

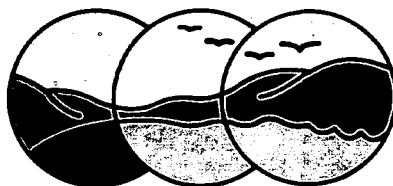


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Subsurface Assessment Handbook for Contaminated Sites

**Report CCME EPC-NCSRP-48E
March 1994**

**The National
Contaminated Sites
Remediation Program**



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Subsurface Assessment Handbook for Contaminated Sites

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The Canadian Council of Ministers of the Environment (CCME) is the major intergovernmental forum in Canada for discussion and joint action on environmental issues of national, international and global concern. The 13 member governments work as partners in developing nationally consistent environmental standards, practices and legislation.

Readers who wish to comment on the contents of this report should address their comments to:

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Preface

The National Contaminated Sites Remediation Program

In response to growing public concern over the potential environmental and human health effects associated with contaminated sites, the Canadian Council of Ministers of the Environment (CCME) established the National Contaminated Sites Remediation Program in 1989. The program aims to:

- *remediate high-risk contaminated sites that threaten human health or environmental quality by effective application of the "polluter pays" principle;*
- *provide the necessary government resources to remediate high-risk "orphan" sites for which the owner or responsible parties cannot be identified or are financially unable or unwilling to carry out the necessary work; and*
- *work with private industry to stimulate the development and demonstration of new and innovative site remediation technologies.*

The 5-year program operates on a 50/50 cost-shared \$250 million budget, based on matching funding by the federal government and the provincial and territorial governments. Of the total amount, \$200 million will be directed to the remediation of orphan, high-risk contaminated sites and \$50 million will be used to develop and demonstrate new remediation technologies.

To promote consistency in the assessment and remediation of sites under this program, a series of publications is being developed. Three publications have been issued to date by the CCME.

The first — Interim Canadian Environmental Quality Criteria for Contaminated Sites (CCME, 1991b) — provides numerical values for the assessment and remediation of soil and water based on the safe use of land for agricultural, residential-parkland, and commercial-industrial purposes. The interim criteria were adopted from guidelines and criteria currently in use in the various jurisdictions across Canada. These criteria are currently being validated.

The second — The National Classification System for Contaminated Sites (CCME, 1992) — is a method used to classify contaminated sites into three broad categories of concern according to their level of risk. A site is designated high risk when site contamination is such that it represents a

real or imminent threat to human health or to the environment. In this case, immediate action is necessary to reduce the threat. The two other categories are given lower priority of remediation.

The third — Guidance Manual on Sampling, Analysis, and Data Management for Contaminated Sites, Volumes I and II (CCME, 1993) — provides guidance with respect to sampling, recommends analytical procedures for different contaminants commonly found at contaminated sites, and discusses how to properly manage the data collected. The importance of Quality Assurance/Quality Control during sampling, analysis, and data management is emphasized.

This handbook provides further support for the development of a consistent national approach for assessing contaminated sites. The purpose of the handbook is to improve subsurface investigations at contaminated sites. Site investigations draw on many disciplines (e.g., geology, chemistry, mathematics, and biology) and therefore challenge both investigators and users of the results. This handbook helps those commissioning, conducting, and evaluating assessments of the subsurface at contaminated sites. Advice or suggested actions are presented in an active voice and are aimed at those planning or undertaking some activity. Many of these people are experts and they may have alternate approaches that are as good or better than those suggested, especially for site-specific conditions. For this reason, the advice offered in this handbook should not be considered as absolute requirements.

Although presented simply, subsurface assessment techniques are often complex and at the leading edge of applied research and technological development. Therefore, some principles and basic concepts are presented to help in understanding the advice being offered, particularly in the specialized and very technical areas of geophysics and mathematical models. References to additional information are provided to allow those who are unfamiliar with technical aspects to locate more detailed explanations. The handbook also provides a glossary of technical terms, highlighted at their first use.

The handbook contains seven sections:

- 1 Introduction;*
- 2 Desk-top Review;*
- 3 Geophysics;*
- 4 Hydrogeological Site Investigation;*
- 5 Chemical Hydrogeology;*
- 6 Groundwater Flow and Contaminant Transport Models; and*
- 7 Assessment of Subsurface Remediation.*

1 Introduction

This section outlines the approach to subsurface assessment at contaminated sites. This approach extends from site identification and definition of objectives, through data gathering and interpretation, to reporting, and, in many cases, to remediation. Contaminants are organized into groups having similar physical-chemical properties. The basics of contaminant migration and reaction in the subsurface are outlined. Subsurface conditions are grouped into five broad settings. This section provides the conceptual basis for appreciating how contaminants occur and migrate in the subsurface and sets the stage for assessing contaminants in the subsurface and for assessing remedial efforts.

2 Desk-top Review

Site assessment usually begins with gathering and evaluating existing information. This section outlines the information that should be sought and potential sources of that information. Site activities are investigated to help define the nature and sources of contamination. Maps, reports, and photographs are sought to establish the geological setting and to permit a more focused, efficient site investigation. Similarly, the current land use at the site is established because it may limit access or certain activities in the active site assessment investigations.

3 Geophysics

The subsurface conditions at the contaminated site can often be assessed, at least roughly, by using remote, geophysical techniques. Many geophysical methods operate from the surface and others can be employed as boreholes are drilled. The basis, advantages, and limitations are presented. Methods address different questions such as "are metal drums buried on site?", and the quality of the answers is improved by selecting the method appropriate for both the question and the site conditions. Geophysical methods are just one tool in the site assessment, but they provide information quickly and at a reasonable cost.

4 Hydrogeological Site Assessment

Information about the nature of the subsurface is required to define the current distribution of contaminants and to evaluate the migration of contaminants. This section presents a staged approach designed to obtain the required information quickly and cost-effectively. Boreholes are usually drilled to obtain material for physical and chemical analyses and to allow well installation. Testing of both the wells and the samples defines the likely migration of contaminants.

5 Chemical Hydrogeology

Samples obtained from the site, especially samples from the drilling and from the wells installed in the physical assessment, are chemically tested to evaluate the distribution of contaminants and to evaluate the chemical and microbial processes that could retard or transform the contaminants.

Testing ranges from rapid, qualitative screening of soil gas, for example, to detailed, systematic sampling and analysis of contaminated soils. Sampling and analysis of groundwater, non-aqueous phase liquids, soils, and soil gases or vapours are discussed. Sampling methods are emphasized to ensure the collection of high-quality information.

6 Groundwater Flow and Contaminant Transport Models

Mathematical models are becoming common tools that assist in understanding how contaminants move in the subsurface. The site information can be integrated into a site-specific model that can also be useful in evaluating the effects of remediation. This section presents the purpose and process of modelling and presents the various approaches with their advantages and limitations. Evaluation of model performance, particularly prediction uncertainty, is emphasized.

7 Subsurface Assessment of Remediation

Subsurface assessment is also required during site remediation to ensure that remedial actions produce the desired result. Also, subsurface sampling is required to demonstrate that remedial goals have been achieved. Remedial approaches are outlined and the assessment requirements are presented. The primary need is to demonstrate reduction in contaminant levels, but evaluating the benefits derived from the remedial actions is also a goal of this assessment. Methods are drawn from previous sections in most cases.

Avant-propos

Le Programme national d'assainissement des lieux contaminés

En réaction aux préoccupations croissantes du public quant aux effets possibles des lieux contaminés sur l'environnement et la santé humaine, le Conseil canadien des ministres de l'environnement (CCME) a mis sur pied, en 1989, le Programme national d'assainissement des lieux contaminés. Les objectifs du programme sont les suivants :

- *assainir, par une application efficace du principe «pollueur-payeur», les lieux contaminés à risque élevé menaçant la santé humaine ou la qualité de l'environnement;*
- *fournir les ressources gouvernementales nécessaires à l'assainissement des lieux «orphelins» à risque élevé dont le propriétaire ou les responsables ne peuvent être identifiés, ne sont pas financièrement en mesure d'exécuter les travaux nécessaires ou ne sont pas disposés à le faire;*
- *travailler de concert avec l'industrie privée pour stimuler la mise au point et la démonstration de nouvelles techniques d'assainissement innovatrices.*

Le programme quinquennal est financé à parts égales par le gouvernement fédéral et par les gouvernements provinciaux et territoriaux; il est doté d'un budget de 250 millions de dollars. De cette somme, 200 millions serviront à l'assainissement des lieux orphelins à risque élevé et 50 millions seront consacrés à la mise au point et à la démonstration de nouvelles techniques d'assainissement.

Afin de favoriser la cohérence des évaluations et des travaux d'assainissement réalisés aux termes de ce programme, on est en train d'élaborer une série de documents, dont trois ont été publiés jusqu'à maintenant par le CCME.

Le premier, Critères provisoires canadiens de qualité environnementale pour les lieux contaminés (CCME, 1991b), renferme des valeurs numériques servant à l'évaluation et à l'assainissement des sols et des eaux. Ces valeurs sont fondées sur une utilisation sécuritaire des lieux pour l'agriculture, l'habitation ou les parcs et l'industrie ou le commerce. Les critères provisoires ont été tirés de directives et de critères appliqués

actuellement par diverses instances au Canada, et leur validation est en cours.

Le deuxième, Système national de classification des lieux contaminés (CCME, 1992), décrit une méthode utilisée pour classer les lieux contaminés en trois grandes catégories de niveau de préoccupation selon le degré de risque qu'ils présentent. Un lieu est désigné à risque élevé lorsque sa contamination est telle qu'il constitue une menace réelle ou imminente pour la santé humaine ou l'environnement. Dans un tel cas, il faut prendre des mesures immédiates pour réduire cette menace. La priorité accordée à l'assainissement des lieux compris dans les deux autres catégories est moins élevée.

Le troisième, Guide pour l'échantillonnage, l'analyse des échantillons et la gestion des données des lieux contaminés, vol. I et II (CCME, 1993), renferme des conseils touchant l'échantillonnage, des recommandations sur les méthodes d'analyse des différents contaminants qu'on retrouve couramment dans les lieux contaminés et des suggestions quant à la gestion adéquate des données recueillies. On y souligne l'importance de l'assurance et du contrôle de la qualité pendant l'échantillonnage, l'analyse des échantillons et la gestion des données.

Le présent manuel vient aussi appuyer la mise au point d'une approche nationale cohérente pour l'évaluation des lieux contaminés. Il a pour but d'améliorer les études de la subsurface de ces lieux. Ces études font appel à de nombreuses disciplines (p. ex., géologie, chimie, mathématiques et biologie) et sont donc très exigeantes, tant pour les personnes qui sont chargées de les réaliser que pour celles qui en utilisent les résultats. Le manuel vise à aider ceux qui commandent, effectuent ou évaluent des études de la subsurface des lieux contaminés. Il offre des suggestions ou des conseils aux personnes qui planifient ou exécutent certaines activités d'évaluation. Beaucoup de ces personnes sont des spécialistes et peuvent avoir recours à d'autres approches qui sont aussi bonnes ou meilleures que celles suggérées ici, particulièrement au regard des conditions propres à des lieux donnés. C'est pourquoi les conseils offerts dans le manuel ne devraient pas être considérés comme des exigences absolues.

Bien qu'elles soient décrites simplement, les techniques d'évaluation de la subsurface sont souvent complexes et à la fine pointe de la recherche appliquée et du développement technologique. C'est pourquoi on présente quelques principes et notions de base pour aider le lecteur à comprendre les conseils fournis, particulièrement dans les domaines spécialisés et très techniques de la géophysique et des modèles mathématiques. On fournit aussi des renvois à des ouvrages supplémentaires afin que les personnes qui ne sont pas au fait des aspects techniques des études puissent trouver des explications plus détaillées. Le

manuel renferme également un glossaire de termes techniques; ceux-ci sont en caractères gras dans le texte lorsqu'ils sont utilisés pour la première fois.

Le manuel est divisé en sept sections :

- 1 Introduction
- 2 L'analyse documentaire
- 3 Les levés géophysiques
- 4 La reconnaissance hydrogéologique
- 5 L'analyse chimique
- 6 Les modèles de l'écoulement des eaux souterraines et du transport des contaminants
- 7 L'évaluation de l'assainissement de la subsurface

1 Introduction

Cette section donne une vue d'ensemble de l'approche à adopter pour l'évaluation de la subsurface d'un lieu contaminé. Cette approche va de l'identification du lieu et de la définition des objectifs, en passant par la collecte et l'interprétation des données, jusqu'à la production d'un rapport et, dans de nombreux cas, à l'**assainissement** du lieu contaminé. Dans cette section, on réunit les **contaminants** en groupes présentant des propriétés physicochimiques semblables. On expose les rudiments de leur **migration** et de leurs réactions dans la subsurface, et on regroupe les diverses conditions de la subsurface pour définir cinq grands types de milieux. Cette section renferme l'assise théorique permettant de comprendre de quelle façon les contaminants se présentent et migrent dans la subsurface; elle ouvre ainsi la voie à l'évaluation des contaminants présents dans la subsurface et des mesures d'assainissement.

2 L'analyse documentaire

L'évaluation d'un lieu contaminé commence habituellement par la collecte et l'étude de l'information existante. Dans cette section, on donne une vue d'ensemble de l'information qu'il faudrait trouver et des sources possibles de cette information. Il faut examiner les activités qui se sont déroulées sur le lieu à l'étude pour définir la nature et les sources de la contamination. On doit aussi consulter des cartes, des rapports et des photographies afin de déterminer le type de milieu géologique et d'accroître la pertinence et l'efficacité des études menées sur place. De même, il faut déterminer l'utilisation actuelle du terrain, étant donné qu'elle peut entraîner des limitations touchant l'accès au lieu contaminé ou la réalisation de certaines études sur place.

3 Les levés géophysiques

L'état de la subsurface d'un lieu contaminé peut souvent être évalué, du moins en gros, grâce à des techniques géophysiques de télédétection.

Beaucoup de celles-ci peuvent être appliquées à partir de la surface, tandis que d'autres sont utilisées lors du forage de **trous de sonde**. Dans cette section, on présente les fondements, les avantages et les limites de ces méthodes. Celles-ci permettent de répondre à différentes questions telles que : «Des fûts métalliques sont-ils enfouis sur le site?». En choisissant la méthode convenant tant à la question qu'à l'état des lieux, on peut améliorer la qualité des réponses obtenues. Les levés géophysiques ne sont qu'un instrument dans l'évaluation des lieux contaminés, mais ils fournissent des renseignements rapidement et à un coût raisonnable.

4 La reconnaissance hydrogéologique

Il faut disposer de renseignements sur la nature de la subsurface pour déterminer la distribution actuelle des contaminants et pour évaluer leur migration. Cette section présente une approche par étapes permettant d'obtenir les renseignements requis rapidement et au moindre coût. On a habituellement recours à des trous de sonde pour prélever des échantillons destinés aux analyses physiques et chimiques et pour permettre l'aménagement de puits. Les essais touchant les puits et les échantillons permettent de déterminer la migration probable des contaminants.

5 L'analyse chimique

Les échantillons prélevés sur le lieu contaminé, surtout ceux des trous de sonde et des puits aménagés pendant l'évaluation physique, sont soumis à des essais chimiques permettant d'évaluer la distribution des contaminants et les processus chimiques et microbiens susceptibles de les **ralentir** ou de les **transformer**. Par exemple, les essais vont d'un **examen préalable**, rapide et qualitatif, des **gaz du sol** jusqu'à un échantillonnage et à une analyse détaillée et systématique des sols contaminés. Dans cette section, on traite de l'échantillonnage et de l'analyse des **eaux souterraines**, des **liquides en phase non aqueuse**, des sols et des gaz ou vapeurs des sols. On porte une attention particulière aux méthodes d'échantillonnage, en vue d'assurer la collecte d'informations de haute qualité.

6 Les modèles de l'écoulement des eaux souterraines et du transport des contaminants

Les **modèles mathématiques** deviennent des outils d'usage courant qui aident à comprendre comment les contaminants se déplacent dans la subsurface. Les renseignements recueillis peuvent être intégrés à un modèle propre au lieu, qui peut également être utile dans l'évaluation des effets de l'assainissement. Dans cette section, on présente le but et la démarche de la modélisation, ainsi que les diverses approches possibles, leurs avantages et leurs limites. On insiste également sur l'évaluation de la performance des modèles, particulièrement en ce qui a trait à l'incertitude des prévisions.

7 L'évaluation de l'assainissement de la subsurface

Il faut aussi procéder à une évaluation de la subsurface pendant l'assainissement du lieu afin de s'assurer que les mesures correctives donnent le résultat souhaité. En outre, il est nécessaire de prélever des échantillons dans la subsurface pour démontrer que les objectifs de l'assainissement ont été atteints. Dans cette section, on présente les techniques d'assainissement ainsi que les exigences applicables à l'évaluation. Le but premier de cette évaluation est de démontrer que les concentrations de contaminants ont diminué; toutefois, elle vise aussi à déterminer les avantages découlant des mesures correctives. Dans la plupart des cas, les méthodes sont tirées des sections précédentes.

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Glossary

AAA

Acoustic impedance: Reflects the ability of a boundary to reflect seismic energy. It is the contrast of density times velocity across the boundary. A measure of the seismic inertia of the medium.

Accuracy: Refers to closeness of a measurement to the true value.

Action level: The concentration of a contaminant above which some action (e.g., monitoring or clean up) is required by regulation.

Active layer/zone: In permafrost terrains, the zone that undergoes cycles of freezing and thawing.

Advection: Process by which a solute is transported in groundwater, and moves at the same velocity.

Aeration: Process by which air dissolves in water.

Aerobic: Refers to any process carried out in the presence of oxygen.

Alluvium: A general term for unconsolidated material (e.g., clay, silt, sand, and gravel) deposited from running water. Often a sorted or semi-sorted sediment in the bed of a stream or on its floodplain or delta. The deposit may be in the form of an alluvial fan.

Amplitude: The maximum departure of a wave from the average value.

Anion: A negatively charged atom or radical.

Anisotropic: Having a physical property that varies with direction.

Annulus: The space between a well casing or screen and the borehole wall, or between a drill pipe and a casing, or between separate sets of casing.

Anomaly: Refers to deviation from uniformity in a physical property.

Apparent resistivity/conductivity: The resistivity/conductivity of a homogeneous isotropic ground that would give the same voltage/current or secondary/primary field ratios that are observed in the field with resistivity or electromagnetic (EM) methods. Apparent conductivity is the reciprocal of apparent resistivity.

Aquifer: Rocks or unconsolidated sediments that are capable of yielding a significant amount of water to a well or a spring.

Aquifer test: A test that involves adding to (or discharging from) a well, measured quantities of water, and recording the resulting changes in head in the aquifer (during and after addition/withdrawal). Examples are slug tests, bail tests, and pumping tests.

Aquitard: Geologic formation(s) of low hydraulic conductivity, typically saturated, that yield a limited amount of water to wells.

Archie's Law: An empirical relationship linking formation resistivity (ρ_t), formation water resistivity (ρ_w), and porosity θ . The form of the relationship is: $\rho_t = a\rho_w\theta^{-m}$, where a and m are experimentally determined constants.

Artesian: Refers to groundwater rising above the top of its aquifer, and often discharging on the ground surface.

Attenuation, attenuate: The reduction or removal of groundwater constituents by the sum of all physical, chemical, and biological factors acting upon the groundwater. In geophysical terms, it refers to a reduction in energy or amplitude caused by the physical characteristics of a transmitting system.

Auger: Any rotary drilling device that continuously removes cuttings from the borehole using mechanical means without the use of fluids. Used in soils or unconsolidated materials.

Auger flights: Winding metal strips welded to auger sections. The flights carry cuttings to the surface during drilling.

Average linear groundwater velocity: The velocity of groundwater moving through porous rock or sediment. It is the time required for the water to move from A to B divided by the linear distance from A to B.

BBB

Backfill: Material used temporarily during construction (e.g., of wells) or permanently during mining to replace the material being removed.

Bail test: A test carried out to determine *in situ* hydraulic conductivity by instantaneously removing a known water quantity from a well and measuring the resulting well recovery. Used for single wells in

formations of low to moderate hydraulic conductivity. Also called rising head test.

Bailer: A long, narrow tube with an open top and a check valve at the bottom. It is used to remove water and/or cuttings from a borehole or well.

Bedding plane: A planar or nearly planar surface, within a mass of stratified rock layers, that visibly separates each successive layer.

Bedrock: A general term referring to rock that underlies unconsolidated material.

Bentonite: A hydrous aluminium silicate clay mineral that is used to provide a seal between the well casing and the borehole. Sometimes it is added to drilling fluid to increase its viscosity.

Bias, biasing: A systematic difference between the true and measured value.

Biological activity: In the subsurface, usually the action of microorganisms, especially bacteria.

Bit: A cutting tool attached to the bottom of the drill stem. The design of the bit varies according to the type of drilling equipment used and the type of formation that is to be drilled.

Bladder pump: The pump consists of a flexible bladder within a rigid cylindrical frame. The lower end of the bladder is connected to the intake port and the upper end is connected to the sample line. A gas line leads from the surface of the ground to the space between the bladder and the frame. After the bladder is filled under hydrostatic pressure, the application of gas pressure causes the bladder to collapse, and forces the sample to the surface through the sample line.

Blanks: Samples that are the same as the samples of interest except with respect to one factor whose influence on the samples is being evaluated. For example, a trip blank is transported just like actual samples, but it does not contain the chemicals to be analyzed. The purpose of the blank is to evaluate the possibility that a chemical could seep into the samples during transportation to the laboratory.

Borehole: A hole drilled or bored into the earth, and into which casing or screen can be installed to construct a well.

Boundary condition: A mathematical model must be defined within a physical domain; the idealized flow or transport behaviour along the domain boundaries form the boundary conditions of the model.

Bouguer correction: The process of correcting gravity data for the mass of the rock between a given station and its reference (base) station. Application of the Bouguer correction to the data set, as well as corrections for latitude, topography, meter drift and elevation, yields the Bouguer anomaly.

Breakthrough curve: A plot of column effluent concentration over time. In the field, monitoring a well produces a breakthrough curve for a column from a source to the well screen.

Buffer: A substance (or mixture of substances) capable of neutralizing both acids and bases when added to a solution, but without significantly changing its original acidity or alkalinity.

Bulk mass density: The weight of a material divided by its volume (including the volume of its pore spaces). Specifically, it refers to the weight per unit volume of a soil mass that has been oven-dried to a constant weight at 105°C.

Bulk modulus: A modulus of elasticity, relating change in volume to the hydrostatic state of stress. It is the reciprocal of compressibility.

CCC

Calibration: The process of matching a model simulation with observed data. Typically, one or more model parameters are varied within reasonable limits until a suitable match is obtained.

Capillary fringe: The zone immediately above the water table, in which water is drawn upward by capillary action, and the pores are filled with water under pressure that is less than atmospheric pressure.

Capture zone: That portion of the groundwater flow system where the action of a pumping well causes the groundwater to flow to or be captured by that well.

Cation: A positively charged atom or radical.

Cation exchange capacity (CEC): A measure of the availability of cations that can be displaced from a solid surface and exchanged for other cations. For geologic materials, the cation exchange capacity is the

number of milliequivalents of cations that can be exchanged per 100 grams of dry sample.

Centrifugation: Process that uses centrifugal force to separate liquids of different specific gravities or suspended colloidal particles, according to particle-size fractions.

Characteristic curve: (a) A curve to show the relation between two changing values; and (b) refers to one of a pair of conjugate curves in a surface, which has the property that the directions of the tangents through any point of the curve are the characteristic directions of the surface.

Charge balance: A calculation in which the total number of positive charges in cations are compared with the number of negative charges in anions. Because groundwater is electrically neutral, the charges should be balanced.

Chargeability: The normalized (using the primary voltage) area under an induced polarization (IP) decay curve, between two times, after the transmitted current is stopped in a time domain survey (usually expressed in millivolt-seconds per volt).

Chemical and microbiological transformation: The conversion of a chemical to other chemicals by either chemical or microbial processes.

Cohesion: The tendency of similar parts of a body to hold together, due to intermolecular forces. Cohesionless materials (e.g., sand on a beach) lack this tendency.

Colloids: Fine-grained material in suspension. Specifically refers to a particle-size range of less than 0.00024 mm.

Complex number: Comprised of a real and imaginary part.

Complex resistivity (CR): A geophysical effect, also the basis of the CR method, in which polarization within the medium results in the voltage and applied current being out of phase (i.e., their ratio is complex). Also known as spectral IP. Induced polarization (IP) is one form of complex resistivity.

Compositing: The combining and homogenizing of samples (e.g., soils) before performing an analysis of the composite sample.

Compressibility: The relative volume reduction that geological material can undergo when a force is applied or water is removed from the vicinity by pumping.

Computational algorithm: That part of the computer code containing the step-by-step solution procedure for the mathematical equations of the hydrogeological model.

Computer code: The complete set of computer-language instructions that contains the input data statements, computational algorithm, and output statements. Common computer languages include Basic, Fortran, and Pascal.

Concentration gradient: The change in concentration from one point to another. This is the “force” driving diffusion.

Conceptual model: Our idealization of a hydrogeological system on which we can base a mathematical model. The conceptual model includes assumptions on the hydrostratigraphy, material properties, dimensionality, and governing processes.

Conductance: The product of conductivity and thickness (units are siemens).

Conduction currents: Electrical current resulting from the movement of free charges (contrast with displacement current).

Conductivity (electrical): The ability of a material to conduct electrical current. In isotropic material, it is the reciprocal of resistivity (units are siemens per metre).

Confining layer: A geologic body of low hydraulic conductivity above or below one or more aquifers. Also called an aquiclude.

Connectivity: The degree to which a fracture network is connected. When defined statistically, fracture connectivity can be used to generate many different fracture network realizations for use in groundwater flow and mass transport models.

Conservative: A dissolved substance that moves as fast as water in the groundwater system, and is not prone to attenuation beyond that occurring by diffusion and/or dispersion.

Consolidated: Naturally occurring geologic material that has been lithified and, therefore, has strength and resists disintegration.

Consolidation test: A test in which a sample is confined laterally in a ring and compressed between porous plates that are saturated with water.

Contaminant: Any physical, chemical, biological, or radiological substance in air, soil, or water that has an adverse effect.

Contamination: The introduction into soil, air, or water of a chemical, organic or radioactive material, or live organism that will adversely affect the quality of the medium.

Contamination concept: The model that considers the source(s), migration, fate, and impact of subsurface contaminants. Its precision should improve as site assessment progresses.

Contoured map: A map with contour lines drawn at regular intervals to show surface configuration (elevation) and geophysical and geochemical data distributions.

Core: A continuous columnar sample of subsurface material extracted from a borehole. Such a sample preserves the features of the sampled material.

Cross-hole: Geophysical methods carried out between boreholes (see also tomography).

Cultural noise: Geophysical noise caused by anthropogenic sources (e.g., cars and pumps) as well as wind and moving tree roots.

Cultural environment: The part of the environment that represents anthropogenic features (e.g., roads, buildings, canals, bridges) as opposed to natural features.

Current density: A measure of current flow through a given (oriented) area (units are amperes per square metre).

Current channelling/gathering: Channelling is a restriction of current flow due to an insulating barrier or to narrowing of a conductor. Current gathering is a concentration of current in a locally, more conductive zone. The disproportionate influence of lakes and swamps on VLF surveys is a well known example.

Cuttings: Fragments of soil or rock created by the drilling process (with or without free water). Also called drill cuttings.

DDD

Data quality objectives (DQAs): Statements developed by data users to define the quality of data needed to meet the objectives of a site assessment activity.

Darcy's Law/equation: An empirical law that states that flow velocity through a porous medium is directly proportional to the hydraulic gradient (assuming there is laminar flow and negligible inertia).

Decay: The gradual reduction in the magnitude of a quantity.

Degassing: Process of removing dissolved gases from a liquid.

Deionized water: Water from which all free ions have been removed.

Deconvolution: A type of inverse filtering; the process of recovering information that has been removed by natural and/or instrumental processes (e.g., the earth and recording equipment) from the true signal. Generally improves resolution, sharpens images.

Dense-non-aqueous-phase liquids (DNAPLs): Organic liquids that are more dense than water. They often coalesce in an immiscible layer at the bottom of a saturated geologic unit.

Desorption: Process of removing a sorbed substance by reversing adsorption or absorption.

Detection limit: The lowest concentration of a chemical that can be reliably reported to be different from zero.

Dewatering: (a) Removing water from a solid material by solid-liquid separation techniques (e.g., titration, centrifugation); and (b) removing or draining water from an enclosure (e.g., a river bed) by pumping or evaporation.

Dielectric constant: A measure of the ability of a material to store charge when an electric field is applied.

Dielectric permittivity: Describes the charge separation or polarization in a medium.

Diffusion (molecular): Process whereby ionic or molecular constituents move in the direction of decreasing concentration.

Diffusion coefficient: A parameter that measures how rapidly a constituent will diffuse in water.

Dimensionality: The number (1, 2, 3) and orientation (vertical, areal, radial) of dimensions chosen when modelling aspects of the subsurface.

Dipole: A pair of equal charges or poles of opposite signs.

Discharge: The rate of flow at a given time, measured as volume per unit time.

Discharge area/zone: An area in which there is upward groundwater flow in the subsurface. Groundwater flows toward the surface in a discharge area and may escape as a spring, seep, or baseflow, or by evaporation and transpiration.

Dispersion: Process of contaminant transport that occurs as a result of mechanical mixing and molecular diffusion; the extent to which a substance spreads as it moves through the system.

Dispersion coefficient: A measure of the spreading of a flowing substance as a result of the nature of the porous medium.

Dispersivity: The property of a porous medium that determines its dispersion characteristics by relating the pore velocity components to the dispersion coefficient.

Displacement currents: The movement of charge within a material by polarization, as opposed to the flow of free ions or electrons. Related to the applied electric field by the electric permittivity (dielectric constant).

Dissolution, dissolve: Process of dissolving a solid or NAPL to form ions or molecules uniformly distributed in water or another solvent.

Domain: In modelling, the segment of the subsurface being considered. It is defined by its boundaries and interior geometry (based on its hydrostratigraphy), and its material properties (e.g., porosity and hydraulic conductivity).

Drainage pattern: The arrangement of natural stream courses in an area, in plan view. It depends on local geologic/geomorphologic features and history.

Drawdown: The reduction in the height of the water table or of the piezometric surface caused by pumping groundwater from a well. The drawdown *versus* pumping rate can help define the hydraulic characteristics of the aquifer.

Drill bit: The device that actual cuts through the subsurface materials. Usually advanced downward at the end of a drill string.

Drill cuttings: The rock fragments, sand grains, and other materials produced at the drill bit by the drilling action and circulated to the surface in the drilling fluid (where they can be sampled).

Drilling fluid: A water- or air-based fluid used during well drilling to remove cuttings, clean and cool the bit, hold the borehole open, and reduce friction between the drill string and the borehole sides. Also called mud or drilling mud.

Drill rod: Hollow jointed or coupled rods, rotated in the borehole through their connection at the bottom to the drill bit, and at the top to the driving mechanism of the rig.

Drill string: The pipe string that extends down from the driving mechanism and rotates the bit.

Drive shoe: A forged steel collar on the bottom of a driven casing, with a cutting edge to shear off irregularities in the hole as it advances.

Driving force: A force that produces movement of water, gas, NAPL, or of a chemical.

Dual porosity: Describes subsurface material in which groundwater flow occurs through both fractures and pore space. An example is a fractured till, where groundwater can flow through the fractures and also through the pore space among the till particles.

EEE

Effective porosity: The amount of interconnected pore space through which fluids can pass. Effective porosity is usually less than total porosity because some deadend pores may be occupied by static fluid.

Electric field: A vector field describing the force on a unit electrical charge (units are newtons per coulomb = volts per metre).

Elastic moduli (elastic constants): Elastic moduli specify the stress–strain properties of isotropic materials in which stress is proportional to strain. They include bulk and shear moduli.

Electrical logs: Provide information on porosity, hydraulic conductivity, and fluid content of formations drilled in fluid-filled boreholes. This record is based on the dielectric properties (e.g., electrical resistivity) of the aquifer materials measured by geophysical devices lowered down boreholes or wells.

Electrode: A piece of metallic material that acts as an electric contact with a non-metal. In chemistry, it refers to an instrument designed to measure an electrical response that is proportional to the condition being assessed (e.g., pH or resistivity).

Electromagnetic method: A method that measures magnetic and/or electric fields associated with subsurface currents.

Equilibrium: Condition that exists in a system when the system does not undergo any change of properties over time; usually multiple forces produce a steady balance, resulting in no change over time.

Equipotential map: A plot in which points of equal hydraulic head are connected.

Evapotranspiration: Discharge of water from the surface of the earth to the atmosphere by evaporation from water bodies and soil surfaces and by transpiration from plants.

Extractant, extraction: A liquid solvent used to remove a solute from another liquid.

FFF

Fan shooting: A seismic refraction technique where the sensors (geophones) are deployed on a segment of a circle centred on the seismic source. Variations in the time of arrival are caused by radial variations in the velocity structure. Could be used, for example, to search for low velocity anomalies caused by buried waste.

Fate: The immediate or ultimate change in a chemical typically brought about by chemical or biological reaction.

Fault: A fracture or zone of fractures along which there has been a displacement of the sides relative to one another and parallel to the fracture.

Ferrimagnetic: Substances having positive and relatively large magnetic susceptibility as well as generally large hysteresis and remanence. Ferrimagnetism is caused by the interaction of atoms and the coupling of magnetic moments that are aligned in opposition, which result in non-zero net moments. Ferrimagnetic minerals have this property.

Field: That space in which an effect, such as gravity or magnetism, is measurable.

Field capacity: The maximum quantity of water that a soil can hold against gravitational pull. Also called specific retention.

Filter pack: Clean, uniform and well-rounded sand or gravel that is placed between the borehole wall and well screen to prevent formation material from entering through the well screen. It also serves to stabilize the adjacent formation.

Filtering: (a) The attenuation of components of a signal based on a measurable property (usually frequency). Filtering usually involves a numerical operation that enhances only a portion of the signal. (b) Fluid passage through a material that retains particles or colloids above a certain size.

Finite Element Model: An advanced numerical technique for solving partial differential equations; most useful for hydrogeological sites with complex geometry. As with finite difference models, a finite element model solves the hydrogeological system over a grid of many subregions or elements.

Flow lines: Flow lines indicate the direction of groundwater flow toward points of discharge. They are perpendicular to equipotential lines in homogeneous media. Also known as streamlines.

Flow net: A geometric representation of a two-dimensional steady-state flow field using intersecting lines that join points of equal hydraulic head and flow lines.

Fluid flow: The movement of a liquid or gas.

Fluid flux: The volume of fluid flowing through a specified cross-sectional area per unit time.

Foundry sand: Waste sand often contaminated by the metal processing and forming that occurs in foundries.

Fraction of organic carbon (f_{oc}): The portion or fraction of the solid material that is organic carbon. Typically ranges from 0.05 (5%) in organic-rich soils to less than 0.0001 (0.01%) in pure quartz beach sands.

Fracture: A break in a rock formation as a result of structural stresses (e.g., faults, joints, and shears). If they are open, fractures may provide pathways for fluid movement.

Frequency domain: In geophysics, refers to measurements analyzed according to their constituent frequencies. The usual alternative is time domain measurements.

GGG

Gaining stream: A stream or part of a stream where the flow is solely or partly contributed to by the inflow of groundwater. Also called effluent stream.

Galvanic: Describes geophysical techniques that require direct contact with the ground to pass current. The alternative is to induce currents in the earth.

Gas chromatography (GC): A method for separating, identifying, and measuring concentrations of organic compounds. Compounds pass through a chromatographic column and the differences in their rates of travel form the basis for their separation and identification. Detection limits are usually 1 to 10 micrograms per litre.

Gas chromatography/mass spectroscopy (GC/MS): A method for separating, identifying, and quantifying organic compounds. The compounds are separated in the GC, but their identification is based on both their retention time in the GC column and their mass spectral pattern. Quantification is achieved by measuring peak heights in the mass spectra. Detection limits are usually 5 to 10 micrograms per litre.

Gas drive pump: The pump mechanism depends on using a pressurized gas to lift a column of water from within the pump body and attached tubing.

Geomagnetic field: The magnetic field of the earth.

Geophones: Receivers used to record the seismic energy arriving from a source (in seismic geophysical methods).

Geophysical mapping: Locating geophysical anomalies in space (as opposed to time, which is geophysical monitoring).

Geophysical monitoring: Observing the change in a geophysical measurement with time.

Grain size: General dimensions of sediment or rock particles. The grain size distribution describes the occurrence of sediment grains of different sizes and can be related to the hydraulic conductivity of the granular material.

Ground penetrating radar (GPR): A geophysical method in which bursts of electromagnetic energy are transmitted downward from the surface, to be reflected and refracted by velocity contrasts within the subsurface. Also known as “Ground probing radar”.

Groundwater: Water under hydrostatic pressure in interconnected pores of the saturated zone. This water emerges from springs and enters wells.

Groundwater divide: The rather vague division between groundwater basins. When the divide meets the land surface, water on one side of the divide will flow into one groundwater system; whereas, water recharging on the other side of the divide will flow into another groundwater system or basin. Somewhat analogous to surface water basins and divides.

Groundwater flow: Movement of water through openings in sediment and rock of the saturated zone.

Groundwater zone: All the rocks in the saturated zone, including those containing perched groundwater.

Grout: A fluid mixture of cement and water with additives (or a bentonite slurry) that can be placed between the borehole and the well casing to form a seal.

HHH

Half-life: Radioactively, half-life is the time required for half of a given quantity of material to decay. Chemically, it is the time required for half of a given quantity of material to undergo a chemical reaction.

Headspace: The empty volume in a container between the cap and the water level of the sample.

Headwaters: The source and upper part of a large stream or river, including the drainage basin.

Heavy metals: Metallic elements, some of which are required in trace concentrations for plant and/or animal nutrition, but which become toxic at higher concentrations (e.g., lead and mercury).

Heavy oils: Petroleum products dominantly composed of large molecular weight, structurally complex compounds.

Henry's Law: An empirical law that states that the quantity of gas/vapour dissolved in water is proportional to the pressure of the gas/vapour in contact with the water at a specified temperature (i.e., as gas pressure increases, gas concentration in the water increases).

Heterogeneous: Composed of non-uniform constituents whose material properties vary in space. All geological material is heterogeneous, but the property of interest (e.g., porosity) may be sufficiently uniform for the material to be treated as homogeneous in terms of that property.

Heterogeneity: The part of the subsurface that is different in some property (e.g., hydraulic conductivity).

Homogeneous: Composed of uniform constituents throughout. That is, having material properties (e.g., hydraulic conductivity) that do not vary in space.

Hydraulic conductivity: A coefficient of proportionality that describes the ease with which a fluid can move through a porous medium. It is a function of both the medium and of fluid flowing through the medium.

Hydraulic gradient: The ratio of the change in total head to distance in a given direction.

Hydraulic head: The height to which water can raise itself above an arbitrary datum level. Commonly measured in a well.

Hydrogeological model: A representation, often simplified and perhaps conceptual, of the hydrogeological flow system. The aspects important for the site are emphasized. See also model.

Hydrophobic: Pertaining to a substance that avoids being dissolved in water and is more attracted to non-polar liquids (e.g., oils) or solids.

Hydrostratigraphic unit: A formation, part of a formation, or a group of formations that have similar hydrologic characteristics.

Hysteresis, hysteretic: (a) A change in the shape of the soil water characteristic curve, depending on whether the soil is wetting or drying; and (b) the property of a rock when its magnetization is non-reversible.

III

Igneous rock: A rock or mineral that solidified from molten or partly molten material (i.e., from a magma).

Imaging work station: Consists of a microcomputer with a high-resolution colour monitor and accompanying software that allows the manipulation, enhancement, and visual display of digital data.

Immiscible: Pertaining to two or more phases that, at mutual equilibrium, cannot dissolve completely in one another.

Impermeable: A material that does not easily transmit a fluid. It is often defined arbitrarily and in relation to more permeable materials present in the same area. For example, a shale may be impermeable relative to a nearby sandstone. An impermeable boundary is assumed to be the edge of impermeable material.

Induced polarization (IP). A geophysical effect whereby electrical charge is momentarily polarized within a material, usually a disseminated ore or a clay. This effect is the basis for the IP method, in which a decaying voltage due to this polarization is measured after the activating current is turned off in time domain surveying. See also complex resistivity.

Induced magnetization: Magnetization caused by an applied magnetic field. Contrast with remanent magnetization.

Induction number: A quantitative measure of the quality of a target for EM methods. The formulation varies for different targets but in general it involves the product of target conductivity, magnetic permeability, frequency of the transmitter, and a cross-sectional dimension of the target (the induction number is dimensionless).

Induction (EM), induce: The process, described by Faraday's Law, whereby a variable magnetic field generates an electric field (voltage) that, in the presence of a conductor, will produce electric currents.

Infiltrometer: An instrument that measures the infiltration of water into soil.

Infiltration: The flow of water downward from the land surface into and through soil and rock pores.

Injection well: A well used for injecting fluids into a subsurface soil or rock layer.

Inorganic constituents/inorganics: Any substance that is not a compound of carbon, with the exception of carbon oxides. They include metals and other ions (e.g., chloride, sulfate, and nitrate).

In-phase: That part of a periodic signal that has zero phase shift with a reference signal. See also quadrature.

Interpolation: A method to determine intermediate values from surrounding known values.

Interpretation: Transforming geophysical measurements into subsurface structure. More general term than inversion.

Intrinsic permeability: The relative ease with which a porous medium can transmit a liquid under a hydraulic gradient. It depends on properties of the medium alone.

Inversion, inverting: The process of deriving a model of the subsurface that is consistent with the geophysical data obtained. Generally refers to a more specific methodology than interpretation.

Isothermal: Being at constant temperature.

Isotope: One of two or more atoms that have the same atomic number, but different mass number.

Isotropic: Having properties that are the same in all directions.

JJJ

Joint: Surface of a fracture or parting in a rock, without displacement.

KKK

Karst: Topographic area that has been created by the dissolution of carbonate rock terrain. It is characterized by caverns, sinkholes, and the absence of surface streams.

LLL

Lacustrine: Formed in, produced by, or pertaining to a lake.

Lagoon: A shallow pond where wastewater is stored and/or partially treated through exposure to sunlight, oxygen, and microorganisms.

Landfarming: The practice of spreading organic wastes over an area of land, then relying on natural microbial degradation (and volatilization) to degrade the wastes. Can also be used to treat shallow soils contaminated by some organic chemicals.

Landfill: A disposal facility where waste is placed in or on land, but which is not a land treatment facility, a surface impoundment, or an injection well.

Leach: To wash or drain solids (e.g., wastes) by percolation. Usually, the washing fluid removes or leaches chemicals from the solid.

Leachate: A solution produced by the percolation of liquid through soil or solid waste, and the dissolution of certain constituents in the water.

Leakage: The flow of water from one hydrogeologic unit to another. It may be natural or anthropogenic.

Lens: A geologic deposit surrounded by converging surfaces; therefore, it is thick in the middle and thins out toward the edges.

Light non-aqueous phase liquids (LNAPLs): Fluids that are lighter than water. They are capable of forming an immiscible layer that floats on the water table (e.g., petroleum hydrocarbons or other organic liquids). Also referred to as Floaters.

Liquid limit: The water-content boundary between the semi-liquid and plastic states of a sediment (e.g., soil).

Lithology, lithologic: A system for the description of rocks, with respect to mineral composition and texture.

Losing stream: A stream or part of a stream in which water flows from the stream bed down into groundwater. Also called an influent stream.

Lysimeter: A suction device used in the unsaturated zone to collect soil pore water. It is capable of retaining the accumulated water within the sampling container.

MMM

Magnetics, geomagnetics: Geophysical methodology for studying anomalies in the geomagnetic field due to non-uniform magnetization of the subsurface. Measured using magnetometers.

Magnetic permeability: Characteristic of a material, it is proportional to the magnetism induced in that material divided by the strength of the magnetic field used.

Magnetic susceptibility: A measure of the extent to which a substance may be magnetized; it represents the ratio of magnetization to magnetic field strength.

Magnetization: The magnetic moment per unit volume. It is a vector quantity. See also magnetic susceptibility.

Magnetometer: A device for measuring the magnetic field of the earth. Variations in the field strength may indicate changes in magnetic properties of soil and rock or presence of ferrous metals.

Manometer: A tubular device used to measure fluid (or vapour) pressures. A liquid or vapour is introduced into the tube, the level of which is determined by fluid pressure; height of the liquid may be read from a scale.

Mapping: Locating geological, chemical, or geophysical information in space (as opposed to time, which is monitoring). The results are usually summarized as maps.

Mass flux: Like fluid flux, but the mass of a chemical dissolved in groundwater that moves through a specified cross-sectional area per unit time.

Matrix: The solid framework of a porous medium.

Mechanical pump: A device that brings water to the surface by mechanical means.

Meteoric water line (MWL): A plot of the ^{18}O versus ^2H isotopes in water samples will plot along this line if that water has not been effected by interaction with minerals and has not undergone significant evaporation.

Microbiological transformation: The conversion of a chemical to other chemicals (products) and biological cell mass.

Micro-gravity survey: A surface geophysical survey method, undertaken on a very small scale (typically station spacings of a few metres) and requiring high meter sensitivity. Measures the gravitational field of the earth at different points over an area of interest. Variations in the field are related to differences in subsurface density distributions, which in turn are associated with changes in soil, rock, and cultural factors. Typically used for cavern or fracture detection.

Migration: The movement of chemicals, bacteria, and gases in flowing water or vapour in the subsurface. Also, a seismic/radar term that generally means the correction of the recorded image for the effects of reflector dip. A very typical result of migration is the removal of hyperbolic events on the record resulting from diffractions from faults and other discontinuities.

Mine tailings: Portions of washed or milled ore that are too poor for further treatment.

Mineralogy: The study of minerals — formation, composition, properties, classification, and occurrence.

Model: A conceptual, mathematical, or physical system intended to represent a real system. The behaviour of a model is used to understand processes in the physical system to which it is analogous.

Moisture content: The quantity of water in a body, expressed as a fraction of its total mass.

Monitoring: Observing the change in a geophysical, hydrogeological, or geochemical measurement with time.

Monitoring well: A well that is used to extract groundwater for physical, chemical, or biological testing, or to measure water levels.

Monte Carlo Analysis: In this modelling approach, parameter uncertainty is addressed by varying the input parameters systematically and

repeating the simulations for each set of parameters, or each realization. The results can then be averaged or interpreted statistically.

NNN

Neutron scattering: Change in neutron direction as a result of collisions with nuclei in a material.

Neutron thermalization: See neutron scattering.

Noise: Any unwanted signal; a disturbance that is not part of the signal from a specified source. In electrical or induced polarization (IP) surveys, noise may result from interference of power lines, motor-generators, or atmospheric electrical discharges. See cultural noise.

Non-aqueous phase liquid (NAPL): Elements or compounds in the liquid phase other than water. This phase is immiscible in water. Examples include petroleum hydrocarbons (e.g., gasoline) and solvents (e.g., trichloroethylene).

Nonlinear system: A mathematical system or process is nonlinear if there are at least two unknown quantities that depend on each other. Density-dependent transport and reactive geochemical transport are common examples. These systems require more computational effort to solve compared with linear systems.

Non-unique: In geophysical interpretation and mathematical modelling, a problem for which two or more subsurface models satisfy the data equally well.

OOO

Optimum offset: Seismic reflection technique that employs an optimum window.

Optimum window: The best shot-geophone separation for obtaining reflections from a given interface. Chosen to lie between the earlier refractions and the later surface waves.

Organic contaminant or compound: Substances containing carbon, with the exception of carbon dioxide (CO₂) and carbonates (e.g., calcium carbonate, CaCO₃).

Orphan site: A contaminated site whose owner cannot be found or who cannot be held responsible for the clean-up of the site.

Outcrop: Exposed bedrock or strata that projects through overlying unconsolidated sediments or soils.

Overburden: All geologic material that lies above bedrock.

PPP

P-wave: An elastic body wave in which particles move in the direction of propagation. It is the wave assumed in most seismic surveys. Also called primary or push-pull wave.

Packer: A device placed in a well or borehole to isolate or seal a section at a certain level.

Particle mass density: The oven-dried mass of the sample divided by the volume of the solid particles.

Pathogen: A disease-producing agent; usually a living organism.

Peat: An unconsolidated deposit of partially decomposed plant matter with high moisture content, in a water-saturated environment.

Percentage frequency effect (PFE): The percentage difference in resistivity measured at two frequencies (one high, one low). It is the basic polarization parameter measured in frequency domain resistivity surveys. Equivalent to chargeability in time domain surveys.

Perched: Normally refers to a perched water table, which is a water table for a zone saturated with water, but underlain by an unsaturated zone and another water table. Often caused by a low-permeability layer that causes infiltrating water to “pond” or perch above the low-permeability layer.

Percussion drilling: A method in which a hammering action by a bit breaks rock into small particles that can be removed from the borehole, thus advancing the borehole.

Peristaltic pump: A low-volume pump in which suction is induced by the compression of a flexible tube by a rotor.

Permafrost: Perennially frozen ground in areas where the temperature remains at or below 0°C for two or more years in a row.

Permanent magnetism: See remanent magnetism.

Permeameter: A laboratory device that measures the intrinsic permeability and hydraulic conductivity of a solid or rock sample.

Permittivity: The property that enables a three-dimensional material to store electrical charge (i.e., its capacitivity).

Phase: A homogeneous, physically distinct portion of the subsurface (e.g., groundwater and soil gas). For geophysical use, see in-phase and phase shift.

Phase shift: A measure of the offset between two periodic signals of the same frequency (units are degrees or radians per milliradians).

Phreatophytes: Plants with deep root systems that allow them to get water from the groundwater or the capillary fringe.

Piezometer: A nonpumping well that is used to measure the elevation of the water table or potentiometric surface. It can be used to measure head at a point in the subsurface.

Piezometric level: see potentiometric surface.

Piston pump: A pump that has a piston rod, cylinder and check valve mechanism and forces water to the surface by positive displacement.

Plasticity: The property of a solid body when it experiences a permanent change in shape or size due to a stress exceeding a certain value.

Plume: A body of contaminated groundwater or vapour originating from a specific source and influenced by certain factors such as local groundwater or soil vapour flow patterns and the character of the aquifer.

Poisson ratio: The ratio of the transverse contracting strain to the elongation strain when a rod is stretched by forces applied at its ends, parallel to its axis.

Polarize, polarization, polarizable: Separation of charge, as in induced polarization or IP.

Pore pressure: The stress produced by fluid that fills the voids between soil or rock particles.

Pore space: An opening, void, or interstice in a soil or rock mass.

Porosity: The ratio of the volume of pore spaces in a rock or sediment to the total volume of the rock or sediment.

Porosity, primary: The pore spaces that were created at the time of deposition of a soil or rock unit.

Porosity, secondary: The pore spaces that were created after the time of deposition of a soil or rock unit (e.g., fractures or solution channels).

Potentiometric map: A map that shows through contour lines or other symbols, the potentiometric surface elevation of an aquifer.

Precipitation: (a) Formation of solids out of dissolved constituents; it is caused by a change in conditions (e.g., temperature); and (b) water that falls to the ground surface from the atmosphere as rain, snow, hail, or sleet.

Precision: The reproducibility of a measurement; the closeness of each of a set of similar measurements to the arithmetic mean of that set.

Pressure head: The height of a column of static fluid that is necessary to develop a specific pressure.

Primary (magnetic field): The magnetic field generated by an EM transmitter. May induce a secondary magnetic field.

Primary porosity: See porosity, primary.

Processing: Geophysically, to change data to emphasize certain aspects or correct for known influences, and thereby to facilitate interpretation.

Profiling: In geophysics, a survey method whereby an array of sensors is moved along the surface of the earth without change in its configuration, to detect lateral changes in the properties of the subsurface (e.g., faults and buried channels). The alternative is usually a sounding.

Pseudosection: A cross section showing the distribution of a geophysical property (e.g., seismic travel time) from which the distribution of the geological property of interest (e.g., depth to bedrock) can be interpreted.

Pumping test: An aquifer test in which a well is pumped for a certain time and the change in hydraulic head in observation wells is recorded. It is used to determine the capacity of a well and the hydraulic characteristics of the aquifer.

Purge, purging: Process of removing stagnant water from a well before sampling.

Purge-and-trap (P&T): An analytical method in which volatile organics are purged from a water sample by a gas stream and then trapped onto a solid as the gas passes that solid. The organics are then thermally desorbed from the solid and carried into the GC or GC/MS for analysis.

QQQ

Quadrature. That part of a periodic signal that is 90 degrees out of phase with a reference signal. See also in-phase.

Quality assessment (QS): Activities that assess the quality of data being gathered in the site assessment (e.g., analyzing replicate samples to define analytical precision).

Quality assurance (QA): Management of the data to ensure they meet the data quality objectives. This includes steps to control data quality and to assess data quality. It commonly includes designing appropriate protocols, ensuring they are carried out, and independently testing data quality.

Quality control: Management of the collection and analysis of data to ensure they meet the data quality objectives. Activities include following sampling protocols, and routinely checking calibration of laboratory equipment.

RRR

Radar: A system whereby short electromagnetic waves are transmitted and any energy that is scattered back by reflecting objects is detected. Acronym for “radio detection and ranging”.

Realization: One simulation of a hydrogeological problem using one set of input parameters. Normally, many realizations are produced and the statistical distribution of results is examined.

Receiver: The part of an acquisition system that senses the information signal.

Recharge: Addition of water to the groundwater system by natural or artificial processes.

Recharge area/zone: Area in the aquifer where there are downward components of hydraulic head. In this area, infiltration travels down into the deeper sections of the aquifer.

Reclaimed surface: The shallow surface zone that was contaminated, but has been cleaned up.

Reconnaissance sampling: A non-systematic sampling, in which sampling locations are based, in large part, on knowledge about the site. For example, former lagoon sites could be selected for sampling; whereas, unused areas of the site would not be sampled.

Recovery: The rise in static water level in a well, after discharge from that well or a nearby well has ended.

Redox level: The level of oxidation in a redox system, which is a chemical system in which reduction and oxidation reactions occur.

Reducing conditions: Geochemical conditions that favour reduction reactions (e.g., SO_4^{4-} conversion to H_2S). Indicated by the occurrence of reduced forms of iron (Fe^{2+}) and other species.

Reflection coefficient. A term used in seismic reflection and GPR to describe the ratio of the reflected to incident amplitudes of a pulse reflected from an interface.

Remnent magnetization (remnence): Magnetization remaining after the application of magnetic field has ceased.

Remediation: The clean up of contaminated soil or groundwater.

Residuals: Volumes of NAPL remaining in subsurface material after the flow of the NAPL has ceased. These are not mobile, but may slowly dissolve in groundwater or evaporate into soil vapour and therefore may be the source of vapour or groundwater contamination.

Resistivity (electrical): Electrical resistance to the passage of a current (units are ohm-meters; the reciprocal of conductivity).

Resolution: Refers to the smallest unit of measurement that can be distinguished using a particular instrument or method; based on the ability to separate two measurements that are very close.

Retardation, retard: Retention of certain contaminants in the subsurface because of one or more physical, chemical, or biological factors. Also known as attenuation.

Rotary drilling: A hydraulic drilling process that uses a hard-toothed bit attached to a rotating drill pipe. Cuttings are carried up by circulating a drilling fluid.

Roughness: A parameter describing a surface characteristic of a fracture plane. Roughness is important in determining resistance to flow.

SSS

S-wave: A body wave in which particles move perpendicular to the direction of propagation. Also known as secondary or shear wave.

Saturated zone: The zone where voids in the soil or rock are filled with water at greater than atmospheric pressure. In an unconfined aquifer, the water table forms the upper boundary of the saturated zone.

Scan: A qualitative analysis, usually conducted for trace organics by gas chromatography/mass spectroscopy, to identify (not accurately determine the concentration of) chemicals present in the sample.

Screening: A rapid analysis to determine if further action (e.g., detailed analysis or clean-up) is warranted.

Seal: A low hydraulic conductivity material (e.g., cement grout or bentonite) placed in the space between the permanent well casing and the borehole wall to prevent downhole movement of surface water and/or vertical mixing of water from various water-bearing areas.

Search sampling: See reconnaissance sampling.

Secondary (magnetic field): The magnetic field that is generated by currents that are induced to flow in the ground by time variations in the primary magnetic field of the transmitter.

Secondary porosity: See porosity, secondary.

Seismic reflection: A surface geophysical method that records seismic waves reflected from geologic strata and gives an estimate of their depth and thickness.

Seismic refraction: A surface geophysical method that records seismic waves refracted by geologic strata.

Self potential (SP): A geophysical method that measures the natural, static voltage existing between sets of points on the ground surface.

Sensitivity Analysis: After a model is calibrated, a sensitivity analysis is often completed to address the sensitivity of the simulation to specific input parameters. A sensitivity analysis is useful to determine additional field data requirements and to identify non-uniqueness.

Shear modulus: The stress-strain ratio for simple shear in isotropic materials that obey Hooke's law.

Shear strength: The maximum resistance of a soil or rock to shearing stresses. It can also refer to the measure of shear or gel properties of a drilling fluid or grout.

Sink: A process or mechanism by which water or chemicals are removed from the subsurface system. A karst channel is sometimes a sink for groundwater flow. Biodegradation is a sink for a biodegradable chemical.

Skin depth: The effective depth of penetration in a conducting medium of electromagnetic energy (when displacement currents can be ignored); the depth at which the amplitude of a plane wave has been attenuated to $1/e$ (0.37).

Slingram: A popular configuration of transmitter and receiver for HLEM profiling whereby the two coils are coplanar (usually with axes vertical) and a fixed distance apart.

Sludge: The solid residue resulting from a process that also produces liquid effluent.

Slug test: A test carried out to determine *in situ* hydraulic conductivity by instantaneously adding a known water quantity (or solid cylindrical object of known displacement) to a well, and measuring the resulting well recovery. Used for single wells in low to moderate hydraulic conductivity formations. Also called falling head test.

Soil gas: The vapour or gas that is found in the unsaturated zone.

Solubility: The total quantity of chemical that will remain in a solution, in contact with the solid or NAPL from which the chemical is derived.

Solute: A substance dissolved in a solution.

Solution channel: An open cavity created when rock is dissolved by groundwaters moving along a narrow path (e.g., a fracture).

Solvent: Any substance that can dissolve another substance (e.g., petroleum hydrocarbons). Although water is a solvent, the term is often reserved for organic liquids.

Sorption: Process by which some material leaves the fluid phase and associates with the solid phase. The chemicals associated with the solid phase are sorbed.

Sorption coefficient: A parameter that represents the tendency of a solute to sorb onto solids. Usually expressed as K_d (units are millilitres per milligram).

Sorptive retardation: The slowing of the migration of a chemical in groundwater or soil vapour due to interaction (sorption/desorption) with the subsurface solids.

Sounding: In geophysics, a survey method whereby the geometry and/or frequency of an array of sensors is varied to measure the physical properties of the earth as a function of depth beneath the configuration. The alternative is usually profiling.

Specific conductance: The ability of a cubic centimetre of water to conduct electricity; depends on the quantity of ionized minerals in the water (units are microohms per centimetre).

Specific storage: The quantity of water released from or taken into storage per unit volume of a porous medium, per unit change in head.

Specific yield: The ratio of the volume of yield of water by gravity drainage from a rock or soil (after being saturated), to the volume of the rock or soil.

Spectral induced polarization (IP): See complex resistivity.

Spring: A discrete place where groundwater flows onto the land surface or into a body of water.

Steady state: The state of a system whereby conditions at each point do not change with time.

Storage coefficient: The water volume released from storage in a vertical column of 1.0 ft³ (930 cm³) of aquifer when the water table or other piezometric surface declines 1.0 ft (30.5 cm).

Storativity: The volume of water released from or taken into storage per unit surface area of aquifer, per unit change in head. Also known as storage coefficient.

Stratigraphy: The study of original succession (stratigraphic sequence) and age of unconsolidated materials and rock strata, dealing with their form, distribution, lithologic composition, fossil content, and geophysical and geochemical properties.

Stream function: Stream functions are mathematical entities that define the steady state groundwater flow paths within a groundwater flow system. In combination with hydraulic potentials, stream functions are used to simulate groundwater flownets.

Streaming potential: A voltage resulting from flow of an ionic fluid.

Surface water: The portion of water that appears on the land surface (e.g., oceans, lakes, and rivers).

Surface wave: A wave that travels along, or near to, the surface; its motion dropping off rapidly with distance from the surface. A distinct seismic mode from the body waves, P and S.

Systematic sampling: Sampling that follows a pre-set, regular pattern. For example, sampling at a fixed depth at the nodes of a rectangular grid laid over a site.

TTT

Talik: The permanent or temporary layer of unfrozen ground above, within, or below permafrost.

Target: The object at which a survey sighting is aimed.

Tensiometer: A porous, permeable cup connected through a rigid tube to a pressure measuring device (e.g., manometer or vacuum gage) that records *in situ* soil water matric potential (or tension).

Tension: The condition whereby pore water rests at a pressure less than atmospheric.

Tensor: In three dimensions, there are nine components of hydraulic conductivity or dispersion and, in matrix form, they form a second-rank symmetric tensor. When the principal directions of anisotropy coincide with the x, y, and z coordinate axes, the nine components reduce to three. This is the usual approach for simplification in modelling.

Terrain conductivity: Geophysical method in which EM methods measure directly the average electrical conductivity of the ground. Operates at low induction number.

Test pit: A shallow pit, made using a backhoe, to characterize the subsurface.

Thermistor: A circuit component with a high negative temperature coefficient of resistance; its resistance decreases as temperature increases.

Thermocouple: A device consisting of two dissimilar conductors joined together at their ends. Between the two junctions, a thermoelectric voltage is developed that is proportional to the temperature difference between them. A thermocouple can be used to measure the temperature of one of the junctions when the other is held at a fixed, known temperature, or to convert radiant energy into electric energy.

Thermoplastics: Anthropogenic materials used for well casing; composed of different formulations of plastics (e.g., PVC) that are softened by heating and hardened by cooling so that they are easily moulded and extruded.

Till: Unsorted, non-layered sediment carried by or deposited from a glacier.

Time domain: In geophysics, refers to measurements analyzed according to their behaviour in time. The usual alternative is frequency domain measurements.

Time domain reflectometry (TDR): A device that measures electrical characteristics of wideband transmission systems. A system for measuring soil moisture content.

Titration: A method for analyzing solution composition by adding known quantities of a standardized solution until a certain reaction (e.g., colour change or precipitation) is produced.

Tomography: a method for determining the distribution of physical properties within the earth by inverting the results of a large number of measurements made in three dimensions (e.g., seismic, radar, resistivity, and EM) between different source and receiver locations.

Topography: The relief and form of the land.

Tortuosity, tortuous: The relationship between the length of the flow channel followed by water and the length of the porous media in which the flow is occurring. Groundwater follows a tortuous path therefore, in this definition, tortuosity is always >1 .

Trace (element): Any chemical (element) present in minute quantities in soil or water.

Transducer: A device or element that converts an input signal into an output signal of a different form. For example, a pressure transducer converts pressure to an electric signal.

Transformation: A chemical or biological change in the structure of a chemical. For example, toluene may be transformed to toluic acid, or to H_2O and CO_2 .

Transient: Occurring when the system is still changing with time (i.e., a steady state has not been attained). Most groundwater flow systems are transient, not steady state.

Transmissivity: The rate at which water of a certain density and viscosity is transmitted under a unit hydraulic gradient through a unit width of an aquifer (or confining bed). Transmissivity depends on properties of the liquid and porous medium. Also known as the coefficient of transmissibility.

Transmitter: In resistivity and induced polarization (IP) surveys, where current is injected into the ground, it is a current waveform generator. In electromagnetic surveys, which induce currents in the ground, it is typically a loop or grounded wire.

Transpiration: Process by which water vapour is released through the leaves of plants. This water usually comes from the groundwater.

UUU

Uncertainty: The estimated quantity by which an observed or calculated value may depart from the true value.

Unconfined aquifer: An aquifer that has a water table and is not bounded by an overlying layer of distinctly lower permeability.

Unconsolidated material: Naturally occurring geologic material that has not been lithified into cohesive rock.

Unsaturated zone: The area between the ground surface and the water table, including the root zone, intermediate zone, and capillary fringe. Pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Also known as vadose zone or zone of aeration.

Utility corridor/trenches: A subsurface trench in which pipes or electrical lines are placed. It is usually filled with coarse material and therefore may be much more permeable than the surrounding material.

VVV

Validation: Before a mathematical model can be accepted for use, it must be validated, or proven to realistically simulate the processes for which it was designed. Validation is usually completed by comparing model results with a controlled laboratory or field-scale experiment.

Vapour pressure: The pressure exerted by vapours of a chemical when the vapours and the liquid chemical are in equilibrium.

Verification: A mathematical model is verified by comparing the results with a known exact solution, often obtained using an analytical model.

Viscosity: The property of a fluid describing its resistance to flow (units are pascal-seconds). Also known as dynamic viscosity.

Volatile organics/Volatile organic compounds (VOCs): Liquid or solid organic compounds that tend to pass into the vapour state.

WWW

Water table: The upper limit of the saturated zone. It is measured by installing wells that extend a few feet into the saturated zone and then recording the water level in those wells.

Well log: A record describing geologic formations and well testing or development techniques used during well construction. Often refers to a geophysical well log in which the physical properties of the formations are measured by geophysical tools (e.g., E-logs and neutron logs).

Well screen: A filtering device that allows groundwater to flow freely from a formation into a well and minimizes the sediment entering the well.

Willow ring: A circle of (phreatophyte) shrubs/trees (usually willows) that form around periodically ponded low areas. These plants indicate very wet soil conditions.

Winkler titration: A chemical method used to estimate the amount of dissolved oxygen in water.

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Section 1

Introduction (J.F. Barker)

The objectives of the overall site investigation must be defined before the subsurface assessment begins. Broadly, the objective is to define the nature and extent of contamination at a site, ascertain the environmental impact, and if required, clean-up the identified problems. Section 1.1 provides a conceptual or general approach for the subsurface assessment activities, and most sections in this handbook will deal with specific aspects of this approach.

The chemical properties of contaminants are reviewed and similar chemicals are grouped (Section 1.2). Each group imposes specific requirements on the subsurface assessment. For example, **volatile organic** contaminants require study of soil gases or vapours; whereas, nonvolatile **organic contaminants** do not. Subsurface contaminants are considered to occur in up to five phases or forms, and these are defined. Assessments must define the form in which the contaminants occur.

The processes controlling contaminant migration and **fate** in the subsurface are introduced in Section 1.3. The nature of the subsurface materials controls, to a large extent, the migration of contaminants at a site. All sites are unique, but it is useful to discuss sites in terms of some general features. Five “conceptual” settings, encompassing the commonly encountered subsurface materials, are introduced in Section 1.4. The concepts of migration and fate of contaminants within settings of subsurface materials provide the conceptual framework in which to conduct the subsurface assessment. These concepts reoccur throughout this handbook and, combined with the chemistry of the contaminants, define the site assessment methods suited to a particular site.

As in all sections of this handbook, sources of additional information are provided. This recognizes the varied background of readers of the handbook.

1.1 Subsurface Assessment of Contaminated Sites

Contaminated site conditions are generally too complex and diverse to conform to a standard subsurface assessment plan. A staged or phased approach is usually used. Preliminary information is collected and then more detailed information, as required, is collected. Modify the procedure to suit the specific site. It will likely be necessary to combine different investigative techniques:

- research the site history and use;
- conduct various on-site investigations;
- use computer models of potential subsurface movement of contaminants; and

- clean-up the contamination and monitor the progress.

Figure 1 outlines a conceptual approach to subsurface assessment. The activities are briefly presented. Note the iteration within this approach. Each Section begins with the conceptual flow chart, highlighting what covers the Section.

1.1.1 Identify Site

The initial task is to identify the site. Some contaminated or potentially contaminated sites are obvious, like sanitary **landfills**. Others appear innocuous, with the potential contamination hidden underground, or perhaps beneath a **reclaimed surface**. This handbook deals only with identified sites, although Section 2 outlines sources of information that may help identify potentially contaminated sites.

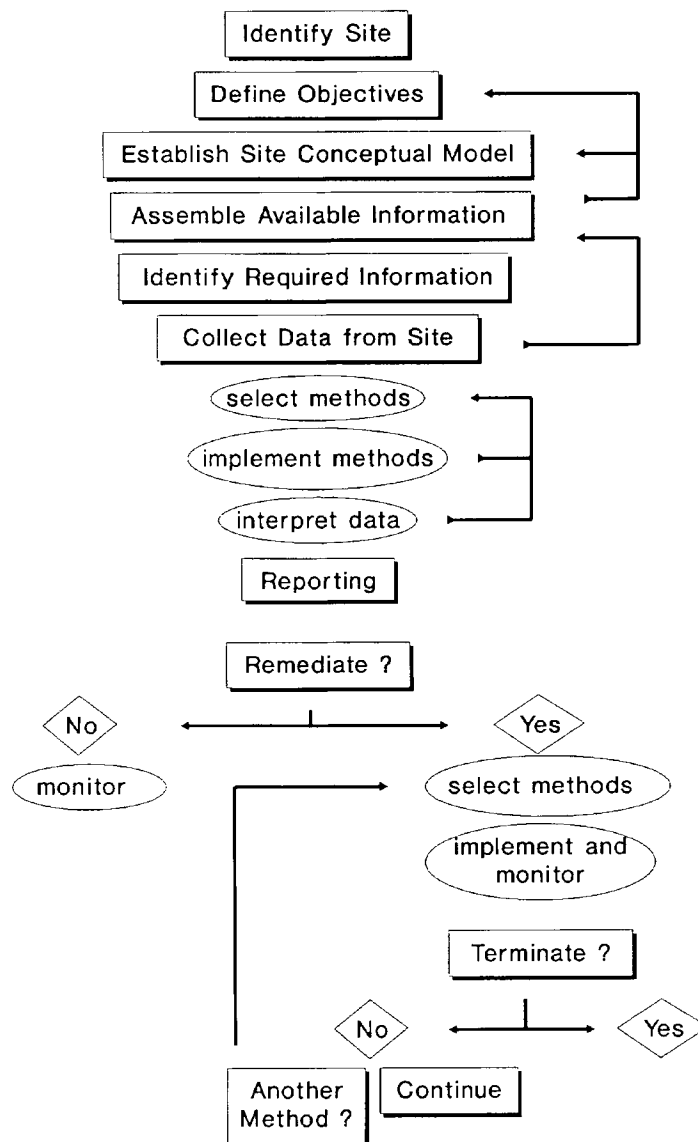


Figure 1 A Flowchart Outlining the Subsurface Site Assessment Process. Activities usually proceed from the top downward, but iteration (arrows) back to previous activities, are common.

1.1.2 Define Objectives

The objectives of the subsurface investigation should be defined within the overall objectives of the site investigation. Typical objectives of the overall site investigation are to:

- define the distribution of contaminants in the environment (air, water, and soil);
- determine the risks from exposure to these contaminants; and
- evaluate the possibility of mitigating these risks, and then mitigating the risks.

The objectives for the subsurface assessment must support the overall objectives, but they will be specific to the subsurface. Because the objectives are likely to change as the investigation uncovers additional information, update them regularly. For example, initial objectives may be to define the distribution of subsurface contamination. However, when serious contamination is found, an additional objective may be to examine clean-up possibilities. This is why arrows lead back to this activity in Figure 1.

1.1.3 Establish Site Conceptual Model

It is important to have a conceptual model of the site, which emphasizes the type and extent of the subsurface contamination, defines the pathways for contaminant migration, and identifies potential receptors (e.g., well users and surface water bodies). For example, at a landfill site, the conceptual model may identify the landfill as a potential source of dissolved contaminants that could move in the **permeable** sands thought to underlie the site toward a drinking water supply well 1.5 km away. This concept forms the basis for action; it allows us to choose what information must be collected. In the landfill example, we need to know the direction and rate of **groundwater flow**. The model evolves and improves as the subsurface assessment progresses. The conceptual model should be established at the onset (obviously in a very rough form) and revised again, as indicated by the arrow in Figure 1, as more information becomes available. Remember, however, that the purpose of the assessment is not to develop a great model, it is to meet the study objectives. Pursue improvement of the site conceptual model only as long as this supports meeting the site investigation objectives.

1.1.4 Assemble Available Information

To maximize time and cost efficiency, first assemble the information already available for the site and surrounding area (see Section 2). Try to obtain information about the possible contaminants as well as information about the subsurface conditions. The specific information you will eventually want to accumulate is based partially on the conceptual model. For example, if the model suggests contaminants could migrate in **fractures in bedrock**, examine geological information about the site vicinity to define the likely location and orientation of the fracture pathways. As this information is examined, the initial objectives and concept should be re-examined (see arrow in Figure 1).

This is also the time to begin considering health and safety issues and practical problems such as limitations of site access. Consider developing a preliminary work plan for subsequent site investigation at this stage.

1.1.5 Identify Required Information

Based on the available information and the **contamination concept**, identify the additional information required to meet the objectives. Also identify aspects of the subsequent data collection process that may have implications on human health and safety. A visit to the site is usually essential.

