REPORT ON:

Fractured Bedrock Field Methods and Analytical Tools

Volume I : Main Report

Submitted to:
The Ministry of Environment
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Submitted by:
Science Advisory Board
For Contaminated Sites in British Columbia

Prepared under contract by
Golder Associates Ltd.
Burnaby, British Columbia

Acknowledgements

The report herein on *Fractured Bedrock Field Methods and Analytical Tools* with a second volume of Appendices is presented for the information and benefit of the Contaminated Sites community in British Columbia. It is hoped that it will be of interest to practitioners in other jurisdictions as well.

The work was supervised by the SABCS through a Task Force chaired by Dr. Jean Cho. Golder Associates Ltd. were contracted to prepare the report and appendices. The Task Force was comprised of SABCS members Dr. J. Leslie Smith of the University of British Columbia, Steve Wilbur of Jacques Whitford, and chaired by Dr. Cho. Lavinia Zanini was the BC Ministry of Environment representative on the Task Force. Dr. Thomas Doe was the principal author, and the SABCS appreciates benefitting from his widely recognized expertise in the field. Special recognition is given to Dr. Ian Hers for his tireless efforts in bringing the work to completion.

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Science Advisory Board for Contaminated Sites in British Columbia
April 2010.

Disclaimer

Practitioners and others with interests in contaminated sites should be aware that this report including the appendices has not been adopted in whole or in part by the Ministry of Environment of British Columbia. While every effort has been made to incorporate the best available science, it should be used solely as scientific review and commentary by the reader and applied in practice solely at the readers discretion and responsibility. This disclaimer is consistent with SABCS Policy. See also the disclaimer included in the main report (which also applies to the appendices) that is endorsed by the SABCS

Use of this Material

Request for Comments

The Science Advisory Board for Contaminated Sites in British Columbia is soliciting comment on the documents, which together constitute a report to the BC Ministry of Environment on recommendations for the development of guidance on Fractured Bedrock for practitioners in British Columbia. Comments will be reviewed and compiled by the SABCS, and will be much appreciated.

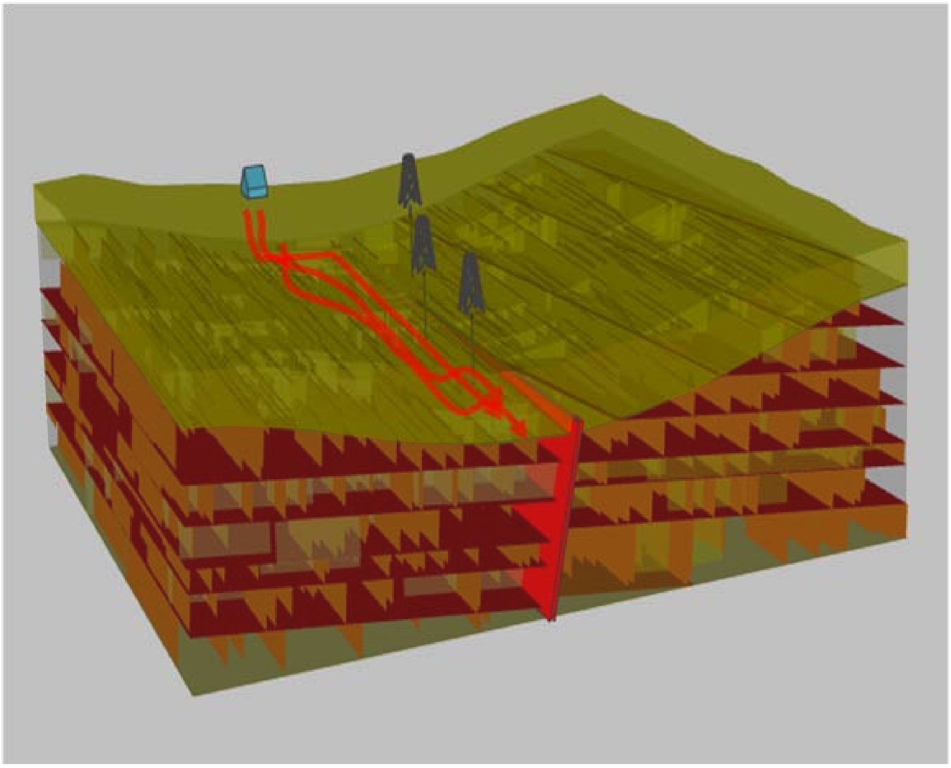
Please send your comments to the Science Advisory Board for contaminated Sites by email or email attachment to pwest@uvic.ca. Comments received by June 30, 2010 will be most useful in further refinement of this work. However, comments at any time on SABCS work are always appreciated.

Paul West, President
Science Advisory Board for Contaminated Sites in British Columbia

REPORT

FRACTURED BEDROCK FIELD METHODS AND ANALYTICAL TOOLS

Main Report



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Executive Summary

This report presents guidance for assessment of groundwater flow and contaminant transport in fractured bedrock.

Standard hydrogeologic assessment methods are designed for porous media, such as unconsolidated sediments and soils, and may be inappropriate for fractured bedrock. Porous media theory rests on assumptions of homogeneity, isotropy, and continuity. Fractures confine flow to a network that may introduce high degrees of discontinuity, anisotropy, and heterogeneity to a hydrogeologic system. Associated with contaminant transport in fractured porous media are additional concerns with the retardation and storage created by matrix diffusion. Flow involving immiscible, non-aqueous phase liquids creates further complexity with capillary and gravity forces.

The major sections of this guidance are the following:

- A description of the characteristics that indicate fracture-controlled flow with the goal of identifying bedrock sites where fracture-based protocols may be needed.
- A description of site characterisation methods and how they should be used in a staged program of site assessment.
- Appendices with background material on the basics of fracture flow with further discussion of characterisation methodologies and numerical simulation approaches.

Fractures are likely to be the main controls on flow in any rock that has low porosity and deforms in a brittle manner. These include most metamorphic and igneous rocks (excluding pyroclastics) as well as sedimentary rocks that are well-cemented or consolidated. Although weathering and high fracture intensities can create porous-like conditions for flow, some key observations that indicate that fractures control groundwater flow are:

- The contrast of hydraulic conductivity values between laboratory tests and field tests;
- The variability of hydraulic conductivity values between wells;
- Anisotropic behaviours;
- Anomalous connectivity; and
- Rapid propagation of head disturbances and fast transport of solutes.

Fractured-bedrock characterisation methods have advanced considerably in the past thirty years stimulated by research efforts from radioactive waste, petroleum development, and contaminant hydrogeology. Recognition that a limited number of fractures usually dominates the flow is central to the assessment strategy. These may be specific fractures or types, such as exfoliation joints, bedding planes, or faults. A site assessment must focus on identifying and characterising these controlling fractures using modern tools such as flow logging and optical televiewer logging. Single-well and multi-well pump tests also provide insight to the geometry of the conducting fracture network. Multi-zone piezometers are necessary to isolate flowing fractures and to map fracture connectivities from natural and human-induced perturbations. Matrix diffusion, which may significantly retard contaminant migration, requires attention to rock matrix porosity and porosity developed by weathering and alteration around fractures. Immiscible contaminants require an assessment of multiphase flow.

For fractured bedrock assessment, an iterative and integrative approach is vital. *Iterative* means creating a conceptual model, testing the model with data, and revising the model as information is gathered. *Integrative* means using all the geologic, hydrologic, geophysical, and geochemical data to mutually constrain site interpretations.

This report divides a site assessment into four stages:

- Desk studies;
- Surface-based characterisation;
- Single-well characterisation; and
- Multi-well characterisation.

Desk studies identify a range of possible site conditions using published information on regional geology, existing data from nearby sites, and data from analog sites in similar hydrogeologic settings. This stage should produce a preliminary conceptual model of flow. It also should produce characterisation plans that define a detailed surface characterisation program and a general subsurface characterisation program.

Surface-based studies should investigate rock exposures for characteristics that influence or indicate groundwater flow such as open fractures, preferred orientations of fractures, water seepage, and weathering along fracture surfaces. Surface-based geophysics does not have the resolution to locate individual flowing fractures, but it may discover thicker features such as faults or fracture zones that concentrate groundwater flow. The most useful methods are electrical including, ground penetrating radar, electrical sounding, and VLF (very low frequency) electromagnetic surveys.

Single-well characterisation starts with a subsurface investigation plan. Well drilling should be done iteratively using the information from each hole to plan the location and activities of the next. The most important activity in a well is the identification of conducting fractures, which should be done using a hydraulic method such as flow logging or detailed packer testing. It is not possible to identify conducting features based on geologic or geophysical interpretation alone without some hydraulic confirmation. Fortunately, flow logging has become practical for this purpose.

Image logs using optical televiewers provide the geometric and geologic characteristics of the flowing fractures. Image logs reduce the need for core; however, core complements the image log for direct observations of contaminants and for assessing matrix diffusion by providing rock samples for porosity testing or by direct observations of contaminants in the rock matrix. Flow logs should be run in both ambient (non-pumping) and pumping modes. The ambient flow log gives valuable information on vertical hydraulic gradients. Flow logs with pumping identify the conducting fractures and their depths. The final stage of characterisation in a well consists of pumping, packer, or slug tests for hydraulic properties and groundwater sampling of specific conducting features.

A multipoint monitoring system must be installed with separate zones for each significant conducting feature. The multipoint system should eliminate the well as a pathway for contaminant transport. Sampling and hydraulic characterisation may be run after the installation of the monitoring systems, if it has the capacity for pumping from its zones.

Multi-well characterisation begins with monitoring the responses in the first well to drilling and testing in subsequent wells. These interference data provide valuable information on fracture-network connectivity. Each new well should be characterised by the approach outlined for single-well characterisation. The multi-well data set should be sufficient to define the groundwater flow field, identify the controlling fractures, map the important aspects of the fracture network, and define the spread of contaminated groundwater from the site. This data set supports assessments of future contaminant movement and the design of remediation programs.

Respectfully submitted,
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Disclaimer

This report provides a scientific review and guidance for fractured bedrock prepared for the Science Advisory Board for Contaminated Sites (SABCS). Any use that a third party may make of this report, or any reliance on or decisions made based on it, are the responsibility of the third parties. We disclaim responsibility or consequential financial effects on site management, or requirements for follow-up actions and costs.

The services performed as described in this report were conducted in a manner consistent with the level of care and skill normally exercised by other members of the science professions currently practicing under similar conditions, subject to the time limits and financial and physical constraints applicable to the services. This report provides professional opinions and, therefore, no warranty is expressed, implied, or made as to the conclusions, advice, and recommendations offered in this report. This report does not provide a legal opinion regarding compliance with applicable laws or regulations.

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1.0 INTRODUCTION

Fractured bedrock is perhaps the most challenging hydrogeologic environment for groundwater contamination (EPA, 2001). The mention of fractures and hydrogeology invokes uncertainty, unpredictability, and complexity. Fracture networks may be highly transmissive, and capable of rapid transport of contaminants through a groundwater flow system. The non-uniform connectivity of fractures creates flow paths that bypass wells near a contaminant source and paradoxically appear in wells further away. A site clean-up by pumping and treating can appear to be successful, only to have the contaminants reappear later due to storage in the porous matrix. Multiphase flow of water in the vadose zone, and water with immiscible contaminants in the saturated zone becomes especially complex with the introduction of density and capillary pressure effects.

Despite these challenges, the past 30 years has seen considerable progress in assessing contaminant behaviour in fractured bedrock. A successful fractured-bedrock assessment program relies on the following:

- Defining the subset of significant fractures that control migration;
- Understanding how the geometry and hydraulic properties of these significant fractures influence flow and transport;
- Measuring hydraulic heads in three-dimensions to define hydraulic gradients and assess fracture network connectivity;
- Recognizing the role of matrix diffusion in retarding contaminant velocity and providing contaminant storage; and
- Consideration of fluid density and capillary effects on movements of immiscible contaminants (dense and light non-aqueous phase liquid, or DNAPL and LNAPL).

New well-based technologies for flow logging, high-resolution image logging, and multi-zone monitoring complement conventional hydrogeologic methods to support a site characterization strategy that is feasible and cost-effective.

1.1 Report Structure

This report addresses two major topics:

- When is flow fracture-controlled, and what distinguishes fractured rock from porous media for the purposes of assessing groundwater contamination (Chapter 2)?
- What constitutes an appropriate program of site characterisation and analysis to predict contaminant transport (Chapter 3)?

1.1.1 Topic 1: When is Flow Fracture Controlled?

Chapter 2 addresses the distinctions between fractured media from porous media to determine when conventional hydrogeologic methods are appropriate and when fracture-focussed methods should be applied. This topic comes from the recognition that fractured media differs from porous media in fundamental ways. The theory of groundwater hydrology arose from heat flow principles (Carslaw and Jaeger, 1959) that assume a high degree of homogeneity, isotropy, and continuity. No geologic material adheres to these conditions perfectly, but hydrogeologic practice has confirmed their suitability for unconsolidated sediments and soils that make up a significant portion of groundwater aquifers.

Fracture-dominated flow systems depart from these assumptions. Fracture networks confine flow to discrete pathways that may be strongly heterogeneous, discontinuous, and anisotropic. The assessment of contaminant transport in fractured rocks requires a site assessment and analysis approach that differs from the standard methods of porous-medium hydrogeology by defining these fracture flow pathways and their hydraulic properties. Although this guidance specifically addresses fractured bedrock, its approaches also apply to some well-consolidated sediments and soils, like glacial till, which may contain fractures (Keller et al., 1986; Helmke et al., 2005; Harrar et al., 2007; Klint and Graveson, 1999).

1.1.2 Topic 2: Characterising fractured bedrock

Chapter 3 addresses the components of a fracture-focussed, site investigation program. A program for fractured rock must address the following key questions:

- Where is groundwater moving;
- What are the groundwater velocities; and
- How is groundwater transporting contaminants?

The answers involve:

- Understanding the geology and geometry of the water-conducting portion of the fracture network;
- Knowing the flow and transport properties of the fractures;
- Assessing contaminant exchanges between fractures and matrix porosity; and
- Addressing the complexities of multiphase flow in the vadose zone and at sites where there are immiscible contaminants.

The characterisation and analysis chapter lays out a step-wise approach to assessing fractured rock sites starting with literature and desk studies, through surface-based characterisation, and into well-based characterisation as necessary. The chapter recommends suites of geologic, geophysical, chemical, and hydrologic tools to efficiently collect information and address issues at each stage. The results of characterisation efforts provide data for analytical and numerical tools to determine the implications of the site information to groundwater and contaminant behaviour.

1.1.3 Fundamentals and methodologies

The techniques of characterisation and analysis of fracture networks are relatively new having been developed mostly in the past twenty-five years. Research at underground test facilities and at selected contaminated sites has developed practical tools for fractured rock that are now entering general use for groundwater assessment. These are sufficiently mature and field-tested that they can form the basis for regulatory recommendations for site assessment. There are numerous examples from both research and site application to demonstrate the effectiveness and practicality of an integrated assessment approach for fractured bedrock (Mabee and Hardcastle, 1997; Cho et al., 2008; Johnson et al., 2001; Karasaki et al., 2000; Rhén et al., 2007; Hardisty et al., 2003; Nastev et al., 2008; Day-Lewis et al., 2006; Muldoon and Bradbury, 2005).

Hydrogeology textbooks do not address fracture flow in detail, and modern fracture flow studies are not part of most hydrogeologic curricula except in advanced courses. Hence, the fundamentals of fracture flow are not familiar to many hydrogeologic professionals. To address this knowledge gap, this report's appendices provide additional material on the fundamentals of fracture flow including flow principles in fractures, fracture-matrix interaction, and multiphase fracture flow. The appendices also contain more detail on fracture-focussed characterisation and numerical methods along with references for further information.

1.2 Background

1.2.1 Fracture flow issues

The past thirty years has seen a major thrust of activity in studying fractured bedrock. The motivations for understanding fluid movements in fractures have come not only from the contaminant hydrogeology community, but also from radioactive waste research and the petroleum industry, which have very similar fracture flow concerns. Fracture flow also will influence emerging sub-surface flow issues with carbon sequestration and geothermal development. The contaminant hydrogeology profession can derive considerable value by taking these related disciplines into account.

Although much remains to be done and uncertainties still remain, the collective efforts of fracture flow research have developed a methodology for fractured sites that has been successful in a range of fractured geologic settings. The approach to fractured bedrock sites draws on several basic principles, which are:

- Flow and transport occurs in a limited number of important fractures, which must be identified and understood.
- In fractured porous rock, the interchange of contaminants between fractures and the matrix must be understood and characterised (Neretinieks, 1980; Lipson et al., 2005; Maloszewski and Zuber, 1991). These effects are not limited to sedimentary materials; fractures in hard, non-porous rock are often bordered by zones of elevated porosity from mechanical damage during the fracturing processes as well as alteration from weathering and other chemical interactions.
- Sites with non-aqueous phase liquid (NAPL) contaminants (Light NAPL if less dense than water or Dense NAPL if more dense) must consider the capillary pressure as an impediment to movement (Kueper and McWhorter, 1991). These effects also act between air, water, and liquid contaminants in the unsaturated zone. Matrix diffusion and NAPL dissolution can lead to the disappearance of NAPL into the rock matrix (Parker et al., 1994; Parker et al., 1997).
- Wells should be completed with multi-zone monitoring systems that isolate the flow-controlling fractures from one another to avoid well-induced cross-contamination (Einarson, 2006; CL:AIRE, 2002b). Instrumentation tied to these zones should monitor head and provide access for water sampling. Everything that perturbs the groundwater flow at a site - both human and naturally caused - creates responses that are valuable for site characterisation.
- Science-based characterisation involves multiple iterations between the development of conceptual models (hypotheses) and data collection. Numerical simulation tools implemented from the beginning of a programme are a necessary part of this approach.
- An integrative approach using geologic, hydrologic, geophysical, and geochemical data is necessary as the results of any one method have multiple, non-unique interpretations. The hypotheses that are most likely to represent actual site conditions are those that are consistent with multiple, independent lines of evidence.

Although characterisation of fractured rock is challenging, site investigations in these settings have much in common with conventional porous media. The physical principles that control flow in fractured rocks are largely the same as porous media:

- Groundwater moves in fractures under gradients of hydraulic head with flow rates and velocities that obey Darcy's law, except for unusual cases where turbulent flow may occur.
- Multiple phases (NAPL, water, and air) create interfacial capillary tensions that inhibit the entry of non-wetting phases into smaller voids.
- Fracture networks can have geometries that produce the same well test responses as porous media; consistency with Theis curves, for example, is not uniquely diagnostic of porous or fractured media.

Fractured media also may differ from porous sedimentary media in several significant ways:

- Fractures are very efficient conductors for the space they occupy, and they are capable of moving water at higher velocities than porous rocks with similar flow-carrying properties.
- Fractures are highly variable. A few fractures typically carry the major portion of the groundwater flow, while smaller fractures and the porous matrix act as storage.
- Fracture conductors are not constrained to having a layered geometry, like porous sediments. They may interconnect in complex, cross-cutting geometries, and sparse networks may form isolated flow compartments.
- Although flow in fractures follows the hydraulic gradient within a fracture plane, strongly oriented fracture sets may direct flow in directions other than the larger-scale hydraulic gradient.
- The diffusion of contaminants from fractures into the rock matrix storage retards the contaminant velocity with respect to the flowing water.
- In multiphase, density-driven NAPL flow, gravity forces are reduced according to the cosine of the fracture's dip-angle. Fracture opening, or aperture, controls the entry of NAPL's to the bedrock from overlying soils, and the vertical continuity of fracture networks determines migration depths.

1.2.2 Knowledge from research sites

Groundwater flow in fractured bedrock has been the focus of numerous research test sites. Radioactive waste programs began underground experimentation around 1977 with the Stripa Mine in central Sweden (Carlson, 1986; Witherspoon, 2000; Witherspoon et al., 1981) leading to an international cooperative program that included Canada lasting until 1992. Canada operated its own underground test facility adjacent to Atomic Energy of Canada's facility at Whiteshell near Winnipeg, Manitoba (Davidson, 1984; Chandler, 2003).

Similar underground research laboratories have been active in Switzerland, Japan, and Finland, as well as a dedicated mine in Sweden at the Äspö Hard Rock Laboratory, which began operation in about 1990 and continues today (Svemar et al., 2003). Japan is similarly developing both sedimentary and granitic underground laboratories that are currently under construction. In the meantime, Sweden and Finland have been undertaking site investigation programs leading to selection of a final disposal location for radioactive wastes in those countries (Rhén et al., 2007). The US programme for high-level waste disposal at Yucca Mountain, Nevada has contributed to a better understanding of unsaturated flow in fractures (Bodvarsson et al., 2003). Studies in the Culebra Dolomite at New Mexico's now-operating Waste Isolation Pilot Plant have investigated rock-fracture interaction and regional-scale fracture flow issues in fractured, porous carbonate rocks (Meigs and Beauheim, 2001).

The investments in radioactive waste laboratories have dwarfed the funding for similar efforts in non-radioactive contaminant hydrogeology. Nonetheless, international cooperative research has studied contaminated sites at Smithville, Ontario (Novakowski et al., 1999; Zanini et al., 2000; Oxtobee and Novakowski, 2002) and Storrs, Connecticut (Lane et al., 2002). The US Geological Survey has performed research in fractured sedimentary rock at the US Naval Warfare site near Trenton, New Jersey (Goode et al., 2007), at a site in the Newark Basin of New Jersey (Matter et al., 2006), and in a major multidisciplinary program in fractured granite at Mirror Lake, New Hampshire (Shapiro et al., 2007). The US Environmental Protection Agency (US EPA) supported work to assess characterisation methods for fractured granite at the Raymond Quarry in central California in the 1990's (Cohen et al., 1996; Karasaki et al., 2000). All of these research sites have provided venues for bringing testing approaches out of research and into practice.

1.2.3 Major summary volumes, symposia, and guidances

Several milestone syntheses have contributed to the advance of fractured rock hydrogeology. Two of these were US National Academy of Sciences studies, one in 1996, "*Rock Fractures and Fluid Flow*" (NRC, 1996), and the other in 2001, "*Conceptual Models of Flow and Transport in the Vadose Zone*" (NRC, 2001).

