13	---	---	5	---	1	---
	29-May-03	0.14	(0.012)	<0.009	---	---	2.97	---	2.5	6.1
	26-Aug-03	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	22-Oct-03	0.148	<0.004	0.078	---	---	1.53	---	0.3	2.5
	10-Feb-04	0.108	<0.002	0.046	0.508	0.015	0.523	---	0.3	1.1
	04-Jun-04	0.28	<0.04	0.18	4.02	0.88	4.9	---	<10	6.3
	25-Aug-04	0.36	<0.06	0.22	6.7	0.81	7.5	---	1.5	9.5
	20-Oct-04	0.3	<0.04	0.26	8.48	1.15	9.63	---	4	14.2
	25-Feb-05	0.23	<0.04	-0.05	4.97	0.87	5.84	---	1.8	7.9
	03-May-05	0.2	<0.06	0.24	6.2	0.58	6.7	---	1.9	9.9
	15-Aug-05	0.2	<0.04	0.23	---	---	6.73	---	2.3	---
	13-Sep-05	0.22	<0.06	0.34	---	---	9.3	---	2.6	---
	24-Feb-06	0.11	<0.04	<0.04	---	---	6.2	---	3.4	---
	15-May-06	0.18	<0.01	0.06	---	---	4.23	---	4.2	---
	14-Aug-06	0.25	<0.04	0.16	---	---	4.93	---	0.4	---
98-18A	18-Dec-98	<0.0009	<0.0009	<0.0009	<0.002	<0.0009	<0.0029	---	---	<0.1
	18-May-99	0.067	0.049	<0.004	<0.007	<0.004	<0.011	---	---	0.8
	02-Jul-99	1.2	2.4	-0.03	0.42	0.17	0.59	---	---	9.2
	29-Jul-99	0.266	0.0272	0.0009	0.0931	0.0376	0.131	---	---	1.4
	31-Aug-99	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	19-Oct-99	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	26-Nov-99	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	02-Jun-00	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	16-Jun-00	<0.0009	<0.0009	<0.0009	<0.002	<0.0009	<0.0029	---	---	<0.1
	27-Jul-00	0.42	<0.02	<0.02	<0.04	0.07	(0.070	---	---	0.5
	24-Aug-00	0.464	<0.009	<0.009	0.05	<0.009	(0.050	---	---	0.6
	20-Sep-00	0.481	<0.006	<0.006	0.03	<0.006	(0.030	---	---	0.8
	25-Sep-00	0.302	<0.009	<0.009	0.06	<0.009	(0.060	---	---	0.5
	24-Oct-00	0.359	<0.006	<0.006	<0.01	<0.006	<0.016	---	---	1
	04-Dec-00	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	10-May-01	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	06-Jul-01	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	09-Aug-01	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	13-Sep-01	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	19-Oct-01	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	23-May-02	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	15-Aug-02	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	28-Oct-02	0.0098	<0.0009	<0.0009	---	---	<0.002	---	<0.1	<0.1
	13-Feb-03	0.0008	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	29-May-03	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	26-Aug-03	0.0008	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	22-Oct-03	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1