1.1.6 Collect Data from Site

Now collect the specific additional information needed to meet the objectives. Sections 3 to 7 discuss methods to gain, to assess, and to interpret this information. Some of the selected methods may not be successful. Perhaps they cannot be implemented because of some features of the site. For example, wells may not produce reliable groundwater samples from **impermeable** units such as clay. Perhaps they do not produce the required data or the data cannot be reliably interpreted. New sampling methods must be selected and implemented (see arrows). As Figure 1 indicates, analyses accumulate information that may change objectives and concepts and may identify new information to collect. Analyses may also save time and expense by identifying some information that is unnecessary to meet the study objectives. For example, when assessing the extent of groundwater contamination, and finding uncontaminated groundwater at some distance from the site, investigation further from the site may not be necessary. This staged approach uses iteration between objectives, concept, data collection, and interpretation. Often staged approaches are underemphasized in actual site investigations because of practical limitations such as time constraints.

1.1.7 Reporting

The final report of the subsurface assessment outlines how the analyses have met the objectives of the investigation. State the objectives, present the results and the methods used, and separate data from the interpretation. The report may compare soil, water, or air **contamination** on site with appropriate standards and criteria (such as those provided by CCME or local agencies) so that a decision to clean-up the site or to leave the site essentially as is can be made by the responsible parties.

1.1.8 Remediation

We might decide to actively remediate the contaminated site; “Yes” in Figure 1. Remediation involves selecting and implementing cleanup methods and then evaluating their success. Initial methods may prove inadequate and it may be necessary to select additional methods and to continue remedial efforts. This activity is also iterative, as shown in Figure 1.

Keep the possibility of this remedial activity or phase in mind during the earlier activities. It is often easiest to collect subsurface information relative to remedial actions in the earlier phases of the site assessment. Even if remediation is not an initial objective of the subsurface assessment, it is usually added to the objectives as evidence of site contamination mounts.

Typical cleanup methods are outlined in Section 7, but the major objective of this handbook is to provide guidance on the subsurface monitoring required to both assess the progress of remediation and provide an adequate basis for ending the remediation.

1.2 Contaminant Chemistry

Potential contamination that prompts subsurface assessments is either chemical or, to a lesser degree, microbial (bacterial and viral). Water quality standards reflect the level of concern about specific contaminants: some, like iron (Fe) are only a nuisance; whereas, others are toxic or carcinogenic. In addition, the properties of other chemicals, which are of little concern from a water quality perspective, may be useful in defining potential pathways for contaminant movement. The thousands of specific constituents that could be of interest can be broken down as:

- **inorganics;**
- major inorganic constituents (e.g., calcium, sulphate, and iron);
- **trace** metals (e.g., arsenic, mercury, and lead);
- gases (e.g., methane);
- organics;
- volatile organics (e.g., vinyl chloride and benzene);
- non-volatile organics (e.g., pentachlorophenol and atrazine);
- microbiological;
- bacterial (e.g., *Salmonella typhosa*); and
- viral (e.g., hepatitis A).

The similarities within each group simplify sampling, which can deal with groups of parameters rather than only with individual parameters.

Contaminants can be found in five phases or compartments in the subsurface (see Figure 2):

- solid grains, rock, or waste (e.g., **mine tailings** solids);
- ions or molecules weakly bound (**sorbed**) to solids that both contaminate these solids and can be released into water or vapour;
- gas or vapour in the **pore spaces** around these solids (**unsaturated zone**);
- water in the pore spaces, either along with vapour in the unsaturated zone or completely filling the pore spaces in the **saturated zone**; and

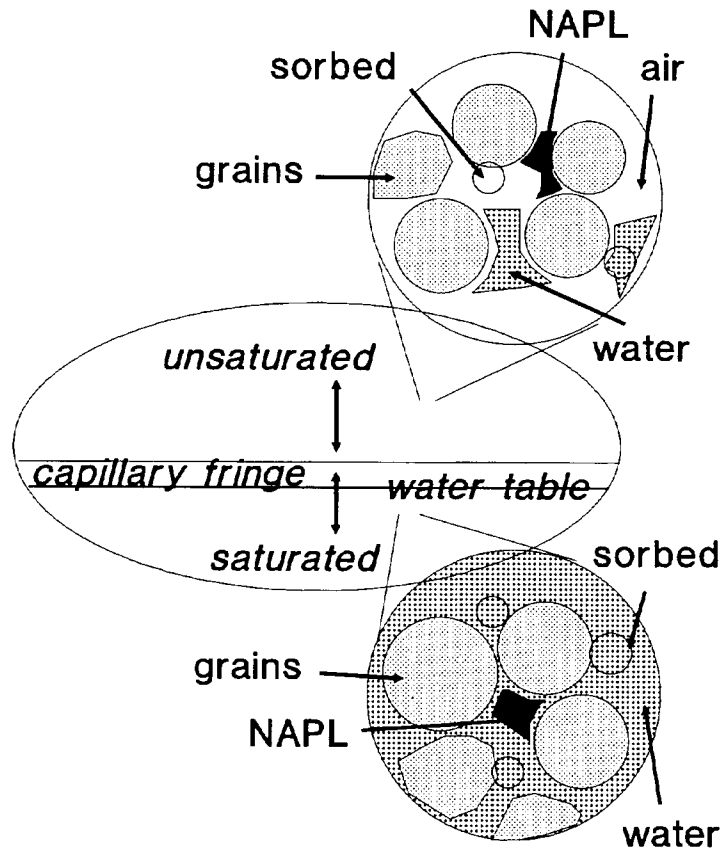


Figure 2 **Diagram of Subsurface Compartments in Unsaturated and Saturated Zones**

- non-aqueous-phase-liquid (NAPL), either as a mobile, continuous phase or as immobile, discontinuous **residual**.

Contaminants in mobile phases (water, NAPL, and vapour) can migrate. Contaminants from immobile phases (solids or residual NAPL) can contaminate subsurface water and vapour (see Figures 3 and 4). Typical sources of groundwater contaminants are:

- vapours that can also **dissolve** in groundwater (e.g., gasoline);
- solids that produce undesirable dissolved constituents (e.g., arsenopyrite, a mineral from which arsenic can leach) and that are toxic themselves;
- chemicals sorbed onto solid surfaces that can enter groundwater through various **desorption** processes; and

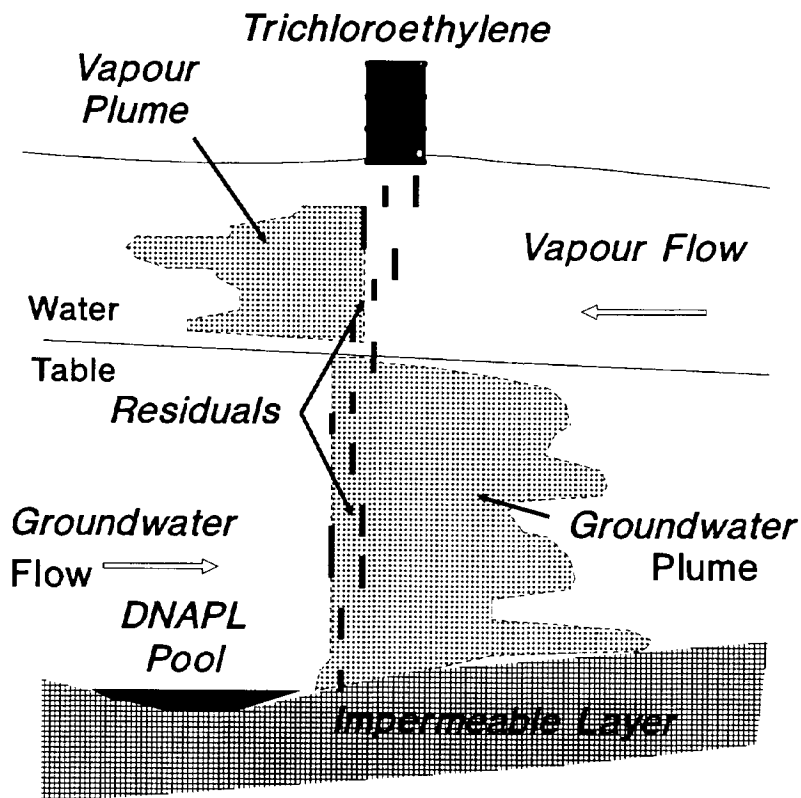


Figure 3 Subsurface Cross Section of DNAPLs and Plumes. Note the plumes stemming from residual DNAPLs and the DNAPL pool below the water table and resting on impermeable material.

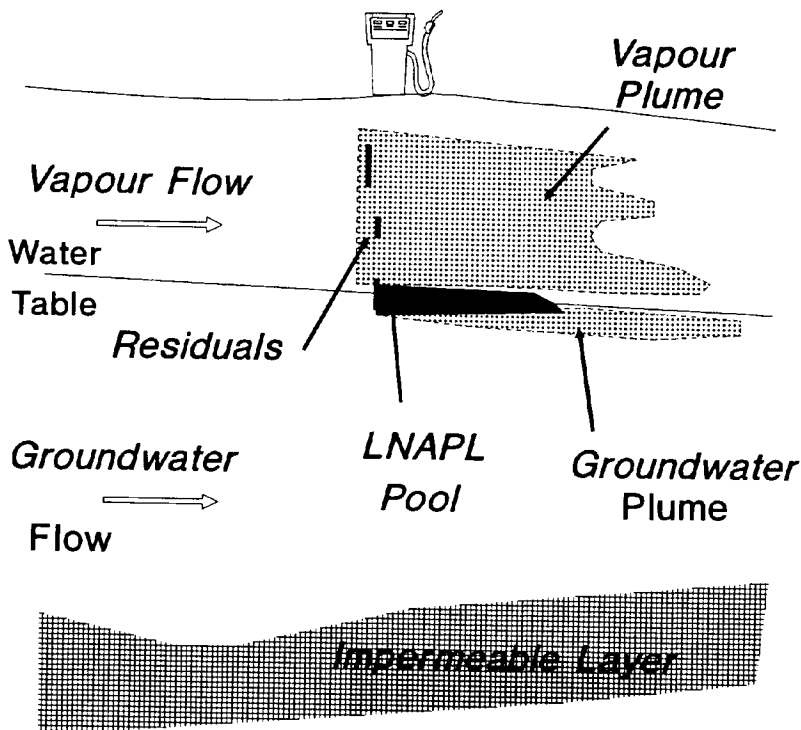


Figure 4 Subsurface Cross Section of LNAPLs and Plumes. Note the plumes stemming from residuals and the LNAPL pool near the water table.

- pools of NAPLs that are potentially mobile and are either: lighter (less dense) than water (LNAPLs, e.g., gasoline); heavier than water (DNAPLs, e.g., creosote and trichloroethylene); NAPL residuals, which are immobile, but can **leach** into groundwater or soil vapour; or dissolved in groundwater and may be capable of sorbing onto the aquifer solids.

Contaminants tend to distribute themselves among these phases or compartments to attain or approach an **equilibrium**. By determining this distribution it may be possible to identify one or two phases that contain most of the contaminant. If one phase is mobile, you will have identified the dominant vehicle for contaminant migration. If the phase containing the bulk of the contaminant is immobile, migration may be slow. In other cases, it may be better to sample and analyze the solid material to define the distribution of a contaminant, such as dioxin, which partitions very strongly onto the solid material rather than into water. Contaminants strongly partitioned or sorbed onto solids from water will not be highly concentrated in groundwater. Equilibrium partitioning of contaminants between subsurface phases can be approximated by the parameters outlined in Table 1.

Some “rules of thumb” stem from consideration of partitioning. Contaminants in a solid phase, whose **solubility** exceeds about twice the “**action level**”, or acceptable concentration in water, of the contaminant, may cause groundwater contamination. Other solids are not soluble enough to produce unacceptable contaminant concentrations in groundwater. Contaminants with **sorption coefficients** (K_d) less than about 10 mL/g will be mobile in groundwater. Others will be rather immobile. Contaminants with Henry’s Law constants greater than about 10^{-3} atm·m³/mol may be significantly transported in the vapour phases; whereas, other contaminants will likely be

Table 1 Parameters that Describe the Equilibrium Partitioning of Contaminants Between Various Phases or Compartments of the Subsurface.

For Equilibrium Between	Parameter
NAPL–air	Vapour Pressure, P_{VP}
NAPL–water	Solubility, S
water–air	Henry’s Law Constant, H
solid–water	Solubility Product, K_{SP}
water–sorbed	Sorption Distribution Coefficient, K_d
air–sorbed	Currently uncertain, perhaps combine H and K_d

transported in groundwater or will be rather immobile. Although this handbook does not deal directly with contaminant migration and fate, Section 2 (Table 2) suggests some sources for such environmental properties of the contaminants.

1.3 Principles of Migration and Fate of Contaminants

Contamination can come from a variety of sources. Some sources, such as landfills and refineries, may be very old and may contaminate a broad area for a long time. Contamination can also come from local, sudden releases of chemicals, such as leaking pipelines or underground storage tanks.

Most subsurface investigations will evaluate not only the current distribution of contaminants, but also the factors that control their migration and fate. The important controlling processes are:

- **fluid flow and diffusion;**
- **dispersion;**
- **sorption;**
- **precipitation and dissolution; and**
- **chemical and microbiological transformation.**

1.3.1 Fluid Flow

Non-aqueous-phase-liquids (NAPLs) can flow in the subsurface. Those less dense than water (LNAPLs) are not usually found below the **water table**. NAPLs more dense than water (DNAPLs) can flow below the water table. Essentially all chemical contaminants can dissolve in groundwater to some extent and therefore move along with flowing groundwater. Contaminants that are present in the vapour phase can also move with the vapour. Thus, moving fluids (NAPLs, groundwater, or subsurface vapour) can carry contaminants.

Fluid flow is usually expressed as the **fluid flux** (q , in L/T), produced by a **driving force**, the difference of **hydraulic head** over some distance of interest, dh/dl (dimensionless), with the material providing a resistance to flow, expressed by the **hydraulic conductivity** (K , in L/T) of the material. This relationship is expressed by the **Darcy equation**:

$$q = -K \, dh/dl \quad [1]$$

The negative sign indicates that fluids move from areas of high head to areas of low head. The hydraulic conductivity is a function of the material and the fluid as indicated by:

$$K = k \rho g \mu \quad [2]$$

where k (L^2) is the **intrinsic permeability** of the material, ρ (M/L^3) is the fluid's mass density, g (L/T^2) is the gravitational constant, and μ (M/LT) is the fluid's **viscosity**. The **average linear groundwater velocity** (v , in L/T), is related to q as:

$$v = q/\theta \quad [3]$$

where θ (dimensionless) is the **porosity** (volume of voids/volume of **aquifer** material) involved in the fluid movement. To describe how fast subsurface fluids are moving, the hydraulic head, hydraulic conductivity (permeability and fluid properties if not water), distribution of hydraulic head, and **effective porosity** need to be measured or estimated. Section 4 describes how to make these measurements. Section 6 indicates how such values can be incorporated into mathematical models to describe contaminant movement.

1.3.2 Diffusion

When fluids do not flow at a significant rate, contaminants can still move by the process of diffusion. This process is described by Fick's first law:

$$F = -D \, dC/dl \quad [4]$$

where the **mass flux** of chemical (F , in M/L^2T), is related to the **diffusion coefficient** (D , in L^2/T), and the **concentration gradient** (dC/dl), which is the driving force. The negative sign in Fick's first law indicates that chemical diffusion moves some of the chemical from high concentration regions to low concentration regions. Diffusion is generally much slower than fluid movement and is only important where fluids are essentially not moving. This normally occurs where impermeable subsurface materials prevent fluid movement.

1.3.3 Dispersion

Smoke from a smoke stack becomes less obvious as the air flow mixes the smoke-laden air with clean air. This mixing is termed dispersion. Dispersion lowers contaminant concentrations in fluids. Dispersion is weak in groundwater and in the confines of subsurface materials, but is still an important process in lowering contaminant concentrations. Dispersion generally increases as the **heterogeneity** of the subsurface increases. Section 4 provides guidance in assessing the subsurface heterogeneity.

1.3.4 Sorption

Contaminants dissolved in water or in vapour can interact with subsurface solids. One interaction is sorption, in which some of the contaminant leaves the fluid and associates with the solid phase. The sorptive interaction processes are often complex and poorly understood, but the overall results are well appreciated. Sorption is usually reversible; therefore, it will not permanently remove the contaminant from the mobile fluid. It does, however, slow the contaminant migration. Measure or test subsurface materials to estimate the **sorptive retardation** (see Subsection 5.7.1).

1.3.5 Chemical and Microbial Transformation

Some contaminants may become solidified through a chemical reaction called precipitation. The formation of rust from well water is an example in which dissolved iron reacts with oxygen and water to form a precipitate. Also, solids can react with water and/or dissolved chemicals to form additional dissolved chemicals. Solids such as salt are readily soluble and form sodium and chloride ions in water. Section 5 mentions some chemical models to evaluate precipitation and dissolution.

Some chemical changes do not involve solids. For example, a change in water acidity can change the specific form of a chemical like bicarbonate (HCO_3^-). At high pH it becomes carbonate (CO_3^{2-}). **Biological activity** can convert organic chemicals, such as benzene, to CO_2 and H_2O . Evidence of such reactions at contaminated sites may indicate how the current contaminant pattern came about and how the pattern will change over time. Section 5 discusses how to gather the specific required information.

Figure 5 illustrates how these processes influence the movement and shape of contaminants in groundwater. Groundwater flow moves the contaminated groundwater laterally. Dispersion

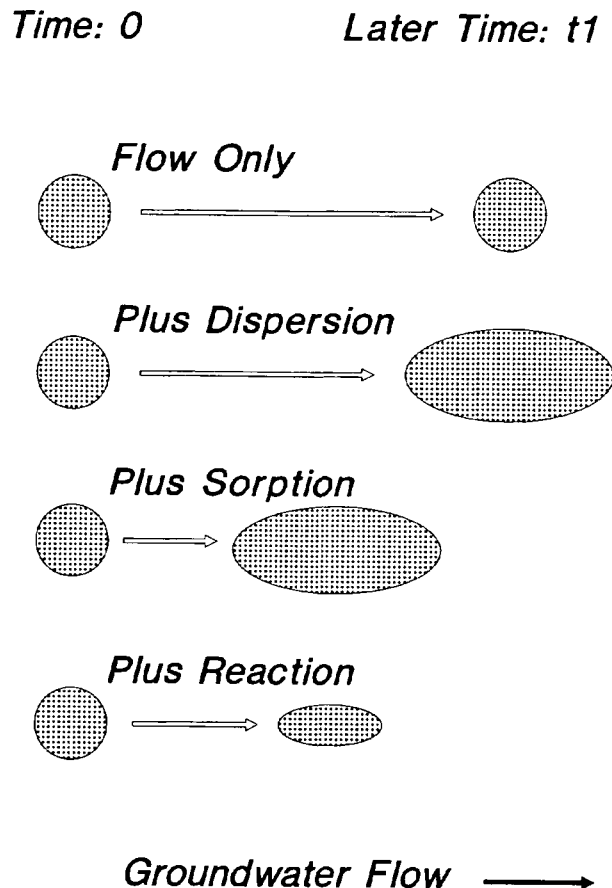


Figure 5 **A Schematic Cross Section Showing the Effects of Processes on the Movement of Contaminants Initially Dissolved in a Sphere of Contaminated Groundwater.**

spreads the zone of contamination, but leaves lower concentrations in the contaminated zone. Sorption retards the contaminants' movement; whereas, a reaction may remove some of the contaminant from the whole system.

Subsurface assessment will likely involve both analyses of specific contaminants and analyses of other properties to evaluate the movement and fate of contaminants. Geophysical measurements (Section 3) and hydrogeological measurements (Section 4) concentrate on the physical aspects of the subsurface materials that control fluid flow. Sampling for chemical analysis, which addresses sorption, reaction, and transformation processes, is emphasized in Section 5.

1.4 Hydrogeological Settings

The subsurface assessment usually investigates subsurface pathways for contaminant migration. These pathways are controlled mainly by the nature of the subsurface materials and therefore are site specific. Where possible and appropriate, this handbook provides guidance specific to the site hydrogeological setting. This handbook establishes five general settings that represent actual settings and emphasize the flow pattern and flow speed typical of each.

- (1) porous, non-fractured material (Figure 6), e.g., sands, sandstones, and unfractured clays. Flow is by intergranular porosity, or diffusion if permeability is low.
- (2) porous, fractured material (Figure 7), e.g., as in setting 1 with significant flow through fractures. Diffusion into **matrix** porosity may **attenuate** contaminants.
- (3) non-porous, fractured material (Figure 8), e.g., **igneous** bedrock, with fractures. Flow is along fractures without diffusion into the matrix porosity.
- (4) fissured material (Figure 9), e.g., channel flow, limestone **karst** and some basalt. Flow is often rapid and through large openings.
- (5) **permafrost** (Figure 10). Water and contaminant flow by freeze-thaw cycles as well as by normal flow when thawed.

Actual sites usually contain mixtures of these settings. For example, shallow sand may overlies fractured igneous bedrock. Also, frozen ground (permafrost-like) conditions often exist seasonally.

The conceptual model for the site under investigation attempts to define the hydrogeological setting that, in turn, defines the likely pathways for subsurface migration of contaminants. For example, pathways for rapid movement of contaminants off-site could include a very permeable material like gravel at shallow depth (setting 1), or **solution channels** developed in a deeper, karst bedrock surface (setting 4). These are very different targets for investigation and involve very different investigation strategies. Therefore, define the hydrogeological setting as early as possible in the subsurface investigation to ensure that the best site investigation approaches are

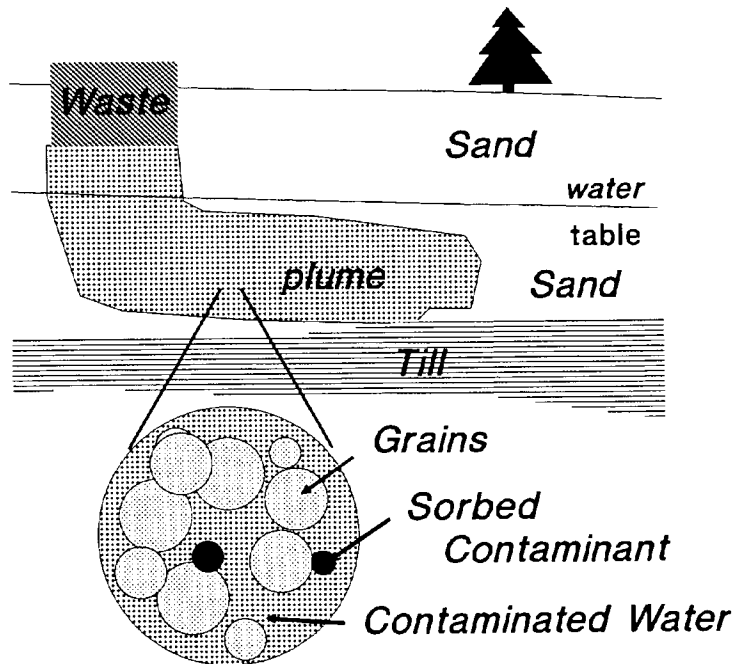


Figure 6 **Subsurface Cross Section of Setting 1: Porous, Non-fractured.** The plume emanating from the waste site is rather regular and its position is controlled mainly by groundwater flow.

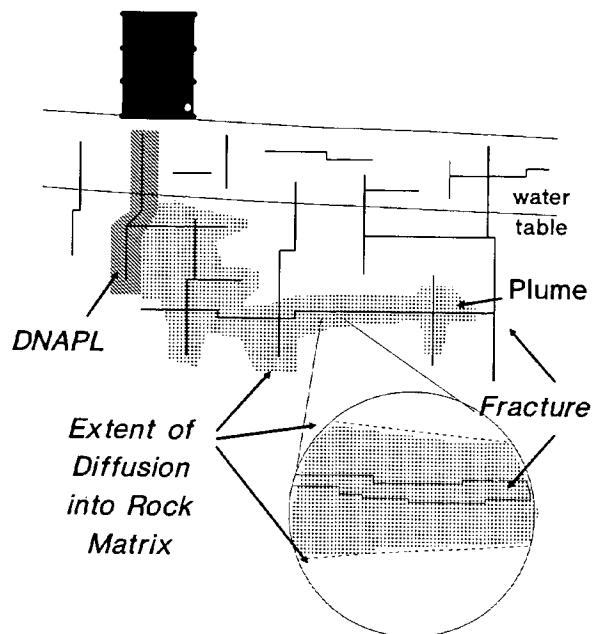


Figure 7 **Subsurface Cross Section of Setting 2: Porous, Fractured.** The DNAPL has penetrated below the water table and groundwater flow takes dissolved contaminants laterally. Note that contaminants slowly diffuse into the porous rock, attenuating somewhat like their migration in the fractures.

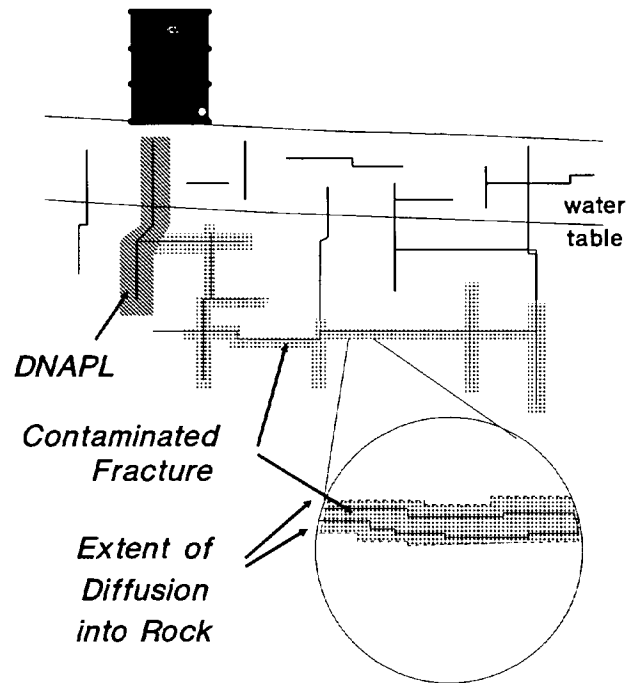


Figure 8 **Subsurface Cross Section of Setting 3: Non-porous, Fractured.** Similar to Figure 7 except that diffusion into the rock is very limited and therefore attenuation of the dissolved contaminants is reduced.

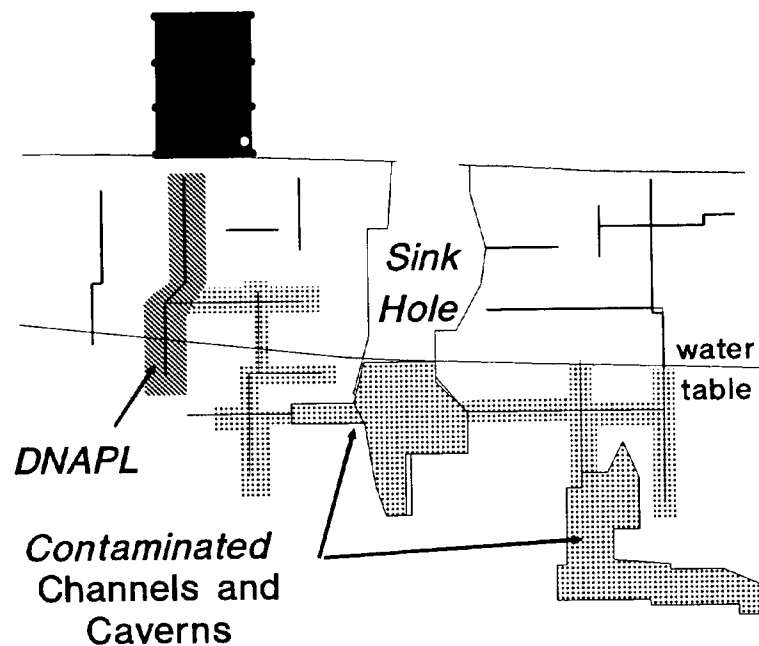


Figure 9 **Subsurface Cross Section of Setting 4: Channel Flow.** Dissolved contaminants move mainly through open channels that can conduct large volumes of contaminated groundwater for long distances in short times.

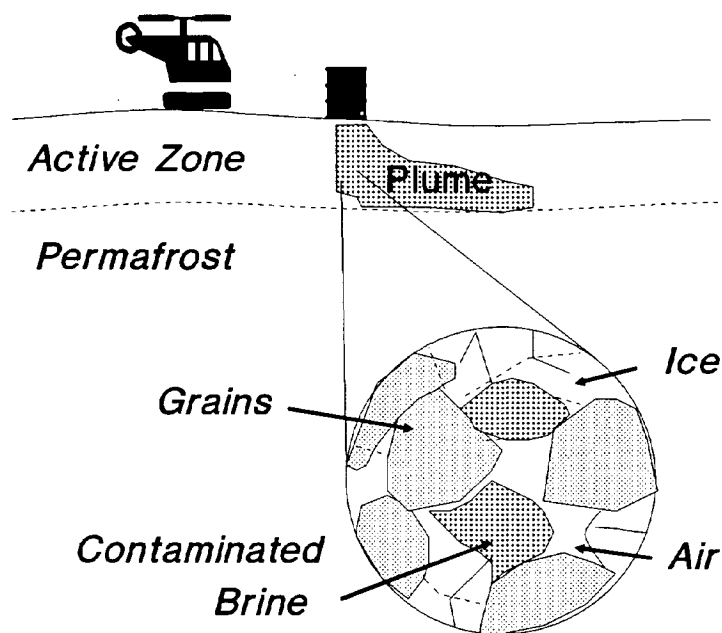


Figure 10 **Subsurface Cross Section of Setting 5: Permafrost.** Dissolved contaminants are restricted to the active zone where they concentrate and migrate in unfrozen water (usually brine) moving at freezing fronts.

used. Unfortunately, you may be unable to correctly establish the hydrogeological setting until you begin collecting subsurface information.

Subsurface assessment is a rapidly evolving field. Where possible, limitations of current techniques are noted and procedures that are being developed and evaluated are mentioned. Simply relying on current practice or, where applicable, regulatory requirements, may not produce adequate subsurface assessments at contaminated sites. Explore and critically evaluate promising methods to produce better assessment practices.

1.5 *Additional Information*

Three texts are recommended for additional information and explanation:

- Freeze, R.A. and J.A. Cherry, *Groundwater*, Prentice-Hall, Englewood Cliffs, New Jersey (1979).

This is the standard text for groundwater contaminant transport. Although it does not deal with organic contaminants, the principles and concepts are very clearly presented.

- Domenico, P.A. and F.W. Schwartz, *Physical and Chemical Hydrogeology*, John Wiley & Sons, New York, New York (1990).

This is a more up-to-date consideration of how contaminants move in the subsurface. Organics are included as are sampling and some case studies.

- Schuille, F.W., *Dense Chlorinated Solvents in Porous and Fractured Media: Model Experiments*, (Translated by Pankow, J.F.), Lewis Publishers, Chelsea, Michigan (1988).
An excellent description and discussion of how NAPLs move and contaminate the subsurface.

NAPLs pose particular problems in subsurface contamination. This document provides a brief overview of the problem and approaches:

- Huling, S.G. and J.W. Weaver, *Dense Nonaqueous Phase Liquids*, United States Environmental Protection Agency, EPA/540/4-91-002, Washington, D.C. (1991).
Some articles, including case studies of subsurface contamination in the five general hydrogeological settings outlined in this section, are suggested if you want to see the nature of the contamination and the methods of research investigation:

Setting 1, Porous, Non-fractured Material:

- Barker, J.F., J.S. Tessman, P.E. Plotz, and M. Reinhard, "The Organic Geochemistry of Selected Trace Organics of a Sanitary Landfill Leachate Plume", *Journal of Contaminant Hydrology*, 1: 171–189 (1986).

Setting 2, Porous, Fractured Material:

- Barker, J.F., J.E. Barbash, and M. Labonte, "Groundwater Contamination at a Landfill Sited on Fractured Carbonate and Shale", *Journal of Contaminant Hydrology*, 3: 1–25 (1988).
- Kueper, B.H., C.S. Haase, and H.L. King, "Leakage of Dense, Nonaqueous Phase Liquids from Waste Impoundments Constructed in Fractured Rock and Clay: Theory and Case History", *Canadian Geotechnical Journal*, 29: 234–244 (1992).

Setting 3, Non-porous, Fractured Material:

- Bottomley, D.J., J.D. Ross, and B.W. Graham, "A Borehole Methodology for Hydrogeological Investigations in Fractured Rock", *Water Resource Research*, 20: 1277–1300 (1984).

Setting 4, Fissured Material:

- Quinlan, J.F., *Groundwater Monitoring in Karst Terrains: Recommended Protocols and Implicit Assumptions*, United States Environmental Protection Agency, EPA 600/X-89/050, Washington, D.C. (1989).

Setting 5, Permafrost:

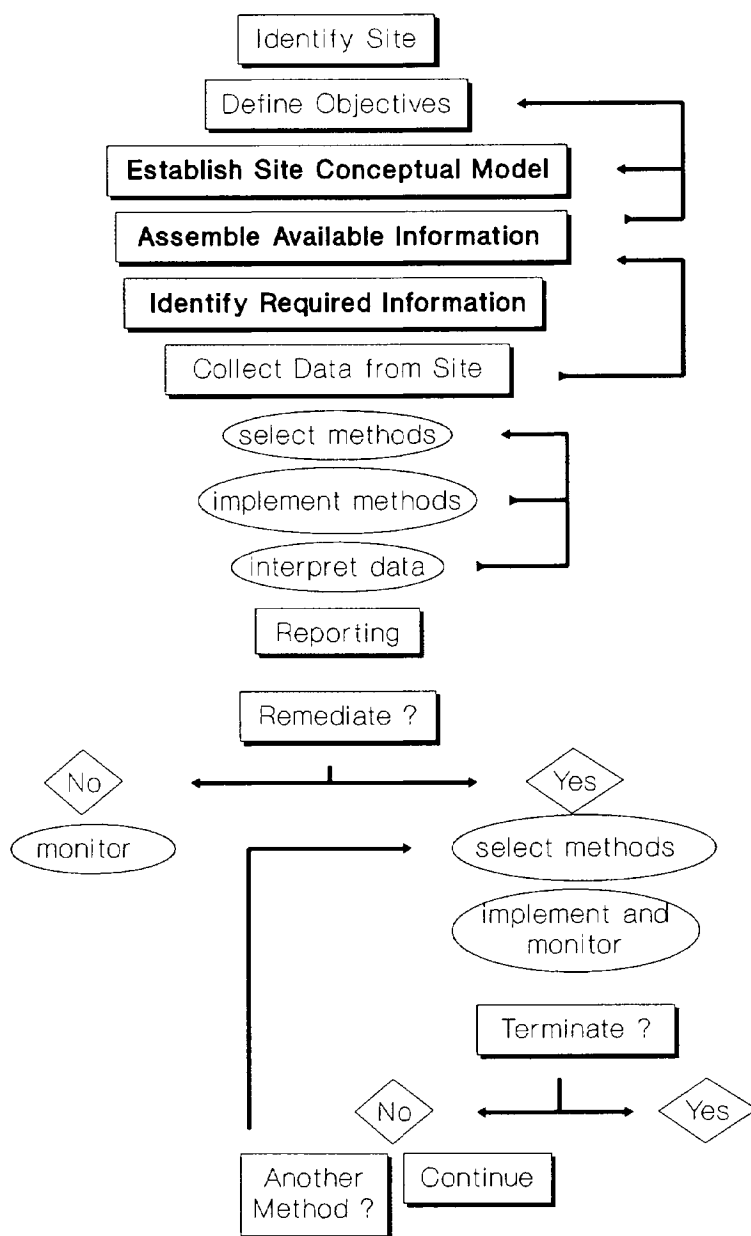
- Konrad, J.M. and A.W. McCammon, "Solute Partitioning in Freezing Soils", *Canadian Geotechnical Journal*, 67: 726–736 (1990).

Professional short courses covering various aspects of contamination in the subsurface are also offered. Contact the organizations directly to determine what is of interest:

- The National Ground Water Association, 6375 Riverside Drive, Dublin, OH 43017; and
- Waterloo Centre for Groundwater Research, University of Waterloo, Waterloo, Ontario N2L 3G1.

Additional groups may also offer useful courses and various professional societies and organizations offer conferences and workshops on this topic. They will likely be advertised or announced in journals such as *Ground Water* and *Ground Water Monitoring Review* and in newsletters such as:

- *Resilog* (published by the Technology Development Directorate, Environment Canada); and
- *The Association of Ground Water Scientists and Engineers Newsletter* (published by Ground Water Publishing Co., 6375 Riverside Drive, Dublin, OH 43017).



Section 2

Desk-top Review (R. Nicholson and D. Smyth)

Before actually collecting data in the field, you can accomplish a lot by reviewing existing data. This “desk-top review” of existing data is the major activity in the initial phase of a site investigation. This section provides guidance for collecting pertinent information on:

- what information to collect;
- where to collect it; and
- what to do with it.

At this point, you have defined the objectives of the subsurface investigation, at least initially. This section prepares you to efficiently and thoroughly collect additional information at the site. In the desk-top review, you examine the site history (Section 2.2) to determine the types and possible distribution of contaminant sources. From the information about contaminant chemistry, start to develop a health and safety plan for subsequent on-site investigation (Section 2.4). You develop the site conceptual model and assemble any existing information that is pertinent to the investigation objectives. Information about the contaminants, the regional and site subsurface materials, hydrogeology (Section 2.5), and hydrology (Section 2.6) should be emphasized. You define the additional information required to meet the subsurface investigation objectives and you formulate initial work plans to collect the required information (Section 2.8). Sources of additional information and guidance are given in Section 2.10.

2.1 Introduction

A comprehensive desk-top review of existing and historical information about the site can facilitate appropriate planning and ensure the implementation of an efficient, safe, and thorough field investigation program. Consequently, this can minimize the time, effort, and cost associated with the overall site investigation. The desk-top review has three purposes:

- to identify potential subsurface contaminants and environmental concerns at the site;
- to identify, in a preliminary manner, the subsurface conditions at, and in the vicinity of, the site and thereby develop the site conceptual model; and
- to establish the framework for the subsequent site investigation (to establish the work plan).

The site conceptual model will undergo considerable development to provide guidance for the subsequent phases of field investigation and interpretation of the findings. Whether hydrogeologists formalize this development process as a “working model” or not, this approach is almost always followed.

The data found at this stage are usually sparse, so avoid the tendency to oversimplify the conceptual model. Although a simple model is useful to gain an appreciation of the “large picture”, respect and consider the uncertainties and complexities of the real setting in developing the work plan. Also include non-technical considerations, such as regulatory requirements for site work, health and safety procedures, and the “community relations” aspect of the investigation.

2.2 *Sources of Information on Site History*

Information about current and historical land use and activities can indicate the existence or likelihood of subsurface contamination at the site. The types of information and possible sources of this information are summarized in Table 2.

Table 2 Information Sources for Site History

Sources of Information	Type of Information	Availability
Owner and regulatory agency files	Site operational and environmental history	Site owner and government agencies (environment and regulatory)
Land use and ownership history	Site activities and operations	Municipal tax records and directories, and title searches
Aerial photographs	Land use history physical and drainage features	Government agencies (natural resources/national and local archives)
Archival records	Historical photographs operational history	National and local archives corporate files
Site plans and engineering drawings	Site layout and features	Corporate and municipal files
Historical maps and fire insurance plans	Land use and industrial process areas	National and local archives
Anecdotal reports	Site history and practices	Present and former employees, local residents, and local historians
Industrial activities and processes	Manufacture, use, storage, and disposal of chemicals	Corporate archives and historical and contemporary trade journals and texts

2.2.1 Owner and Regulatory Agency Files

Although there may be occasions when property owners are reluctant to reveal details about site use and operations, you can only develop the most effective subsurface assessment programs when all pertinent information related to environmental affairs at a property are disclosed. For example, past incineration practices could have distributed contaminated ash on site. The past practices may be a current embarrassment for the owner, but it is important information for site assessment. Inform the site owner of why you require the information and how you will use it. Avoid collecting information not pertinent to the site investigation.

If the property has changed hands recently, there may have been a brief evaluation of the environmental condition of the site at the time of sale. This "environmental audit" may be kept by the purchaser and their insurer. It could provide a good start to evaluating contamination at the site.

At orphan sites or industrial sites that have a long and varied land-use history, there may be many unknowns about site conditions. The following sections suggest sources of information about such sites. In contrast, for most modern sites, particularly as a consequence of the recent strict environmental regulations, there is a strong possibility that the owner has a good database of subsurface information. Be aware also, that operating and environmental staff have a good knowledge of potential problem areas. Using these databases, in combination with the input of the owner's staff, can help identify the potential for, and nature of, subsurface contamination at a site. Regulatory agencies may also have pertinent environmental data about specific sites. Seek their information through local offices.

Review shipment, inventory, and billing records as another means of identifying the types of chemicals and materials used or handled on site. For facilities in which large volumes of chemicals are used and stored, discrepancies between received, inventory, and usage/sales may indicate potential loss of chemicals to the environment. Large-scale leaks at gasoline stations have been identified in this manner. However, the inaccuracy of inventory measurement at gasoline stations precludes detection of small, but potentially environmentally significant, losses of products to the subsurface.

2.2.2 Land Use and Ownership Histories

The title search for a property will generally identify legal ownership for several decades and may also yield information about the types of on-site activities. Only in some circumstances, such as the presence of on-site licensed waste management facilities, registered storage tanks, or an easement for a utility corridor, might the title search identify a specific area or areas of the property where subsurface contamination may exist. Employ personnel or firms experienced in title searches.

2.2.3 Aerial Photographs

Aerial photographs are widely available (check the yellow pages) and provide a convenient means for confirming on-site and nearby land-use practices. If historical sequences of aerial photographs are available, it may also be possible to identify how land-use practices have changed. Historical changes in land-use practices may result in changes in the types of materials

used and handled on the site, and in the nature and the location of contamination of the subsurface.

2.2.4 Archival Records

Archives for a particular property or area may be available from the local, municipal, state, or provincial governments. Archives may also be available for a specific property in corporate records if one corporation owned the property for an extended period of time. Although archived records are unlikely to focus specifically on the occurrence of subsurface contamination, the archives may indicate the nature of past activities at the site, and allow you to make some inferences concerning the potential for the historical introduction of contaminants to the subsurface.

2.2.5 Site Plans and Engineering Drawings

For many industrial and commercial sites, engineering design and as-built drawings for structures and facilities are available. You can often identify features such as pipelines, transfer facilities, and storage tanks and use this information to target further search for potential sources of contamination. Reports from previous site investigations for geotechnical and foundation engineering are a valuable source of information about subsurface conditions at the site and are generally pertinent to assessment of subsurface contamination. Site owners are the best source of current site drawings and reports. Previous owners, utility providers, and local governments may have historical plans, drawings, and reports.

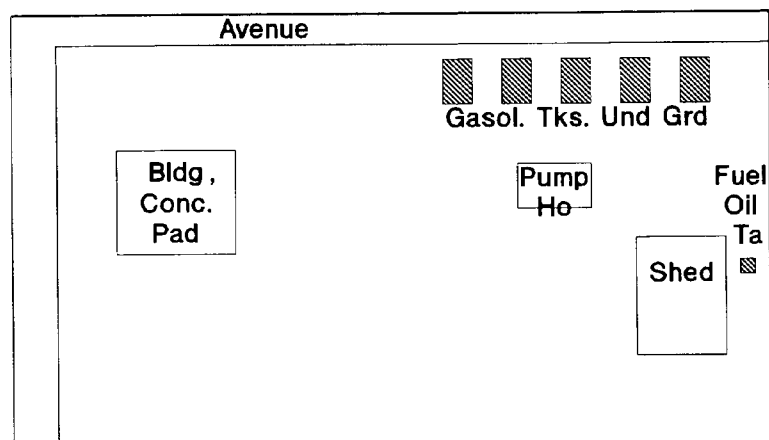
2.2.6 Insurance Maps and Records

Fire insurance maps were commonly prepared for many industrial and manufacturing facilities from the mid-1800s to the mid-1900s. These maps may be available for older sites (particularly in cities and communities where there has been a historical industrial base) from national, provincial, and local archives. Raven *et al.* (1987), for example, used fire insurance maps in compiling an inventory of coal gasification plants and associated contaminant problems in Ontario. Insurance records may also identify the types of chemicals manufactured or used at a particular site, from which you can infer the types and likelihood of associated subsurface contamination problems. Figure 11 illustrates the potential usefulness of fire insurance maps and site plans.

2.2.7 Anecdotal Reports

Interviews with former employees, operators, customers, or neighbours of an historical, industrial, or commercial operation can provide anecdotal information about general operational and waste disposal practices that, for example, have no formal records. The form of the interview is critical to avoid intimidating the subject. Recognize that many historical, industrial and commercial practices, although accepted by society and regulatory agencies as the norm in the past, may violate current laws and regulations. Use experienced, sensitive interviewers. Information from interviews is often inaccurate and contradictory; therefore, use it cautiously.

Fire Insurance Map



Current Land Use

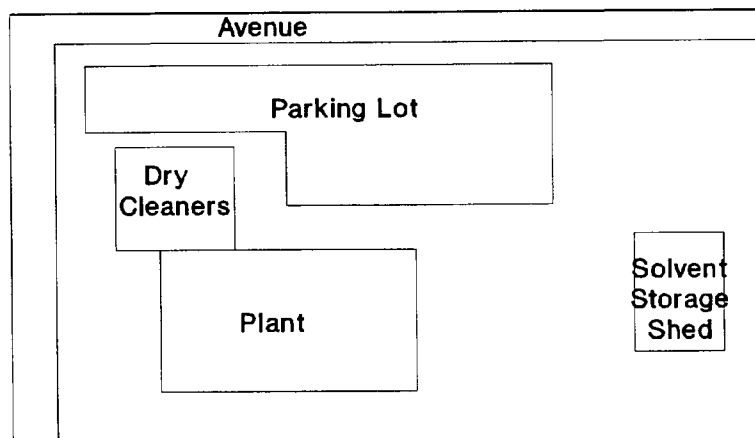


Figure 11 Hypothetical Fire Insurance Map and Current Land Use (Site Plan) Drawings. Examination of the current land use would focus attention on chlorinated solvent contamination near the buildings and shed. The fire insurance map would identify additional concerns: contamination by petroleum products near the underground gasoline tanks (Gasol. Tks. Und Grd), near the above-ground fuel oil tank (Fuel Oil Ta), and near the pump house (Pump Ho).

2.3 *Contaminant Data*

During the desk-top review you can collect essential information about subsurface contaminants. Key issues to consider at the desk-top review stage include:

- the nature of known or suspected contamination;
- the sources, or possible sources, of contamination;
- the extent of contamination; and
- the implications for site investigations and monitoring with respect to environmental quality, regulatory requirements, and public perception.

2.3.1 *Nature of Contamination*

It is very important to recognize the nature of known or suspected contamination early in the site assessment process. The behaviour and environmental fate of specific contaminants are functions of their environmental properties and the degree to which they are influenced by physical, chemical, and biological processes in the subsurface. As introduced in Section 1, the number of potential subsurface contaminants is immense and, at any specific site, they may also occur in complex mixtures or associations. Thus, in terms of site assessment, it is generally convenient to classify the potential contaminants into groups according to their subsurface behaviour (see Section 1.2).

It is also very important to recognize the possible risk posed to the environment and humans by contamination at a site. For some chemicals, toxicity and environmental threat have been recognized and standards and guidelines for air emissions, discharge water quality, and drinking water quality have been adopted by regulatory agencies (e.g., World Health Organization Drinking Water Guidelines; CCME, 1991b).

For potential and known contaminants at the site, review and list:

- environmental standards based on health concerns (water, soil, and air) (e.g., CCME, 1991b);
- health and safety standards based on contact in the work environment (e.g., CCME, 1991b); and
- environmental properties of organic chemicals (use described in Section 1.2; sources listed in Table 3).

Attempt a preliminary classification of contaminants on the basis of their likely subsurface behaviour. A six-member grouping system is suggested:

(1) Soil Contaminants. In most circumstances, subsurface contamination by these chemicals is restricted to surficial soil and very shallow subsoil, or to the limits of buried, immobile wastes. Such wastes can include **heavy metals in foundry sand**, polychlorinated biphenyl compounds

Table 3 Environmental Parameters and Sources of Data for Processes Influencing Subsurface Contaminant Transport

Chemical Group	Processes (• Approach, ○ Sources, and ↔ Typical Ranges)		
	Solubility	Sorption	Volatilization
Major Inorganics (e.g., Ca, SO ₄)	<ul style="list-style-type: none">• Solubility product of potential mineral phases○ Morel (1983) ↔ μg/L to g/L	<ul style="list-style-type: none">• Experimental K_d measurements○ Matthess (1982) and Section 2.2) ↔ 1 to 10 ⁵ mL/g anions (low); cations (low to high)	Not significant except for methylated metals
Trace Inorganics (e.g., Zn, U)			
Inorganic Gases (e.g., CO ₂ , N ₂)	<ul style="list-style-type: none">• Experimental○ Wilhelm <i>et al.</i> (1977) ↔ mg/L	not significant	<ul style="list-style-type: none">• Henry's Law Constant○ Hansch and Leo (1979) ↔ 10 ⁻⁹ to 3 atm·m ³ /mol
Volatile Organics (e.g., vinyl chloride)	<ul style="list-style-type: none">• Experimental or Solubility (K_{ow} relationships)○ Lyman <i>et al.</i> (1990) ↔ ng/L to miscible	<ul style="list-style-type: none">• Experimental or K_d - K_{ow} relationships○ Lyman <i>et al.</i> (1990) ↔ 1 to 10 ⁶ mL/g	
Organics (e.g., dioxins)			Not significant

in waste oil, or land-applied **heavy oils**. These contaminants are characterized by low solubility in groundwater and a strong affinity for sorption to soil particles (high K_d), and their occurrence does not necessarily result in the generation of contaminated groundwater.

(2) Groundwater Contaminants. These are soluble, mobile chemicals (low K_d) including many soluble organics, soluble metals (e.g., arsenic) and soluble radionuclides (e.g., tritium). In some circumstances, **plumes** of groundwater contaminated by such compounds emanate from a source. Examples include:

- shallow groundwater contaminated by hexavalent chromium (Cr^{+6}) from electroplating waste disposal;
- ferrous iron (Fe^{+2}) and toxic metals in acidic groundwater as a consequence of sulphide mineral oxidation in mine milling wastes;
- nitrate contamination from septic and sewage lagoon systems; and
- contamination by constituents such as chloride and sulphate, and organics such as toluene and organic acids, from domestic landfills.

(3) Light Non-aqueous Phase Liquids (LNAPLs). These fluids, such as gasoline and other petroleum hydrocarbons, are lighter than water; therefore, their downward penetration is restricted by the water-saturated **capillary fringe** immediately above the water table (see Figure 4). Although LNAPLs are generally **immiscible** in water, some components, benzene in gasoline for example, are sufficiently soluble to cause groundwater problems. As indicated in Figure 4, volatilization of chemicals from the pool of LNAPL at the water table and from LNAPL residual along the path of migration through the unsaturated zone can result in significant spreading of contamination through soil vapour.

(4) Dense Non-aqueous Phase Liquids (DNAPLs). These fluids, typically chlorinated solvents, wood preservative wastes, and coal tar wastes, are more dense than water and, when released to the subsurface, can migrate downward under the force of gravity or laterally along the surface of low-permeability units to depths not restricted by the water table (see Figure 3).

DNAPLs move as a separate liquid phase but a portion of the DNAPL is retained as a residual phase by the geological media through which the liquid has passed. As in the case of LNAPLs, many DNAPL chemicals are volatile and soluble relative to their respective environmental standards; therefore, vapour-phase transport of DNAPL chemicals in the unsaturated zone and dissolution and transport of DNAPL chemicals with groundwater flow can increase the extent of subsurface contamination. Unlike LNAPLs, DNAPLs can penetrate to depth within the **groundwater zone**, and the lateral spread of DNAPLs is controlled by geological conditions and can be independent of groundwater flow. This factor has an important influence on the distribution of contaminants throughout the subsurface, and has very important and unique implications to site monitoring and remediation. Therefore, it is critical to recognize the occurrence or potential occurrence of DNAPL chemicals in the subsurface.

(5) Volatile Contaminants. Methane gas, for example, can be generated from the decomposition of wastes in landfills. This may be an issue of concern at properties with below-grade structures on or near landfills.

(6) Biological Contaminants. Migration of either bacteria or viruses may be an issue at some sites with on-site sewage systems.

2.3.2 Sources of Contamination

To establish the site conceptual model, identify the source(s) or potential source(s) of contamination. At a site of known or confirmed contamination, identify possible sources of contamination in the desk-top review. At sites where contamination of the subsurface is suspected, identify potential sources of contamination.

Some potential sources of contamination are obvious, and their locations or limits may be defined in the desk-top review. Examples include, waste management and disposal facilities such as chemical storage facilities, liquid waste lagoons, **injection wells**, and solid-waste disposal areas.

Piping, and the associated joints and valves, between storage tanks and transfer facilities are also potential sources of contaminants to the subsurface. Historically, the transfer of bulk chemicals and petroleum products to train and truck transport commonly generated uncontrolled spillage on the ground; the cumulative effects are significant sources of subsurface contamination.

Although the contamination potential of some practices and facilities can be readily recognized, the potential of others may be masked and may only be available in anecdotal reports. Such practices as the inappropriate disposal of used **solvents** or solvent **sludges** outside the back door may not be documented in conventional reports, but may be recalled by employees.

During the desk-top review, it is important to identify, where possible, that types of changes have been made to operations at the site. Whereas some facilities may have been physically removed, the contaminant remnants from these facilities may still exist within the subsurface. The present appearance of a site, especially subsequent to surficial additions of fill or pavement, can readily mask potential sources of contamination (see case illustrated in Figure 11).

Past chemical processes may be very different from current processes at a facility. Confusion often arises in site assessment when chemicals that have not recently been used at a site are found in soils and water. Also, some chemicals are not considered in the desk-top review because their past use is not on record. If the past chemical process is identified, check older technical books or journals that can provide clues to the chemical inventory.

2.3.3 Potential Extent of Contamination

The extent of known or suspected contamination will depend on the environmental properties and volumes of chemicals introduced to the subsurface and the nature of the subsurface environment. It may be possible, within the desk-top review, to identify the likely introduction of large volumes of wastes or chemicals to the subsurface. The desk-top review will, however, likely be less successful in identifying small sources of contamination. Some issues that can affect the extent of contamination include:

- volatility—volatile organic contaminants deposited in a small area can rapidly migrate through the unsaturated zone to contaminate large areas. In the desk-top review note the **vapour pressure** of the contaminants and the depth to the water table (i.e., the depth of the unsaturated zone);

- atmospheric fallout—some chemicals may be deposited on the surface from atmospheric discharge. Note possible sources, such as air vents or chimneys, and the prevailing wind direction;
- subsurface conduits—particularly those in low conductivity geologic media. Note in particular, coarse, granular **backfill** used in the construction of foundations, subsurface piping, and **utility trenches**. Subsurface conduits can provide preferred routes of subsurface migration of contaminants and increase the extent of contamination beyond what might be predicted in the undisturbed hydrogeologic settings.

2.4 *Implications for Health and Safety*

A comprehensive assessment of a site will likely require a rigorous field investigation and monitoring program. The desk-top review can indicate health and safety precautions that should be considered in designing and implementing the field program. A detailed health and safety plan will likely be needed. It should be specific to the site and consider risks likely present at the site. This plan may need to be modified as more information becomes available during subsequent investigations.

Consider not only workers involved directly in the implementation of the field program, but other workers at the site, and the general public on neighbouring properties. Health and safety issues can be exacerbated by perceived problems; for example, a **test pit** excavation program that results in the exposure of highly odorous but non-hazardous subsoil to the air may elicit overwhelming response from neighbours for aesthetic reasons. Consider these issues in advance of the field evaluation program. Obtain as much of the pertinent information as possible in the desk-top review.

Safety issues are covered by various health and safety acts related to worker safety. Some must be met as legal requirements and others will form a good code of practice at sites. An example of an occupational health and safety plan is given in Appendix B of CCME (1991a). Table 4 outlines a checklist of safety issues.

2.5 *Geologic and Hydrogeologic Information*

The focus of this section is on the subsurface materials and their properties that can affect water flow and movement of contaminants. The information on subsurface conditions is collected at this stage to further develop the conceptual model for the site. Developing an accurate model at this stage will minimize the amount of data gathering and instrumentation needed during the subsequent phases of the site study. Background information can provide insight into the nature of geologic materials that will be encountered in the field investigation, and that may play a role in contaminant migration. Some historical information on the site will have already suggested the nature of potential contaminants and possible source locations. It will be important to track down the most significant sources and extract the relevant information without making a major project out of this review. The list of sources presented here is not complete but should provide a starting point for those not familiar with this type of review.

Table 4 Checklist of Safety Issues

Hazards	Issues
Electrical	Underground and above ground power cables
Physical	Unstable slopes, dangerous debris, heavy machinery, and surface water
Noise	Aesthetic impact and ear damage
Temperature	Stress and heat exhaustion
Radiation	Exposure
Biologic	Disease, infection, and parasites
Chemical	Explosion, fires, skin and eye contact irritants, inhalation, and ingestion

2.5.1 A Focused Approach: From Regional to Local Scale

The hydrogeologic setting of any site plays a critical role in the movement of water and contaminants in the subsurface. In the desk-top review, develop some guidelines for collecting and synthesizing information on the subsurface setting. Scale plays an important role. Start with a view to regional systems with a narrowing focus to the site scale to better understand the local hydrogeology.

A groundwater flow system has areas of **recharge** (water-in) and **discharge** (water out) (see Figure 12). Groundwater generally flows from areas of high elevation to lower areas. The diagram illustrates an aspect of scale: long flow lines and large travel times for regional flow and shorter flow lines and smaller travel times for local flow. Most systems are more complex than this, but the diagram is useful to understand the scale of the problem at any site, and to establish a reasonable conceptual model.

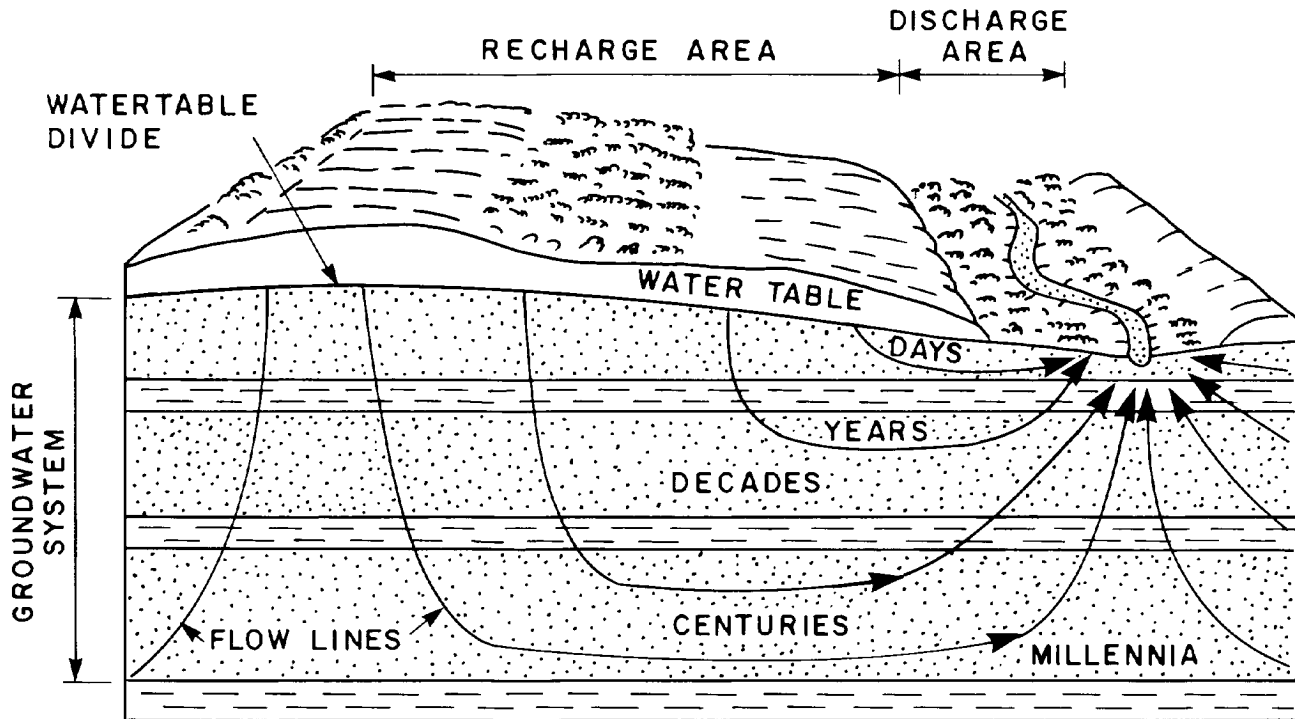


Figure 12 Block Diagram Showing the Different Scales and Travel Time Flow in a Simple Groundwater Flow System.

Significant differences can occur at different scales. This is evident in Figure 13 where the regional flow in the cross-section (associated with the lower aquifer) occurs from right to left; whereas, shallow local flow from the landfill travels in the opposite direction toward the stream. In this case, the landfill remains a potential threat to water quality in the lower or regional aquifer, and the contaminants may move in a direction unexpected from assessment of the shallow aquifer only.

Take a focused approach. Start with simple interpretation of significant surface and subsurface conditions at the regional scale and identify key hydrologic features and characteristics down to the scale of the site itself. Potential recharge and discharge zones, depth to the water table, general groundwater flow directions, surface drainage patterns, and potentially significant groundwater units are but a few of the features that can be identified during the desk-top review. **Surface water** features are also considered in Section 2.6.

2.5.2 Previous Investigations in the Study Area

Reports on previous investigations at or in the vicinity of the site can usually provide information quickly. Assess the reliability of these reports; hydrogeological expertise may be particularly useful. Do not rely on these reports to provide the complete background history for the site under investigation. It is common for previous investigations to have different objectives or to have been completed at a time when some issues of contamination were not recognized as

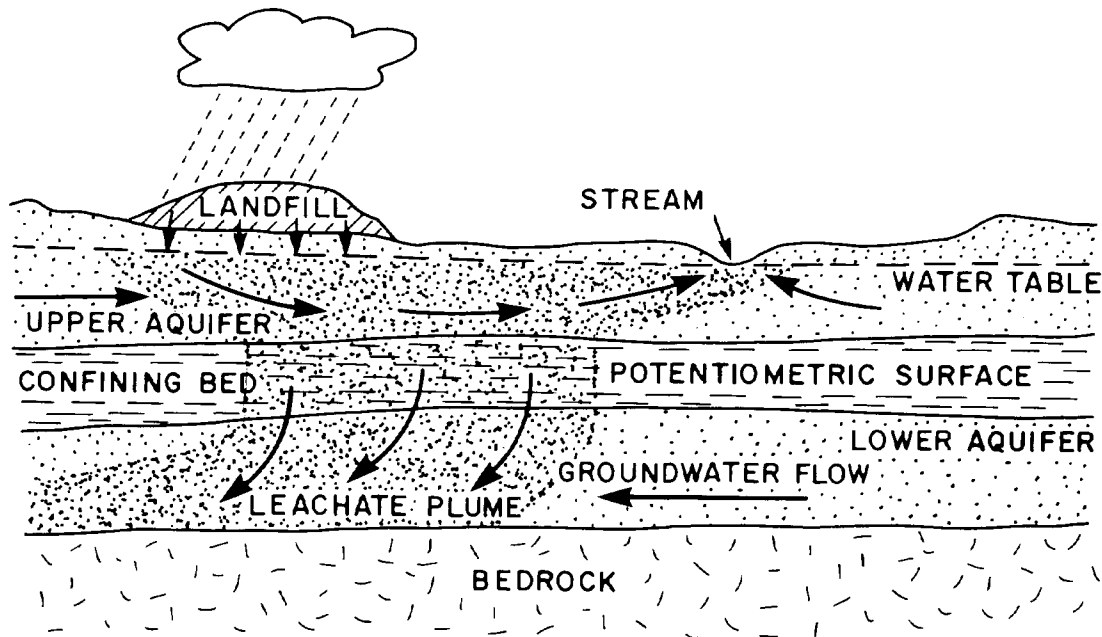


Figure 13 Block Diagram Showing a Landfill Contaminating a Two-aquifer System with Opposite Flow Directions.

important (e.g., DNAPLs). If previous reports meet the current objectives at the site, further investigation may not be required.

2.5.3 *Geology and Soils Reports*

These reports are generally published by the Federal and Provincial governments. They cover physiographic regions or sectors defined on the National Topographic System (NTS) maps. The focus of these reports is usually bedrock but overburden description and thicknesses are often provided. Bedrock elevations are commonly given and can be used to estimate depths of overlying sediments or soils at specific sites even if overburden details are absent. Soils and overburden material maps are usually available as well. Key information available from the reports include:

- description of geologic materials and **stratigraphic sequence**;
- elevation of the top of bedrock;
- regional setting; and
- structural features (e.g., fractures in bedrock).

Use soils and geological reports (when available) to develop geological profiles at regional and site (or local) scales. Soil reports generally provide information related to agricultural practices or forestation. Soil type can be useful for inferring subsurface material properties such as permeability. The geological reports of the origin of the surficial sediments and bedrock will provide information on the probable extent of individual units and their role in water movement, and may even suggest potential chemical interaction with contaminants of concern. For example, surficial sand units deposited in a river setting may be of limited lateral extent and interfingered with less conductive silt units. Groundwater flow is likely less rapid and more complex than if the sand units were massive (as might form in a beach setting). The silt units may be more sorptive than sand and therefore could slow the migration of sorbing contaminants such as lead. See Subsections 2.6.4 and 2.6.5 for methods to estimate infiltration rates and the depth of the water table using meteorological and geological information.

2.5.4 Geotechnical Reports

These are usually available for specific sites where construction has taken place. Larger scale construction projects usually require more detailed geotechnical investigations that will be kept on file at that facility and with the engineering firm or agency that undertook the work. Although the emphasis in such studies is on the structural integrity of the soils and rock, descriptions of the subsurface materials and water levels are usually given. Some reinterpretation of these data may be required to provide information for hydrogeologic purposes. Material properties such as **plasticity, liquid limits, compressibility, and shear strength** give clues to the type of geologic materials encountered. Depth and the nature of bedrock is commonly reported.

These reports usually focus on the shallow subsurface, to depths of a few tens of metres; therefore, data for the deeper zones may be lacking. Reported water levels in boreholes of interest for groundwater flow determination (Subsection 4.3.1) are often taken within a few hours of drilling, and therefore may not have attained equilibrium levels. Be suspicious of water-level data from low permeability materials that may not be representative of actual equilibrium water levels.

2.5.5 Aerial Photographs

In addition to their applicability to the review of land use and activities at a site, aerial photographs also provide an excellent assessment of geology and surficial drainage features. In a historical perspective, sequences of aerial photographs from different areas may also indicate how the natural hydrologic regime has been disrupted or diverted by construction and on-site development. For example, a permeable stream channel deposit of sand may have been covered with impermeable fill. The channel could still be a major pathway for contaminated groundwater migration and must be investigated.

2.5.6 Maps

Although detailed reports on areas of interest may not be available, maps are often available and may provide data pertinent to site evaluation. Any or all of the maps listed here can be useful in preparing a conceptual model of the site and a work plan:

- topographic — National Topographic System (NTS) or similar maps provide topographic information at a range of scales;
- other maps that may be available through both federal and provincial or state agencies — geology; soils; surface drainage; groundwater potential/susceptibility to contamination; and well yields.

Figure 14 illustrates one use of topographic maps. Because groundwater is usually recharged from higher elevations and flows to lower elevations, the higher elevation of the spring relative to the contaminated site makes the site an unlikely source of contamination in the spring.

2.5.7 Well Records

Well logs, records produced by water well drillers during well installations, provide limited, but useful information. The depths to which wells are drilled will indicate the depth of the most

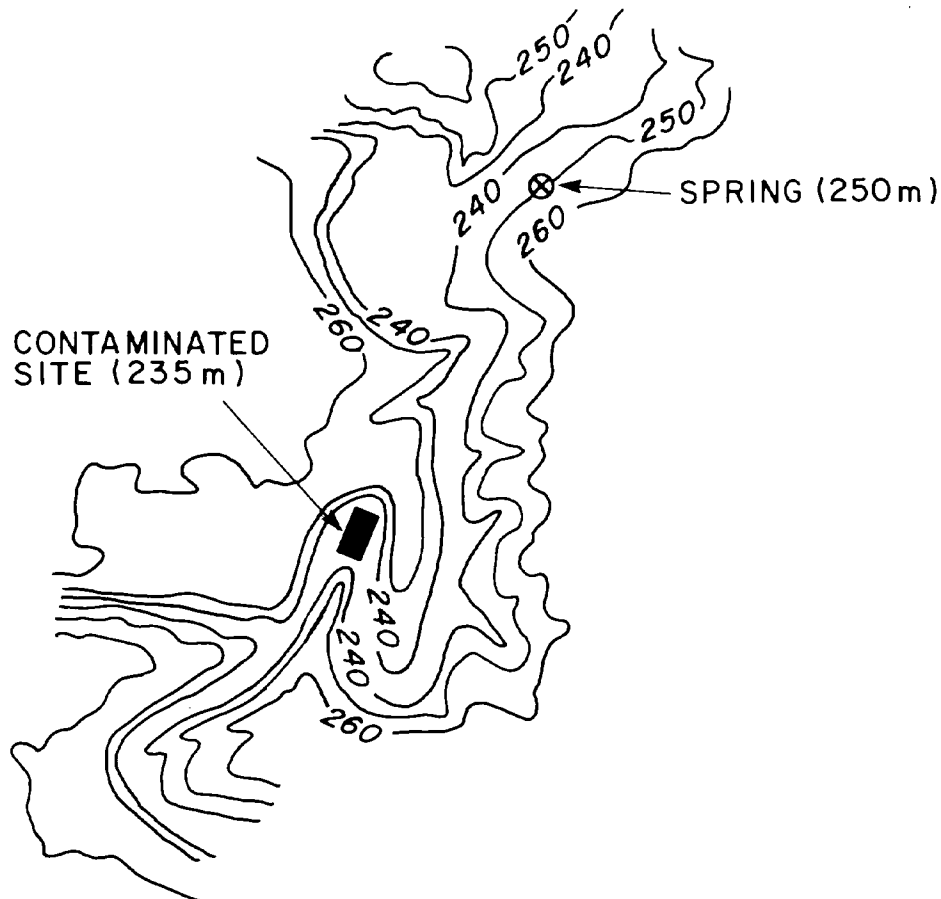


Figure 14 **Schematic Topographic Map.** Shows elevation contours (metres above mean sea level) and the location and elevation of a contaminated site and a spring suspected of being impacted by leachate from that site (modified after Brice *et al.* 1991).

useful aquifer. The driller is most interested in zones that produce useful quantities of water (or aquifers), but general information about the geological conditions encountered during drilling are recorded and may be quite useful in developing a hydrogeologic model of the area. Occasionally, observations of water quality may provide information on the chemical characteristics of specific zones within the subsurface (e.g., rotten egg smell is an indication of hydrogen sulphide and **reducing conditions**).

Geophysical logs of water supply wells can assist interpretation of subsurface conditions for the water well industry, and may be available in some areas. For example, **electrical logs** on new water wells are mandated in Saskatchewan; therefore, regardless of the geologic description on individual well logs, comparable electric signatures are available for examination.

Where the information is available, you should draw general stratigraphic cross-sections, based on the lithologic logs of the driller and local geologic information. Keep in mind that drillers' logs are not usually prepared by a geologist. They may, however, help visualize the continuity and relative position of different hydrogeologic units. If water-level data are available from the wells you should plot the static or pre-pumping levels on cross-section views and on a contoured plan view map (referred to as a **potentiometric map**). The map may permit a preliminary interpretation of the regional groundwater flow directions in the vicinity of the site.

Commonly, shallow dug or bored wells and deeper drilled wells exist in a given area. These two families of wells often extract groundwater from different aquifer units and you will find it useful to prepare a separate potentiometric map for both sets of wells. A preliminary indication of vertical hydraulic gradients is then also available from the two maps.

The pumping levels in the wells are also important because they may indicate variations in the water table (through **drawdown**) that will influence groundwater and contaminant transport directions when wells are in use. You should also prepare a potentiometric map of the pumping water levels if a reasonable amount of data is available. Further suggestions are given in Section 4. This data will provide a more accurate preliminary conceptual model of the system.

2.5.8 Land Use Maps and Reports

These maps and reports provide useful information about the current activities in the area. For example, if irrigation projects exist near the site, artificially high amounts of infiltration recharge may exist. On the other hand, tile or ditch drainage systems and irrigation extraction wells may serve to lower the water table and influence local groundwater flow patterns. Residential development in the area may indicate the potential use of groundwater for human consumption (and thus a high sensitivity to groundwater contamination) and the presence of septic fields. Contamination emanating from septic tile fields adjacent to the site may migrate onto the site and complicate the interpretation of groundwater quality. You should consult maps of industrial development and of waste disposal available from municipal authorities.

2.6 *Hydrologic Information*

The focus of this section is on surface water: its location, movement, quality, and connection to groundwater. Much information about sources and direction of flow of water can be estimated from topographic maps. More detail can be found in more specialized water resources reports. Some of the existing information may also be useful at later stages of the investigation. For example, the flow rates of nearby streams and rainfall data, although they may not immediately affect the next phase of data gathering, might be useful for later calculation of the amount of water moving through the subsurface from **infiltration** to discharge into streams. Some aspects are described here.