In honour of Paul Witherspoon's contributions to the field of fractured rock hydrogeology, Lawrence Berkeley Laboratory sponsored two symposia in 1999 and 2004 with follow-on publications by the American Geophysical Union (Faybishenko et al., 2000; Faybishenko et al., 2005).

Three major symposia have been held under the joint sponsorship of the Canadian and US environmental agencies focusing on fractured bedrock. The first of these occurred in Toronto as the Fractured Rock 2001 Conference. This conference highlighted fractured-rock contamination research in carbonate bedrock at Smithville, Ontario. Two subsequent meetings with a fractured-rock contamination focus followed in Portland, Maine under that sponsorship of the US EPA and the National Ground Water Association (NGWA). Both the 2004 and 2007 conferences were entitled, "*Fractured Rock Conference: State of the Science and Measuring Success in Remediation*". Kinner et al. (2005) prepared a summary of the 2004 meeting. Coordinated with these activities, the US EPA has maintained a web site, *http://clu-in.org/fracrock/*, focused on fractured-rock technologies and case histories including links to papers from the 2007 meeting.

In the United Kingdom, an independent, non-profit organization called the Contaminated Lands Applications in Real Environments (CL:AIRE) has issued a series of case studies, guidances, and technical bulletins regarding contaminated lands issues. CL:AIRE is a membership organisation that distributes some of its studies publicly and others only to its members. Three publicly accessible technical bulletins address fractured rock -- integrated site investigation approaches (CL:AIRE, 2002a), monitoring systems (CL:AIRE, 2002b), and geophysical methods (CL:AIRE, 2007).

In addition to these collective efforts, several individual authors have written review and summary papers highlighting the major issues of fractured-rock flow including Lapcevic et al. (1999a), Neuman (2005), and Berkowitz (2002). Sara (2003) prepared a particularly thorough chapter on fractured rock methods in his handbook on site assessment and remediation.

2.0 WHEN IS A FLOW SYSTEM FRACTURE-CONTROLLED?

2.1 Porous Media Assumptions

The discipline of hydrogeology often assumes that fluid flow (gas, water, or non-aqueous liquids) occurs in a porous medium that is homogenous, isotropic, and continuous. Specifically,

- ***Homogeneity*** implies that hydraulic properties do not vary significantly in space;
- ***Isotropy*** implies that hydraulic properties do not have directional components; and
- ***Continuity*** implies that all points in a flow system are connected to one another.

These assumptions arise in part from hydrogeology's extensive use of heat flow analogues for much of its mathematical basis. Arguably, the theoretical underpinning of both hydrogeology and petroleum engineering is Carslaw and Jaeger's (1959) "*Heat Conduction in Solids*".

Although no geologic material meets these conditions rigorously, this theoretical basis has supported the advance of groundwater practice for nearly eighty years. For the sedimentary materials that make up most developed aquifers, these approximations are sufficiently valid to allow the solution of many practical problems of groundwater management.

Fractured settings often represent major exceptions to these fundamental assumptions, and fractures appear in a wide range of geologic environments. Although fractures are most commonly associated with consolidated bedrock, they may form in any cohesive material including well-consolidated soils and sediments, like glacial till (Helmke et al., 2005).

Specifically,

- Fractures introduce significant heterogeneity through their behaviours as localized, transmissive conduits for fluids and gasses, which may have transmissivities spanning several orders of magnitude;
- Fractures introduce anisotropy as they have preferred directions that reflect the stresses and strains that formed them; and
- Fracture networks may be highly discontinuous that are well connected at local scales but poorly connected at larger scales.

The extreme heterogeneity of fracture flow relates to two concepts – the cubic equation of fracture flow and the skewed statistics of fracture geometry and hydraulic properties. The idealisation of a single fracture as a conductor with two parallel walls leads to the well-known cubic equation of fluid mechanics that relates the fracture's flow capacity (transmissivity, or T) to the third power of the separation of the fracture walls, or aperture (Snow, 1965):

$$T = \rho g \frac{e^3}{12\mu}$$

where ρ is fluid density, μ is fluid viscosity, and g is gravitational acceleration.

If one compares two fractures, the one with the larger aperture, even only slightly larger, will carry the dominant flow. Although real fractures are not the ideal parallel plates of fluid mechanics theory, the cubic general relationship has held up well to experimentation (Witherspoon et al., 1980; Pyrak-Nolte and Cook, 1988; Konszuk and Kueper, 2003) with the cautions that aperture (besides being heterogeneous itself) may have at least three values – one for flux or flow rate, one for velocity, and another for storage. For example, a flow-based aperture derived from transmissivity using the cubic law may be inappropriate for predicting velocity and storage.

Snow (1970) further showed that the statistics of apertures, fracture transmissivities, and spacings followed highly skewed distributions rather than symmetric, normal distributions. Fracture sizes typically are similarly skewed following lognormal or power-law statistics (Bonnet et al., 2001; Odling et al., 2004; Molz, 2004; see Priest, 1993 for an overview).

The cubic law and fracture statistics give key insights to fracture heterogeneity. They lead to the concept that small numbers of fractures will dominate the flow in a fractured-rock system. If larger fractures are more open, then statistics tells us that flow will be controlled by the largest, most open, and most transmissive fractures. The bulk of a fracture population will be relatively inactive with respect to flow and velocity yielding this role to the small portion of the population with characteristics in the upper tails of a skewed distribution. That is not to say one can ignore the rest of the fractures, as these may control fracture porosity and serve a diffusive role in contaminant transport. Further discussion of aperture and fracture statistics appears in Appendix A.

Characterising the network of the significant conducting fractures should thus be the target of site assessment. The control of flow by the network can be illustrated by comparing fracture networks to porous media, which is much like comparing an air- or water-based transportation system to one involving roads or rails. Airplanes and boats operate in a continuous medium, where one can travel from one point to another without being constrained to paths (except by traffic controllers). Fracture networks, on the other hand, confine flow to fracture pathways, in the same way that automobile traffic or railroads are constrained to fixed roads and rails. Not all points are connected, and those that are may connect through circuitous routes (Figure 1). The frequent failure of fracture-dominated flow systems to adhere to theses three conditions - homogeneity, isotropy, and continuity – has given fractured bedrock a reputation for unpredictability and uncertainty.

That said, flow in fractures follows the same physical principles as porous flow, specifically:

- Fluxes and velocities are proportional to gradients of hydraulic head obeying Darcy's Law, except for conditions like turbulent flow;
- Gravitational potential energy drives flow in fractured media as well as porous media. Groundwater in fractures moves from locations of high groundwater head to low groundwater head; and
- Flow in a planar single fracture or fault zone behaves in the same way as flow in a confined, planar aquifer.

A major difference between fractured rock and porous media is the possibility of geometric complexity. The porous, sedimentary media lie in parallel strata of alternating aquifers and aquitards that do not intersect except where strata merge or pinch out. Furthermore, unconsolidated aquifers that form a major portion of groundwater sources are geologically young enough that their strata are still nearly horizontal.

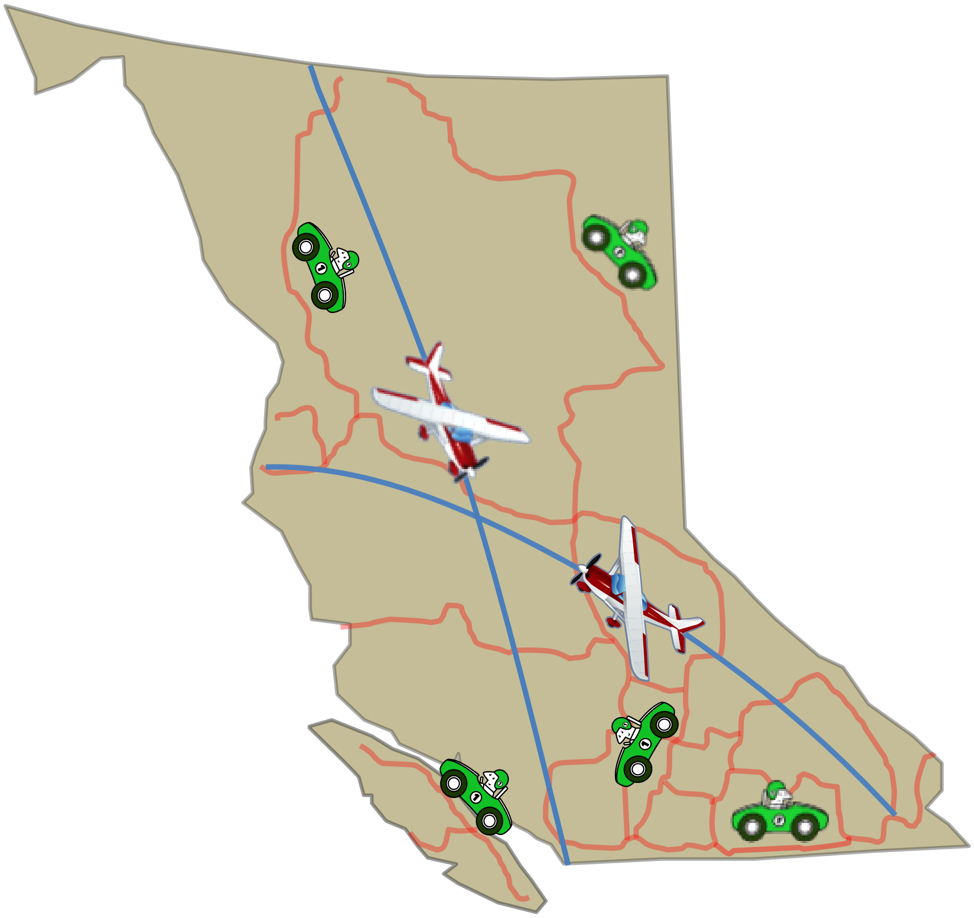
A fracture network can be thought of as a network of confined aquifers that are not constrained to parallel layers and are free to assume multiple, intersecting orientations. Fracture flow may be strongly anisotropic when there is a single, dominant orientation, or where one set is more open than others. Fractures may be well-interconnected, or sparse fracture networks may form poorly connected compartments.

Flow in fracture networks does not necessarily follow the shortest, Euclidian, path from high to low hydraulic head (Figure 2). Rather, fracture flow is constrained to pathways within the fracture network. As Figure 2 shows, the direction of groundwater flow is controlled jointly by the direction of the hydraulic gradient and the fracture set orientations and properties.

That said, fractures and fracture networks do not have to be geometrically complex. A single sub-horizontal fracture, like an exfoliation or sheeting joint, may behave geometrically like a single confined aquifer. Similarly, a fractured sedimentary layer with a hydraulically inactive matrix and a well-connected fracture system will behave geometrically like any other porous confined aquifer. What distinguishes fracture flow from porous flow in these cases is not the geometry, but the high-transmissivity and low storage properties of the fractured case, which can lead to flow rates and velocities that may be greater than their porous counterparts.

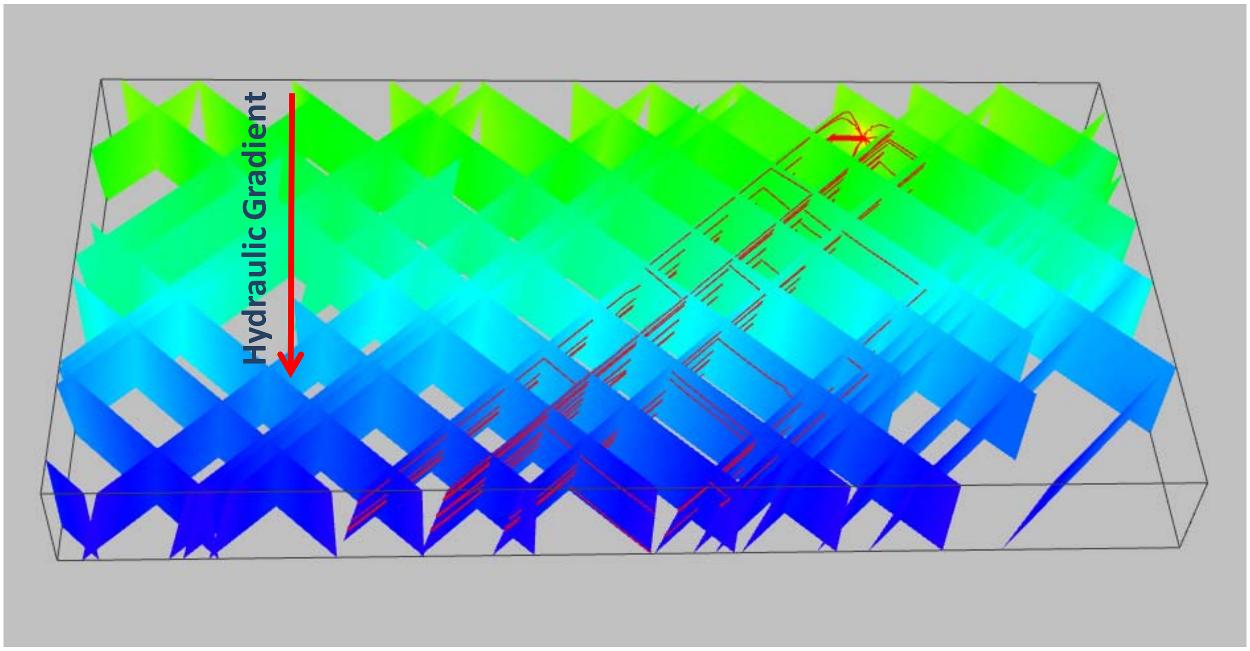
As a final point, geometric complexity is, by itself, not an indicator of fracture flow, as sedimentary systems that were formed in complex depositional or diagenetic environments or that have undergone complex structural histories can also have complex flow geometries. Heterogeneity, in general, is a challenge in contaminant hydrogeology, regardless of the source of variability.

Figure 1. Highway and flight path analog of fracture and porous flow.



Highway systems, like fractures, constrain flow to specific pathways. Connectivity may be incomplete, and point-to-point pathways may be tortuous. Air transport systems, like porous media, allow complete connectivity of all points on direct paths. Fractures pathways, unlike highways, are generally faster than porous paths if they are connected.

Figure 2. Fracture anisotropy controls on flow direction.



Fracture network model with boundary conditions as shown (no flow top and bottom). NE trending fractures have twice the transmissivity as the NW-trending fractures. The colours in the fractures show a head varying from 100 m (green) to 0 m (blue). Model scale is 200-m on the side; the top and bottom boundary conditions are no flow boundaries. Red lines are particle tracks showing how fracture anisotropy controls flow direction from a point source in the upper right.

2.2 Representation of Fracture-Flow Systems

There are several different ways to represent fracture flow systems for the quantitative analysis of groundwater flow and transport. These are summarised in Figure 3 and described below.

Discrete Fracture Network (DFN) --The most geologically realistic is a Discrete Fracture Network (DFN) model, which represents each hydraulically-significant fracture as a planar feature with its correct location, size, and hydraulic properties. A DFN approach analyses the geology and geometric statistics to create a network description of the flow system. Models typically include both deterministic fractures, which are those major features with known locations and properties, and stochastic fractures, which are generated by random, or *Monte Carlo*, sampling from probability distributions. The stochastic fractures are either the smaller fractures in the network, or fractures in portions of a modelled region where information on deterministic fractures is sparse.

Discrete fracture network models rose out of several dissertations in the early 1980's (Long et al., 1982; Dershowitz, 1984; Dershowitz et al., 1998; Cacas et al., 1990; Andersson and Dverstorp, 1987) among others. DFN models usually have a fracture generator that creates 2-D fracture features. These polygons can be discretized into finite-element grids for solution of flow and transport. Continuum modellers have criticized DFN models as having data requirements that are impractical (Neuman, 2005). Nonetheless, DFN models have seen considerable success in applications for radioactive waste disposal especially in Sweden and Finland (Rhén et al., 2007).

Equivalent Porous Medium (EPM) – An equivalent porous medium is an idealised porous continuum that produces the same behaviour as the fracture network that it represents. For example, the EPM equivalent of a 50 cubic meter volume of non-uniform fractured rock would be a similar volume of a porous medium that would conduct water with the same flow rate and velocity as the fracture network. EPMs may be either isotropic or anisotropic to reflect directional properties of fracture networks.

Central to the application of an EPM concept is the existence of a REV or Representative Elementary Volume (Bear, 1972). The existence of a REV assumes that heterogeneity goes away at a certain scale. For example, flow in sand may be heterogeneous at the scale of pores, but becomes relatively homogenous at scales that are a few orders of magnitude larger than the pore sizes. The scaling of fracture networks for REV's may be more complicated. Unlike sedimentary pores, fractures span a range of sizes from microcracks to crustal-scale faults. Hence, larger scales of observation tend to bring in larger scales of fractures.

Stochastic Continua - Stochastic continua are EPM's that have heterogeneous properties. A stochastic continuum does not depend on the existence of REV's. It uses spatially correlated properties usually derived using the methods of geostatistics to create variability that reflects the variability of the underlying fracture network (Ando et al., 2003; Neuman, 2005).

Another approach to constructing continuum models involves superposing a fracture network on a fine grid in a way that mimics the network structure of the fracture system (Svensson, 2001; Mun and Uchrin, 2004). Upscaling a DFN model to a continuum grid can preserve much of the network structure (Figure 4).

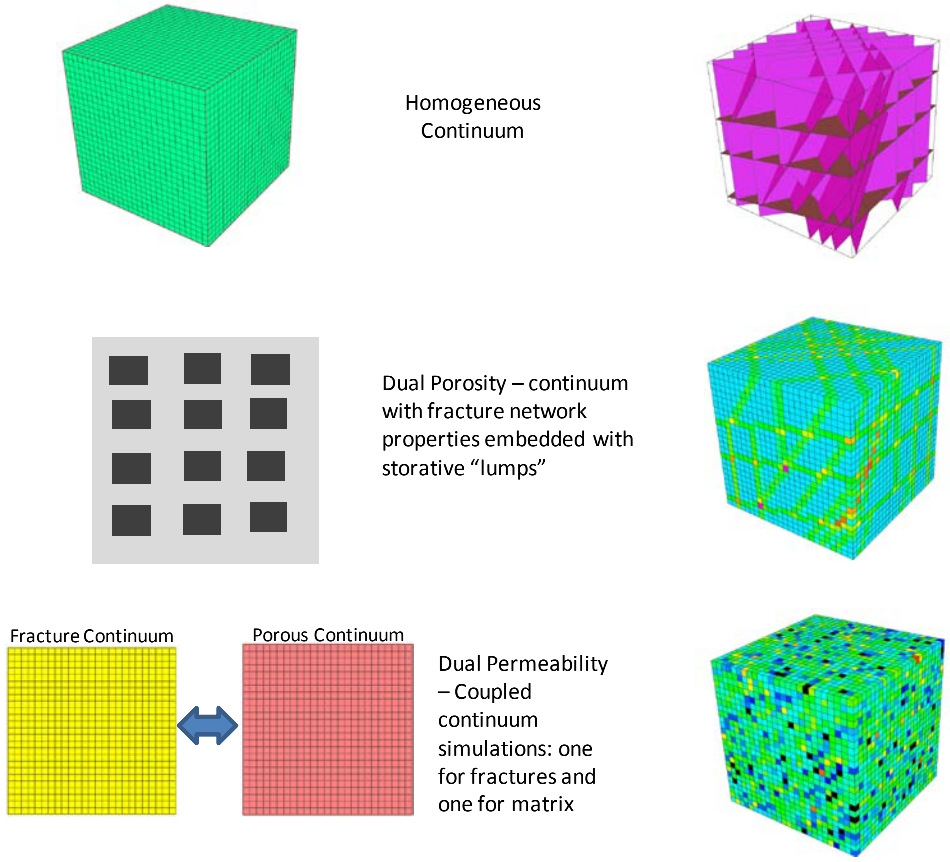
Dual Porosity Models - Dual Porosity refers to a fracture-matrix system where flow occurs dominantly or entirely in the fractures, while the matrix serves as a storage repository that communicates with the flow system through the fracture network (Warren and Root, 1963). A major portion of fractured oil and gas reservoirs depend on fractures for their production, but would not be economic without large volumes of oil or gas in the porous matrix.

Dual porosity implies that the movement of water through the porous matrix is negligible compared with the flow in the fractures. Nonetheless, fluid may move between matrix blocks into fractures whenever there is a pressure change in the fracture network. Dual-porosity effects occur with respect to both pressure and contaminant transport. The matrix also plays a crucial role in contaminant transport, where storage in the matrix can have a strong retarding effect on migration.

Dual-porosity numerical simulators are often represented by stacks of "sugar-cubes" of matrix separated by planar fractures (Warren and Root, 1963). While this representation appears geologic, a more accurate representation of the mathematics is closer to the picture in Figure 3, where the matrix consists of lumps embedded in a continuous porous medium that represents the fractures. The transfer of mass between the matrix and fractures depends on the lumps' size and shape, which may be spheres, cubes, slabs, or any arbitrary solid form. The choice of shape often depends on mathematical convenience.

Dual Permeability – These are models where the matrix has a high enough hydraulic conductivity that flow occurs in both the matrix and the fractures, hence the matrix is serving both a flow and a storage function.

Figure 3. Representations of fractured media.