Table 12

Site C Water Quality: Dissolved Hydrocarbons

Monitoring Station	Date (d-m-y)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylene-m&p (mg/L)	Xylene-o (mg/L)	Xylenes-total (mg/L)	PHC F_1 (C_6-C_{10}) (mg/L)	PHC F_1 (C_6-C_{10})-BTEX (mg/L)	TPH (C_3-C_{10}) (mg/L)
	10-Feb-04	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	<0.1	<0.1
	04-Jun-04	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	<0.1	<0.1
	25-Aug-04	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0008	---	<0.1	<0.1
	20-Oct-04	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0008	---	<0.1	<0.1
	25-Feb-05	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	<0.1	<0.1
	03-May-05	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0008	---	<0.1	<0.1
	15-Aug-05	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	13-Sep-05	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	24-Feb-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	16-May-06	0.0015	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	14-Aug-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
98-19A	18-Dec-98	21	47	1.7	21	7.3	28.3	---	---	125
	18-May-99	11.4	22.6	0.9	13.7	4	17.7	---	---	52.5
	02-Jul-99	18.3	35.3	0.8	15.3	4.8	20.1	---	---	118
	29-Jul-99	12.9	24.9	<2	14.1	5	19.1	---	---	73
	31-Aug-99	15.8	34.5	1.4	19.8	6.5	26.3	---	---	175
	19-Oct-99	12.4	37.7	1	24.7	8.2	32.9	---	---	97.4
	02-Jun-00	4.8	18.4	1.1	15.4	5.2	20.6	---	---	65.7
	27-Jul-00	2.41	7.45	0.84	15.1	4.84	19.9	---	---	30.6
	24-Aug-00	2.7	5.8	1.1	18.9	5.5	24.4	---	---	72.8
	20-Sep-00	2.6	4.8	<0.4	14.9	4.7	19.6	---	---	66
	25-Sep-00	4.4	9.1	0.8	13.1	4.3	17.4	---	---	67.6
	24-Oct-00	4.15	5.15	0.71	15	3.97	19	---	---	51.5
	04-Dec-00	3.3	3.3	<0.9	12.3	3.9	16.2	---	---	56.4
	10-May-01	1.43	5.24	0.31	11.2	3.13	14.3	---	---	35.4
	06-Jul-01	1.12	3.26	0.5	9.81	2.99	12.8	---	---	32.4
	09-Aug-01	0.71	2.76	0.33	10.7	3.45	14.2	---	---	18
	13-Sep-01	1.12	3.95	0.23	13.8	4.4	18.2	---	---	128
	19-Oct-01	2.12	7.1	0.18	18.9	5.61	24.5	---	---	53.4
	13-May-02	0.33	2.16	0.27	12	3.37	15.4	42.4	24	54
	23-May-02	0.54	2.05	0.21	---	---	12.5	---	10.6	28.7
	20-Jun-02	0.27	0.14	<0.04	6.49	1.95	8.44	---	---	42.6
	16-Jul-02	0.48	2.16	0.15	---	---	14.9	---	11.1	33.2
	15-Aug-02	0.3	1.28	0.45	---	---	11.8	---	5	20.3
	12-Sep-02	0.33	1	0.47	---	---	11.4	---	18.2	33.9
	28-Oct-02	0.17	0.1	0.21	---	---	4.02	---	4.3	9.6
	28-Oct-02	0.2	0.12	0.23	---	---	4.89	---	6	12.4
	13-Feb-03	0.274	0.008	0.164	---	---	2.11	---	2.8	---
	29-May-03	0.15	<0.04	0.53	---	---	9.2	---	7.6	20.1
	29-May-03	0.18	<0.04	0.51	---	---	9.66	---	4.5	16.7
	26-Aug-03	0.27	<0.03	0.29	---	---	5.34	---	<7	10.1
	26-Aug-03	0.29	<0.01	0.34	---	---	5.33	---	3.3	10.5
	22-Oct-03	0.186	<0.004	0.168	---	---	2.84	---	2.3	6.7
	22-Oct-03	0.219	<0.004	0.217	---	---	3.59	---	2.9	8.3
	04-Jun-04	0.212	<0.008	0.352	4.96	1.05	6.01	---	1	7.9
	04-Jun-04	0.212	<0.008	0.347	4.91	1.04	5.95	---	0.8	7.7
	25-Aug-04	0.37	<0.06	0.32	6	0.28	6.3	---	2.3	9.3
	25-Aug-04	0.39	<0.04	0.33	5.84	0.24	6.08	---	2	8.8
	20-Oct-04	0.19	<0.02	0.3	6.02	0.11	6.13	---	3.2	9.8
	20-Oct-04	0.19	<0.02	0.28	---	---	5.97	---	2.3	8.9
	25-Feb-05	0.2	<0.04	0.26	3.87	<0.04	(3.87	---	1.3	5.7
	25-Feb-05	0.19	<0.04	0.22	3.57	<0.04	(3.57	---	1.5	5.5
	03-May-05	0.23	<0.06	0.42	7.4	0.31	7.71	---	2.3	11.7
	03-May-05	0.18	<0.06	0.38	6.1	0.26	7.6	---	<0.4	8.1
	15-Aug-05	0.2	<0.02	0.32	---	---	6.76	---	2.5	---
	15-Aug-05	0.18	<0.02	0.21	---	---	4.33	---	1	---
	13-Sep-05	0.193	<0.009	0.389	---	---	6.47	---	2	---
	13-Sep-05	0.194	<0.009	0.385	---	---	6.54	---	2	---
	24-Feb-06	0.19	<0.04	<0.04	---	---	5.02	---	2.6	---
	24-Feb-06	0.2	<0.04	<0.04	---	---	4.8	---	2.7	---
	16-May-06	0.15	<0.01	0.1	---	---	3.81	---	3.2	---
	16-May-06	0.16	0.01	0.24	---	---	4.24	---	6.5	---
	14-Aug-06	0.19	<0.04	0.27	---	---	5.76	---	0.3	---
	14-Aug-06	0.16	<0.04	0.26	---	---	5.17	---	<0.3	---