2.6.1 *Topography*

Surface elevations and the slopes or gradients determined from **topographic** maps indicate the general directions of water flow. Both surface water and groundwater move down gradients from topographic highs to lows. Permanent surface water features such as streams, lakes, swamps, or marshes are usually shown clearly on topographic maps. Small or intermittent streams and ponds, however, may not be noted at the common map scale of 1:50 000. Although the topographic high areas are generally associated with recharge of the groundwater system, surface water in the low areas generally represents the water table where groundwater is discharging. This may not be the case in semi-arid to arid regions such as some prairie environs, sub-arctic areas, and interior valleys. Here, for example, sloughs may represent **perched water tables** and may be local recharge areas. Therefore, generalized inferences should not be drawn. The hydrology of such regions can be more complex.

2.6.2 *Regional Drainage*

If there is potential for contaminants to migrate to, or within, geologic units that have a large areal extent or that are connected to large hydrologic features (e.g., lower aquifer, Figure 12), it is useful to have this regional groundwater flow information. At this stage, cursory assessment of possible impacts associated with regional flow is suggested. Identify major features, such as recharge and discharge areas, if possible. At the very least, regional groundwater flow directions should be established.

The assessment of recharge and discharge areas on a regional scale can usually be accomplished with two sets of information: topographic and geologic. The regional upland areas are where groundwater recharges. These areas may also correspond to the head-water regions of surface water **drainage basins**. Regional topographic trends should indicate the direction of regional flow. The geologic units that are expected to transmit this flow should be identified through the review of geologic maps or reports. If these units are laterally extensive, interpretation of a simple flow system is possible. If no such unit can be identified at or beyond the site, regional topographic trends should at least be noted to determine the general directions of flow.

Discharge areas generally correspond to topographic lows and surface water features such as streams, lakes, and rivers. Regional discharge will usually be directed toward larger features that represent drainage channels for larger hydrologic basins. It is important to identify these areas to understand where the contaminants may migrate if they leave the site along a regional pathway.

This will allow a preliminary assessment of the possible impacts of groundwater on nearby surface-water systems.

2.6.3 Local Drainage

Local topographic highs and lows will likely indicate groundwater recharge and discharge areas on and near the site. However, neither feature may be discernible on the site. Often, small sites, such as industrial properties, are dominantly recharge or discharge zones and groundwater flow is downward or upward, respectively. If local features such as streams or ponds are present on or adjacent to the site, it should be possible to identify local flow (shallow) conditions from the topographic highs to these areas. Where possible, obtain records of water levels and, if available, flow rates in streams and lakes. This will provide some guidance for instrumentation and sampling during the field program of the site assessment.

Take care when interpreting local drainage features in arid or semi-arid regions. Streams and lakes may provide a focus for recharge after rainfall or snowmelt events. These features may be transient and are referred to as “**losing streams**” or “**willow rings**”. Low areas may act as collection zones for runoff where infiltration continues after precipitation. Recharge in topographically low areas may also occur even in areas of low to very low relief. When very low relief occurs in the region of the site, interpret the groundwater flow direction with caution.

2.6.4 Meteorological Data

Precise meteorological data are usually not required at this stage of the investigation. However, information on rain and snowfall is useful or required for the modelling of groundwater flow and the transport of contaminants. Precipitation data are the most useful meteorological information. A station where these data are collected as close to the site as possible should be identified for further reference. Consult government weather services for station locations. With the precipitation records and estimates of monthly **evapotranspiration** rates, you can estimate the annual fluctuation in infiltration or meteoric recharge to the hydrogeologic system. Chow *et al.* (1988) offer details on estimating infiltration rates from climatic data in various terrains.

2.6.5 Depth of the Water Table

The location of the water table is evident from permanent streams, ponds, lakes, or swamps. However, in the absence of such surface-water features, it may be possible to estimate the depth to the water table very roughly based on the properties of subsurface material and climate conditions. As a general rule, the depth to the water table is related to the permeability of the geologic materials in the subsurface and the amount of infiltration of rain and snow melt. The water table will be shallow or near the ground surface in low permeability materials like clay, glacial tills, and unfractured rocks when infiltration is large (centimetres per year). Conversely, a deep water table is expected in very permeable deposits and when infiltration rates are low (millimetres per year). There are numerous exceptions to these “rules”, however.

2.6.6 Water Resources

Depending on the jurisdiction in which the specific site is located, the availability and content of local water resources reports will vary considerably. They have generally been published at the provincial or state level, and emphasize different aspects of water supply issues. The most

valuable information will probably be found in groundwater reports that provide information on the yield of wells and the geologic unit or depths that are used for supplies within the selected region. Surface water reports that give information on the regional drainage basin surrounding the study site may also be useful to establish boundary conditions if modelling studies are undertaken (Section 6).

2.6.7 Local Pumping or Dewatering Activities

Active quarries and pits usually pump out groundwater during their operation. Many urban industrial areas have active site investigations and/or clean-up operations. Some of these may include groundwater pumping. Also, some construction requires pumping to lower the water table. These activities can significantly affect local flow conditions. Information about such activity can be obtained by contacting property owners/tenants and regulatory agencies that issue water taking permits.

2.7 What Should Now Be in the Conceptual Model?

The conceptual model is an evolving and working tool; as new information is collected during the desk-top review, update the model to reflect the additional data. After the desk-top review, the conceptual model should include several basic components.

(1) The Geologic Setting at, and in the Vicinity of, the Site. The conceptual model will distinguish between various geologic units in terms of their hydraulic characteristics. The model will attempt to indicate the significance of the various units in influencing the groundwater flow system, and their potential control of the migration of contaminants in the subsurface. Use this information to classify the site in terms of one of the five (or as aspects of more than one) hydrogeologic settings discussed in Section 1.4. This classification will provide a basis for understanding the flow regime and evaluating the extent and migration of contaminants in the subsurface. It is particularly useful to identify, if possible, subsurface units of low conductivity that may be the lower boundary of subsequent investigations.

(2) The Regional and Local Surface Water and Groundwater Flow Systems. The conceptual model should identify the interaction between the groundwater and surface water systems in the vicinity of the site, and also indicate the interrelationships between the regional and local groundwater flow systems. Incorporate topographic and stratigraphic information (together with any details on groundwater levels at the site) into schematic diagrams of the groundwater flow system in both plan view and cross-section. If sufficient data are available, undertake preliminary flow analysis (see Section 4). Flow analysis provides a general, if crude, indication of groundwater flow directions at the site and can provide guidance in the development of the work plan and the logical selection of the location of monitoring wells.

(3) The Definition of Human Alterations to, and Influences on, the Groundwater Flow Systems that Could Modify Groundwater Flow and Contaminant Movement Through the Subsurface. For example, buried pipelines, utilities, and sewers and their associated coarse-grained backfill often provide conduits for the preferred flow of LNAPLs and groundwater contaminants through the subsurface, particularly at sites underlain predominantly

by low hydraulic conductivity, fine-grained geologic materials. Many buildings are constructed with underdrains to prevent water seepage in basements and damage to foundations. These underdrains also represent preferential pathways for contaminants. The operation of groundwater pumping wells in the vicinity of a site may also alter **hydraulic gradients** and modify the local groundwater flow system.

(4) The Identification of Natural, Preferential Pathways for the Migration of Contaminants Beneath and from the Site. These pathways might, for example, include high hydraulic conductivity layers or **lenses** in geological materials, or fractures or fracture systems in fractured clays or rocks. Preferential pathways will likely be the focus of detailed field investigations.

(5) The Definition of the Receptor or Potential Receptor of Contaminants to Evaluate the Degree of Environmental Impact. Receptors may include people using affected well water or aquatic organisms in discharge areas. Preliminary analysis, once the receptor has been identified, may also indicate the degree of urgency associated with implementing precautionary actions and with undertaking the site investigation.

(6) The Identification of Special Characteristics of Specific Contaminants. As noted in Section 1, and previously in this section, different types of contaminants may behave in vastly different ways in the subsurface. It is important to incorporate the behavioral characteristics of contaminants in the development of the conceptual model to ensure that potential areas of occurrence and migration can become the focus of site monitoring and investigation programs. The modes of, and potential controls on, migration of specific contaminants in the subsurface are important considerations in many aspects of planning field programs at contaminated sites.

2.8 *Establishing the Work Plan*

The collation and evaluation of existing background information during the desk-top review assists in the development of a comprehensive work plan or program for subsequent stages of the site assessment process. For some sites, it may be apparent at the completion of the desk-top review that little additional work is necessary to provide an adequate site assessment. In other cases, however, further site investigations will be required. In these cases, information and concepts developed during the desk-top review will be the basis for an efficient work plan.

As the desk-top review proceeds and the conceptual model of the site is modified, it is important to consider the implications to the scale and type of field investigations that might be required to adequately characterize subsurface conditions, contamination at the site, and possible remedial actions. The physical hydrogeologic setting and the nature of potential contaminants are critical to these considerations.

Procedures and techniques that can be employed to assess contaminated sites are described in detail in subsequent sections. When preparing the work plan, however, a knowledge about the utility and limitations of site investigation methods is extremely useful. This list provides some guidance to developing a work plan:

- re-evaluate objectives;

- consider a preliminary field survey to define the extent of known groundwater and soil contamination;
- establish priorities;
- plan for urgent actions (i.e., fire hazards and immediate threats);
- plan for longer term activities;
- begin a health and safety plan;
- review/address regulatory requirements;
- review/address public relations issues;
- list and address information gaps;
- re-evaluate budget;
- plan details of investigation approach;
- establish data requirements and data collection methods, and start a quality assurance plan (see Sections 4 and 5 for specific advice);
- consider predrilling methods (e.g., geophysics, see Section 3)
- suggest sample/analysis types;
- select analytical laboratory;
- establish field sampling and laboratory protocols for site setting and expected contaminants;
- consider well/sample locations and numbers; and
- investigate possible types of drilling, sampling, and wells for the specific site conditions.

Many of these points were likely addressed in general terms in the initial site assessment proposal, and before there was adequate site-specific information. Refine and adjust for site-specific conditions and issues after the comprehensive desk-top review.

The work plan should account for special physical features at a site. For example, low permeability layers on site may protect deeper zones from near surface contamination. Inappropriate drilling techniques may jeopardize the integrity of such features and create increased contamination. Some investigative techniques are more successfully applied in certain geologic environments than in others; therefore, geologic conditions definitely influence the selection of appropriate methods of investigation (see Sections 3 to 5).

Special characteristics of the contaminants of concern at a site should also be considered in the development of the work plan and the selection of investigative techniques. Examples of these considerations are included in this section:

(1) Suitability of the Overall Approach to Site Investigation. Be extremely cautious when implementing a field investigation program to avoid making a subsurface contamination problem worse. The conceptual model should therefore identify where natural protection from contamination is afforded by geologic media, such as clay layers, and where such protection may be jeopardized by inappropriate installation or investigative techniques. The issue is particularly critical to sites contaminated by DNAPLs. The leakage of DNAPL liquids to greater depths as a consequence of inappropriate drilling can dramatically magnify the extent of groundwater contamination. Note the requirements and precautions when developing the work plan.

(2) Suitability of Non-drilling Monitoring Techniques. For example, Section 3 provides a discussion on geophysical surveys that may be useful when determining the subsurface hydrogeology and the distribution of contamination in the subsurface. Also, the use of soil gas monitoring, as described in Section 5, may identify the presence of volatile organic compounds (from LNAPL or DNAPL spills or releases) in the zone above the water table. This monitoring may be appropriate in some settings.

(3) Compatibility Between Suspected Contaminants and Proposed Monitoring Well Materials. Some materials may be inappropriate and their use should be avoided (see Section 5).

(4) Suitability of Drilling, Monitoring Well Installation or Soil Sampling Techniques. Certain drilling, installation, or sampling techniques have advantages in specific situations. The selection of appropriate techniques is discussed in Section 4.

2.9 *Summary*

Various approaches can be taken to conduct the desk-top review of a contaminated site assessment. The approach outlined in this section encourages the use of all available data to:

- ascertain the site history and identify contaminants of documented or potential concern; and
- develop a conceptual model or framework to describe subsurface materials, surface and groundwater flows, and contaminant pathways at the site.

Evaluate the quality of the existing information and data. Judicious evaluation at the desk-top review will improve planning for initial and subsequent field phases and, thereby, improve the success and efficiency of the overall site assessment process.

2.10 *Additional Information*

Unfortunately, there are no textbooks dealing comprehensively with desk-top review. Brassington, *Field Hydrogeology*, John Wiley & Sons, Toronto, Ontario (1990) offers some advice about hydrogeological aspects.

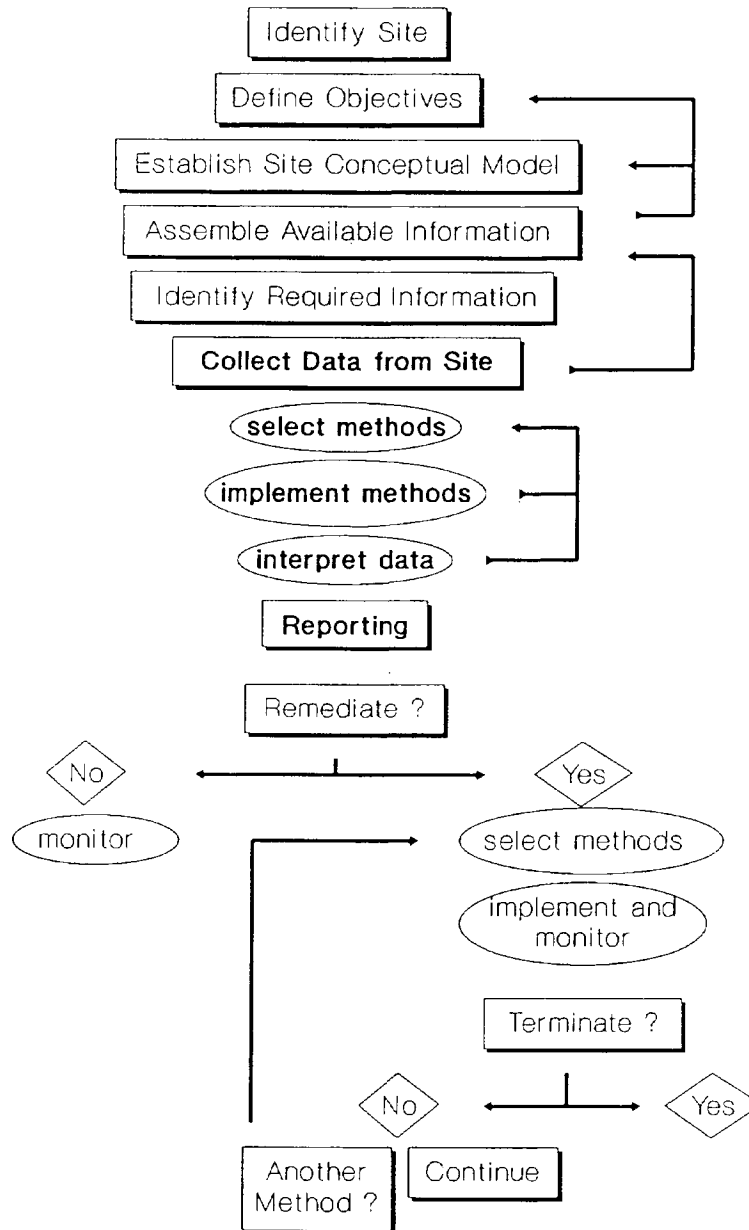
Consider attending short courses, workshops, and conferences dealing with this topic. Conference proceedings often provide useful information. See, for example:

- Proceedings of 1991 Environmental Site Assessments Case Studies and Strategies: the Conference, 29–31 July, Association of Ground Water Scientists and Engineers, 6375 Riverside Drive, Dublin, OH 43017

These educational opportunities are advertised in newsletters such as:

- *Resilog* (published by the Technology Development Directorate, Environment Canada); and
- *The Association of Ground Water Scientists and Engineers Newsletter* (published by Ground Water Publishing Co., 6375 Riverside Drive, Dublin, OH 43017).

Courses are also advertised in journals such as *Ground Water* and *Groundwater Monitoring Review*.



Section 3

Geophysics (J. Greenhouse and P. Gudjurgis)

Geophysics is the application of physical principles to the study of the earth. It involves the interpretation of **fields** (such as magnetism and gravity) that can penetrate the subsurface and are influenced by its structure. This section attempts to provide basic information, a balanced view, and the correct questions to ask. The section adopts the perspective of the client with limited geophysical background who is considering using geophysical methods for a site assessment. This assumed lack of background requires a more thorough consideration of principles underlying the geophysical techniques.

After introducing geophysics, we present the fundamental geophysical properties underlying geophysical techniques. Then, 13 geophysical methods are discussed in terms of:

- basic principle;
- penetration and resolution;
- equipment;
- presentation and interpretation of results; and
- example of application.

This section tells you how geophysics answers questions about the subsurface at contaminated sites.

The next section looks at how geophysics is actually done. We provide advice on planning, undertaking, and assessing the results of a geophysical survey. The need for interaction between clients and the geophysical contractor to produce successful results is emphasized. The objective of the survey, how the survey will be done and how results will be interpreted, and the likely cost of geophysical surveys are discussed. It is particularly important to understand the relationship between client questions about the subsurface and the measured geophysical response. The correct geophysical tool for the site-specific questions and conditions is essential. Five typical sources of contamination are considered and five geological settings are considered to illustrate what geophysical surveys offer. The suitability of the various geophysical methods to identify selected geological aspects of the subsurface at contaminated sites (e.g., internal structure of sediments and porosity) is also evaluated.

As in other sections, sources of additional information, including glossary explanations and specific references, are presented.

3.1 *Introduction*

Geophysics has a well substantiated and quantitative foundation in the laws of physics. It is technical and quantitative and involves physics, mathematics, hardware, software, jargon, and data processing. But, as applied to subsurface exploration, it is also surprisingly qualitative. Confused by the claims of geophysicists, potential clients tend to become polarized into those who reject the methodology out of hand, and those who embrace it too uncritically.

The direct result of a geophysical survey — a map of the distribution in space or time of some physical property such as electrical conductivity — is not of itself likely to answer the questions that prompted the survey. For example, rocks containing very pure water and rocks containing almost none can have similarly low conductivities. The map is only one piece in a puzzle.

The measured physical property must be translated into a useful parameter. It may be necessary to relate the measured electrical resistivity to porosity, permeability, or groundwater contamination. The relationships between measured fields and physical properties, and between physical properties and the useful parameter, are approximate. The result is an image of the subsurface that is smeared and clouded by these uncertainties, but that has a scope that would require thousands of hydrogeological tests to reproduce.

From this point of view there are three basic requirements:

- The objectives of the geophysical survey must be clear to client and contractor. This requires that the contractor know in some detail what the client wants to learn from the survey; strangely, this is often not the case. It also requires a contractor who, through training, personality, or experience, can understand the objectives from the client's perspective. Client and contractor must not be looking for two different things. It also requires good communications and planning. Surveys conducted just to see what will turn up are seldom satisfactory.
- The client must have a very basic understanding of what the geophysicists can and cannot do with the equipment and the money available. We must have reasonable and educated expectations of our contractor.
- We should examine case histories. The experience gained by others in similar environments, fairly interpreted and impartially presented, is an invaluable guide to our own geophysical undertakings.

The approach a geophysicist takes to a contaminated waste site investigation raises the following questions in approximately the order given. These questions provide a conceptual organization for the section.

- What is the source of the contamination? The type of source will determine the characteristics of the **target**. Examples include: buried metal and buried inorganic waste (e.g., an old landfill).

- What is the target of the survey? For example, a municipal landfill may be the source and a contaminant plume emanating from it the target.
- What is the objective of the survey? The objective is not the target itself but rather certain clearly specified characteristics of the target. It must be emphasized again that a misunderstanding of the objective is a major source of grief between client and geophysicist. If the target is a contaminant plume, the objectives might define any or all of: the areal extent of the plume; details of the upper and lower boundaries of the plume; and changes in the plume on a daily, weekly, or annual basis.
- What is the geological environment? The five general hydrogeological settings presented in Section 1 can be redefined somewhat for geophysical purposes to include: clays; unconsolidated surficial deposits (overburden); fractured non-porous rocks; fissured material (Karst); and permafrost.
- What physical properties of the target contrast with its natural environment? Which are best suited to the objectives? A clear understanding of physical properties and their relationships to the measured fields, and the relevant parameters (e.g., lithology, porosity, and permeability) is required.
- What other geophysical surveys have been carried out in this setting and for this type of target? Section 3.7 lists sources of case histories.
- What methodologies should be employed? In Section 3.3, we identify 13 geophysical techniques that are used in contaminated site investigations. Brief commentary is also given on several other geophysical methods that are not commonly used in waste site assessment, but which may be useful in specific cases. These are not all equally important; some, like terrain conductivity, are ubiquitous; whereas, others have only very limited applicability. They are: terrain conductivity; horizontal loop EM; transient EM; airborne EM; VLF resistivity; galvanic resistivity; complex resistivity (IP); seismic refraction; seismic reflection; ground penetrating radar; magnetics; gravity; borehole geophysics; and other methods.
- How should the survey be carried out? Consideration must be given to practical matters such as the size of the survey, personnel required, safety on the job, data quality, and so forth. These factors are discussed in Section 3.4.
- How should the results be interpreted and presented? The budget and the requirements of the survey will dictate the level of sophistication required for the interpretation and for the report. Section 3.4 discusses these matters, and reviews the problems of assessing the quality and relevance of the survey in relation to the objectives of the survey.
- How much will this cost? Section 3.6 addresses this delicate but central issue.

Geophysics is usually defined as the application of physics to geology. However, geophysical **interpretation** is better described as the application of geology to physics. At some point during

the interpretation of a geophysical survey, a good knowledge of site geology is necessary. This section discusses some common concepts and misconceptions about geophysical exploration.

The strength of geophysics lies in its ability to provide a broad view of the subsurface that complements the very localized information from a core or water sample. Figure 15 shows geological interpretations from several cores superimposed on a **ground penetrating radar** section. The cores alone could never portray the complexity of the glaciofluvial environment imaged by the radar. A groundwater contamination plume would be strongly influenced by this geological complexity.

Whether performed from the surface or from nearby boreholes, geophysical methods attempt to describe a target without physical penetration. This can be particularly important when the waste is hazardous to the drillers, or when penetration can adversely affect the situation. Sites containing dense non-aqueous phase liquids (DNAPLs), for example, are difficult to drill. The dense solvents may migrate down the borehole to previously uncontaminated strata. Geophysics offers one possibility for remote detection of the solvents.

3.1.1 Precision

Geophysical measurements can be made very precisely, but the same cannot be said of a geophysical interpretation. **Inverting** geophysical data in terms of the subsurface structure that produces them is almost always non-unique. For example, a survey may identify an anomalously

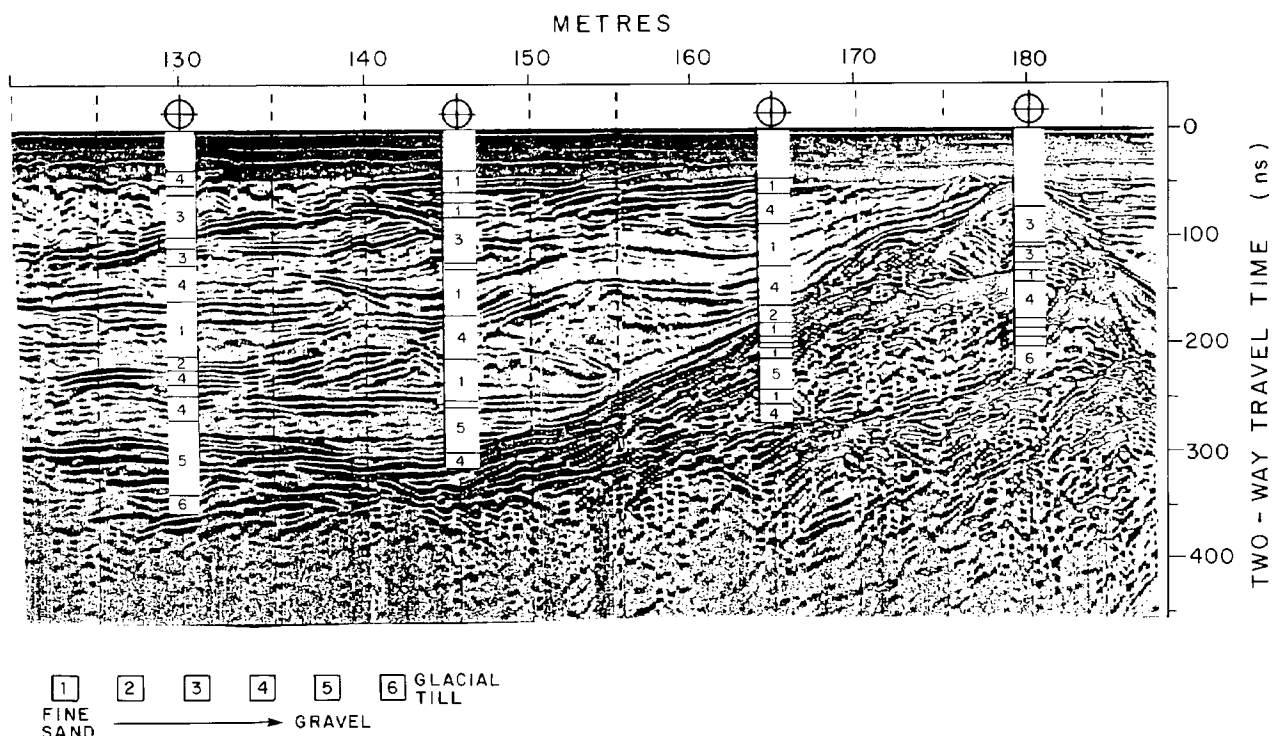


Figure 15 A Ground Penetrating Radar Survey near North Bay, Ontario (After Cosgrave *et al.*, 1987b) with Core Descriptions Superimposed. Note that even the comparatively close-spaced cores cannot portray the complexity in the section that can be obtained by the radar.

magnetic object beneath the surface, and put some reasonable bounds on its dimensions, its horizontal and vertical location, and its magnetization. It will seldom clarify the picture further.

3.1.2 *Penetration*

“How deep can you see with that thing?” is a simple question with a difficult answer. Geophysical methods do not penetrate a fixed distance; their depth capabilities depend on several factors, and the interrelationship of these factors can be complicated. Penetration should be defined as the maximum depth of detection of a specific target in a specific environment with a specific geophysical method. It is intricately related to **resolution**.

3.1.3 *Imaging*

“Image” is used to describe the result of a geophysical survey, the final representation of the subsurface. With the simpler techniques, this image can be extremely vague. With other techniques, particularly **seismic reflection** and **radar**, this image can be almost visual. Seismic, electrical, and radar **tomography** can produce three-dimensional images of a surrounded volume of the earth.

In some cases, however, the image is more apparent than real, having more to do with data processing than physics. Modern magnetic and **terrain conductivity** surveys are a case in point. The same data that were contoured by hand a decade ago are now routinely computer-displayed as a shaded and/or colour image. These processes can provide real insights, but they can also make data look better than they are. It is good practice to make sure that the actual sampling points are plotted on these maps to ensure there is no misunderstanding as to what is known and what is interpolated.

3.1.4 *Resolution*

Geophysical images are of varying clarity. Adjacent objects can be difficult to identify individually, i.e., to **resolve**. The resolution is the minimum distance that separates two targets (or features of a single target), when they can be individually recognized using a given method. Resolution is classified as vertical and horizontal; the two may well be quite different for the same geophysical technique. Therefore we may talk of a “horizontal resolution of 1 metre” for a magnetometer survey of barrels, meaning that we can recognize two individual barrels separated by one metre.

Resolution depends on the geological environment hosting the targets, on the depth to the targets, and on the nature of the targets themselves. Deeper targets are almost always harder to resolve than shallower ones.

3.1.5 *Data Processing*

The geophysical image is the result of one or more stages of data **processing** of the original measurements. Processing implies everything, from simple organization and display, to intricate operations on the data that remove unwanted **noise** or enhance trends or events of interest. Therefore, it has a measure of subjectivity; not in the processing itself, which is usually automated, but in the choice of processing method.

Geophysical processes include:

- **filtering** to smooth or sharpen data;
- **deconvolution** or inverse filtering to undo the effects of filtering caused by equipment or the earth itself;
- seismic **migration**, which corrects for distortions of the image produced by dipping and non-planar structures such as faults and anticlines; and
- **interpolation**, the familiar and sometimes arbitrary technique used to fabricate data between measuring points.

Processing is a great aid to our understanding of data. On the other hand, because processing is readily available at the click of a mouse button, the opportunities for misapplication are great. It is good practice to examine the processed data in the presence of the raw data. Processing should only serve to clarify aspects that were present in the original data set. If you cannot see the connection between the two, you should be wary of the process.

3.1.6 Interpretation

There is often confusion between processing and interpretation. Processing does not interpret; people do. An interpretation, being human-based, is subjective and even two “experts” may not agree on the meaning of the data.

The experts themselves may be suspect. Geophysicists are required to register only in Alberta, British Columbia, and Newfoundland. An interpretation that depends on shapes and trends of lines and contours can attract charlatans who can (through force of personality, combined with client ignorance) convince the unwary that they see what cannot be seen. The only defence is a knowledgeable client and a sound choice of contractor.

3.1.7 Limits to Detection

Clearly related to the concepts of penetration and resolution, detection requires strong contrast in the physical properties of the target and the surrounding environment and suitable factors of scale and shape. Detection is usually defined in terms of certain minimum required properties of the target. For example, a contaminant plume at a depth of 10 m in a sandy aquifer will require a certain combination of thickness, width, and conductivity contrast to be detectable with a given electromagnetic technique. To estimate the required properties of a specified target in a specified environment, mathematical modelling in one or more dimensions may be required. Experience will suffice in other cases.

The sampling interval and line spacing also play a major role in detection. Undersampling can result in an anomaly distortion or in missing the target altogether.

3.1.8 Monitoring Versus Mapping

Geophysical mapping locates a target in space and identifies it on the basis of some property that contrasts with its surroundings. **Geophysical monitoring** measures changes in the target with time. For example, geophysical monitoring can define changes in the state of groundwater contamination. Although the same basic techniques of geophysics are used in both, the approaches differ. With geophysical monitoring, the ability to detect changes in the properties of a target is usually considerably greater than the ability to detect the properties themselves. This is because there is a baseline of data with which to compare later surveys.

Figure 16 shows the variation in measurements of **dielectric permittivity** made at fixed points in a shallow aquifer over a period of 1000 h. The permittivity changes because the solvent (perchloroethylene) moves through the aquifer. Although measurements at any time can probably not detect the presence of perchloroethylene (against the natural variability of permittivity in aquifer materials), they can readily detect the changes with time.

3.2 Summary of Geophysical Properties

This section discusses the fundamental geophysical properties. For each property, a basic definition is given and SI units and the most commonly used notation symbols are provided.

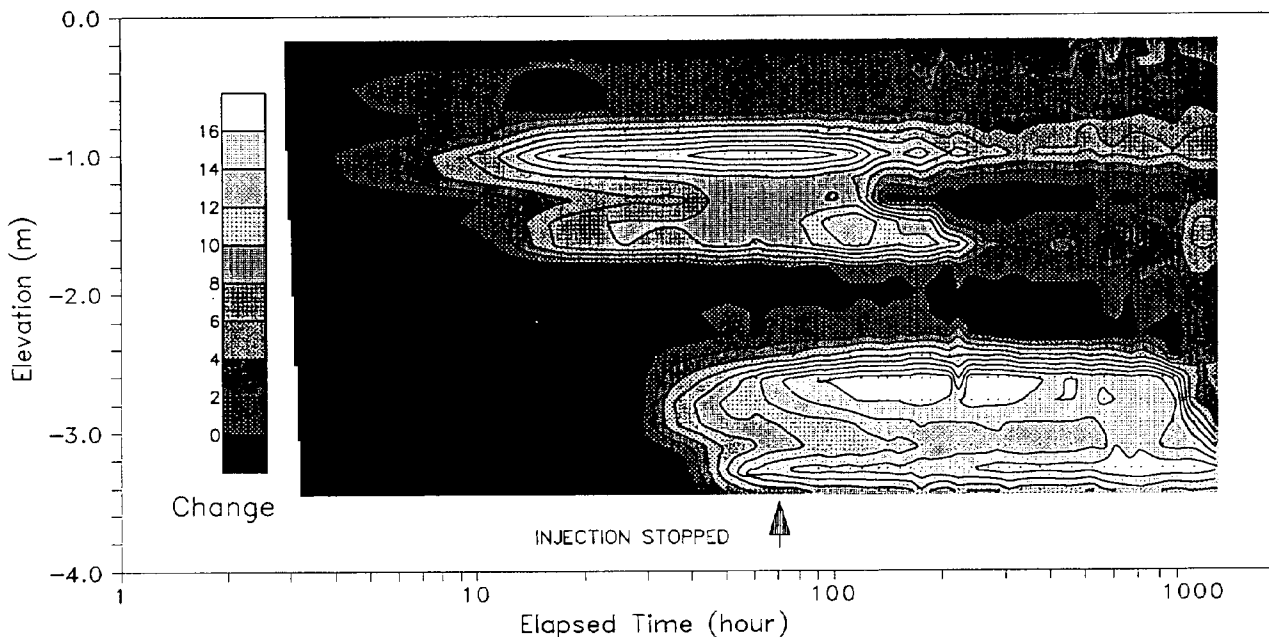


Figure 16 **Relative Dielectric Permittivity Measured as a Function of Time During an Experiment at Canadian Forces Base Borden, Ontario (After Redman and Annan, 1992).** Measurements were made every 16 cm on a vertical probe extending from the surface to the base of a sandy aquifer at 3.3 m. Perchloroethylene (770 L) was injected 1 m away, at a depth of 60 cm, and over 77 h. The DNAPL sinks. Changes in the dielectric constant (K) are shown as percentage of the pre-spill value.

These descriptions are, for reasons of space, extremely limited. The reader is encouraged to investigate physical properties in greater depth with a textbook such as Telford *et al.* (1990) or obtain a copy of the *Practical Handbook of Physical Properties of Rocks and Minerals* (Carmichael, 1989). Concluding this section are graphs showing typical physical property values for a variety of geological and anthropogenic materials. We caution that these graphs are only guides because geophysical properties show considerable variation.

3.2.1 *Electrical Conductivity (σ) and Resistivity (ρ)*

These are the most important geophysical parameters involved in contaminated site investigations. **Conductivity**, with units of siemens per metre (S/m) or millisiemens per metre (mS/m), is the proportionality factor relating the current that flows in a medium to the electric force that is applied. It is a measure of the ability of electrical charge to move through a medium. Ohm's Law states this as follows:

$$J = \sigma E \quad [5]$$

where J is the **current density** and E is the **electric field**. Like its counterpart in hydrogeology, the hydraulic conductivity (K), σ ranges over several orders of magnitude, and can be inhomogeneous and anisotropic. Conductivity need not be a constant in time. Its value can change with temperature, pressure, and various environmental factors. Buried metallic waste and some ground water contaminant plumes have a large conductivity contrast with their surroundings that can be detected with electrical and **electromagnetic methods**. Different geological environments are also recognized by their distinctive electrical conductivities. In porous rocks, resistivity is often related to porosity through an empirical relationship known as **Archie's Law**. Empirical links to permeability are also available, but are much more problematic.

Resistivity (ρ) is the reciprocal of conductivity. It is a measure of the resistance to current flow by a medium. Resistivity has units of ohm-metres. For some geophysical surveys, such as induced polarization and DC (direct current) electrical soundings, it is preferable to use resistivity rather than conductivity to describe the electrical property.

It is important to distinguish between the intrinsic resistivity of a medium and the **apparent resistivity** measured at the surface by an electrical or electromagnetic survey. Apparent resistivity is defined as the resistivity of a homogeneous half-space (i.e., entire region beneath the surface of the earth) that will produce the same response measured over the real earth. Because of heterogeneities in the subsurface, the measured or average resistivity value at a grid point is an apparent value. The apparent resistivity is equal to the intrinsic or true resistivity only for the case of a homogeneous half-space. The concept of apparent resistivity, which evolved in electrical methods, has also been applied to electromagnetic methods and usually in the form of **apparent conductivity**.

Conductivity is also a dominant influence on the penetration of electromagnetic waves into the subsurface (see **skin depth** and **attenuation**).

3.2.2 Dielectric Permittivity (ϵ) and Dielectric Constant (K)

Permittivity is conceptually similar to electrical conductivity. It describes charge separation (polarization) rather than charge flow (current). Unlike conductivity, permittivity has a well-defined value in free space or vacuum (ϵ_0). It has units of farads/m.

Permittivity is often expressed as a function of the permittivity of free space in terms of the **dielectric constant** (K):

$$\epsilon = K\epsilon_0 \quad [6]$$

The dielectric constant (K) is dimensionless and varies from its free space value of 1 to a maximum of about 80 for water. Permittivity is the primary factor influencing the speed of electromagnetic radiation in earth materials. In combination with the **magnetic permeability** (μ) it defines the velocity (V) of electromagnetic waves as:

$$V = (\mu\epsilon)^{-1/2} \quad [7]$$

Contrasts in the dielectric constant, in turn, produce reflections of electromagnetic energy with the earth. The ratio (R) of the reflected to incident amplitude for an EM signal travelling from a medium 1 toward a medium 2 is known as the **reflection coefficient**:

$$R = (K_1^{1/2} - K_2^{1/2}) / (K_1^{1/2} + K_2^{1/2}) \quad [8]$$

Thus K is the major influence on ground-penetrating radar measurements.

3.2.3 Induced Polarization (IP) and Complex Resistivity (CR)

Electrical properties become frequency-dependent when a moving charge accumulates near energy barriers and causes **polarization**. In general, the resistivity of a material varies with frequency (f) and is **complex**; that is, it comprises in-phase (real) and **quadrature** (out-of-phase, or "imaginary") components. This behaviour can be expressed in terms of amplitude and phase as:

$$\rho(f) = |\rho(f)| e^{i\phi(f)} \quad [9]$$

where $|\rho(f)|$ is the **amplitude** and Φ , is the **phase**. The angle Φ , is usually expressed in milliradians (mrad).

At low frequency, this behaviour is referred to as **induced polarization** (IP). A rock that exhibits an IP response is **polarizable**. Induced polarization results from the accumulation of charge at boundaries where ionic conduction in pore water changes to semiconduction in metallic minerals, and from the generation of diffusion gradients where exchange cations influence the current flow through the medium. The latter phenomenon is often associated with clay.

Induced polarization phenomena can be measured in the **time domain**, as well as in the **frequency domain**. In the time domain, the IP phenomenon is observed as a gradual **decay** of currents in the ground when an applied voltage pulse is terminated.

In frequency domain IP surveys, the **percentage frequency effect** (PFE) is defined as the normalized difference between the resistivities measured at two different frequencies (typically 0.1 and 10 Hz). The equivalent parameter in time domain IP is the **chargeability** (m), which is given as the normalized area under the voltage decay curve over a specified time. The phase angle (Φ) provides another measure of the IP effect.

Complex resistivity or **spectral IP** is simply the measurement of IP phenomenon over a broad range of frequencies. Olhoeft (1986) has demonstrated the utility of spectral IP in detecting organic contamination in the presence of significant clay. Vanhala *et al.* (1992) suggest that spectral IP can detect organic chemical contaminants in glacial till environments having little clay content. Because traditional EM methods have had little success in mapping organic contaminants (which generally poorly conduct), spectral IP is attracting considerable attention.

3.2.4 Magnetic Susceptibility (k)

The **geomagnetic field** of the earth can induce a magnetization in rocks and anthropogenic materials that have appreciable quantities of **ferrimagnetic minerals** such as magnetite. **Magnetic susceptibility** is a measure of the ability of a material to become magnetized. The intensity of induced **magnetization** increases with susceptibility of a target and therefore increases the magnitude of an **anomaly** relative to the field of the earth. An anomaly represents a distortion of the natural geomagnetic field.

The magnetization (J) is related to the magnetic susceptibility (k) and the intensity of the magnetic field of the earth (T , in Teslas) by:

$$J = kT/[(1+k)\mu_0] \quad [10]$$

Magnetic susceptibility is dimensionless in SI units. Magnetization has units of amperes m^{-1} and the geomagnetic field is measured in Teslas. The accepted unit of magnetic field is the nanoTesla (nT) or “gamma”.

Both the magnetization (J) and the intensity of the magnetic field of the earth (T) are vector quantities. The relation in equation [10] holds for **induced magnetization**. If a body also displays a **remnant** or **permanent magnetization**, this component will combine vectorially with the induced magnetization.

For waste site magnetic investigations that target buried metal objects, the susceptibility of the host rock is usually of little consequence. In general, unconsolidated sediments are non-magnetic. However, if the underlying bedrock has appreciable susceptibility (e.g., a basalt) this could be used to advantage. Faults and fracture zones that are potential migration channels for liquid waste often appear as magnetic lows within the more magnetic background.

3.2.5 Density (ρ)

Density is a well-known concept, defined as mass per unit volume. The SI density units are kilograms per cubic metre (kg/m^3). Numerically, 1000 kg/m^3 is equal to 1 gram per cubic centimetre (g/cm^3). The symbols used for density and resistivity are unfortunately the same.

A gravity survey detects density variations in the subsurface. Buried waste itself is seldom a target for a gravity survey, but these surveys can be useful for detecting relevant subsurface conditions. Buried valleys, for example, can often be detected by gravity because of the density contrast between the unconsolidated sediments (typically 2000 kg/m^3) and bedrock (2500 to 3000 kg/m^3). Seismic velocities are also a function of the density of the medium.

3.2.6 Seismic Velocities (V_p , V_s)

A chemical explosion or a hammer blow that stresses the ground generates elastic waves of three fundamental types: P (primary, push-pull) waves; S (secondary, shear) waves; and **surface** waves.

P waves are characterized by a particle motion in the direction of propagation; whereas, S waves have particle motions transverse to the direction of propagation. P waves are the faster of the two, with velocities typically 50% higher than those for associated S waves. The wave velocities (metres per second) V_p and V_s are related to the **elastic moduli** and the density ρ as:

$$V_p^2 = (1.33\lambda + \mu) / \rho \text{ and } V_s^2 = \mu / \rho \quad [11]$$

where λ and μ are the **bulk** and **shear moduli**, respectively. (These relationships follow from the conservation of energy. The elastic moduli are a measure of the potential energy stored per unit volume. As such, they can be equated to the kinetic energy of that unit volume, proportioned to ρV^2 .) Because liquids have no shear rigidity ($\mu=0$), shear waves cannot propagate through them.

Seismic velocities are rarely diagnostic of buried waste because there are usually better ways to detect these targets. However, seismic velocities are very useful in understanding the geological environment, and are widely used in this context. Surface wave methods are not often applied to shallow geotechnical targets.

The ability of a boundary to reflect seismic energy depends on the contrast in the product of density and velocity [known as the acoustic impedance (ρV)] across the boundary. The ratio (R) of the reflected to incident amplitude for a seismic signal travelling from a medium 1 to a medium 2, normal to the boundary, is:

$$R = (\rho_2 V_2 - \rho_1 V_1) / (\rho_2 V_2 + \rho_1 V_1) \quad [12]$$

Figures 17 to 20 show typical ranges in geophysical properties for common materials. These physical parameter data were obtained from: Annan and Cosway (1991); Telford *et al.* (1990); Lankston (1990); Hinze (1990); Carmichael (1989); Keller (1988); Palacky (1988); McNeill (1980b); and Breiner (1973).

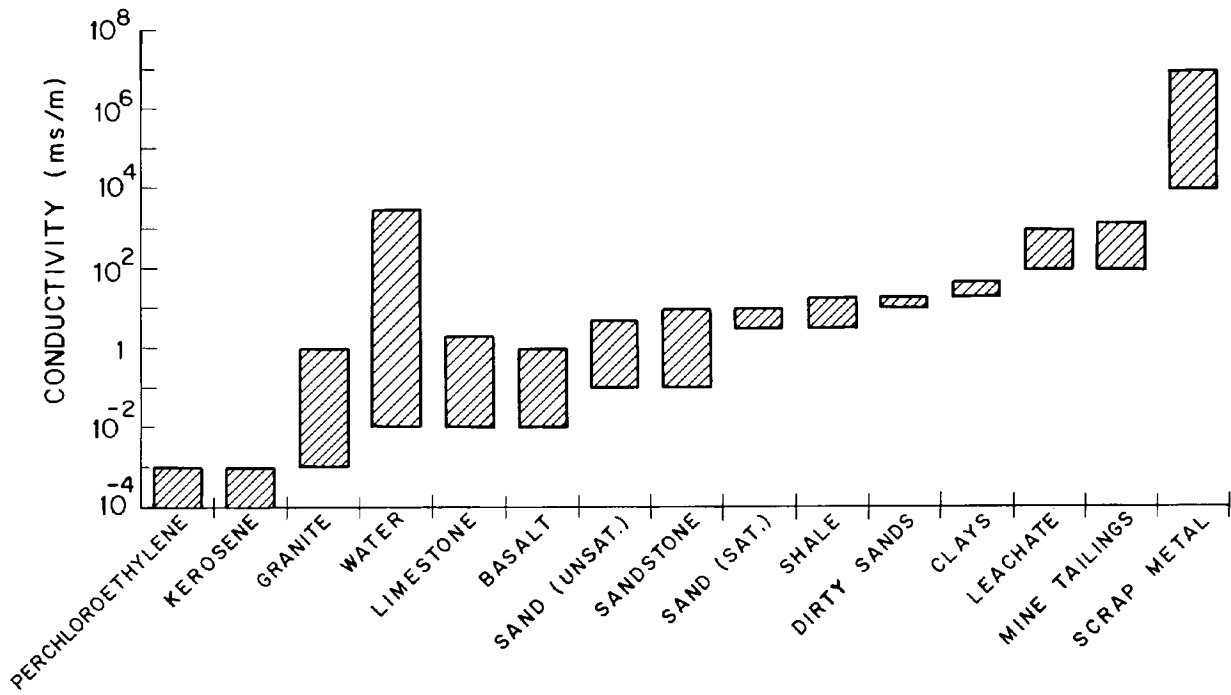


Figure 17 Typical Ranges of Electrical Conductivity (mS/m) for Common Materials

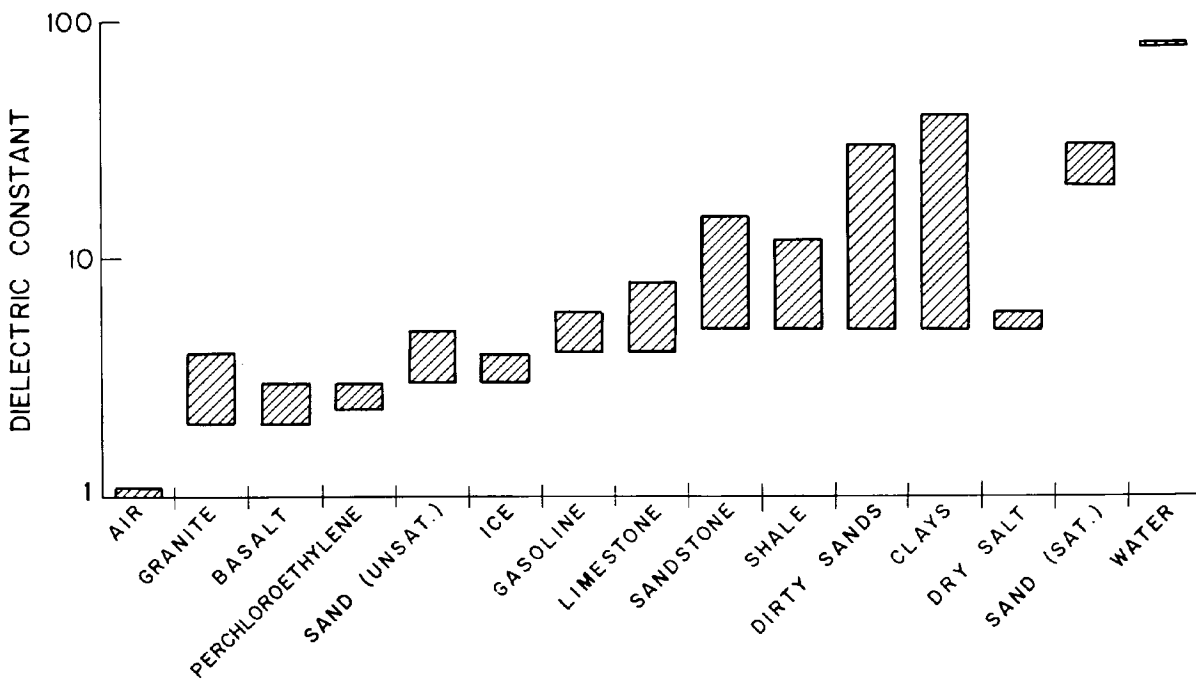


Figure 18 Typical Ranges in the Dielectric Constant (Dimensionless) for Common Materials

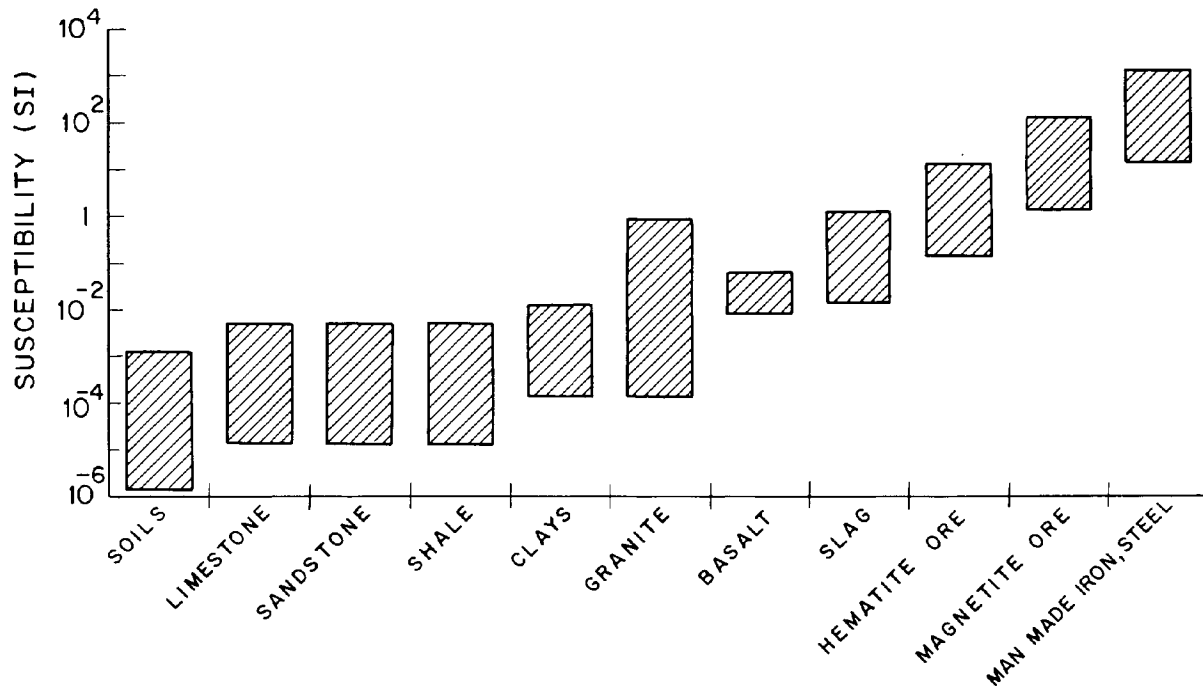


Figure 19 Typical Ranges in Magnetic Susceptibility (Dimensionless) for Common Materials

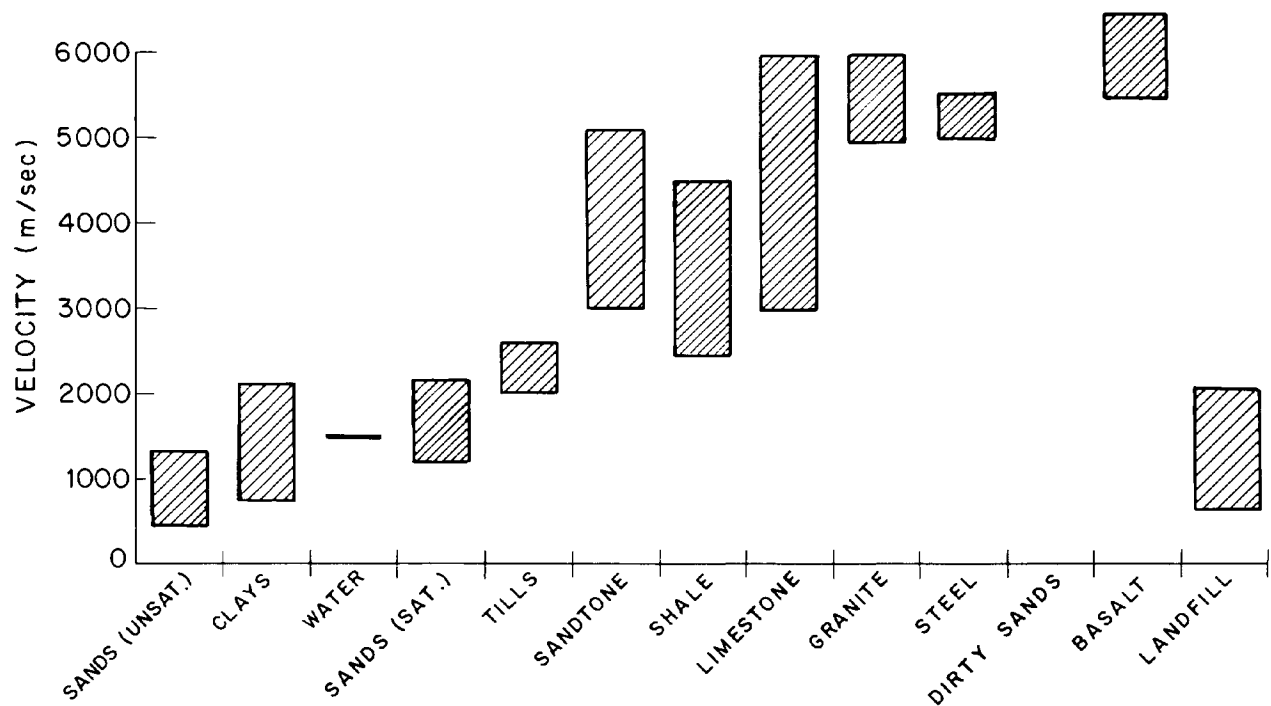


Figure 20 Typical Ranges in P-wave Velocity (m/s) for Common Materials

3.3 *Summary of Geophysical Methods*

This section provides short descriptions of 13 geophysical methods that are used in waste site investigation. The treatment is necessarily brief, and is not an operating manual for the method or the equipment. Rather, it is a guide to having the method used. The principle of each technique is explained, as is the required equipment. Penetration, resolution, and the preferred form of data presentation are described. In some cases, an example is given; whereas, in others, references are given to pertinent case histories.

3.3.1 *Terrain Conductivity*

Figures 21 and 22 show the most popular terrain conductivity units (EM-31 and EM-34) in use in the field.

Principle. Terrain conductivity is probably the single most used geophysical technique for contaminated site investigations. The principles of terrain conductivity have been discussed in detail by McNeill (1980b) (see Subsection 3.2.1). It is an electromagnetic (EM) technique that works (with variations) on a simple principle. In Figure 23, a **transmitter (TX)** produces a time varying electromagnetic (**primary**) field that, on penetrating the ground, induces a voltage (V) that causes current (i) to flow in a conducting subsurface. The subsurface currents in turn create a **secondary magnetic field** that is measured by the **receiver (RX)**. The secondary field is proportional to the ground currents and therefore to the ground conductivity; at low frequencies (low **induction numbers**), so is the receiver signal.



Figure 21 **EM-31 on Survey Site.** (Photograph Courtesy of Geonics Ltd.).



Figure 22 EM-34 on Survey Site. The Instrument is Being Operated in the Horizontal Mode (Photograph Courtesy of Geonics Ltd.).

Terrain conductivity equipment measures that part of the RX signal that is in quadrature (90° out of phase with the primary field). For the receiver signal to be linearly related to conductivity, the skin depth at typical operating frequencies (5 to 15kHz) must be large compared with the TX/RX spacing. For ground conductivities above 100mS/m, these conditions start to break down and the reading will be increasingly in error. The Geonics EM-31 can also measure the real (**in-phase**) part of the signal that, although no longer linear in its response, is very sensitive to buried metals.

Penetration, Resolution. Figure 24 describes the vertical penetration and resolution of the Geonics instruments (EM-31 and EM-41) in horizontal and vertical coil axis modes. Depth is normalized by the coil spacing of the particular instrument. The graphed response is a relative measure of the sensitivity to a thin horizontal layer at a given (normalized) depth. Sensitivity falls off quickly at depths much below one coil spacing, and the vertical coil configuration penetrates deeper and is less sensitive to surface materials. This simple representation of the physical response of these terrain conductivity instruments is unique among the common EM instruments. These response functions are also available in mathematical form and can readily be programmed for spreadsheets.

The instruments record conductivities that are averages (in the sense described by the curves in Figure 24) over volumes of the subsurface with dimensions roughly equal to the coil spacing.

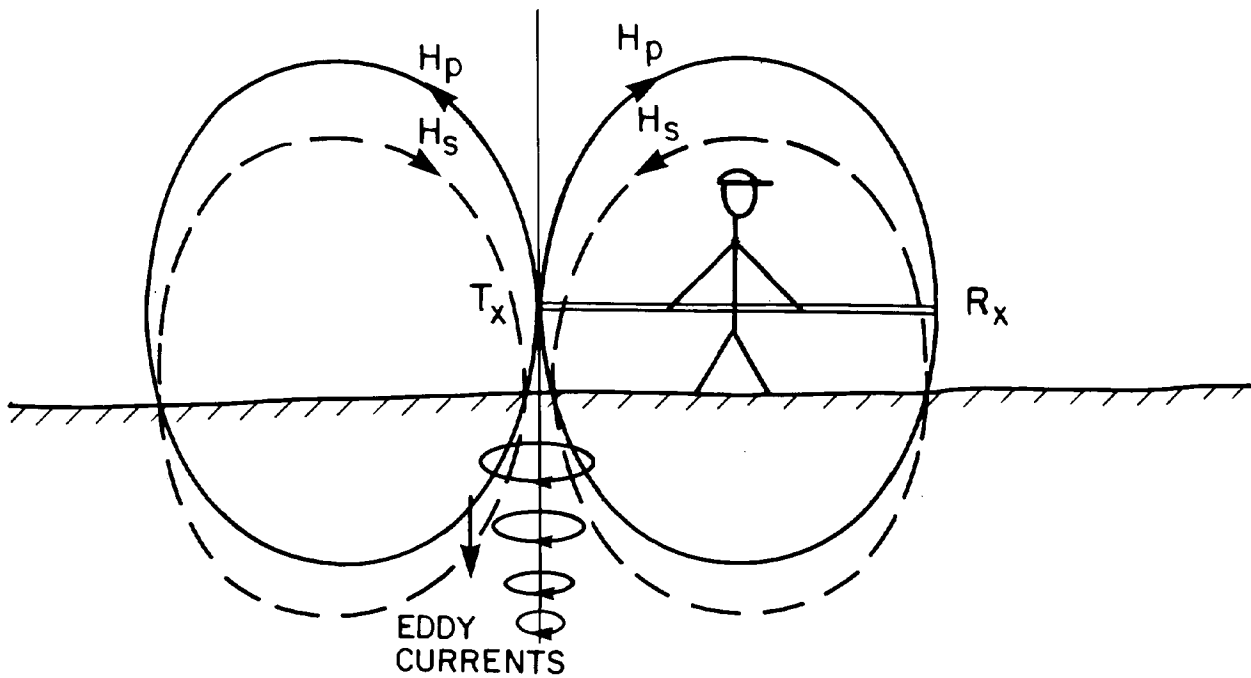


Figure 23 Electromagnetic Induction. Transmitter (TX) creates a time varying primary magnetic field (H_p) that induces currents in the subsurface. These in turn induce signals in receiver (RX). The ratio of the secondary (H_s) to primary field (H_p) is proportional to the frequency (f), square of the intercoil spacing (s^2), and terrain conductivity (McNeill, 1980a).

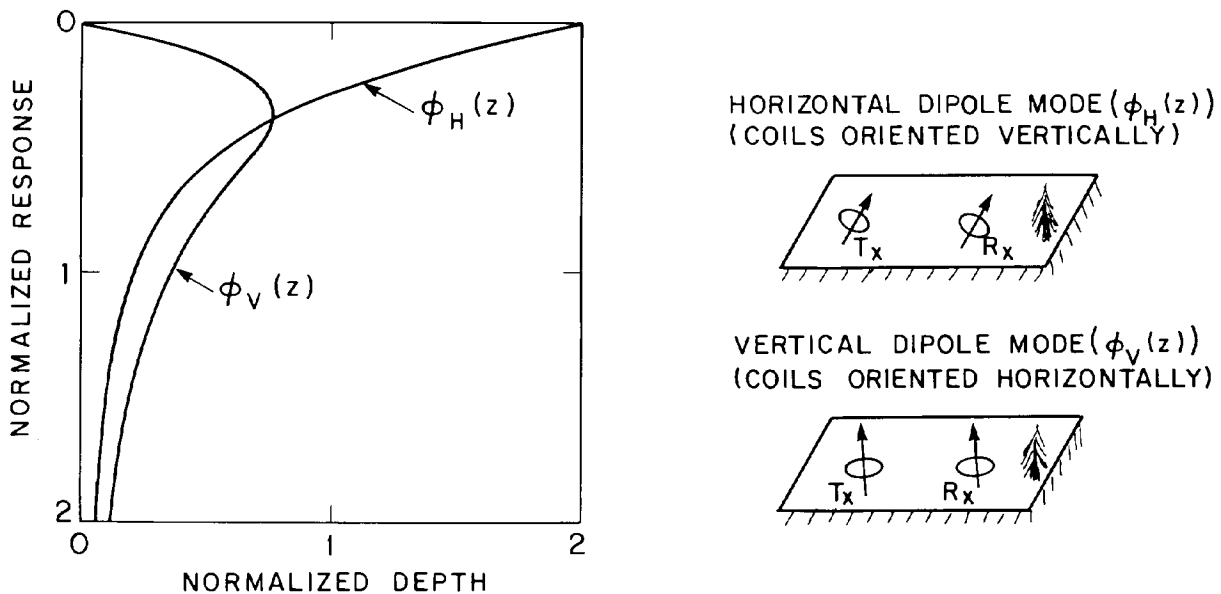


Figure 24 Terrain Conductivity Response as a Function of Depth for Vertical and Horizontal Dipole Modes of the Geonics EM-31 and EM-34. The vertical axis is depth-normalized by the coil spacing and the horizontal axis gives relative response.

Therefore, lateral resolution is also limited by the coil spacing. The response for small objects such as single barrels will fall off roughly as r^{-6} , where r is the distance between transmitter and target.

These instruments are usually used for lateral **profiling**. In principle, several combinations of horizontal and vertical modes and coil spacings can be used to effect a vertical **sounding**. However, this is usually unsuccessful primarily because of the difficulty in obtaining a uniform calibration of the several instruments and geometries involved.

Equipment. Equipment for terrain conductivity is currently manufactured exclusively by Geonics Ltd. of Mississauga, Ontario, and rented by Geonics and certain other agencies. The instruments can be read in horizontal and vertical coil-orientation modes, which varies their effective depth of penetration. They are typically calibrated over low conductivity ground (such as granite or dolomite outcrop), or suspended in air. Digital recorders that can be downloaded to an office or field computer are now commonly used with these instruments.

Presentation, Interpretation. Simple relationships for the response to layered structures, which can be programmed on computer or calculator, are available from the Geonics manual (McNeill, 1980b). These allow the response of a hypothetical layered structure to be predicted and compared with the observed anomalies. The data are usually plotted in plan view and contoured, or shown in three-dimensional perspective. Shaded and coloured plots are also increasingly used for these applications.

Example. Figure 25 depicts the contamination released from a municipal landfill in Novo Horizonte, Brazil. The contours define a high conductivity plume that clearly originates in the landfill and intersects the (contaminated) well at a farmhouse about 200 m away. Note that the conductivity anomaly itself does not confirm the existence of a groundwater contamination anomaly. There are other interpretations (e.g., clay lenses). On the basis of this map, however, a drilling and sampling program was initiated that confirmed the link between the contaminated well and the landfill. The geophysics provided an excellent reconnaissance-grade map to guide the eventual hydrogeological investigation.

3.3.2 *Horizontal Loop (HLEM)*

Horizontal loop or **slingram** surveying is distinguished here from terrain conductivity, although terrain conductivity often employs a horizontal loop configuration. The distinction between terrain conductivity mapping and conventional HLEM is that the HLEM method always uses both the in-phase and quadrature data, and the HLEM equipment does not read directly in apparent conductivity.

Although HLEM is a primary mining geophysical exploration tool for delineating moderate-to-strong conductors located within 100 m of the ground surface, it is not yet routinely used in environmental or geotechnical applications. The focus of this section is the application of HLEM to environments beyond the range of investigation of Geonics EM-31 and EM-34.

Principle. The HLEM is based on the principle that the ratio of the quadrature and in-phase parts of the secondary, vertical magnetic field measured at the receiver provides a measure of the

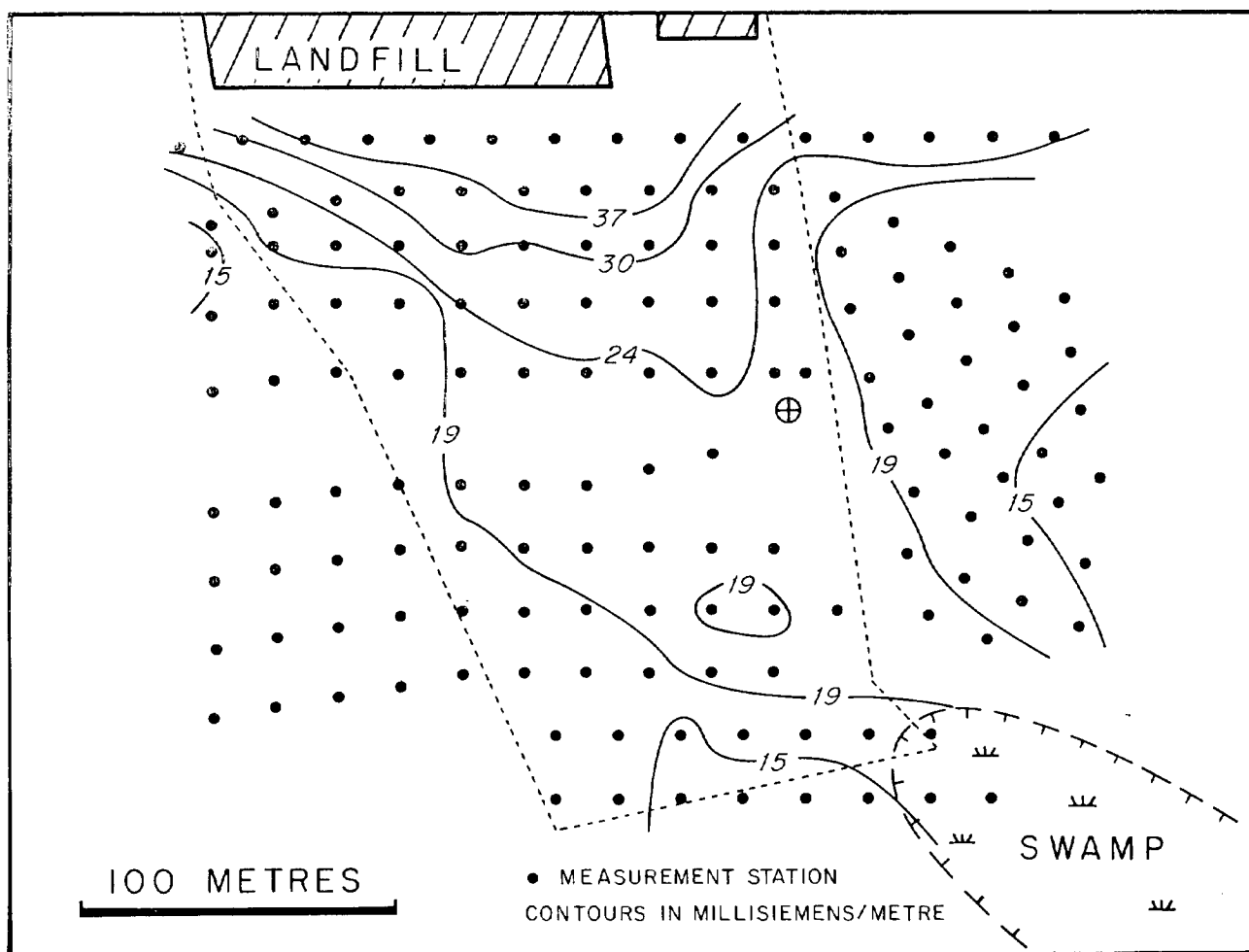


Figure 25 An EM-34 Survey Near Nova Horizonte, Brazil. Leachate from a landfill (top of diagram) moves toward discharge in a swamp (lower right), passes under a farmhouse, and contaminates its well (indicated as a crossed circle). The survey measurements were made at each of the dots. Contours are in mS/m (after Greenhouse *et al.*, 1989).

quality of the conductor generating that secondary field. Typically, at least two frequencies are employed. An HLEM survey dedicated to environmental or geotechnical investigations might be conducted with either or both of the following objectives:

- to delineate lateral variations in the thickness or conductivity of an overburden layer (e.g., a buried valley); and
- to determine the thickness and conductivity of a uniform overburden layer.

In the case of the first objective, the survey is conducted in a profiling mode using one transmitter–receiver separation; in the second case, the survey is conducted in a sounding mode normally using at least four frequencies and often more than one transmitter–receiver separation distance.

In its use as a profiler, the HLEM offers greater depth penetration than the terrain conductivity devices. In a survey area where the overburden cover is relatively thick (say greater than 30 m), an EM-34 survey may not be able to detect the presence of an overburden trough. In sounding, HLEM offers real advantages over terrain conductivity. Up to 10 frequencies can be employed to obtain conductivity estimates to different depths.

In general, an HLEM survey should be considered if the delineation of overburden to depths below 30 m is the main objective, or if an approximate estimate of the thickness and conductivity of a fairly conductive, relatively uniform, layer is required. Compared with resistivity surveys, HLEM surveys are fast and relatively inexpensive (roughly one-quarter the cost) and can often be used effectively for the same objectives.

Equipment. The Apex Parametrics MaxMin I is the most commonly used HLEM unit in North America. The MaxMin I can operate at 10 frequencies and a range of coil separations and can provide both profiling and sounding capability. The in-phase and quadrature data are usually recorded digitally with a data logger. The unit can be ordered from Apex Parametrics Ltd., Uxbridge, Ontario. An HLEM survey is performed by a two-person crew that operates the transmitter and receiver modules; a reference cable links the transmitter with the receiver.

Penetration, Resolution. The penetration and resolution are determined by the separation between coils, the operating frequency, the **conductance** of the target, and the contrast between the host rock and the target. As a rule of thumb, depth of investigation is taken to be about one-quarter to one-half the intercoil separation. In general, the coil separation is chosen to be the minimum required to investigate a suspected target, typically 50 to 100 m in overburden studies well-suited to this technique. The radial range of investigation is roughly that of the depth of investigation.

Presentation, Interpretation. The HLEM profile data are usually presented in plan as “stacked” profiles that display both in-phase and quadrature results. Separate maps are typically generated for each frequency used. Sounding data are presented as plots of in-phase *versus* quadrature response for the range of frequencies employed. Individual plots are created for each sounding site.

The HLEM data can be manually interpreted using curves, or modelled by computer using commercially available programs. The objectives of manual or computer modelling of the data might include the determination of the location, dimension, and conductance of an overburden trough, or the determination of the conductance of an overburden layer in a sounding survey.

Example. An excellent example of this technique is given by Palacky and Stephens (1990) who show the results of a multi-frequency HLEM survey in an area of northeastern Ontario covered by glacial till.

3.3.3 *Very Low Frequency (VLF) Resistivity*

The VLF resistivity should not be confused with VLF-EM. The VLH resistivity method requires the use of electrodes that make electrical contact with the ground and measures earth resistivity directly; the VLF-EM method does neither. Regular VLF-EM is normally used to locate large

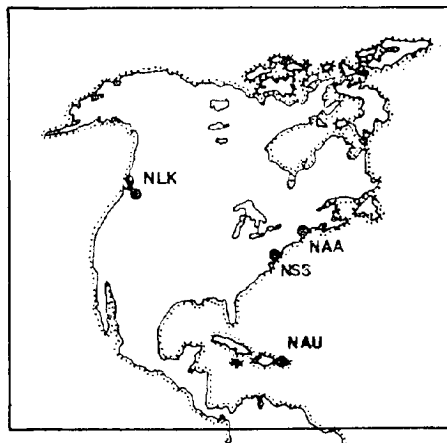
mineralized zones (such as occur in dykes), but can also be used to delineate shear zones and overburden troughs. Refer to Wright (1988) and McNeill and Labson (1991) for comprehensive reviews of VLF-EM.

Principle. The VLF resistivity should be considered as an alternative for terrain conductivity methods in many environmental and engineering surveys. The VLF resistivity method uses the carrier waves from high powered military transmitters operating in the so-called very low frequency band of the electromagnetic spectrum. Transmitter frequencies range from 15 kHz (15 000 Hz) to 30 kHz.

The VLF transmitters are essentially long vertical wires installed at military installations at places like Cutler, Maine and Annapolis, Maryland. Figure 26, a map of transmitters available in North America, gives an idea of the coverage available. At a large distance from a VLF transmitter, the radiated field is a plane wave that consists of a horizontal magnetic field perpendicular to the direction of propagation, a horizontal electric field component in the direction of propagation, and a vertical electric field component. Figure 27 depicts these components.