Homogeneous Continuum

Discrete Fracture Network Model

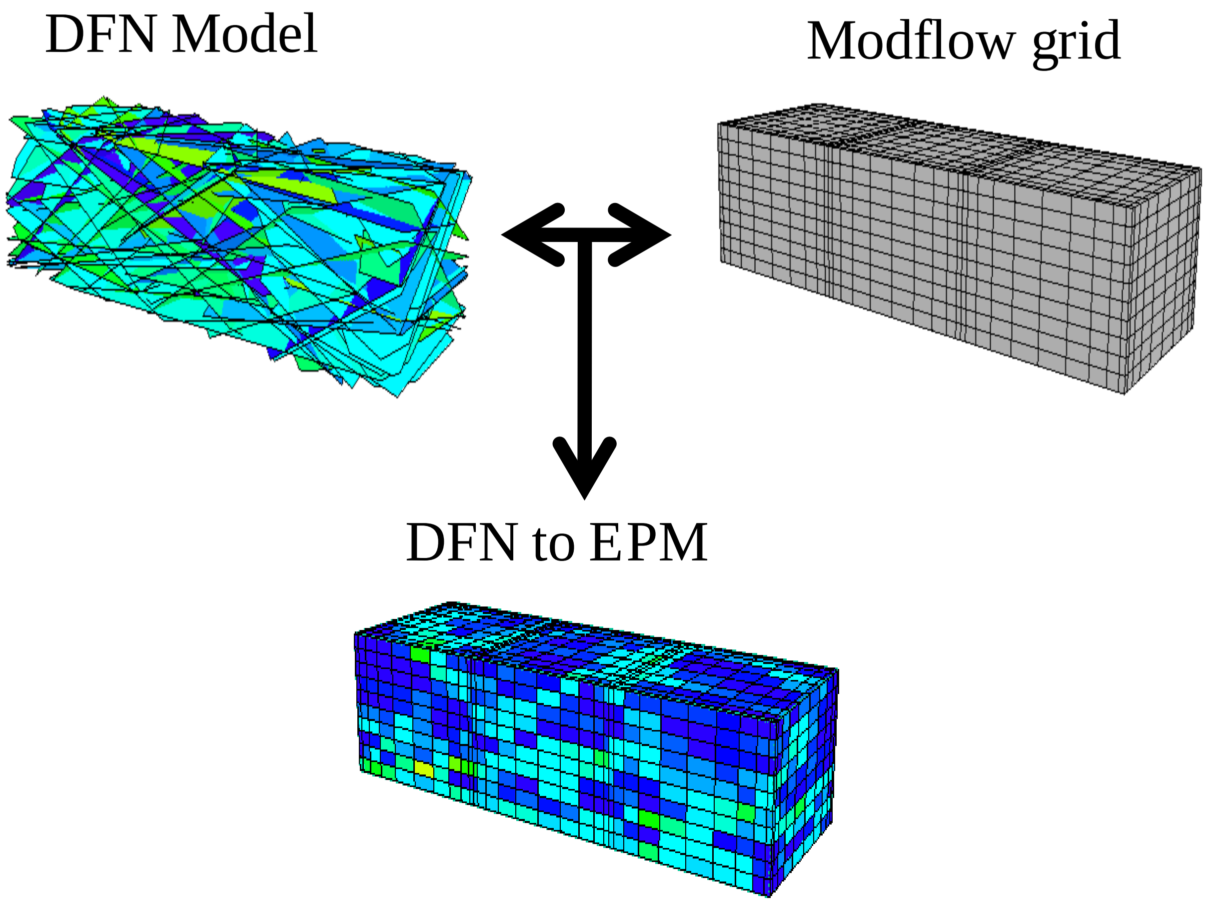
Dual Porosity – continuum with fracture network properties embedded with storative "lumps"

Continuum Conditioned to DFN, Background EPM

Dual Permeability – Coupled continuum simulations: one for fractures and one for matrix

Random Stochastic Continuum

Figure 4. Upscaling DFN models to continuum grids.



Further discussion of fracture representation and numerical modelling approaches appears in Appendix C. Although there is a large range of opinions on the best modeling approaches for fractured rock, the need to identify and represent the important, controlling features in a model as discrete features is generally accepted – either in a DFN model or by arranging grid properties in a heterogeneous continuum model to mimic discrete fractures. Provided a simulator can capture the key geometric features of the network, the choice of method is largely a matter of the user's preference.

The issue of matrix interaction is very important for contaminant transport, as matrix diffusion is becoming increasingly recognised as a significant mechanism for controlling and retarding contaminant velocities with respect to the groundwater (Neretinieks, 1980; Sudicky and Frind, 1982; Parker et al., 1994; see also Appendix A).

With respect to matrix interaction, Nelson (2001) proposed a classification of fractured oil and gas reservoirs that also has relevance for groundwater contamination. The classification looks at the relative conductivity and storage properties of the fractures and the rock matrix. The four types he proposes are the following (Figure 5):

- Type 1: Conductivity and storage in fractures, but negligible flow and storage in the rock's porous matrix. This is a single porosity and permeability system with only fracture contributions.
- Type 2: Conductivity in the fractures, with storage in high-porosity, low-conductivity rock matrix porosity. Oil and gas reservoirs of this type have large reserves that only can be produced economically through fractures. These are called *dual porosity* systems.
- Type 3: Rock matrix that is both conductive and storative, but with fractures that enhance the fluid production. These rocks can be economic producers on the strength of their matrix properties alone, but the fractures provide an additional flow component. These are *dual permeability* systems.
- Type 4: Rock with a highly porous and conductive matrix where fractures are present but do not affect oil and gas production or contaminant transport and recovery.

The equivalents of Type 1 reservoirs in contaminant hydrogeology are igneous, metamorphic, and well-cemented sedimentary rocks. The characterization of these aquifers must focus on the factors that control the fracture network geometry and properties.

Type 2 systems are some of the most important for oil and gas production, as they have large matrix reserves but production is from fractures. Type 2 fractured aquifers, where non-aqueous phase liquid contamination is involved (DNAPL or LNAPL), have the same issues of multiphase flow that exist for oil fields. For dissolved contaminants, the Type 2 equivalents additionally have matrix diffusion effects where there may be significant retardation when contaminants are entering the flow system, and delayed recovery during contaminant clean up operations. As with oil reservoirs, the size and shape of matrix blocks between fractures, as well as the contrast of fracture to matrix conductivity has a major effect on contaminant behaviour.

In Type 3 systems, the fracture matrix interaction is not as dominant as in Type 2 systems, as there is a significant component of flow in the matrix as well as in the fractures. Diffusion is less significant, but may be present depending on the hydraulic gradients, the flow velocities, and rock heterogeneity.

Type 4 systems are those where the rock matrix is both significantly conductive and porous. Fractures are present, but do not affect flow either because they have conductivities that are similar to the matrix or the fractures are poorly connected and do not form a conducting network. Such bedrock would not require an investigation approach directed at fractures.

2.3 Criteria for Fracture-Dominated Flow Systems

As discussed above, fracture systems do not conform to one or more of the basic porous media assumptions of homogeneity, isotropy, and continuity. Hence, the evidence that a flow system is fracture-controlled, usually involves some aspect of heterogeneity, anisotropy, and discontinuity.

Fracture-control of flow and transport in an aquifer reveals itself in a number of ways including the following:

- *Contrast of hydraulic conductivity values from laboratory tests and field tests.* Well tests in a fracture-controlled system produce hydraulic conductivity values that are greatly in excess of those expected for the rock matrix.
- *Variability of hydraulic conductivity values.* A fracture dominated system will typically have hydraulic conductivity or transmissivity values that vary over several orders of magnitude where the highest values are concentrated in a small portion of the fracture populations. Well productivities in fractured bedrock may vary widely depending on the well's intersection with this transmissive portion of the fracture population.
- *High hydraulic conductivity:* As the porous matrix of consolidated bedrock generally has a low hydraulic conductivity, any bedrock that has a hydraulic conductivity exceeding 10^{-6} ms^{-1} should be suspected of being fractured. The prevalence of fractures in bedrock near the surface suggests that any bedrock should be assumed to be fractured unless demonstrated otherwise.
- *Anisotropic behaviours*. Preferred orientations of fractures, or preferred openings of fractures in particular orientations create strong anisotropies in flow and velocity. Directionality in the shapes of drawdown maps in response to pumping or the spread of contaminant plumes may indicate a fracture control.

- *Anomalous connectivity*. The connectivity of an observation well to a pumping well depends on the fracture pathways. Drawdown responses that appear chaotic rather than symmetric to the pumping well may indicate heterogeneous connectivities along fracture networks. Similarly, the non-uniform spread of a contaminant plume or anomalous responses of tracer tests may also indicate fracture control.
- *Rapid propagation of head disturbances and fast transport of solutes*. Fractures have higher pressure diffusivities than porous media, that is, the pressure propagation from a disturbance in a flow system is faster in fracture networks than in porous media with similar hydraulic conductivity. Similarly, tracer or contaminants will move faster in fractured rock than in porous rock with similar conductivities, as fractured rock has lower effective porosity values.

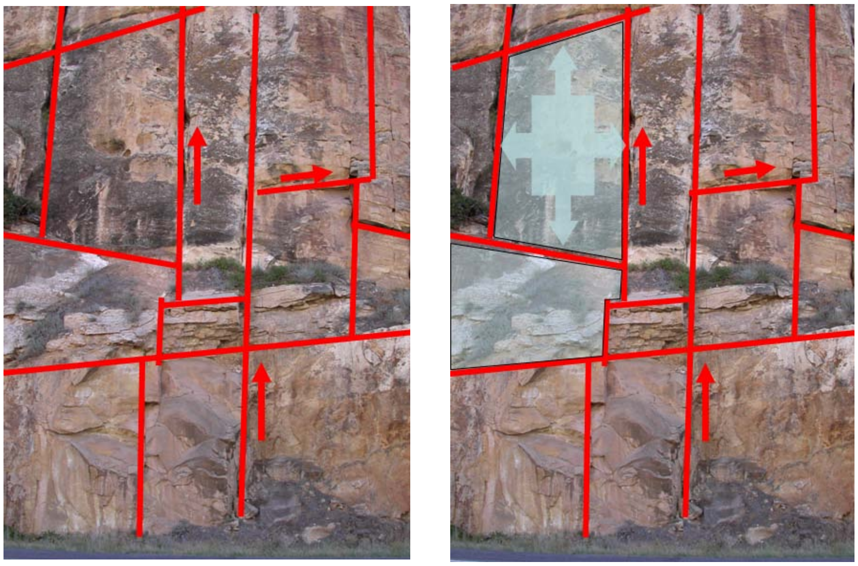
While anisotropic and discontinuous behaviours are associated with fracture flow, well-connected fracture networks with multiple conducting sets may produce isotropic and continuous effects in head responses and contaminant migration. Similarly, complex sedimentary systems can have heterogeneous and anisotropic properties. Hence the determination that a flow system is fracture controlled must also consider the geologic setting of the site in question.

The presence of fractures; however, does not necessarily mean that fractures will control the flow and transport in ways that violate porous media assumptions. A number of conditions can counteract the effects of fractures. These conditions may not alleviate the concern about groundwater contamination; however, they may indicate that a site is amenable to porous media methods, and protocols for fractured bedrock may not be required. These conditions include the following:

- *High fracture density:* A rock with very high densities of open fractures becomes effectively rubble or a breccia. Under such conditions, the fractured medium may act as a porous medium.
- *Highly weathered systems:* Intense weathering and alteration of rocks that normally are considered fractured, like igneous or metamorphic rocks, can create a porous medium, or something like Nelson’s Type 4 system. Deeply weathered rock may occur near the surface or anywhere where fractures have conducted rock-altering fluids.
- *Flow systems with very low velocities (diffusion dominated):* Under conditions of very low velocity, especially in rocks with matrix porosity, diffusion may dominate transport processes, and the fracture contributions to flow may become negligible. Such conditions are more likely to exist in deep, stagnant flow systems rather than near-surface systems close to most contaminant sources.
- *Flow systems with upward gradients:* For overlying soil or sediment, contaminants may not enter fractured bedrock if there is an upward hydraulic gradient. Assessment of such conditions must consider the densities of contaminants and the relative contributions of viscous and gravity forces, especially when DNAPLs are present.

- *NAPL contaminated sites where bedrock fracture apertures are small:* The downward movement of NAPLs from soil to fractured bedrock may be blocked by capillary pressure effects in the fractures, which increase with decreasing aperture.
- *Transport versus flow:* A fractured rock may behave as a porous medium with respect to flow but not transport if there is a rock matrix with sufficient porosity to retain solutes that enter diffusively from the fractures. In such cases, solute velocities may be controlled by matrix properties rather than fracture properties.

Figure 5. Nelson (2000) Classification of fractured reservoirs based on relative importance of fractures and porous matrix.



Type 1: Flow and Storage only in Fractures (Single Porosity)

Type 2: Fracture Flow Only, Matrix Storage (Dual Porosity)

Type 3: Flow in Fractures and Matrix, Storage in Matrix (Dual Permeability)

Type 4: Flow and Storage in Matrix, Fractures Assist Flow (Single Porosity)

3.0 INTEGRATED SITE CHARACTERIZATION

This chapter presents recommendations for site assessment in fractured bedrock. It starts with the key questions that a site investigation must address along with the key inputs to address those questions. The second part of the chapter then looks at the staging of a site investigation from desk studies through on-site investigations discussing what methods may be applied, what results can be expected, and what decisions can be supported. The final part of the chapter presents a hypothetical site assessment for a leak from a gas station over bedrock as an example of how this methodology can be applied. This chapter does not discuss the background of characterisation methods in detail. A further discussion of methods appears in Appendix B.

3.1 Key Questions for Site Assessment

The purpose of contaminated site investigations in fractured rock is the assessment of the spatial distributions of contaminants and the prediction of where those contaminants may move in the future. Once this is known, the site assessment should also provide a conceptual basis and site data to support the design of remediation efforts. The key questions that a site assessment must address are:

- Where is groundwater moving from the site?
- How fast is groundwater moving?
- How are contaminants distributed and in what form?

3.1.1 Where is groundwater moving?

The question of where groundwater moves depends on two main inputs – the geometry of the fracture network and the distributions of hydraulic head, which are the driving forces for groundwater flow. As discussed in Chapter 2, fracture flow differs from porous media flow in the confinement of groundwater flow to the fracture network. Like porous media; however, differences of hydraulic potential energy, or head, drive groundwater flow with movement from locations with high heads to low heads.

The main assessment needs for answering the “where” question are (1) the geometry of the fracture network and its hydraulic properties, and (2) the distributions of hydraulic head and the magnitude and directions of hydraulic gradients. Note the hydraulic gradients in discontinuous fracture networks may also be discontinuous.

This discussion focuses so far on flow in the saturated zone. In the unsaturated, or vadose zone, groundwater flow is mainly vertical in porous systems that are homogeneous. In fracture networks, flow follows the fracture dip. If there are vertical fractures that are well connected, the vadose zone flow will be vertical, but in fractures that may be dominantly shallow-dipping, the flow is still gravity controlled, but will follow the fracture dip.

3.1.2 How fast is groundwater moving?

Once one has a conceptual model of where groundwater is moving, the velocity is mainly a question of effective porosity. A basic knowledge of hydraulic gradient and fracture transmissivity provides only the groundwater flux, that is, a volume rate of movement with time. For porous media flow, the velocity in a stream tube with a given cross-sectional area is the flux in that tube divided by the area and the rock's effective porosity. In a fracture network, each fracture has a transmissivity that controls the flux of water under a given hydraulic gradient. For a unit width of fracture, the average velocity is the flux divided by the unit width and the fracture's opening or aperture.

Fracture aperture is commonly calculated from the so-called cubic law, as discussed in Section 2 and Appendix A. The use of the cubic law to determine transport aperture from transmissivity measurements may significantly over-predict the actual groundwater velocity. The use of transmissivity alone to calculate an aperture for determining velocity is highly uncertain. The preferred method of obtaining aperture information is either from tracer tests on well-defined fracture pathways, or back-calculating aperture from contaminant or solute movements in defined plumes.

The other major consideration in groundwater velocity is the role of hydrodynamic dispersion. Groundwater moves with a range of velocities due to both microscopic and macroscopic effects. At the micro-scale, the flow in a single pore or in a single fracture has a velocity profile where water moves fastest in the center of the conduit and moves more slowly in boundary layers near the solid surface of the pore or fractures. At a macro-scale, variations in hydraulic properties among porous pathways as well as heterogeneities within and between fractures result in a spectrum of groundwater velocities.

In the vadose zone, the flow is complicated by multiphase considerations, multiphase being the presence of air, water, or any other fluid that does not mix with water like DNAPLs or LNAPLs. Conventional treatments of vadose zone velocity and flux use relative permeability concepts, that is, the movement of each phase has a permeability or transmissivity that is a portion, less than 100%, of the permeability or transmissivity for a single phase. Multiphase flow in fractures is a highly complex issue that is discussed in more detail in Appendix A.

3.1.3 What is the spatial distribution of contaminants?

The most important issue for contaminated site assessment is the distribution and fate of the contaminants themselves. An assessment of where contaminants go starts with the flow and velocity of the groundwater, which are the topics of the first two questions.

Contaminant distribution in a fracture flow system depends on three concerns:

- Is the matrix rock significantly porous?
- Does the contaminant chemically interact with the materials on the fracture or on matrix pores?
- Is the contaminant dissolved or is it immiscible?

If the matrix is significantly porous, then dissolved contaminants will diffuse into the matrix from the fractures (Figure 6). Once in the matrix, the contaminant will have little or no significant movement in the groundwater flow system. Whenever there is a contrast between the concentration of a solute in the fracture and in matrix pores, the mass of the contaminant will move towards the pore volume that has the lower concentration. In the initial contamination of a site, this movement is generally from the fractures to the matrix with the effect of reducing the contaminant concentration in the fractures. Once the source of contamination is removed or during remediation, the contaminant concentrations in the matrix will exceed those in the fractures, and the direction of movement will be reversed from the matrix back to the fractures. While matrix diffusion helps reduce concentrations during initial contamination, it can later complicate remediation as the contaminants slowly return to the fracture network.

Figure 6. Matrix diffusion.

Matrix diffusion is clearly important in sedimentary rock with relatively high porosities, but it can also be important in any rock type where fractures and faults may have high-porosity damage zones, and in near-surface environments where weathering has affected the porosity of the rock.

Chemical interactions of contaminants with the bedrock also can produce strong retardation effects (Sudicky and Frind, 1982; Wels et al., 1996). The chemical interaction of the rock with the contaminants in the water is called sorption. Fractures commonly have mineralization on their surfaces, which can react with contaminants to reduce their mobility. If the rock matrix also reacts with the contaminants, then the combination of matrix diffusion with sorption reactions has an even stronger retardation effect than either process separately.

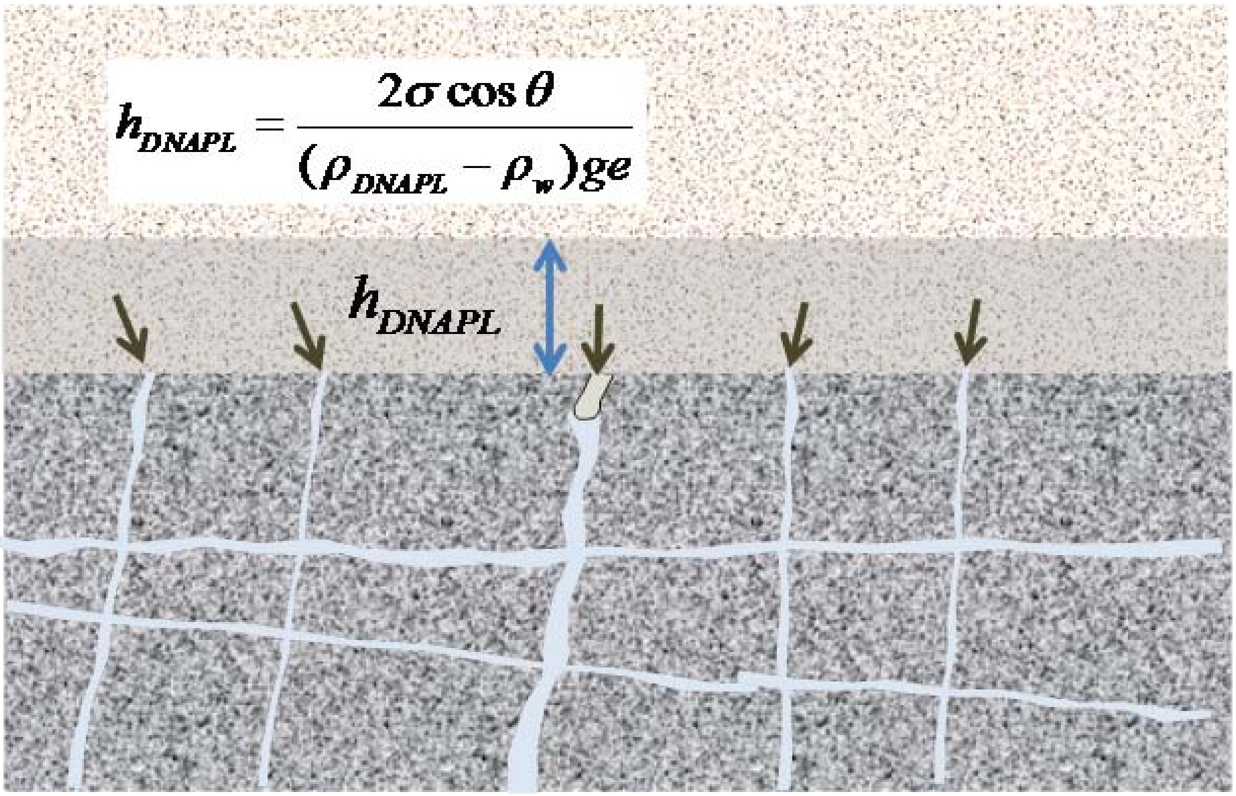
The third question involves whether or not the contaminant is dissolved or immiscible. If the contaminant is immiscible, then its transport will involve multiphase effects. Immiscible contaminants are referred to as Non-Aqueous Phase Liquids, or NAPLs. NAPLS may float or sink relative to water depending on the density contrasts, the strength of vertical groundwater head gradients, capillary effects, and geometric effects of the fracture networks. Such multiphase flow problems in fractures are a complex and still evolving field of study (Kueper and McWhorter, 1991; Fourar et al., 1993; Doe, 2000; Or, 2008). Further background on this topic appears in Appendix A.

Simply stated, the physics of single phase groundwater flow involves the driving forces of gravitational potential energy and the resisting forces of viscous interactions of the fluid with the rock pores or fractures. In multiphase flow, density-based gravitational forces come into play along with capillary forces that act along the interfaces between the fluids (or gasses) and the solid surfaces of the pores or fractures. The significance of these forces – gravity, viscosity, and capillarity – vary with the pore size or fracture aperture, where capillarity dominates in smaller pores or fractures and gravity dominates in larger ones. In a multiphase flow system, capillary pressures can immobilize wetting phase fluid in the smallest aperture fractures. In larger fractures, flow occurs according to Darcy's law but with different permeabilities for each phase that depend on their saturations. In the largest fractures, gravity dominates flow, producing a variety of non-Darcian flow processes that may be very rapid and are still poorly understood (Faybishenko, 2004; Or, 2008).