Table 12

Site C Water Quality: Dissolved Hydrocarbons

Monitoring Station	Date (d-m-y)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylene-m&p (mg/L)	Xylene-o (mg/L)	Xylenes-total (mg/L)	PHC F$_1$ (C$_6$-C$_{10}$) (mg/L)	PHC F$_1$ (C$_6$-C$_{10}$)-BTEX (mg/L)	TPH (C$_3$-C$_{10}$) (mg/L)
99-20A	02-Jul-99	14.9	23.9	-0.5	10.2	3.2	13.4	---	---	76.7
	29-Jul-99	11.1	11	0.5	8.3	2.7	11	---	---	38.6
	31-Aug-99	9.62	5.66	0.27	7.9	2.22	10.1	---	---	55.1
	19-Oct-99	8.27	1.08	0.23	4.9	1.46	6.36	---	---	15.9
	26-Nov-99	8.6	0.2	0.4	5.8	1	6.8	---	---	16.6
	09-May-00	3.77	-0.05	0.52	4.92	1	5.92	---	---	15.2
	16-Jun-00	2.07	<0.04	0.19	2.05	0.33	2.38	---	---	6.6
	27-Jul-00	2.25	0.46	0.31	3.35	0.53	3.88	---	---	6.9
	24-Aug-00	0.698	<0.009	<0.009	0.05	(0.013)	0.063	---	---	0.8
	20-Sep-00	1.39	0.02	0.05	0.99	0.05	1.04	---	---	5.6
	25-Sep-00	2.71	0.08	0.26	2.38	0.38	2.76	---	---	8.4
	24-Oct-00	2.14	<0.03	0.15	2.26	0.33	2.59	---	---	4.9
	04-Dec-00	3.85	<0.07	-0.12	2.1	0.38	2.48	---	---	9.4
	13-Jun-01	0.24	<0.02	<0.02	1.48	0.22	1.7	---	---	1.9
	06-Jul-01	1.16	0.12	-0.02	2.94	0.57	3.51	---	---	6
	09-Aug-01	0.85	0.11	0.15	2.57	0.5	3.07	---	---	5.9
	13-Sep-01	0.66	0.13	0.1	3.76	0.87	4.63	---	---	8.3
	19-Oct-01	0.199	<0.007	<0.007	2.93	0.439	3.37	---	---	5.7
	23-May-02	0.12	0.02	<0.01	---	---	3.24	---	1.8	5.7
	15-Aug-02	0.15	(0.02)	0.12	---	---	2.01	---	0.4	3.4
	28-Oct-02	0.23	<0.02	0.14	---	---	3.04	---	0.8	4.6
	13-Feb-03	0.12	<0.002	0.094	---	---	1.06	---	0.4	---
	29-May-03	0.118	0.026	0.131	---	---	2.99	---	2.7	6.9
	26-Aug-03	0.077	(0.010)	0.064	---	---	1.69	---	0.4	2.6
	22-Oct-03	0.058	(0.004)	0.071	---	---	1.22	---	0.3	1.9
	10-Feb-04	0.109	<0.0009	0.115	1.34	0.009	1.35	---	0.5	2.4
	04-Jun-04	0.072	<0.004	0.098	1.46	0.05	1.51	---	0.4	2.1
	25-Aug-04	0.121	<0.006	0.137	2.17	0.025	2.2	---	0.4	2.9
	20-Oct-04	0.11	<0.02	0.16	2.43	0.04	2.47	---	1.4	4.1
	25-Feb-05	0.061	<0.004	0.115	1.34	0.024	1.36	---	0.7	2.4
	03-May-05	0.069	<0.002	0.192	1.51	0.005	1.51	---	2.8	5.2
	15-Aug-05	0.065	<0.006	0.221	---	---	3.17	---	1.2	---
	13-Sep-05	0.054	<0.006	0.17	---	---	2.14	---	0.9	---
	24-Feb-06	0.006	<0.004	<0.004	---	---	0.609	---	0.6	---