The choice of transmitter is determined primarily by signal strength, which in turn is governed by the power of, and distance to, the transmitter. The direction of the transmitted field can also be important for narrow conductive units that have a well-defined strike direction.

The presence of a large, discrete conductor will modify the secondary magnetic and electric fields observed by the VLF receiver. The ratio of the orthogonal horizontal components $|E_x/H_y|$ has units of ohms, and over horizontally stratified deposits it is related to the average resistivity of that section of the subsurface penetrated by the fields. The phase difference between E_x and H_y contains information on the vertical conductivity structure. Both the resistivity and the phase are recorded by the instrument.



VLF Stations			
Call Sign	Frequency (kHz)	Power (kw)	Location
NLK	24.8	200	Jim Creek, WA
NAA	24.0	1000	Cutler, MA
NSS	21.4	1000	Annapolis, MD
NAU	28.5	1000	Aguada, Puerto Rico

Figure 26 Locations of VLF Transmitters Available in North America and Listing of Call Signs, Operating Frequencies, and Transmitter Power (After Wright, 1988)

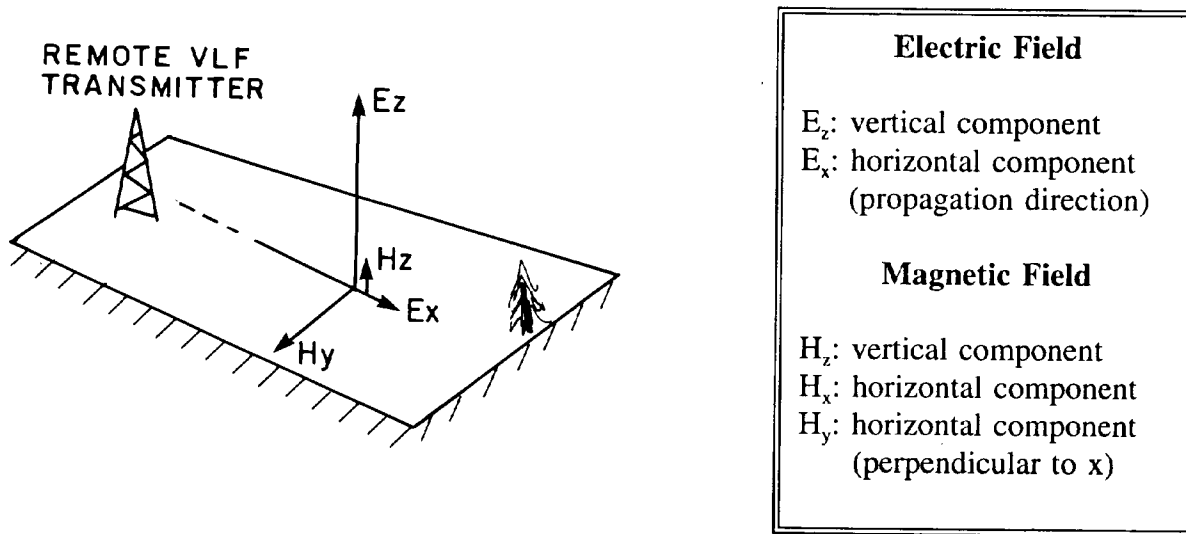


Figure 27 Electric and Magnetic Field Components for a VLF Transmitter

Of all frequency domain methods, the VLF methods experience the largest “**current gathering**” effects because of the high operating frequencies and regionally uniform source field. This means that features like lakes and swamps, which do not have a particularly high conductivity, but (because of their size) have a large conductance, can collect and channel disproportionate amounts of current.

Equipment. The Geonics EM-16R has been on the market for over 15 years and is still in widespread use. Modern, computer controlled equipment is available from Scintrex and Gem Systems (see Section 3.7). The newer equipment can simultaneously record data for three different transmitting stations.

Penetration, Resolution. Because of the high operating frequency and small skin depth, the penetration attained by a VLF resistivity survey is smaller than the penetration achieved by other methods. As a rule of thumb, the exploration depth is taken to be roughly two-thirds of skin depth. In typical overburden of 100 ohm-m resistivity, this is about 20 m. Conversely, the resolution of near-surface targets is often superior to that of other EM/resistivity methods because of the high operating frequency.

Presentation, Interpretation. The VLF data are normally presented as profiles or as contour maps of resistivity and phase. Multilayer, one-dimensional models can be readily computed; two-dimensional modelling is available. The resistivity and phase can be inverted in terms of a one-dimensional, two-layer model if one of the three parameters [ρ_1 , ρ_2 , or depth (h)] is specified.

Example. Figure 28 is a contour map of VLF resistivity over an area near North Bay, Ontario. This simple representation clearly shows the location of a contaminant plume moving away from a municipal landfill.

3.3.4 Time Domain EM (TDEM)

The advantages of TDEM lie in the very large depth of penetration that can be achieved and in the ability to “see through” very conductive overburden. In the environmental field, TDEM is usually applied to deep-seated problems such as salt water intrusion or contamination associated with oil field production. Improvements in the instrumentation, however, will soon open other (shallower) targets to this method.

Principle. When EM is conducted in the time domain, the response to a sharp onset or turning off of a magnetic field is recorded. Because this sharp signal contains a great many frequencies, the time domain method is, in principle, equivalent to several single frequency measurements that might be made with terrain conductivity, HLEM, or VLF. The transmitter generates a series of periodic pulses (Figure 29). When the current in the transmitting coil is quickly shut off, an induced electromotive force (voltage) generates eddy currents in the ground. The currents decay, resulting in a decaying secondary magnetic field, that is sampled over time at the receiver. The rate of decay (τ) is a measure of the conductivity of the target and is inversely related to the skin depth in frequency domain measurements. Figure 30 depicts the decaying secondary magnetic

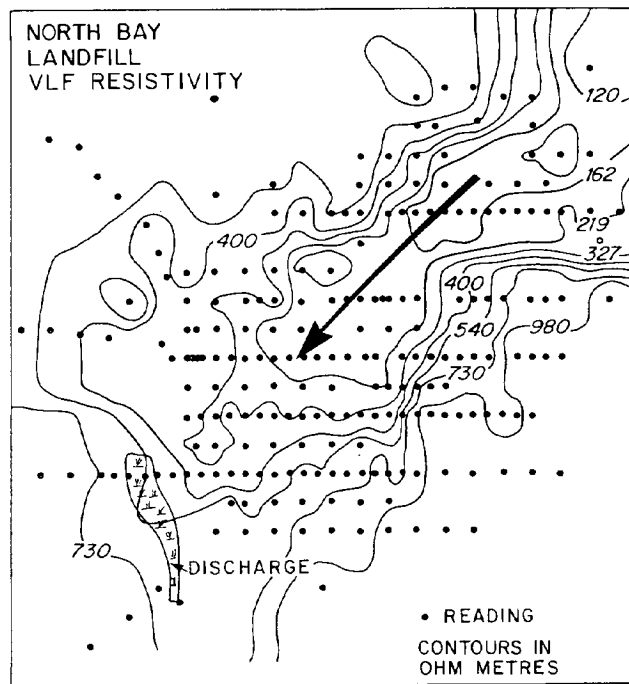


Figure 28 Apparent Resistivity Contours Over Contaminant Plume Near North Bay, Ontario (After Ben Miloud, 1986). Contaminated groundwater emanates from a landfill source (upper right) and moves toward discharge point in a swamp. Readings were made at the dots. The contaminated unit is a sand, typically 10-m thick, overlying a crystalline bedrock.

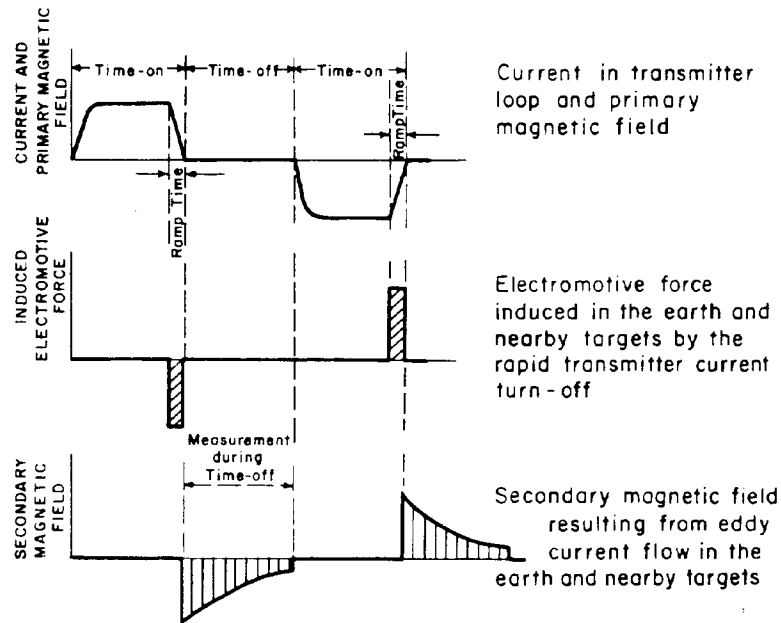


Figure 29 Time Domain EM Wave Forms. (After McNeill, 1990 and with permission of the Society of Exploration Geophysicists).

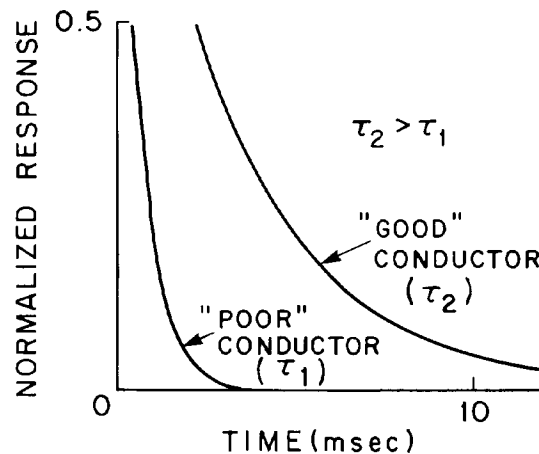


Figure 30 Decay of Secondary Magnetic Field for Good and Poor Conductors

field for a good and poor conductor. Note that, unlike frequency domain methods, the secondary magnetic field is usually measured in the absence of the primary field.

Conductors are resolved and interpreted on the basis of this rate of decay of the secondary magnetic field. The field is sampled using 10 to 20 “channels” (discrete measurement points spanning early to late time of the decay). Early channels contain information on shallow structures, later channels on deep structures.

The method can be used in a **sounding** mode, in which a layered conductivity model of the earth beneath the apparatus is constructed from all the channels, or in a **profiling** mode, in which one or more channels are tracked or contoured over an area. The profiling mode is typically used

when the target is discrete and sub-vertical in dip. Use of TDEM should be considered when the target is moderately to strongly conductive and located at depths exceeding a few tens of metres. Unlike many other EM methods, it is also effective where the overburden is highly conductive.

Penetration, Resolution. The depth of penetration of a TDEM survey can be hundreds of meters if the host rock and overburden cover is not excessively conductive. The resolution of near surface conductors may not be quite as good as that achieved by frequency domain methods. Compared with resistivity soundings, which require large electrode spacings (see Figure 32), TDEM soundings are less time-consuming and provide better lateral resolution. Note that, in contrast to resistivity soundings where the array is expanded to increase the depth of investigation, TDEM penetration is achieved by measuring the decaying magnetic field at successively later times.

Equipment. TDEM equipment is manufactured in Canada by Geonics (the EM-37, EM-47, and EM-57), Lamontagne Geophysics (UTEM 3), and Crone Geophysics and Exploration (PEM and DEEPEM). All TDEM equipment is microprocessor-controlled, and data are digitally recorded. Certain companies also manufacture borehole versions of the TDEM gear.

Presentation, Interpretation. Time domain data can be presented in a variety of ways, ranging from profiles of multi-channel vertical component results to conductivity *versus* depth sections of sounding data. Interpretation of the data can be highly sophisticated and usually involves computer modelling. Comprehensive reviews of TDEM are given in Nabighian (1991). Computer modelling programs are commercially available. One example is the MULTILoop program developed by Lamontagne Geophysics and marketed by Lamontagne Geophysics and Geopak Systems.

Examples. Interested readers are referred to examples of TDEM soundings in hydrogeological applications given by Fitterman and Stewart (1986) and Meekes and van Will (1991).

3.3.5 Airborne EM

Airborne EM surveying, like ground surveying, can be undertaken in both the time and frequency domain. Time domain surveys employ a large transmitting loop that is best handled with a fixed-wing aircraft. On the other hand, frequency domain surveys normally use a “bird” containing both the transmitter and receiver and are almost exclusively helicopter-borne.

Because of the superior lateral resolution provided by a helicopter EM (HEM) survey, helicopter surveys comprise the majority of airborne surveys now performed. Time domain surveys are usually restricted to areas where the overburden is thick and/or very conductive, or where the target is deeply buried. They are often regional in scale.

A helicopter EM survey can be a viable alternative to a ground survey where the target is large or the terrain difficult.

Principle. The principles governing HEM surveying (conducted in the frequency domain) are the same as those governing other frequency domain surveys conducted on the ground (such as HLEM). All systems measure the in-phase and quadrature response of the secondary magnetic

field at several frequencies. These can be inverted to yield information on the geometry, depth, and quality of the target.

Equipment. Currently, the two major HEM contractors in Canada (Aerodat and Digheem, both of Mississauga, Ontario) have systems that operate at five simultaneous frequencies ranging from approximately 1 kHz (1000 Hz) to 100 kHz. The frequency range permits investigation of terrain ranging from conductive to resistive. Contact these contractors for technical information and case histories.

Geoterrex and Questor, both based in Canada, manufacture and fly time domain systems that are refinements of the INPUT system developed by Barringer Research in the mid-1960s. Technical literature can be obtained from both firms.

Penetration, Resolution. The penetration or depth of investigation achieved by HEM systems is governed by the principles that apply to all frequency domain systems. The skin depth always provides an approximate upper limit on penetration, but the coil spacing, height of the bird, and sensitivity of the receiver will usually further reduce the effective depth of penetration. The position of the bird, relative to a local coordinate system established by transponders in the area, can be determined within several metres. Surveys are routinely flown using a 100-m line spacing, but more detailed grids can be requested.

When planning an HEM survey in an area where no ground EM data are available, some computer modelling (assuming reasonable parameters for the size and conductivity of the target) should be considered.

Presentation, Interpretation. Data are presented as multi-channel profiles, line contour maps of apparent resistivity, and colour/shadow resistivity maps. The multi-channel profiles usually display computer modelling results that are superimposed on the profile data. Depending on how detailed the survey is, maps can be presented at an expanded scale such as 1:5000.

Survey data are usually automatically inverted by computer. However, there are substantial differences in the amount of interpretation and reporting routinely undertaken by different contractors. The data can be quite complex. If a detailed interpretation report is not provided, it may be necessary to engage a consultant.

Example. In a relevant case history, Johnson and Seigel (1986) show an interesting example of mapping a coastal aquifer.

3.3.6 *Resistivity Methods*

Resistivity methods differ fundamentally from electromagnetic methods because they require injection of current through electrodes into the ground (they are **galvanic** methods). The EM methods **induce** currents in the ground; they do not require physical contact. Some hybrid methods such as VLF resistivity (Subsection 3.3.3), however, employ electrodes to measure electric fields induced in the ground by the **primary magnetic field**.

Resistivity methods can provide information on the subsurface in areas of moderately high resistivity where secondary EM fields would be small. This, coupled with their low cost and fairly simple equipment requirements, constitutes the primary advantage of the resistivity methods. Resistivity measurements are collected during all IP surveys (see Subsection 3.3.7).

Principle. When current is injected into the ground through a pair of electrodes, the patterns of subsurface current flow reflect the resistivity of the subsurface. These current patterns can be mapped on the surface by another pair of electrodes that measure the associated voltage variations. These voltages are a measure of the energy that must be expended to pass current through the earth materials (its resistivity, see Subsection 3.2.1). Figure 31 depicts the distribution of current and voltage (potential) lines in a homogeneous subsurface and shows the distribution of current lines near a conducting mass (such as a contaminant plume) in a more resistive medium, and near a resistive mass in a more conductive medium.

The reader should note that there is an analogy between the flow of fluid through a porous medium and the flow of electricity through a conductive medium. For example, fluid potential and specific discharge are analogous to voltage and current.

Many surveys accomplish profiling and sounding simultaneously. In profiling, the lateral distribution of resistivity is studied by maintaining a relatively constant depth of investigation controlled by the spacing of the electrodes. If there are significant lateral variations in resistivity, profiling is recommended. Vertical electrical soundings (VES) study the vertical variation of

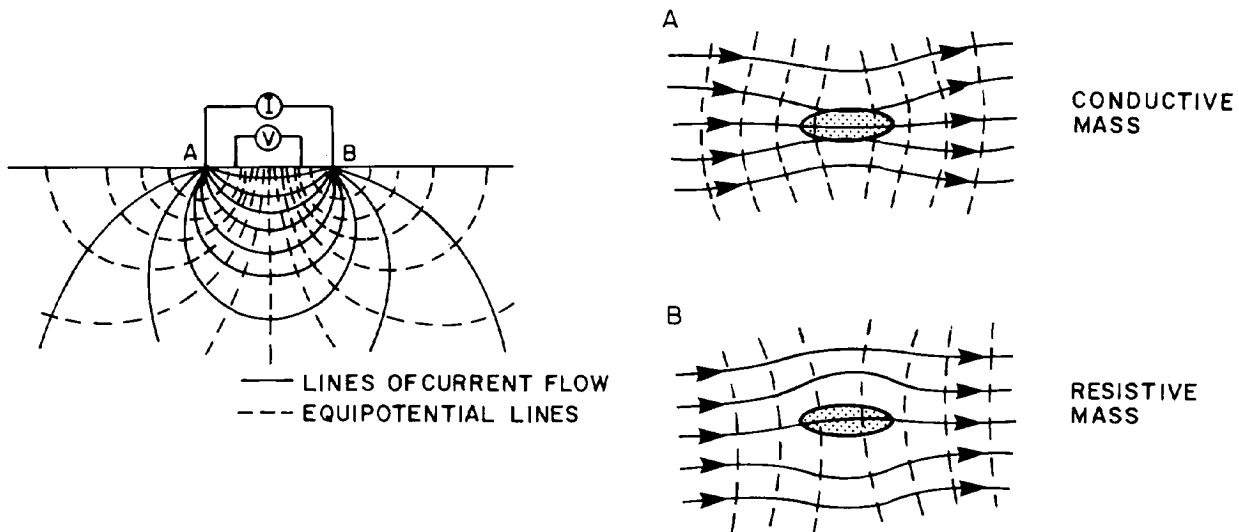


Figure 31 Current Flow and Equipotential Lines for a Resistivity Survey Over a Homogeneous Subsurface (Left). Current Flow Lines in Vicinity of a Conducting Mass (Top, Right) and Resistive Mass (Bottom, Right)

resistivity with increasing depth of investigation. Soundings are most applicable if the geology is flat to gently dipping and laterally homogeneous.

Sounding and profiling are made with an arrangement of four electrodes known as “arrays”. The three most commonly used in ground water studies are the Wenner, Schlumberger, and dipole-dipole arrays. Figure 32 shows these electrode configurations. Other fairly common arrays are the pole-pole and pole-dipole. Each has its advantages, either in terms of resolution or field logistics, but all accomplish much the same thing—a weighted average of the resistivity of the earth down to some depth related to the size of the array. That resistivity has the form $K\Delta V/I$, where ΔV is the voltage measured across two electrodes, I is the current passed through the other two electrodes, and K is a constant that depends only on the array geometry. The calculated resistivity is an apparent resistivity (Subsection 3.2.1).

Equipment. One of the great advantages of the resistivity method is that it requires, in its simplest form, very inexpensive equipment compared with its TDEM and seismic competitors. The equipment, which is similar to that required for an IP survey, consists of a power supply (battery pack or motor-generator), transmitter/receiver (which may occupy a single module), wire, and current/potential electrodes. Resistivity theory assumes that the currents used are direct (DC) but, in practice, a very low frequency (<100 Hz) signal is usually employed. In Canada, Scintrex of Concord, Ontario manufactures resistivity equipment.

New generation resistivity equipment records data digitally, and can be programmed to transmit and measure different waveforms and to handle arrays using more than 100 electrodes.

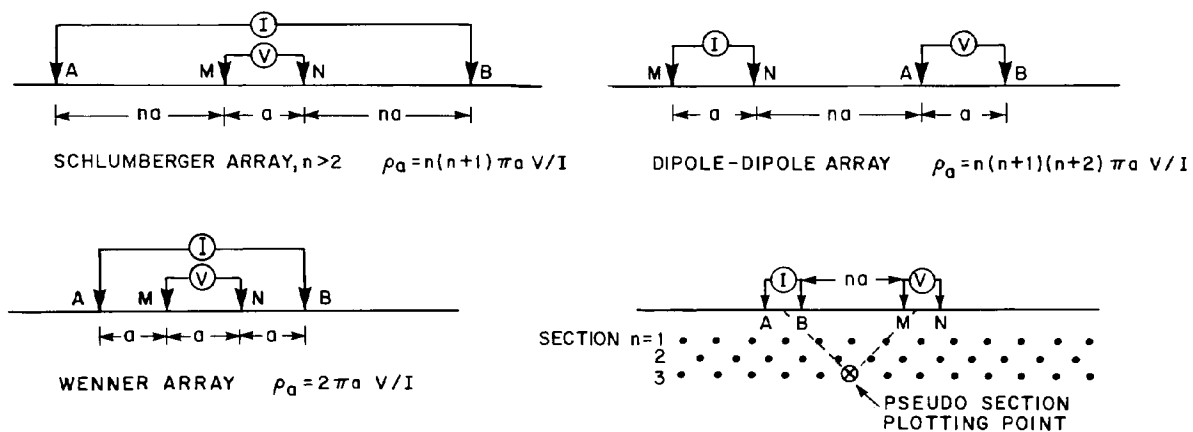


Figure 32 Electrode Arrays: Schlumberger (Top Left); Wenner Array (Bottom Left); Dipole-dipole Array (Top Right); and Pseudosection Plotting Convention (Bottom Right)

Resistivity surveys can also be undertaken using any generation of IP equipment, and are a byproduct of any IP survey.

Penetration, Resolution. Theoretically, there is no limit to the penetration of the resistivity method because penetration is linked to the separation of the current electrodes. Resistivity soundings sometimes target horizons located hundreds and even thousands of meters subsurface. Lateral resolution is limited by the spacing of the voltage (potential) electrode and the current electrodes. Vertical resolution varies, depending on the conducting environment, but as a rule of thumb it is difficult to resolve a layer that is thinner than the depth to its upper surface.

Presentation, Interpretation. Profile data are conventionally plotted as apparent resistivity versus distance. Sounding data (VES data) are plotted on log-log paper as apparent resistivity *versus* array spacing. A combination display called a “**pseudosection**” is also employed. In the pseudosection, profiles are recorded with a variety of array spacings and are plotted using the spacing as a measure of the depth to the apparent resistivity (see Figure 32). Pseudosections are useful representations to an experienced interpreter, but they should not be considered as a literal image of the subsurface. Ward (1990) provides a thorough review of the resistivity methods and includes examples of data presentation and interpretation.

In the past, VES interpretation was undertaken by matching field data to catalogues of standard graphs prepared for each array type. Today, interpretation is undertaken on microcomputers using both forward and inverse modelling software. Sources of this software include Interpex of Golden, Colorado, and most equipment manufacturers. However, a suite of interpretation curves is still a good acquisition for any interpreter.

Example. Recent hydrogeologic studies by Meekes and vanWill (1991) compare TDEM, VES, and seismic reflection data for the same targets. Figure 33 shows a resistivity survey that located slumping material adjacent to chemical disposal pits.

3.3.7 Complex Resistivity (CR)

A complex resistivity (CR) survey is essentially a resistivity survey that uses alternating (AC) current (see Subsection 3.2.3). The magnitude and phase (or, equivalently, real and imaginary parts) of the voltage to current ratio is measured using a standard resistivity electrode array (see Subsection 3.3.6) over a range of frequencies. The terms “complex resistivity” and “spectral IP” are used interchangeably. Induced polarization (IP), a staple method of the mining exploration industry and predecessor to CR, is a low frequency form of complex resistivity.

The CR surveys involve sophisticated equipment, are expensive to undertake, and are not routinely employed in contaminated site assessment. In the future, complex resistivity could see considerably more applicability in the detection of organic contaminants (see Subsection 3.2.3).

Principle. A complex resistivity (CR) response is a plot of the complex apparent resistivity as a function of frequency, typically in the range of DO to 10 000 Hz. Variations in the response arise from pore-scale phenomena (see Subsection 3.2.3). The resistivity is complex because the voltage lags behind the current injected into the subsurface. The amplitude of the voltage to

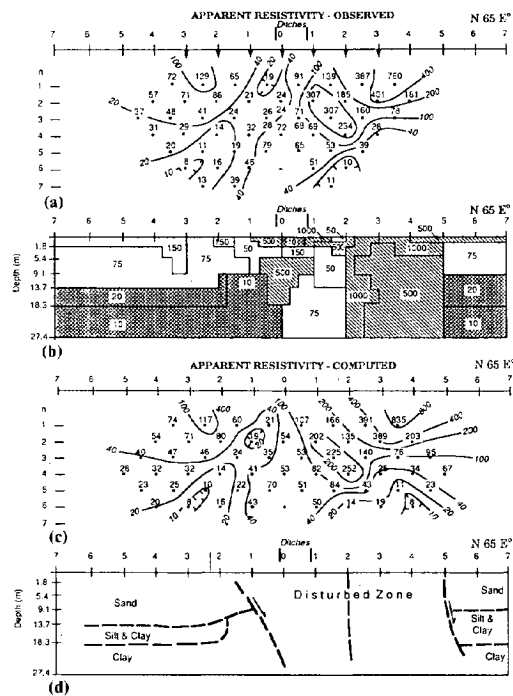


Figure 33 Dipole-dipole Resistivity Profile Across a Chemical Disposal Pit (After Ross *et al.*, 1990). Interpretation of the data (a) using the unusually complex model (b) yields (c). The geological interpretation is shown as (d). Note the disturbed zone centred on the disposal pits and the layered structure of the materials on either side of the pits. Reprinted with permission of the Society of Exploration Geophysicists.

current ratio V/I (Subsection 3.3.6) generally decreases with increasing frequency as the resistance to current flow decreases.

Complex resistivity data provide information that is complementary to simple resistivity data. For example, it is generally true that a “clean”, porous sedimentary rock has a resistivity that is independent of frequency. However, with the addition of clay or disseminated metallic minerals such as pyrite, there is a notable dependence of resistivity on frequency.

Equipment. The equipment required to undertake a CR survey differs from that of an ordinary IP/resistivity survey primarily in the degree of sophistication of the receiver required by the CR survey. The complex resistivity method requires a very precise knowledge of the transmitter wave form and the phase difference between the current and voltage. In Canada, IP and CR equipment is manufactured by Phoenix Geophysics, Androtex, and Scintrex. Complex resistivity systems are manufactured by U.S. firms such as Zonge Engineering and Research, Tuscon, Arizona.

Penetration, Resolution. Penetration and resolution for the CR method are similar to those of conventional resistivity. However, because of skin effects associated with the AC current, penetration will be somewhat less than for the DC case. The type of array employed, conductance of the surficial sediments, bedrock topography, and signal to noise ratio (which can

increase with the amount of current injected by the transmitter) are some factors that play a role in both resolution and penetration..

Presentation, Interpretation. Complex resistivity data can be presented in a variety of ways in both plan and section (Ward, 1990). The IP profile data collected using a **dipole-dipole** array are traditionally presented as so called “pseudosection” plots (see Subsection 3.3.6). Complex resistivity spectral data are often displayed as logarithmic plots of resistivity and phase *versus* frequency.

Both forward and inverse modelling packages are available for IP, but the interpretation of full range complex resistivity data can be quite involved. Moreover, these data can be quite noisy. The limitations and subtleties of the data can be appreciated only after gaining considerable experience.

Example. Induced polarization has often been used to detect the presence of clays, and may be used to discriminate between terrain conductivity or conventional resistivity anomalies caused by contamination or by the presence of clay. A good example of IP surveys for groundwater exploration is given by Draskovits *et al.* (1990).

Figures 34 and 35 show complex resistivity results associated with the interaction of toluene with glacial till. Figure 34 shows laboratory results obtained for a core sample; Figure 35 shows simulated field results (modelled) derived for a dipole-dipole array.

3.3.8 Magnetics

The primary objective of most contaminated-site **magnetometer** surveys is to locate buried magnetic objects. However, magnetic surveys can also provide useful information on the geological environment. For example, they can provide an estimate of the thickness of non-magnetic **alluvium** or sediments overlying magnetic “basement” rock and map the location of faults in the basement (Subsection 3.2.4).

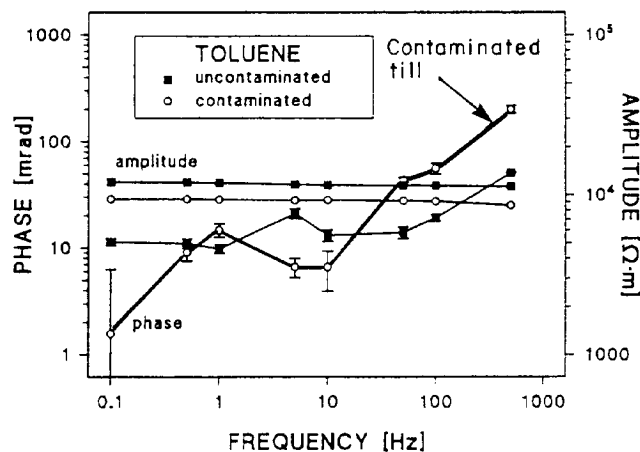


Figure 34 Measured Phase and Amplitude Spectra for Toluene Contaminated (2%) and Non-contaminated Glacial Till (Vanhala *et al.*, 1992). Note phase response of contaminated till. Reprinted with permission of the Society of Exploration Geophysicists.

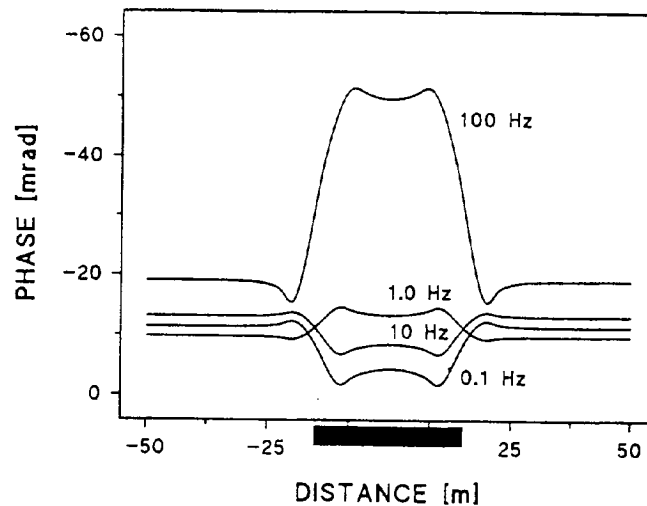


Figure 35 Calculated (Modelled) Phase Anomaly for Toluene Contaminated (2%) Till, Dipole-dipole Survey. The solid bar shows the contaminated zone. Reprinted with permission of the Society of Exploration Geophysicists.

Principle. Breiner (1973) provides a basic review of **magnetics** and includes many examples of characteristic anomalies that may be encountered in geological, geotechnical, and environmental investigations. In a magnetometer survey, the objective is usually to measure the total magnetic field over the site, and to look for anomalous highs and lows that would indicate ferromagnetic waste. In addition, the vertical gradient of the geomagnetic field is often measured by recording the magnetic field at two different elevations simultaneously. Figure 36 shows a magnetic gradiometer in use in the field.

Equipment. There are two basic designs of magnetic sensors on the market. Proton precession magnetometers measure the amplitude of the total magnetic field; whereas, fluxgate magnetometers measure the component of the magnetic field in a particular direction (usually vertical). Both can be used in a gradient configuration. Generally speaking, fluxgate equipment is more difficult to operate because it must be oriented, but by describing the entire magnetic field vector it yields more information. Cesium vapour magnetometers are also employed in exploration, particularly in high sensitivity aeromagnetic surveys.

Modern, portable magnetometers have on-board computers that prompt the operator and store data. It is now standard practice in ground surveys, as in airborne surveys, to digitally record magnetic diurnal variations (variations with time) by employing a base station, on or near, the survey site. The use of a base station has led to a very significant improvement in data quality.

The continuous reading mode of surveying (the readings are stored every second as the operator walks the grid) is also popular. With some equipment, magnetic surveys can be conducted more or less concurrently with VLF surveys, which saves survey time.

Penetration, Resolution. The anomalous magnetic field of dipolar objects (e.g., single barrels) falls off as the inverse of distance cubed (r^{-3}). Therefore, anomaly size decreases very rapidly with the depth of the target and limits most single-barrel surveys to a penetration of about 2 m.



Figure 36 Magnetic Gradiometer. Magnetic gradient data are acquired by recording total field values simultaneously at two elevations (photograph courtesy of Scintrex Ltd.).

For a line of dipoles (barrels) the fall-off is r^{-2} ; for an array of dipoles r^{-1} . Somewhat greater effective penetration can, therefore, be expected for these larger accumulations of metal. For simple formulae that can be used to determine penetration and resolution, refer to Hinze (1990) or any standard geophysical textbook.

The horizontal resolution of a magnetic target is limited by the width of its anomaly. A rule of thumb requires that the anomalous field be sampled at a spacing that is no larger than one half the shallowest depth to the target that is to be resolved. For barrels buried at 1 m, for example, readings should be made on at most a 0.5-m grid. Vertical gradient measurements can assist in the resolution of closely spaced magnetic features (Hood *et al.*, 1979).

Presentation, Interpretation. Hinze (1990) and Goodacre (1991) give comprehensive reviews of current data processing, presentation, and interpretation procedures for gravity as well as magnetic data. Magnetic data are now almost always presented as colour and shadow plots as well as profile and contour maps. Frequently, the gridded data are supplied on diskette to allow the client to manipulate the data on an **imaging work station**. An imaging work station can greatly enhance a qualitative interpretation of magnetic, gravity, and other geophysical data sets (see comments on processing in Section 3.1).

Example. A wide variety of filtering or data enhancement techniques can be applied to magnetic and gravity data (described by Broome, 1991). The interpretation of magnetic anomalies, in its

simplest form, consists of matching the observed anomaly to simple models such as dipoles, sheets, and cylinders. The matching can be done by hand, or with computer libraries of type curves. However, most interpretations are now undertaken using forward and/or inverse computer modelling programs that are widely available.

Figures 37 and 38 illustrate the magnetic profile responses observed over a dipping sheet (sheet metal), sphere (barrel), vertical cylinder, and horizontal cylinder (pipeline). Figure 39 plots contours of total field magnetics over buried magnetic waste (A1, B1, and B2).

3.3.9 Gravity

Gravity surveys measure density variations in the subsurface. The main applications of gravity surveys in contaminated site investigations are the delineation of buried valleys and overburden troughs in glaciated terrain, and the location of cavities in karst environments, which might compromise the integrity of the site. A gravity survey can be undertaken in areas where "cultural" noise precludes EM, electrical, and even seismic surveying.

Principle. Changes in gravity values (after correcting for latitude, elevation, and topography) arise from vertical and lateral density contrasts in the subsurface. A gravity survey provides a cumulative or integrated response from subsurface density variations. Figure 40 illustrates gravity anomalies over a fractured limestone aquifer.

In theory, an infinite number of geological geometries or cross-sections can account for the response observed on the surface. There is an inherent non-uniqueness problem in all potential

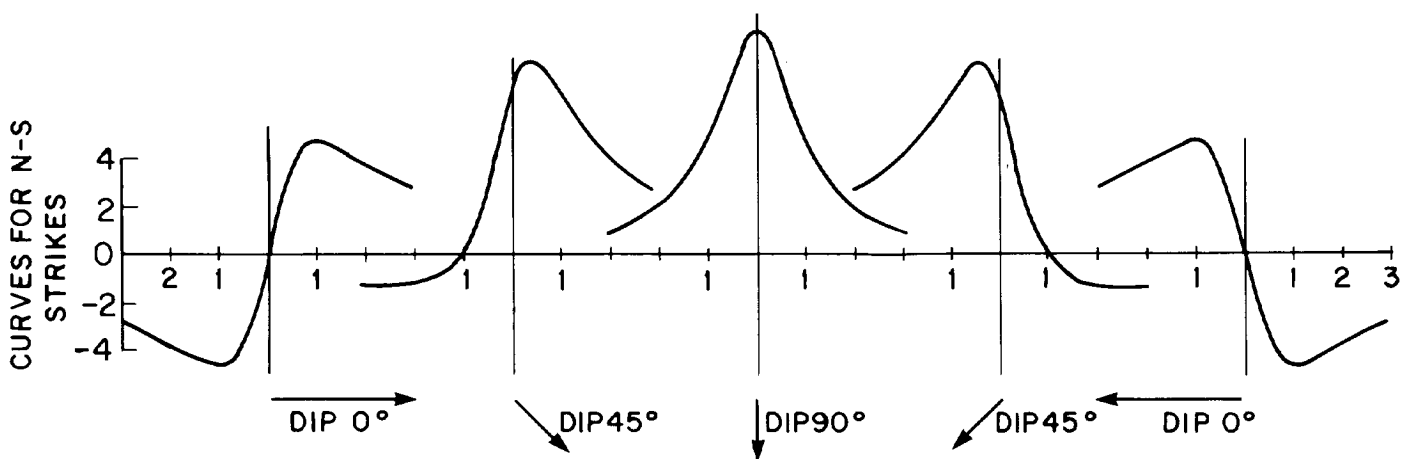


Figure 37 Total Field Magnetic Profiles Along North-South Traverses Caused by Dipping Sheets at Magnetic Inclination of 75 Degrees. (After Reford, 1964). Horizontal units are in terms of depth to the top of the sheet.

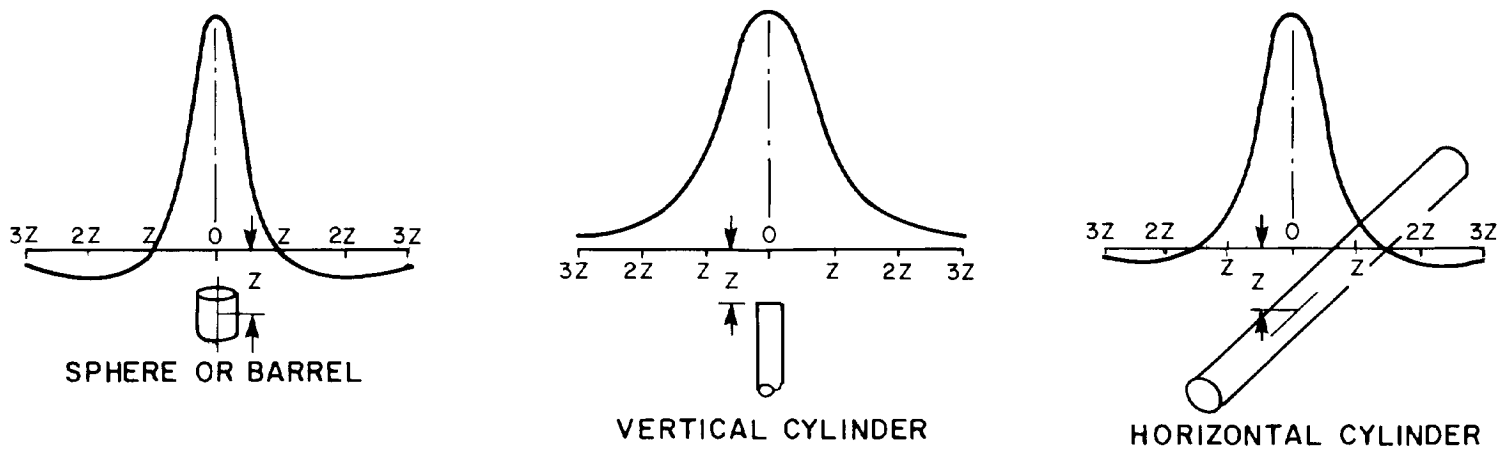


Figure 38 Total Field Magnetic Profiles Caused by a Sphere, Vertical Cylinder, and Horizontal Cylinder at Magnetic Inclination of 90 Degrees. Note negative troughs accompanying the central positive response (dipole response) of the sphere and horizontal cylinder.

field data. In practice, however, available geological or geophysical information limits the geologically reasonable solution to a fairly narrow range of density cross-sections.

Equipment. Until recently, the Lacoste Romberg geodetic meters have been the standard meter for most high-quality gravity surveys. These highly regarded meters are mechanical units that do not incorporate electronics. Scintrex Ltd. recently introduced a microprocessor-controlled gravity meter (the CG-3) that features automatic reading and data acquisition.

Accurate elevation data, which are a prerequisite to good gravity data, can be collected using an electronic level, such as the unit manufactured by GDD Instrumentation of Ste-Foy, Quebec. However, the optical levelling method is preferred where the highest quality data are required. The error resulting from inaccurate elevations is large (approximately 0.2 milligals/m for rocks having a density of 2.67 g/cm^3). Geographic positioning systems (GPS) are rapidly approaching the accuracy required to make gravity corrections for both latitude and elevation.

Penetration, Resolution. Gravity anomalies of objects, whose dimensions are small compared with their depth of burial, fall off as $1/r^2$, which is much slower than for their magnetic counterpart ($1/r^3$). Therefore, gravity anomalies are generally broader than their associated magnetic anomalies, and although penetration is greater, lateral resolution is worse. As with magnetics, questions of penetration and resolution are best answered by referring to the formulae widely available for single target models (e.g., Hinze, 1990).

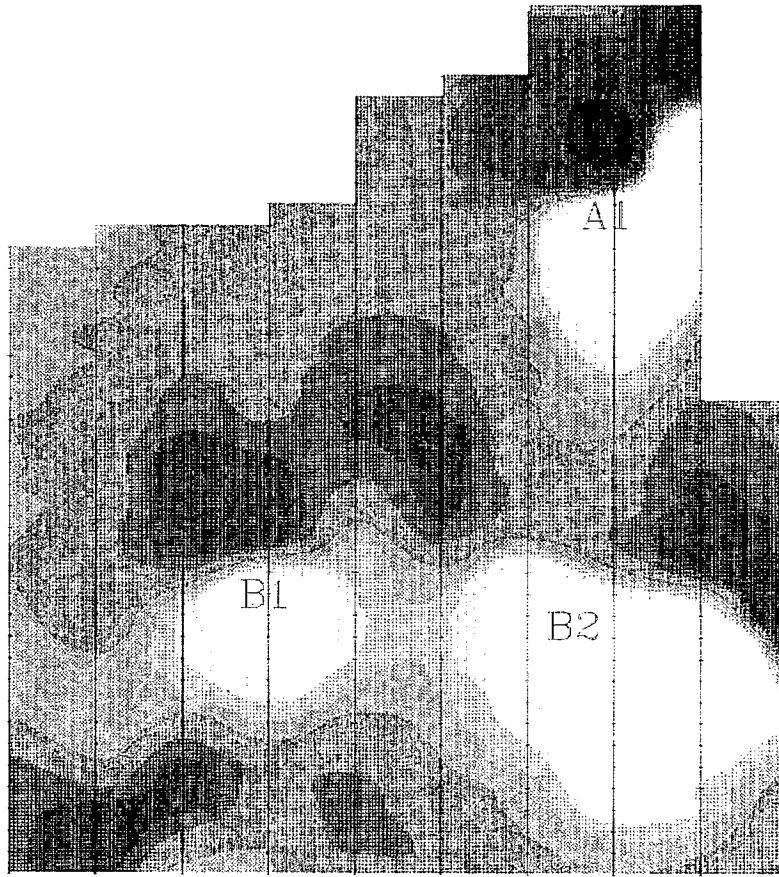


Figure 39 **Contours of Total Field Magnetic Data Collected Over Buried Magnetic Waste.** Contour interval is 5 nT. Plots courtesy of MPH Consulting Ltd.

Presentation, Interpretation. Gravity data are presented as **Bouguer anomalies** after a series of corrections involving an instrument calibration factor, earth tidal effects, the elevation of the station above a datum (usually sea level), changes in latitude, the density of material between the station and the datum, and effects of terrain in areas of significant topography. Goodacre (1991) discusses data reduction in detail.

The qualitative interpretation (e.g., the study of trends and discontinuities) of both gravity and magnetic data is undertaken using contour maps and coloured/shadowed images. Profile data provide the basis for the quantitative interpretation (modelling) of the data. There are numerous interpretation packages available in both the public and private domains. One example is the MAGGRAV program written by John Broome of the Geological Survey of Canada. Simultaneous modelling (i.e., joint inversion) using both gravity and magnetic data can be performed with some programs.

Before undertaking a gravity survey, some preliminary modelling should be undertaken to investigate the feasibility of the method given the survey objectives. Carmichael and Henry (1977) demonstrate the utility of this approach in groundwater studies in glaciated terrain.

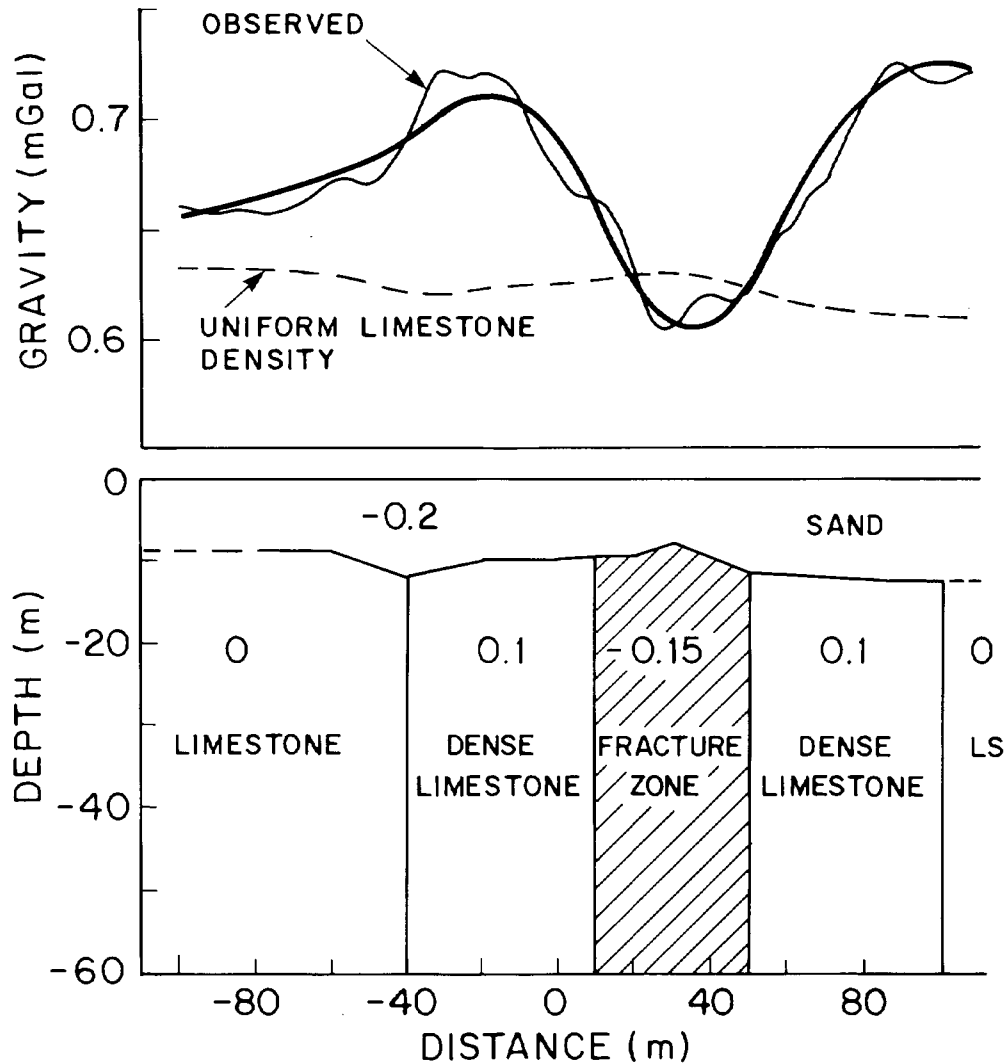
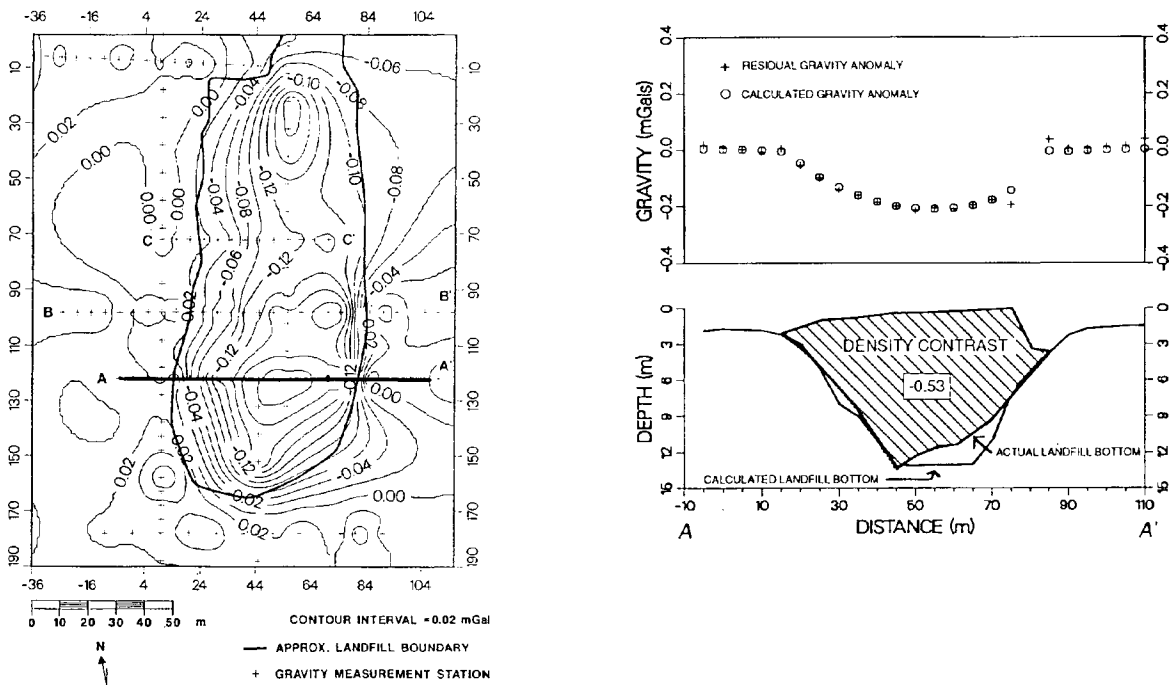


Figure 40 Gravity Data Over Limestone Aquifer, Florida. (After Stewart and Wood, 1990). Note that low gravity coincides with fractured zone (where water replaces some small portion of the denser rock matrix). Reprinted with permission of the Society of Exploration Geophysicists.

Example. Examples of successful gravity surveys to locate cavities in karst terrain are found in Barrows and Fett (1985) and Butler (1984). Figure 41 demonstrates the use of gravity data to outline a landfill site and determine landfill thickness. The gravity survey was just one of a suite of surveys conducted to determine the landfill characteristics.

3.3.10 Ground Penetrating Radar (GPR)

Principle. Ground Penetrating Radar is an EM exploration method, but the underlying principles are quite different from the EM methods discussed previously. In many respects, GPR is similar to the seismic reflection method — a pulse of electromagnetic energy substitutes for the pulse of elastic (seismic) energy. The GPR operates in the range 10 MHz to 1 000 MHz. For comparison



(e.g., drums and pipelines) and permittivity (see Subsection 3.2.2). Figure 42 provides a conceptual illustration of the method and results.

Equipment. Equipment and survey design have been described by Davis and Annan (1989) and Annan and Cosway (1991). A GPR system consists of four modules: transmitting and receiving units; a control unit; and a display unit. The transmitter generates a short pulse of EM energy that is radiated through an antenna into the ground as radio waves. The energy is reflected back to the receiving antenna and to the receiver, and its signal is amplified, formatted, stored, and displayed. The operating frequency is chosen to provide the most advantageous trade-off between penetration and resolution for the specific job. Most systems can operate at a number of frequencies, but frequencies in the range 100 MHz to 500 MHz are usually used in environmental and geotechnical studies.

Sensors and Software Corp. (5566 Tomken Road, Mississauga, Ont., L4W 1P4, Canada), OYO (2-19 Daitakubo, 2-Chrome, Vrama, Saitama 336, Japan), and Geophysical Survey Systems Inc. (P.O. Box 97, North Salem, NH 03073-0097 U.S.A.) are the major sources of GPR systems.

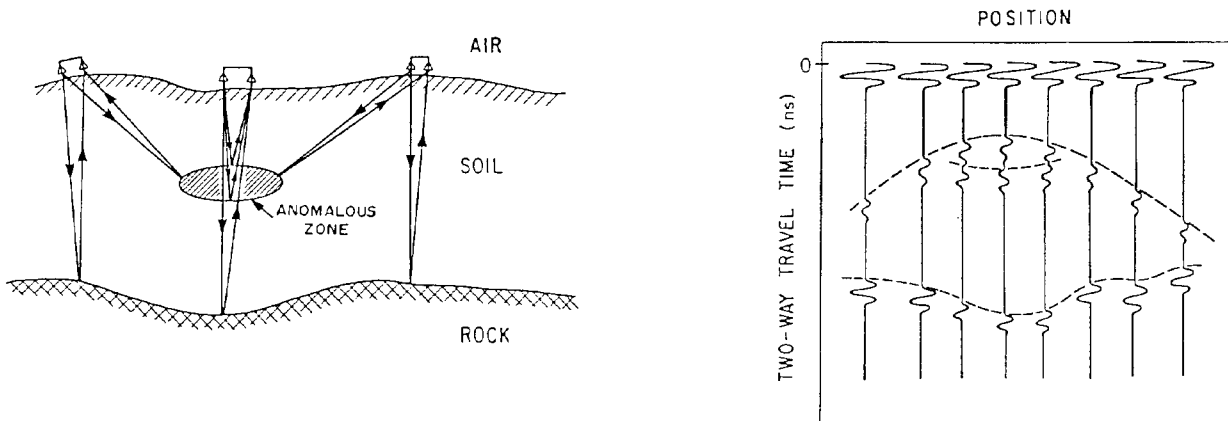


Figure 42 **Ground Penetrating Radar.** A conceptual illustration of reflections from two targets and idealized results (Davis and Annan, 1989). Reprinted with permission of the European Association of Exploration Geophysicists.

Penetration, Resolution. Penetration of the radar pulse into the subsurface is limited primarily by the attenuation, which in turn is governed mainly by the conductivity of the ground. In low conductivity conditions, penetrations of more than 20 m are possible. Conversely, a conductive clay can restrict penetration to less than 1 m.

The vertical resolution of reflection methods is limited by the wavelength or pulse width (λ). Wavelength is related to frequency (f) and velocity (V) as:

$$\lambda = Vf^{-1} \quad [13]$$

Two pulses, one reflected from the top of a resolvable strata and the other from the bottom, should be distinguishable from each other when they are offset by at least one-quarter wavelength. Thus, higher resolution (seeing thinner strata) requires shorter wavelengths or higher frequencies. For example, in a typical aquifer ($K = 25$) with a 100 MHz GPR system, the vertical resolution ($\lambda/4$) is 15 cm.

The horizontal resolution is determined by the antenna radiation pattern, which can be likened to a flashlight beam whose illuminated area broadens with distance to the target. The antenna pattern is complex but is roughly a vertical cone (slope 30°), with its apex at the transmitter. Reflected information is an average over the illuminated reflecting surface.

Presentation, Interpretation. Data are usually presented in a format similar to that of a seismic reflection profile where travel time to reflectors *versus* position is displayed (Figure 42). However, data can also be collected and presented in CMP (common midpoint) and WARR (wide angle reflection and refraction) sounding modes (see Annan and Cosway, 1991). The objective of these two procedures is to obtain an estimate of velocity *versus* depth. If the depth of a reflective horizon is known independently at several locations, or if the velocity is known as a function of depth, the radar sections provide a “depth section” for the reflector.

Examples. Figures 43 to 45 demonstrate the use of GPR in three different applications:

- mapping soil stratigraphy and bedrock depth (Figure 43);
- detecting fractures in bedrock (Figure 44); and
- delineating a conductive contaminant plume (Figure 45).

3.3.11 Seismic Refraction

There are two basic seismic exploration methods: reflection and refraction. Each method is reviewed in exceptional papers in Volume 1 of the three volume SEG Geotechnical and Environmental Geophysics series (Section 3.7). Steeples and Miller (1990) review the reflection method and Lankston (1990) reviews the refraction method. Another good collection of papers is Romig (1986). Figure 46 illustrates the difference between the reflected and refracted wave paths.

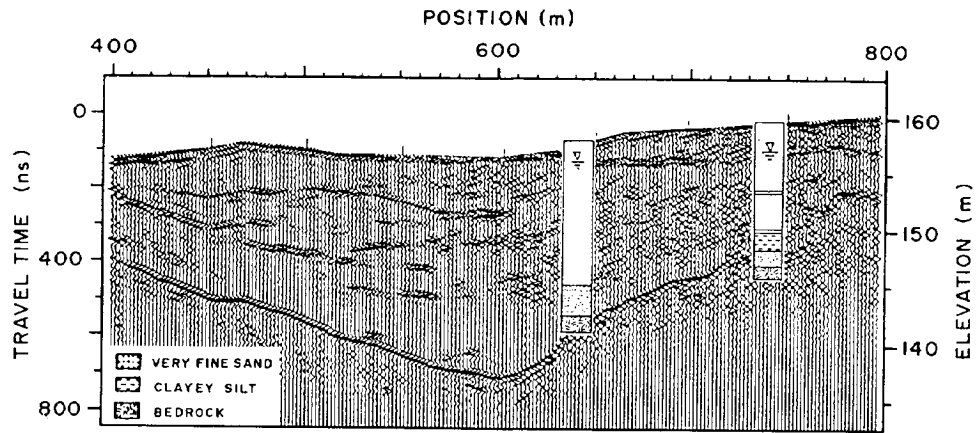


Figure 43 PulseEKKO III Radar Record Showing Bedrock Topography and Silt and Sand Layering in Overburden, Eastern Ontario. (Davis and Annan, 1989). The core descriptions from two boreholes are superimposed. Reprinted with permission of the European Association of Exploration Geophysicists.

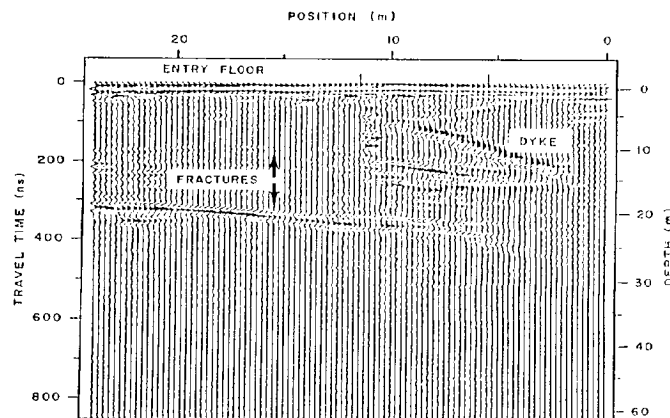


Figure 44 PulseEKKO III Radar Recorded in a Tunnel Through Granite. (Davis and Annan, 1989). Clearly identified are sub-horizontal fractures and a dipping dyke that intersects the tunnel. Reprinted with permission of the European Association of Exploration Geophysicists.

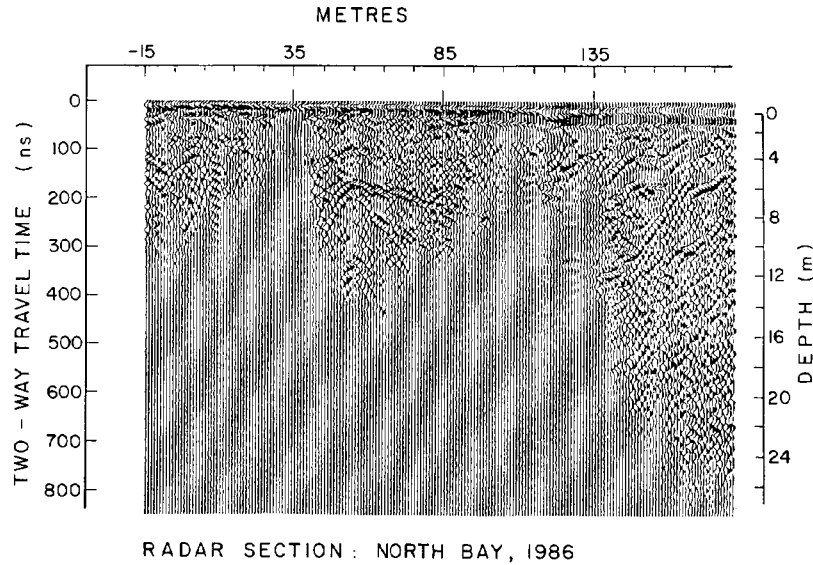
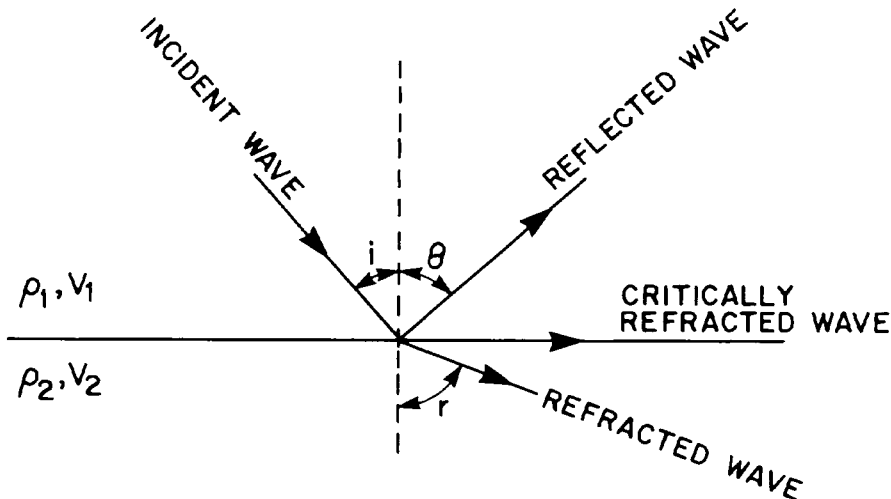


Figure 45 Radar Record of a 100-MHz GPR Survey Along a 200-m Traverse that Crosses a Contaminant Plume, North Bay, Ontario. The plume is mapped by the attenuation in the radar signal and is clearly present at depth in the section from 85 to 135 m. Groundwater samples show that the onset of signal blanking corresponds to a conductivity of about 1500 $\mu\text{S}/\text{cm}$.



Reflection

$$\theta = i$$

Reflection Coefficient

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

Refraction

Snell's Law

General Case:

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

Critical Refraction

$$\theta = 90^\circ, i = i_c$$

$$\frac{\sin i_c}{\sin 90^\circ} = \frac{V_1}{V_2} = \sin i_c$$

Figure 46 Paths of the Incident, Reflected, Refracted, and Critically Refracted Waves at the Boundary Between Two Media

The seismic reflection method has been the predominant geophysical exploration tool in oil exploration for over 60 years. However, seismic reflection is also the most expensive ground geophysical method, and until fairly recently has not been used extensively in environmental and geotechnical applications.

Principle. Refer to Telford *et al.* (1990) for an elaboration of the principles of seismic exploration. Seismic methods rely on the contrast in acoustical properties between geologic materials to delineate boundaries (Subsection 3.2.6). In the reflection method, the incident rays are reflected directly back to the surface (Figure 51); in the refraction method, the incident rays are critically refracted along the boundary and then re-radiated back to the surface (Figure 47).

Most environmental and geotechnical surveys study only P-waves. There is much to be learned from S-waves, but they are harder to generate and record than P-waves. The seismic refraction method is ideally applied when continuous coverage (at high vertical and lateral resolution) of a relatively shallow and low to moderately dipping target is the objective.

The method records the time required for energy to travel to an array of **geophones** by the direct and critically refracted paths (Figure 47). From a detailed plot of arrival times *versus* geophone distance, the velocities of the layers and the depth to their interfaces can be resolved.

Traditionally the refraction method has been used to determine the topography of the “basement” beneath an overburden layer. It is simpler to carry out and easier to process and interpret than a reflection survey with the same objectives.

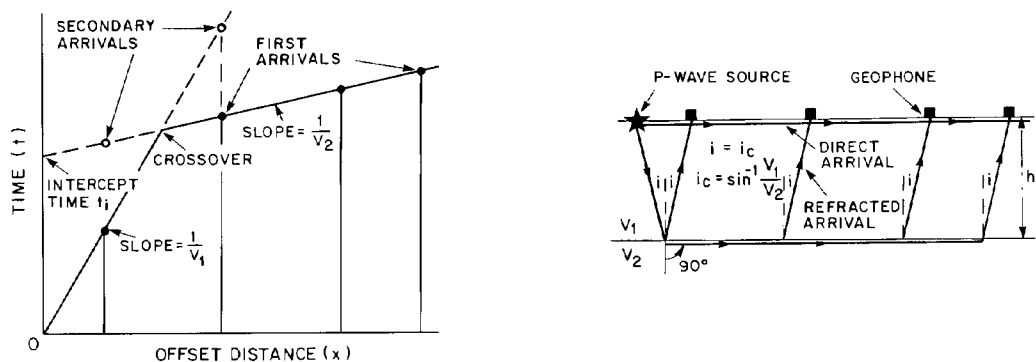


Figure 47 Seismic Refraction Ray Paths Between a P-wave Source and One or More Receivers (Geophones) and the Time–Distance Plot of Energy Arrival. The energy reaching the geophones is critically refracted at the boundary, transmitted along the boundary and retransmitted back to the surface at the critical angle. Note that the refracted energy arrives at the nearest geophone after the direct wave, but the refracted wave is the first to arrive at the other geophones. After Lankston (1990) and with permission of the Society of Exploration Geophysicists.

There is one significant limitation to the refraction method. For most practical purposes, the method requires that seismic velocity increases with depth. For most applications, this not a problem. However, certain geological scenarios such as an interbedded sand–gravel–clay sequence can present a problem. It is very difficult to resolve a thin, low velocity sand–gravel bed beneath a high velocity clay layer (a velocity inversion).

Equipment. A simple refraction survey with the objective of determining the depth of basement beneath a meter or two of unconsolidated sediments can be undertaken with minimal equipment (a seismograph, a sledgehammer, and a single geophone). Survey production would not be optimum and data quality would not be the best, but the objectives could be achieved.

Sophisticated, digital, multi-channel systems are now quite affordable. Systems offering 6, 12, and 24 channels are available from a number of manufacturers. The sole Canadian supplier of seismographs is Scintrex Ltd.. Advanced processing of the multi-channel data permits the application of the refraction method in environments that were previously restricted to seismic reflection. Surveys undertaken using multi-channel systems and larger geophone spacing generally use explosives as the source of seismic energy. Solid chemicals such as dynamite and shotgun shells are common explosive sources.

Penetration, Resolution. Both the penetration and the resolution of the refraction method are inferior to the penetration and resolution of the seismic reflection method if both techniques use the same strength of source and work well in a given situation. Penetration is usually limited to 10 m with a hammer, and to 20 to 30 m with shotgun shells. Lateral resolution is governed by the geophone spacing; vertical resolution of a stratum requires that it have a thickness that is a substantial fraction of the depth to its upper surface. Specific situations can be addressed by simple models of the seismic refraction process.

Presentation, Interpretation. Refraction data can be presented in several ways, depending on how involved the processing and interpretation and how detailed the survey. Figure 48 shows an example of the results of an interpretation. Interpretation is based on the analysis of the so-called first breaks — the time that the first seismic wave (a P-wave) arrives at a geophone.

Turnkey interpretation packages are available from a variety of sources. A leading Canadian manufacturer is Viewlog Systems (VIEWSEIS). Oyo Corporation markets QSEIS. The journals *Geophysics: The Leading Edge*; and *First Break* (Section 3.7) are two good sources of information on other available software.

Example. Figure 48 shows an interpretation displaying final velocities and depth section from a seismic refraction survey.

3.3.12 Seismic Reflection

The advent of inexpensive, micro-processor controlled equipment and refinement in shallow reflection methods has lead to increasing use of the reflection method in environmental and geotechnical studies. The optimum conditions for shallow reflection methods occur when overburden is fine-grained and saturated — conditions that are usually unfavourable to GPR (Subsection 3.3.10).

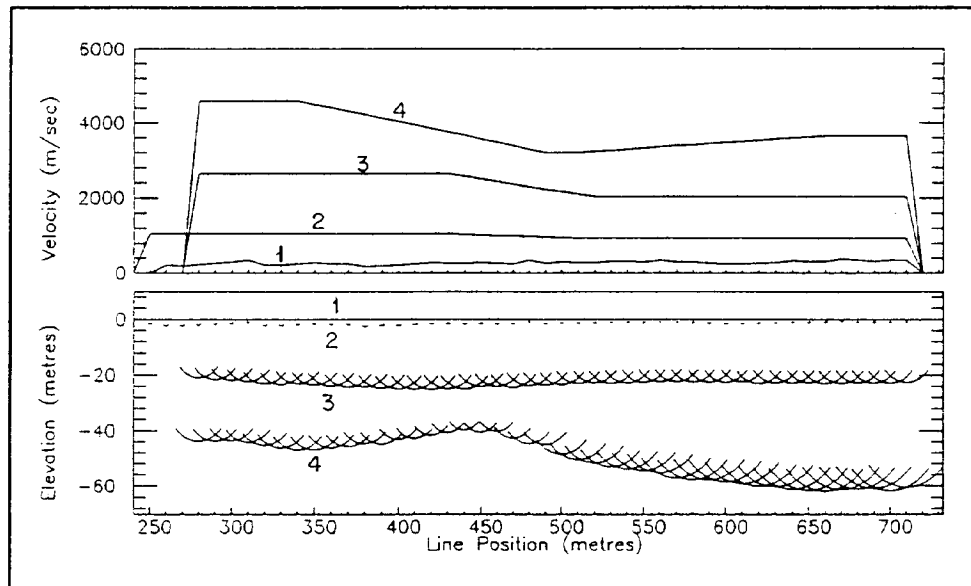


Figure 48 **Seismic Refraction Interpretation by VIEWSEIS. (Kassenaar, 1991).** Upper plot displays seismic velocities and the lower section shows interpreted depths to the base of three distinct layers (1 to 3) overlying the halfspace (4) along a 500-m section.

Principle. Two seismic reflection techniques, the **optimum offset** and common-depth-point (CDP), are in common use. Hunter *et al.* (1989) describe the **optimum window** concept and the optimum offset technique. The optimum window is the range of source–receiver separations that allows a single target reflector to be observed with minimum interference from other events. Figure 49 shows a composite seismic reflection record and a corresponding time–distance plot illustrating the optimum window concept. Note that the reflection arrival is well separated from the earlier refraction and the later air waves and ground roll (surface waves). Figure 50 illustrates an optimum offset field technique that uses a single source–receiver offset (lying within the optimum window) moved laterally along the transect. Examples are shown in Figures 52 and 53.

The optimum offset technique was developed to provide better resolution of the overburden itself. To establish the optimum offset and window at a particular site, an expanding spread must first be shot in the survey area. Within this window, one particular source–receiver separation is selected.

The common-depth-point (CDP) concept is illustrated in Figure 51. In the CDP method, the seismic sources and geophones are placed so that the reflection from each source comes from the same point on the reflector. After correcting for differences in the source–geophone distance, the data are stacked (summed). Summing the data enhances the signal to noise ratio. The processing required for CDP is considerably more complex than the processing required for the optimum window method.

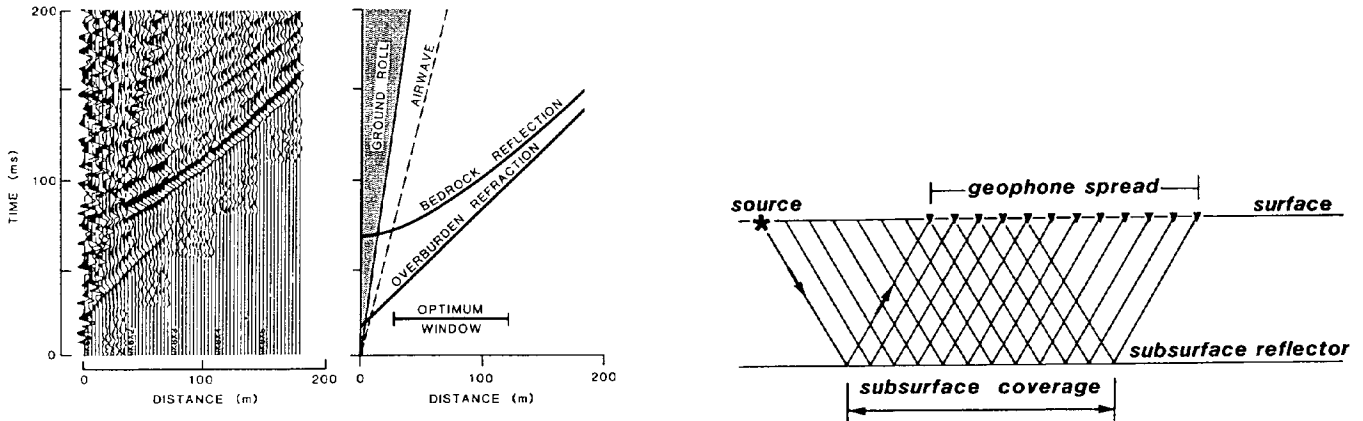


Figure 49 Composite Seismic Reflection Record from Winkler, Manitoba (Left) and Time-Distance Plot (Right). (Hunter *et al.*, 1989). The “optimum window” allows the survey to focus on a particular target horizon. Reprinted with permission from the Ontario Geological Survey.