Capillary effects determine whether or not NAPL's enter the bedrock at all and how they move in the bedrock (Figure 7). NAPL from a contaminant source will pool in the soils overlying the bedrock until the pool's thickness, or head, overcomes the capillary pressure in the fracture. This critical capillary pressure is the *entry pressure*, which is inversely related to the fracture aperture (Kueper and McWhorter, 1990). The balance between the pool depth, h_{NAPL}, and the entry pressure appears in Figure 7 where $2\sigma\cos\theta$

is the product of the NAPL-water-rock surface tension and contact angle, $\rho_{DNAPL} - \rho_w$ is density contrast of the DNAPL and water, and g is gravitational acceleration, and *e* is fracture aperture.

Figure 7. Effect of fracture aperture on entry pressure for DNAPL.

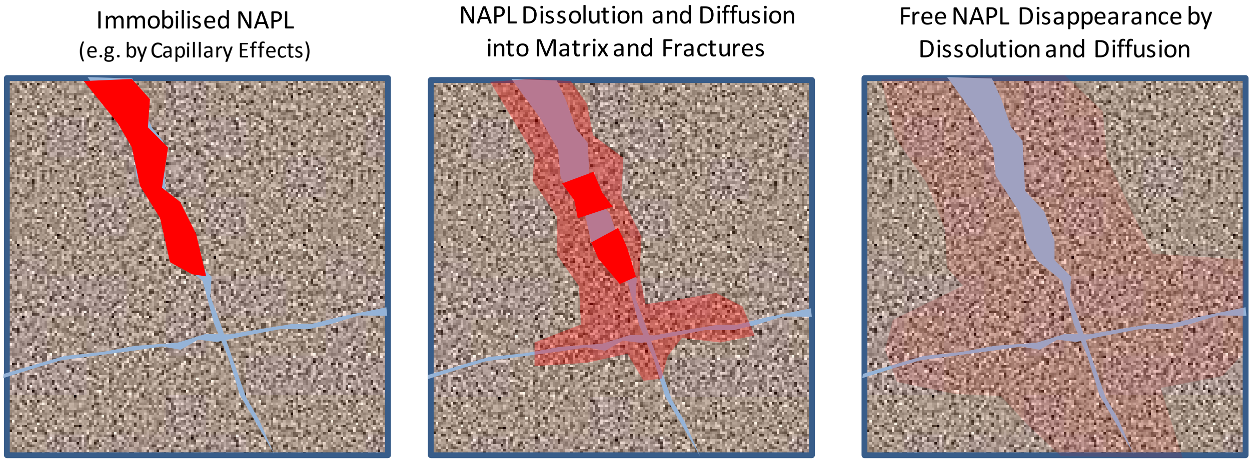


Although LNAPLS may be expected to stay above the water due to density effects, they can be driven into the saturated zone when the thickness of the LNAPL column has a head that overcomes both the capillary entry pressure of the fractures and the density contrast of the fluids. LNAPLs also can occur below the water table when water levels rise and they become trapped beneath a layer with a high capillary entry pressure (Hardisty et al., 2003). The entry of any non-aqueous phase liquid will be enhanced by downward hydraulic gradients and resisted by upward gradients.

When NAPLs become trapped in fractures in the saturated zone, either by discontinuity in flow paths or by capillary effects, they may disappear as a free phase over time by a combination of dissolving into the water and diffusing into the rock matrix (Parker et al., 1994). The process of NAPL disappearance starts with immobilization due to the combined effects of density, capillarity, and permeability. NAPLs may begin to dissolve into the water and diffuse into the matrix or be transported advectively in the fractures.

The time for free-phase NAPL to disappear can be relatively rapid depending on the contaminant solubilities and the rate of diffusion in the matrix (Figure 8).

Figure 8. NAPL disappearance.



Immobilised NAPL (e.g. by Capillary Effects)

NAPL Dissolution and Diffusion into Matrix and Fractures

Free NAPL Disappearance by Dissolution and Diffusion

3.2 Groundwater Conceptual Models

The scientific method proposes hypotheses, which it tests by experiments or field studies. In a scientific approach to site assessment, the hypotheses are proposed in the form of conceptual models. Conceptual models represent the analyst's beliefs about the groundwater flow system at a site. As all site assessments contain uncertainties, the conceptual models should include alternatives that are consistent with what is known about the site.

Conceptual models exist at every stage of site assessment, and the development of the site assessment program and the directions that it will take over its course involve comparing conceptual models with new information as a scientific test of the model's validity.

The objective of site assessment is public protection, as defined within a regulatory framework. Although it uses scientific approaches, its objectives differ from a scientific investigation, where the goal may be knowledge for its own sake. A site assessment needs to test its conceptual models with a view to their consequences. The efficient use of resources for environmental protection demands that the priorities of data collection and other activities focus on consequential alternatives, that is, unresolved site issues that have the greatest impact on site safety, while uncertainties that have no consequences to this goal may be given little or no attention.

3.2.1 The hydrostructural model and the fracture stratigraphic model

A fundamental requirement for most groundwater investigations in porous media is a ***hydro-stratigraphic*** model. This model starts with a geo-stratigraphic model, which is a description including the composition of the sediments or sedimentary rocks, descriptions of textures and sedimentary features, and inferences of depositional environments. The hydro-stratigraphic model augments the geo-stratigraphic model with information on the hydraulic properties of the strata, defining hydro-stratigraphic units in terms of their function in the groundwater flow system. The hydro-stratigraphic model uses information on the distribution of stratigraphic units to develop a subsurface model of the distribution of hydrogeologic properties.

The corresponding model for fractured media is called a ***hydro-structural*** model. The hydro-structural model differs from a hydro-stratigraphic model in recognizing that structural geologic features, like fractures and faults, also control groundwater movement. The hydro-structural model is often more complex than a hydro-stratigraphic model, because fractures and fracture networks have multiple orientations and cross-cutting relations.

The processes of developing a hydro-structural model and hydro-stratigraphic model are fundamentally the same. A hydro-stratigraphic model defines the layering of the system using units that have similar hydrologic functions, that is, aquifers and aquitards. A hydro-structural model separates the water-bearing structural features – faults, fracture zones, and fractures – from those that don't have a hydrologic function for inclusion in the model.

A ***fracture stratigraphic model*** combines aspects of both the hydro-stratigraphic and hydro-structural model. The frequency and hydraulic properties of fractures are sometimes controlled by the mechanical properties of sedimentary units. Fracture frequency is commonly related to bed thickness (Narr, 1991), and fractures often terminate at the layer boundaries. Thus one can define layering based on fracture properties, which generally will follow lithologic variations. Fracture stratigraphy is particularly important in layered rocks that alternate with brittle rocks, like limestones or well-cemented sandstones with more ductile shales.

Petroleum studies have established that oil and gas reservoirs may have a conceptual model with all three elements: a hydro-stratigraphic model of the layering, a fracture stratigraphic model of the fracturing in particular layers, and a hydro-structural model of regional fractures and faults that do not have a stratigraphic control.

3.2.2 The hydro-dynamic model

The hydro-dynamic model describes the forces that drive groundwater movement. Like porous media, gradients of hydraulic head drive saturated groundwater flow. Like heterogeneous porous media, the directions of groundwater flow are controlled both by the magnitude and direction of the hydraulic gradient and preferential flow within specific geologic features. The groundwater flow direction in a confined aquifer is in the direction of the gradient within that unit and not necessarily in the direction of maximum gradient, which may be across an aquitard towards another aquifer. Similarly for fractures, flow is guided by the orientation of the fracture as well as the gradient, and a fracture network with strong preferred orientations will direct groundwater flow in directions other than the maximum hydraulic gradient.

The site characterisation components of the hydrodynamic model include:

- Identification of the vadose zone;
- Spatial distribution of hydraulic head values in the saturated zone, from water wells;
- Locations of recharge and discharge; and
- Temporal variations in recharge and discharge.

The development of the hydro-dynamic model uses information from various sources including:

- Knowledge of regional groundwater flow patterns;
- Identification of topographic features that may control local recharge and discharge locations;
- Information on rainfall and infiltration of water to the bedrock;
- Water levels from existing wells;
- Water levels and piezometric information taken during hydraulic testing and groundwater monitoring systems;
- Single or multiwall tracer tests under passive (no pumping or injection) conditions;
- Mapping of contaminant plumes;
- Hydro-chemical sampling to identify fracture-network compartments or other mutually isolated flow sub-systems; and
- Interference tests (pumping tests with observation wells) for evidence of mutually isolated flow systems.

3.2.3 The hydro-processes model

The hydro-processes model is concerned with the processes that affect the fate of contaminants in the groundwater flow system, specifically those processes that act to retard, accelerate, retain, or transform contaminants. With the exception of matrix diffusion and to a limited extent sorption, these are beyond the scope of this review, but they include:

- Matrix diffusion;
- Dissolution of NAPLs;
- Micro-biologic processes;
- Sorption on surfaces of fractures and matrix pores; and
- Colloidal processes.

3.3 Groundwater Analysis and Numerical Modeling

Every site assessment needs some quantitative analysis of the results. Analysis simply means calculations, that is, a quantitative treatment of the data to answer the key questions raised in section 3.1: *where is water going, how fast is it going,* and *how are contaminants moving*. The calculations that make up the analysis approach can be very simple or very complex. They may use straightforward analytical solutions, or they may involve detailed numerical simulations. The choices will be site specific and will depend on what is required to determine public risk and to prescribe an appropriate remediation approach.

Every site assessment should employ analytical solutions or simple numerical models. These are the basis of scoping calculations. Sometimes these simple calculations are enough to make site decisions. Even if the program decides to proceed with more complex numerical modeling, scoping calculations are needed to provide quality checks on numerical results. Some simple analytical models of transport in fractured porous rock appear in Tang et al. (1981), Sudicky and Frind (1982), Maloszewski and Zuber (1990), and West et al. (2005). The differences lie mainly in the boundary condition assumptions. Using these solutions requires some computer coding as they are expressed as LaPlace transforms, which require numerical inversion (Carnahan and Remer, 1984), or as transformed solutions that require numerical integrations.

Analytical solutions and simple numerical models may be sufficient for many sites. A complex simulation requiring large effort is justified only for complex sites where the modeling results affect decisions that have large cost and public-risk consequences.

There is no consensus among academics or professionals on the best approach to numerical modeling. Section 3.2 discusses representations of fracture systems that form a basis for making calculations and building models. Appendix D reviews alternative methods for numerical modeling from discrete network methods to heterogeneous continua.

Rather than prescribe methods, a guidance should state more general objectives, specifically, that a model should be capable of representing the key features of a fractured bedrock system, which are:

- The locations and geometries of key conducting features;
- The boundary conditions likely to be active at the sites; and
- The key processes that are controlling groundwater and contaminant movement.

Furthermore,

- The calculations must consider likely uncertainties; and
- The effort devoted to analysis and simulation must be appropriate to the site decisions, such as the threat to the environment and the approach to remediation.

3.4 Key Data Needs

Based on the discussion above, a fractured-bedrock site investigation must address several key questions about the groundwater flow system. Table 1 summarises the relationships between key data needs and the three key questions.

Fundamental to all site investigations is the need for an understanding of the flow field, which requires first a description of the fracture network geometry and the hydraulic properties of the fracture network and second, an understanding of the heads that drive flow and transport in that fracture network. These determine where groundwater moves.

The velocity of groundwater further requires information on the fracture apertures, which determine the effective porosity in the bedrock. The groundwater velocity is a key input; however, it does not entirely describe contaminant movement as contaminants may move at slower velocities than the groundwater itself. The other forces that control contaminant movement are mainly gravity and capillary effects that appear when the contaminant is an immiscible liquid or moving in the vadose zone.

The main source of retardation, matrix diffusion, may be enhanced by sorption, which encompasses chemical interactions between the contaminant and the surfaces of fractures and matrix pores. Neglecting retardation in a site assessment will generally over-predict contaminant velocities. Since matrix diffusion also retards clean up, its neglect may also under-predict the clean-up times for remediation by pumping and treating. Matrix diffusion further requires some description of the porosity of the rock matrix, which may be viewed broadly as including not only rock that is porous by nature, but also rock that is made porous by chemical alteration, such as weathering.

If the contaminant is an immiscible fluid, a NAPL, then one needs to estimate the fracture apertures that control entry pressures at the interfaces of soil and bedrock. In addition, it is important to know the density contrast of the contaminant and water, as this determines the gravity forces that interact with capillarity to control pooling, bedrock entry, and density-driven flow. Multiphase effects also may move contaminants in different directions than the groundwater itself depending on the magnitudes of the gravity and capillary effects. Specifically, gravity will act on fluids with contrasting densities according to the dip angle of the fractures, hence gravity effects may be less in fracture networks than in a continuous porous medium (Doe, 2000).

3.4.1 Fracture network geometry and hydraulic properties

Evaluating the fracture network geometry is fundamental to any site investigation. A modern approach to fracture characterisation integrates geologic, hydrogeologic, geophysical, and geochemical tools with the goal of defining that portion of the fracture network that is important for fluid flow.

As discussed in Chapter 2, in most sites a subset of the fracture population is controlling the flow. This subset may be near-surface exfoliation features, or fracture zones, or fractures controlled by rock textures, such as bedding or foliation. In the near-surface environment, which is the focus of most contaminant studies, fractures enhanced by weathering or near-surface rock movements may be important as well (Figure 9).

The tools for assessing fracture network geometry are the following:

- Geologic methods including surface mapping, core analysis, and borehole image log analysis;
- Geophysical methods, including airborne, surface, borehole, and cross-borehole;
- Hydraulic methods, including packer testing, flow logging, pump testing (both single and cross-hole), and monitoring; and
- Chemical methods, involving sampling and mapping of contaminant and water types.

Detailed packer testing, which is the traditional method for such studies, has been augmented and sometimes replaced by flow logging. Optical image logs of holes can sometimes see indications of flow. Inspections of surface exposures should look for seeps or other indicators of flow activity.

The use of surface geophysical methods has advanced greatly in the area of fracture detection. The primary methods in use involve either seismic or resistivity approaches (Appendix B). Ground penetrating radar and resistivity sounding have been particular successful in finding major fracture zones and faults. With the exception of well flow logging, geophysical methods are less successful in distinguishing flowing fractures from non-flowing fractures that do not have thick damage zones. With respect to fracture mapping and well characterization, there is generally no substitute for detecting flowing fractures other than by direct measurement of flow using well tests, packer tests, or well flow logs. The combination of well flow logging and modern methods of well image logging especially using computer-enhanced optical imaging, has proven to be very powerful and efficient for identifying flowing fractures and their geologic identity.

Figure 9. Near surface fracture enhancement.

3.4.2 Hydraulic heads and the dynamics of groundwater flow systems

The distribution of hydraulic heads spatially can be determined from the identification of recharge and discharge locations as well as from direct measurements of groundwater head in wells. Information on hydraulic head gradients can also come from well flow logging under ambient conditions, where one is observing the vertical flow of water between fractures that intersect in the well. The directions of these flows indicate the direction of the hydraulic gradient. It is extremely important both for groundwater protection and management of head that any wells be completed with multi-zone piezometers that isolate flowing fractures from one another.

Hydraulic head monitoring is a powerful tool for mapping fracture connectivity. Discontinuous networks form pressure or flow compartments. Fractures that are part of the same compartment respond together to perturbations, while disconnected fractures show little or delayed responses. The responses to rainfall events can show how well a network is connected to the surface. When drilling of a new well intersects a conductive fracture, the responses in a piezometer network provide a connectivity map to that feature.

3.4.3 Matrix properties

The porosity of the rock matrix is essential to the estimation of matrix diffusion effects. As discussed in the appendices, matrix diffusion is a very significant source of retardation in contaminant transport. The porosity can be measured from rock samples or cores, or initial estimates can be taken from literature surveys. Air measurements for volatile organic compounds (VOC's) on cores can indicate the presence of contaminants in porous matrix. Observations of haloes of contamination around fractures provide further evidence for matrix diffusion. Geophysical logging in wells can also be a source of porosity data.

3.4.4 Fracture aperture characterisation

Fracture aperture is critical both for velocity calculations and capillary pressure assessment, specifically entry pressures for NAPL's moving into bedrock fractures. As discussed in Appendix A, methods that use the cubic law to estimate aperture from flow measurements of transmissivity are questionable and likely to under predict aperture values, possibly by orders of magnitude. This discrepancy arises from differences between real fracture surfaces and the ideal, smooth plates of fluid mechanics theory. The under-prediction of the transport aperture would imply over prediction of groundwater velocity. While this may be conservative, a large over prediction of velocity could be very misleading for site assessment. The appeal of the cubic law comes partly from the lack of alternative methods of measurement. The transport aperture, which provides the groundwater velocity from flow measurements, is very difficult to assess except by direct velocity measurements through tracer tests or inverse modeling of contaminant plumes.

The under prediction of aperture using the cubic law is not conservative for capillary entry pressure, as under predicted apertures lead to over predicted capillary entry pressures. A more reliable entry pressure determination may require back-calculation using the height of ponded NAPLs. Appendix A discusses the question of aperture measurements in further detail.

3.5 Site Characterisation Phases and Methods

A site investigation typically involves four stages which are:

- Desk studies;

- Surface-based characterisation;
- Single-hole characterisation; and
- Multi-hole characterisation.

Table 2 relates recommended characterisation methodologies to each stage. Table 3 presents an overall workflow including the products, analyses, and decisions that accompany each stage. Figure 11 presents a condensed flow chart of the assessment approach.

3.5.1 Desk studies

Desk studies form the initial stage of any site investigation. They use existing site data, if available, as well as data from case histories of similar contaminated sites nearby or analog sites in the technical literature. At the desk studies stage, it should be possible to develop a preliminary model of the hydrodynamics of the local groundwater flow system based on the identification of likely recharge and discharge locations as well as head data from existing wells in the area.

3.5.1.1 Use of existing data sources

The characteristics of fractures and the identification of important fractures for flow at the desk study stage should rely heavily on experience from any nearby contaminated sites in similar rock types and geologic settings, if these are available.

Fractures may express their geometric patterns on the earth's surface, even when the bedrock has some thickness of cover. Linear patterns in topography and vegetation are often detectable in air photos, satellite images, and other forms of remote sensing. Major faults and fracture zones may produce topographic lineaments that can be identified in air photos or in LIDAR images from existing sources (Gleeson and Novakowski, 2009; Nyborg et al., 2007; Rhén et al., 2007). Early-stage characterisation work may also use airborne geophysical data from aeromagnetic or VLF (very-low frequency) data (Nyborg et al., 2007; Pedersen et al., 2009).

Until these linear features are ground-checked for their origin, they are called lineaments. Not all lineaments are water conductors, and not all major water conductors produce lineaments (Mabee et al.,

Table 1. Data inputs to key questions.

	Fracture Network Geometry and Hydraulic Properties	Boundary Conditions	Fracture Transport Aperture	Matrix Porosity and Sorption Properties	Fracture Capillary Aperture
Where	Anisotropy, Compartmental-isation	Head distribution controls flow direction with network geometry and hydraulic properties			Multiphase pooling, NAPL bedrock entry
How Fast	Tortuosity, Connectivity to boundaries		Main property controlling velocity	Retardation due to diffusion	
Concentration	Dispersivity and dead-end diffusion, fracture porosity	Source strength and character	Dispersivity		

Table 2. Characterisation recommendations by stage. Key to fonts: ***Essential***, **Very Useful, Somewhat useful,** ***Research***

	Desk Study	Surface-Based Characterization	Single Well Characterisation	Monitoring and Completion	Multi-Well Characterisation
Geology	***Case histories and analog sites*** Lineament interpretation of existing air photo and Lidar data	***Map fractures in rock exposures (preferably quantitative)***	***Optical televiewer logging*** ***Core fracture description*** ***Acoustic televiewer logging***		**Correlation of key fractures between wells**
Geophysics	Existing Airborne Geophysics	**Ground penetrating radar** Resistivity sounding Seismic refraction/reflection	Temperature, fluid conductivity *Single hole radar reflection*		*Cross hole tomography*
Hydraulic Properties	***Case histories and analog sites***	**Fracture mapping for aperture estimation and indicators of active flow,** **Assessment of fracture weathering from surface mapping**	***Flow logging (pumping)*** **Single hole transient tests**	***Monitor heads for Responses during drilling and natural perturbations***	***Transient interference tests*** ***Monitor head perturbations***
Hydrodynamics	***Recharge and discharge locations*** ***Head data from existing wells***	***Measure heads in existing wells***	***Ambient flow logging or head measurements during detailed packer testing***	***Monitor hydraulic heads***	***Monitor hydraulic heads***
Transport Properties	***Case histories and analog sites***		**Porosity measurements on cores**	***Plume mapping***	**Tracer tests**
Water Chemistry and Contaminant	***Case histories and analog sites***	***Sample surface-water discharges***	***Plume mapping*** ***Checking core for***	***Sampling from multipoint***	**Sample for water chemistry changes**

Characterisation			***<u>contaminant saturation</u>***	***<u>piezometers</u>***	

Table 3. Site Characterisation Workflow

Stage	Methods	Product	Numerical Analysis	Decisions
Desk Study	Case Studies	Preliminary conceptual model	Scoping calculations	Likely fractured or non-compliant?
		Flow field		
	Existing Map and Remote Sensing Data	Overburden, likely weathering		
		Possible fracture types and styles	Simple numerical models	Characterisation strategy
		Likely contaminants		
	Existing well data	Likely multiphase or matrix diffusion		Surface characterisation plan
Surface Characterisation	Mapping rock exposures	Updated conceptual model	Updated scoping calculations	Fractured or non-fractured?
	Heads in existing wells	Overburden type thickness		
		Possible major fracture zones		
	Sample existing wells and surface discharges	Fracture weathering and fracture types	Simple numerical models	Updated characterisation plan with first hole location and generalised drilling locations
	Surface geophysics	Matrix properties (if accessible to rock)		
Single Well Characterisation	Detailed flow characterisation	Updated conceptual model	Updated scoping calculations	Fractured or non-fractured?
	Geologic description of conducting features	Identification of key fractures and fracture types		
	Ambient and pumped flow logging	Preliminary aperture assessment	Initial site numerical model	Updated characterisation plan with second hole location and more specific drilling locations
	Sampling with depth	Preliminary hydraulic and transport properties		
	First multizone piezometer	Updated plume model		
Multiwell Characterisation	Monitoring multipoint systems	Tested conceptual model	Updated scoping calculations	Fractured or non-fractured?
	Continued sampling	Conducting fracture network		

	Cross hole well tests	Flow field		
		Final hydraulic and transport properties	Site numerical model	Updated characterisation plan (or decision to stop field work)
	Tracer tests	Plume configuration		

Figure 10. Site characterisation workflow.