	16-May-06	0.063	0.014	0.143	---	---	2.27	---	2.3	---
	14-Aug-06	0.09	<0.02	0.2	---	---	2.95	---	0.5	---
99-21A	02-Jul-99	14.7	37.4	-0.6	15.7	4.6	20.3	---	---	98.8
	29-Jul-99	14.4	35.7	0.8	15.9	5.7	21.6	---	---	78.5
	31-Aug-99	16.2	38.4	-0.8	19	6.3	25.3	---	---	80.6
	19-Oct-99	5.49	9.17	<0.07	15.4	6.81	22.2	---	---	38
	09-May-00	0.15	0.22	<0.04	4.23	3.82	8.05	---	---	12
	16-Jun-00	0.15	0.22	<0.02	1.78	1.32	3.1	---	---	5
	27-Jul-00	<0.02	0.09	<0.02	2.36	1.28	3.64	---	---	3.7
	24-Aug-00	0.084	0.005	<0.002	0.801	0.673	1.47	---	---	2.6
	25-Sep-00	0.013	0.022	<0.001	0.193	0.107	0.3	---	---	1.1
	24-Oct-00	0.12	0.08	<0.03	2.98	1.66	4.64	---	---	7.7
	04-Dec-00	0.61	0.14	<0.04	2.23	1.47	3.7	---	---	5.8
	10-May-01	0.019	<0.004	<0.004	0.293	0.168	0.461	---	---	1.5
	06-Jul-01	0.83	1.63	<0.04	5.92	2.21	8.13	---	---	14.7
	09-Aug-01	1.36	1.99	0.14	9.08	3.91	13	---	---	19.3
	13-Sep-01	1.21	1.45	<0.06	11.8	4.55	16.4	---	---	27.1
	19-Oct-01	0.055	<0.003	<0.003	2.24	0.943	3.18	---	---	5
	13-May-02	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0008	0.012	<0.1	(0.1)
	23-May-02	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	16-Jul-02	0.096	0.104	<0.009	---	---	2.41	---	1.6	4.5
	15-Aug-02	0.25	0.39	0.13	---	---	3.4	---	0.7	5.5
	12-Sep-02	0.064	(0.004)	0.037	---	---	0.787	---	0.5	1.6
	28-Oct-02	0.09	0.082	0.09	---	---	2.51	---	0.8	3.8
	13-Feb-03	0.211	(0.002)	0.23	---	---	1.88	---	0.5	---
	29-May-03	0.003	0.0009	0.0018	---	---	0.0715	---	(0.1)	0.3
	26-Aug-03	0.0294	(0.0006)	0.0151	---	---	0.102	---	<0.1	0.2
	22-Oct-03	0.028	<0.001	0.026	---	---	0.356	---	(0.1)	0.6
	04-Jun-04	0.0048	<0.0004	0.0033	0.0364	0.0192	0.0556	---	<0.1	<0.1
	25-Aug-04	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0008	---	<0.1	<0.1
	20-Oct-04	0.0029	<0.0004	0.0015	0.026	0.0034	0.0295	---	<0.1	<0.1
	25-Feb-05	0.0008	<0.0004	<0.0004	0.0016	<0.0004	(0.0016	---	<0.1	<0.1
	03-May-05	0.002	0.0007	<0.0004	0.0036	0.001	0.0044	---	<0.1	<0.1
	15-Aug-05	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	13-Sep-05	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	24-Feb-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	16-May-06	0.0023	<0.0004	<0.0004	---	---	0.0008	---	<0.1	---