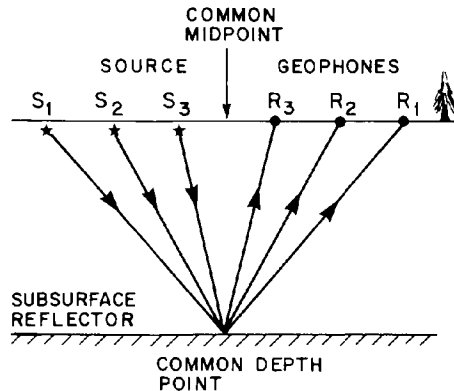


Figure 50 The Setup for Recording an “Optimum Offset” Record and Ray Paths for Each of the Shots Required. (Hunter *et al.*, 1989). Reprinted with permission from the Ontario Geological Survey.

Shaping the frequency content of the received signals is a major concern because, resolution (the thinness of the distinguishable stratum) is proportional to frequency (inversely proportional to pulse width). Source design, and recording and processing techniques, are used to enhance the high-frequency content (sharpness) of the recorded pulses on the final product.

Equipment. Most reflection surveys use a 24-channel digital seismograph. Modern seismographs have sophisticated internal software for monitoring noise, sampling, storing and filtering data. Scintrex Ltd., Concord, Ontario, manufactures seismographs suitable for reflection work. Other popular seismographs are manufactured by: Bison, Minneapolis; OYO, Japan; and Geometrics, Sunnyvale, California.

Penetration, Resolution. Seismic reflection methods have been applied to the study of sedimentary basins thousands of meters thick. Penetration is an issue only for choosing an appropriate energy source for the site. Only a simple sledgehammer may be required for a very

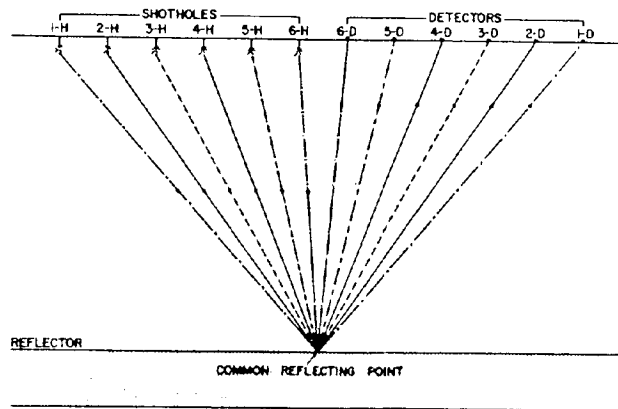


Figure 51 Common-depth-point Concept. Signals associated with a particular reflection point are “stacked” (summed) using different shot and geophone pairs.

shallow survey. Usually, however, explosives of some sort [e.g., an in-hole shotgun (buffalo gun) or a high calibre rifle] are employed. Miller *et al.* (1986) provide a discussion of various seismic sources.

The vertical resolution capabilities of the reflection method are second only to GPR. Using Equation [9], an aquifer with velocity (V) = 2000 m/s and frequency (f) = 500 Hz, yields a maximum resolution of 1 m.

Presentation, Interpretation. Processed data are presented as reflection sections. These sections represent the end result of considerable processing. Much of the “interpretation” concerns the choosing of appropriate processing parameters. Highly sophisticated interpretation packages, which were previously proprietary to the oil industry, are now commercially available at “reasonable” cost. Two low-cost Canadian-developed software packages are QSEIS and PROSEIS. A more costly but very versatile Canadian product is VISTA.

Examples. The seismic reflection method is useful for mapping both fairly rugged subsurface topography (Figure 52) and the structure of overburden (Figure 53).

3.3.13 Borehole Methods

This section can only touch on the wide variety of geophysical techniques that can be applied in boreholes. Daniels and Keys (1990), and Mwenifumbo (1991) provide good overviews of borehole geophysics in environmental applications.

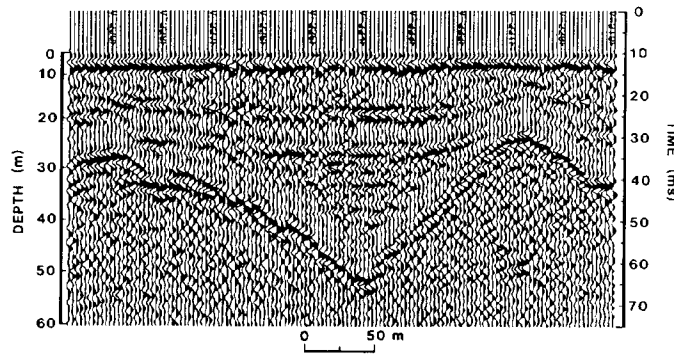


Figure 52 Optimum Offset, Shallow Reflection Section Over Rugged Subsurface Topography, Val Gagne, Quebec. (Hunter *et al.*, 1989). Reprinted with Permission from the Ontario Geological Survey.

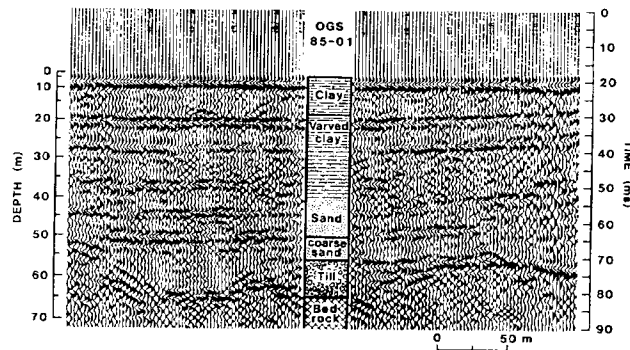


Figure 53 Optimum Offset, Shallow Reflection Section Detailing Structure in the Overburden, Val Gagne, Quebec. (Hunter *et al.*, 1989). Reprinted with Permission from the Ontario Geological Survey.

Borehole methods, like their counterparts on the surface, are generally applied to characterize the lithology of the subsurface and to indirectly, rather than directly, “map” contamination. They determine physical properties such as permeability and porosity and expand the “radius of investigation” of the borehole. Figure 54 shows a typical block diagram for a logging system.

The fundamental advantage that borehole measurements have over surface measurements is that they provide *in-situ* values for a particular parameter. In cases where core material is lost, a borehole survey can provide vital information. Unfortunately, borehole geophysics is generally not employed to its potential. Far too often, boreholes are drilled and sampled but no consideration is given to borehole geophysics, which could provide information at reasonable cost.

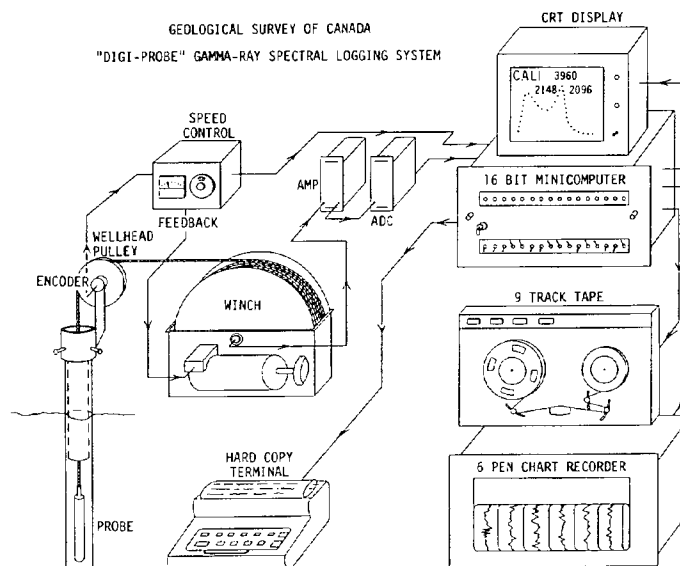


Figure 54 Block Diagram of the Geological Survey of Canada Borehole Logging System. (Urbancic and Mwenifumbo, 1985). Reprinted with Permission of the Geological Survey of Canada.

Measurements between two boreholes are termed “**cross-hole**”. It is now quite common for cross-hole seismic, radar, and electrical measurements to be used to construct tomographic images of the intervening earth.

Principle. The principles governing borehole and surface geophysics are the same. One is deployed horizontally, the other vertically. Interpretation of borehole data can be complicated by the location of the water table where changes in physical properties occur. As noted by Daniels and Keys (1990), natural gamma ray surveys are probably the only surveys that can be reliably undertaken above the water table in all geological conditions.

A further complication, which can be prohibitive for some surveys, is the borehole casing. For example, SP, IP, and resistivity surveys cannot be undertaken in cased holes, although, in certain cases, surveys are undertaken in boreholes where well-perforated plastic casings have been installed.

Table 5 lists the more commonly employed methods and their applicability to different borehole environments.

Borehole methods can be used directly or indirectly for:

Table 5 Logging Applicability in Different Borehole Environments (After Mwenifumbo, 1991 and with Permission from the Canadian Institute of Mining, Metallurgy and Petroleum)

Geophysical Method	Uncased		Cased	
	Air-filled	Fluid-filled	Plastic	Steel
Gamma ray	X ^a	X	X	X
Gamma gamma density	X	X	X	X
Neutron-neutron	X	X	X	—
Electromagnetic induction	X	X	X	—
TDR	—	X	X	—
Resistivity	—	X	—	—
SP	—	X	—	—
Complex resistivity	—	X	—	—
Temperature	—	X	X	X
Magnetic susceptibility	X	X	X	—
Three component magnetometer	X	X	—	—
Sonic velocity	—	X	—	—
Calliper	X	X	—	—

^a X applicable; — not applicable.

- site selection;
- determinations of the extent of contamination at existing sites; and
- long-term monitoring of the migration of contaminants.

Table 6 summarizes the properties that are measured and the applications of the various tools used in mineral exploration, but it is equally relevant to environmental investigations. Of these downhole methods, the most routinely used appear to be electrical resistivity, (inductive) conductivity, and temperature.

Table 6 Logging Tools, Property Measured, and Typical Application (After Glenn and Hohmann, 1981 and with Permission of Economic Geology Publication Co.)

Logging tool	Property Measured	Application
Natural gamma	Natural gamma radiation from lithology, borehole fluids	Separating clays from contaminated sands on conductivity logs
Gamma-gamma	Scattered gamma rays	Bulk density, porosity, lithology
Neutron-neutron	Thermal, epithermal, or fission neutrons, capture gamma rays	Porosity, chemically bound water, lithology, chloride content
Electromagnetic induction	Conductivity	Lithology, clay content, conductive plumes
Resistivity	Resistivity	Lithology, clay content, conductive plumes
SP	Natural voltage in the earth	Lithology, clay-sand boundaries, water flow
Temperature	Temperature	Fracturing, fluid flow, oxidation, lithology, correction of other measurements
Magnetic	Magnetic susceptibility	Lithology, susceptibility, alteration zones
Three component magnetometer	X, Y, and Z components	Detailed lithology, alteration zones
Sonic velocity	Velocity of P-waves	Lithology, porosity, fracturing
Calliper	Hole size	Hole completion, fractures, lithology, corrections for other measurements

Equipment. Figure 54 gives a schematic view of a typical logging system. Refer to Daniels and Keys (1990) and Keys (1988) for general descriptions of the various tools and logging systems. Canadian manufacturers include Geonics Ltd., makers of the very popular EM-39 induction log.

Penetration, Resolution. Many boreholes directly penetrate zones of interest. Where a borehole does not intersect the zone of interest, downhole measurements can provide a measure of physical properties at some distance away from the borehole. The depth of investigation or penetration can range from a few tens of centimetres, in the case of a natural gamma survey, to tens of meters, in the case of cross-hole surveys.

The resolution of borehole surveys actually intersecting a zone of interest is unparalleled. A sampling interval in the range of centimetres can be accomplished, if so desired.

Presentation, Interpretation. Well-log data are presented in cross-section as shown in Figure 55. The interpretation can be complex. Daniels and Keys (1990) note the irony in the fact that sediments close to the surface are often the most difficult of all geologic regimes to interpret from geologic logs. Interpretations usually involve a study of core samples, the whole suite of available geophysical logs, and other geological and geochemical information.

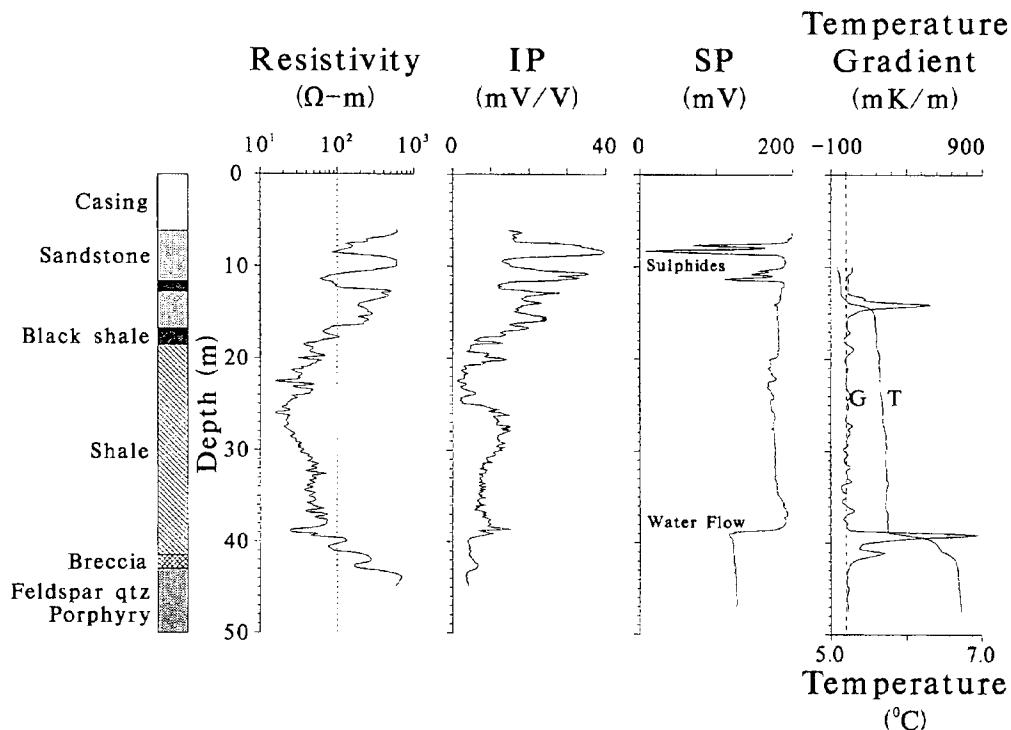


Figure 55 Resistivity, IP, SP, Temperature, and Temperature Gradient Logs Recorded at the Yava Sandstone Deposit. A temperature and SP anomaly caused by groundwater flow is indicated at approximately 40 m. The IP log distinguishes SP anomalies due to sulphides (8 to 12 m) from those caused by water flow and temperature change (Mwenifumbo, 1991). See Table 6 for description of logs. Reprinted with permission of the Canadian Institute of Mining and Metallurgy.

Examples. Figure 56 shows an example of the successful application of a borehole induction logger (EM-39) for mapping a conductive zone of chloride contamination.

3.3.14 Other Methods

Self Potential. The self potential or SP method is a very old and very simple geophysical technique that nevertheless has applications in waste site characterization. Fundamentally, SP is a detector of voltage generated *by the target*, not induced or otherwise generated by an external source. Buried metal or metallic ore is the primary source of these voltages, and is usually the result of different parts of the body being subjected to different degrees of oxidation or reduction (on surfaces above and below the water table, for example). Voltages at the surface can reach several hundred millivolts, and are relatively easily measured by a voltmeter placed between two stable, low-noise electrodes — one fixed and the other moved on a grid over the site of interest. The result is an equipotential map (a map of equal voltage levels measured at the roving electrode) that generally exhibits a relative low over the target.

Despite the simple requirements, this method has its drawbacks. Logistically it can be slow; cables must be dragged behind the operator. The size of the effect that a given target will produce is difficult to predict because it depends on the subsurface environment. Finally, the results require an experienced interpreter. For these reasons, magnetics or terrain conductivity are preferred methods for metal detection.

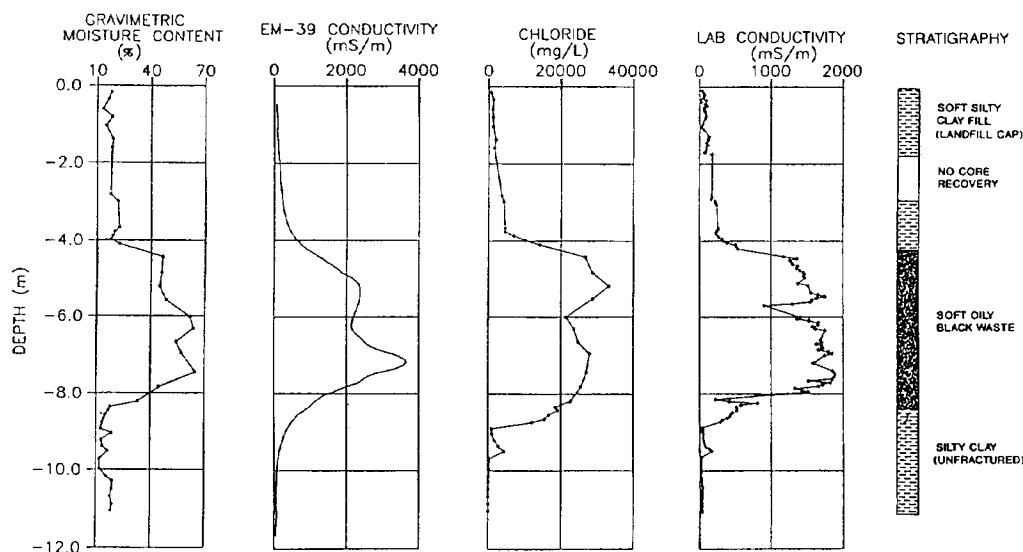


Figure 56 EM-39 Conductivity, Gravimetric Moisture Content, Chloride, and Laboratory Conductivity Logs for a Shallow Borehole Near Sarnia, Ontario. Observe the narrow zone of waste at 7 m delineated by the EM-39 (Balfour, 1991).

Streaming Potential. The movement of water through a pore produces a small voltage called the streaming potential. (Dewatering, the inverse effect, is probably better known. Water is forced to leave an embankment or a damp wall by applying an electrical voltage across the structure.) Streaming potential is often used to locate leaks in dams. The equipment required is identical to the equipment needed for SP (a good voltmeter, non-polarizing electrodes, and plenty of cable).

The method may be the only choice for detecting leaks from storage ponds or through liners, where the leaked material itself is not a suitable target. An excellent review is Butler *et al.* (1990). The logistics are relatively simple and the equipment inexpensive. Interpretation can be problematic, however, and requires experience.

Time Domain Reflectometry. Time Domain Reflectometry (TDR) is a well-known method for measuring soil moisture (see Subsection 4.9.2). It is usually thought of as a soil physics rather than a geophysics technique. The velocity of electromagnetic waves in the ground, and therefore the dielectric constant, is measured by timing reflections from known interruptions in a waveguide placed below the surface. The technique is increasingly being used as a calibration for GPR data (which require EM velocities to translate the time of a reflection into the depth) and as a detector of organic materials such as solvents and hydrocarbons that replace water in the ground and thereby increase EM velocity. Brewster *et al.* (1992) give a good description of this application.

Audio Frequency Magnetics (AFMAG) and Controlled Source Audiofrequency Magnetotellurics (CSAMT). These methods have some application in locating deep-seated contamination. They use naturally occurring (AFMAG) and artificially generated (CSAMT) EM fields, in the audio frequency range 1 to 1000 Hz for AFMAG and 1 to 50 000 Hz for CSAMT, to sound the earth for variations in electrical conductivity. These are complex techniques that are expensive to implement. The interpretation requires appropriate expertise. The CSAMT method in particular might compete with time domain EM (TDEM) methods for detecting very substantial contamination at depths exceeding 100 m. Sandberg and Hohman (1982) and Bartel (1990) describe the CSAMT method and some of its applications.

3.4 *Planning, Undertaking, and Assessing a Survey*

Previous sections have addressed how geophysics *works*. In this section we look at how geophysics is *done*. Clients should interact with the contractor in the planning, field work, and assessment stages of the survey. It is essential that clients be involved in planning to ensure that their objectives are well understood and that the scope of the work is within their budget. The field work is the proper domain of the contractor, but clients should be aware of certain limitations. Finally, clients must decide whether the results shed light on the survey objectives. Were enough data collected? Is the quality of the data acceptable? Are the data in a form suitable for later use?

3.4.1 *Planning a Survey*

It is not uncommon for geophysics to be used as a last resort. In some cases, site managers, left with no other means of gaining the required information, may tell the geophysicist to try anything just to see what happens. Some geophysicists in this type of situation may view this as a “blank cheque” and set out to cover the ground with electrodes and shot holes.

All geophysical surveys should be planned and the objectives clearly identified. The client and the geophysicist should ask each other some basic questions.

Exactly what do we want to know? This is by far the most important issue between client and contractor. It is essential that they both clearly understand the objectives and their context. Clients must decide what they want and contractors must advise whether, and how, geophysics can meet these objectives.

Can the target of interest be detected? With what methods? Once the targets and objectives are identified, contractors should be prepared to justify their choices of techniques and approaches to the problem. Simple numerical modelling exercises, addressing both the best case and worst case scenarios, can often assess the viability of a proposed method. For example, buried drums can be treated as simple dipoles in magnetics; and cavities can be treated as spheres and tunnels as buried cylinders in gravity. Plane layered models can be posed and responses calculated for resistivity, VLF, terrain conductivity, and radar.

If similar surveys have been run in the area, or are available elsewhere, they should be studied carefully to determine the penetration and resolution achieved and the difficulties encountered. This step helps us to avoid mistakes that were made in the past.

What is the scope of the geophysical survey? How long and how expensive must the project be to meet the objectives? The scope of the project will be defined by the number and type of surveys planned, the size of the area to be searched, the size of the target, and the available budget. The potential benefits of geophysics should be compared cost-wise with direct subsurface investigation methods like drilling or excavating (see Section 3.6).

What is the timing and sequence of the surveys? If a program undertaken in support of a subsurface assessment of a contaminated site involves several geophysical surveys, when and in what sequence should the surveys be run? These guidelines are generally applicable:

- Decide when to survey — Weather can be an important factor in both the quality and the cost of data collection. Remember that some ground surveys should be conducted only in the winter, as unfrozen lakes, swamps, and streams can severely impede production and fragment a survey block. Furthermore, conducting a survey on very short notice is always a poor strategy; “Murphy’s Law” governs all field operations.
- Proceed from the general to the particular — Most projects require some reconnaissance surveys as an integral part of the planning. Look for broad, general coverage of the area of interest as a guide to later detailed surveys.

- Do the cheaper, simpler surveys first. Do the profiling-type surveys before the sounding-type — Quick, inexpensive surveys such as terrain conductivity and VLF may be all that is required to meet the objectives. These surveys should therefore be undertaken first, before more expensive surveys such as resistivity, gravity, and seismic. These simple surveys will often delineate the areas where further, more sophisticated work is required.

For example, a study was recently undertaken to map bedrock below a mine tailings dam. The objective was to determine how known leakage of acidic water beneath the dam might be moving beyond the client's property. The target was bedrock, the objective its depth, and, in particular, any evidence of a bedrock valley. There was a temptation to begin with detailed seismic investigations, but much faster and less expensive VLF resistivity reconnaissance methods provided a crude but useful regional map of bedrock depth. On this basis the search for bedrock valleys narrowed considerably, and seismic refraction was used to refine this map.

If the area is large, and the target moderately large and conductive and/or magnetic, an airborne survey could be considered. Helicopter surveys can now provide detail that approaches the detail achieved on the ground. These helicopter surveys merit consideration if access on the ground is difficult or restricted.

What are the key elements in a contract? Survey contracts are often tendered on a daily-rate basis, especially for more complex surveys such as seismic, GPR, and IP. However, contracts on a cost per line-km, cost plus, and lump sum basis are also used. If possible, obtain a sample copy of a contract written by an experienced user of the geophysical method. The following list outlines several items that are important in any contract:

- Data quality — A non-expert may not be able to recognize bad or marginally bad data. A review of open-file data published by government agencies is one way to become familiar with data quality. Should there be any reason to be apprehensive about data quality, contact a consultant who is expert in the particular survey method.

In practice, there is usually some “give and take” on contract specifications relating to data quality. For example, if the noise envelope exceeds specifications on a small part of the line in a non-anomalous, “uninteresting” area, this area does not necessarily need to be re-surveyed. On the other hand, excessively noisy data occurring in an area of interest must be resurveyed at the expense of the contractor.

- Products delivered — The digital data should be supplied on diskette or magnetic tape in a format that will be compatible with in-house standards. Original field products such as logs, analogue charts, and digital records should accompany the final report and maps.

Be clear about the nature of the report that will be supplied with the results. Will the report include line plots (profiles and contours), microfiche of plots, colour and shadow plots of the original gridded data and filtered data, and interpretation maps? Will it include a thorough, detailed interpretation of the data, present a preliminary or qualitative interpretation, or merely discuss logistics? In the latter case an interpretation of the data by a consultant (at extra cost)

may be required. A summary of the survey results that clearly addresses the question of whether or not the objectives were met should be mandatory.

- **Cost** — The true costs of a survey often exceed the amount specified in the contract. Most major cost over-runs result from bad weather and unforeseen conditions that impede the progress of geophysical surveys. Hidden and in-house costs can also be an unpleasant surprise. When budgeting a geophysical survey, allowance should be made for: logistical expenses; legal expenses; in-house field support; in-house reporting, drafting, and typing; management costs; outside consulting; and generation of additional plots.

Ideally, the cost of a survey should be estimated using previous surveys of the same type (in similar conditions) as a guide. If the final report must be submitted by a given date, this should be specified in the contract and a penalty clause included. Nelson (1988) lists additional items that should be recognized when budgeting for a geophysical survey.

- **Health and safety** — For surveys performed by contractors, responsibility for the safe completion of these surveys lies with the contractor. Indeed, nearly all contracts absolve the client from any responsibility regarding the safety of the employees of the contractor. Nevertheless, health and safety are of concern to both parties. Safe handling of machinery or electrical/electronic equipment is a matter of common sense to any experienced user. A novice, however, may not fully appreciate potential dangers unless given proper training. Contaminated sites can be extremely hazardous and the health and safety aspects raised in Section 2.4 apply to geophysicists on site.

3.4.2 Undertaking a Geophysical Survey

Strictly speaking, undertaking a survey is the responsibility of the geophysicist, not the client. However, there are questions regarding the design and execution of a survey that are of interest to the client as well as the geophysicist.

Inexperienced geophysical users might refer to Geophysics Expert Advisor, by Dr. Gary Olhoeft of the U.S. Geological Survey (see Section 3.7). This interactive program provides an easy introduction to the technicalities of planning and undertaking appropriate geophysical surveys. The program is also a good source of questions that can be posed to a geophysical contractor. Some of the questions that must be addressed are:

- What is the target depth and geometry?
- What are appropriate survey parameters?
- What type of coordinate system should be used?

It is to the advantage of both the client and geophysicist that factors that can impede the progress of (or in an extreme case, prohibit) a survey be discussed before the survey is started. There are several common problems.

Cultural Noise. Unwanted EM signals that come from power lines, buried cables, telephone lines, fences, and buildings are known as **cultural noise**. They radiate disruptive EM signals over an area, or serve as decoy targets that confuse the definition of subsurface targets in EM and IP surveys. They can induce **noise** in seismic cables, especially when the cables are wet. They do not usually influence magnetic or gravity measurements.

Traffic, drilling, wind, trees. Vibrations from heavily travelled roads, from the roots of trees that are moving in the wind, and from nearby drilling or construction can all present problems for seismic and gravity surveys.

“Natural” electrical and magnetic noise. EM noise from local and distant electrical storms (“sferics”) and naturally induced ground (telluric) currents can severely hamper EM and IP/resistivity surveys. Transient geomagnetic field variations (magnetic storms) can seriously degrade a magnetic survey even if a base station is employed. A forecast of magnetic conditions is available from the Earth Physics Branch of the Geological Survey of Canada.

Topography. Corrections for elevation and topography are required in gravity and seismic surveys. Also, they are often necessary in high-quality conductivity-mapping and resistivity surveys. Moreover, rugged topography can significantly slow geophysical surveys.

3.4.3 Assessing a Survey

The client should consider asking some of these questions.

Are the survey objectives met? Provided the objectives have been made clear at the outset, it should be straightforward to determine from the report whether they have been met. Beware of any hedging on this, the most fundamental, issue.

Is the interpretation presented a reasonable one? Although the intricacies of how the interpretation is reached may not be a concern of the client, the interpretation should be consistent with what you know of the site. If not, the interpretation should be reviewed (by an outside consultant if necessary).

How much data processing is enough? Most contractors and consultants have an arsenal of data processing techniques at their disposal, and are anxious to use them. Beyond the bare minimum, some additional processing of the data can legitimately enhance data and aid interpretation, but beware of unnecessary complexity. The aim of processing is simply to prepare data for interpretation. The contractor should demonstrate and convince the client of the benefits of “bells and whistles” beyond the minimum required.

Is additional work necessary? Based on the results of the survey, additional work may be required. Perhaps the survey limits need to be expanded. Or perhaps “infill” lines are required to provide better resolution of the target. Sometimes a complementary geophysical survey may help resolve ambiguities. These points should be discussed with the contractor.

Was the work unsatisfactory? On occasion the survey data may not meet contract specifications. Usually there is some “give and take” on data quality, but an independent

consultant should be retained in the event that this issue is a point of contention. Significant amounts of bad data, for example, should not be accepted. It is best that bad data be recognized as soon as possible. Re-mobilization of a survey crew is an anathema to all contractors.

If significant portions of the survey data are clearly below the quality specified, the client can insist that these portions be resurveyed or, alternatively, payment can be withheld (as specified by the contract).

3.5 *Sources and Environments*

Contaminated sites are best characterized geophysically in terms of: (1) the **type** or source of waste; and (2) the **geological environment** in which that waste occurs.

Five waste types are discussed briefly, although the lines between them are somewhat arbitrary. For example, urban landfills contain inorganic, metallic, and probably a good deal of organic materials, and therefore span three of the type sources. There are usually two or more techniques that are suitable for any of the scenarios. The choice will be up to the contractor and will depend on a variety of factors, not the least of which is the availability of equipment.

The geological setting in which a given waste rests or moves constrains the usefulness of a geophysical technique. For example, a contaminant plume in a shallow, unconfined sand aquifer makes a good target for terrain conductivity methods. Within or beneath a clay-rich stratum, that same target is much more elusive because the clay reduces the conductivity contrast. In fractured rock, the plume would also be a difficult target because of the low porosity (and therefore conductivity contrast) of the contaminated formation.

The general suitability of methods for targets in a porous, clay-free environment, is discussed in Subsection 3.5.1 and is summarized in Figure 57. Brief notes are included to guide the client, but a detailed assessment must come from an experienced consultant or contractor. In Subsection 3.5.2, other geological settings are discussed to the extent that they modify the conclusions of the first section (for a porous, clay-free environment).

Subsection 3.5.3 looks briefly at the case in which the geological setting itself is the target. This subject is down-played in this section because of our focus on contaminated targets. Figure 58 summarizes this section.

3.5.1 *Waste Targets*

Metallic waste. Metallic waste is always very conductive. If it is ferrous metal, it is also highly magnetic compared with its surroundings. The choice of geophysical methods is therefore clear — either an electromagnetic device, a magnetometer, or both. The choice is often one of personal preference or equipment availability, but there are times when one or the other method may be advantageous.

In areas of severe electrical noise, for example, a magnetometer may function better than an EM device. In clay-rich environments that attenuate EM signals, a magnetometer may also be

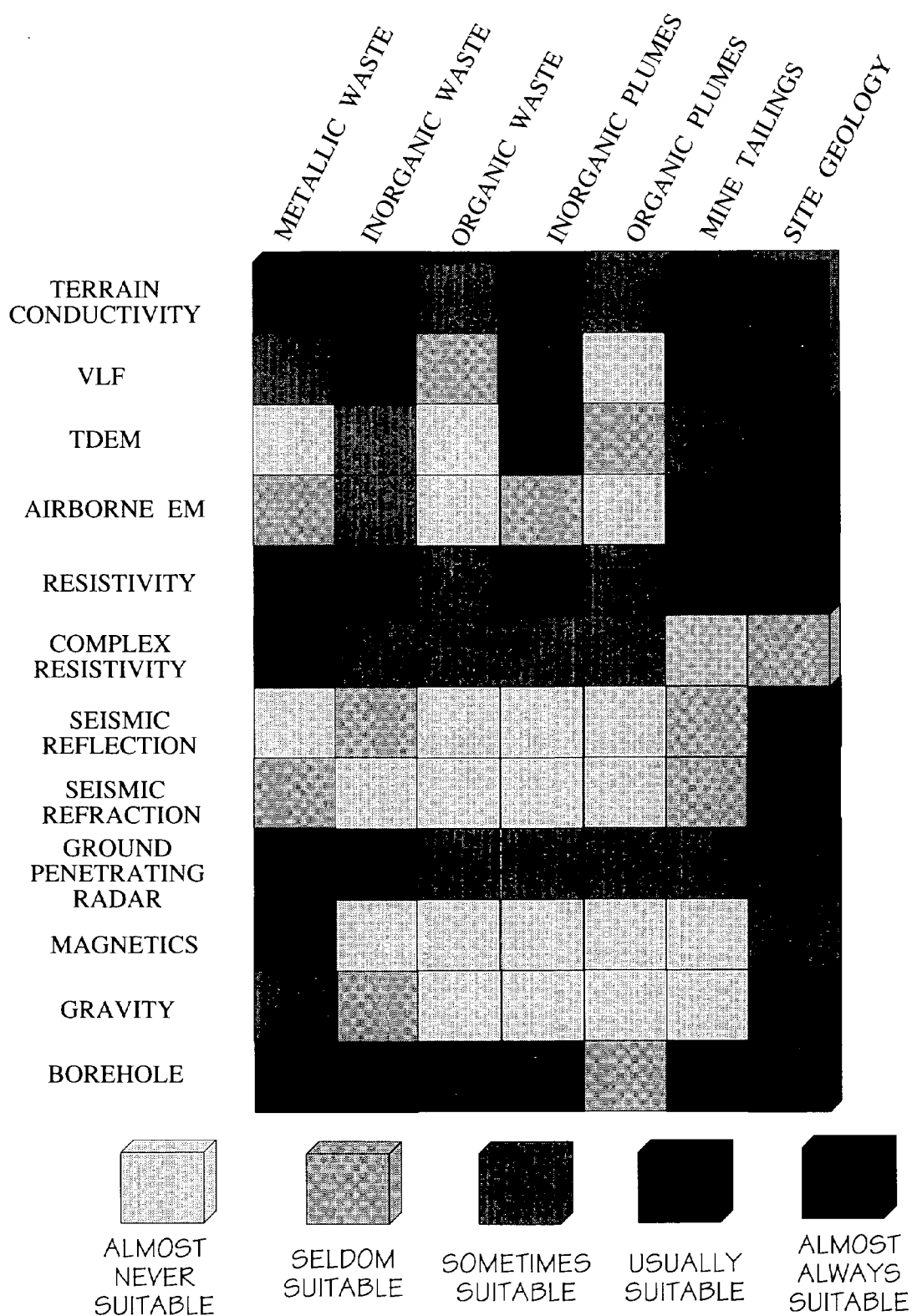


Figure 57 General Suitability of Geophysical Methods for Targets in a Porous, Clay-free Environment

superior. On the other hand, the excavation undertaken to bury the metal will often have a distinctive conductivity response that enhances and enlarges the metal anomaly, but does not influence the magnetometer readings. An IP survey can sometimes be effective in picking up the disseminated metal, but would not normally be considered unless run as an integral part of a resistivity survey.

In situations where magnetic and electrical noise are both a problem, and where the density of the metal in question contrasts well with the surroundings, a **micro-gravity survey** may possibly work. The very basic modelling equations (e.g., sphere and cylinder) can be used to estimate the anomaly that would be recorded. Seismic refraction **fan shooting** might also assist in difficult cases. We emphasize that these techniques are in general a low priority — useful only where magnetic, electrical, or electromagnetic methods are not practical for some reason.

Buried inorganic wastes. Often a geophysical survey is required to find the limits of an old landfill. Because the groundwater will mound in these wastes, they are usually very conductive compared with their surroundings. If the waste is buried on or beneath clay, however, this contrast will be minimal. Locating the edges and the top of the refuse may be quite feasible; however, the base of a refuse layer is a difficult geophysical target.

In most cases a resistivity or EM survey is the most appropriate. An IP can be useful if clay is present. That is, the lack of a strong resistivity contrast between refuse and clay can perhaps be countered by a polarization contrast between the two media.

Inorganic groundwater plumes. One of the major targets of environmental geophysics over the past decade has been groundwater plumes from contaminated sites. These are characterized by conductivities many times higher than the natural groundwater. Their detectability is determined by their contrast with surroundings, depth, and lateral extent. Again resistivity and terrain conductivity methods are the most applicable methods.

Buried organic waste. Organic wastes are characterized by their low density, low conductivity, and low dielectric constant. In fact, an “organic” waste site cannot be counted on to have any of these characteristics. More often than not, the organics are associated with metal containers, and mixed liberally with water and inorganic species. A resistivity or EM survey is therefore always appropriate. In the case of a pure, liquid organic phase, low conductivity and low permittivity zones may be detectable with surface and borehole methods. Be aware that these are very difficult targets (see Pitchford *et al.*, 1989).

Organic plumes. Detecting dissolved organic contaminants using geophysical methods is difficult and is the subject of some controversy. The trace levels of organics that migrate from the site have very low physical property contrasts with their surroundings. There are many claims of success for electrical or EM methods in which the contamination is detected as a low conductivity anomaly, but the client should be aware that the physical basis for detection is, in most cases, very poorly substantiated.

As noted in Subsection 3.2.3, there are some encouraging results from complex resistivity surveys for the detection of organics. Also, work described by Redman and Annan (1992) has

shown that organic solvents can be detected at residual levels with resistivity, GPR, TDR (permittivity), and thermal neutron absorption techniques (under ideal conditions).

Mine tailings. Mine tailings are recognized as a source of groundwater contamination in many communities. The highly acidic nature of these materials invariably makes them anomalously conductive. Locating the extent of current and abandoned tailings deposits is a typical objective. Furthermore, groundwater plumes are often found moving away from leaks around tailings dams. As with buried inorganic wastes in general, EM or resistivity surveys are always appropriate. The scale of some of these tailings areas is so large that airborne EM should also be considered. The conductivities of tailings are usually so high that high frequency EM or radar have very limited penetration.

3.5.2 The Influence of Geological Settings

The geological environment in which the waste target is located will clearly influence the effectiveness of the method used. From a geological perspective, geological settings are most usefully considered as clays, other unconsolidated surficial deposits, fractured, no-porous rocks and Karst.

Clays. The presence of clay in the matrix will:

- lower the contrast that inorganic contaminants such as refuse or plumes make with the normal background;
- lower the penetration of EM and GPR methods; and
- potentially assist in the detection of organic contaminants with complex resistivity methods.

Terrain conductivity or other EM methods thereby become less effective. Radar penetration is reduced. Massive clays situated above or even directly underneath the target make these types of surveys very difficult. Metallic targets have sufficient conductivity to overcome the problem of diminished contrast, but the problem of penetration still remains.

For organic, non-conducting contaminants such as solvents or hydrocarbons, the presence of clay might actually increase the conductivity contrast of the affected zone. As discussed in Subsection 3.2.3, there are interesting and only poorly understood reactions between clays and organics that offer some hope in this area (Olhoeft, 1986).

Although slightly more magnetic than their silicious or carbonaceous surroundings, clays do not pose any additional problems in the detection of buried magnetic metallic objects using a magnetometer survey.

In surface and borehole surveys, the high electrical conductivity of a clay-rich stratum is usually indistinguishable from the conductivity that would be produced by a zone of contaminated groundwater. In borehole surveys, however, clays are easily recognized by their high gamma log response. It is for this reason that resistivity or induction logs should always be run in conjunction with gamma logs. Parenthetically, it is important to note that separation of the

two effects in surface surveys can usually be made by observing whether the conductivity anomaly emanates as a plume from a known source of (inorganic) contamination.

Unconsolidated Surficial Deposits. Unconsolidated surficial deposits, the major environment for contaminated site assessment surveys in Canada, can be quite diverse. They range from coarse gravel (or boulders) to fine clay and weathered bedrock. Equally importantly, they can be unsorted and unstratified units comprising tills or they can be homogeneous stratified or layered features such as lacustrine clays.

Unconsolidated surficial deposits differ from the basic porous medium assumed in Subsection 3.5.1 in their heterogeneity, their generally higher porosity, and their clay content. Their electrical resistivities and seismic velocities are generally lower than their (consolidated) counterparts. Of the variety of geophysical methods briefly discussed in this section, EM and electrical methods have been favoured in the study of unconsolidated surficial deposits because the resistivities of various units comprising the deposits are often diagnostic. Good overviews of the electrical properties of unconsolidated sediments are given by McNeill (1980a) and Palacky (1988). Tables of apparent resistivities for a wide range of surficial materials are included in both these references.

The bedrock upon which unconsolidated sediments lie is usually weathered or altered to some extent. The altered zone can be quite extensive. Sometimes the electrical and seismic properties of the altered bedrock are similar to those of the overlying unconsolidated sediments. If the bedrock is igneous, the magnetic background may be considerable higher than the magnetism of the overburden. Palacky (1988) should be consulted for a discussion of the electrical properties of weathered bedrock.

Fractured Non-porous Rocks. Organic or inorganic contamination that enters directly, or by downward percolation through porous overburden, into a fractured bedrock, becomes very difficult to detect with surface geophysics. The low overall porosity proportionally reduces the contrast that a contaminant would produce. As a result, there are very few claims of success for the detection of inorganic or organic contamination in fractures with surface electrical methods.

Borehole measurements are more likely to be productive in this setting simply because they bring the sensors closer to the target. The results of detailed geophysical studies conducted in granitic, fractured non-porous rocks by Soonawala *et al.* (1990) showed that resistivity, acoustic velocity, density, and thermal neutron count rates all decrease significantly in fracture zones. They also present tables that summarize some of the differences in physical properties of fractured and unfractured sections in one drill hole. Geophysical logs may detect the changes in the resistivity or conductivity log signature of a fracture that has become contaminated. In this mode, however, the geophysics is in direct competition with conventional hydrogeological sampling techniques.

Channel Flow (Karst). Because the geophysical properties encountered in karstic or other channel flow settings are very variable, detecting the overprint of groundwater contamination is particularly difficult. The contamination usually adds in only a very minor way to the physical

contrasts associated with these features. These settings are also very diverse, making generalizations particularly problematic. Each situation should be evaluated independently.

Permafrost. The physical properties of saturated geological materials experience significant changes when they are frozen. The geophysical delineation of zones of permafrost are based on this fact. A review of permafrost geophysics is given by Scott *et al.* (1990), who provide a comprehensive list of references.

Permafrost does not impede magnetometer or EM searches for buried metallic waste. Resistivity or IP methods become more difficult because ground contact for electrodes is required. However, these methods are still feasible. Groundwater contamination in permafrost areas is generally limited to the active zone where freezing and thawing take place each year. The impermeable permafrost usually serves as a highly resistive, high velocity base to the target. If the unconsolidated sediments are reasonably homogeneous and resistive, a simple EM-31 survey may be ideal for outlining the surface trace of a shallow conductive plume. An example, from Inuvik in the Northwest Territories, is given by Greenhouse and Slaine (1983).

3.5.3 Site Geology

There are many occasions when site geology, not contamination, is the target. In this case, geophysics can usually describe the environment in which the waste is resident or through which it will migrate. Four typical site geology applications are summarized in Figure 58 in terms of their suitability for the various geophysical techniques.

Depth to a confining layer (e.g., bedrock) is perhaps the most common requirement. Techniques with good lateral and vertical resolution of boundaries are best (e.g., seismic refraction, reflection, electrical resistivity, or TDEM). Borehole geophysics is clearly useful for this application if boreholes are available.

The relative usefulness of the various techniques in Figure 58 is subjective to an extent and also site-specific. Availability of equipment will be a factor in the choice. A contractor planning to map depth to bedrock with one of the techniques that is not highly rated should be prepared to explain why.

The second column in the figure shows that seismic reflection and radar are the best hopes for obtaining information on the internal structure of aquifers, including aspects such as the continuity of confining lenses and stochastic descriptions of their spatial distribution for input to numerical models.

Porosity and clay content of the subsurface are two common targets of site surveys and are factors that constrain the movement of waste or influence the suitability of a site for containing waste. These parameters are best estimated from electrical resistivity or conductivity.

Borehole methods are particularly suitable for the detection of fractures. A detailed review of geophysical well logging methods as applied to the study of fractures in fractured, non-porous rocks is given by Howard (1990).

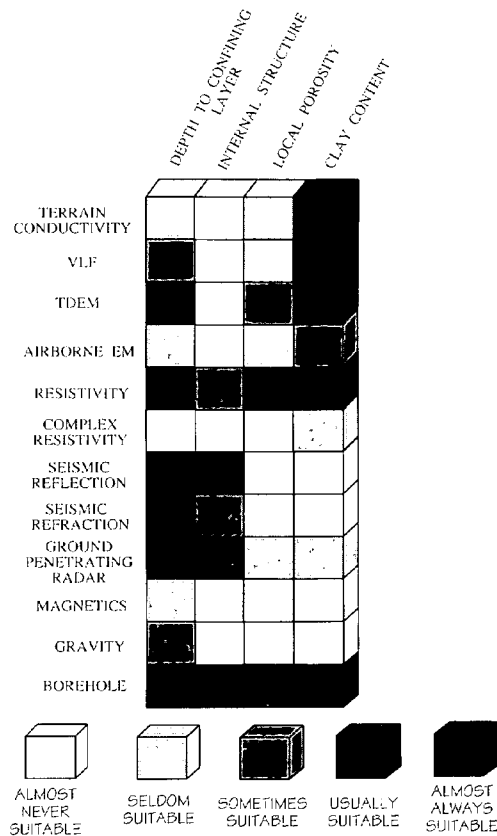


Figure 58 General Suitability of Geophysical Methods for Typical Site Geology Problems

Traditionally, micro (high sensitivity) gravity surveys have been preferred to locate limestone caverns and other voids. Stewart and Wood (1990) successfully employed microgravity, resistivity, and borehole methods in a study of fracture zones in a carbonate aquifer. However, other methods such as GPR, seismic reflection, and resistivity are useful in theory, and have been applied with some success. Very detailed gravity surveys that delineate subsurface cavities and tunnels have been reported by Butler (1984). For most of his work, Butler employed readings on a 3-m grid, and demonstrated the tight sampling interval required to map small structures.

As with every other target, fractures can be detected only to the extent that they disturb the physical properties of the rock volume influencing the geophysical measurement. Clearly one 3-cm wide fracture within the zone of influence of a VLF resistivity survey (several tens of metres across) will not produce a resistivity anomaly. A broad fracture zone, on the other hand, may well be detected with this technique. Simple estimates of the volumetric change in density, resistivity, or seismic velocity associated with a fractured target will usually establish the likelihood of success.

Often it is not the fractures themselves but associated phenomena that produce the geophysical anomaly. For example, fracture zones might coincide with bedrock depressions, conduct high conductivity fluids to the overburden, or be associated with the intrusion of relatively highly magnetized dikes.

3.6 The Cost of Geophysics

Geophysical surveys are generally less expensive than drilling or excavating. The comparison is always difficult because the products of geophysics and other types of surveys are not always comparable.

We nonetheless propose a geophysics price index that uses the cost of a rotary hole drilled to 10 m in a comparable geophysical environment as its basic unit, geophysics price unit (GPU). The GPU is based on the average cost (\$30/m, 1992 rates) for a small rig in southern Ontario that is mobilized for one day, and assumes unconsolidated overburden sediments. The index is the approximate one-day cost of the equipment and crew, but assumes mobilization for one week of work. The cost of borehole geophysics is based on the cost of renting a Geonics EM39 induction/gamma log. The geophysical survey would include a very basic report (comparable to a driller's log) but no extensive interpretation. The data were obtained by surveying geophysical contractors in southern Ontario. The GPU of 12 of the geophysical methods is summarized in Figure 59.

Figure 59 serves as a guide to cost, but cannot address the relative merits or quantities of the information obtained. For example, an airborne survey might collect several hundred line-kilometres of multi-channel data in a single day; whereas, a ground survey might collect less than 10 km or even less than 1 km in a day. Assessing the relative merits of different information still requires judgement, based on a clear understanding of the goals of the survey, a good understanding of the capabilities of the various tools available, and a good geological background.

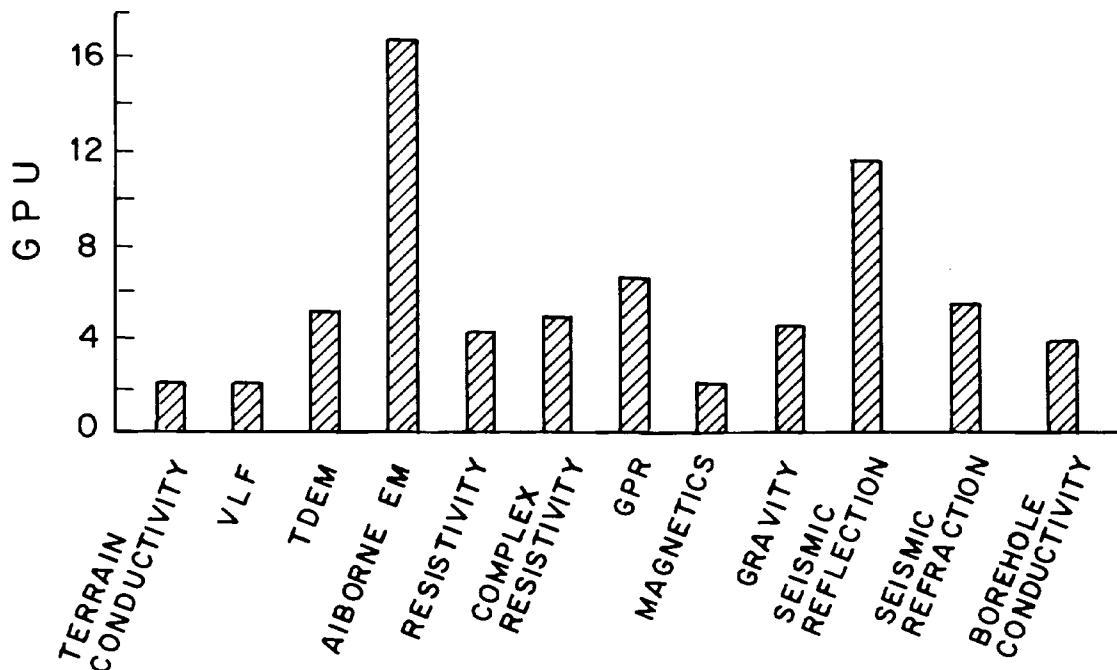


Figure 59 The Geophysics Price Index

3.7 *Additional Information*

The resources described in this section include short courses, textbooks, reference books, journals, trade shows, equipment reviews, equipment manufacturers, computer-based expert systems, and geophysical software suppliers.

Three organizations give short courses in the United States and Canada:

The National Ground Water Association (NGWA).
6375 Riverside Drive
Dublin, Ohio, 43017 USA

The Society of Exploration Geophysicists (SEG)
Box 702740
Tulsa, Oklahoma, 74170-2740 USA

The Environmental and Engineering Geophysical Society
(formerly the Society of Engineering and Mineral Exploration Geophysicists)
Contract Station 19, Box 207
Denver, Colorado, 80231
USA

Contact these organizations for their course offerings.

We believe that these books will be useful for a long time. They are in alphabetical order by author.

Garland, G.D. (ed.), *Proceedings of Exploration '87; Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater*, The Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario, P3E 6B5 (1989).

This large volume, available at reasonable cost, is devoted in large part to mining exploration but contains a number of articles in the area of geochemistry and geophysics as applied to groundwater and geothermal studies.

Kearey, P. and M. Brooks, *An Introduction to Geophysical Exploration (2nd Edition)*, Blackwell Scientific Publications (1990).

An extremely readable text at the introductory university level. The latest edition uses more examples from environmental topics.

Keyes, W.S., *Borehole Geophysics Applied to Groundwater Investigations*, The National Water Well Association, 6375 Riverside Drive, Dublin, Ohio 43017 (1989).

An excellent introductory text, at a reasonable price, on geophysical well logging.

Nabigian, M.N., (ed.), *Investigations in Geophysics No. 3; Electromagnetic Methods in Applied Geophysics: Volume 1: Theory*, The Society of Exploration Geophysicists, P.O. Box 702740, Tulsa, Oklahoma 74170-2740 (1988); and **Nabigian, M.N., (ed.),** *Investigations in Geophysics No. 3; Electromagnetic Methods in Applied Geophysics: Volume 2: Applications (Parts A and B)*, The Society of Exploration Geophysicists, P.O. Box 702740, Tulsa, Oklahoma (1991).

Electromagnetic methods are arguably the single most important of the major geophysical methodologies for studies of waste sites. This two-volume set (consisting of three books) is the acknowledged "bible" of electromagnetics, and will stay so for some time. The first volume covers theory. The second volume, published in two parts, provides the most complete exposition available of the uses of the various airborne and ground methods.

Proceedings of the Biannual Conference on Ground Penetrating Radar, 1988–1992.

This series of conferences has been organized by ad-hoc committees but there is, in the proceedings, an excellent record of the development of this fast-growing field. The three volumes are all available from different sources. Contact Dr. Peter Annan, Sensors and Software Inc., 5566 Tomken Road, Mississauga, Ontario L4W 1P4.

Sheriff, R.E., *Encyclopedic Dictionary of Exploration Geophysics, (3rd Edition)*, The Society of Exploration Geophysicists, P.O. Box 702740, Tulsa, Oklahoma (1991).

Definitions of all common geophysical terms, and many uncommon ones as well. Well written and illustrated.

Telford, W.M., L.P. Geldart, and R.E. Sheriff, 1990. *Applied Geophysics, (2nd Edition)*, Cambridge University Press, Cambridge, U.K. (1990).

This is a standard reference for intermediate to advanced level geophysical courses at universities throughout the world. Comprehensive, well written, and well illustrated.

The National Water Well Association, *Proceedings of the Annual National Outdoor Action Conference on Aquifer Restoration, Groundwater Monitoring and Geophysical Methods*, 6375 Riverside Drive, Dublin, Ohio, 43017 USA (1987).

The annual Las Vegas meeting sponsored by the NWWA produces a volume of papers that are useful because they are aimed primarily at users of geophysics rather than at other geophysicists. Contains a great many case histories.

The Environmental and Engineering Geophysical Society, *Proceedings of the Symposia on the Application of Geophysics to Engineering and Environmental Problems*, (EEGS), Contract Station 19, Box 207, Denver, Colorado, 80231, USA (1987 to 1992).

Unlike the NWWA proceedings, these case histories and technical papers are aimed primarily, but not exclusively, at geophysicists.

Ward, S.H., (ed.), *Investigations in Geophysics No. 5: Geotechnical and Environmental Geophysics*, The Society of Exploration Geophysicists, P.O. Box 702740, Tulsa, Oklahoma (1990).

This three-volume set (now available under one cover) is the standard reference on the application of most commonly used geophysical techniques in environmental, groundwater, and geotechnical applications. Volume 1 provides an excellent review/tutorial on geophysical methods. Volume 2 presents a wide variety of case histories in the environmental and groundwater areas; whereas, Volume 3 concentrates on more geotechnical applications. If you can afford only one volume, buy Volume 1.

These journals and indexes are recommended:

Geophysical Prospecting and First Break. The European Association of Exploration Geophysicists, Utrechtseweg 62, P.O. Box 298, 3700 AG Zeist, The Netherlands.

Geophysics and Geophysics: The Leading Edge. The Society of Exploration Geophysicists, P.O. Box 702740, Tulsa, Oklahoma 74170-2740. (*First Break* and *The Leading Edge* present articles of a general nature with emphasis on case histories. They are therefore more suitable for the non-geophysicist.)

Groundwater and Groundwater Monitoring Review. Groundwater Publishing Company, 6375 Riverside Drive, Dublin, Ohio, 43017 USA. (These journals emphasize case histories.)

The SEG Cumulative Index of Geophysics, compiled and edited by W.J. Zwart. Available from the Society of Exploration Geophysicists, P.O. Box 702740, Tulsa, Oklahoma. It covers the journals: *Geophysics*; *Geophysical Prospecting*; *Geophysics: the Leading Edge of Exploration*; and *First Break*. The index is also available on diskette: **The SEG Digital Cumulative Index**, compiled and edited by Brian R. Spies.

Another interesting resource is in the electronic medium:

Geophysics Expert Advisor. This very useful guide to geophysics for environmental problems is distributed by the USGS in the form of an Expert System, and at a very moderate price. It can be purchased from:

Branch of Geophysics: Attn. Dr. Gary Olhoeft
 The U.S. Geological Survey
 Department of the Interior
 Denver, Colorado, 80225-0046 USA

A special issue of the **Northern Miner Magazine**, published in January or February of each year, is a good source of information on equipment manufacturers, geophysical contractors, and consultants. Available from: The Northern Miner Magazine, 1450 Don Mills Road, Don Mills, Ontario, M3B 2X7.

The journal **Ground Water Monitoring Review (GWMR)** also publishes an annual buyer's guide (fall issue) listing geophysical equipment and software suppliers. Available from Ground Water Publishing Co., 6375 Riverside Dr., Dublin, OH 43017, USA.

In North America, there are three main trade shows (and two smaller ones) at which to view geophysical equipment and interview contractors:

The Prospectors and Developers Association. Holds its annual meeting in Toronto in March. Although heavily mining oriented, this is an excellent venue to see the major equipment manufacturers. Contact: The Prospectors and Developers Association of Canada, 74 Victoria Street, Toronto, Ontario.

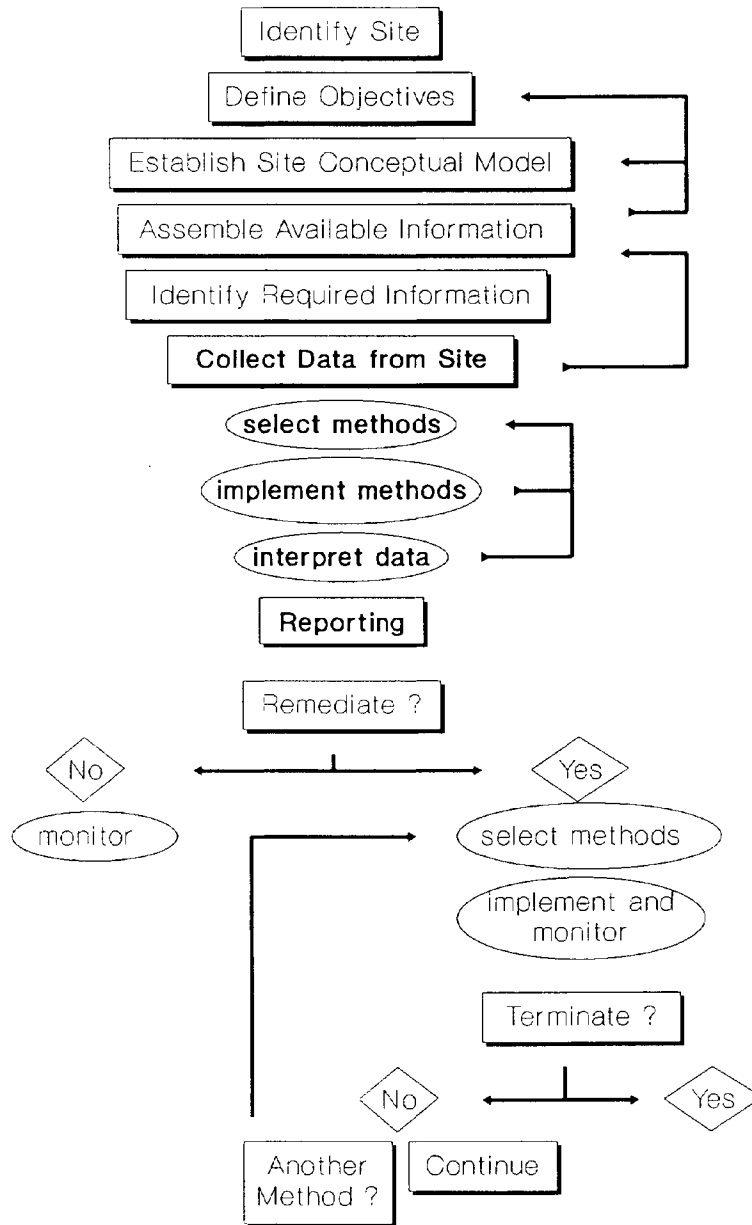
Society of Exploration Geophysicists Annual Meeting. This meeting has historically been dominated by the petroleum industry but the environmental component continues to increase. Contact: Society for Exploration Geophysicists, P.O. Box 702740, Tulsa, Oklahoma. In Europe, the comparable organization is the European Association of Exploration Geophysicists, Utrechtseweg 62, P.O. Box 298, 3700 AG Zeist, The Netherlands.

National Outdoor Action Conference on Aquifer Restoration, Groundwater Monitoring, and Geophysical Methods. Held usually in Las Vegas in May by the National Ground Water Association. This is a major geophysical show in the environmental area. This conference pioneered the idea of holding the manufacturer's displays outside, so that some equipment can be seen operating under more or less real conditions. For information contact the NWWA at 6375 Riverside Dr., Dublin, OH 43017, USA.

Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP). Held in the spring at a different locale each year. This conference is now sponsored by the Environmental and Engineering Geophysical Society (EEGS), Contact Station 19, Box 207, Denver, Colorado, 80231, USA.

The International Conferences on Ground Penetrating Radar. These are held every two years typically alternating between Europe and North America. Organized by an ad-hoc committee rather than a society, these conferences have "no fixed address". Those interested in attending should write or call the Terrain Sciences Division of the Geological Survey of Canada for information on the next meeting.

Most manufacturers and suppliers of equipment, software, and services advertise and are reviewed in journals, and participate in trade shows. The business is growing and evolving; therefore, it is not possible to generate a comprehensive, up-to-date listing of these firms. Start your search with these sources.



Section 4

Hydrogeological Site Investigation (D. Rudolph)

This section examines the physical characteristics of the subsurface system that control contaminant migration at a given site. The main factors of interest are:

- hydrological — form and occurrence of precipitation, variations in temperature, surface drainage, and vegetation and land use;
- geological — surface topography, stratigraphic sequence and geometry, and structural features such as **faults**, **joints**, and **bedding planes**; and
- hydrogeological — vertical and horizontal hydraulic gradients, water table depth and fluctuations, and hydraulic properties of the subsurface materials.

Several steps are required if data collection and assimilation are to adequately assess the hydrogeological conditions at a given site. Information from the desk-top review (Section 2), from a phased field investigation program (Sections 3 and 4), and from laboratory analyses (Sections 4 and 5) are necessary. Physical conditions vary dramatically between sites, as does the level of previous information available and the site investigation budget. Therefore, field investigation strategies are very site-specific.

The information that this hydrogeological portion contributes to the overall site investigation is critical for geochemical investigations (Section 5), for numerical simulations (Section 6), and for remediation activities (Section 7). The hydrogeological site investigation program aims to:

- determine the direction and rate of groundwater movement;
- delineate the principal pathways and factors controlling the migration of contaminants in the subsurface; and
- quantify the physical parameters controlling groundwater flow and contaminant transport in the subsurface.

To achieve these goals, a rigorous, site-specific investigation program must be developed. Because it is not possible to specify a detailed set of guidelines to suit all sites, this section uses a more general approach, and refers to the five conceptual settings outlined in Section 1. This section proposes the appropriate investigative strategies, field methodologies, and laboratory procedures in these general hydrogeological settings. In each case, it will be assumed that little, if any, information is available about the field sites. Of course, in most situations, the desk top review will provide extensive information that will permit a more efficient design of the hydrogeological site investigation.

4.1 *Staged Investigation Approach*

The site-specific, hydrogeological program must ensure that the field investigation stays within budgetary constraints while meeting the investigation objectives and satisfying all data requirements. A series of steps or stages is recommended for the investigation program in which new field data are continuously incorporated into existing information. Hopefully, this will provide a logical sequence to follow when selecting the appropriate field activities and methods, and allow the required information to be collected in the most efficient way.

A four-staged approach, outlined in Table 7, is recommended. Each stage has very specific objectives and activities. Each of these stages updates and redefines the conceptual **hydrogeological model** for the given site. The data collection procedure increases in detail as the investigation program advances. The results and conclusions from each preceding stage dictating the activities of the next stage.

Table 7 Main Stages of the Hydrogeological Site Investigation

Stage		Activities
Stage 1:	Preliminary Site Visit and Initial Assessment	Review desk top study
		Undertake initial visit to site
		Develop preliminary conceptual hydrogeological model
Stage 2:	Preliminary Field Investigation	Place initial monitoring wells
		Define general hydrostratigraphy
		Focus additional field activities
Stage 3:	Detailed Site Investigation	Expand monitoring well network and sediment sampling
		Evaluate groundwater flow velocities and contaminant transport pathways
Stage 4:	Reporting	Construct plan-view and sectional flow nets
		Tabulate values of critical physical parameters
		Summarize/report and plan for follow-up monitoring

The following sections discuss the different stages in the site investigation program, and emphasize what must be in hand before progressing to the next stage. Details on recommended laboratory procedures and field techniques for drilling, sediment sampling, and monitoring well installation are contained in subsequent sections and are referred to when appropriate.

4.2 *Stage 1: Preliminary Site Reconnaissance and Initial Assessment*

This stage involves a review of existing data and a visit to the field site (Table 7). The objective of this stage is to prepare an initial interpretation of the hydrogeological setting based on the available information and the observations and experience of the investigator. Stage 1 aims to:

- delineate the general geological features of the site and verify information from the desk top review;
- document local hydrology, including precipitation and surface drainage patterns;
- collect evidence of source and nature of contamination;
- confirm or refine the conceptual model of the hydrogeological system; and
- evaluate potential problems related to health and safety and site access.

Once you meet these aims, you should have enough insight into the specific site conditions to direct the preliminary field investigation in Stage 2.

Draw most of this information directly from the desk-top review. The information required for the hydrogeological study includes:

- topography;
- thickness and distribution of geological and fill materials;
- distribution of potential aquifers;
- structural make-up of the subsurface;
- precipitation and general climatic records;
- surface drainage patterns;
- drainage characteristics of soils;
- land use and surface vegetation cover;
- groundwater and surface water use in the area; and

- nature of contamination at the site [where, when, and chemistry of the source(s)].

Where possible, maps, cross-sections, and a preliminary conceptual model of the site hydrogeology will have been produced in the desk-top review (Section 2). After the hydrogeologists have carefully reviewed this data and the resulting conceptual model, visit the site to directly observe the physical conditions and evaluate other factors such as site access, residential development in the area, and potential health hazards for the field personnel.

4.2.1 Preliminary Site Visit

The main purpose of this initial visit is to allow first-hand inspection of the general conditions on the site. For the site visit, bring:

- all relevant maps, cross-sections, and air photos;
- a shovel and hand auger for shallow inspection of the surficial materials; and
- sample bottles to collect surface water or **spring** samples.

Examine site accessibility for anticipated drilling equipment. Also observe the site topography and vegetation and the current conditions of surface water bodies on-site. Investigate any recent changes (such as new construction and development) to the area around the site that may not have been obvious in the existing information sources. You can often document historical modifications in land-use practices by reviewing various sets of air photos taken at different times.

With the shovel and hand auger collect samples of near-surface materials and either examine them on-site or return to the laboratory to evaluate them. Nearby construction or surface mining excavations and road cuts provide excellent opportunities to examine the subsurface materials in the area. At this stage, collect water samples from surface water bodies and springs. Chemical analysis of these samples will provide you with a preliminary indication of local water quality. In some cases, liquid contamination or **leachate** emanating from the contamination source may be visible at the surface of the ground. Also note any staining of surface soils, stressed and dying vegetation, or the existence of drums or storage tanks on the site. These are potential indicators of contamination. Map these occurrences and collect samples for chemical analysis.

Carefully document the location of high voltage powerlines, buried cables and pipes, and other potential health risks that may impact on field activities and personnel. On-site inspection and information from local utility operators (telephone, water, natural gas) will assist in evaluating these potential risks.

Depending on the complexity of the site and the level of existing information, a fairly detailed understanding of the hydrogeology at the site may exist at the end of this first stage of the investigation. It is sufficient, however, if the conceptual model is advanced enough to:

- select the appropriate drilling technique for the subsequent field investigation program;

- estimate the depth to which the test holes should be completed; and
- define the principal usable aquifers in the vicinity of the site.

At this point, the site investigation is ready to advance to Stage 2.

4.3 *Stage 2: Preliminary Field Investigation*

The main objectives of Stage 2 are:

- to define the principal **hydrostratigraphic units**;
- to determine general groundwater flow directions on site; and
- collect sufficient information to develop a detailed site investigation plan (Stage 3).

The hydrogeological features at the site will dictate, to a large degree, the field activities in Stage 2. This section will outline a general strategy for the Stage 2 field program and discuss general drilling, material sampling, and monitoring strategies. Details on specific field techniques are contained in subsequent sections.

4.3.1 *Field Program*

Where very little detailed subsurface information exists on the study site, consider using surface geophysical techniques as an initial step in the field program to provide information on the general stratigraphic sequence underlying the site. Section 3 discusses the appropriate geophysical techniques. The results of these surveys, used in conjunction with the existing geological data, can help determine both the types of materials that will likely be intercepted during the test drilling, and the appropriate depth of test drilling required to intercept the lower bounding unit, which may be bedrock or some low-permeability sediment. Also use surface geophysical surveys to locate buried waste containers such as steel tanks and barrels. These surveys may be extremely useful in some cases for locating the potential source of contamination, and for directing the placement of monitoring wells to avoid piercing buried containers during drilling.

Once the general subsurface geologic features at the site are known, begin an initial test drilling program to more accurately delineate the stratigraphic sequence. Use a minimum of three boreholes, arranged roughly in a triangular pattern. Log each borehole in detail and instrument each with a **monitoring well**. The three boreholes are generally not sufficient to characterize the hydrogeological system completely, especially at large sites or where the geology is complex. They do, however, provide enough data to allow construction of a general map of the groundwater flow field. They also indicate continuity of the hydrostratigraphic units. This is the initial information required to design Stage 3, i.e., detailed site investigations.

This preliminary drilling program aims to define the main hydrostratigraphic units underlying the site. Delineating these units is the first step in assessing the risk of contaminant movement

from the source and determining potential migration pathways. Compile a detailed record or log of the subsurface stratigraphy encountered during drilling. The drilling and subsurface sampling method that you select for a given site depends not only on the site conditions and assumed subsurface geology but also on the type of sample required and the end use of the borehole.

The specific drilling and sediment sampling techniques that you choose for a given site will be dictated by:

- the subsurface material that you expect to encounter;
- the accessibility to the site itself; and
- the availability of the drilling equipment.

For assistance in selecting the appropriate drilling and sediment sampling techniques for your site, refer to Sections 4.5 and 4.7.

The initial drilling and sediment sampling program of Stage 2 should provide the:

- relative position and thickness of each major stratigraphic unit underlying the site;
- physical description of each unit;
- sediment or rock type (geological description);
- **mineralogy**;
- approximate description of **grain size distribution** and plasticity;
- estimate of **primary porosity** and permeability;
- evidence of **secondary porosity** (fracturing); and
- estimate of degree of water saturation.

You can base the physical description of the geologic materials on a number of different standard methods, including those presented in U.S. EPA (1991) and in American Society for Testing and Materials Publications D420-87, D2488-90, C294-86, D653-90, and D422-63.

To collect this data, samples of the subsurface material must be obtained at appropriate intervals from the borehole. If very little is known about the hydrostratigraphy, you should take relatively continuous, undisturbed **cores** through the total depth in at least one of these preliminary test holes. Many coring techniques are discussed in Section 4.5. After inspecting of the core samples, you can select appropriate sampling depths in subsequent holes to obtain relatively undisturbed samples of all major hydrostratigraphic units from each borehole.

Portions of the samples collected during Stage 2 will be used for additional laboratory analyses in Stage 3 and they should be stored carefully in a cool location. In addition to taking core samples, the boreholes should be logged through **drill cuttings**, (Section 4.5) and appropriate geophysical logging (Section 3).

Consider selecting a minimum of three test drilling locations that are in a triangular pattern and relatively evenly spaced so that you can construct a **contoured map** of the hydraulic heads. If the source is small and well defined, you may be able to drill the holes around its perimeter and confine the source within the triangulated area between the wells [Figure 60(a)].

On larger sites, three boreholes might not allow delineation of the groundwater flow field, because flow directions may change significantly over the site. The three-borehole approach aims to provide you with basic data to update the conceptual model of the hydrogeological system and to help plan the more extensive field program in Stage 3. In extremely remote sites, it may be very costly to mobilize the drill rig to the site. In these cases, it is necessary to complete the Stage 2 evaluation and design and implement the Stage 3 field program as quickly as possible to make the most efficient use of the drilling equipment.