Desk Study

Tools:

Review analog sites and existing data

Air photo or and Lidar data for major lineaments

Products:

Preliminary conceptual models

Surface Characterisation Plan

Decisions:

Is site subject to fracture protocols?

Assess likely contaminants and likelihood of matrix diffusion or multiphase flow (NAPLs)

Surface-Based Characterisation

Tools:

Inspect/Map/Sample surface bedrock exposures, springs, water discharges

Identify existing wells, sample water, measure heads

Surface geophysics (GPR, Resistivity, or seismic) to overburden thickness, and faults or fracture zones (if suspected)

Products:

Assess likely contaminants and likelihood of matrix diffusion or multiphase flow (NAPLs)

Revised conceptual models, scoping calculations, simple numerical models

Borehole Characterisation Plan (specific for first borehole, and general for later boreholes)

Decisions:

Is site subject to fracture protocols?

Single-Borehole Characterisation

Tools:

Optical televiewer

Core (preferred for first hole, especially useful for matrix diffusion assessment)

Flow logging (ambient and pumping) or detailed packer testing to identify significant flowing fractures

Sampling from discrete zones

Installation of multi-zone monitoring system

Products:

Revised conceptual models, scoping calculations, preliminary site numerical model

Borehole Characterisation Plan for second and subsequent boreholes as needed

Decisions:

Is site understanding sufficient for delineating and predicting contaminant transport?

Multi-Borehole Characterisation

Tools:

Same as single-borehole

Monitor heads in piezometers during drilling, testing, and sampling

Sampling and interference (pump) testing

Tracer test (as needed)

Products:

Final conceptual model, site numerical model

Final site assessment

Decisions:

Is site understanding sufficient for delineating and predicting contaminant transport?

2002), but the existence of some relationship between lineaments and water-bearing features has been well established (Lattman and Parizek, 1964; Mabee et al., 1994; Sander, 2007). Transport properties and contaminant characterization should rely on case histories to the extent that data from similar sites are available.

3.5.1.2 *Desk study products and decisions*

The desk study should produce the following results:

- A preliminary conceptual model for the flow field;
- An estimate of the overburden thickness and fracture types;
- The likely contaminants and their properties; and
- An assessment of whether or not multiphase and matrix diffusion effects are important for the investigation.

The flow field at this stage may not adequately account for discontinuity and compartmentalisation effects unless existing well heads show a high level of variability that is difficult to explain.

Scoping calculations and simple numerical models may also be valuable at this stage to identify the range of possible site behaviours.

The decisions of the desk study should include the following:

- An assessment of whether there is sufficient evidence to determine whether fractured bedrock is not likely present and fracture protocols are unnecessary; and
- A general strategy for site assessment with a specific plan for surface-based characterization.

3.5.2 Surface characterization

Surface-based characterization involves site activities that do not require well drilling. For fracture characterization, the primary methods involve mapping rock exposures and some surface geophysics.

3.5.2.1 *Surface geophysics*

Surface geophysics can be useful at this stage for determining the depth to bedrock by resistivity surveys, ground penetrating radar (GPR), or seismic refraction. The properties of materials that are determined from geophysical surveys may also indicate whether or not the rock is heavily weathered. Surface geophysics may indicate the presence of major fracture zones or faults, but it will not give information on the intensity or hydraulic properties of smaller joints and fractures.

Resistivity sounding is well suited to detecting larger, thicker zones of altered rock like fault zones. Sounding methods have been successful for finding such features at the USGS research site at Storrs, Connecticut (Johnson et al., 2001). Electrical properties over larger scales can have properties of direction and persistence that are controlled in part by the preferred direction and connectivity of fractures with water or with conductive alteration zones (al-Hagrey, 1994; Skinner et al., 2004; Yadav and Singh, 2007).

GPR has been successful in defining fractures in the shallow subsurface (Stevens et al., 1995; Grasmuek, 1996; Travassos and Menezes, 2004; Porsani et al., 2006). The USGS also used GPR with confirmatory flow logging in boreholes to identify sheet-like fractures at the Storrs site (Johnson et. al., 2001, 2002a).

Seismic surveys have been applied in radioactive waste studies. Kim (et al., 1994) obtained good seismic reflections from open, exfoliation fractures to over 100 meters depth at Atomic Energy of Canada's underground laboratory site in Manitoba. Juhlin (1995) and Juhlin and Stevens (2006) used seismic reflection to delineate a major, sub-horizontal fracture zone at a granitic study area in Sweden.

In summary, surface geophysical methods are useful primarily for identifying larger features prior to drilling, particularly faults and fracture zones that have some thickness, or fractures that are surrounded by a thick alteration zone. The presence of conductive fluids can enhance electrical results. GPR can be effective in locating resistive rocks that are not buried under a conductive overburden.

3.5.2.2 Surface fracture mapping and sampling

Geologic activities during the surface-based stage involve inspecting and mapping existing bedrock exposures. The mapping should note types of fractures present (exfoliation, bedding, tectonic fractures, fracture zones, etc.) as well as observed weathering, alteration, and indicators of seepage. Geologic work may use 2-D surfaces to produce fracture maps, or outcrops may be investigated using scanline surveys. Good examples of mapping to identify hydro-structural domains in British Columbia's Gulf Islands appear in Surrette (et al. 2007, 2008) and Chesnaux (et al., 2009). Modern methods using photogrammetry and LIDAR can greatly improve the mapping efficiency using computer processing (Kemeny and Post, 2003; Tonon and Kottestette, 2006). Computer-assisted fracture analysis has advanced greatly in recent years being driven by rock engineering needs for rapid assessments of rock slopes.

Water sampling from seeps may be as useful as well sample collection if there are surface discharges that reflect groundwater flow paths that pass through the site. A sampling program at the site targeting the shallow overburden will help to define the contaminant types and possible NAPL pooling in the overburden.

For some sites where the overburden is relatively thin or nonexistent, there may be value in stripping the soils down to bedrock. Direct mapping of fractures of the bedrock surface underneath contamination sources can show directly if contaminants have entered the groundwater flow system and the likely fractures where entry might have occurred. Soil gas surveys may also indicate which fractures have been taking contaminants. On these surfaces it may also be possible to observe whether or not contaminants have migrated into the matrix. The importance of matrix diffusion may be assessed both by these direct observations and by the collection of samples for porosity measurements.

3.5.2.3 Activities in existing wells

The desk study phase should identify existing wells near the site, and determine their accessibility. If there are accessible wells, these should have head measurements and water samples taken.

3.5.2.4 Surface-base characterisation products and decisions

Surface-based characterization should produce the following:

- An updated conceptual model including the flow field, as well as identifying possible major fracture zones, overburden types, and their thicknesses;
- An updated assessment of contaminant present; and
- Scoping calculations on the directions and possible extent of contaminant migration. Simple numerical models may be appropriate at this stage to evaluate the consistency of conceptual models with site observations.

The decisions that should result from surface-based characterization include:

- An updated assessment of whether or not the site is fractured and subject to fracture protocols; and
- A sub-surface characterization plan with specific plans for the location of the first hole and generalized plans for locating subsequent holes.

Each well, as with every site assessment activity, should address specific hypotheses or data needs. The plan for each well should predict what it will find based on the site conceptual model. The predictions should include alternative outcomes that are based on site uncertainties. The site plan also should address how different outcomes would affect subsequent characterisation efforts.

3.5.3 Single well characterization

3.5.3.1 Planning the drilling

The site investigation should start with a very clear plan for the first well. This well is critical for testing the preliminary conceptual models that were developed in the desk study and surface characterisation phases. The planning must consider the types of contaminants that are likely to be present and how they would have migrated.

A successful program clearly depends on intersecting the conductive fractures. Desk studies and surface characterisation should have defined the types of fractures that are likely to be present. This may require non-vertical drilling to intersect the conducting fractures if they are steeply dipping. Angle-hole drilling may not be necessary if there are shallow dipping fractures, such as bedding-plane fractures or exfoliation fractures that provide hydraulic connections to other, more steeply dipping fractures. Drilling strategies need to be adaptable if the assumptions of the pre-drilling studies are not valid.

3.5.3.2 Flow logging and packer testing

The main goal of flow logging and packer testing is the identification of the flowing fractures in the well. For this purposes the hydraulic characterisation, whether by flow logging or packer testing, must cover the entire hole length and not selected zones based on core or camera logging. Only flow testing can determine reliably whether a fracture is conducting, and one cannot rely on geologic inspection or geophysical surveys.

Hydraulic characterisation can use either flow logging or detailed packer testing. Flow logging is more efficient than packer testing for locating conducting fractures and for determining the direction of vertical hydraulic gradient. Packer testing allows more flexibility to sample and test specific zones. Flow logging and packer testing can be combined to let the logging locate the conducting fractures. The packer testing can focus detailed sampling and pump or slug testing to the fractures identified by flow logging.

Flow logging uses downhole flow meters that are placed in the hole using tubing or a wireline. The common flow meter types are the spinner log, heat pulse flowmeter log, and electromagnetic flow meter log. Spinner logs (Molz et al., 1994) use an impeller that rotates at a speed proportional to the flow rate. Although these logs are common in the oil industry, where they are called production logs, in groundwater work these have been replaced by heat pulse or EM (electromagnetic) flow meter logs except in higher flow cases. The heat-pulse flow log is currently the most widely applied logging method (Paillet and Pedler, 1996; Paillet, 1998; Williams and Paillet, 2002). The logging tool employs either a packer or flexible rubber cups to isolate a logging interval. The log may be used with a single packer or flexible cup to measure the total flow from the hole beneath the measurement point, or it may use double seals to measure flow from a limited depth zone.

Flow logging should be run in both ambient and pumping modes. The ambient flow log is run without pumping. If there is no vertical hydraulic gradient at the site, the ambient log will not measure any flows. If there is a vertical hydraulic gradient, the ambient log will shows flows between fractures that have different hydraulic heads, and the direction of the flow, up or down, will indicate the direction of the hydraulic gradient (Figure 11). For example, consider a well that intersects three flowing fractures at a site where the middle fracture has a lower static head than the upper and lower fractures. The ambient flow log will show water entering the well at the upper and lower fractures, and leaving the well at the middle fracture. This will appear as an upward flow from the lower fracture to the middle fracture, and downward flow from the upper fracture to the middle fracture.

The ambient log is qualitative as the flow rates are a function of both the head difference and the transmissivities of the fractures. A quantitative interpretation requires independent information on either head or transmissivity from the flowing fractures. The ambient flow log is also critical for designing the multi-zone piezometer installations. While it is desirable to isolate every flowing fracture, it is imperative that fractures that show ambient flows are isolated in separate intervals.

The pumping flow log shows the depths of flowing fractures and the magnitudes of those flows. The transmissivity of each flow fracture can be estimated from the flow and the drawdown of the well; however, the flow rate for the transmissivity calculation should use the difference between the ambient and pumping rates.

Packer testing can also provide this detail. Packer testing should be conducted with a sufficiently short straddle interval to provide resolution of the conducting fracture depths. Packer testing may be conducted efficiently in two passes, one with a large straddle interval over the entire hole, followed by a short straddle interval that would test only in large-straddle intervals that had flow. An advantage of packer testing is the ability to estimate groundwater heads and to obtain better hydraulic property values using transient test methods.

3.5.3.3 Well test methods: packer tests, pump tests, slug tests, and derivatives

Packer testing is a general term for hydraulic tests that use inflatable rubber seals (packers) to isolate testing intervals. Civil engineering investigations (Moye, 1967; Braester and Thunvik ,1984; Brassington and Walthall, 1985) commonly use packers to test fixed, contiguous intervals of boreholes, for example, 10m-15m, 15m-20m, and so on. Many diamond core drillers offer packer testing as a service as part of the drilling. Such tests commonly use water injection, which may not be appropriate for contaminated sites.

Hydraulic tests, including flow logs, derive hydraulic properties using either steady-flow or transient flow methods. Steady flow-methods assume the perturbation of the test has reached a steady state, that is, the pressures and flow are not changing with time. Transient methods use the change in pressure or flow with time in response to the perturbation of the test. Transient responses change over the duration of the test to show how properties and geometries vary with distance from the well. Steady methods do not have this power, and their results are dominated by the properties of the rock that is immediately around the well. If hydraulic properties are constant with distance, both methods give similar results, but more commonly there is a “skin” of lower conductivity material near the well coming from either drill cutting invasion or the natural variability of the rock that causes steady methods to underestimate the flow properties of the rock.

Most packer tests use steady flow methods to derive test-zone transmissivity. There are many variants of the steady flow equation, but essentially they are the specific capacity of the test zone (flow rate divided by head change) with a shape factor for an assumed flow geometry (see Mathias and Butler, 2007, for a recent compilation of steady-flow approaches). Flow logs do not measure transient behaviours, and thus rely on steady-flow interpretations. A common alternative to the constant-pressure injection of packer tests or the constant-rate withdrawal of pumping tests, are tests that simply withdraw a volume of water quickly from the well and record the head recovery. These are known as slug tests among hydrogeologists or as falling-head (or rising-head) tests among engineers. The analysis methods for slug tests use either steady flow (Hvorslev, 1951; Bouwer and Rice, 1976) or transient flow assumptions (Cooper et al., 1968; Butler, 1997). Transient methods, which incorporate storativity, should be preferred.

The pressure derivative plot is a recent development in the petroleum-industry (Bourdet et al., 1983; Horne, 2000) that is gaining use in hydrogeology as well (Spane and Wurster, 1993). Pressure derivatives use double-logarithmic plots of transient head along with the semi-log derivative of the transient head. Understanding that “derivative” refers to a semi-log derivative clarifies a significant source of confusion. The semi-log derivative derives from the most common method of pump-test interpretation, which uses the Cooper-Jacob approximation (Cooper and Jacob, 1946) of the Theis (or exponential integral) function. This solution applies to radially convergent flow to a point source in a two-dimensional, planar feature. It produces head changes that are a linear function of log time. Hence, when the conditions of the semi-log approximation are met, the heads will follow a semi-log straight line, whose slope is inverse to the planar feature’s transmissivity. As the derivative plot is the semi log slope, it has a constant value and thus a zero slope when the Cooper-Jacob approximation is valid. It is important to note that Theis or Jacob-Cooper behaviours are not, by themselves, indicators of porous or fractured media flow. Flow in a single horizontal fracture follows this solution, as does flow in a well-connected fracture network that is confined to a planar region, like a stratum. Indeed, any test curve can be interpreted using either fracture or porous medium assumptions.

While derivative plot's original intent was defining the validity of the Cooper-Jacob approximation, it has proven to be a powerful method to assess flow geometry and flow regimes in general. Channel, or linear, flow, which appears from a fracture network with one dominant sub-vertical fracture set, produces a distinctive half-slope, while spherical flow in well-connected, three-dimensional networks produces a negative half slope. Hydraulic boundaries and well effects, like storage and skin, produce their own distinctive derivative responses. Figure 12 shows the variety of responses in idealised derivative curves as follows:

- Upper graph: Well effects followed by two-dimensional (Jacob-Cooper) flow with later boundary effects that are either closed (no-flow) or highly conductive are shown.
- Lower graph: Flow in a planar feature (flat derivative) followed by flow in a channel-like feature (half-slope, linear or one-dimensional flow) or flow in a well-connected three-dimensional network (negative half-slope, spherical flow). The dip in the curve shown on the red line is diagnostic of dual porosity behaviour.

Chakrabarty and Enachescu (1997) show how slug-test data can be deconvoluted to give the derivative behaviour of an equivalent constant-rate test.

Figure 11. Flow logging results for a three-conductor system at different static heads.

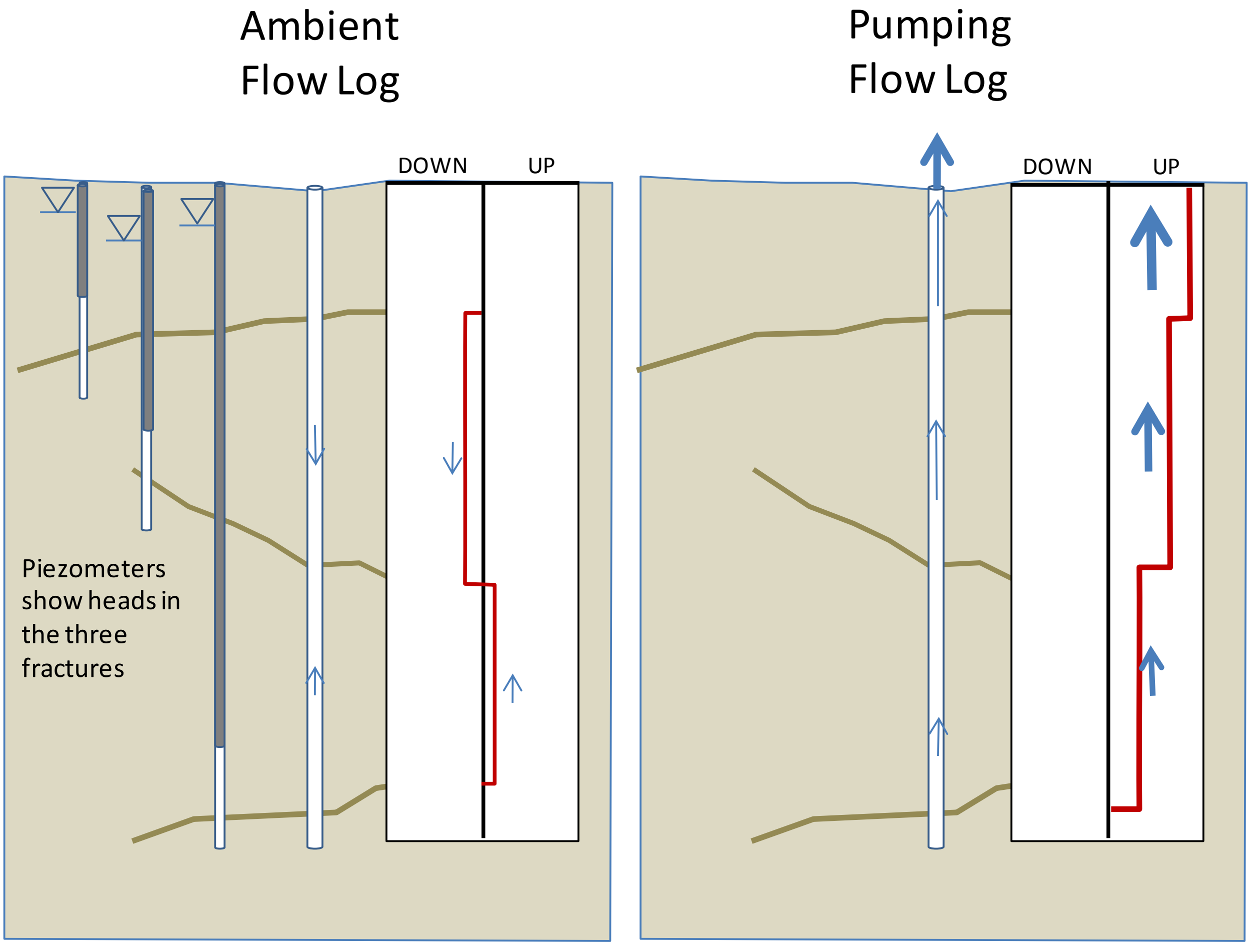
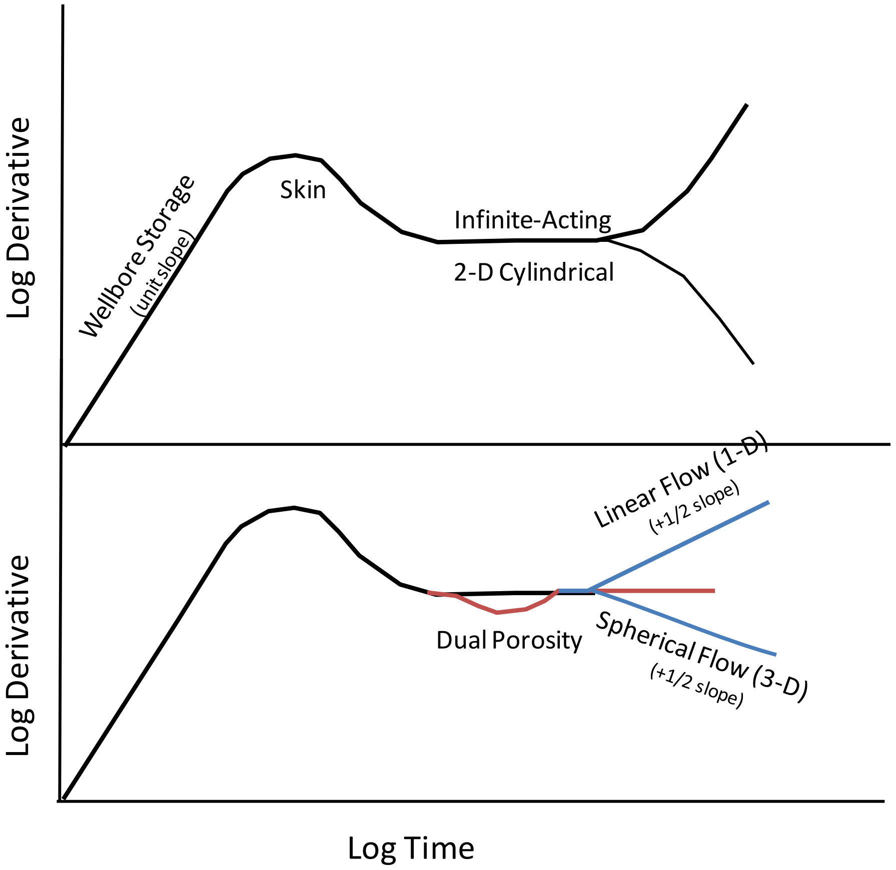


Figure 12. Basic elements of pressure derivative interpretation.