Table 12

Site C Water Quality: Dissolved Hydrocarbons

Monitoring Station	Date (d-m-y)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylene-m&p (mg/L)	Xylene-o (mg/L)	Xylenes-total (mg/L)	PHC F_1 (C_6-C_{10}) (mg/L)	PHC F_1 (C_6-C_{10})-BTEX (mg/L)	TPH (C_3-C_{10}) (mg/L)
	14-Aug-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
99-22A	02-Jul-99	0.47	0.66	<0.02	1.36	0.87	2.23	---	---	4.4
	29-Jul-99	1.52	8.04	0.31	8.3	3.67	12	---	---	24.9
	31-Aug-99	3.8	10.4	<0.3	8.5	3.6	12.1	---	---	57.9
	19-Oct-99	5.6	19.2	0.4	17.1	6.4	23.5	---	---	48.7
	27-Jul-00	-0.02	0.13	<0.02	2.07	1.15	3.22	---	---	6.8
99-23A	02-Jun-00	1.9	17.5	2.2	36.9	14.6	51.5	---	---	92.3
	02-Jun-00	1.6	14.4	1.8	29.7	11.8	41.5	---	---	75.9
	20-Sep-00	3.7	18.2	-0.7	15.5	5.8	21.3	---	---	76.5
	10-May-01	1.3	9.6	<0.4	22.5	8.2	30.7	---	---	77.7
	19-Oct-01	4.6	12.8	-0.3	19	6.7	25.7	---	---	72.7
	23-May-02	0.55	4.1	<0.06	---	---	17.2	---	10.8	32.6
	15-Aug-02	1.09	4.15	0.32	---	---	15.7	---	4.2	25.9
	12-Sep-02	3.8	8.89	0.27	---	---	8.95	---	6.8	30
	28-Oct-02	0.61	2.12	0.13	---	---	4.88	---	2.2	10.5
	20-Dec-02	2.96	10.4	0.7	---	---	16	---	5.3	---
	13-Feb-03	5.7	20.9	1.11	---	---	20.5	---	1.7	---
	29-May-03	0.309	0.958	0.132	---	---	4.55	---	5	12.1
	26-Aug-03	1.26	1.92	0.118	---	---	2.97	---	0.7	7.2
	22-Oct-03	1.44	1.43	0.089	---	---	2.68	---	0.6	6.8
	10-Feb-04	4.5	10.8	-0.5	9.8	2.4	12.2	---	5	34.1
	04-Jun-04	0.288	0.961	0.094	1.97	0.52	2.49	---	0.2	4.1
	25-Aug-04	0.146	0.142	0.047	0.93	0.178	1.11	---	2.3	3.7
	20-Oct-04	0.072	0.129	0.036	0.808	0.14	0.948	---	1.4	2.6
	25-Feb-05	0.702	1.51	0.083	1.63	0.453	2.08	---	3.1	7.6
	03-May-05	0.0146	0.0074	0.0057	0.0836	0.0127	0.0961	---	0.3	0.6
	15-Aug-05	0.0539	0.0361	0.0171	---	---	0.297	---	0.5	---
	13-Sep-05	0.0647	0.0396	0.0156	---	---	0.223	---	0.4	---
	24-Feb-06	0.741	1.19	<0.006	---	---	1.98	---	0.9	---
	16-May-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	0.2	---
	14-Aug-06	0.067	0.04	0.024	---	---	0.282	---	0.5	---
99-24A	09-May-00	5.28	10.8	-0.11	4.1	1.82	5.92	---	---	23.8
	20-Sep-00	5.08	7.8	0.18	4.4	1.81	6.21	---	---	25.2