Consider several factors when locating the initial boreholes. Specific surface features, such as an active stream, can locally influence the groundwater flow field and make interpretation of the flow pattern difficult. Locate the initial boreholes a reasonable distance away from this type of feature. In addition, the contaminant source is sometimes associated with an artificial topographic mound (the case in many landfills). Do not locate the preliminary boreholes in these areas. Rather, investigate them as part of the Stage 3 field program. Property boundaries and access limitations may also influence the siting of these three boreholes.

How deep should the test drilling go? The answer is site-specific, but usually extends until a lower boundary of low permeability material is reached. In surficial deposits, advance the borehole until bedrock is reached if no previous information is available. The hydrogeologist can assess whether additional drilling into the bedrock is warranted. This will depend on the estimated hydraulic conductivity of the rock, its depth, and its significance as an aquifer. If the **overburden** materials at the site are very thick, low-permeability material such as clay or **till**, limit the depth of investigative drilling to ensure that more permeable units at greater depth cannot be affected by contamination carried down during drilling from sources near the surface.

If the low permeability sediments are fractured, deeper drilling will generally be warranted than would be the case if the sediments were massive or unfractured. Selecting the low-permeability, lower boundary will require hydrogeological judgement.

After you have drilled and logged a test hole, you can install appropriate monitoring wells in the borehole. You can install individual or multiple wells, depending on local site conditions and on the nature of the contamination (Section 5). If you place multiple wells in each borehole, the hydraulic head data that you obtain from these installations will permit the vertical hydraulic gradients and the direction of lateral groundwater flow in each major hydrostratigraphic unit to be estimated.

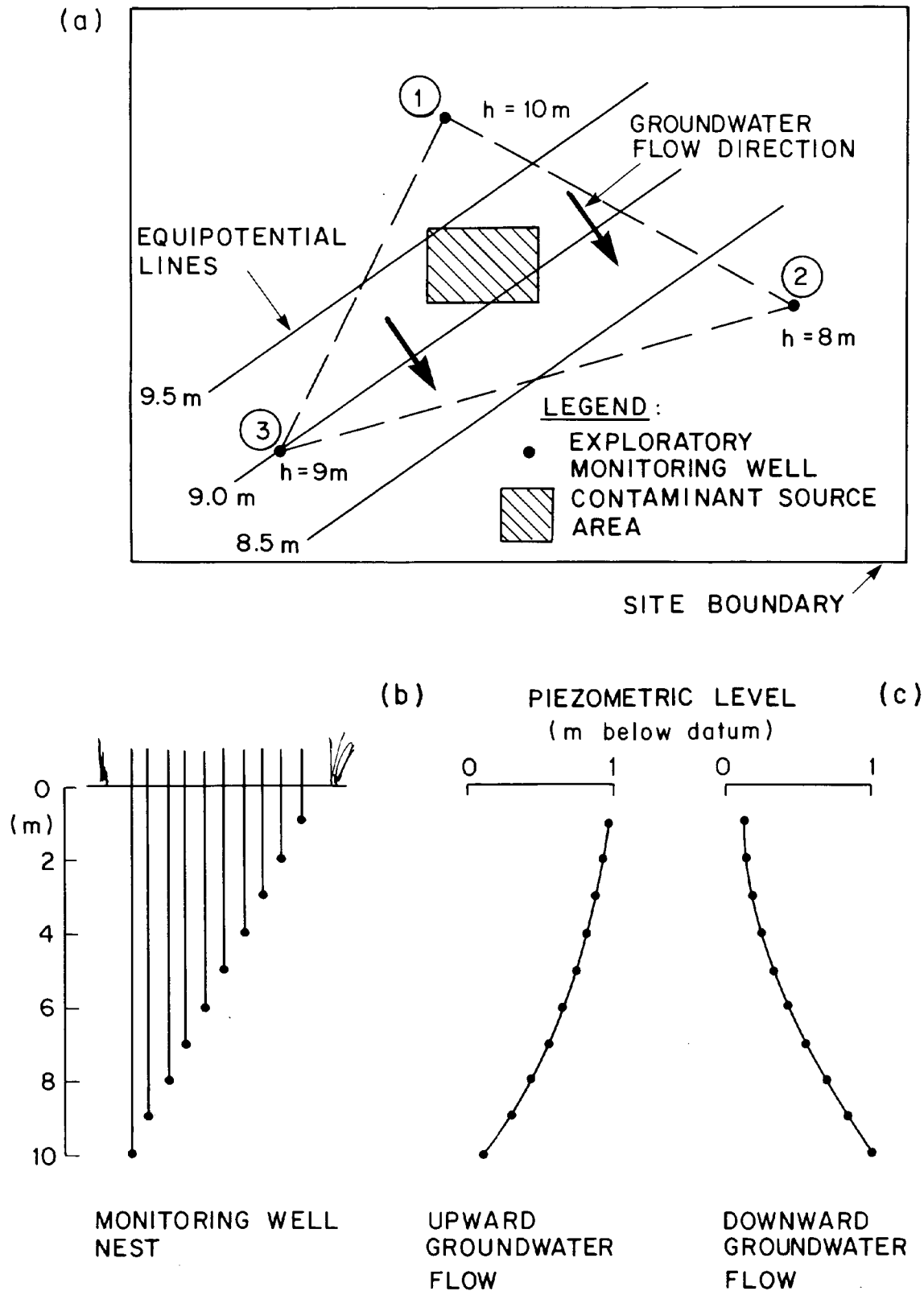


Figure 60 (a) Triangular Placement of Test Holes and Monitoring Wells for Preliminary Field Investigation; (b) Vertical Piezometric Profile Indicating Upward Groundwater Flow; and (c) Vertical Piezometric Profile Indicating Downward Groundwater Flow

Sections 4.6 and 4.7 assist in selecting the most appropriate monitoring well installation technique for your site.

As a general rule, at each of the three locations, place at least one well in each hydrostratigraphic unit and, if the units are thick (<15 m), consider using two wells. Monitor and record the **recovery** of the **piezometric levels** in the monitoring wells after installation. This is explained in Subsection 4.8.2. Wells in permeable sediments such as sands and gravels will recover quickly; whereas, wells in lower permeability materials may take weeks or months to fully recover to an equilibrium state.

Next, plot the hydraulic heads from the completely recovered monitoring wells on a plan-view map. Contour these to produce a potentiometric or **equipotential map**. As illustrated in Figure 60(a), you can interpret the groundwater flow directions from this map. Individual equipotential maps should be drawn for each permeable, hydrostratigraphic unit. Note also, that, to relate the hydraulic head values in each monitoring well to the others in the network, you must accurately determine the elevation of a reference point (e.g., the top of the casing) on each well using a level survey.

At each of the monitored sites, you can plot the hydraulic head data on a vertical profile with respect to depth of well placement. Use these plots to evaluate the vertical hydraulic gradients through the entire profile [Figures 60(b) and (c)]. These vertical and horizontal hydraulic gradients provide an indication, in a general sense, of the potential direction of contaminant migration.

As an additional consideration, note that drill cuttings that are brought to the surface during the drilling process may be highly contaminated and, therefore, require special handling and disposal. Take very rigorous safety precautions to protect the field crew from inadvertent exposure. Such precautions may include protective clothing and, in the case of volatile contaminants, respiration equipment. Section 2.4 discusses safety plans.

During drilling, collect samples of the **cuttings** for on-site chemical analysis. This screening will provide a preliminary indication of the nature of contamination in the subsurface. Section 5.3 presents screening techniques.

When drilling in contaminated soil, the potential of enhanced mobilization of contaminants as a result of the drilling operation is always present. You risk drilling through highly contaminated areas and either carrying the contamination downward with the drill **bit** and **drilling fluid** or providing a vertical conduit for the contaminants to move much deeper than they had been.

With the results of the preliminary drilling program in hand, the design of the detailed site investigation can begin and the hydrogeological program can move into Stage 3.

4.4 *Stage 3: Detailed Site Investigation*

By the third stage of the site investigation program, a realistic conceptual model of the hydrogeological system has been developed. You have delineated the main hydrostratigraphic

units and mapped the groundwater flow field in the vicinity of the site. A qualitative assessment of the susceptibility of the subsurface materials to contamination is possible and the potential contaminant transport pathways are identified. Stage 3 aims mainly to:

- develop a detailed understanding of the hydrogeological system at the site; and
- obtain the information required for quantitative analysis of the groundwater flow system.

Stage 3 involves additional field activities and laboratory analyses (see Table 7). Selection of appropriate activities and analyses is again site specific. Therefore, in this section, a general strategy is presented for expanding the monitoring well network on the site and collecting additional samples of the subsurface materials. Because this stage of the investigation stresses the quantification of various physical parameters, reference to appropriate *in situ* and laboratory measurement techniques will be made. The techniques are discussed in Section 4.8.

4.4.1 Objectives

Stage 3 involves selecting locations, depths, and construction materials for the new installations, as well as collecting appropriate sediment samples during the drilling process. The objectives are to:

- evaluate groundwater flow conditions in the vicinity of all surface water bodies;
- delineate the lateral extent of each hydrostratigraphic unit within the study site; and
- determine realistic values of the main hydraulic parameters of each hydrostratigraphic unit.

At the end of Stage 3, essentially all physical data required for mathematical modelling of the groundwater flow field and for consideration of remediation options should be compiled.

4.4.2 Extending the Monitoring Well Network

At this point, you have installed a minimum of three monitoring wells in each hydrostratigraphic unit [see Figure 60(a)]. On the basis of water level data from these monitoring wells, you have determined general directions of groundwater flow in each hydrostratigraphic unit. You must now expand the monitoring well network. Use the experience gained through the Stage 2 preliminary drilling program to select the appropriate drilling and sediment sampling techniques, and the monitoring well type, for the extended Stage 3 field program.

Use the same approach to selecting appropriate sampling and well placement depths as you developed in Stage 2 unless significantly different subsurface conditions are encountered. If Stage 3 drilling encounters different conditions, additional sampling is likely warranted. You need to be able to adapt your field activities to accommodate the specific-site conditions. Refer to Sections 4.5, 4.6, and 4.7 for drilling, sediment sampling, and monitoring well advice.

At small sites (e.g., 500 m × 500 m) where the ground surface is flat, the hydrostratigraphy is simple and uniform, and there are no surface water bodies nearby, the three-well system may

provide sufficient information. Such sites may require additional monitoring wells only to evaluate contaminant distribution (see Section 5). However, considering water level data from just these three wells can lead to erroneous interpretation of the flow field (see Figure 61).

Note that physical features and conditions (e.g., surface topography; springs, streams, rivers, and lakes; stratigraphic discontinuities; and large excavations and groundwater extraction) can influence patterns of groundwater flow, and they should be considered before relying on the three-well system. Also, consider these features when selecting additional monitoring points.

Consider installing several additional multilevel monitoring wells in a fairly even pattern over the site. When selecting the locations for these wells (and the materials to use) the investigator responsible for monitoring the groundwater quality at the site should be involved (Section 5). Because these monitoring wells provide information on both the physical and chemical conditions at the site, it may be possible to locate the wells in the areas that will be the most useful for both parts of the study.

Recharging conditions and associated mounding of the water table generally occurs under areas of higher elevation (hills). In the lower topographic areas, groundwater discharge conditions often prevail. These features influence both the horizontal and vertical movement of groundwater (see Figure 62). At least one multilevel monitoring well should be located near each of these physiographic features. If a stream or river flows through the site, determine its influence on the groundwater flow system. A stream that receives groundwater discharge (a **gaining stream**) is a focus for shallow groundwater discharge and therefore influences the groundwater flow direction. If the stream provides recharge to the groundwater system (a **losing stream**) mounding on the water table near the stream should be anticipated. Installing multilevel wells at the edge of the stream or river will allow you to measure the vertical hydraulic gradient and to determine whether it is a gaining or losing stream. If streams flow for a fairly large distance over the site, consider using several evenly spaced multilevels because vertical flow gradients may change along the stream. Ponds or lakes also require installation of additional monitoring nests along their shores to determine if they are centres of groundwater discharge or recharge.

Springs are areas where upward groundwater flow discharges to the surface. Small creeks often have their **headwaters** at the spring. Often, dense vegetation, including **phreatophytes**, centre around the springs because of the available water. These indicators can help to locate springs in the field or from air photos. Installing a monitoring well cluster near the springs on the site can also provide information on the magnitude of the vertical hydraulic gradients.

Be aware of several other points regarding surface water bodies. Often, the flow in a stream or river, or the level of a lake, changes rapidly and drastically in response to rain storms or rapid snow melt. Because of this, the vertical hydraulic gradients may also change to the point where a gaining stream may become a losing stream. These changes can cause significant variations in groundwater flow directions on the study site, particularly when you are evaluating the long-term behaviour of the groundwater flow system.

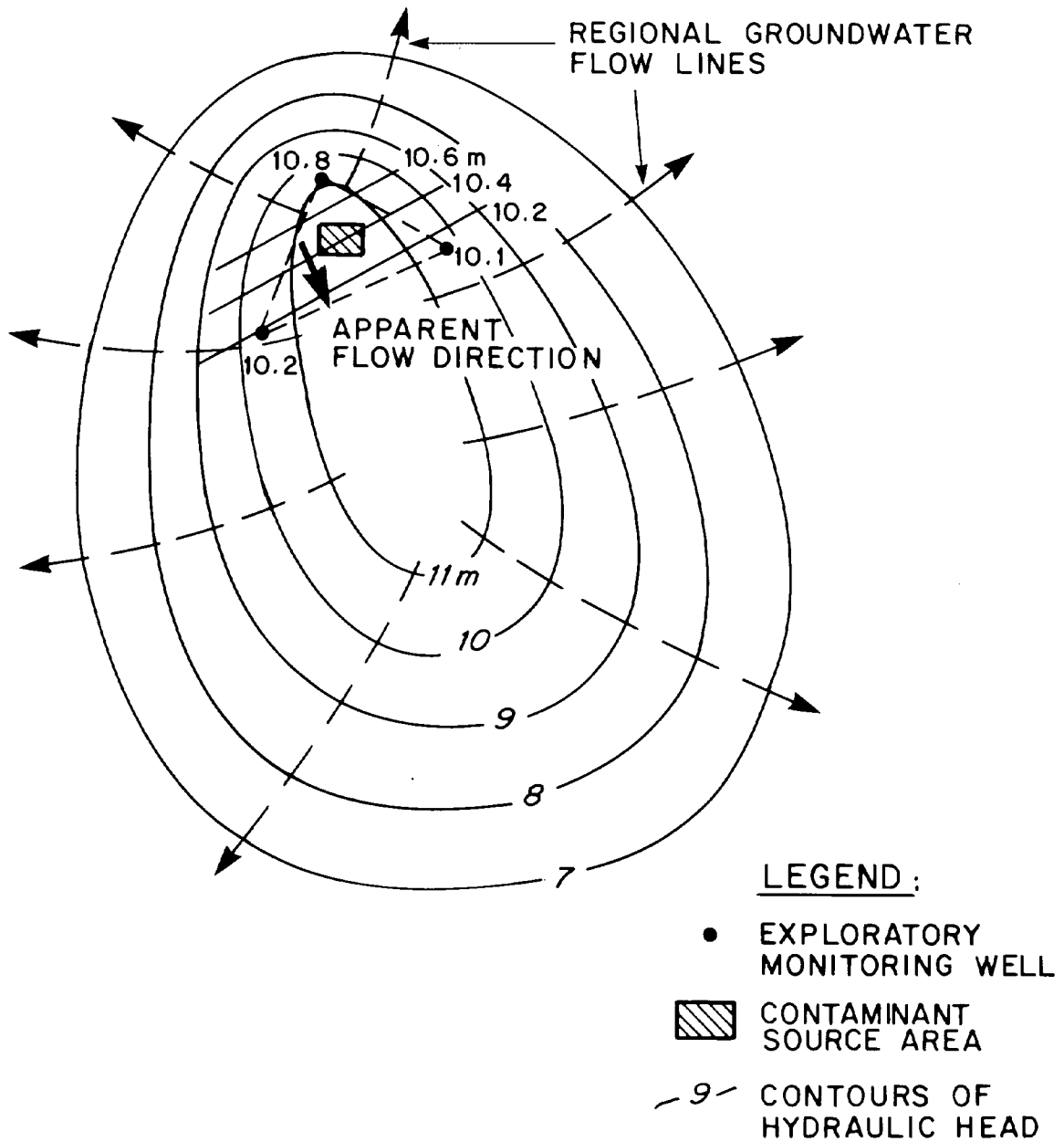


Figure 61 A Misinterpretation of Groundwater Flow Direction from a Three-well System

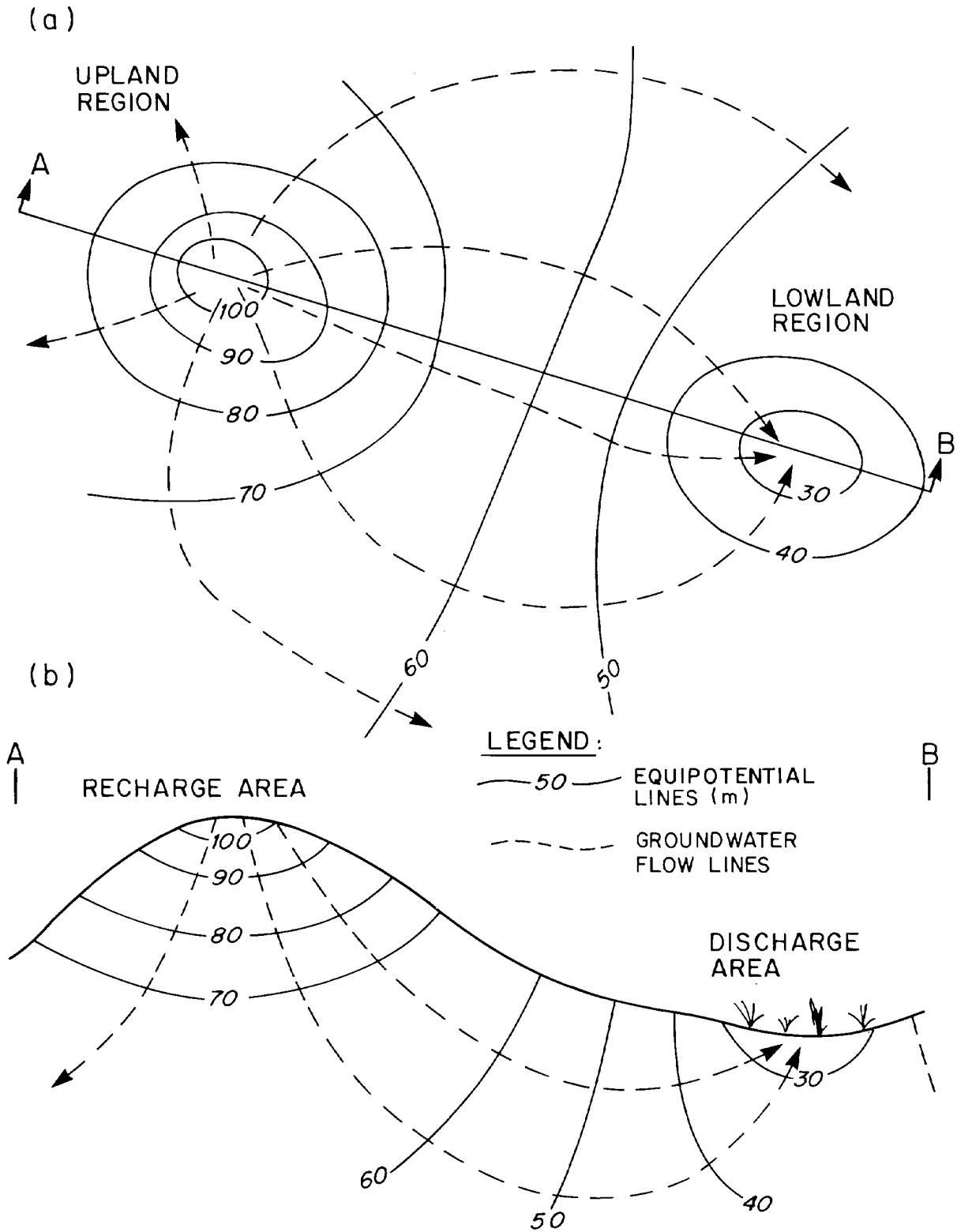


Figure 62 Groundwater Flow in the Vicinity of a Recharge and Discharge Area Shown in Plan View (a), and in Vertical Cross Section (b)

In some cases, surface water bodies may be isolated or disconnected from the shallow water table. This is referred to as a **perched** condition. When this occurs, unsaturated sediment separates the base of the surface water body from the water table. Under these conditions, the influence of the surface feature on the groundwater system is often insignificant. Monitoring of the unsaturated zone is discussed in Section 4.9.

4.4.3 Detailed Hydrostratigraphy and Quantifying Physical Parameters

Determining if you have sufficiently assessed the continuity of the hydrostratigraphic units across the site is very difficult. With the drill logs from the three initial test holes, you have the basic stratigraphy. If the units appear to have the same geometric configuration at each test hole, it may not be necessary to drill additional test holes specifically to map the hydrostratigraphic units. At large sites, several additional boreholes are generally warranted to ensure stratigraphic continuity, however, the additional monitoring wells placed near surface water features (see Subsection 4.4.2) may fulfil this requirement. If the preliminary data show that the critical units, such as the permeable aquifers, are thin or quite variable in thickness, a larger number of boreholes may be required. The exact number of additional test holes required is difficult to predict. Again, discussions with the contaminant hydrogeologist regarding efficient placement of monitoring points for geochemical mapping is recommended.

This process of extending the monitoring well network is an iterative, evolving one, based on the data recovered from each new borehole and a continually revised conceptual model of the site.

The final objective of the Stage 3 field investigation is to quantify the main physical hydraulic parameters that influence groundwater flow. This information is critical for numerical modelling (Section 6) and for the design of remediation strategies (Section 7).

To determine groundwater flow velocities and flow volumes, it is necessary to measure several characteristic hydraulic properties of the subsurface materials, including: porosity; permeability; hydraulic conductivity; **transmissivity**; **compressibility**; **specific storage**; **storativity**; and **specific yield**.

Selecting the appropriate technique depends on:

- the subsurface material involved;
- the type of samples available;
- the field instrumentation; and
- the type of contamination on site.

Try to obtain representative values of these physical parameters for each of the major hydrostratigraphic units encountered at the site. The samples collected during the coring operation at each borehole can now be taken to the laboratory for analysis. The commonly used laboratory measurements are presented in Subsection 4.8.1.

In general, it will not be necessary to conduct physical parameter measurements on all samples. If a given hydrostratigraphic unit appears relatively **homogeneous** throughout the site, only two or three laboratory measurements will likely be required to obtain a reasonable estimation of the physical parameters of that unit. Where the units appear to change character significantly at the different boreholes, additional lab measurements will be warranted. Discussions with the modeller (Section 6) may help to decide how many measurements should be done.

In addition to the laboratory parameter measurements, several *in situ* or field-scale techniques are available to estimate some of the physical parameters required. These include individual monitoring well tests and pumping tests (see Subsection 4.8.2). It is recommended that single well tests be conducted on every monitoring well installed on-site because the tests are usually simple to conduct and generally provide valuable information. The choice of whether to run an extensive pumping test will depend on many factors including budget and potential problems with mobilizing contaminants during this test.

One of the most difficult decisions of the hydrogeological site investigation will be whether sufficient data have been collected in Stage 3 to terminate the field investigation. The field hydrogeologist must consult with the contaminant hydrogeologist and the mathematical modeller to determine whether enough information is in hand to define the hydrogeological conditions on-site to a sufficient level. Once a consensus is reached, the investigation program can move to Stage 4, reporting of the information (Section 4.11).

4.4.4 Long-term Monitoring

If possible, take water level readings every 2 to 4 weeks during the entire year, and more frequently during periods of intense infiltration such as spring melt. The water levels in the wells may fluctuate considerably in response to seasonal changes. Groundwater flow directions and rates will also vary accordingly. These variations can have a considerable influence on the migration characteristics of contaminants in the groundwater. There are also automatic recording systems that permit continuous or time-variant remote monitoring of well water levels.

4.5 Drilling and Sediment Sampling Methods

This section briefly reviews the most common drilling and sediment sampling techniques used in contaminated site investigations. Section 4.12 refers you to several other documents for a more complete coverage of the topic.

Obtain the services of a drilling contractor experienced in site assessment drilling. The requirements are different than in water well drilling or geotechnical drilling and the assessment quality will reflect the ability of the contractor.

4.5.1 Drilling Methods

Cable Tool. The cable tool drilling technique falls into the general category of **percussion drilling**. With this technique, a massive, chisel-type **bit** is connected to a weighted **drill rod** and the drill rig lifts and drops the entire **drill string** repeatedly in the borehole to break or crush the geologic material [Figure 63(a)]. The cuttings are removed from the borehole by extracting the

drill stem and lowering a **bailer** to retrieve the cuttings. For the bailer to be effective, sufficient water must be present in the hole to develop a liquid slurry of the cuttings. In low-permeability geologic materials that do not produce sufficient water to form a slurry, or in unsaturated sediments, you must add clean water to the borehole.

When drilling in **unconsolidated materials**, it is common to advance a steel casing along with the drill bit to avoid collapse of the borehole. **Consolidated materials**, on the other hand, are often drilled without the use of casing.

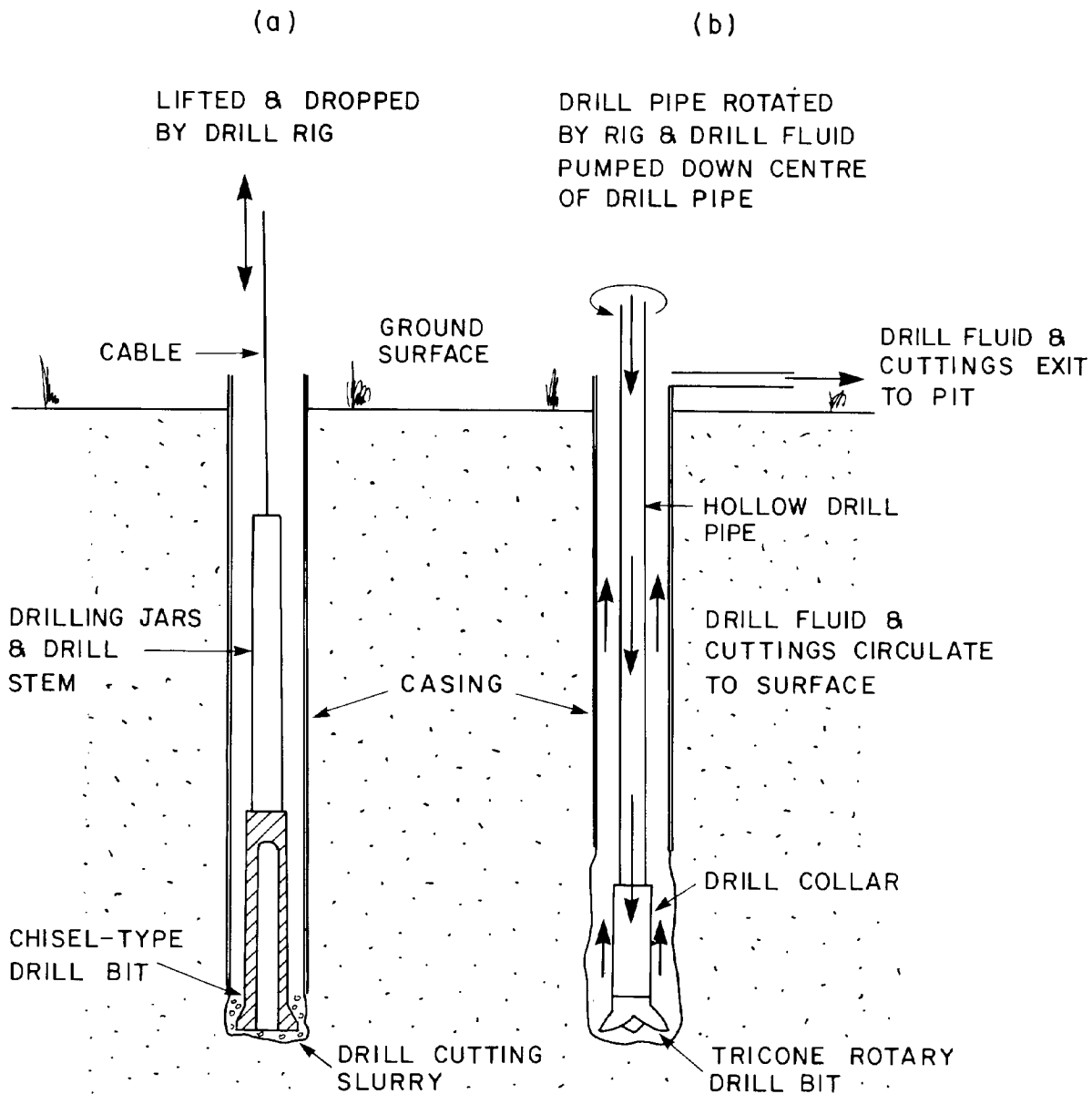


Figure 63 Schematic of: (a) Cable Tool Drilling; and (b) Direct Mud Rotary Drilling

Cable tool drilling is generally very slow (an average drilling rate of 5 to 8 m/day). When drilling in consolidated or highly compacted sediments, the pounding action tends to destroy the geologic material; therefore, the samples bailed from the borehole may not be representative of the *in situ* material. In addition, the need to add water to form the cutting slurry may jeopardize subsequent water quality monitoring.

The cable tool technique has the advantage of being able to drill to great depths in any type of geologic material. The stratigraphic logs that drillers produce tend to be very detailed because of the slow advance of the drill bit. Alteration to the side wall of the borehole also tends to be minimal. Simultaneously installing borehole casing provides for efficient monitoring well installation. Because you remove the cable tool bit from the hole each time you bail the slurry out, you can clean the bit continuously, which minimizes the chance of carrying shallower contaminants downward.

Rotary Drilling. The rotary drilling methods are the most commonly used for water supply well drilling and are therefore available in most places. The drilling process involves the rotation of a bit and drill stem while a fluid is circulated through the drill stem and back to the surface to continuously remove the drill cuttings in the vicinity of the bit. Rotary methods are categorized by the type of fluid used for lifting the cuttings and by the direction in which the fluid is circulated.

The direct mud rotary technique uses a liquid circulation fluid, generally consisting of a suspended clay slurry, that is pumped down the centre of the drill rod, out through the drill bit and back up the borehole in the **annulus** between the drill stem and the borehole wall [Figure 63(b)]. It is fairly rapid and has a large depth range. It can be used in nearly all materials.

As part of the process, drilling mud is forced into the formation as the bit advances and forms a mud cake along the borehole wall. This assists in keeping the uncased borehole from collapsing during drilling. Introducing the drilling fluid into the geologic formation can cause modification of groundwater quality. This may influence future sampling programs.

The installation of a monitoring well is generally done while the borehole is filled with the drilling fluid. The drilling fluid must ultimately be flushed from the monitoring well to insure it does not significantly influence the response of the well.

You can obtain samples of the drilled material by filtering the cuttings out of the circulating drill mud. These samples tend to be highly disturbed and, as a result of the mixing process in the annulus, you cannot always determine the exact depth from which they came. Therefore, detailed stratigraphic logging is often difficult.

Another drilling system is the air rotary method. The process is the same as the mud rotary except that the drilling fluid is compressed air. This technique is generally used in consolidated materials, but, if a casing is driven down as the bit advances, you can use it in unconsolidated materials as well. This technique has the advantage that drilling does not introduce foreign fluid into the formation during drilling. The samples forced to the surface from the bit are highly

disturbed but they tend to be more representative of the material currently being drilled because of the shorter travel time in the borehole annulus.

A foam agent may be mixed with the circulating air to aid in lifting the drill cuttings. However, this foam can enter the formation and alter the chemistry of the groundwater. You must take care to remove any lubricating oils from the circulating air as these can also influence the groundwater quality. Installing a casing as drilling proceeds permits convenient construction of the monitoring well. You can then remove the casing after the well has been constructed. High pressure lifting of drill cuttings can result in contaminated material or water being brought to the surface rapidly. Take care to protect the drill crew and the environment.

As with the mud rotary system, you can use this technique to drill very deeply. With the casing driver, it will function in both consolidated and unconsolidated materials.

Another technique used in unconsolidated sediments is the dual-wall reverse circulation rotary method. With this system, you pump the drilling fluid, generally air, down the annulus between the drill rod and an outer casing that advances with the bit. The air picks up the cuttings and circulates them to the surface through the centre of the bit and up the drill rod. This method has all the advantages of the air rotary system but also permits the collection of more representative samples of the drilled materials.

Solid-Stem Auger. For the installation of shallow monitoring wells, continuous flight auger drill rigs are the most common and desirable techniques. The solid-stem **auger** consists of a cutting-style drill bit connected to a spiral auger drill stem [Figure 64(a)] that is rotated by the drill rig. As the bit cuts through the subsurface materials, the continuous spiral **auger flights** or blades convey the cuttings up to the surface. Augers can vary in diameter from 10 cm to over 50 cm. This drilling technique is only suitable in relatively soft, unconsolidated sediments.

Samples from the auger drill stem or flight are collected at the surface of the ground, but it is often difficult to tell the depth from which they were derived. The samples also tend to be highly disturbed by the drilling action. To collect undisturbed samples or install a monitoring well, you must completely remove the drill stem from the borehole. This may result in formation collapse, especially below the water table.

This technique does not use drilling fluid. Drilling is quite rapid and in most unconsolidated sediments, the drilling depth is limited to approximately 40 m. There are also very portable techniques available that can be carried to site manually. These are quite practical where site access is limited. However, the portable units are often more restricted in drilling depth.

Hollow-Stem Auger. Likely the most versatile technique for installing monitoring wells and collecting undisturbed samples is the hollow-stem auger system. This method operates in the same way as the solid-stem auger, but the central drill rod on which the auger flights are welded has a larger diameter and is hollow [Figure 64(b)]. During drilling, a plug is placed at the end of a centre drill rod to keep materials from entering the interior of the auger. The outside auger flight and the inner drill rod and plug advance together into the sediment. Once you reach a desired target depth and the centre rod and plug are removed, you can either retrieve a sample of

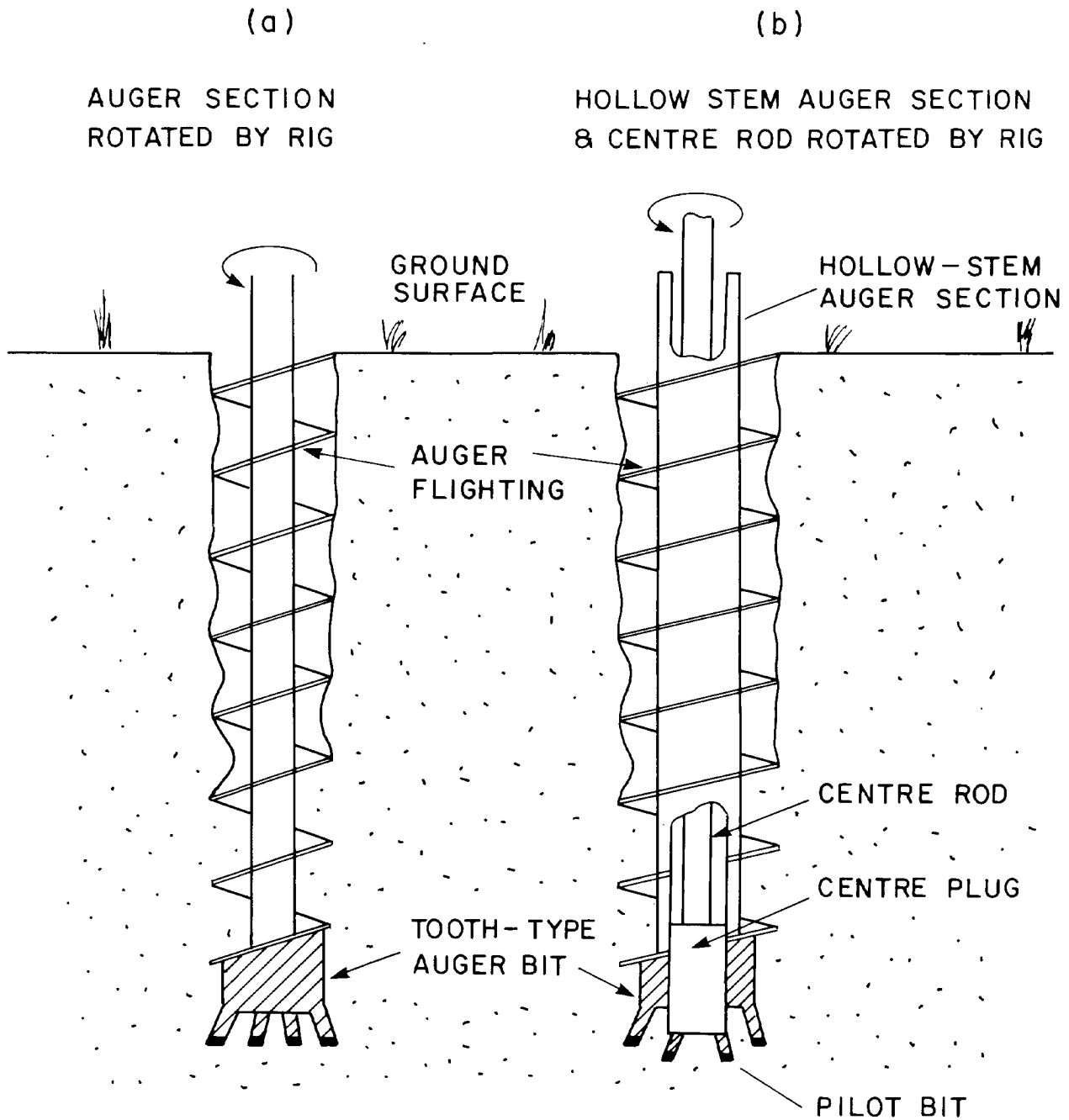


Figure 64 Schematic Illustrating the Difference Between: (a) Solid-stem Auger Flights; and (b) Hollow-stem Auger Flights

the undisturbed material below the bit, or place a monitoring well within the central part of the auger flight while the flights are removed from the ground.

This technique has the same limitations as the solid-stem auger system with respect to sediment type and maximum drilling depth. However, you do not have to remove the augers each time you require a sediment sample, and monitoring wells are easy to install. Therefore, hollow-stem augering is much more desirable for site investigations.

If the material being augered is fairly loose, it is common for sediment at the bottom of the augers to rise up into the auger string when you remove the centre plug. In these situations, you can add water to the augers to counteract this. Although this water will not likely enter far into the formation, the potential exists for modification of the water chemistry by its introduction.

4.5.2 Caution — Drilling in Contaminated Areas

Avoid drilling through contaminated zones. Angle drilling may permit sampling from under a contaminated zone without penetrating the contaminated materials. When you must drill through contaminated zones consider installing casing securely **grouted** or cemented into a **confining layer**. Then you can decontaminate the interior of the casing and advance a smaller-diameter borehole through the bottom of the casing. Alternately, an air rotary method combined with a casing driver or a dual-tube air percussion method (Holsten and Morgan, 1989), may reduce contamination.

Of particular concern at the drilling stage is the potential to “carry down” DNAPLs. This “carry down” has two implications:

- environmentally significant contamination may be spread to lower zones; and
- subsequent groundwater samples will reveal the DNAPL components at greater depth than they were prior to drilling. (This could produce inappropriate effort evaluating hydrogeological pathways to depth, when the pathway was not natural, but caused by the drilling.)

Where DNAPLs are pooled on less-permeable layers (**aquitards**), drilling through this zone may provide a path for DNAPLs to continue moving to greater depths. Therefore, aquitards should not be penetrated in the early stages of site characterization. You may also consider initially drilling only in areas well-removed from potential DNAPL occurrences. Only when there is no indication of DNAPL (see Feenstra *et al.*, 1991 for suggested indicators), should you drill through aquitards. Alternately, you could install an intermediate casing.

4.5.3 Sediment Sampling Methods

In nearly all hydrogeological site investigations, sampling of the subsurface materials is a significant and vital component of the field program. There are many alternative techniques available for the collection of samples and the selection of the most appropriate one in any given case depends on:

- the objective of the sampling program;
- the type of material being sampled; and
- the drilling technique being used.

In designing the sampling program, consider the end-use for the samples. As an example, if you require general **lithologic** information in a borehole, drill cuttings generally provide samples of sufficient quality. If you plan to carry out laboratory tests on the samples, then samples as representative of the material as possible are required and cuttings will not be sufficient. This subsection presents several of the most common sampling techniques and Section 4.12 directs the reader to additional references for further information. For the most part, the sampling methods presented are compatible with the drilling techniques that have been discussed.

Samples from Drill Cuttings. During any drilling operation, the cutting action of the drill bit produces fragments of the geologic material being penetrated. In a preliminary drilling program, you can use these cuttings to provide basic information on mineralogy, grain size, and stratigraphy. Samples that you take from the cable tool bailer represent the last advancement of the bit. In relatively coarse-grained unconsolidated material, such as sand or gravel, the bit may help loosen and mix the material at the base of the borehole. Thus, although completely remixed, the bailed samples may be quite representative of the material.

With both the direct and the reverse circulation mud rotary techniques, the circulating drilling fluid transports cuttings from the bit to the surface of the ground in a thick clay-rich slurry. To get a representative sample from a specific depth, the common practise is to cease advancement of the drill bit just above the point of interest and circulate the drilling fluid with the drill rod rotating until the borehole has been cleared of cuttings. The drill bit is then advanced a short distance and the fresh cuttings are trapped in a settling tank on surface.

As the cuttings are lifted to the surface, clay and silt-size particles may be lost and the sample may not be representative. Often material erodes from the borehole wall as the drilling fluid circulates and is incorporated into the cuttings from the bit. Obtaining reasonably representative samples from depths greater than 180 m is extremely difficult with this technique.

Cuttings with the air rotary method are transported very rapidly to the surface. Therefore, it is easier to interpret the depth from which they were derived. There also tends to be less side wall material mixed with the fresh cuttings than when drilling mud is used. Samples collected from the air rotary rig generally contain all grain sizes and are therefore more representative of the subsurface material.

In the auger drilling techniques, samples of stiff sands and silts and cohesive soils come to surface in a disturbed form, but generally with the full grain-size distribution intact. In softer sediments, samples may be forced back into the borehole side wall or may fall back down the hole as caving occurs, making sampling impossible.

An effective technique for collecting drill cutting samples with the auger rig is to carefully rotate the auger flight into the sediment you want to sample and then stop the auger rotation and extract the flight with the blades filled with relatively undisturbed sediment. By doing this, you can ensure that the depth of sampling is more exact and that the samples collected are more representative of the formation.

Core Samples. In many cases, samples of drill cuttings are not enough to obtain the required physical or chemical information. For laboratory measurement of hydraulic conductivity for instance, undisturbed, continuous core samples are preferable.

The most common coring technique for unconsolidated sediments is the split-spoon sampler. This device consists of a hardened steel **drive shoe** screwed onto a hollow steel tube that is split down the middle. The top of the tube is connected to a head assembly that attaches to the drill rod [Figure 65(a)]. The core tube is 45 or 60 cm in length and is commonly between 5 and 10 cm in diameter.

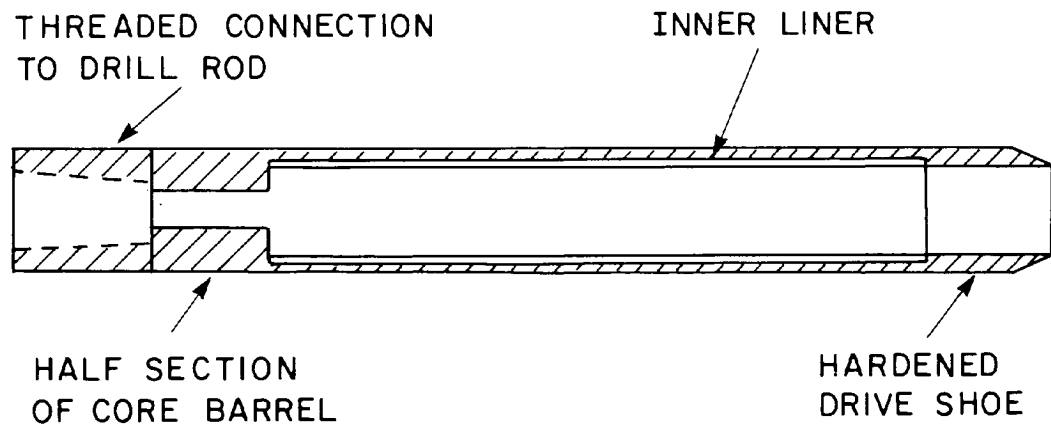
You can advance a borehole to just above the region where you require a sample with any of the rotary or auger techniques discussed. Remove the drill rod from the hole and lower the split-spoon sampler back down to the bottom. With the hollow-stem auger you need only remove the centre rod; the auger flights act as a temporary casing, keeping the hole from collapsing during the sampling procedure. The sampler is then driven into the sediment by a hammering device on the surface. The number of blows required to advance the sampler its full length is recorded. You can use this information to interpret stiffness characteristics of the unconsolidated sediment. This is referred to as the standard penetration test (Lambe and Whitman, 1969; Craig, 1978, American Society for Testing and Materials Publication D1586-84).

The sampler is retrieved and the core tube split open to examine or remove the sample. You can then advance the borehole to the next sampling interval and repeat the sampling procedure. You can also fit the split spoon core barrel with a thin inner liner that acts as a protective container for the sample when it is shipped to the laboratory.

The samples collected from the split-spoon method are generally somewhat disturbed because of the pounding action of the hammer. If the drill rod must be removed each time, there is always a possibility of side wall collapse or heaving at the base of the hole. This would mean that the sample collected might not be representative of the material at the target depth. The hollow-stem auger rig provides the most efficient and reliable method of collecting the split-spoon sample because the sample can be taken below the bit inside the augers by only removing the centre stem. Again, the augers may have to be filled with water to minimize heave.

The solid-barrel sampler is a tube that is not split down the middle but contains an inner liner that will house the sample as it enters the drive shoe. You can remove the liner at the surface. These samplers range in length from 30 to 150 cm and in width from 3 to 15 cm. The solid barrel sampler is commonly used with rotary rigs and can collect very high quality samples. With the exception of extremely stiff and compact sediments, the drive-sample methods are suitable for all types of unconsolidated materials.

(a)



(b)

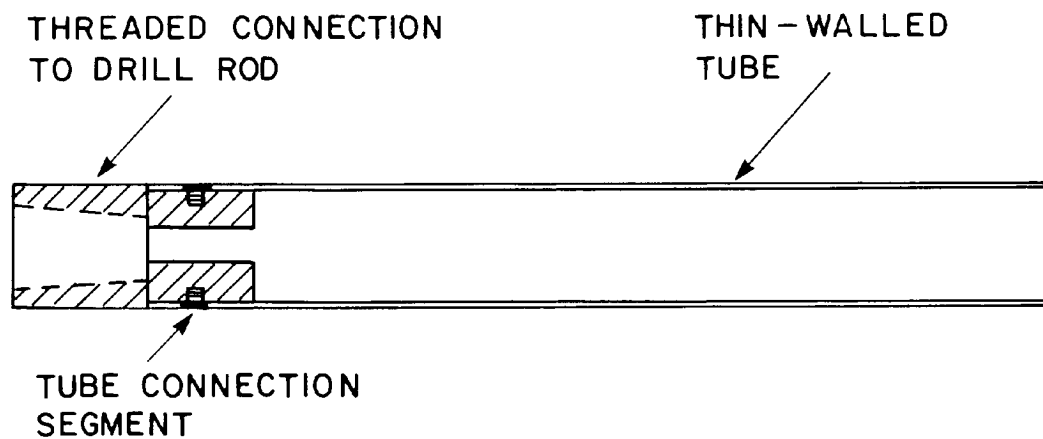


Figure 65 Illustration of: (a) Split-spoon Core Sampler; and (b) Shelby Tube Core Sampler

To minimize sample disturbance from the heavy drive shoe, you can use thin-walled tube samplers (Shelby tubes). The sampler consists of a steel or hardened aluminum tube, between 75 and 90 cm in length, and between 5 and 10 cm in diameter. It is sharpened at the cutting end and fastened to a connecting head on the drill rod. The wall thickness of the sample tube is approximately 1 mm [Figure 65(b)]. Instead of pounding with a hammer, the drill rig hydraulically pushes the Shelby tube into the surface material. In this way, sample disturbance is minimized. This technique is suitable for collecting samples of soft to fairly stiff clay and till or loose to fairly compact silt to fine gravel. If the sediments are very stiff or compact, the thin-walled tube may collapse while being pushed. In addition, coarse-grained sediments such as gravel, tend to fall out of the sample tube during retrieval and the sample recovery tends to be low. Samples collected with this method are generally of extremely high quality and are suitable for most laboratory measurements. More details on thin-walled sampling is found in the American Society for Testing and Materials Publication D1587-83.

Several specialized sediment samplers are available. Typically, a solid-barrel sampler (generally using a liner), or a thin-walled tube sampler, is fitted with an internal piston that can move along the inner wall of the sample tube as the sediment enters. The main advantage of the piston is that when you retrieve the sample, the suction generated between the piston and the pore water in the sample helps to keep the sample intact while it is lifted out of the borehole. For example, Zapico *et al.* (1987) developed a solid-barrel sampler with a piston assembly that you can use with a hollow-stem auger rig to collect undisturbed samples of very coarse sediment [Figure 66(a)]. Another system (Starr and Ingleton, 1992), is a thin-walled piston sampler that you can operate manually, without a drilling rig [Figure 66(b)], to take cores in saturated, unconsolidated materials to depths of at least 20 m.

You can also obtain undisturbed samples with core barrels. In this type of sampling, the drill bit cuts around the outside of a core of undisturbed sediment or rock, the core moves up into a stationary tube or core barrel, and the drill stem advances deeper into the borehole. For unconsolidated materials, a hollow-stem auger is used, and a core barrel is positioned on the end of a central rod or wire line to replace the centre plug [Figure 64(b)]. After drilling the length of the core barrel into the sediment, bring the core barrel back to surface and place an empty core barrel down the centre of the auger so that the next sample can be taken. In this way, the sediment can be cored continuously and efficiently. The same type of system can obtain cores of rock; however, a high speed rotary rig and a drilling fluid is generally necessary.

4.6 *Monitoring Well Installation Techniques*

After the test borehole is drilled, the subsurface material is sampled, and an adequate stratigraphic log is prepared, you can install an appropriate monitoring device in the borehole to permit sampling of the groundwater, measurement of piezometric levels, and possibly, geophysical logging (Subsection 3.3.13). Selection of the appropriate monitoring well design and installation method depends on the:

- type of subsurface material encountered;
- number of vertical monitoring points required per borehole;

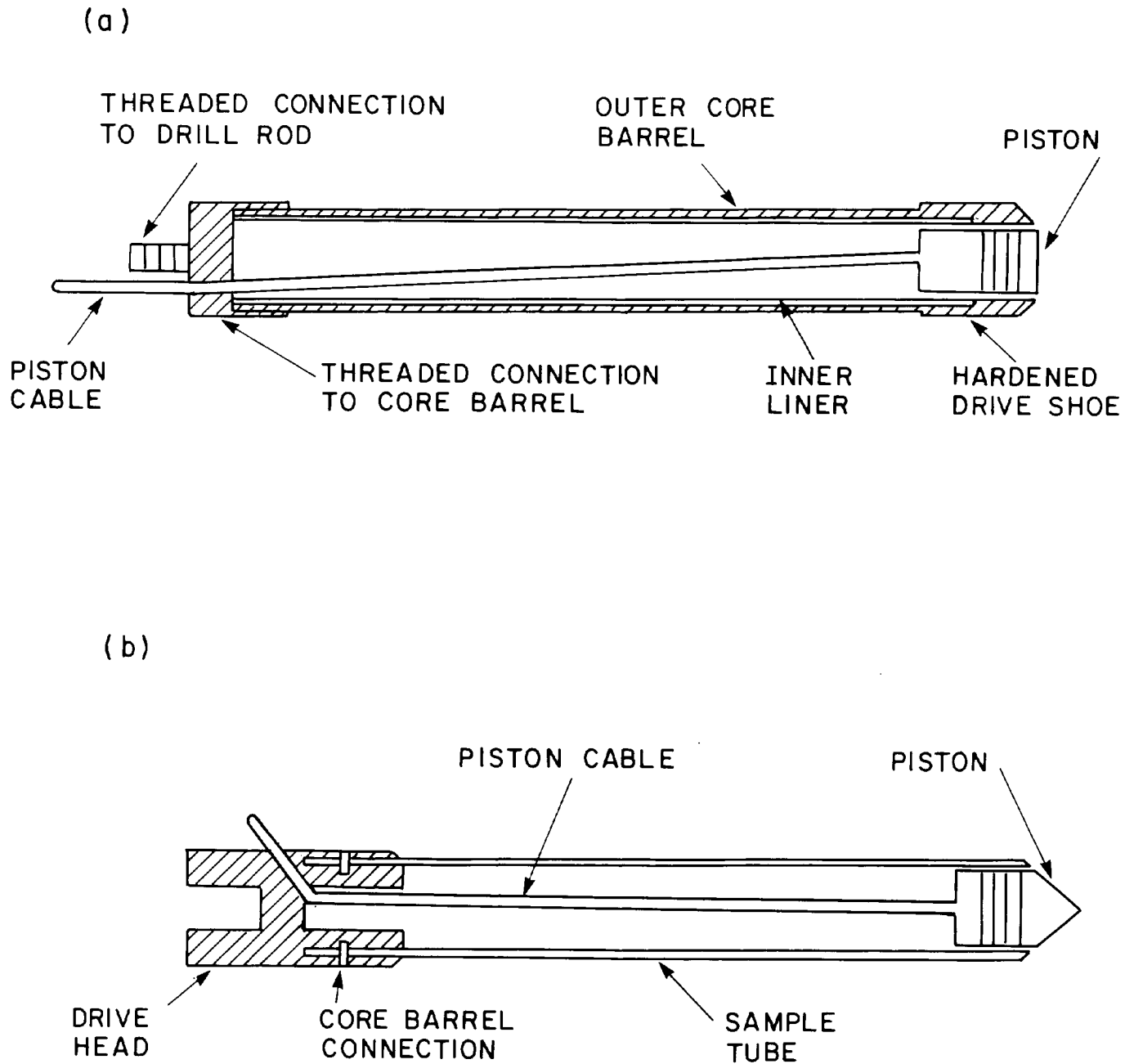


Figure 66 Illustration of: (a) A Piston Core Sampler (After Zapico *et al.*, 1987); and (b) A Manual Core Sampler (After Starr and Ingleton, 1992)

- drilling method used;
- types of contaminants to be monitored; and
- end use(s) of the monitoring device.

In all monitoring well installations ensure that:

- the **well screen** is completely isolated in the borehole at the specified depth;
- the borehole wall near the screen is not severely modified by the drilling operation;
- the groundwater quality has not been significantly modified by the drilling process;
- the diameter of the well casing is large enough to permit access of water level, water sampling, and geophysical equipment (if required); and
- the material used to construct the well is compatible with the contaminants being monitored (see Section 5.4 for specific considerations).

4.6.1 Drive-point Wells

The simplest and least expensive technique to install a monitoring well is to drive the well screen and casing down to the desired depth with a hammering device. High quality monitoring wells can be installed rapidly. This method does not need a drilling rig; for example, a gasoline-powered jack hammer or rock drill can be used to advance the drive point to the desired depth. The drive-point well consists of a steel or stainless steel tip and screen assembly that connects to standard black iron, steel, or stainless steel pipe that serves as a drive casing. At the surface, a drive head connects to the casing pipe, allowing the device to be pounded into the subsurface. Commonly, a polyethylene tube is connected to the well screen and run up the inside of the drive casing to ground level. The groundwater entering the drive-point monitoring well then only comes in contact with the stainless steel and polyethylene tube (Figure 67).

Drive-point monitoring wells commonly range in diameter from 1.5 to 3 cm. They have been successfully installed in soft sediments, such as loose sand and gravel deposits, to over 20 m, and in soft clay, to over 30 m. The length of the screen commonly ranges between 20 and 100 cm. No foreign fluid is introduced and the *in situ* conditions are only minimally altered. Also, because of the vibrating driving action of the installation process, there is no need to use a seal or backfill material to isolate the tip. You can install the drive-point wells at nearly any angle.

There are also several other drive-point type monitoring well installation systems. One is designed to be pushed into soft sediments by a drill rig (Desaulnier, 1983; see Figure 67b). The drill casing (5 cm) is placed over the well screen and well casing and sits on a broader drive-point tip. The drive-point tip is forced into the subsurface material by a pounding device or a hydraulic press and the well screen and casing are pushed in along with the drive-point tip. At the desired depth, the drill casing is pulled out of the hole, leaving the drive-point well and the tip in place. **Bentonite** rings, placed around the casing above the well screen, are now in contact

with the formation water and expand to seal the well screen at the selected depth (in case the formation material does not collapse around the well casing).

4.6.2 Drilled Individual Monitoring Wells

The most common type of monitoring well is the individual well installed in a drilled borehole. Consider the following during the monitoring well construction and the installation process:

- the purpose of the well, especially chemical sampling (see Section 5);
- the nature of the borehole produced by the drilling operation;
- the type of subsurface material encountered;

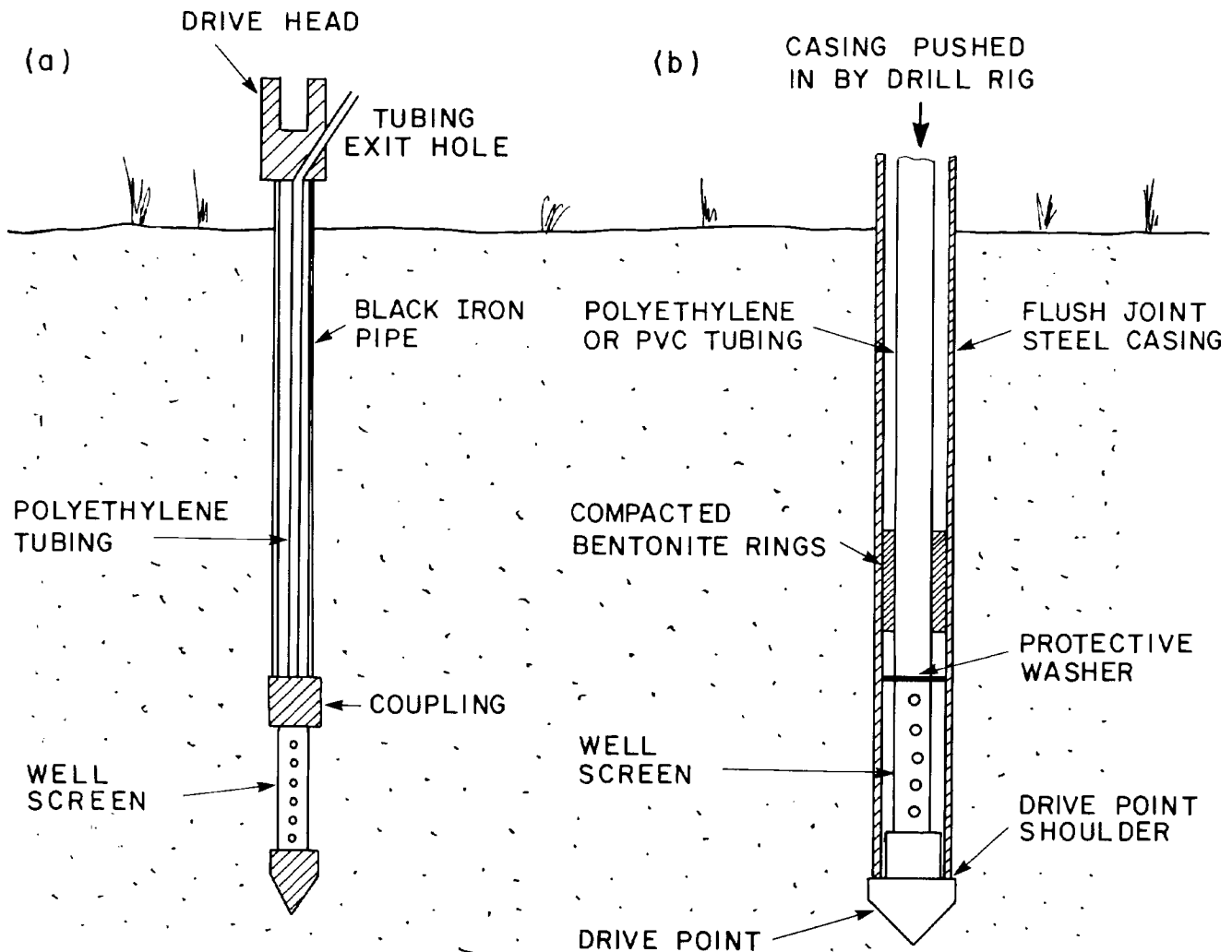


Figure 67 Drive-point-type Monitoring Wells: (a) Standard Drive-point Well; and (b) A Push-type Monitoring Well (After Desaulnier, 1983)

- the contaminant type;
- the length of the well screen;
- the diameter of the well casing;
- the filter pack and backfill material;
- the well construction material; and
- the surface completion.

Place the selected well screen and casing down into the borehole to the required depth. Install permeable **filter pack** material around and slightly above the well screen to allow groundwater from the adjacent formation to flow freely to the well screen. The material should be chemically inert (e.g., quartz sand). Above the filter pack, place a sealing material (e.g., expandable clay) to isolate the well screen from the rest of the borehole. You then backfill the annulus above the **seal** with a clay slurry or cement **grout** to the surface (Figure 68a). Install a protective cover over the well casing at ground level for security and to prevent precipitation from entering the well.

These types of monitoring wells commonly range from 2 to 10 cm in diameter. They are typically constructed of steel, stainless steel, PVC, or teflon, depending upon the requirements for chemical sampling (Section 5.4). The screen that you select for the monitoring well depends on several factors, including the grain-size distribution of the material and the nature of the contamination. The most common types of screens are the machine-slotted and the continuous-slot, wire-wound types. The screen (and filter pack) should ensure that formation water can pass easily into the monitoring well. This also facilitates measurements of hydraulic parameters. However, a screen with smaller openings (and a finer filter pack) may be desirable to exclude silt from subsequent chemical samples. Consider the end-use of the monitoring well before selecting the screen and filter pack size.

The length of screen in the monitoring well has a significant impact on both the mapping of groundwater contamination and the measurement of hydraulic head. If you use a short well screen (10 to 50 cm), a small section of the subsurface material will provide water to the monitoring well. The advantage of this is that you can make depth-specific measurements of hydraulic head and water chemistry. However, a short well screen may not intercept the contaminated zone and you may erroneously conclude that no contamination exists. Multiple wells may be needed.

Do not use well screens longer than about 5 m. Groundwater from over the entire screened section can enter the well and the water sample will be a mixture from the total depth. Dilution may be so great that you may not detect low concentrations of contaminants in narrow zones. Long screens also provide open conduits for contaminants to freely circulate in the borehole and throughout the formation. An additional problem is that the hydraulic head measured in the full screened well is a depth-averaged value. If significant vertical gradients exist, you may find it extremely difficult to interpret the hydraulic head data.

The most common materials used to form borehole seals are either a swelling clay (referred to as bentonite) or cement. These materials tend to expand somewhat in contact with water after you place them in the borehole and they adhere well to the borehole wall and well casing. Commonly, you install bentonite in a dry form as powder or as a small pellet, and the cement mixture as a liquid slurry. You can also mix these materials.

Both bentonite and cement may alter the chemical nature of the groundwater that enters the monitoring well. Fortunately, little water actually contacts the seal; therefore, this problem is rarely serious with well constructed seals. When sand pack and seal material are inadvertently mixed during installation, major problems may result. Groundwater pH levels above 10 are usually the result of contact with cement. More details are available from the general references in Section 4.12.

In **cohesionless** material such as sand or gravel, you may not have to use a filter pack and seal. Below the water table, the borehole generally collapses around the well after you remove the drill stem or temporary casing. In these types of sediments, the hollow-stem auger rig is the most convenient system to use. Advance the borehole to the desired depth, remove the centre rod and plug, and lower the well screen and casing into the open central part of the auger. Once you have placed the well at the base of the augers, pull the augers back out of the borehole, allowing the *in situ* material to collapse on the well (Figure 68b).

At depths greater than about 40 m, you may have to use either a cable tool rig or a rotary rig. With the cable tool, you advance the hole to the selected depth and install the well inside the temporary casing. When the casing is removed, the formation can collapse around the monitoring well. When using a mud rotary rig, install the monitoring well in the drilling fluid that remains in the hole (keeping it from collapsing). In this case, use a filter pack and seal to complete the well. In addition you must flush the drilling fluid from the well and filter pack to ensure that the formation water can easily flow to the well screen.

You can use both solid-stem and hollow-stem augers to install individual monitoring wells in **cohesive** sediments such as clay. However, the hollow-stem auger is generally more convenient. The augering process tends to disturb and smear the borehole side wall. To minimize the effect of this smearing, drive a small diameter Shelby-tube sampler into the undisturbed material. The diameter of the thin-walled tube should be just slightly larger than the well screen. Place the monitoring well into this cored hole and install a filter pack material around and just above the screen (Figure 68c). Because the borehole will likely collapse, you must place a seal material above the sand pack and backfill the rest of the borehole to the surface.

Auger rigs are generally only useful to depths of about 40 m. Below this, you can use a cable tool or mud rotary rig in the cohesive sediments. If you use a mud rotary rig you can circulate clean water through the borehole once you achieve the specified drilling depth. This will flush the drilling mud from the borehole. Use a thin-walled sampler to core a small hole below the depth of drilling for the monitoring well screen.

In rock, use a cable tool, rotary, or rock coring rig. The well completion technique is similar to the technique used in cohesive sediments (a filter pack, seal, and backfill; see Figure 68a).

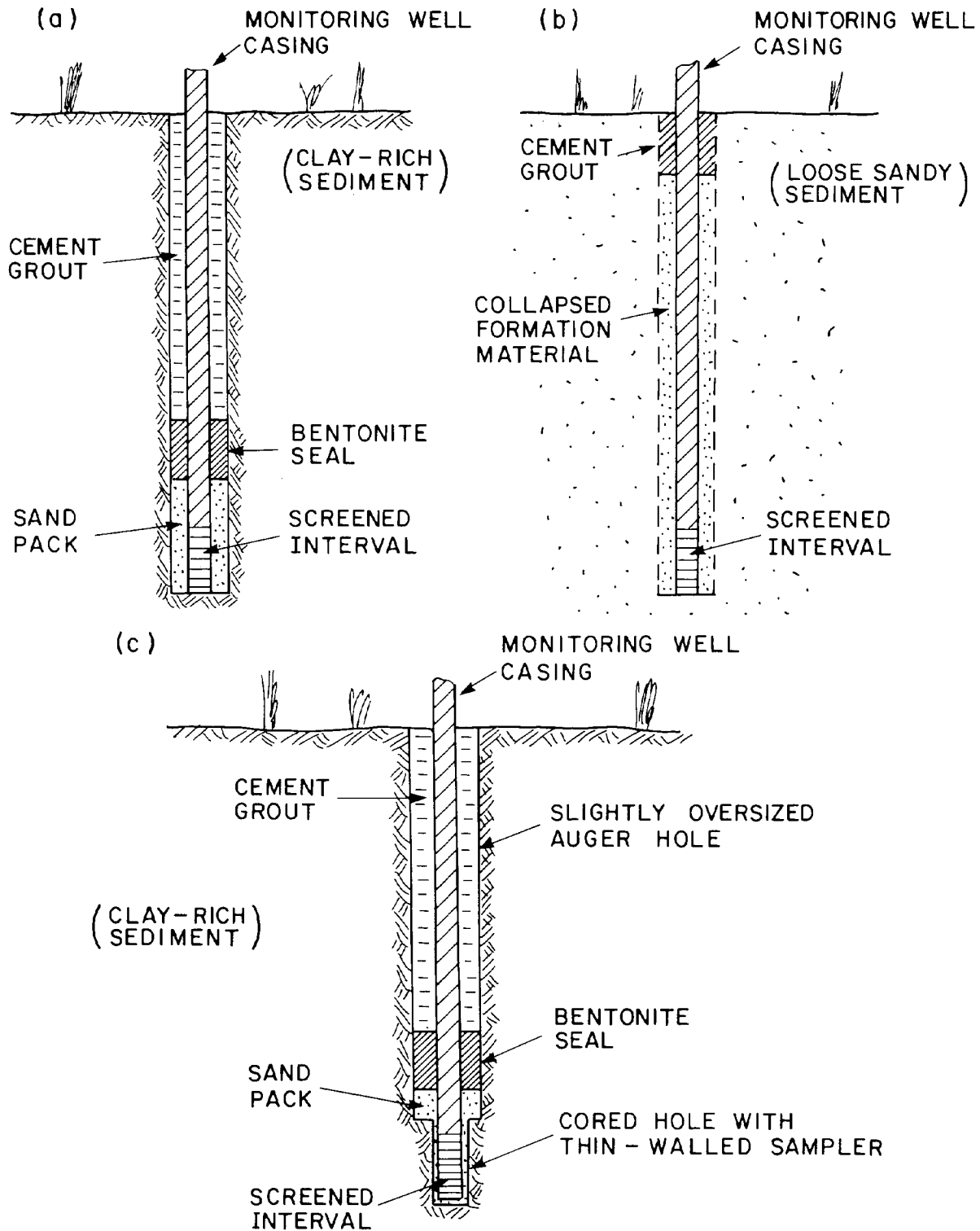


Figure 68 Typical Completion of Individual Monitoring Wells in: (a) Cohesive Material; (b) Cohesionless Material; and (c) Cohesive Material (with a Shelby-tube Cored Bottom to Minimize Side Wall Disturbance Around the Screen)

You will find further details on the design and installation of individual monitoring wells in American Society for Testing and Materials Publication D5092-90.

4.6.3 Clustered and Multilevel Monitoring Wells

In most site investigation programs, you must measure the vertical distribution of hydraulic head and contaminant concentration. To obtain this data, you must place monitoring wells at various depths at a single location. Use either individual clustered wells, or multiple wells installed in a single borehole. Several alternative designs are listed in Table 8 and illustrated in Figures 69 and 70. Choices include:

- one well per borehole, with multiple boreholes;
- multiple wells, screened at different depths, per borehole;
- a single well, with multiple sampling ports per borehole; and
- a single borehole or fully-screened well with a packer-isolated sampling interval moved up or down the borehole.

The choice often depends on the subsurface material and the drilling method available.

Multiple wells per borehole are cheaper and more rapidly installed than the equivalent number of individual wells, each in its own borehole. All the drilling techniques described for single well installation in unconsolidated materials are applicable to multiple well installations. Care must be taken to ensure the integrity of the seals between the various levels. For consolidated materials, consider using either the filter pack-seal sequence shown in Figure 69b, or the packer systems (either Westbay® or the “Waterloo system”; see Table 8 and Figure 70).

4.7 Recommended Methods for Specific Hydrogeological Settings

Section 1 introduced five conceptual hydrogeological settings as a framework for discussing various aspects of the site investigation process. This section groups the scenarios, in somewhat more general categories, based on the physical nature of the materials involved. The applicability of the various drilling, sediment sampling, and monitoring well design technologies are then reviewed in terms of these conceptual settings. The section aims to provide advice regarding the most appropriate techniques to select for a specific set of site conditions.

4.7.1 Unconsolidated Noncohesive Geologic Materials

The unconsolidated, cohesionless sediments include granular materials ranging from coarse gravel to fine sand and silt — materials considered in Setting 1, porous, non-fractured material. During drilling, these materials usually collapse back into the borehole when you remove the drill stem. This can make sampling and continued drilling difficult. Drilling fluids may be necessary, but these can impregnate the side wall sediments causing extensive contamination of the natural groundwater in the vicinity of the borehole and modifying the hydraulic properties of the adjacent *in situ* material.

Table 8 Some Systems Allowing Multiple, Vertical Sampling of Groundwater. The Settings are Numbered as in Section 1.

Method	Settings Where Used	Description	Features & Limitations
Double packer sampling	1, 2, 3 consolidated	Open borehole sampled from movable, packered interval	Inexpensive; needs competent rock; time consuming sampling; open borehole permits interconnection of aquifers within the well
MLS system ^a	1, 2, 3	Open borehole sampled by dialysis bags placed in semi-isolated intervals	Detailed sampling; potential loss of isolation; sorption of organics onto bags
Bundle multilevel	1 cohesion-less	Centre stock with tubing to various depths	Inexpensive; unlimited sampling points; no isolation of intervals; needs peristaltic pump
Multiple wells	1, 2, 3, 4	Individual wells in individual boreholes	Expensive drilling; simple installation
Stacked wells	1, 2, 3	Alternate wells screened in sand pack with seals	Inexpensive; limited number of wells; difficult completion; permanent
Chalk River system ^b	1,2,3 consolidated	Multiple inflatable packers & standpipes	Inexpensive, removable; some sorption potential
Waterloo system	1, 2, 3 consolidated	Permanent water-activated packers isolating sample intervals	Packer sealing & leaching; permanent; requires double-valve pump
Westbay® system ^c	1, 2, 3 consolidated	Permanent seals (packers or grout) with samples drawn with a down-hole probe	Sampled at formation pressures; expensive; slow sampling; permanent
Drive point samplers and Hydropunch® ^d	1, 2 unconsolidated, permeable	Small diameter casing is driven, bottom opened for sampling	Requires peristaltic pump or BAT® sampler; inexpensive; temporary well only; mainly screening
Screened augers ^e	1, 2 unconsolidated, permeable	Augers are screened so water can be collected inside augers	Needs auger drilling; inexpensive; potential cross contamination; mainly for screening analyses

^a See Kaplan *et al.* (1991).