3.5.3.4 *Water sampling and contaminant profiling*

The flowing zones should be sampled for groundwater chemistry and the presence of contamination using a packer system to isolate the flowing zone. Alternatively, the sampling may be deferred until after piezometer completion, if the piezometer is a type that supports sampling.

Groundwater sampling can have two purposes:

- The identification of contaminants and concentration profiles within fractures along the well; and
- Identifying natural chemical variation to delineate flow systems and fracture networks.

Water sampling of the overburden above the well is critical to define the contaminant concentrations at the top of bedrock. The presence of contamination in the overburden requires particular care in casing the overburden to prevent the spread of contamination during drilling. Similarly, drilling should pause and consider isolation measures if it encounters open fractures with high concentrations of contaminants or NAPLs. Such fractures may appear at any depth, but are most likely to appear near the surface where there may be exfoliation features and good connection to contaminant sources at the surface.

If NAPLs are the known contaminants, the drilling plan must allow for the following:

- Defining the thickness of NAPL pooling, if any, at the bedrock surface;
- Looking for ponded NAPLs at any depth where fracture connectivity and aperture reduction may impede movement; and
- Considering the possibility of dissolved contaminants originating from NAPL in matrix rock.

If the total release of NAPL can be estimated, then the sampling program should try to account for the distribution of that volume in the rock. Although this may be imprecise, the accounting can guide decisions about where and how deep to drill. For example, a comparison of the estimated release with the volume of NAPL in the overburden may indicate how much may be ponded on bedrock and how much may have penetrated into bedrock fractures. DNAPL masses that are not accounted for in overburden, the matrix porosity, or in sampled fractures may have migrated laterally with groundwater flow or down the dip of fractures or bedding surfaces. Similar accounting for LNAPL should not assume that density effects limit contamination to the water table, as water table fluctuations can result in LNAPL trapping below layers with high capillary entry pressure (Hardisty et al., 2003).

Aside from defining contaminant spatial distribution, groundwater sampling can define fracture connectivity from the distributions of groundwater types. Low groundwater velocities and relatively stagnant conditions can be inferred from chemical products that show long residence times for the groundwater in the fractures.

3.5.3.5 Geologic characterisation: image logging and core studies

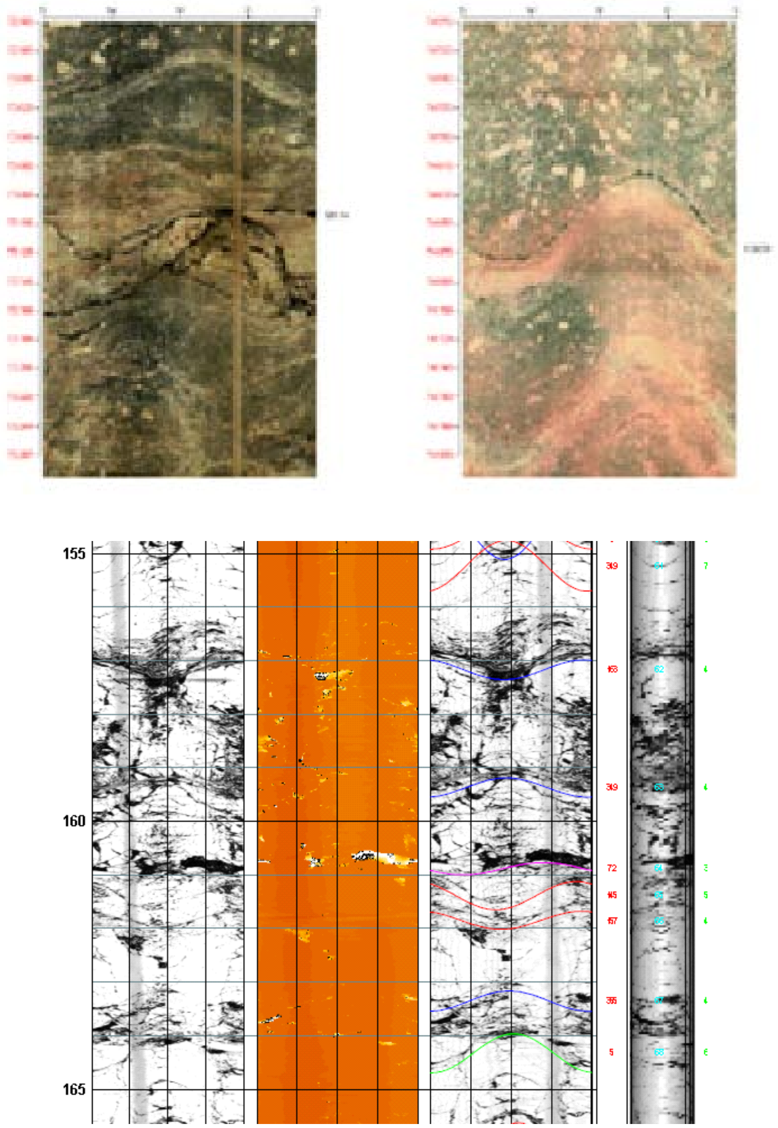
Having identified the flowing fractures, it is important to obtain a geologic description of those fractures. The description should include geologic controls on the fracture such as bedding, foliation, tectonic fractures, or exfoliation. It is also important to note whether the flowing zone is a single feature or part of fracture zone or fault zone. Noting the presence of clay gouge along faults or fracture zones can be helpful for identifying potential flow barriers.

A qualitative description of porosity around the fracture is important for assessing matrix diffusion. This porosity may be a primary porosity of the rock or it may be an alteration or weathering enhanced porosity. Observations of contaminants in core from the well, either visually or by VOC measurements provide further indications of matrix diffusion. Fractures with porous alteration may also have elevated effective porosities that will decrease the groundwater flow velocity compared with an unweathered open fracture with the same transmissivity.

The geologic description of the well may use image logging, core or both. Image logging uses borehole television, optical televiewers, or acoustic televiewers. Borehole television uses a downhole camera which looks down the well, or uses mirrors to see the well wall. These are relatively inexpensive, but create distorted images. Optical televiewers (Williams and Johnson, 2004; Johnson et al., 2002b) digitally process optical images of the borehole wall producing core-quality, distortion-free images amenable to fracture analysis (Figure 13). Acoustic televiewers use acoustic waves to image fractures using the reflection times to map the well surface topography and the reflection amplitudes to map the elastic properties of the rock. Optical televiewers provide a better basis for geologic interpretation; however, acoustic televiewers have the advantage that they work in holes where water clarity is an issue.

For fracture characterisation alone, image logs may be a suitable replacement for core, which can be expensive to drill. Image logs have advantages over core in highly fractured zones where core is often not retrieved or where the core comes to the surface as rubble. Core may be very helpful to show if contaminants have penetrated the matrix porosity or to provide samples for porosity measurements.

Figure 13. Image logging by optical televiewer in plutonic rock and acoustic televiewer image in volcanic rocks.



3.5.3.6 Geophysical logging

Wireline geophysical logs, including electrical and acoustic, are widely used for fracture characterisation particularly in the oil and gas industry. For the purposes of identifying conducting fractures, these geophysical logs are redundant if there is a flow log. Other geophysical logs, particularly resistivity logs, may be helpful for assessing matrix and alteration porosity and to identify pore fluids that affect geophysical properties including saline water and some contaminants.

3.5.3.7 Multi-zone piezometer completion

Multi-level monitoring systems have been in use for about 30 years. They began as research tools, but have gained increasing acceptance especially in the last 15 years. The first commercial installation was the Westbay system in the late 1970's followed by the Waterloo systems of the 1980s, and more recently flexible liner systems from the late 1980's (Parker et al., 2006).

A simple system for multi-level monitoring uses either (1) separate wells for each test zone or (2) installs multiple, nested pipes set to different depths with cement or bentonite grouts isolating the monitoring zones. Nested piezometers can be effective if neither the number of zones nor their depths is great. Another cost-effective monitoring method for head measurements simply cements pressure transducers into a well, which can be surprisingly effective provided the transducers are located at the depths of conducting fractures (McKenna, 1969; Mikkelsen, 2002; Contreras et al., 2008). A variation on a nested piezometer is Continuous Multichannel Tubing (CMT; Einarson and Cherry, 2002) which uses a plastic tube with segments that can be ported to different depth zones, which are isolated by alternating sand and grout-backfill.

Recent advances in monitoring-system design use specially-designed casings that allow multiple isolations in a single well. The Westbay (Black et al., 1986) and Waterloo-Solinst (Cherry and Johnson, 1982) technologies use a modular system of casing and ports, which are adapted to sampling or pressure measurement. Packers or a grout backfill isolate the monitoring zones.

Flexible liner systems, commercially known as FLUTe systems (Keller et al., 2006; Cherry et al., 2007) are soft thin liners that make a continuous seal along the borehole using an internal, positive hydraulic pressure. Tubes are welded into the liner wall at monitoring points, where spacers separate the liner from the borehole wall to make a monitoring interval. The tubes provide access for sampling or pressure measurement.

When the well logging is completed, a multi-zone monitoring system must be installed isolating the significant conducting features, particularly if the ambient flow logging showed that there were vertical groundwater head gradients (Figure 14). This piezometer should be set up with a system that monitors the hydraulic heads both for the determination of static groundwater head and to track head changes from rainfall events and from future drilling activities. Multi-zone monitoring types are described further in the appendices.

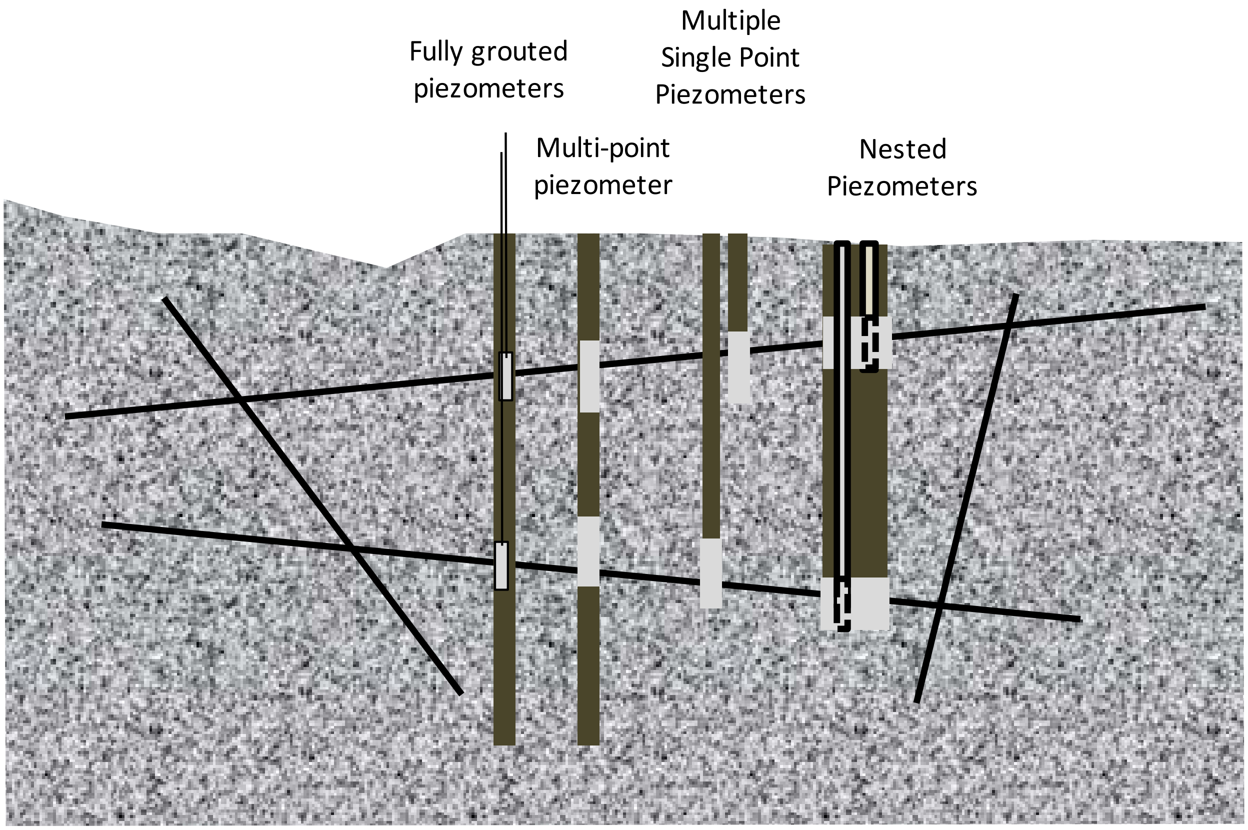
3.5.3.8 Single well characterisation products and decisions

The results of single well characterization provide a strong test of the preliminary conceptual model of groundwater flow at the site. It should identify the key fractures and key fracture types responsible for groundwater flow. Image logs can provide a primary assessment of aperture as well as an initial set of hydraulic and transport properties. If there is a contaminant plume, sampling may provide information on the vertical and lateral extent of its development.

The data from the first hole along with surface characterisation and desk studies should define a site conceptual model to a moderate level of confidence, or to constrain the site conditions to a limited number of alternative conceptual models. These data should be sufficient to support updated scoping calculations and to build an initial numerical model of the site. If there are data on contaminant migration, these may be used to validate key aspects of the conceptual model, such as the importance of matrix diffusion or multiphase effects. These conceptual models, with their quantitative representations (either as scoping calculations or numerical simulations) should provide a basis for siting additional wells. The plans for new wells should include predictions of the conditions they will encounter. These predictions should include both a base case conceptual model as well as likely alternatives to provide scientific tests of the conceptual models' hypotheses.

As with previous characterization stages, a site may be deemed as non-fractured if the hydraulic characterization indicates the porous medium rather than fractures represents the primary means of groundwater flow. Also after the characterization at the first well, the site characterization plan should be updated to determine the specific location of the second well, and likely locations for subsequent wells.

Figure 14. Multi-zone piezometers.



3.5.4 Multi-well characterization

The drilling of the second well and subsequent wells should provide the necessary data to assess the flow field, characterise the fracture network geometry and connectivity, determine the extent of contamination, and provide an assessment of matrix diffusion and multi-phase effects.

Single-well characterisation should produce a conceptual model of the hydrogeology of the site with alternatives to reflect uncertainty. Each new well should be designed to test the conceptual model to build confidence in its accuracy or to indicate how it should be changed. The drilling program for multiple wells must be adaptable to change locations and depths if new data from a particular well changes the conceptual model of the site. Hence it is important that new wells be located and designed sequentially rather than rigidly and specified in advance. The information from three wells is often enough to verify a site conceptual model; however, more drilling may be required for geologically complex sites, sites where the initial drilling significantly changes the conceptual model, or sites with extensive contaminant plumes.

3.5.4.1 Single-well characterisation of additional wells

The program of drilling, testing, and piezometer installation for each new well should follow the procedure of the single well program outlined in section 3.4.3.

3.5.4.2 Head responses in the piezometer network

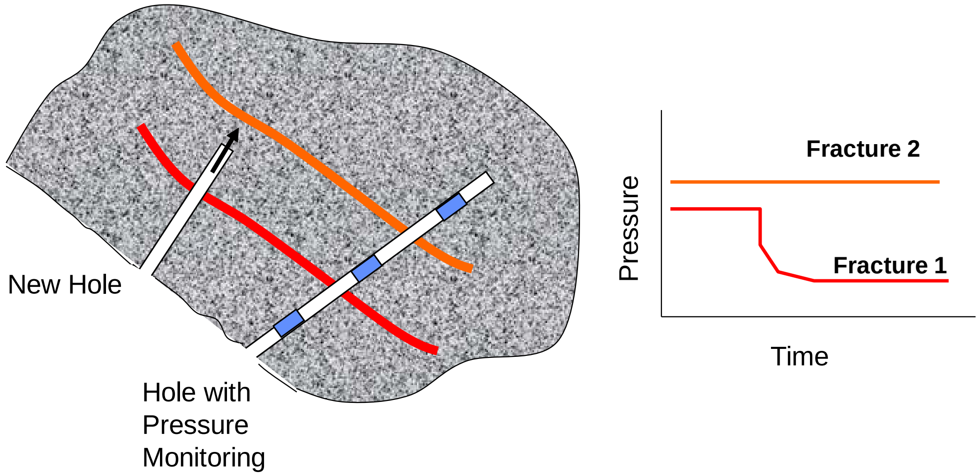
Head monitoring in the piezometer network serves two objectives:

- Mapping hydraulic heads and assessing hydraulic gradients; and
- Mapping fracture connections from responses to natural events, drilling, and pumping.

When a new well intersects conducting fractures, the drilling may create head responses in piezometer intervals that are connected through the fracture network. The spatial distribution of the responses, and non-responses, maps the fracture network. Similar effects may also appear in response to other perturbations in the flow system such as rainfall events.

Further definition of the hydraulic properties of the fracture network may be obtained by multi-well pumping tests using the piezometer network. As with the single well program, the sampling activities should be designed as pumping tests to provide information on the hydraulic properties and geometry of the fracture network.

Figure 15. Head monitoring during drilling.



Left: Drilling a new hole with fractures connecting the new hole and the monitored hole. Right: pressure response of the piezometer zone to drilling and penetration of fracture 1 (Note: example of drilling from underground).

3.5.4.3 *Multi-well pump testing*

With the piezometer network installed, pumping tests become a powerful tool for characterising the fracture network. Observation well responses to pumping are good indicators of fracture connectivity. A key parameter for analysis is the diffusivity, η , which is the parameter that controls the speed of pressure propagation from a perturbation. Diffusivity is the ratio of transmissivity to storativity. It can be approximated by the radius of the influence equation, (Streltsova, 1988)

$$r = 2\sqrt{\eta t}$$

where r is the distance between the source and observation point and t is the time lag between a perturbation and the observation-well response. Note that this distance is measured along the fracture pathway and may exceed the straight-line distance due to tortuosity. Diffusivity is good mapping tool for fracture connection (Knudby and Carrera, 2006). Diffusivity is essential for determining storativity, which is related to fracture aperture and fracture porosity. Estimating transport apertures and fracture porosities from storage values are an alternative to using the cubic law with transmissivity values.

Figure 16 and Figure 17 show the use of pressure derivatives with multi-well data. This simple system contains three fractures, which may represent different fracture networks. The simulation has two main fractures, Fracture 1 and Fracture 2, connected by a lower transmissivity fracture. The derivative plots for the observation well responses to pumping a well in Fracture 1 appear in the upper part of Figure 17. The observation wells that are connected to Fracture 1 show earlier and stronger responses than those in Fracture 2, which communicates to Fracture 1 through the tighter connecting fracture. The lower part of Figure 17 compares the derivative curves for each of the five wells, when it is a pumping source. Note that derivatives vary due to local properties in the early part of the test. At the end of the five tests, the derivative curves merge into two curves, one for the Fracture 1 wells and the other for the Fracture 2 wells.

Pumping tests are usually run with a constant-rate source; however, slug tests may be effective for mapping fracture connections from pressure responses within the piezometer network (Stephenson and Novakowski, 2006). Slug tests have a further advantage in reducing the costs of pumping and water handling.

3.5.4.4 *Water sampling and mapping contamination spread*

Water sampling from the piezometer network will define the spatial distribution of contaminants. The concentrations of natural chemical constituents may also vary depending on the connectivity of the fracture networks to different water sources. Water chemistry may also reflect chemical interactions with the rock, which can indicate stagnation if the products of these effects are concentrated.

Groundwater velocity and retardation behaviours are best determined by assessments of contaminants or natural solutes that serve as tracers. Back calculations that reproduce data are necessary to demonstrate the value of the site conceptual model. The analysis of transport also must account for the likely mass of contaminants that are in the groundwater. Missing mass, or mass that is not accounted for in observations suggests that there are pathways or processes that have not been discovered or considered.

Figure 16. Fracture network model to show effects of connectivity on pumping tests.