	24-Oct-00	4.9	3.9	0.2	4	1	5	---	---	17.9
	13-Jun-01	1.65	3.6	<0.04	5.77	2.91	8.68	---	---	13.9
	19-Oct-01	0.18	(0.01)	<0.01	0.29	0.29	0.58	---	---	1.7
	23-May-02	0.82	1.33	<0.03	---	---	5.17	---	1.6	8.9
	15-Aug-02	0.34	0.16	0.04	---	---	2.33	---	0.3	3.4
	28-Oct-02	0.352	0.044	0.035	---	---	1.62	---	0.4	2.6
	13-Feb-03	0.372	0.005	0.091	---	---	0.979	---	0.5	---
	29-May-03	0.354	0.028	0.08	---	---	1.6	---	1.4	3.9
	26-Aug-03	0.454	0.057	2.22	---	---	2.45	---	<0.1	3.8
	22-Oct-03	0.262	0.007	0.042	---	---	0.916	---	0.4	1.8
	10-Feb-04	0.187	0.017	0.059	0.737	0.052	0.789	---	0.6	2
	04-Jun-04	0.0954	0.0038	0.0267	0.351	0.122	0.473	---	<0.1	0.7
	25-Aug-04	0.104	(0.0007)	0.0162	0.184	0.0231	0.207	---	(0.1)	0.5
	20-Oct-04	0.0754	<0.0004	0.0182	0.173	0.0036	0.177	---	<0.1	0.4
	25-Feb-05	0.0631	0.0027	0.0294	0.112	0.0017	0.114	---	<0.1	0.2
	03-May-05	0.0209	0.0008	0.0081	0.0238	<0.0004	0.0237	---	<0.1	0.1
	15-Aug-05	0.0385	<0.0004	0.0072	---	---	0.0204	---	<0.1	---
	13-Sep-05	0.0259	0.0005	0.0072	---	---	0.0173	---	<0.1	---
	24-Feb-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	16-May-06	0.0068	<0.0004	0.0016	---	---	0.008	---	<0.1	---
	14-Aug-06	0.0099	<0.0004	0.0007	---	---	0.0019	---	<0.1	---
99-25A	09-May-00	3.42	7.56	0.22	3.5	1.16	4.66	---	---	15.9
	20-Sep-00	4.67	6.93	<0.09	5.8	1.89	7.69	---	---	20.3
	24-Oct-00	3.9	4.4	<0.1	5.2	1.4	6.6	---	---	19.2
	13-Jun-01	3.41	2.65	<0.04	9.37	2.37	11.7	---	---	17.8
	19-Oct-01	0.98	0.23	<0.01	1.31	0.54	1.85	---	---	5.8
	23-May-02	1.38	1.53	<0.03	---	---	5.58	---	2.3	10.8
	15-Aug-02	0.73	0.13	0.04	---	---	1.76	---	0.6	3.9
	28-Oct-02	0.589	0.138	0.036	---	---	2.5	---	0.4	3.9
	13-Feb-03	0.663	(0.007)	0.059	---	---	1.26	---	0.7	---
	29-May-03	1.01	0.18	0.1	---	---	3.26	---	1.7	11.4
	26-Aug-03	0.956	0.108	2.71	---	---	2.86	---	<0.1	5.3
	22-Oct-03	0.298	0.013	0.037	---	---	0.839	---	0.4	1.7
	10-Feb-04	0.095	(0.003)	0.033	0.422	0.019	0.441	---	0.4	1.1
	10-Feb-04	0.106	0.037	0.005	0.514	0.029	0.543	---	0.4	1.3
	04-Jun-04	0.0917	0.0107	0.0224	0.39	0.0815	0.472	---	<0.1	0.7