^b See Welch and Lee (1987).

^c See Novakowski (1988).

^d See Bergren *et al.* (1990).

^e See Taylor and Serafini (1988).

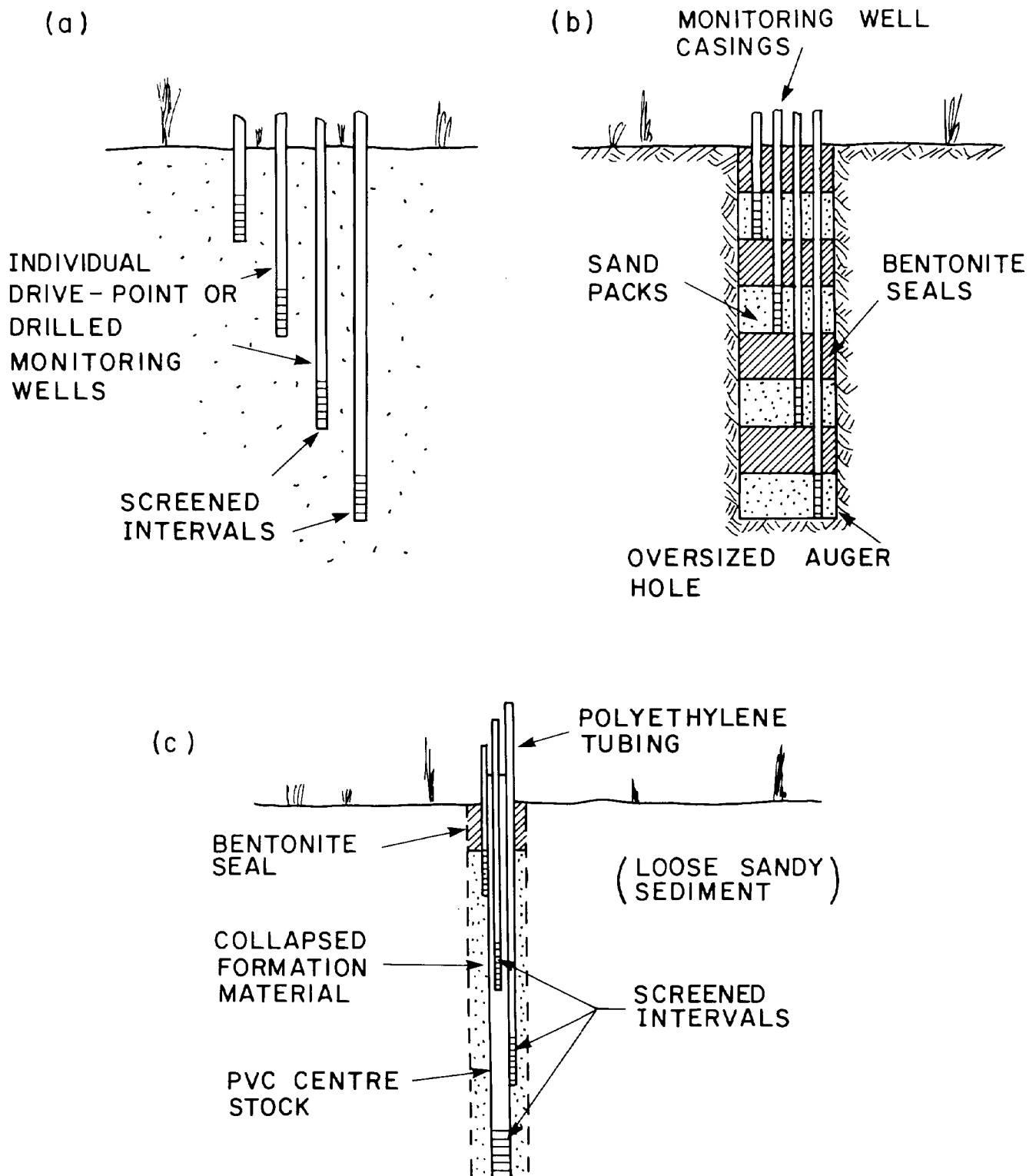


Figure 69 Some Clustered and Multilevel Monitoring Wells: (a) Cluster of Individual Monitoring Wells Completed at Different Depths; (b) Multilevel Monitoring Well Installed in a Single Borehole with Individual Seals Between Each Monitoring Level; and (c) A Bundle Multilevel Monitoring Well

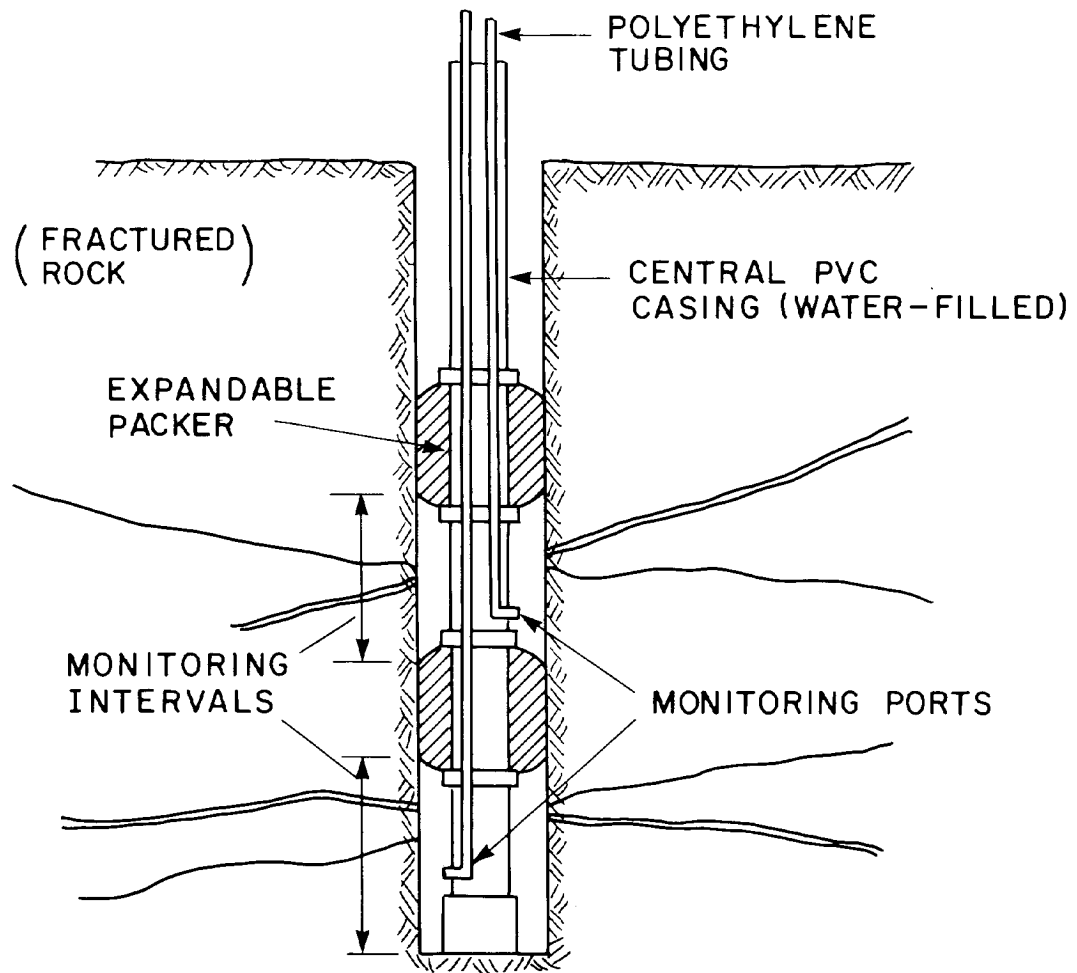


Figure 70 Multilevel Packer Device with Expandable Chemical Packers (“Waterloo System”)

If you restrict the drilling program to depths of less than 40 m, the hollow-stem auger technique is the most efficient and suitable method. This method does not introduce foreign drilling fluid and the auger flights provide a temporary casing that facilitates sampling. The cable tool rig is the next best method in this type of sediment as the hole is simultaneously cased during drilling and no drilling fluid is used. Using an air rotary drill with a driven casing may also work well (Table 9). For drilling deeper than 40 m, the hollow-stem auger rig is usually not effective; therefore, the cable tool rig or the air rotary drill with a driven casing may be the most acceptable methods.

Table 9 also ranks the relative costs of the different drilling techniques. Technical advantages are, however, much more important in ranking the applicability of the drilling methods.

Table 9 Applicability of Selected Drilling Methods in Various Subsurface Materials

Material Type	Drilling Method				
	Cable Tool	Mud Rotary	Air Rotary	Solid-Stem Auger	Hollow-Stem Auger
Unconsolidated, noncohesive materials < 40 m depth	2 ^a	4	3	5	1
Unconsolidated, noncohesive materials > 40 m depth	1	3	2	NA ^b	NA
Unconsolidated, cohesive materials < 40 m depth	3	4	5	2	1
Unconsolidated, cohesive materials > 40 m depth	1	2	3	NA	NA
Consolidated materials (low porosity and few fractures)	3	2	1	NA	NA
Consolidated materials (highly porous and fractured)	1	3	2	NA	NA
Relative cost ^c	3	1	2	5	4

^a Numerical rating illustrates most appropriate (1) to least appropriate (5).

^b NA = not applicable.

^c Costs range from highest (1) to lowest (5) based on average drilling conditions in applicable material type.

When collecting undisturbed samples of these unconsolidated, noncohesive geologic materials, the piston-type sampler may be the most effective in obtaining complete and undisturbed material. If the sediments are medium to fine-grained and relatively loose, use a thin-walled piston sampler. For coarser and stiffer materials use a heavy-walled piston sampler like that described by Zapico *et al.* (1987). Core barrels, Shelby tube samplers, and split-spoon samplers will likely show progressively lower success rates (Table 10). Within the upper 20 m, you can use manual drive-point piston-samplers.

Take advantage of noncohesive geologic material. Because the formation tends to collapse when the auger flight or temporary casing is removed, consider using the bundle-type multilevel monitoring wells (Figure 69c; Table 8). Individual drive-point wells are also quite effective in the upper 30 m.

Table 10 Applicability of Selected Sampling Techniques in Various Subsurface Materials

Material Type	Sampling Techniques				
	Split-Spoon	Shelby Tube	Piston Samplers	Core Barrels	Manual Techniques
Unconsolidated-noncohesive materials < 20 m depth	5 ^a	3	1	4	2
Unconsolidated-noncohesive materials > 20 m depth	4	2	1	3	NA ^b
Unconsolidated-cohesive materials < 20 m depth	5	1	3	4	2
Unconsolidated-cohesive materials > 20 m depth	4	1	2	3	NA
Consolidated materials (low porosity, few fractures)	NA	NA	NA	1	NA
Consolidated materials (highly porous and fractured)	NA	NA	NA	1	NA

^a Numerical rating illustrates most appropriate (1) to least appropriate (5). Judgement based mainly on obtaining complete and undisturbed material. Less appropriate techniques may have practical advantages and should be considered where problems are encountered applying the preferred technique.

^b NA = not applicable.

4.7.2 Unconsolidated, Cohesive Geologic Materials

Unconsolidated, cohesive geologic materials (Settings 1 and 2) include materials such as glacial till, **lacustrine** or marine clays, and **peat**. These materials are predominantly very fine-grained and possess relatively high intergranular cohesion. The permeability of these sediments is generally quite low but fracturing is common.

Both the hollow-stem and solid-stem auger methods work well in this material to a depth of 40 m, unless the sediment is extremely stiff (as is occasionally the case with glacial till deposits). Cable tool rigs tend to be slow and often have to use a small amount of some drilling fluid. The mud rotary rig also functions reasonably well in these materials because the drilling fluid does

not usually penetrate the formation very far, unless fractures are present. Where fractures are present, the drilling fluid can be forced into the fractures and cause their blockage. The borehole tends to stay open without significant side wall collapse; therefore, you do not have to use a temporary casing. In stiff cohesive materials or at drilling depths greater than about 40 m, the cable tool rig or mud rotary rig are suitable techniques (see Table 9).

You can obtain shallow, undisturbed samples (< 20 m) of these sediments with either manual thin-walled piston samplers or, if you use an auger rig, with Shelby tube samplers. With both the manual technique and the hollow-stem auger, you can drill boreholes at selected angles. In this way, the coring device can intercept vertical fractures.

When you use the large core barrels and the heavy-walled split-spoon sampler, recovery is often low because the first section of cohesive material that enters the sampling tube may form a plug, and force the *in situ* material to bypass the sampler, rather than enter it. Table 10 provides a general rating of various sampling techniques. When collecting samples deeper in the profile, the thin-walled Shelby tube or piston-type samplers are very effective.

Monitoring wells installed in individual drill holes, with a small subcore at the bottom of the hole for the well screen, are generally the most effective in cohesive sediments. Carefully placing multiple wells in a single borehole can also be effective, although somewhat more difficult to construct. In the top 20 to 25 m, drive-point wells can be very cost effective and functional if the sediment is not too stiff.

4.7.3 Consolidated Materials

This category involves consolidated materials or rocks from Settings 1 through 4. With consolidated material, you must use either percussion or rotary drilling techniques. In essentially unfractured, very low porosity materials such as massive granite, the air rotary or mud rotary rigs are the most efficient. A cable tool rig tends to be slower.

If the consolidated material is highly fractured or very porous (sandstone or karstic limestone), the rotary rigs may not function as well because the drilling fluid may be lost into the formation. The cable tool method is likely the most appropriate. In highly fractured material, the borehole wall can be quite unstable and rock fragments may fall in on the drill stem or into the open hole after you remove the drill rod. The cable tool rig advances a casing with the bit, which is an additional advantage.

Use the mud rotary system in conjunction with a diamond coring bit and a core barrel to collect undisturbed samples of consolidated materials. If the drilled material has a low porosity and is not very fractured, the samples collected by diamond coring are usually excellent. In fractured regions, sample quality deteriorates.

The most effective monitoring well installation in consolidated materials is the multiple packer system (Table 8; Figure 70), because the stiff side wall of the borehole provides a strong base for the expanding packer to seal against. Individual boreholes for separate monitoring wells are much more expensive than the packer systems because of the additional drilling required.

4.8 Measuring Hydraulic Parameters

Most measurement techniques, whether laboratory or field, provide small-scale, point measurements. To understand groundwater flow at the field scale, you must extrapolate or average these point measurements over the entire flow system. In some cases, you may use several different techniques to estimate the same parameter. In any case, you need experienced hydrogeologists to plan, conduct, and interpret such measurements.

4.8.1 Laboratory Techniques

This section discusses the most common techniques for measuring the hydraulic parameters of the materials encountered in the five conceptual scenarios. This section also refers you to additional, more detailed descriptions of the methods.

Porosity. The porosity of a medium is the fraction of the total volume of the material that is open pore space or voids. The porosity of a material, therefore, has a great influence on storage capacity and on the groundwater or vapour velocity. In determining the porosity of an unconsolidated sediment such as sand or clay, try to obtain a sample from the field site in the most undisturbed form possible. If the sample is highly disturbed and the grains have been rearranged, the porosity measured in the lab may not be representative of the *in situ* value. You can obtain this sample with various thin-walled sampling devices (e.g., a Shelby tube sampler).

In the case of fine grained materials, the sample will generally be completely saturated if taken near or below the water table. The general procedure is to weigh a known volume of the material and then completely oven-dry the specimen. Weigh the sample again and the difference is the weight of the water that filled the void space. You can then convert this to volume by dividing this weight by the density of water (1.0 g/cm^3). If the material is more coarsely grained, you may have to resaturate the sample before making the measurements, because some drainage may have occurred during handling. As an alternative, you can determine the porosity by using the **bulk mass density** and **particle mass density** of the sediment (Freeze and Cherry, 1979; Nielsen, 1991).

You can also use these techniques to determine the porosity of rocks. Be aware, however, that porosity can vary considerably between different materials (<0.1 to 35%) and even between materials that appear very similar in many other respects. Refer to American Society for Testing and Materials Publication D4404-84 for details of porosity determinations.

Hydraulic Conductivity. Often the terms permeability and hydraulic conductivity become confused. Where pure water is flowing through the material, hydraulic conductivity and permeability are related through a constant (see Section 1.3). Because contaminant hydrogeology generally uses hydraulic conductivity, this section restricts discussion to the measurement of hydraulic conductivity (K).

A wide variety of laboratory methods are available to determine the hydraulic conductivity of porous media. If the material is non-cohesive (anything ranging from a silt to coarse gravel), you can use a laboratory apparatus called a **permeameter** to determine hydraulic conductivity. The

device allows water to flow through a known volume of material under controlled conditions and permits measurement of the transmissive capabilities of the sediment. Select either a falling-head or constant-head configuration for the test (see Figure 71). In the falling-head test, an elevated hydraulic head is initially applied to the top of the saturated sample and allowed to decrease as water flows through the sample. By monitoring the head drop over time, the hydraulic conductivity is calculated (Freeze and Cherry, 1979). When you use the constant-head method, the head difference develops through a known length of sediment and remains constant. By knowing the cross-sectional area of the sample and monitoring the flow rate at steady-state, you can calculate the hydraulic conductivity with Darcy's Law ($q = -K i$), where i is the hydraulic gradient and q is the flow rate per unit area (see American Society for Testing and Materials Publication D2434-68).

Usually, you perform these tests on unconsolidated sediments. You should make every attempt to collect undisturbed samples of the material in question. In many cases, however, you must remove the samples from the sample tube and repack them into the permeameter cell. This repacking may cause the loss of some of the finer grained material and it usually destroys the natural structure of the sediment.

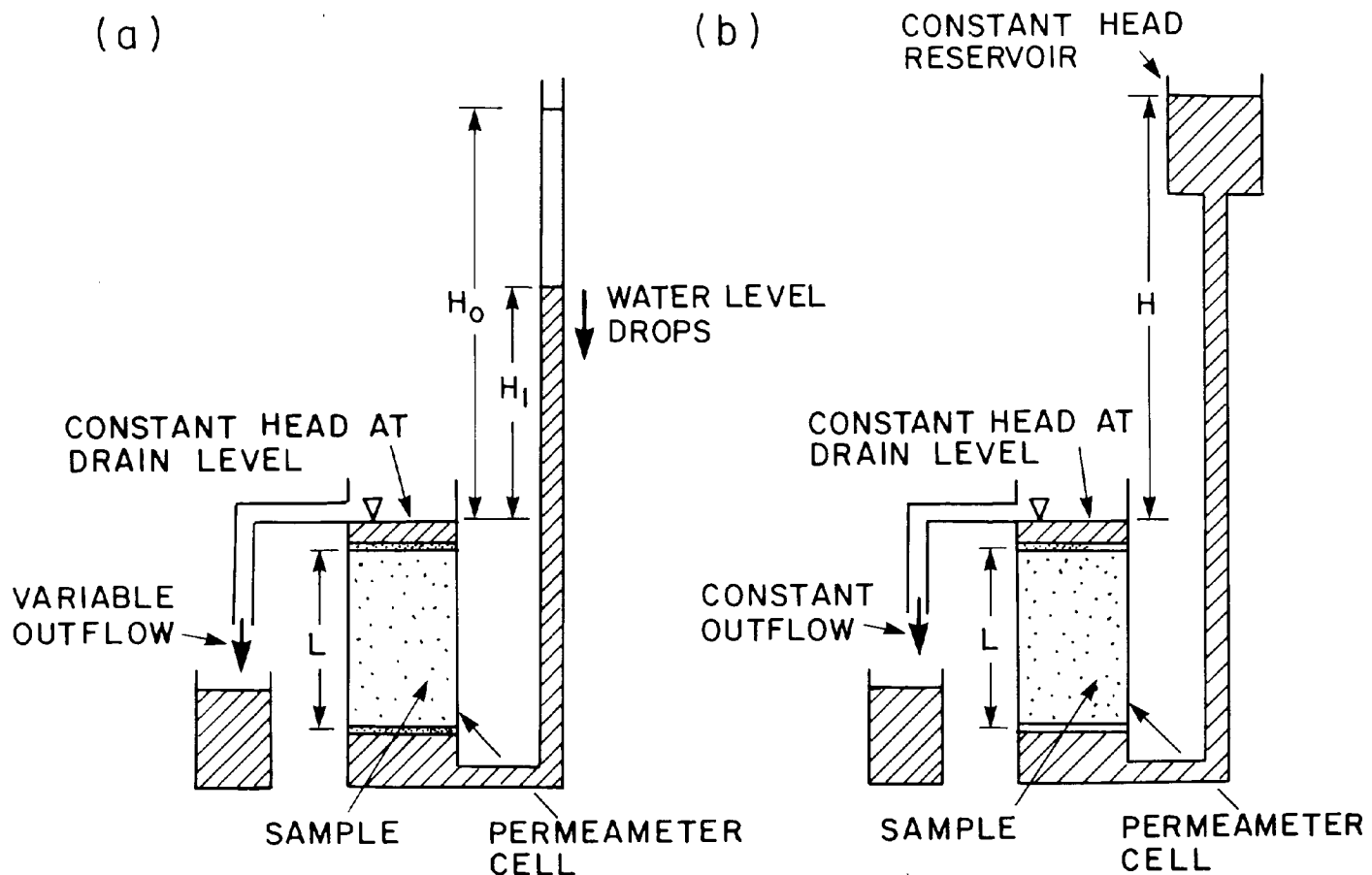


Figure 71 Measuring Hydraulic Conductivity Using: (a) A Falling-head Permeameter Test; and (b) A Constant-head Permeameter Test (After Freeze and Cherry, 1979)

For coarser sediments such as sand and gravel, the effect of the repacking is often minor if the material is repacked back to the density of the *in situ* material (Wolf *et al.*, 1991). As the material becomes more finely grained, the remixing affects generally

become more significant. It is also important to realize that if the sample is removed undisturbed from the core barrel and placed directly into the permeameter, the hydraulic conductivity that is measured is the vertical value. If the material is **anisotropic**, the horizontal value of K may be considerably different. Overall, the falling-head test seems to be best for lower permeability sediments; whereas, the constant-head technique works well on materials that are more highly conductive.

If the unconsolidated material is fine grained and less permeable (e.g., clay or till), the permeameter methods are generally not very useful. As an alternative, you can determine the hydraulic conductivity of these sediments using a **consolidation test**. An undisturbed sample of the material is placed under a progressively increasing vertical load in a confining cell. After you apply each load increment, you monitor the compression of the sample until the sample stops deforming. The time it takes for the pore water to drain as the sample deforms is directly related to the compressibility and hydraulic conductivity of the material. Several graphic techniques are available to interpret the consolidation test data (see Lambe and Whitman, 1969; Craig, 1978). The American Society for Testing and Materials Publication D2435-90 presents additional information on consolidation tests.

Nielsen (1991) discusses a variety of techniques for determining the hydraulic conductivity of unconsolidated materials. Hydraulic conductivities of consolidated materials are generally measured using field methods. These are described in Section 4.8.2. Table 11 gives a summary of typical values of hydraulic conductivities.

Specific Yield and Specific Storage. The storage capacity of porous medium is measured to evaluate both the water resource potential of a given geologic sequence and to interpret the transient response of the groundwater flow system. The specific yield (S) generally refers to the volume of water that is removed from storage in a unit volume of saturated material under a unit decline in the water table level. To measure this in the laboratory, saturate a sample of material and allow it to drain under a unit drop in the water level (which depends on the size of the sample) until the amount of water draining from the bottom of the sample is negligible. Next, measure the total drained volume, which represents the specific yield of the material. This measurement of the storage property is commonly restricted to fairly permeable materials ranging from silts to sands.

The specific storage (S_s), is the amount of pore water a unit volume of saturated geologic material releases as a result of a unit decline in hydraulic head. In this case the material remains fully saturated. As the **pore pressure** is lowered, water can expand and the granular material can collapse. Both mechanisms cause a release of water from storage. Use the specific storage parameter in the case of a semiconfined aquifer, where the piezometric level in the aquifer has been lowered by pumping but the aquifer material has not dewatered.

Table 11 Typical Hydraulic Conductivities of Common Geologic Materials

Material	Hydraulic Conductivity, K (m/s)
Gravel	10^{-1} to 1
Clean sand	10^{-3} to 10^{-2}
Silty sand	10^{-5} to 10^{-1}
Glacial till	10^{-10} to 10^{-4}
Unfractured clay	10^{-10} to 10^{-7}
Unfractured igneous rocks	$<10^{-12}$ to 10^{-8}
Fractured igneous rocks	10^{-6} to 10^{-2}
Limestone	10^{-7} to 10^{-3}
Karst limestone	10^{-4} to 1

In low permeability, compressible sediments such as clays, you typically measure this parameter using a consolidation test. You expose an undisturbed sample of the material to an increasing vertical load and observe the compressibility of the material in relation to the applied load. The deformation of the sample is related directly to the amount of water that can be removed from storage by a given change in pore pressure. Rudolph and Frind (1991), and most soil mechanics text books, cover the application of the consolidation test to determine specific storage of compressible sediments. In more permeable sediments that tend not to be very compressible (e.g., sands and gravels), the standard consolidation test is generally not useful for measuring S_s . Several field methods for determining S_s in various material types will be discussed.

4.8.2 Field or In Situ Techniques

Techniques for estimating hydraulic conductivity and specific storage in the field (**aquifer tests**) can be conveniently categorized into: single-well tests; packer tests; and **pumping tests**.

The choice depends on the material type and the nature of the monitoring wells on site. The principal advantage of a field test is that you evaluate a larger volume of material under more realistic conditions than would be possible in the laboratory. However, *in situ* tests are difficult to conduct under conditions as controlled as conditions in the laboratory.

Single-well Tests. These tests involve monitoring an artificially induced pressure change in the saturated formation. Commonly, you introduce or remove a known volume of water from a monitoring well, and observe the response of the water level as it returns to the initial static

level. Removing water from the well is referred to as a **bail test** or rising head test. Adding water to the well is called a **slug test** or falling head test. To avoid actually adding water to the well, use a solid cylinder of known volume to cause the volumetric displacement.

In this type of test, water is forced in or out of the monitoring well screen in response to a sudden change in hydraulic head. The rate at which the water transfers between the formation and the well depends on the size of the hydraulic head change, the geometry of the well screen, and the hydraulic properties of the formation material. Figure 72 illustrates the geometric configuration for a falling head test in one well that contains a short well screen and another that is open at the bottom.

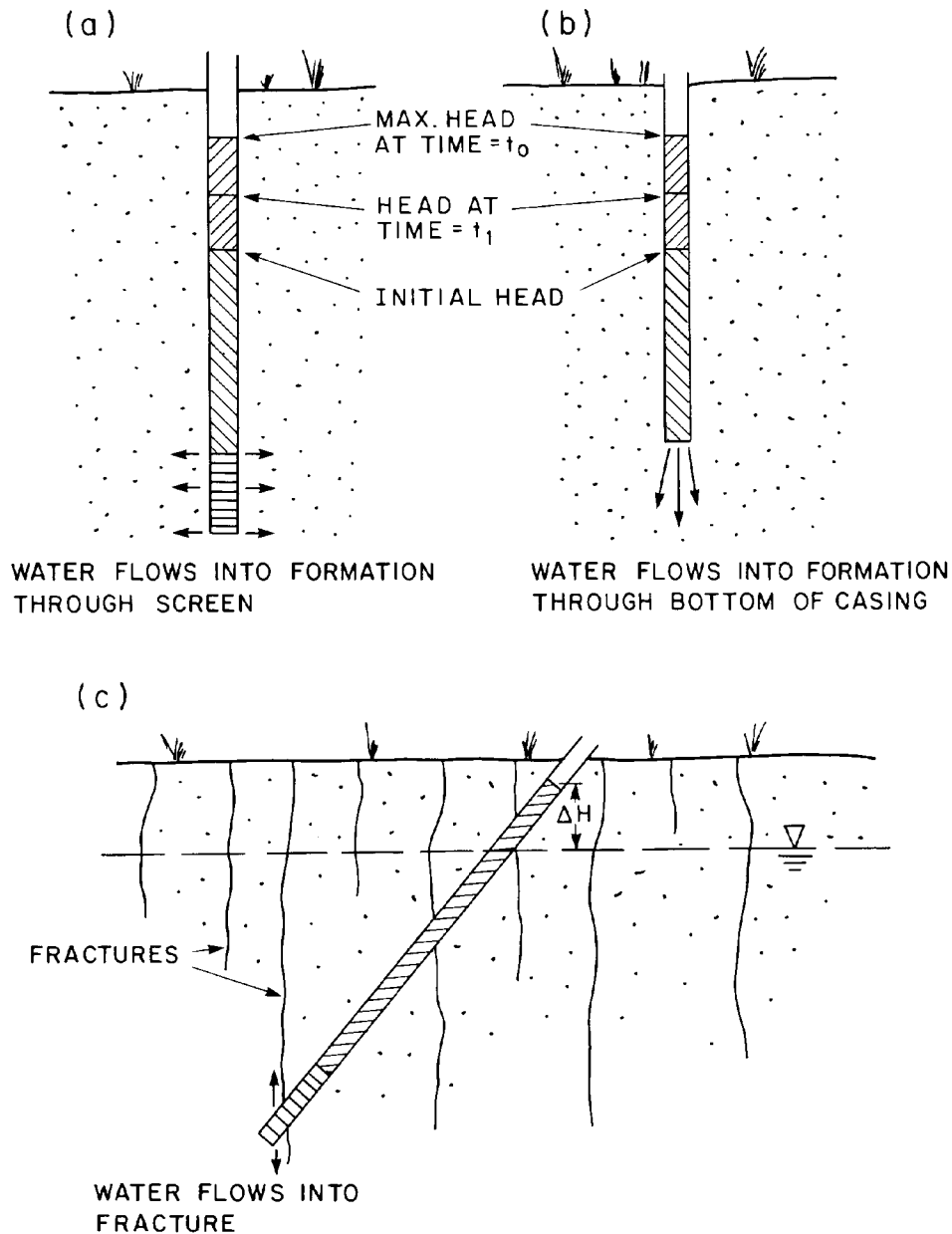


Figure 72 Groundwater Flow During Piezometer Tests: (a) In the Vicinity of a Well Screen; (b) At the Base of an Open Casing; and (c) In an Angled Borehole

When you conduct a bail test or a slug test, measure the initial water level in the monitoring well and administer the volume change within the well as instantaneously as possible. You should then monitor and record the water level with a water level meter until the initial static level is again achieved. You then plot this level *versus* time and analyze the data by any of a number of methods. The analytical method of Hvorslev (1951) only permits the estimation of hydraulic conductivity. Other methods that permit the determination of both hydraulic conductivity and specific storage under a variety of conditions are discussed in Nielsen (1991) and Freeze and Cherry (1979).

Single-well tests allow you to estimate the hydraulic parameters of material within a small radius of the well screen (essentially point measurements). This type of test tends to be the most successful in materials of moderate permeability. In highly permeable materials the response is often so fast that you cannot accurately monitor the transient water levels except with electronic pressure **transducers** and recording equipment. If the material has a very low hydraulic conductivity, the response may be exceedingly slow. In fractured materials, you can install the monitoring wells on an angle to intercept vertical fractures (Figure 72c).

Packer Tests. The packer test permits multiple measurements of K along the vertical length of a fully screened monitoring well or an open borehole (Figure 73). Lower a device, consisting of two inflatable packers that flank an inlet port, into the borehole. This port connects to a monitoring tube that runs to the surface. You position the device at the depth of interest and inflate the packers. This isolates the inlet tube in a certain portion of the formation. You can inflate the packers from ground level with either water or a gas. At this point, you can carry out a test very similar to the slug or bail test. Once you have completed the test at a given depth, you can deflate the packers and move them to another depth in the borehole and repeat the process.

If the material is fairly homogeneous, using a wide packer spacing (2 m) may be sufficient to observe the vertical variations in K . On the other hand, if the structure is quite complex, you may have to use a much smaller packer spacing (25 cm). If the borehole has been properly logged and core samples are available for inspection, you can make a decision on packer spacing and appropriate measurement depths based on this information.

This technique is very successful for measuring the hydraulic conductivity of fractured rocks because it allows you to isolate and test individual fractures or fracture zones to determine their hydraulic characteristics. Again, you can determine the location of the fractures from the core samples. Consult Nielsen (1991) or American Society for Testing and Materials Publications D4630-86 and D4631-86 for further information on packer tests.

As a final note on hydraulic testing of individual monitoring wells, the test itself essentially measures the hydraulic properties of the formation material immediately adjacent to the borehole. During drilling and well installation, the drill bit or the drilling fluid often modifies the side walls of the borehole. These alterations may influence the values of the hydraulic parameters obtained by single-well tests. Therefore, you should take care to evaluate the potential for this condition (generally referred to as skin effects).

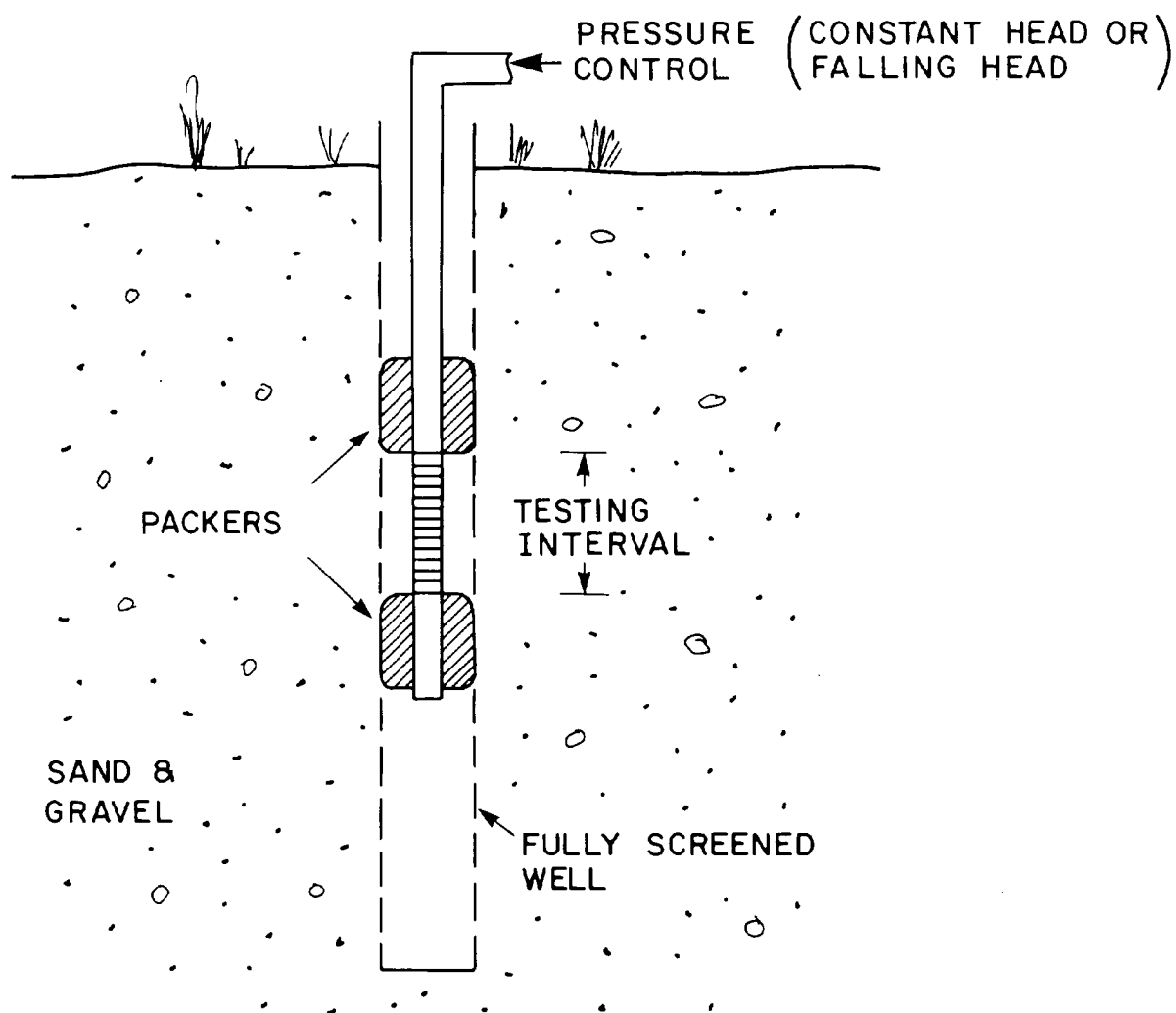


Figure 73 **Packer Test in a Fully Screened Monitoring Well or in an Open Borehole in Rock**

Aquifer Response Tests or Pumping Tests. All of the techniques described to estimate the hydraulic parameters of porous media have been point measurements at a very small scale. To make a regional assessment of the spatial distribution of these parameters you must interpolate between the discrete measurements. In many cases, you need information on the hydraulic properties of the subsurface materials on a larger, more regional scale. You can use averaged or bulk values of a given parameter to predict much of the larger scale behaviour of the groundwater flow system. As an alternative to the point measurement approach, consider using aquifer response tests or pumping tests. These tests impose a larger scale hydraulic change on the system and observations at locations away from where you apply the hydraulic change permit assessment of the overall system response.

Generally, you install a well in a permeable unit and pump groundwater from the well under very controlled conditions. Install observation or monitoring wells both in the unit being pumped and in other units in the vertical sequence. Record the variation in water level in these wells during the pumping period. Analyzing the response of observation wells over time permits the determination of the bulk hydraulic parameters for the different units.

Literally dozens of different analytical approaches exist for pumping tests in a wide variety of hydrogeological environments. Kruseman and de Ridder (1970) provide a very complete discussion of many analytical methods. Figure 74 shows an example of a pumping test in a complex hydrogeologic system.

Conducting a pumping test is more involved, requires several days to conduct, and is generally more expensive than individual well tests. However, there are several advantages to pumping tests:

- the hydraulic parameters are representative of the scale of the groundwater contamination problem;
- the response observed in different hydrostratigraphic units during the pumping tests, allows you can to evaluate the degree of hydraulic connection between the different units and determine potential pathways for contaminant movement; and
- the effect of groundwater pumping near or in the surface water bodies provides additional insight into the hydraulic connection between the surface water and groundwater.

It is often very difficult to determine the bulk hydraulic conductivity of a low-permeability fractured aquitard by simply analyzing core samples or by using slug tests. This is because the borehole may not intercept individual fractures that can control the hydraulic conductivity of the unit. The pumping test will allow you to evaluate the hydraulic response of the aquitard on a larger scale and to observe the influence of these discrete features (see Keller *et al.*, 1990).

By pumping a permeable unit beneath a contaminated site for an extended period, you may induce contaminated groundwater to migrate at a higher rate than would naturally occur. Contaminants may also move into different parts of the hydrogeological system in response to the pumping. You must evaluate the potential for undesirable migration of the contaminants

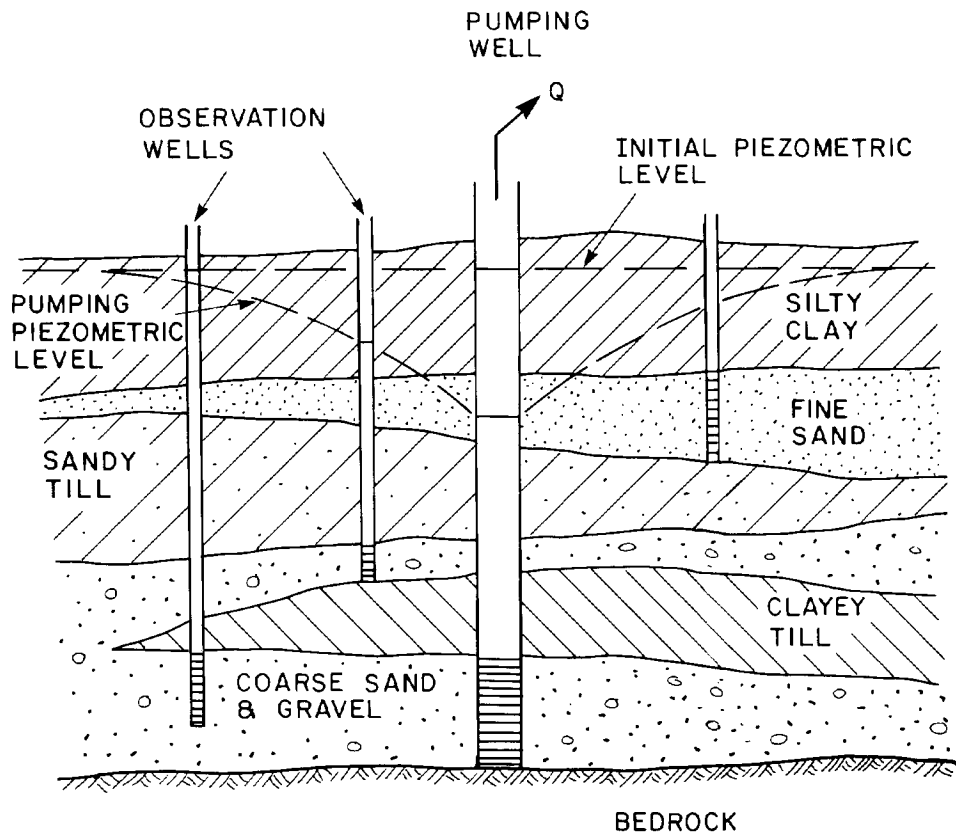


Figure 74 **Aquifer Response Test in a Complex Hydrogeologic System**

before you conduct a pumping test. If the groundwater being pumped at the site is contaminated, you may have to contain or treat it. In some cases, you can inject water into the pumping well to observe the hydraulic response of the system. By doing this, however, you “push” contaminated groundwater away from the well and introduce foreign water that may compromise geochemical evaluations at the site.

The pumping test techniques are only useful where relatively permeable strata exist. In material such as clays, tills, or unfractured rock, consider using laboratory tests to determine K .

4.9 Monitoring the Unsaturated Zone

The unsaturated zone generally receives little attention although rainfall or snowmelt that recharges subsurface materials, and contaminants that originate on the surface of the ground, must infiltrate through the unsaturated zone before they reach the water table. Also, the gas phase in the unsaturated zone may be a significant pathway for migration of volatile contaminants. At sites where the water table is at or near ground surface (< 1 m), the influence of the zone on the overall behaviour of the groundwater flow system is usually insignificant. During Stage 2 of the site investigation, you can use water table data from the monitoring wells placed in the initial test holes to determine whether or not the unsaturated zone requires attention. You make this decision simply on the depth to the water table. If the water table is deeper than 1 m, you should consider the hydrogeologic conditions in the unsaturated zone.

The main physical characteristic that leads to differences between the unsaturated zone and the groundwater zone is that the pore water is in **tension** (at pressures of less than atmospheric) in the unsaturated zone. The tension generally increases upward away from the water table. As a result, the moisture content generally decreases toward the surface of the ground. Figure 75 illustrates the relationship between **pressure head** and **moisture content**, and shows the saturated zone, the capillary fringe or zone of tension saturation, and the truly unsaturated zone.

The relationship between tension or pressure head and moisture content is not linear and is **hysteretic** — it depends on the drainage and wetting history of the material (see Figure 76a). The hydraulic conductivity in the unsaturated zone is also a hysteretic function of pressure head (ψ) and moisture content (θ) (see Figure 76b). You must determine the functional relationships among K , θ , and ψ to understand the rate at which infiltrating water and contaminants will migrate through the unsaturated zone.

4.9.1 Laboratory Techniques

To determine the functional relationships among K , θ , and ψ , (referred to as the **characteristic curves**, Figure 76) you must collect an undisturbed sample of the material. Load the sample into a specially designed laboratory cell and completely saturate the sample. The cell confines the sample and allows pore water to drain out as you apply suction to the sample. You may have to disturb and repack the sample into the laboratory cell. This can considerably alter the grain

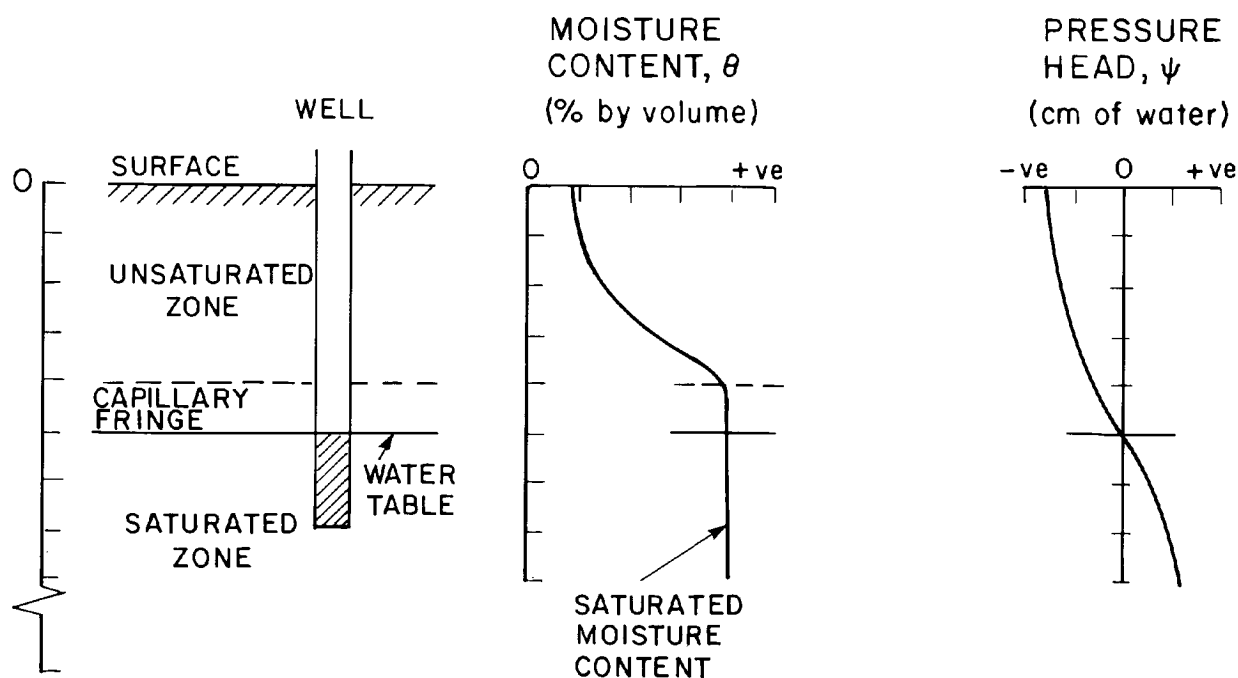


Figure 75 Pressure Head and Moisture Content Distribution in the Unsaturated Zone. Note that the saturated moisture content equals the porosity and that the pressure head is negative in the capillary fringe (after Freeze and Cherry, 1979).

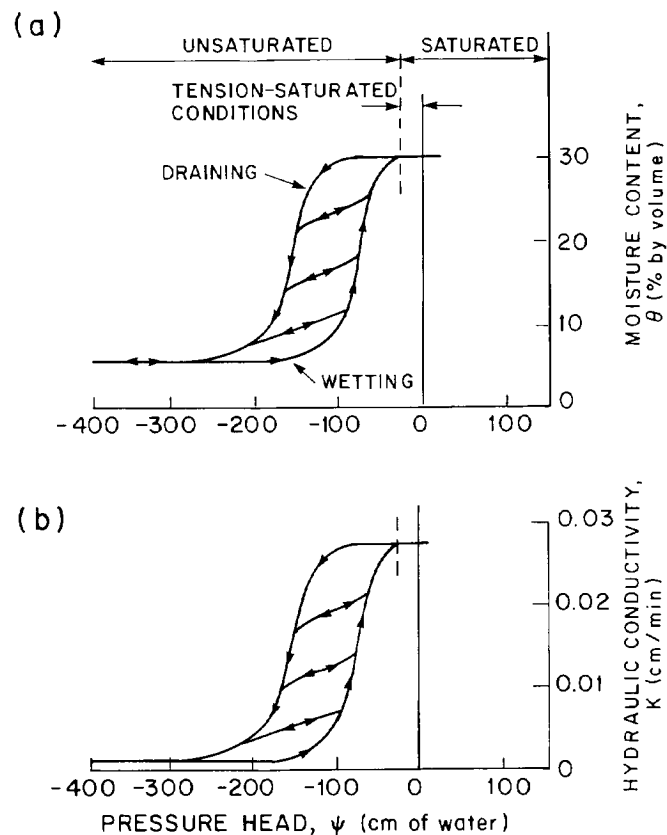


Figure 76 Hysteretic Relationship Between: (a) Pressure Head and Moisture Content; and (b) Pressure Head and Hydraulic Conductivity. (After Freeze and Cherry, 1979). Note that for this sample, the saturated moisture content is 30% (the porosity of the soil) and the saturated hydraulic conductivity is 0.026 cm/min.

structure. Make every effort to avoid losing the fine-grained fraction of the sediment sample because this can significantly influence the values of the measured hydraulic parameters.

To determine the θ *versus* ψ relationship, begin by weighing the fully saturated samples. The moisture content is equal to the total porosity when the sample is fully saturated and this forms the initial data point at 100% saturation. You then apply a specified tension or suction and allow the saturated sample to drain until it achieves equilibrium and stops draining. You then reweigh the sample. The difference between the initial and final sample weight is equal to the change in moisture content at the specified tension. You then increase the tension incrementally and repeat the entire process until you achieve a maximum tension or residual moisture content. You then reverse the procedure, drawing the water back into the sample. Continue this until you achieve saturation. You can then use the data to plot the θ *versus* ψ relationship along the main wetting and draining curves. Morrison (1983) and Klute (1986) describe several laboratory systems available to conduct these measurements, following American Society for Testing and Materials Publication D2335-68.

After you determine the ψ *versus* θ characteristic curve, you must still evaluate the relationships among K , θ , and ψ . It is common to use the mathematical curve matching technique presented by Van Genuchten (1980) to generate the K *versus* θ or K *versus* ψ curve (See Figure 76b). To

use this technique, you must measure a value for the saturated hydraulic conductivity (K_{sat}) of the sediment in a permeameter. By using the measured ψ versus θ characteristic curve, the Van Genuchten model can then provide the required hydraulic conductivity relationships.

After measuring the characteristic curves in the laboratory, you must measure moisture content and pressure head values in the field to estimate infiltration rates through the unsaturated zone.

4.9.2 Field Techniques

Because the pore water in the unsaturated zone is under tension, it is not possible to use a standard monitoring well or **piezometer** to measure the hydraulic head at a given location or to collect a sample of the pore water. To measure the tension or pressure head, use a **tensiometer**. The tensiometer consists of a porous, conductive cup connected to a tube filled with water (Figure 77). Ensure that the porous cup is fully saturated. When the pore water in the formation

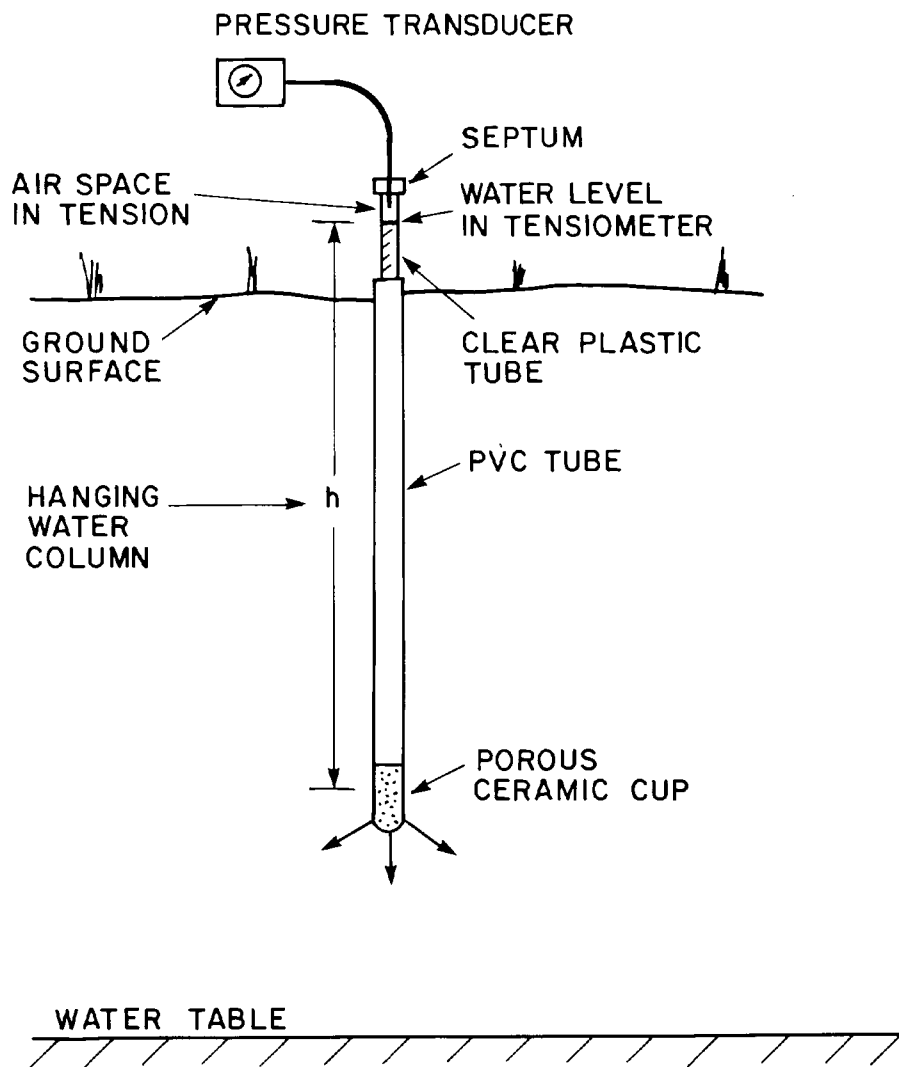


Figure 77 The Porous Cup Tensiometer Used to Measure Tension Head in the Unsaturated Zone

comes in contact with the water in the pores of the ceramic cup, the tension in the formation pore water is transmitted across the wall of the ceramic cup. The water inside the tensiometer then reaches an equilibrium tension equal to the pore water tension. You can then use a **manometer** or tension-sensitive pressure transducer to measure the pressure head in the tensiometer and subsequently in the formation (Figure 77). Consider placing tensiometers at various depths in the unsaturated sediments to measure the vertical hydraulic gradients. Morrison (1983) discusses the installation and operation of tensiometers.

You can measure the moisture content of unsaturated materials in a number of ways. The simplest and likely most accurate way is to obtain an undisturbed core of the material and determine the moisture content gravimetrically by weighing, drying, and reweighing subsamples of the core. Unfortunately this technique is destructive and permits only a single measurement at a given time.

The most common technique for non-destructive measurement of moisture content is the **neutron thermalization** or **neutron scattering** method. With this technique, you lower a source of high speed neutrons down an access tube of aluminum or PVC to the desired depth. The density of the returning low-speed neutrons that the detector measures is proportional to the moisture content in the vicinity of the emitter-detector couple. In general, a measurement at a given depth may take between 1 and 10 min. After you measure the vertical hydraulic gradient with a nest of tensiometers and determine the variation in moisture content, you can use the characteristic curves from the laboratory measurements to calculate the velocity of pore water in the unsaturated zone.

Another technique that has become popular is time domain reflectometry (TDR) discussed in Section 3. The TDR method has the following advantages over neutron thermalization:

- it does not involve a radioactive source, which can be dangerous to handle;
- the wave guides are thin steel and cause very little modification of the sediment; and
- the moisture content measurement is instantaneous and you can monitor its changes over time.

You can also make field measurements of infiltration rates and field saturated hydraulic conductivity with a variety of devices, including single ring and double ring **infiltrimeters**. Reynolds and Elrick (1985) describe a commercial constant head permeameter (the Guelph Permeameter) that estimates field saturated hydraulic conductivity. Section 5.7 discusses water quality monitoring in the unsaturated zone.

4.9.3 Field Monitoring Strategy

Design the detailed site investigation in the unsaturated zone to achieve the study objectives. You typically determine the hydraulic parameters (θ , ψ , K_{sat}) in each unsaturated, hydrostratigraphic units at least two locations on the study site. If you measure significantly different hydraulic parameters in the samples from the same unit, consider additional sampling to determine the spatial variability throughout the site.

In the unsaturated zone, the pore water flow is predominantly vertical and mapping the unsaturated zone flow system in three dimensions is not usually needed. Distributing three to four tensiometer nests evenly throughout the site is likely sufficient to characterize the vertical infiltration rates. Because surface topography can influence the distribution of infiltration, it may be useful to place the tensiometer nests in different topographic settings to evaluate spatial variations in infiltration. Place tensiometers at two different depths in each unsaturated hydrostratigraphic unit to measure the hydraulic gradients. At each of the tensiometer nests, install an access tube for the neutron thermalization probe or, as an alternative, you may use a cluster or nest of TDR probes. You can then make the moisture content measurements at a fairly detailed scale (e.g., every 25 cm).

Consider monitoring pore pressure and moisture content in the unsaturated zone installations on a monthly basis. However, after precipitation, detailed measurements often help to further quantify infiltration rates.

The techniques that have been described have generally been developed for unconsolidated sediments, but most of them may be useful in permeable, consolidated materials and even in fractured materials that are either consolidated or unconsolidated. However, these types of measurements are still in the research stage.

4.10 Hydrogeological Site Investigation in Permafrost Terrain

Permafrost terrains present unique problems for site evaluation and monitoring. Although there are few case studies, enough information exists to propose a general approach to a site investigation.

4.10.1 General Conditions

Groundwater flow in permafrost areas is governed, for the most part, by the same principles as groundwater in non-permafrost regions with some special features:

- seasonal changes in the flow regime;
- difficulties in characterizing the hydraulic parameters; and
- lack of previous work to guide investigation strategies in these settings.

The term permafrost is used to describe any media in which the temperature is constantly less than 0°C for at least 1 year (van Everdingen, 1990). Note that the definition is based on temperature alone and includes a complete range of moisture content. In addition, part, or all, of the moisture in the medium need not be frozen, as pressure and/or dissolved solids may depress the freezing point of the water (van Everdingen, 1990).

Figure 78 shows the general components of the permafrost sequence. The **active layer** is the most dynamic hydrologically. It cyclically freezes and thaws during the seasons and forms the upper layer on the permafrost — often the location of the potential contaminant source.

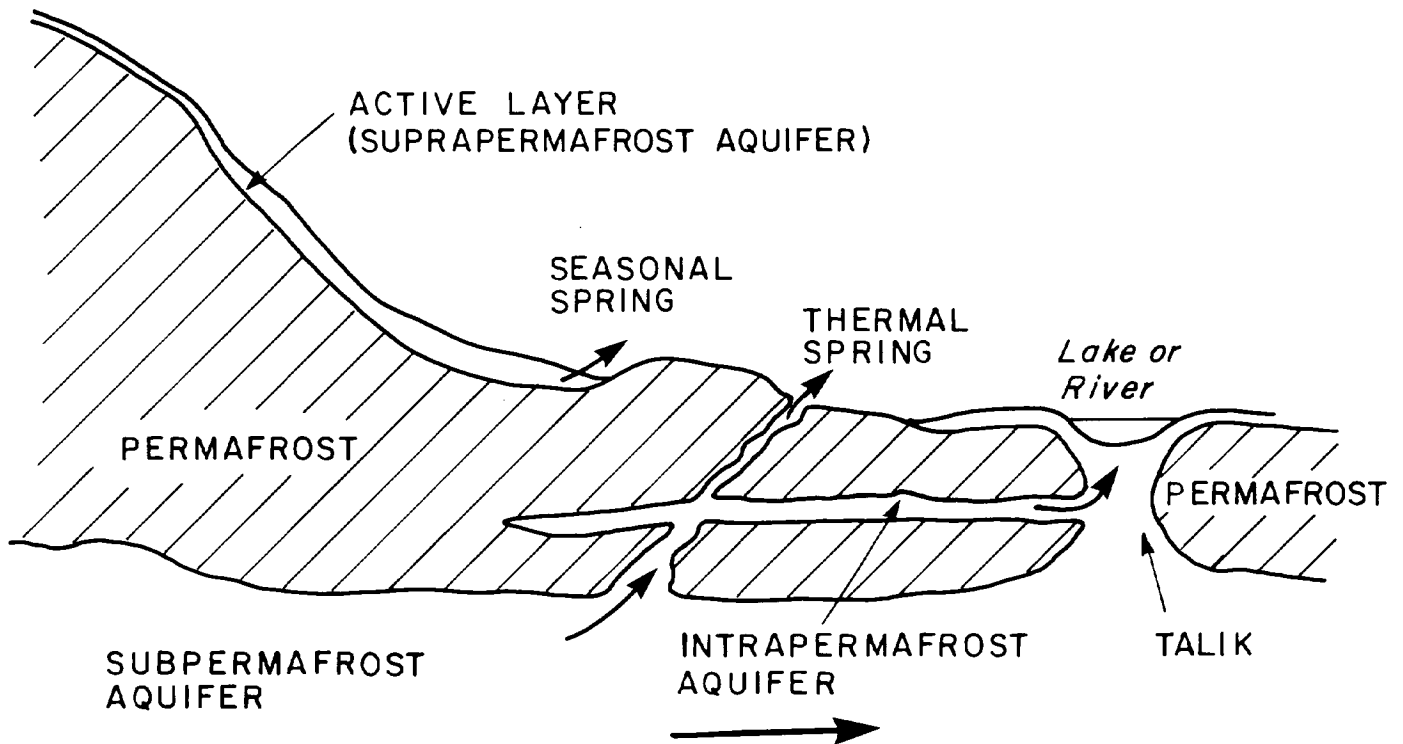


Figure 78 The General Components of Permafrost Terrain and its Hydrostratigraphic Sequence

Depending on the annual temperature, the permafrost condition may be continuous below the active layer, or may be discontinuous. In developing a conceptual model of the hydrostratigraphy in permafrost terrain, the basic distributions of the frozen condition and the aquifers are the most critical factors.

The suprapermafrost aquifers exist near the surface of the ground and the permafrost forms the lower boundary. The intrapermafrost aquifers exist in isolated unfrozen sections within the permafrost, and the subpermafrost aquifers exist below the depth of freezing.

In most situations, contaminants are confined to the suprapermafrost layer. Exceptions occur when infiltration to the subpermafrost aquifer takes place through bedrock exposures, or when a pathway exists, through **taliks** (unfrozen areas) or other routes. Subsurface material is generally unfrozen to some degree beneath surface water bodies such as lakes or rivers (Figure 78). Therefore, these features tend to be associated with areas of active groundwater movement. Lateral movement of groundwater occurs in: unfrozen regions below the permafrost; taliks; and the active layer during the warm season. These areas represent the primary focus in any monitoring program.

Under saturated, frozen conditions, geologic materials tend to be nearly impermeable. If the material is unfrozen, however, fluids may infiltrate through sediments. The depth of the thawed zone and the length of time the material will be unfrozen and can conduct groundwater freely is site specific.

When considering the movement of dissolved contaminant and NAPLs in permafrost terrain, keep in mind that the low temperatures result in higher fluid viscosities that restrict flow. In addition, there are generally only short periods during the year that groundwater flow actually occurs and it is almost entirely restricted to the near surface.

4.10.2 Aspects of Field Monitoring

In permafrost terrain, the most critical field measurements are those that you take during the summer season, when the active layer is thawed. Sampling and installation of instruments is most convenient while the ground surface is still frozen. The field program aims to characterize the:

- material type, geometry, and freeze-thaw cycle of the active zone;
- continuity and thickness of the permafrost; and
- temperature and heat distribution of the active zone and near contaminant source(s).

During the summer months, the active layer may become very soft and you may have difficulty moving equipment. It is critical, however, that you make initial estimates of the thickness of the active zone at the time of maximum thaw. You can do this in soft sediments by pounding a steel probe into the surficial sediments until you encounter the permafrost, or by using a portable, hand-coring device. In stiffer sediments, consider drilling to assess the depth of the active layer. Investigate at least three evenly spaced locations for active layer thickness within the study site, although six to ten locations are more desirable.

Determining the overall thickness of the permafrost zone and its continuity can be difficult and costly. Geophysical techniques may be useful (Subsection 3.5.2).

After this initial phase, decide whether drilling for monitoring well installation, sediment coring, and stratigraphic mapping are necessary. You may have to wait for frozen conditions. In the active zone, when the pore water is liquid, all drilling and sediment sampling techniques discussed for non-permafrost areas will be appropriate. However, when the active zone is frozen, the sediments behave more like consolidated sediments or rocks. If the sediments are unconsolidated, the use of hot fluid during rotary drilling to cause melting at the bit may aide the drilling process. To collect core samples, however, a rotary rig with a rock coring bit is better.

You can install monitoring wells in the active zone with any of the standard techniques outlined for unfrozen sites. Under all frozen conditions, however, you must install and backfill monitoring wells in the same manner discussed for consolidated sediments (with sand pack, seal, and backfilling). Place monitoring wells as a vertical nest throughout the entire active layer, in each unfrozen layer in the permafrost sequence, and below the permafrost. Use at least three

groups of monitoring wells, spaced roughly equidistant in a triangular pattern. You can add more as required. Note that intrapermafrost aquifers are frequently overpressured due to expansion of the surrounding frozen ground. As a result, you may encounter flowing **artesian** conditions in these units. Take care to control flowing conditions in the monitoring well.

Monitoring wells installed in permafrost terrain must withstand severely cold temperatures. Because the wells are subject to cold temperatures and frost heaving during the freeze-thaw cycle, you should use heavy PVC or steel. Some investigators add antifreeze or oil to monitoring wells to keep the fluid from freezing but you should avoid introducing these types of fluids because they can significantly influence geochemical investigations and you must apply density corrections if you make hydraulic head measurements.

By measuring temperature and heat energy in the active zone you can determine the dynamic freeze-thaw cycle. Harris (1986) discusses the various types of **thermistors** and **thermocouples** you can use. Often, sources of contamination (e.g., a landfill) produce significant amounts of heat as a result of the biological decay of the waste. This heat can modify the freeze-thaw cycle in the active zone; therefore, consider making some temperature measurements in the vicinity of any surface contaminant source you suspect is capable of producing heat.

During the time between the initial thaw of the active zone and the freezing period, you should take temperature and hydraulic head measurements as frequently as possible. Considering the remote nature of this type of site, you may have to use automatic data recording systems for these measurements. While the active layer is completely frozen, suspend the data collection process.

4.11 Summary of Field Investigation Program and Reporting Results

The highly variable nature of subsurface conditions makes it impossible to define specific investigation strategies that will be appropriate in all cases. The staged approach provides considerable flexibility and permits the incorporation of new data, as they become available, to help steer subsequent work.

The selection of appropriate drilling and sediment sampling techniques should be made by an experienced hydrogeologist. Although several techniques may be applicable, careful consideration of site-specific factors will usually dictate a certain methodology for cost-effective field activities.

When designing monitoring networks and choosing monitoring well types and configurations, the field hydrogeologist should confer with the contaminant hydrogeologist, the geophysicist, and to some degree, the mathematical modeller to be sure an adequate, efficient monitoring well network is constructed for all end-users.

The final step in the hydrogeological site investigation is reporting the results to the appropriate parties. This represents Stage 4 of the overall field program. The final report should include the following:

- cross-sections illustrating the hydrostratigraphic sequence on-site;
- potentiometric or hydraulic head maps plotted and contoured in plan-view for each major hydrostratigraphic unit;
- cross-sections indicating vertical and lateral directions of groundwater flow;
- tabular summaries of water level data and physical parameter values from all measurement methods;
- a summary of principal contaminant transport pathways and the estimated risk associated with the different pathways;
- a summary of additional site-specific conditions that could influence contaminant transport, and recommendations for continued data collection and follow-up field work; and
- a summary of the methods used during the field program, the location of all monitoring wells, and the handling and storage protocol for sediment samples.

4.12 Additional Information

The following textbooks are good sources of general information on hydrogeological investigations:

- Driscoll, F.G., *Groundwater and Wells* (2nd Edition), Johnson Division, UOP Inc., St. Paul, Minnesota (1986).
- Nielsen, D.M., (ed.), *Practical Handbook of Groundwater Monitoring*, Lewis Publishers Inc., Chelsea, Michigan, 717 p. (1991).
- Nielsen, D.M. and A.I. Johnson, (eds.), *Ground Water and Unsaturated Zone Monitoring*, ASTM Special Technical Publications No. 1053, 313 p. (1989).

Additional information about specific aspects are also recommended:

- Aller, A., T.W. Bennett, G. Hackett, R.J. Petty, J.H. Lehr, H. Sedor, D.M. Nielsen J.E. Denne, *Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells*, National Water Well Association, Dublin, Ohio, 398 p. (1989).
- A handbook focused on the design, construction, and installation of ground water monitoring wells.
- Morrison, R.D., *Ground Water Monitoring Technology, Procedures, Equipment and Applications*, Timco Manufacturing Inc., Prairie du Sac, Wisconsin (1983).

- An extensive review of unsaturated zone monitoring and measurement techniques.
- Walton, W.C., *Ground-water Resource Evaluation*, McGraw-Hill, New York, New York (1970).
- One of the most comprehensive reviews of aquifer tests.

Articles in journals report new advances and evaluations of current techniques. Consider the following journals:

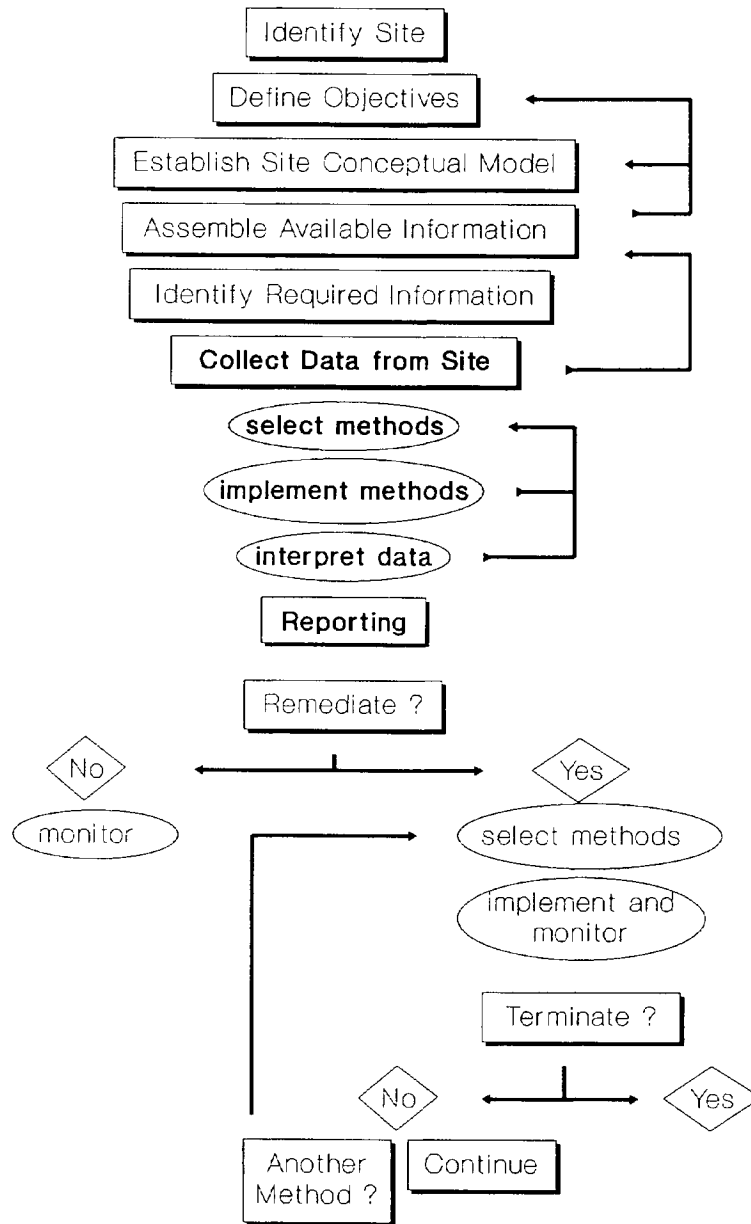
- *Ground Water*; and
- *Ground Water Monitoring Review*.
(Ground water Publishing Co.
6775 Riverside Dr., Dublin, OH, 43017, U.S.A.)

Equipment for hydrogeological investigations is provided by numerous firms that advertise in these journals. Also, *Groundwater Monitoring Review* produces an Annual Buyer's Guide issue that lists most suppliers.

Professional short courses in this area are offered by numerous groups. Advertisements appear in these journals and in the newsletters. Various technical conferences and workshops are also offered and are advertised and listed in the journals and newsletters:

- *Resilog* (Technology Development Directorate, Environment Canada); and
- *The Association of Ground Water Scientists and Engineers Newsletter* (Ground Water Publishing Co., 6375 Riverside Drive, Dublin, Ohio 43017).

Hydrogeological services are offered by many firms who advertise in local phone books (under Environmental Consultants, Engineers – Consultants), journals, and trade magazines. You may want to talk to a few firms before selecting one. Look at their lists of personnel, their experience, and approaches, and talk to their previous clients.



Section 5

Chemical Hydrogeology (J. Barker)

You have assembled all the information about the site as part of the desk-top review. This has probably indicated the chemicals of concern. Geophysical and hydrogeological studies have defined the subsurface conditions and may have located contaminants and their sources. In fact, the geochemical experts have probably been asked to offer advice for those studies. This section describes how you might collect chemical information regarding the source, extent, and movement of subsurface contaminants.