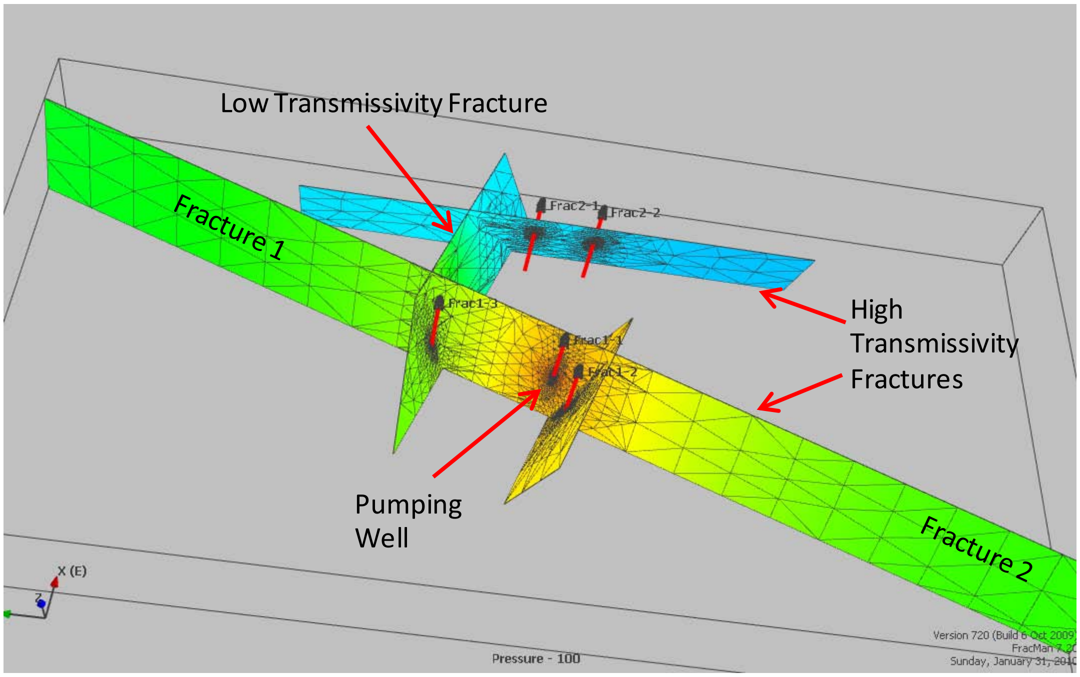
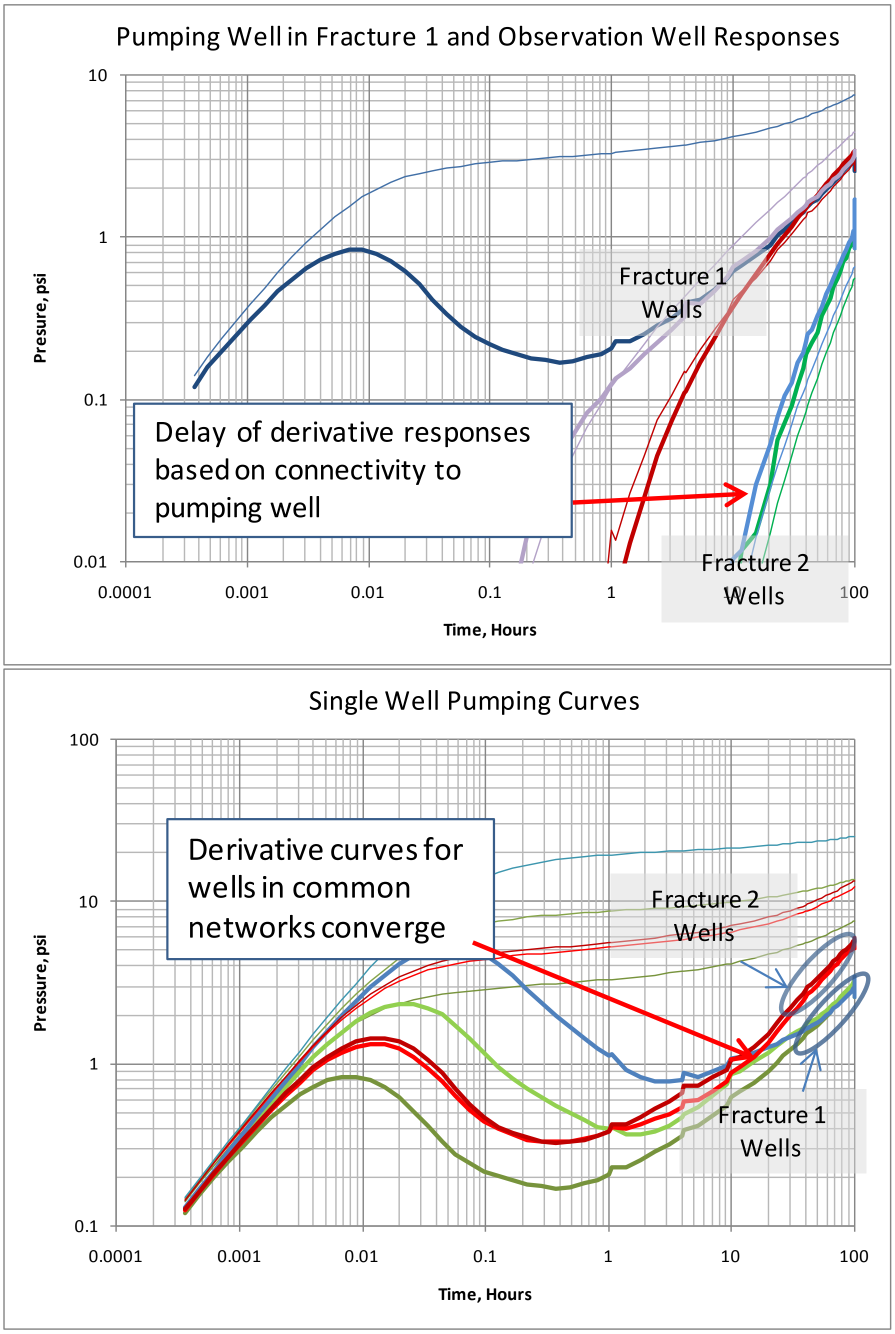


Figure 17. Log-log plots of transient responses from simulations in Figure 16.

Top: Pumping from Fracture 1 with responses in other wells. Wells in Fracture 1 respond early and merge to the pumping well. Wells in Fracture 2 are delayed due to poorer connectivity to pumping well. Bottom: Pressure and derivative curves for pumping tests from each well on a single plot (normalised derivative plot). Derivatives for well merge in late time depending on the fracture they are completed in.


Pumping Well in Fracture 1 and Observation Well Responses

Delay of derivative responses based on connectivity to pumping well

Single Well Pumping Curves

Derivative curves for wells in common networks converge

Pressure drawdown: light lines; Derivative curves: heavy lines.
Pressure curve and corresponding derivative in same color.

3.5.4.5 *Tracer testing*

Tracer testing is the only effective means for obtaining transport apertures and transport properties, other than back-calculating values from the spatial distributions of natural tracers or introduced contaminants. Due to their expense and their difficulty, tracer tests are not used often, but they may be justified when an understanding of groundwater velocity and retardation effects on contaminant movement are critical for transport assessment.

Tracer tests are best used to determine transport properties and processes along pathways that are well-defined based on head interference data and other characterisation results. Tracer tests in fracture systems whose connections are not already mapped are notoriously unpredictable, often producing poor tracer recovery (or no recovery at all).

The tracer test recovery curve provides a number of key insights to the transport processes along the fractures (Figure 18). The breakthrough periods are:

- First arrivals, which are fast paths that are relatively un-dispersed;
- The peak and its spread, which reflects the main advective travel time and dispersion;
- The tail, which may be diffusion or dispersion controlled (matrix diffusion from -3/2 slope or dispersion from heterogeneous pathways); and
- Time lag from retardation by sorption.

The first arrival and the concentration peak of the recovery curve determines fracture transport aperture. The tail gives insights to transport processes. In principle, matrix diffusion has a -3/2 slope tail in logarithmic plots of concentration and time; however, this behaviour is for ideal dual-porosity media, that is, uniform matrix blocks and fractures. Variably-sized blocks produce tails with different slopes depending on the size distribution (Haggerty et al., 2001).

Tracer test designs vary in the layout of source and sink wells as well as the source and sink pumping strengths (Figure 19). The most successful tracer tests from the standpoint of recovery are convergent tracer geometries, where the flow lines are moving toward the pumping well. Divergent tests are those where the tracer is injected into a central point with a pumping rate that is sufficient to produce samples but not great enough to perturb the flow field. This geometry is more likely to produce poor or no recovery due to decreasing concentrations along the flow lines or if the sampling well misses channels in the fracture network. That said, this approach can work in a single fracture or very well-defined network (Lapcevic et al., 1999b). So-called huff-puff tests (Haggerty et al., 1998), where a tracer is injected and recovered from the same well using similar withdrawal and injection rates, yield information on retardation processes from the shape of the recovery curve. These tests are relatively simple, but their design needs to consider background flow under the natural hydraulic gradient.

Tracer test interpretation is further complicated by non-unique solutions, partly due to the similar mathematics of dispersion and diffusion. Using tracers with different diffusivities in water can help constrain the influences of matrix diffusion and heterogeneity-based dispersion (Andersson et al., 2004; Meigs and Beauheim, 2001; Becker and Shapiro, 2000).

Tracer dilution tests are another form of single-well tests that involve injecting tracer into a monitoring interval (Andersson et al., 2004, Pitrak et al., 2007). Dilution tests monitor the decrease in tracer concentration as groundwater flows through the test interval, which is a measure of groundwater velocity. A change in the dilution rate when pumping rates in other wells change is a very good indicator of fracture-network connectivity between the dilution-test zone and the pumping well.

3.5.4.6 Multi-well characterisation products and decisions

The data from multi-well characterization should provide the information needed to support scoping calculations as well as a detailed site numerical model for validating the conceptual model in predicting future contamination transport behaviours.

The site characterization plan should be revisited after every well is drilled and tested to determine the necessity of further characterization work and the locations of further drill holes, if necessary.

Figure 18. Tracer test breakthrough interpretation.

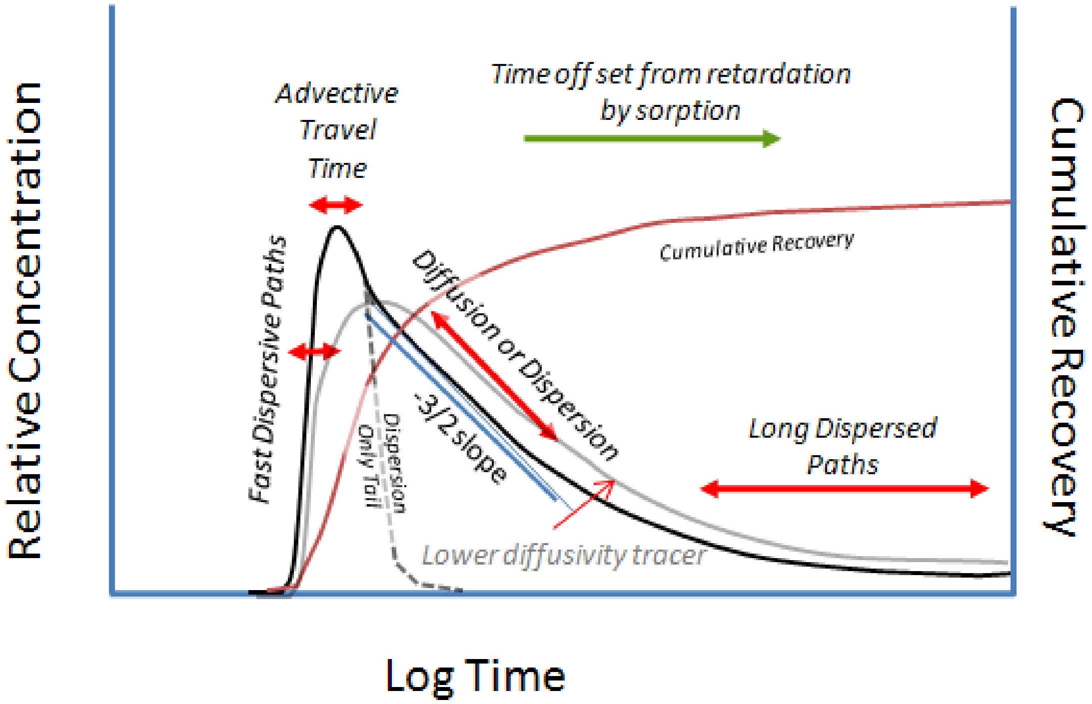
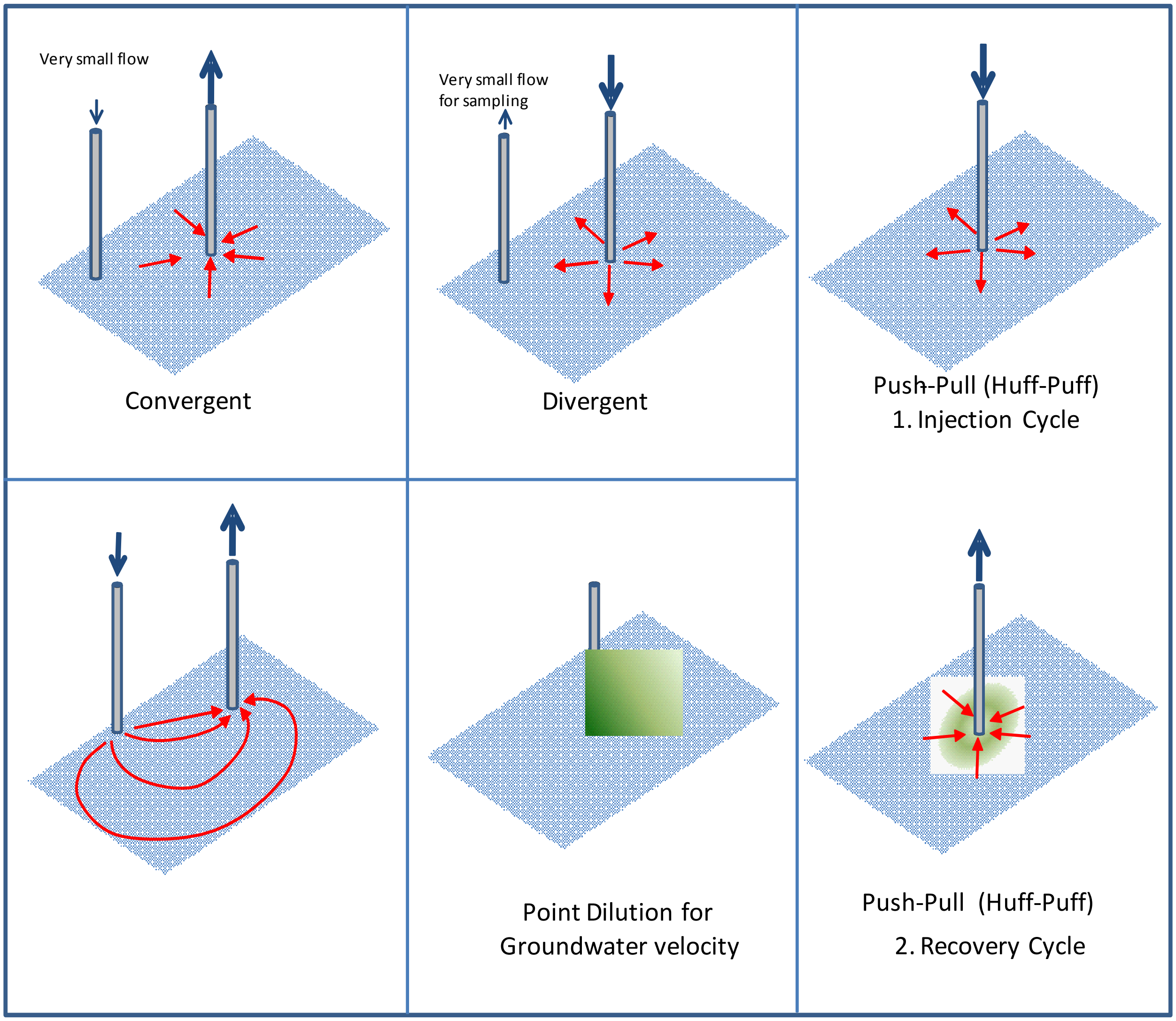


Figure 19. Tracer Testing.



3.5.5 Site characterization summary

A summary of site characterization methods appears in Table 2. This table presents measurement methods, categorized by geology, geophysics, hydraulic properties, hydrodynamics, transport properties, and water chemistry, with their appropriate applications at each of the stage of site characterization. The typeface used for the methods indicates whether these methods are:

- *Essential*: Tools that provide necessary data forming the backbone of a characterisation. One would expect these to be applied at most sites.
- *Very useful*: Tools that complement essential tools. These may be required for site specific issues or for sites that have severe contamination problems and societal consequences.
- *Somewhat Helpful*: Tools that may be useful under specific conditions. These may address similar needs as essential tools but are less effective, for example, using geophysical logs for identifying conductive fractures in holes where flow logging is being applied.
- *Research tools*: Tools that are still in development or are not yet cost-effective for professional applications.

An overview of this table shows that the most important methods do the following:

- Provide direct indications of the transmissive fractures and their geologic description. These include surface fracture mapping, well flow logging (or detailed packer testing), well image logging, and multi-well monitoring of hydraulic heads. Surface geophysical methods are primarily valuable for determining overburden depth and the locations of major fracture zones and faults. Well geophysical measurements, while useful, are secondary to flow logging and image logging for identifying conductive fractures. A possible exception could be electrical logging that may distinguish contaminated from uncontaminated zones or provide estimation of rock matrix porosity for assessing matrix diffusion.
- Determine fracture hydraulic properties and geometry using both single well and multiple well hydraulic tests. Single hole tests, including the interpretations of the source wells in pumping tests, provide data on transmissivity as well as flow geometry. Head responses in observation wells indicate fracture-network connectivity from diffusivity (time-lag) data; however, interpretations of hydraulic properties from observations should recognize the potential for significant error due to heterogeneity. Constant-rate pumping tests are the least ambiguous for interpretation; however, slug tests and packer tests may provide adequate data provided they are performed with transient interpretation in mind. Provide critical information on the groundwater flow field from hydraulic head measurements, and ambient flow logs.

- Provide water chemistry and contaminant concentration data to assess the groundwater flow system and the extent of contaminant migration.
- Address the issue of groundwater velocity and retardation. Tracer tests are perhaps the only means of obtaining good information on transport aperture other than history matching a well-mapped contaminant plume using numerical models. Tracer tests, however, are difficult to design, and should only be used to determine the transport properties of a well-identified pathway. Tracer tests are very inefficient for mapping connectivity and fracture networks, while pressure interference tests are quicker and more reliable.

The modern approach to fracture flow characterization has been developed and proven over the past 25 years. It has been driven by technology developments in radioactive waste research and contaminant transport research, with testing and validation at numerous research sites. The core techniques of flow logging, image logging, and multi-zone well completion are well-established particularly through research efforts of the USGS as well as research consortia that have been active at the University of Waterloo and Queens University in Ontario, among others. There has been sufficient application in professional practice (for example, Cho et al., 2008) to state confidently that these methods have moved beyond research and are sufficiently developed that they can be specified by regulatory guidance.

The overall characterization approach must be both integrative and iterative. The integration involves the use of multiple methods - hydraulic, geologic, geophysical, and geochemical - to assess fracture network properties. It is iterative by being a staged process involving the proposition of alternative conceptual models, designing characterization programs to scientifically test conceptual models, and evaluating the results of characterization to validate those models to determine how they must be updated. An example of the characterization approach described above is presented below for a hypothetical site.

4.0 APPLICATION OF FRACTURE METHODOLOGIES TO A HYPOTHETICAL BEDROCK CONTAMINATION STUDY

4.1 Problem Description

This hypothetical example considers a gas station in an urban area where there has been leakage of fuel from storage tanks. The area has experienced similar leaks in the past, hence there is some information available that indicate the types of overburden and the bedrock geology, as well as some information about the style of fracturing. This particular gas station is located in a small valley where the overburden is relatively thick in comparison to other sites located on the hillsides.

4.2 Desk Studies

The desk studies for the site would compile the bedrock geology from the previous investigations and perhaps obtain an estimate of the overburden thickness. There are air photos available from before urban development as well as LIDAR imagery for the urban area. The linearity of the valley underlying the gas station suggests that it may be underlain by a fault zone (Figure 20). The existence of similar parallel topographic features elsewhere reinforces this interpretation. Hydraulic head data from existing wells suggest that this is a discharge area for local groundwater flow, but steeper head gradients across the fault indicate that it may be acting as a flow barrier.

The bedrock geology consists of marine sandstone with variable porosity. Past experience from other sites suggests that bedding-plane fractures may be important for controlling flow. These data form the basis of a preliminary conceptual model. Alternative conceptual models consider the possibilities that a fault is not present and the topographic lineaments do not have a geologic origin. The porosity of the sandstone in the area of the site is highly variable, hence retardation effects from matrix diffusion effects cannot be predicted with confidence.

The contaminants at the site involve immiscible products and there may be a dissolved groundwater plume (soil vapour is also often a potential concern but not addressed in this example). The immiscible products, primarily gasoline, are LNAPLs that are lighter than water. The desk study should estimate the volume of the releases and their timing based on records from the gas station and experience from similar leaky facilities.

The desk study stage would consider the possible flow system, and identify nearby rock exposures where there might be some seepage down gradient from the site. Scoping calculations would consider a range of groundwater velocities and directions of hydraulic gradient as well as upper and lower estimates of the distance the contamination may have spread based on alternative scenarios including the following:

- The hydrogeologic role of the fault as a conduit or a barrier;
- Retardation from matrix diffusion; and
- Role of bedding plane fractures versus steeply dipping tectonic fractures.

4.3 Surface Investigations

Surface investigations include any site characterisation activity that can be performed without drilling including mapping and geophysical surveys. The surface investigation stage would focus on inspection of nearby outcrops that are in road cuts in the likely direction of groundwater flow from the site. These inspections would include taking fracture orientations and inspecting the fractures for signs of current or past seepage.

As a result of uncertain overburden thickness and because there may be a fault zone present, the investigation team determines that ground penetrating radar (GPR) and electrical resistivity sounding would be cost-effective to determine whether or not the fault zone is present. The GPR also obtains the depth to bedrock and water table elevations including whether or not the groundwater table is being affected by a fault (Figure 21).

The GPR survey indicates that there is a low resistivity zone approximately 5 meters wide underlying the valley. It also suggests that there may be a difference in the groundwater elevation across the valley, but this is not certain. Surface-based characterization also confirms the existence of a well that had been identified by the desk study. This well is about 50 meters down gradient from the gas station across the fault on the other side of the small valley. Groundwater samples from the well do not show the presence of contamination from the gas station. Groundwater levels in this well are inconclusive regarding whether or not there is a discontinuity in the hydraulic gradient across the fault.

Based on the surface characterization, an initial drilling program of three wells is laid out. The first well is placed a short distance down gradient from the gas station between the station and the fault. The existing well across the fault fortunately is available for monitoring heads during the drilling of the first well.

The location of the second well will depend on whether or not there appears to be connectivity across the fault zone. This well might also be placed at the margin of the fault to determine whether or not there is a damage zone that might be a strong pathway for groundwater flow parallel to the fault. Other alternative well locations include the fault zone itself. Another consideration in locating later wells will be the apparent hydraulic gradient both vertically and laterally based on the results of the first well and the database of hydraulic head values from other existing wells.