Table 12

Site C Water Quality: Dissolved Hydrocarbons

Monitoring Station	Date (d-m-y)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylene-m&p (mg/L)	Xylene-o (mg/L)	Xylenes-total (mg/L)	PHC F_1 (C_6-C_{10}) (mg/L)	PHC F_1 (C_6-C_{10})-BTEX (mg/L)	TPH (C_3-C_{10}) (mg/L)
	25-Aug-04	0.136	(0.0004)	0.0186	0.172	0.006	0.178	---	0.3	0.7
	20-Oct-04	0.0818	(0.0005)	0.0141	0.173	0.0367	0.21	---	0.7	1
	25-Feb-05	0.0586	<0.0009	0.0151	0.316	0.037	0.353	---	0.2	0.7
	03-May-05	0.0112	<0.0004	0.0035	0.209	0.0247	0.234	---	0.5	0.8
	15-Aug-05	0.0204	<0.0004	0.0032	---	---	0.0584	---	<0.1	---
	13-Sep-05	0.0184	0.0006	0.0034	---	---	0.108	---	0.2	---
	24-Feb-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	16-May-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	14-Aug-06	0.0029	<0.0004	0.0007	---	---	0.0162	---	<0.1	---
99-26A	02-Jun-00	1.4	12.5	1.5	25.8	10.6	36.4	---	---	57
	20-Sep-00	0.92	1.57	<0.06	5.2	2.59	7.79	---	---	17.2
	24-Oct-00	1.76	3.42	-0.07	8.64	3.75	12.4	---	---	21.7
	10-May-01	0.5	0.3	<0.1	9.9	5	14.9	---	---	25.5
	19-Oct-01	0.162	<0.009	<0.009	4.49	0.166	4.66	---	---	6.4
	19-Oct-01	1.79	0.59	<0.02	2.52	0.42	2.94	---	---	10.7
	23-May-02	0.11	<0.009	<0.009	---	---	2.82	---	(2)	5.3
	15-Aug-02	0.33	0.03	0.02	---	---	2.56	---	0.8	3.8
	12-Sep-02	0.135	0.022	0.016	---	---	0.266	---	0.7	1.4
	28-Oct-02	0.0164	0.0162	(0.0009)	---	---	0.076	---	<0.1	(0.1)
	13-Feb-03	0.85	1.3	0.13	---	---	2.81	---	0.4	---
	29-May-03	0.123	0.01	0.018	---	---	1.46	---	0.9	2.5
	26-Aug-03	0.303	0.058	0.016	---	---	1.04	---	0.8	2.3
	22-Oct-03	0.207	0.0165	0.0129	---	---	0.203	---	0.3	0.9
	10-Feb-04	0.271	<0.004	1.18	0.929	0.033	0.962	---	<0.1	1.9
	04-Jun-04	0.267	0.0822	0.0087	0.404	0.219	0.623	---	<0.1	0.9
	25-Aug-04	0.0953	0.0013	0.0082	0.298	0.0711	0.369	---	0.2	0.6
	20-Oct-04	0.071	(0.002)	0.009	0.479	0.097	0.576	---	0.3	1
	25-Feb-05	0.155	0.005	0.015	0.612	0.126	0.738	---	0.7	1.6
	03-May-05	0.0274	0.001	0.0082	0.245	0.0714	0.316	---	0.8	1.2
	15-Aug-05	0.0484	0.0032	0.0107	---	---	0.44	---	0.6	---
	13-Sep-05	0.0352	0.0025	0.0071	---	---	0.241	---	0.3	---
	24-Feb-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	16-May-06	0.075	<0.001	<0.001	---	---	0.533	---	1	---
	14-Aug-06	0.057	0.006	0.008	---	---	0.29	---	<0.1	---
99-27A	09-May-00	10.4	27.1	1	19.3	6.1	25.4	---	---	63.9
	10-May-01	3.61	16.4	-0.14	19.7	6.45	26.2	---	---	49.8
	19-Oct-01	2.94	6.17	<0.06	10.6	3.35	14	---	---	39.9
	13-May-02	2.44	9.68	0.23	11.4	3.3	14.7	36	<20	38.7
	23-May-02	6.6	16.3	-0.3	---	---	16.5	---	2	42.3
	20-Jun-02	2.85	5.87	<0.06	6.9	2.29	9.19	---	---	55.3
	16-Jul-02	1.42	2.73	<0.04	---	---	6.02	---	2.4	12.5
	15-Aug-02	1.2	3.34	0.09	---	---	4.17	---	<0.1	8.8
	12-Sep-02	1.93	4.55	0.21	---	---	6.88	---	2.6	16.5
	28-Oct-02	1.73	3.02	0.14	---	---	4.55	---	1.5	11.4
	13-Feb-03	4.69	10.2	0.36	---	---	9.1	---	<0.5	---
	29-May-03	1.31	3.09	0.22	---	---	4.45	---	1.3	10.7
	26-Aug-03	3.15	6.6	0.32	---	---	6.66	---	0.2	17.3
	22-Oct-03	3.4	8.8	0.3	---	---	6.8	---	<0.6	20.4
	10-Feb-04	2.9	7.4	<0.4	7.3	1.3	8.6	---	4	23.9
	04-Jun-04	0.3	0.235	0.017	1.61	0.294	1.9	---	<0.1	2.3
	25-Aug-04	0.28	0.65	0.093	1.57	0.16	1.73	---	0.4	3.2
	20-Oct-04	0.39	0.1	0.14	2.07	0.21	2.28	---	1	3.9
	25-Feb-05	0.127	0.0032	0.0122	0.134	0.0159	0.15	---	0.3	0.6
	03-May-05	1.02	2.32	0.22	4.04	0.73	4.75	---	0.5	9.4
	15-Aug-05	0.293	0.232	0.077	---	---	1.4	---	0.4	---
	13-Sep-05	0.552	0.361	0.177	---	---	2.58	---	0.5	---
	24-Feb-06	1.28	1.49	<0.04	---	---	5.67	---	1.7	---
	15-May-06	0.783	1.66	0.017	---	---	5.9	---	3.4	---
	14-Aug-06	0.64	0.61	0.21	---	---	4	---	<0.1	---
99-28A	09-May-00	1.8	8.4	0.5	11.3	4.2	15.5	---	---	29.8
	09-May-00	2.3	10.8	0.6	12.8	4.6	17.4	---	---	35.7
	10-May-01	0.97	1.28	<0.02	2.2	0.65	2.85	---	---	7.9
	19-Oct-01	0.216	<0.009	<0.009	2.15	0.387	2.54	---	---	4.7
	23-May-02	0.28	0.505	<0.006	---	---	0.66	---	0.9	2.7
	20-Jun-02	<0.0009	(0.0014)	<0.0009	<0.002	<0.0009	<0.0029	---	---	0.2
	16-Jul-02	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	15-Aug-02	0.0019	0.002	0.0011	---	---	0.0591	---	0.2	0.3
	12-Sep-02	0.029	0.026	0.029	---	---	0.864	---	0.7	1.8
	28-Oct-02	0.0322	0.0144	0.0123	---	---	0.322	---	0.2	0.6
	20-Dec-02	0.222	0.075	0.078	---	---	<4	---	<0.1	---

Table 12

Site C Water Quality: Dissolved Hydrocarbons

Monitoring Station	Date (d-m-y)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylene-m&p (mg/L)	Xylene-o (mg/L)	Xylenes-total (mg/L)	PHC F_1 (C_6-C_{10}) (mg/L)	PHC F_1 (C_6-C_{10})-BTEX (mg/L)	TPH (C_3-C_{10}) (mg/L)
	13-Feb-03	0.167	0.019	0.065	---	---	0.864	---	0.6	---
	29-May-03	0.288	0.448	0.011	---	---	0.315	---	0.3	1.6
	26-Aug-03	0.346	0.11	0.009	---	---	0.209	---	(0.1)	0.9
	22-Oct-03	0.416	0.068	0.02	---	---	1.67	---	0.3	2.6
	10-Feb-04	0.312	0.02	0.043	0.444	0.051	0.495	---	0.9	2
	04-Jun-04	0.172	0.034	0.0035	0.064	0.0246	0.0886	---	<0.1	0.2
	25-Aug-04	0.0237	0.0042	0.0015	0.0256	0.0048	0.0304	---	<0.1	(0.1)
	20-Oct-04	0.139	0.004	0.003	0.029	0.0065	0.036	---	<0.1	0.3
	25-Feb-05	1.9	3.59	0.21	4.4	0.8	5.2	---	0.7	11.9
	03-May-05	0.266	0.119	<0.002	0.043	0.043	0.085	---	<0.1	0.5
	15-Aug-05	0.0954	0.0018	0.006	---	---	0.06	---	0.1	---
	13-Sep-05	0.0086	0.0006	0.0025	---	---	0.0286	---	<0.1	---
	24-Feb-06	0.0798	0.0085	0.0159	---	---	0.174	---	0.5	---
	16-May-06	0.31	<0.001	<0.001	---	---	0.123	---	0.1	---
	14-Aug-06	0.0113	<0.0004	0.0012	---	---	0.0083	---	<0.1	---
99-29A	09-May-00	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	24-Oct-00	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	13-Jun-01	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	13-Jun-01	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	19-Oct-01	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	---	<0.1
	23-May-02	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	15-Aug-02	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	28-Oct-02	<0.0009	<0.0009	<0.0009	---	---	<0.002	---	<0.1	<0.1
	13-Feb-03	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	29-May-03	0.0096	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	26-Aug-03	0.252	<0.006	0.121	---	---	1.95	---	0.8	3.5
	22-Oct-03	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	<0.1
	10-Feb-04	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	<0.1	<0.1
	04-Jun-04	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	<0.1	<0.1
	25-Aug-04	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0008	---	<0.1	<0.1
	20-Oct-04	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0008	---	<0.1	<0.1
	25-Feb-05	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0012	---	<0.1	<0.1
	03-May-05	<0.0004	<0.0004	<0.0004	<0.0008	<0.0004	<0.0008	---	<0.1	<0.1
	15-Aug-05	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	13-Sep-05	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	24-Feb-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	16-May-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
	07-Aug-06	<0.0004	<0.0004	<0.0004	---	---	<0.0008	---	<0.1	---
02-31A	28-Oct-02	0.78	0.364	0.067	---	---	1.15	---	(0.1)	2.8
	13-Feb-03	0.216	<0.002	0.013	---	---	0.029	---	<0.1	---
	29-May-03	0.377	0.031	0.076	---	---	0.527	---	0.4	1.9
	22-Oct-03	0.214	(0.0009)	0.009	---	---	0.049	---	<0.1	0.3
	04-Jun-04	0.255	0.028	0.0427	0.272	0.055	0.327	---	<0.1	0.6
	20-Oct-04	0.113	(0.0007)	0.0079	0.054	0.005	0.0589	---	<0.1	0.2
	03-May-05	0.192	0.008	0.0325	0.315	0.0515	0.366	---	0.2	1
	13-Sep-05	0.0952	<0.0004	0.005	---	---	0.0318	---	<0.1	---
	16-May-06	0.197	0.005	0.032	---	---	0.519	---	0.4	---

NOTES: *1. --- in detail data row(s) denotes parameter not analyzed.*