4.4 Single Well Characterization

Given the possibility of finding LNAPL contamination in the overburden, the drilling down to bedrock gives very careful attention to the presence of contamination and any evidence of immiscible contaminants between the ground surface and the bedrock surface. The possibility of matrix diffusion effects drives the decision to core the first well to see if there is gasoline or associated products in the matrix and to obtain samples to reserve for porosity measurements.

For the first hole on the site obtaining matrix samples is important, hence the single-well plan specifies a cored hole with a 96-mm diameter and 64-mm core (HQ). The hole will be completed with a multi-zone system both to isolate the conducting intervals and to provide access for testing and sampling. As the number of conductors and monitoring intervals is not known in advance, the plan calls for using packers as a temporary isolation system, reserving the possibility of either completing the well with a multi-port system, such as packers or flexible liners, or reaming the hole to 250-mm to install multiple, 50-mm standpipes.

The drilling of the overburden encounters bedrock at a depth of 3 meters as expected from the GPR survey. The hole is drilled to a depth of 20 meters encountering the water table in the bedrock at 4 meters depth. Overburden samples contain minor amounts of gasoline. The bedrock surface immediately below the overburden shows only a thin rind of contamination. Core with a shallow dipping fracture at a depth of 7.5 meters shows some signs of contaminant in porous matrix about 5 cm around the fracture. The fracture appears to be a bedding plane fracture. The bedding is dipping at approximately 5° from horizontal so it may also be opened partly by stress relief near the surface.

When the hole is completed, ambient flow logging identifies three conducting features, the shallow bedding plane fracture, a second conductor at a depth of 10 meters, and a deep conductor at 18 meters. The ambient flow logging shows there is flow towards the central conducting fracture, downward from the upper conductor, and upward from the deep conductor. A second flow log was performed under pumping conditions to locate the conducting fractures for designing the borehole completion system. This second flow log confirms the location of the flowing fractures and their individual flow rates. Based on steady-flow assumptions, the transmissivity calculation for each flowing fracture uses these flow rates and the overall drawdown from the pumping.

More thorough characterisation of hydraulic properties using transient methods is done through the multi-zone completion system by slug testing and observations during sampling events. An optical televiewer log confirms that this shallow fracture and the fracture at 10 meters depth are bedding plane fractures. After completing the flow logging, a temporary three-packer system is installed. The packer system has valves that can be opened to provide access to each interval for sampling and hydraulic testing. Groundwater sampling indicates that the two deeper intervals are free of contamination, but some gasoline is observed in the sample from the shallow interval.

The head data confirms the vertical hydraulic gradients, with the lowest head in the central fracture and higher heads above and below. While the hydraulic gradients would favour downward migration from the surface, the density contrasts of water and the gasoline as well as poor connectivity between bedding plane fractures may limit downward contaminant movement. The monitoring of the existing well across the fault during the drilling and the pumping for the flow logging shows no response. Pressure monitoring during groundwater pumping for samples in the shallow fracture produces a weak response in the middle conductor and no response the deep conductor.

Upon completion of the sampling, the packers are removed and the hole is reamed to 150-mm diameter. Given the upward hydraulic gradients and the low density of the contaminant, further sampling in the deepest fracture is not considered necessary and it is completed with a grouted-in pressure transducer for head monitoring only. The two shallower fractures are completed with 50-mm standpipes.

Based on the initial information obtained from the first hole, the hydraulic character of the fault zone is not clear, although it may be acting as a flow barrier. As mentioned above, a halo of contamination is observed around a bedding plane fracture at 7.5 meters depth. A scoping calculation uses the solubility of the LNAPL, and a diffusivity estimate based on the rock porosity and the contaminant's free-water diffusion coefficient. Based on the timing of the contaminant release, the scoping calculation affirms this depth is consistent with dissolution and matrix diffusion as a transport mechanism.

Given uncertainties about the hydraulic role of the fault it is decided that the second hole should be installed down gradient from the gas station close to the fault and possibly penetrating it.

4.5 Multi-Well Characterization

The second well is drilled approximately 50 meters down gradient from the gas station location at a similar depth as the first well. Unlike the first well, the overburden is not contaminated at this location. As predicted by the ground penetrating radar, the borehole intersects the fault. This borehole is not cored; however, the optical televiewer shows that there are both bedding-plane fractures and steeply-dipping fractures associated with the fault damage zone. The borehole enters the fault damage zone at approximately the depth of the water table, where dissolved contamination is discovered but at considerably lower concentrations than in the first well.

Based on cuttings, the second borehole appears to enter a clay-rich zone associated with the fault core, which is confirmed by optical televiewer logging. Flow logging again indicates an upward flow in the borehole as well as multiple conducting fractures. The temporary packer system is used to isolate the conducting fractures and to perform initial sampling. The sampling shows the contamination is restricted to the upper zone of the borehole. Based on these results, the borehole completion grouts pressure transducers in deeper intervals, and places a single standpipe that is open to the shallow conducting interval.

A pumping test from the final completion to determine large-scale fracture connections and hydraulic properties produces responses in the other monitoring intervals and no responses in the pre-existing well across the fault. In addition to the upward hydraulic gradient within the second hole, groundwater heads in the second hole are lower than the first well confirming its location down gradient from the gas station.

A third well is then planned to test the hypothesis that contamination is moving from the gas station site along bedding plane fractures into a fault damage zone. The well intersects a fracture zone along the fault, and then penetrates the fault core, which produces clay cuttings. The discovery of clay in the cuttings further supports this hypothesis. The pumping flow log indicates several conducting fractures near the fault zone and above the fault core. The ambient flow log shows no cross flows within the well suggesting that the fault-related fractures are well connected and acting as a single zone. The borehole completion for this well consists of a single monitoring zone within the fault's fracture damage zone.

During the drilling and sampling of the third well, the head-response data affirm the hypothesis that the fault is acting as a barrier to groundwater flow across the fault, but head disturbances appear to be moving along the fault. Sampling indicates contamination at lower concentrations than the second borehole confirming that the fault is a pathway for contaminant transport.

Figure 22 shows the conceptual model of the flow at the end of characterising the third borehole.

4.6 Analysis and Simulation

Given the relative simplicity of the conceptual model and the low level of public risk, a combination of analytical solutions and simple numerical models are considered sufficient to conduct the quantitative analysis of this site.

With a conceptual model of bedrock fractures in hand, predictions of future behaviour can proceed using a combination of analytical and numerical simulations. Analytical solutions are usually one-dimensional involving the identification of a pathway through the bedrock and estimating calculating velocity and flux along that pathway. With that information, the contaminant transport is estimated with additional effects of dispersion, decay, and matrix diffusion (Tang et al., 1981; Sudicky and Frind, 1982; Maloszewski and Zuber, 1990; West et al., 2004). These may include decay of the contaminant (Tang et al., 1981).

An example of a calculation using Maloszewki and Zuber's (1990) solution for transport appears in Figure 23. The equations are essentially the same as Sudicky and Frind (1982) using a slug input of solute mass rather than a continuous source. The parameters of this calculation use a mean aperture of 1 mm, a dispersivity of 1 metre, and a diffusion coefficient of 1 x 10^{-10} m^2/s. This calculation assumes matrix diffusion but no decay or sorption. The three curves show the arrival concentration curve at a location 50 meters downstream of the source. The curves in Figure 23 vary matrix porosity, and the difference between the curves show the strong effect of matrix diffusion with increasing matrix porosity.

The next level of analysis complexity would use a numerical simulator such as Modflow, FEFLOW, FracMan, or Hydrogeosphere. Any simulator is appropriate that can represent the key fracture pathways - the bedding plane fractures and the fault-zone fractures. For this case we choose FracMan, and build a simple model of these fracture types, imputing a range of hydraulic properties, apertures, and retardation factors (Figure 24). We can check the validity of the conceptual model by comparing particle tracks that represent the velocities and concentrations of contaminants against field observations.

At this point in the characterization there should be sufficient data to estimate the groundwater velocities albeit with some uncertainty in the transport aperture. With the addition of samples from a third well further down gradient, it may be possible to constrain whether matrix affects are retarding transport, and if so, to what extent. Additional wells may be required for contaminant plume delineation and to plan remedial actions.

Figure 20. Hypothetical example, desk study stage.

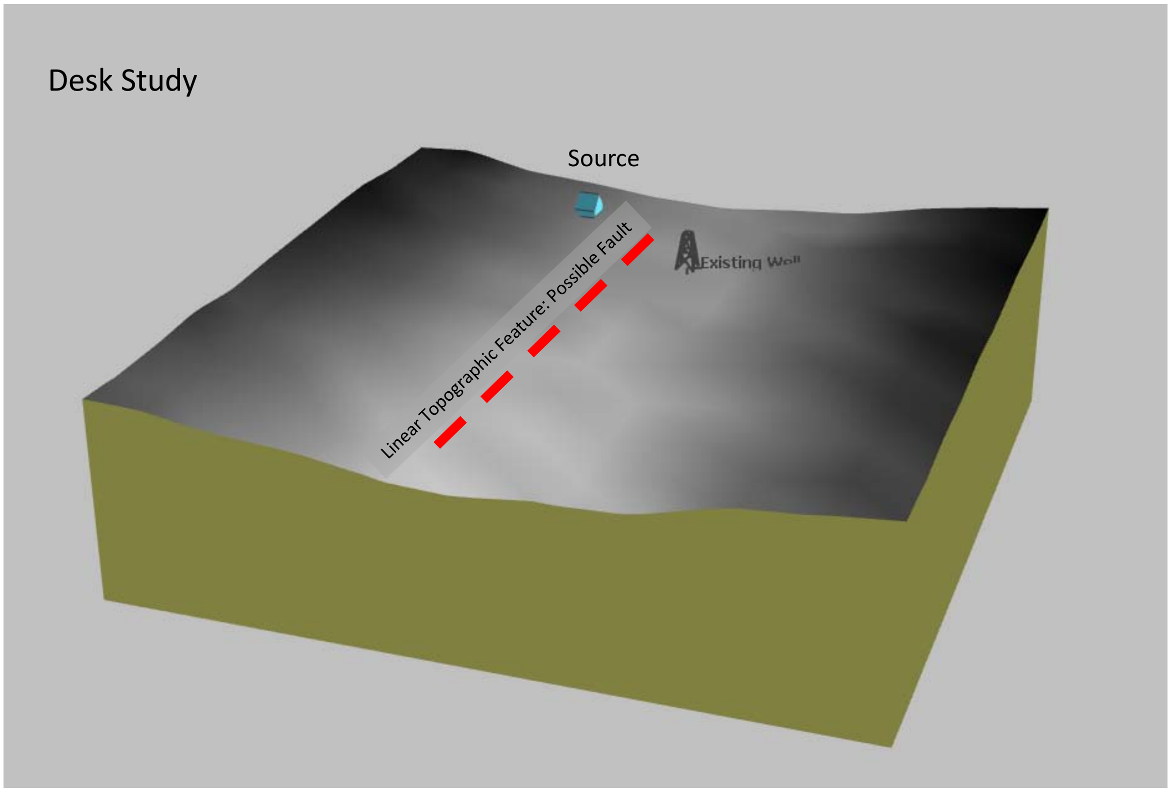


Figure 21. Hypothetical example, surface characterisation stage.

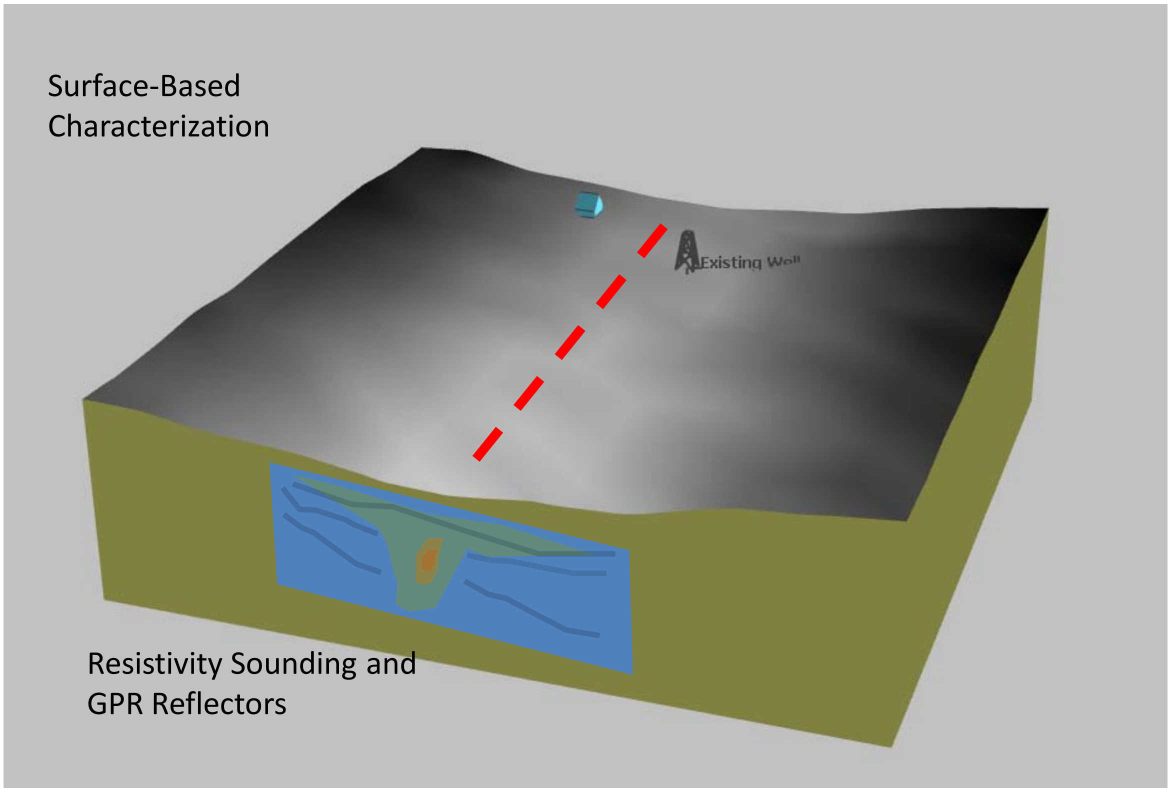


Figure 22. Hypothetical example, drilling-based characterisation stage.

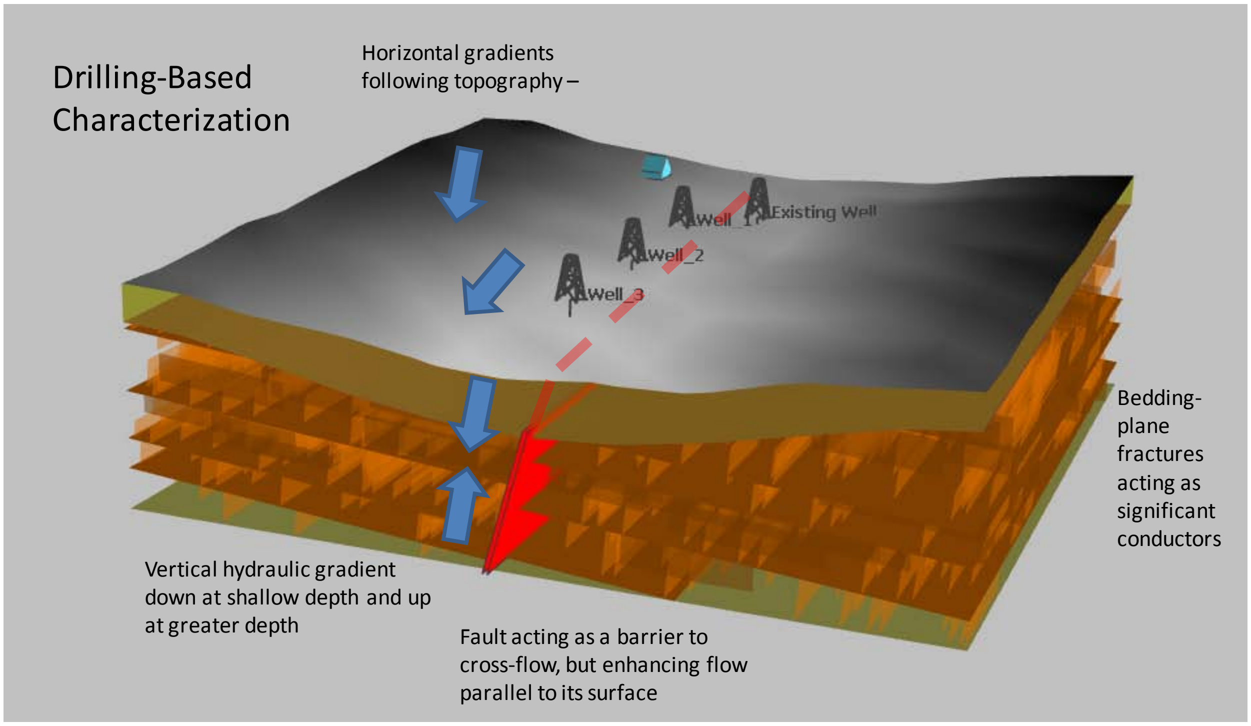


Figure 23. Analytical solutions for transport on a 50-m pathway showing effects of matrix porosity.

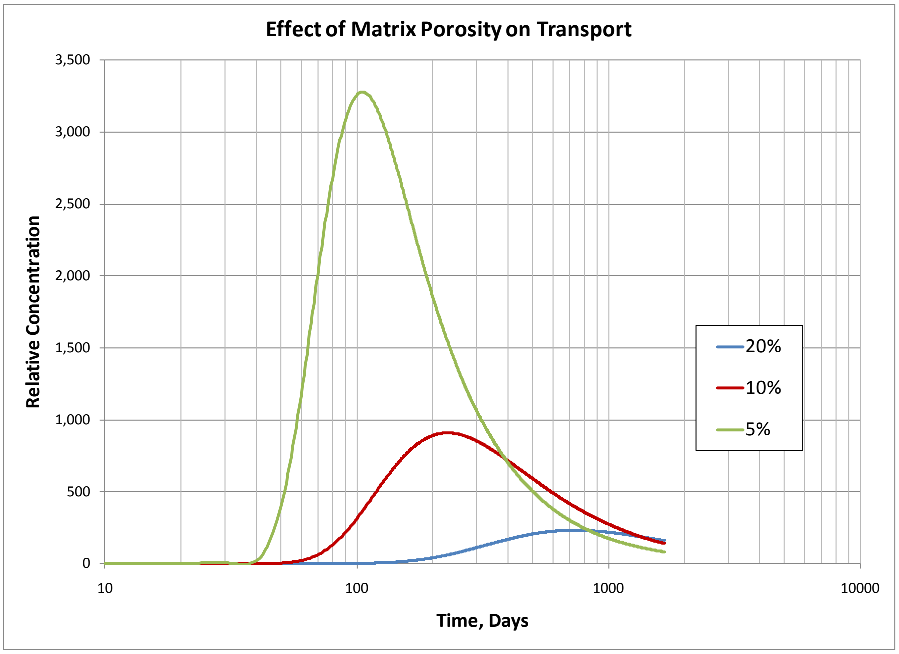
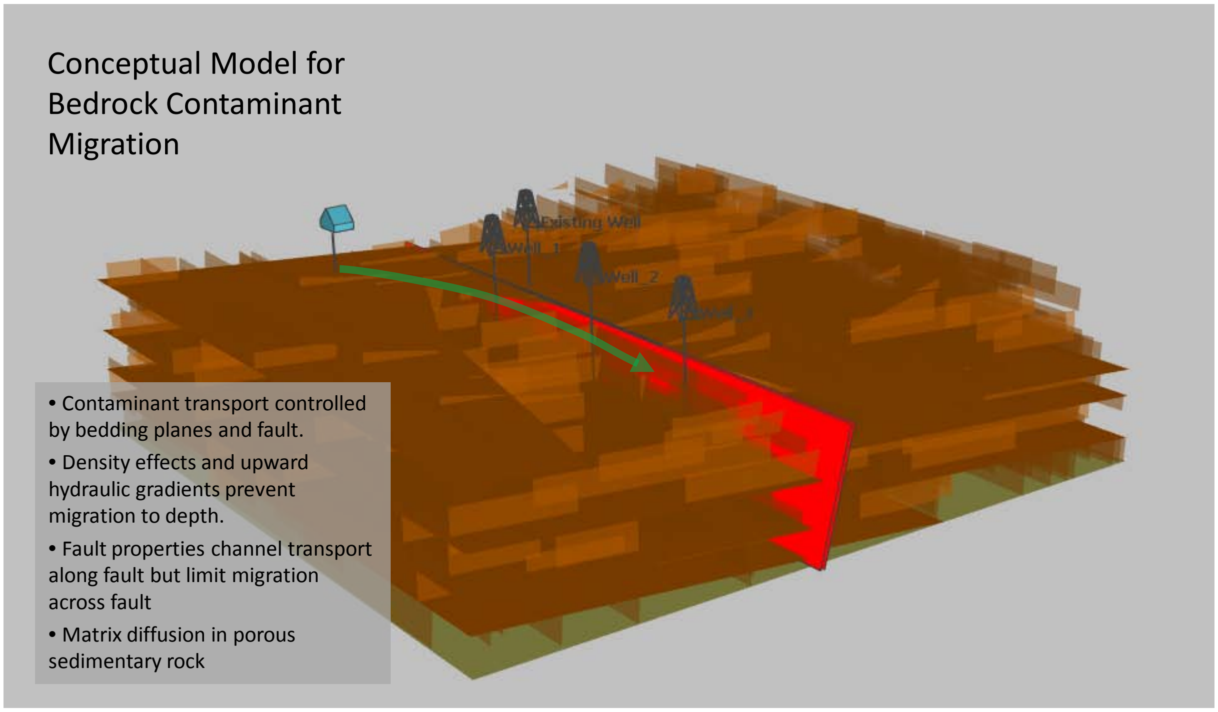


Figure 24. Conceptual model of flow and transport for hypothetical example.

View has overburden removed.



Conceptual Model for Bedrock Contaminant Migration

- Contaminant transport controlled by bedding planes and fault.
- Density effects and upward hydraulic gradients prevent migration to depth.
- Fault properties channel transport along fault but limit migration across fault
- Matrix diffusion in porous sedimentary rock

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