Many sampling and analytical techniques require equipment and experienced staff; therefore, rather than presenting such techniques in detail, references to sources of methods are made.

How you collect chemical information depends on specific site conditions. This section identifies the technical factors you need to consider and offers advice to help you select appropriate methods. It offers advice for sampling groundwater, pore water, soil gas, and subsurface sediments. Quality assurance begins with planning the investigations, and carries through sample collection, analysis, and interpretation. This section tells you how to ensure the quality of the subsurface chemical data.

This section discusses:

- planning to meet the site assessment objectives;
- screening methods to quickly focus subsequent sampling;
- groundwater sampling, including designing sampling networks, sampling a well, and interpreting data;
- analyses;
- quality assurance;
- microbiological sampling; and
- sampling the unsaturate zone (pore water, solids, and soil vapour).

5.1 Introduction

The first steps in any chemical study should be to review the overall study objectives and to identify the additional chemical information needed to meet these objectives. From these objectives, define both the size and contamination level of groundwater, soil, or vapour that must be found. For example, a small volume of contaminated water may not need to be detected to

meet the objectives. You will probably have to do some sampling to define the location, extent, and chemistry of potential sources of subsurface contamination. Sampling along potential contaminant pathways will also be required. This will require consideration of how the contaminants might be migrating in the subsurface, and thus, where they might be found.

Rapid, qualitative, chemical analyses of subsurface materials during the initial investigations (field screening) improve the overall investigation. Consider using soil gas surveys when volatile organic contaminants are anticipated. Analyze solids and water you encounter during drilling. Remember that many sites will contain hazardous chemicals; therefore, personnel will need appropriate information, training, and protection. Sampled water and solids could also be hazardous wastes and may require careful handling and disposal.

5.2 *Objectives and Plans*

To meet the site assessment objectives you typically:

- establish and remediate likely sources of contamination;
- establish the current distribution of chemicals in groundwater, soil vapour, and subsurface solids; and
- interpret the current contaminant distributions, predict future distribution, and design remedial action.

You will need a plan to evaluate the chemical composition and location of potential sources of subsurface contamination. Potential sources include solid waste disposal areas, **lagoons** receiving liquid waste, and storage tanks. Contaminated soils and NAPLs already in the subsurface are less obvious sources. Make sure your plan establishes:

- the size of source that could produce contamination of concern (1 m³ of gasoline-contaminated soil may not produce a significant environmental problem, while 1000 m³ certainly would); and
- the size of source that can, reasonably, be found (1 m³ of dioxin-contaminated soil could be a serious issue but difficult to find; 1 m³ of trichloroethylene, a **DNAPL**, can move to a considerable depth and may never be found, but it could contaminate more than 10⁷ m³ of groundwater to concentrations above the CCME remediation criteria for drinking water of 50 µg/L).

Available information (Section 2) and geophysical surveys (Section 3) may define specific source areas or site contaminants. If these methods fail, plan systematic sampling and comprehensive analyses to define sources. The methods you use to characterize the sources will depend on:

- specific site conditions including the lateral extent and depth of the target sources, including NAPLs;
- the homogeneity of the source(s); and
- the chemical composition of the source(s) (chemically-complex sources may be expensive to analyze).

A staged approach to contaminant source evaluation, like that recommended for establishing the subsurface hydrogeology in Section 4, may be useful. Analyze a few samples qualitatively for a large range of potential contaminants. From this, develop a site-specific list of target chemicals that were identified and that are of environmental concern. Analyze additional samples from contaminated areas for only these target chemicals. You will find advice for collecting and analyzing subsurface samples later in this section.

Contaminants in and near the source area are probably unevenly distributed. Use **reconnaissance sampling** or **search sampling** of suspected or potential contaminated soils (e.g., sludge impoundments) found from the desk-top review or other investigations (Sections 3 and 4). The sampling design and data analysis plan should ensure that contaminant distributions are adequately defined. **Systematic sampling** (sampling according to a regular spatial pattern) is preferred to estimate average and total contamination and to find patterns of contamination. If the pattern is already known or suspected, consider more judgemental sampling, and emphasize sampling of the suspected areas. This is a complex issue, and is both site and contaminant specific. Consider:

- the objectives;
- the costs of alternate sampling plans;
- the anticipated contaminant distribution; and
- practical aspects, such as site accessibility.

Approaches and other considerations are presented by Keith (1991) and Gilbert (1987).

With the contaminant source(s) defined you can plan the subsurface sampling. Choose the media, locations, analytical methods, and frequency of the sampling based on the assessment objectives, the nature of the source(s), and on the subsurface contamination concept. Available information (Section 2) and hydrogeological information (Sections 3 and 4) form the basis of the concept. As more information is collected, the concept may change and the plan may be modified. Therefore, use a staged approach (e.g., reconnaissance sampling followed by more-detailed sampling) to define the distribution of contaminants in the subsurface. A statistical approach may be useful for designing sampling strategies, but make sure that the design is appropriate for the known or suspected subsurface contamination pathways. For example, do not use a regular sampling grid if only a few, well-defined contaminant pathways exist. Locate these pathways and then concentrate the samplings along these pathways.

Figure 79 illustrates two simple hydrogeological settings. The only difference is the rather impermeable layer beneath the site. Lines with arrows are groundwater flow paths, near-vertical lines are hydraulic heads. Note the greater depth of contamination under the waste in an area with a low permeability zone. Also note the different findings from the well immediately down-gradient of the contaminated site. This illustrates that the correct hydrogeology concept is required to locate sampling points on potential pathways.

Gilbert (1987) demonstrated the problem of soil sampling designed to find a “hot spot” of specified size and shape by sampling at various grid spacings. The probability of finding a 10-m radius, circular, hot spot with sampling grid nodes 20, 50, and 100 m apart on a square grid is about 80, 15, and 5%, respectively. If the square site is 1 km per side, these grid spacings imply 2500, 400, and 100 samples, respectively. The smallest spacing may be too expensive; whereas, the larger spacings may be too unreliable. **Compositing** (thorough mixing of individual samples and analysis of a representative subsample) may reduce the analytical cost, but will raise the minimum concentration that can be detected and will leave the hot spot location less well defined.

Designing effective groundwater sampling schemes for karst systems is particularly challenging. In this setting, most groundwater flows through open channels. Locating sampling wells on a

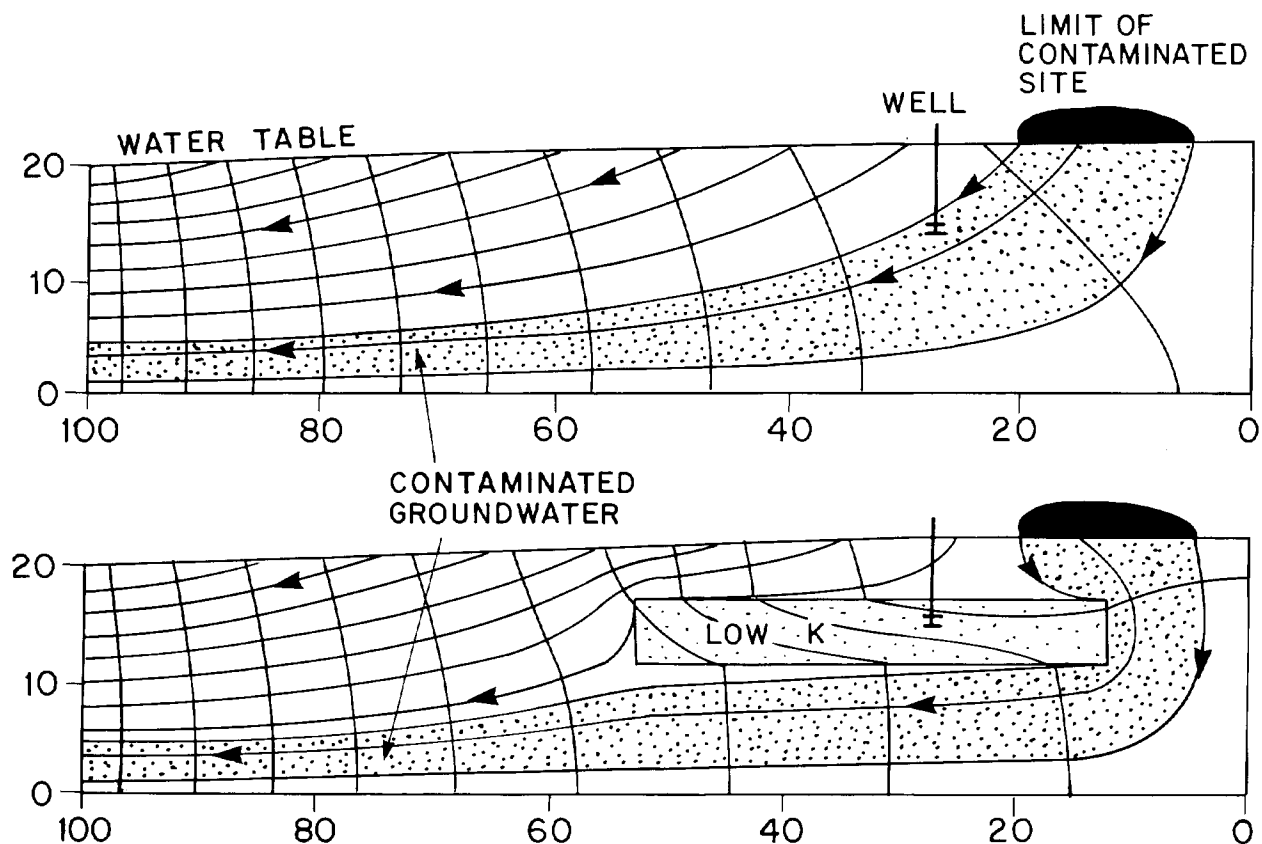


Figure 79 How Simple Differences in Subsurface Materials Can Influence Contaminant Pathways. Groundwater flow (arrows on flow lines) crosses equipotential lines at a right angle.

statistical grid or simply distributing them evenly will not guarantee intersection with these potential contaminant pathways. Although fracture mapping and structural geological mapping may identify some locations where wells can intersect such pathways, do not rely on these wells for groundwater sampling. Rather, concentrate on sampling springs. Groundwater flows through open channels, and active flow networks vary with the volume of water within the network. You should sample flow channels and their discharge springs when they are active, usually after storms or snow melts. It may be difficult to find locations producing reliable background samples. Interpretation of chemical data from karst systems must consider these problems and uncertainties. Quinlan (1989) provides additional recommendations and discussion.

5.3 *Screening Techniques*

You can improve the site investigation by rapidly determining the approximate subsurface contaminant distributions. This is called screening. Methods are often indirect and the analysis qualitative. In addition to the geophysical approaches outlined in Section 3, consider:

- soil gas surveys to identify underlying, volatile organic contamination (e.g., gasoline pools); and
- sampling and analysis of sediment, rock, and groundwater recovered during drilling to provide a basis for decisions on the location of wells and on additional drilling.

5.3.1 *Soil Gas Surveys*

Soil gas surveys are well-established methods of assessing the subsurface distribution of volatile organics. Samples of soil gas are obtained and analyzed, on site, for volatile organics. The contaminant must be volatile; it should have a Henry's law constant of at least $0.0005 \text{ atm} \cdot \text{m}^3/\text{mol}$ and a vapour pressure (at 20°C) of at least 1.0 mm Hg. Consider soil gas surveys as an alternative to conventional drilling and sampling during initial subsurface studies. They can delineate source areas and track some contaminant plumes, allowing you to most accurately place subsequent monitoring well point locations.

There are active and passive sampling approaches. Active sampling is faster, and therefore preferred. Soil gas is drawn from the ground (by pumping shallow, driven probes) and collected in a syringe. Draw samples from deeper than 1 m to avoid the variable concentrations typically found nearer the surface. Analysis is done on site using **gas chromatography (GC)**, alone or even **gas chromatography coupled with mass spectrometry (GC/MS)**. Analytical methods are similar to the methods used for volatile organics and reviewed by CCME (1993). Results are available in minutes and you can modify the sampling plan as the survey progresses.

Soil gas surveys have limitations. Your survey may not detect existing contaminants because soil vapour has not moved from the source to your sampling point. Barriers to soil gas movement include:

- fine-grained materials of low gas permeability;

- high water content materials, especially perched water table zones; and
- sorptive, organic rich soils.

Consult existing information (Section 3 and 4), and consider conducting a preliminary soil boring to evaluate such barriers. Less drastic problems associated with temperature changes, humidity, biological activity, and sorption are discussed by Kerfoot (1991). Soil gas surveys can be a powerful screening technique, but only experienced professionals should plan, conduct, and interpret the results of soil gas surveys.

5.3.2 Screening Groundwater and Solids

As wells are established, the initial groundwater samples can be qualitatively analyzed on site. Information is quickly available and lets you decide on the need for, and best location for, further drilling. Use the analytical methods outlined in Table 12 to screen groundwater samples for chemical parameters.

You can rapidly screen solid subsurface materials for at least volatile organics with total organic vapour (TOV) detectors. You can also perform more reliable, but still often semi-quantitative, analyses of volatile organics using field solvent extraction (U. S. EPA, 1986, SW-846) or **headspace-GC** techniques (Fitzgerald, 1989; Sims *et al.*, 1991). If solid material can be disaggregated, it can be added to distilled water and the leached inorganic chemicals can be measured using the techniques outlined in Table 12.

5.4 Sampling Groundwater

In sampling and analyzing groundwater you are trying to ensure that:

- a sample representative of the *in situ* water is obtained;
- changes in water chemistry prior to analyses are minimal; and
- analyses are reliable (accurate and reproducible).

Normally you drill a borehole, install a well, draw groundwater to the surface, and either measure the chemical parameters of interest or collect a sample to ship to a laboratory for analysis. A screen at the bottom of the well prevents most solid particles from entering the well but permits entry of sufficient groundwater to meet sampling requirements. Refer to Section 4.6 for details on well installation procedures. Considerations important to ensure the quality of subsequent chemical samples will be highlighted in this section. Groundwater sampling wells (monitoring wells) can be located in a regular grid pattern, but normally will be located at specific sites to intersect suspected pathways of contaminated groundwater. Existing information provides the basis for selecting well sites. As indicated in Section 4, a staged approach usually produces the best monitoring network design.

Table 12 Quick, On-site Methods Used to Analyze Groundwater for Selected Chemical Parameters

Parameter	Method	Practical Method Detection Limit (\pm Precision)	Comments
pH	Electrode system	± 0.1 pH unit	Recommended method
Dissolved oxygen	Electrode or chemical titration	0.5 ± 0.1 mg/L	Recommended method
Eh	Electrode	Qualitative only	Where redox sensitive parameters are of interest
Specific conductance	Electrode	($\pm 10\%$)	Recommended method
Total organic vapour (TOV)	Total organic vapour analyzer	1 mg/L ($\pm 20\%$)	Various analyzers available
Volatile organic compounds (VOCs)	Headspace GC	0.1 to 10 $\mu\text{g/L}$ ($\pm 10\%$)	Uses portable GC; tentative identities
Specific VOCs and other organics	Laboratory methods in a field GC and GC/MS	0.1 to 10 $\mu\text{g/L}$ ($\pm 10\%$)	Requires field lab
Chloride, bromide	Specific ion electrode	1 mg/L ($\pm 20\%$)	Some other chemicals interfere
Selected pesticides	Immunoassays	0.01 $\mu\text{g/L}$ ($\pm 20\%$)	New technology, rapidly evolving
Major inorganics (excluding trace metals)	Kits based on colorimetric methods	As laboratory analyses, but poorer precision	Greater interference problems than chloride

Well construction materials should not compromise subsequent sampling but should be as simple, convenient, and cost-effective as possible. Typical materials for well casing and well screens include:

- metals, including stainless steel (SS), carbon steel (CS), and galvanized steel (GS);
- rigid polyvinyl chloride (PVC); and
- fibreglass-reinforced epoxy (FRE) and plastic (FRP).

Other materials, such as polytetrafluoroethylene (PTFE), are infrequently used and are not discussed here. Most well casings are made of PVC or various steels. At some contaminated sites, groundwaters could corrode metal wells and the metals could leach into the sampled water. Therefore, consider selecting PVC instead of SS when sampling groundwaters for metals.

Thermoplastics are susceptible to chemical attack by certain organic solvent NAPLs. Use metal or FRE casing if such NAPL pools are confirmed to be at the site. If you use PVC, insist that lengths of well casing be joined by flush, threaded joints. Flush clean water through a length of casing before it is installed and analyze it for parameters of interest to ensure that the well material is not adding chemicals to subsequent groundwater samples. Leaching of organics, except for perhaps acetone used to clean some PVC, does not appear to be a problem. However, sorption onto PVC could be a problem. Figure 80 indicates that when groundwater is exposed (even for a few minutes) to 5-cm diameter PVC well casing, more than 10% of very **hydrophobic**, insoluble (< 1 millimoles/ m^3) organic contaminants can be lost. Sorption of organics with solubilities of more than about 10 millimoles/ m^3 should not be a significant problem. If reliable analysis of hydrophobic organics is critical, consider using stainless steel well material. In any event, you should minimize the time that the groundwater and well material are in contact.

Minimize the well diameter to reduce the volume of water that must be pumped and disposed of during sampling. Choose the screen opening (slot) size to efficiently transmit water and keep solid particles out of the well. Avoid filter packs, where possible, because they are potential sources of contamination and chemical alteration. In permeable, unconsolidated materials, use naturally developed wells. In low permeability formations you will probably need both a filter pack and a well screen with appropriate slot size (see Section 4.6). Avoid **dewatering** the filter pack because this can enhance the loss of volatile compounds prior to sampling. Consider using as coarse a sand pack if your major objective is to measure NAPL thickness.

Choose the length of the well screen and the filter pack based on the depth interval that the sample will represent. Regardless of the screen or filter pack length, the groundwater comes mainly from the more permeable intervals and will rarely be representative of the total screened interval. Avoid placing screens across multiple aquifers because this might allow groundwater and DNAPL to flow across aquitards. If this happens, you may incorrectly conclude that both aquifers are contaminated.

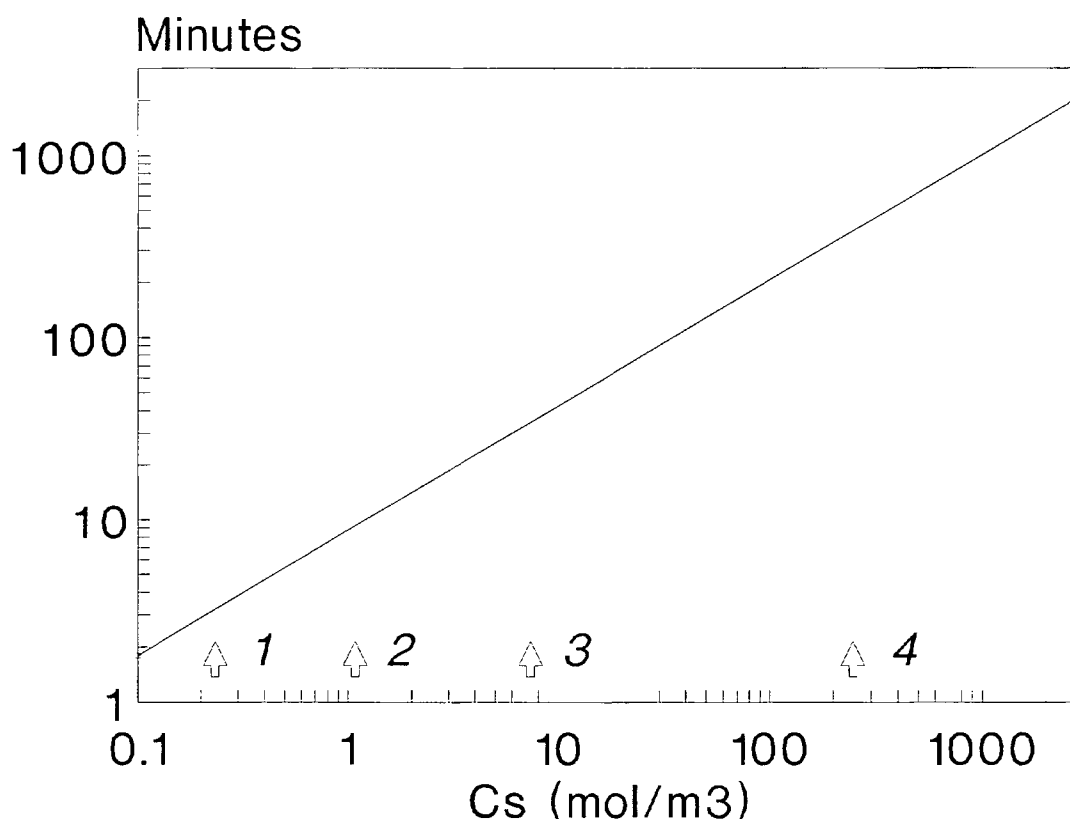


Figure 80 The Approximate Relationship Between the Organic Chemical Solubility (C_s) and the Time of Contact with a PVC Well Casing of 5-cm Diameter that will Produce a 10% Loss of Organic due to Sorption. Larger well diameters will require longer contact time to produce 10% loss. Representative organics and their solubility (bracketed and in millimoles per m³) are: 1 anthracene (0.23); 2 diethylhexylphthalate (1.02); 3 phenanthrene (7.25); and 4 naphthalene (248). Developed from Hoff *et al.*(1990) and Gillham and O'Hannesin (1989).

5.4.1 Preparing to Sample Wells

Develop, document, and follow a detailed groundwater sampling plan. It will be site specific and will depend on the site contaminants and on the type of wells to be sampled. Generally, the sequence of sampling activities will be:

- measure the water level (see Section 4) and the thickness of NAPL (if present in the well);
- sample the NAPL (if present);
- remove (flush or **purge**) the water standing in the well; and
- collect samples of the groundwater and perform and field measurements.

5.4.2 Measuring Thickness and Sampling NAPLs

Determine the thickness of LNAPL and DNAPL in the well using an interface probe or a weighted tape coated with NAPL- and water-indicator pastes. Measured thickness always exceeds actual thickness in the formation.

Pastrovich *et al.* (1979) present a rough estimator of the thickness of LNAPL in the aquifer from the measured thickness in the well:

$$H/h \approx \rho_{\text{LNAPL}} / \rho_{\text{H}_2\text{O}} - \rho_{\text{LNAPL}} \quad [14]$$

where H is the measured LNAPL thickness in the well, h is the average LNAPL thickness in the aquifer near the well, and ρ is the density of the LNAPL and of water, respectively. Typical LNAPL densities are summarized in Table 13. Use this as an *estimate* only. Mercer and Cohen (1990) advise caution when relating the thickness of DNAPL in a well to the thickness in the aquifer. Lenhard and Parker (1990) discuss more sophisticated estimation methods that require additional information.

New methods for sampling the LNAPL are being developed (Durnford *et al.*, 1991), but currently, you should probably sample the LNAPL in the well with a bailer. Sample the DNAPL with a bottom-filling bailer, or slowly pump the DNAPL with the tubing inlet placed at the bottom of the well. Complete your NAPL sampling before well purging to avoid mixing the fluids in the well.

The presence of NAPL in a well precludes obtaining groundwater samples representative of the NAPL chemical concentrations. This is because NAPL may contact any groundwater taken from that well, and the NAPL chemicals could dissolve in that groundwater.

Table 13 Typical LNAPL Densities

LNAPL	Density, ρ (g/cm ³)
Gasoline	0.781 to 0.695
JP-4	0.800 to 0.790
Number 2 fuel oil/Kerosene	0.836 to 0.790
Diesel/Number 2 fuel oil	0.920 to 0.804

5.4.3 *Well Flushing or Purging*

Water standing in the well is not normally representative of groundwater *in situ*. Sampling water from the well screen zone may, in some cases, be as reliable as sampling water recently pumped into the well (Gillham *et al.*, 1983). However, you should usually remove the standing water before sampling. It may be difficult to determine how much water needs to be removed before the well contains water representative of the *in situ* groundwater. Suggested methods include arbitrary advice, calculation methods based on well hydraulics, and purging until selected chemical parameters stabilize.

There is no generally correct protocol for purging. The screen length, sand pack characteristics, and, most significantly, the vertical distribution of the contaminant concentration, control the concentration of contaminants in the pumped water.

A consistent, practical purging protocol must be established, documented, and followed. Consider removing two or three well casing volumes by pumping from just below the air-water interface in the well unless site-specific conditions warrant another approach. For example, when wells do not yield sufficient water, purge all standing water and then collect a sample after sufficient groundwater has entered the well. Chemical alteration of such a sample, due to prolonged exposure to air during recharge of the well, is probable and must be acknowledged in the subsequent data interpretation. To minimize the volume of purged water to be disposed (because it may be contaminated), ensure that wells have the narrowest practical diameter.

5.4.4 *Collecting Groundwater Samples*

Sampling personnel must understand the potential sources of **bias** in sampling and make appropriate adjustments in protocols and schedules on site. Be sure to document all procedures, especially deviations or problems. Field books are essential for documenting field activities and observations. It is important to know when and how protocols change because these changes may change the water chemistry.

Many devices are available for bringing groundwater from the screened interval of the well to the surface for collection. If you use the same sampler in multiple wells, clean it and demonstrate that contaminants were not carried from one well to another by the sampler. Typically, you can rinse the cleared sampler with contaminant-free water and submit that water for analysis. Sampling devices should be dedicated to each well to avoid this problem. The best dedicated system will be capable of both purging and flushing at high flow rates of up to several litres per minute, and sampling the well at much slower pumping rates (typically, 100 mL/min). See list of recommended devices in Table 14.

Samples are taken to provide sufficient water for the desired chemical analyses. Table 15 presents typical required volumes.

5.4.5 *Sampling for Specific Analyses*

Isotopes. Measure naturally occurring stable and radioactive **isotopes** of hydrogen, oxygen, carbon, and sulphur in groundwater samples to investigate the source of water or dissolved chemicals and the “age” of the groundwater (time since recharge). The most common isotopes,

Table 14 Devices for Sampling Groundwater from Wells

Device or System	Examples ^a	Materials ^b	Comments/Limitations
Bailer	Point source bailer	Teflon®, SS, PVC	Double check valves; unsuitable for purging high-yield wells
Syringe sampler	IEA syringe sampler	SS, Teflon®	Unsuitable for purging
Evacuated container	BAT enviro probe, Westbay pressure probe	Glass, SS	Evacuated container fills by hydrostatic pressure; unsuitable for purging
Peristaltic pump	Masterflex®	Teflon®, Viton®	Water sampled before pump; depth to water must be < 7 m
Mechanical pump	Grundfos, Fultz, others	SS, Teflon®	Down-hole submersible pump; needs electricity
Piston pump	Bennett pump, HydroStar®	SS, Teflon®, Viton®	Compressed air-actuated piston pumps; air does not contact sample
Bladder pump	Well Wizard®, Geoguard®	SS, Teflon®	Gas drives bladder that pushes water up; need gas supply
Gas drive pump	Timco air lift, triple tube sampler	Teflon®, SS	Gas drives plug of water up; some gas/water contact; used for sampling non-volatiles
Inertial lift	Waterra® pump	Teflon®, other plastics	Up/down motion of tubing causes water to rise; some agitation in well

^a Use of specific names does not constitute endorsement, but is for illustrative purposes only.

^b SS = stainless steel.

their use, and their sampling requirements are listed in Table 16. Additional advice and sampling assistance is available from isotope laboratories.

Inorganics. Generally, most groundwater sampling introduces little bias for the major inorganic constituents. The major concerns involve parameters sensitive to **degassing** (pH) and to **aeration** (Fe, Mn, pH). Loss of CO₂ by degassing can raise the pH of the sample. Aeration allows oxygen into the water and could induce precipitation of Fe and Mn oxyhydroxides and bias subsequent water analysis. Aeration may occur if water recovers into the well slowly (typical of low permeability environments). Sample only the latest water to enter such a well. Wait for most of the recovery and take the sample from below the standing water level, near the bottom of the well screen. Minimize the contact of the sample with flexible plastic sampling tubing (e.g., Teflon®, polyethylene, silicone, Tygon) because oxygen may diffuse through the tubing and aerate the sample.

Table 15 Typically Recommended Containers, Preservatives, and Maximum Holding Times

Compounds	Sample Container ^b	Preservation	Holding Time
Major cations	P,G; 100 to 1000 mL	HNO ₃ to pH < 2	6 months
Major anions	P,G; 100 to 1000 mL	cool, 4°C ^c	14 to 28 days
N species, P	P,G; 100 to 500 mL	H ₂ SO ₄ to pH < 2	14 to 28 days
Metals	P,G; 50 to 100 mL	HNO ₃ to pH < 2	6 months
Cyanide	P,G; 500 mL	NaOH to pH > 12	14 days
Volatile organics	G; 10 to 250 mL	cool, 4°C, no headspace, and as advised by laboratory	5 to 14 days before analysis or extraction
Semi- and non-volatile organics	G; 100 to 1000 mL	cool, 4°C, and as advised by laboratory	7 days before analysis or extraction

^a The analytical laboratory may have alternate or additional requirements so always consult them before collecting samples. Laboratories should provide sample containers and detailed instructions about preservatives.

^b P = plastic; G = glass.

^c If biological activity is of concern (e.g., sulphate) then use the major cation sample.

Filter a groundwater sample without exposure to air if you need analysis of the “dissolved” chemicals unless:

- you want the total load of chemicals resulting from consuming unfiltered water;
- you want to detect any presence of highly sorbed chemicals (use an unfiltered sample because it will contain the chemical sorbed onto particulate matter);
- the chemical(s) of interest are not significantly sorbed to particulate matter (e.g., chloride) and therefore filtering is not required;
- you are working with karst or fractured aquifers where fracture openings are large, and chemicals attached to particles and **colloids** may be moving (filtration would underestimate the mobile chemicals in this situation); or

Table 16 Environmental Isotopes: Common Use and Sample Requirements

Isotopes	Common Use	Sample Requirements
^2H and ^{18}O in water itself	Type/source of water	10-ml bottle, no headspace, no evaporation or freezing
^3H in water	Time since recharge (if < 50 years)	1-L bottle, no headspace, no evaporation or freezing
^{13}C in dissolved carbon compounds	Source of carbon compounds (e.g. methane)	100 mL, gas-tight vessel, bactericide added
^{14}C in dissolved carbon compounds	Time since recharge (if < 40 000 years)	50 L water with bactericide, or field collection of carbonate as BaCO_3 from about 50 L of groundwater
^{34}S and ^{18}O in dissolved sulphate	Source of sulphate (e.g. acid rain or subsurface minerals)	Field collection as BaSO_4 or ZnS from up to 10 L of groundwater

- suspected contaminants include volatile chemicals (filtering may cause loss and therefore should be avoided, particularly because these chemicals are usually not significantly sorbed to the particulate matter).

Filter in-line and without exposure to air during sample collection. In-line plastic holders with cellulose filters are generally adequate. Filters for organics with high sorption potential (high K_{ow}) should be made of glass fibre with stainless steel filter holders. The effective pore size of the filter is usually arbitrarily selected as 0.45 μm . If the size distribution of the colloids in groundwater is being assessed, use large diameter, in-line polycarbonate filters with 0.1 μm pore size to remove coarser particles and then collect colloids onto finer filters.

Document the filtering protocol and follow it. Changing the filtering protocol usually changes concentrations, particularly of metals.

When sampling for trace metals, minimize sorption onto surfaces, precipitation of metal oxyhydroxides, and leaching of metals from sampling equipment. Avoid galvanized steel and other ferrous materials. Filter carefully to determine “dissolved trace metals” because many trace metals will be sorbed onto particulate matter in the water. Avoid aerating before filtering because the Fe and Mn oxyhydroxide precipitates, formed when aerated, are effective scavengers of some trace metals.

Temperature, specific conductance, pH, Eh, alkalinity, dissolved oxygen concentration, and concentrations of other dissolved gases are often determined on site. If possible, measure water temperature down-hole because it can increase from 1 to 4°C during pumping. Down-hole temperature probes are available.

The specific (electrical) conductance of groundwater is a useful estimate of the total inorganic load or total dissolved solids (TDS) in the groundwater. Conductance varies with water temperature; therefore, water temperature must also be reported. A solution of known specific conductance (0.01 molal KCl usually) should be prepared and occasionally used to confirm the accuracy of the **electrode** system. It suffers little bias otherwise.

A special consideration is bias in pH determinations, because groundwater pH can be changed by numerous processes during sampling:

- degassing or loss of CO₂, resulting in higher pH;
- precipitation of CaCO₃, resulting in lower pH; and
- precipitation of iron and other metal oxyhydroxides, producing lower pH.

Rarely is pH required to an accuracy of better than ± 0.2 units; therefore, it can usually be measured on site with some effort to avoid these problems. For example, electrode measurements can be made in line using flow-through cells. Samples with minimal **headspace** can be kept cool and returned to the laboratory for pH measurement at the *in situ* temperature. Laboratory or field protocols require high-quality, well-maintained electrodes, and at least two reference **buffer** solutions for calibration at field temperatures.

The **redox** level or Eh of the groundwater indicates contamination by reductants such as organic matter and is used to evaluate the chemical form of many dissolved, multivalence metals such as iron (Fe²⁺/Fe³⁺) and arsenic (As³⁺/As⁵⁺). An electrode system with a flow-through cell can be used to assess groundwater Eh, but the measurement is so difficult to make and the interpretation so inexact, that you should probably avoid it. You can estimate the general redox condition of the water from the concentrations (even just presence/absence) of redox-sensitive chemicals such as O₂, NO₃⁻ and ammonia, Fe (total), SO₄⁼ and H₂S, and methane (CH₄). Figure 81 shows the relationship between these parameters and the redox condition of the groundwater.

Alkalinity is determined by **titration** (Clesceri *et al.*, 1989). A consistent sampling and measurement protocol must be used. You may find laboratory analysis simpler and as accurate as field determination.

Gases. Dissolved oxygen (DO) can be determined by an electrode method or probe, by a titration following chemical additions (**Winkler titration**, Clesceri *et al.*, 1989), or colorimetrically. Walton-Day *et al.* (1990), describe a flow-through cell system that uses colorimetric reagents for DO determinations. Reported detection limits are about 0.0005 mg/L (much better than the typical limit of about 1 mg/L with the probe). The Winkler titration has adequate sensitivity (0.03 mg/L O₂), but you must sample using a 50 ml glass syringe and add

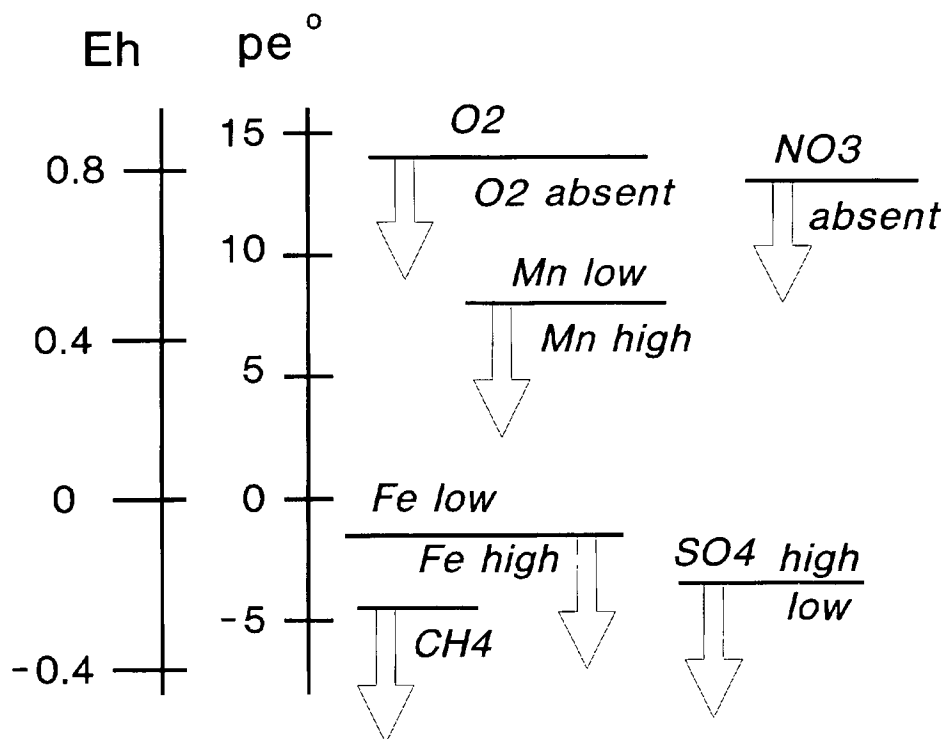


Figure 81 Relationships Among Redox Potential (pe or pe° ; the pe at pH = 7), Eh (volts), and Specific Inorganic Chemical Species. For example, groundwater with no oxygen, nitrate, or methane, but high Fe and SO_4^{2-} concentrations, would be inferred to have an Eh of -0.1 to -0.2 V.

chemicals to the syringe to preclude atmospheric contamination. The syringe can be flushed with oxygen-free gas, and then with groundwater before a sample is drawn.

We recommend using:

- the probe where method detection limits (MDL) of 1 mg/L are adequate;
- the modified Winkler titration for a MDL between 0.1 and 1 mg/L; and
- the flow-cell with colorimetric reagents only where very reliable DO values < 1 mg/L are required.

Samples for other gases are typically collected in glass syringes because plastic syringes are permeable to most gases. A headspace-gas chromatographic analysis can be used (Stainton *et al.*, 1977) for on-site analysis.

Organics. When sampling for trace organic compounds (< about 1 mg/L), two sources of bias must be considered:

- loss of volatile organics to the atmosphere; and

- sorption of organics onto sampling materials.

The sorption problem has been addressed earlier. Minimize the time of contact with sampling materials and use stainless steel, glass, and Teflon® sampling equipment where possible.

Numerous studies have evaluated the potential of losing volatile organics during sampling. The loss is unlikely to exceed that predicted in Figure 82. The prediction requires knowledge or estimation of the Henry's law constant (H) for the constituent, and of the ratio of air to water. Table 17 recommends the caution appropriate when sampling for volatiles.

5.4.6 Containers/Preservatives/Storage

To minimize chemical changes in samples between sampling and analysis, use specific bottles, add preservatives if necessary, and follow recommended storage requirements. Typical requirements are summarized in Table 15. These aspects have been well-established for inorganics, but are not well-established for analysis of trace organics. The laboratories that will perform the analyses should specify the volumes of water required and recommend specific preservation methods. The laboratory should also provide the cleaned bottles and any water required for field or trip blanks. Experience (Patrick *et al.*, 1986) indicates that established protocols may not prevent biotransformation of, for example, monoaromatic hydrocarbons.

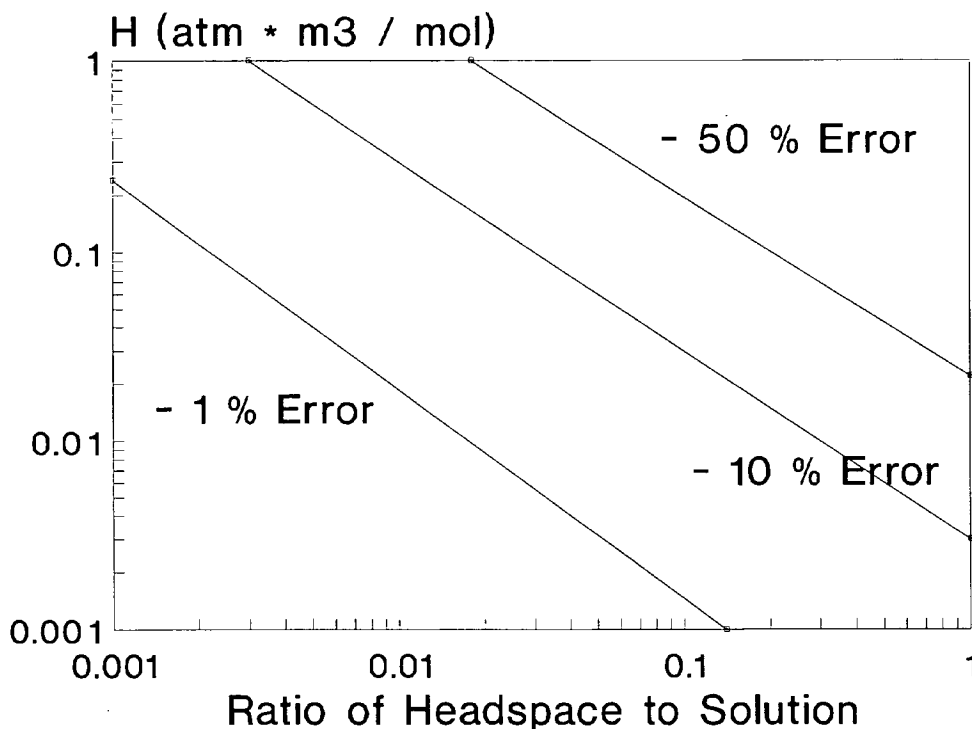


Figure 82 Predicted Error from Loss by Volatilization. (After Pankow, 1986). H is the Henry's law constant for the compound. For example, a compound with H of 0.002 would suffer no more than a 10% loss (read from diagonal lines) into the headspace if the sample bottle was left only 50% full of water (ratio of 1:1 on horizontal axis).

Table 17 Recommended Precautions when Sampling for Volatile Organics and Gases Having Different H Values

H (atm·m ³ /mol)	Avoid	Suggested Samplers
> 0.1	Any exposure to the atmosphere	Syringes, evacuated containers
0.01 to 0.1	Suction samplers	Non-suction samples
< 0.01	No special precautions	No special precautions

However, only add preservatives on advice from experienced laboratories. In all cases, extract the organic constituents of interest from the water matrix as soon as possible. Once extracted, samples for organic analyses are usually stable for weeks or even months. Holding times and conditions, sample preparation, and analysis dates must all be documented and reported by the laboratory.

5.5 *Analysis of Groundwaters*

5.5.1 *Scans*

It is usually worthwhile to determine the chemistry of the contaminated groundwater very early in the site assessment. This analysis is termed a **scan**. It tries to identify, but not necessarily quantify, the chemicals present. From this analysis, indicator chemicals can be selected for quantitation in subsequent groundwater samples.

For inorganics, the inductively coupled plasma/emission spectroscopy (ICP/ES) technique is particularly useful. For organics, analysis is complicated by the myriad of chemicals potentially present, and by our inability to identify each chemical. Typically, volatile organics are scanned by **purge-and-trap (P and T)** gas chromatographic (GC) methods using a mass spectrometer (MS) as the detector. This method is similar to U.S. EPA methods 8240B and 8260A (CCME, 1993). Concentrate non-volatile organics using **extracting** solvents and then analyze them with GC-MS techniques (similar to EPA method 8270A). In these scans, considerable expertise is required to identify as many compounds as possible; therefore, work with experienced analysts.

You will probably want to identify the extent of migration of contaminated groundwater. For this, a **conservative** (non-reactive, moving as fast as the groundwater) constituent or indicator is required. The ideal indicator is conservative, easily sampled, reliably and inexpensively analyzed, and has a large difference in concentration between the potential source of

contamination and uncontaminated groundwater. Typical examples included boron, chloride, bromide, potassium, some volatile organics, and phenol. Given the limited understanding of the fate of organics in groundwater, organics may not be a reliable tracer. Selection will always be site-specific.

5.5.2 *Specific Analyses*

A review of the chemicals identified in the scan should identify specific chemicals for subsequent sampling. Both hydrogeological and analytical considerations must be weighed. Most monitoring should be for a limited suite of chemicals; selective determination of "all" contaminants should be done for fewer samples. Kane (1987) and CCME (1993) outline various analytical techniques for groundwater, soil, and petroleum products that might be useful.

Analyses for most inorganics of interest are by standard methods, and many of the methods are semiautomated. If you encounter very high inorganic concentrations (e.g., brines with TDS of >200 g/L), even inorganics are difficult to determine accurately. Although not without limitations, ICP/ES has the added advantage of having acceptable detection limits and rapid, simultaneous, multi-element analysis capacity. The ICP/ES provides much more information for about the same cost, but it does require additional effort to interpret the additional data.

Only a few hundred of the numerous organic compounds can be analyzed at the sub-ppm levels normally required for regulatory purposes. This is a rapidly evolving area of analytical chemistry and new methods are continually becoming available. Most methods use gas chromatography (GC) or high performance liquid chromatography (HPLC) to separate chemicals. Various detectors, including mass spectrometers (MS) quantify the concentrations. Problems with identification of organics, separation, and reliable quantitation abound. Most attention has been focused on the about 120 or so organic compounds included in the U.S. EPA list of priority pollutants, and analytical methods for these organics have been established. Similarly, CCME has focused attention on more than 130 organic compounds mentioned in the Interim Canadian Environmental Quality Criteria for Contaminated Sites. CCME (1993) reviews sampling and analytical methods for these compounds. Other methods are undoubtedly superior for select contaminant analysis at specific sites. Therefore, you should not simply restrict laboratory analyses to the methods approved by regulators. Meeting the QA/QC requirements for the site assessment should be the critical criterion of the proposed analytical methods.

5.5.3 *Quality Assurance*

Sampling and analysis must meet the **data quality objectives (DQOs)** of the site assessment. These DQOs consider the objectives of the site assessment as well as practical limitations such as resources, site access, and analytical capability. For example, you may be asked to determine if a certain chemical is present in soils at a site. To establish the DQOs, you need to identify what degree of **uncertainty** is acceptable. Specifically, you have to decide how small a concentration is to be detected with what certainty, and how small a volume of contaminated soil needs to be found. If the answer is a very small concentration and a very small volume, then you may not be able to meet these DQOs. For example, there may be no access to certain parts of the site, there may simply be no analytical method of sufficient reliability, or the budget may not let you take and analyze enough samples.

Quality assurance (QA) is those activities that assure us that a defined standard of quality with a stated level of confidence is met. QA is made up of **quality control (QC)**, and **quality assessment (QS)** activities. We must identify and minimize sources of error and uncertainty in the sampling – analysis – interpretation chain in accordance with the data quality objectives. Establish the quality assurance and quality control (QA/QC) program in the planning stage. This section will emphasize the role of site investigators in planning and conducting QA/QC. More thorough coverage of this topic is provided by CCME (1993) and Vitale *et al.* (1991).

All laboratories have some QS plan. You need to know what measures are used in QS, how the QS results are conveyed, and what is the typical performance of laboratories. The laboratory must completely and accurately report all results and their uncertainty. The user must interpret, censor, and take responsibility for subsequent reporting of the laboratory data. To do this accurately, users must establish communication with the laboratory at the planning stage. Establish the reporting format at the onset and seek specific laboratory QC and QS information before contracting for analyses.

Accuracy is usually measured by the bias, which is the difference between the mean value determined and the true value. Therefore, the report from the analytical laboratory must present an evaluation of bias. **Precision** or repeatability is usually determined by repeated analysis of a sample. Precision is commonly reported as the standard deviation (σ) or relative standard deviation (RSD), often as a percentage of the mean value.

Another issue that evolves from accuracy and precision is **detection limits**. Keith (1991) suggested that the limits be established from the standard deviation (for the analysis) and be reported as shown in Table 18. Below some concentrations, the chemical cannot be reliably determined or quantified (limit of quantitation, $LOQ = \text{blank} + 10\sigma$) because of uncertainty of the determination. Below a lower concentration (reliable detection limit, $RDL = \text{blank} + 6\sigma$) the uncertainty is so high that even detection of the chemical is unreliable. Below an even lower concentration (limit of detection, LOD or method detection limit, $MDL = \text{blank} + 3\sigma$) the analytical equipment does not respond to the chemical to a degree significantly different from its response to a blank sample.

Results can be very reliable when the laboratory analysis is technically straightforward, the sample matrix presents no complications, and the concentrations are well above the LOD or MDL. For example, an interlaboratory comparison of U.S. EPA contract laboratories yielded low bias and low RSD for common inorganic parameters (Table 19). Poorer results for many organics are unfortunately typical but may be improved. For example, the positive bias for methylene chloride probably reflects the contamination of samples from the laboratory atmosphere, because methylene chloride is a common laboratory solvent. Negative bias for other volatile organics could reflect volatile loss during sample handling. Laboratories now transfer samples by syringes and avoid many of these causes of bias. CCME (1993) reported much better QS results for similar organics. This suggests that more reliable results can be obtained under some conditions. Site-specific conditions (interfering chemicals or lower concentrations) may limit reliability and the results may not meet DQOs.

Table 18 Guidelines for Laboratory Reporting of Chemical Data (Modified After Keith, 1991, Table 4)^a

Concentration (C)	Relative Reliability	Report As
LOQ < C	Certain detection and quantitation	C (MDL or LOD = x)
RDL < C ≤ LOQ	Certain detection, less certain quantitation	C (MDL or LOD = x)
LOD/MDL < C ≤ RDL	Still uncertain detection, less certain quantitation	C (MDL or LOD = x)
Method blank < C ≤ LOD/MDL	High uncertainty of detection	C (MDL or LOD = x)
≤ Method blank	No reliable signal from detector	ND (MDL or LOD = x)

^a In all cases the MDL or LOD value is reported. Values below the LOD/MDL are flagged, but further explanation or caution is warranted when discussing such data. If the data are above the LOD/MDL, but below the RDL, they are clearly flagged.

Table 19 Results of Interlaboratory Comparisons for Accuracy and Repeatability of Common Inorganic and Organic Chemical Analyses (from Aleckson *et al.*, 1986; Wolff *et al.*, 1986; and Flotard *et al.*, 1986)^a

Inorganic	Bias (%)	RSD (%)	Organic	Bias (%)	RSD (%)
Ca	-4.3	8.8	Methylene chloride	+ 36.6	56
Mg	-3.9	8.4	Chloroform	- 21.1	12
Na	-7.3	5.5	Trichloroethene	- 22.8	17
K	-11.0	13.8	Tetrachloroethene	- 42.5	13
As	-14.4	14.1	2-Chlorophenol	- 21	29
Cr	-3.3	8.8	Naphthalene	- 38	44
Pb	-0.7	32.2	Hexachlorobenzene	- 42	36
Zn	-2.9	6.4	Fluoranthene	- 15	42

^a Ca, Mg, Na, and K at 20 to 45 mg/L; As, Cr, Pb, and Zn at 0.03 to 0.8 mg/L; and organics at 50 to 200 µg/L.

Sampling Quality Assurance. Design the sampling protocol to meet the data quality objectives. After they have been adopted, document field protocols in detail and follow them as part of the QC plan. Some aspects of the field program can and should be subjected to QS. Submit **blanks** for analysis (with samples) on a regular basis as recommended in Table 20. The results should be reviewed and acted on in a predetermined basis. For example, if field blanks demonstrate that a chemical is added during sampling, then the source of that chemical should be identified and eliminated if possible. Given the results of interlaboratory comparisons discussed in this section, check samples seem to be a reasonable QS action. The QS samples suggested in Table 20 cost the same as actual samples. This may seem extravagant, but it is less expensive than the disputes that result from poor data quality. Analytical laboratories can usually assist in developing a QS plan that is appropriate for a specific site.

5.5.4 Groundwater Data Organization, Presentation, and Analysis

The chemical data will be interpreted to meet the subsurface assessment objectives and to give consideration to the quality of the data and the physical hydrogeology of the site. The data will need to be organized and analyzed to aid interpretation. Organization and interpretation depend on specific assessment objectives; therefore, only some suggestions are offered. For example, evidence of adverse impact on groundwater quality may be obtained by a statistical comparison

Table 20 Various Blanks and Checks that Could Form Part of the Quality Assurance Plan

QS Sample	Purpose	Description	Recommended Frequency
Trip blank	To identify contamination of bottles & samples during travel & storage	Laboratory fills containers with contaminant-free water, and samplers ship and store with samples	One per shipment; perhaps only for volatile contaminants
Field blank	To identify contamination of samples during collection	Prepared as trip blank, but expose water to site air (like samples)	One per site or sampling day
Equipment blanks	To identify contamination from well & sampling equipment	Flush casing material and sampling devices with contaminant-free water	Only if problem suspected, e.g., using a bailer for multiple wells for sampling
Blind replicates	To identify lab variability	Split a sample into three containers; label as different samples	One per day or per 10 to 25 samples
Spiked samples	To identify errors due to sample storage & analysis	Add known concentration(s) to sample bottle	One per site or per 25 samples

of the concentrations in the suspect well with the concentration in an unimpacted or background groundwater. Sara and Gibbons (1991) and U.S. EPA (1986) provide guidance for determining when groundwater quality has been impacted, but discussion of the statistical approach continues. Site-specific conditions will likely confound any simple, statistical criteria for declaring groundwater to be impacted.

Stable isotopes of hydrogen and oxygen indicate the source or history of the groundwater: Water that represents unaltered precipitation has oxygen and hydrogen isotopic compositions that fall along the **meteoric water line (MWL)** (Figure 83). Samples that have undergone evaporation plot to the right of the MWL. Therefore, for example, the diagram could assist in differentiating between groundwater that has undergone evaporation in a liquid waste lagoon (falls to right of MWL) and unevaporated, uncontaminated groundwater (falls on MWL) that has been recharged from precipitation. This diagram, along with groundwater "age indicators" (^3H , ^{14}C), may be

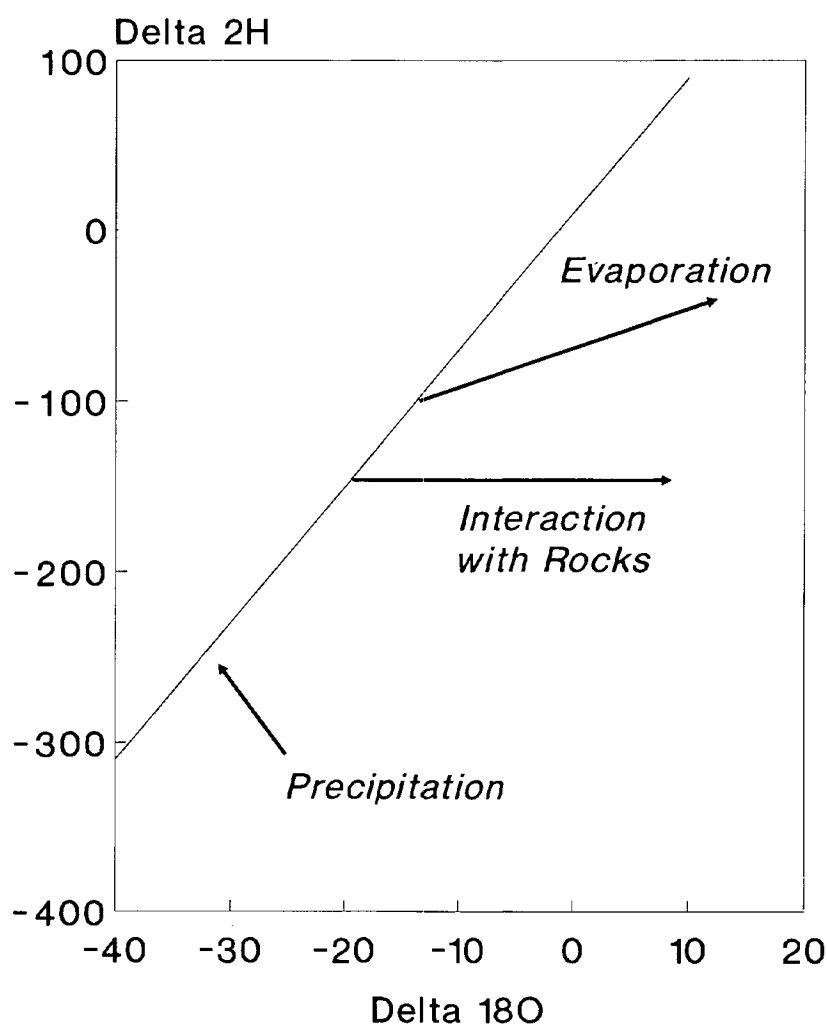


Figure 83 The Relationship Between ^2H and ^{18}O Isotope Content of Waters and the Processes Affecting Those Waters

useful in evaluating the source of groundwater and perhaps distinguishing natural background waters from water that is from contaminated areas. Environmental isotopes also address geochemical questions such as the source of SO_4^{2-} , NO_3^- , CH_4 , and CO_2 in the subsurface. See Fritz and Fontes (1980) for further discussion of the uses of environmental isotopes. Seek advice from experts in environmental isotope geochemistry before initiating sampling and interpretation.

Although the laboratory QC/QS procedures may provide confidence in major inorganic ion analyses, insist on or conduct your own **charge balance** or **cation/anion** ratio calculation. The sum of cations is compared with the sum of anions in units of meq/L. If you find a difference of more than 15 to 20%, there may be an error in determining one or more ions or the analysis may be incomplete. This check does not provide insight into analyses of neutral species (e.g., SiO_2) and is not sensitive to problems in analysis of trace ions (e.g., metals).

Geochemical models provide specific abilities and may aid in data interpretation. With them, you can calculate the concentration of specific species (e.g., $\text{Fe}^{3+}/\text{Fe}^{2+}$) from the chemical analysis of total iron. You can determine if the groundwater is likely to dissolve or precipitate certain mineral phases. Rarely will such models be used in assessments at contaminated sites. Refer to Bassett and Melchior (1988) for a discussion of the specific capabilities and limitations of commonly available inorganic geochemical models.

You will probably want to identify groundwater with grossly different chemistry. For example, you may want to see if groundwater upgradient from a contaminated site is chemically very different from contaminated groundwater. The assessment often involves comparing ratios of chemicals and examining various plots (Hem, 1970). A common diagrammatic presentation is the trilinear Piper plot (Figure 84). In this case, although the groundwaters were formed by mixing various proportions of three end-members, the plot does not show the differences clearly. To recognize patterns of groundwater chemistry, consider various descriptive statistical approaches. Figure 85 shows the grouping of the same groundwater samples based on a descriptive principal components analysis (PCA, Lebart *et al.*, 1984). For these groundwaters, the end members and mixing trends are more evident in the latter plot.

Trace organic contaminant data and geochemical data in general are usually presented as contoured sections or plan view maps. These are often useful simplifications of complex distributions, but the simplification must always be kept in mind during interpretation.

Commonly, inferences about the distribution of organics between subsurface media, phases, or compartments (water, sorbed onto solids, vapour, NAPL) are drawn from analysis of one phase or from analysis of the total organic contaminant in a sample.

This is a very useful, qualitative interpretation. For example, if such an interpretation indicates that almost all of a contaminant is present in the soil vapour and not in the groundwater, then assessing a vapour pathway will be better than searching for groundwater pathways of contaminant migration. The approach is to assume an equilibrium distribution of the organics between all phases. Kerfoot (1991) presents this approach for the unsaturated zone. This approach is recommended for assessing the likelihood that NAPL phases will be present in water or soil analyses (Feenstra *et al.*, 1991).

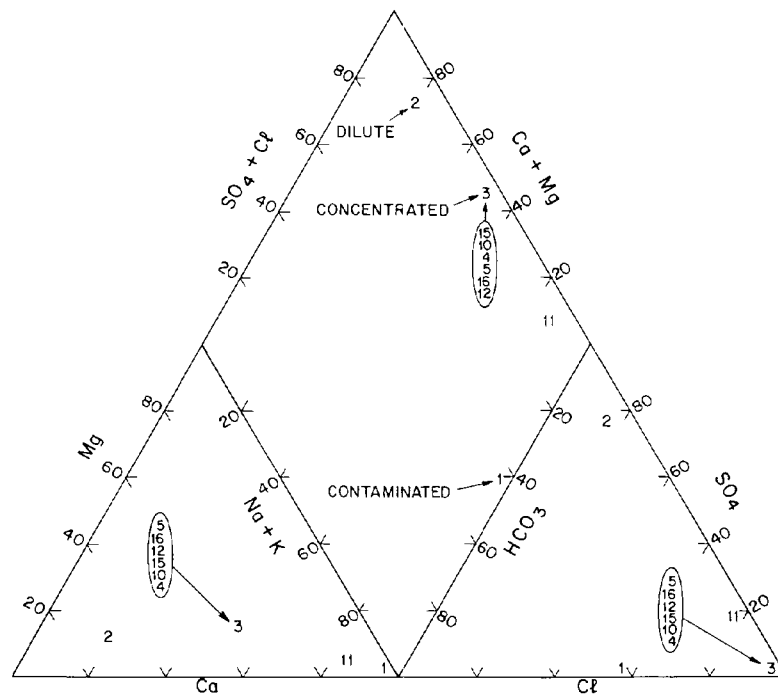
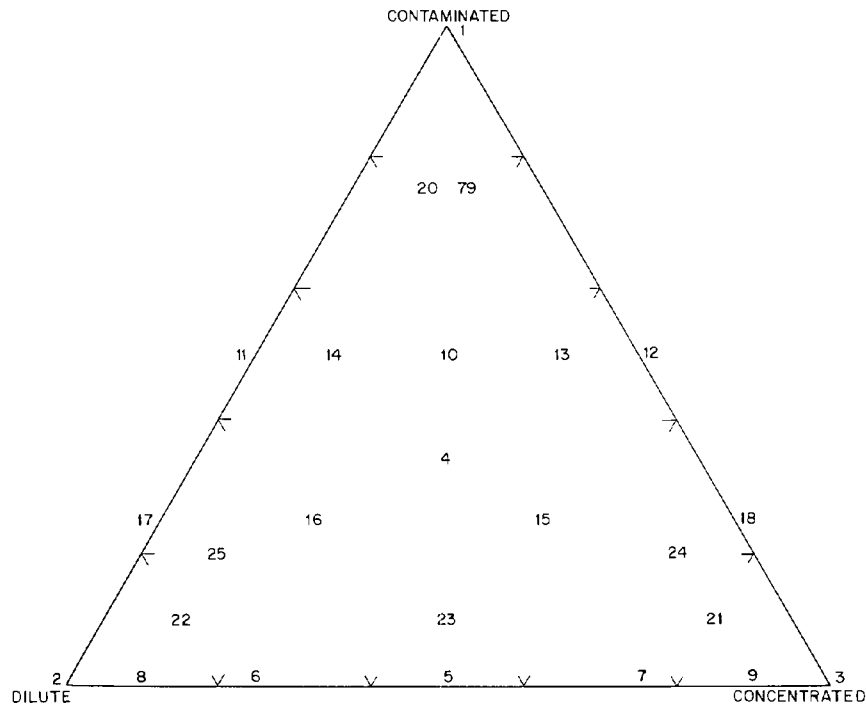


Figure 84 Piper Plot (Large Triangle) of Groundwaters Generated by Combining Proportions of End-members 1, 2, and 3 as Shown in the Upper Triangle. Sample 1 is a landfill leachate; sample 2 a shallow, uncontaminated groundwater; sample 3 a deeper, uncontaminated, high-TDS groundwater (Barker *et al.*, 1988). Note that the analyses of very different water chemistries plot together. In this case, the Piper plot is not useful for identifying “different” groundwaters.

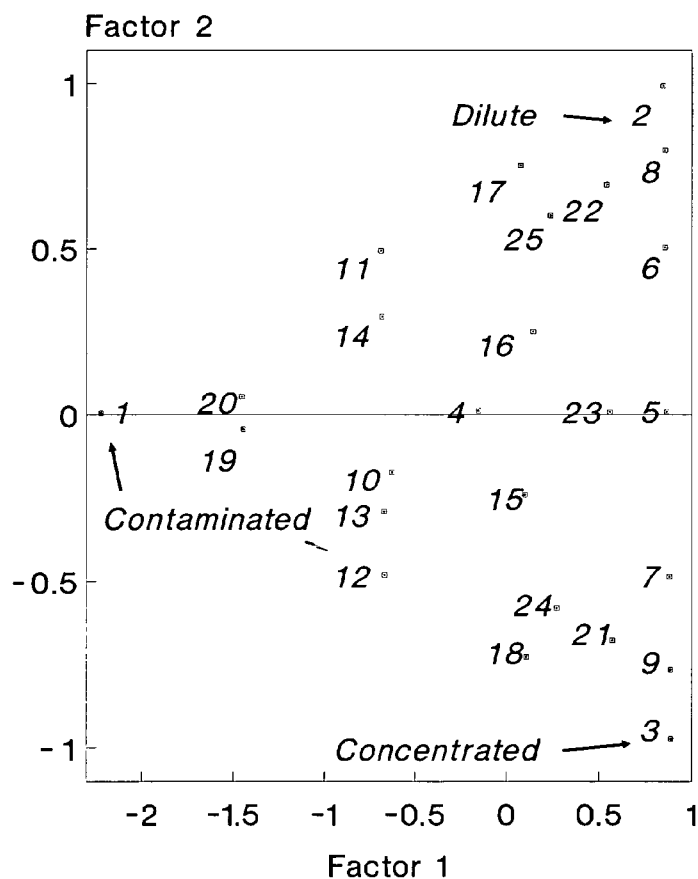


Figure 85 Principal Component Analysis (PCA) Cross-plot of Water Chemistries Calculated as Various Mixtures of 1, 2, and 3 as Shown in the Upper Triangle of Figure 84. Note that the triangular “form” of the data has been recovered, indicating that this plot is useful for recognizing groundwater similar to the end members (e.g., contaminated).

All chemical data should be reported, but a reasonable interpretation must be provided. Hydrogeological factors should be considered before a firm interpretation of the chemical data is presented. For example, in industrial areas, the “background” groundwater upgradient from the site may be contaminated by another site. Measuring the impact from the site being assessed, when the area is already contaminated, may be very difficult. Your choice of the “background” sample location must be supported by the hydrogeological evidence (Section 4) that this location is indeed upgradient.

Groundwater monitoring often generates data collected regularly from the same wells, and sampled and analyzed in a consistent manner. Statistical packages such as WQSTAT II are useful to organize and analyze such data (Loftis *et al.*, 1989). The aim is to identify trends and provide statistical confidence in assessments of changes over time, or of differences between wells. Major difficulties with statistical approaches include the assumptions about data independence and normal distribution and the treatment of data below the LOQ and LOD. Plot and statistically

examine temporal data as an *aid* both to data interpretation and to regulatory decision making. Seek advice from experienced statisticians.

5.6 *Microbiological Sampling*

Microbiologists experienced in soil and water sampling need to be involved in this sampling. You may analyze subsurface samples for potential public health risks including **pathogens** or coliform bacteria, especially if animal or human wastes were disposed on site. Because it is difficult to attribute coliform counts to the aquifer rather than to the well, collecting such information as part of the site assessment is probably not warranted.

You can also assess the potential activity of the subsurface microbial community (to biodegrade contaminants, for example). Because most subsurface microorganisms are attached to solids, the groundwater may not provide a representative sample. Therefore, cores should be taken (aseptically if possible) to provide a more representative sample. For unconsolidated material up to 200-m deep, Leach and Ross (1991) present a method to aseptically sample core by extruding, paring, and transferring samples into bottles using an on-site glove box. Contamination by microorganisms in drilling fluids appears to be minimal. For consolidated material, Weirich and Schweisfurth (1985) describe a method for obtaining estimates of microbial numbers in rock cores. Following core recovery, the method requires that the core be subsectioned and this portion crushed to obtain a sample that is cultured in media. The colony forming units are then counted. In most situations, simply collecting core in a normal manner (Subsection 4.5.3), and subsampling the interior aseptically and as soon as possible (perhaps on site), should provide a reliable sample.

There are no reliable methods to enumerate all bacteria potentially present and no generally accepted protocols for assaying the abilities of the bacterial community to degrade contaminants. The laboratory microcosm protocol of Pritchard (1981) is commonly employed and the *in situ* determination of biodegradation presented by Gillham *et al.* (1990) appears useful. All such determinations should be made to address specific questions (e.g., if oxygen is added *in situ* will the toluene be biodegraded?) and the results should be considered qualitative.

5.7 *Sampling the Unsaturated Zone*

Site assessment often requires that the unsaturated zone containing soil vapour, soil water, and solids be sampled for chemical analyses. Sampling solid, liquid, and sludge wastes is not specifically discussed here except when these often form a continuum with native soils and construction materials on site. Subsurface solids and associated fluids are analyzed to determine:

- the distribution of contaminants; and
- the geochemical properties required to interpret contaminant distribution and behaviour [e.g., **cation exchange capacity (CEC)**, and **fraction of organic carbon (foc)**].

Obtaining samples for physical measurements was outlined in Section 4. This section emphasizes sample collection for chemical analysis. Near surface samples (<1 m) can be collected by excavation (e.g., shovels) if you minimize the loss of volatiles. Use coring devices rather than solid augers for volatile constituents and for deeper samples. Coring devices provide less opportunity for cross contamination and allow subsampling at discrete depths. Use diamond drilling and rock coring to sample consolidated materials. You should subsample from the interior of the sampler because samplers driven into the materials may be contaminated adjacent to the sampler wall. You may find field screening, for VOCs in particular, useful in identifying contaminated samples requiring more analysis.

Minimize exposure of the sample to air. When the sampler is recovered, transfer the material to the sample bottle or container tube (if required), or preferably, leave the sampler intact and seal the ends quickly. Containers should be sealed and frozen (or at least cooled) during storage. If organics are of interest, transfer the samples immediately to a sample bottle containing an extractant (methanol). This approach is consistent with EPA Method 8240B (CCME, 1993). Take subsamples for analysis from the centre parts to minimize contamination from the sampler walls. On-site processing and analysis are probably the best because they reduce storage time and provide data quickly.

5.7.1 *Sample Processing and Analysis*

You may want to analyze pore water or solids, or both. Although the medium selection is site-specific, remember that you can most reliably determine soluble constituents (e.g., Cl and low K_{ow} organics) from the water phase. Strongly sorbed (high K_{ow}) organics may be more reliably determined in the solid/sorbed phase.

Pore Water. You can extract pore water by **centrifugation**, leaching, squeezing, or displacement by immiscible fluids and gases (Fenn *et al.*, 1977). The choice will be site- and chemical-specific. All methods have significant limitations. For example, you cannot squeeze consolidated material or incompressible sediments such as sands and gravels. For compressible, unconsolidated materials, use squeezers based on the design of Paterson *et al.* (1979) made of stainless steel and Teflon® to extract pore water. For incompressible materials use the epoxy plasticizer Paraplex® to displace the pore water. The water displaced last may have contacted the organic fluid and should not be included for analysis. Consider disaggregation followed by leaching with **deionized water** only as a last resort. Determine volatile organics in pore water by a headspace analysis even with consolidated samples (Lawrence *et al.*, 1990).

Solids. Solid samples should be processed without removing pore water. Sample handling, preparation, and analytical protocols must be documented and consistent. Standard methods have been established for preparing and analyzing the total solids for most contaminants (U.S. EPA SW-846, 1986; CCME, 1993). Microwave digestion, coupled with ICP/ES analysis appears particularly useful for major and trace elements, particularly metals. Trace organics sorbed or residual in solid samples, including sludges, are normally extracted exhaustively with solvents and the solvent concentrated and analyzed by GC or GC/MS techniques (see review by CCME, 1993). Volatile organics could also be analyzed by purge-and-trap GC or GC/MS, but slow desorption may produce a negative bias.

The likely precision and bias for the analysis of solid samples will depend on the specific protocol. Table 21 outlines typical results from the U.S. EPA performance evaluation program. Inorganics were determined from filtered samples following digestion; organics were determined from solvent extracts of the solid. Data interpretation must reflect these uncertainties. Protocols and evaluation methods can be found in the references cited in Table 21.

The fraction of organic carbon (f_{oc}) in the sample is a parameter sought for interpretation of organic contaminant distribution and mobility (see Section 1.3). The reliability of methods to measure f_{oc} has not been established, especially for f_{oc} values of less than 0.01 (weight %), which is typical of subsurface materials. See Powell (1990) for a description of methods.

Measuring K_d (see Section 1.3) assesses contaminant mobility. Standard laboratory methods should be followed. Gillham *et al.* (1987) present a comparison of some methods. If sampling and preparing the solid material for laboratory analysis would cause unacceptable chemical changes, consider using the *in situ* determination method of Gillham *et al.* (1990).

Various samplers are available and employ suction, sorption, or free drainage to collect the *in situ* pore water. Specific devices, suggested field protocols, advantages and limitations are presented and reviewed by Everett *et al.* (1988) and Dorrance *et al.* (1991). Pressure-vacuum lysimeters are usually used. These are installed in borings, often with bentonite seals above and

Table 21 Results of Interlaboratory Comparisons for Accuracy and Repeatability of Common Inorganic and Organic Chemical Analyses of Solid Samples
(from Aleckson *et al.*, 1986; Wolff *et al.*, 1986; and Flotard *et al.*, 1986)

Inorganic	Bias (%)	RSD (%)	Organic	Bias (%)	RSD (%)
Fe	-27.0	10.7	Benzene	- 10.3	32
Mg	-10.6	7.5	Chloroform	- 0.1	8
Al	-78.8	14.4	Toluene	+ 13.7	14
Cd	+2.9	33.3	Chlorobenzene	+ 13.3	21
Hg	-9.1	25.0	2-Nitrophenol	- 36	35
Cr	-6.1	7.8	Phenol	- 27	38
Pb	-2.2	9.2	Pentachlorophenol	- 48	17
Zn	-6.2	5.8	Acenaphthalene	- 27	26

below the sand-packed interval to be sampled. Pore water is drawn into the sampler through a porous section by applying a vacuum through a tube to the surface. The water is then drawn to the surface through the suction line or driven to the surface in a second tube by pressurizing the water collection part of the sampler. No significant depth limitation exists. However, obtaining sufficient water is often difficult, especially in soils with low water content (below **field capacity**) and low permeability.

The major concerns about samples collected from lysimeters are:

- water is preferentially drawn from larger pores and the sample may not represent the total pore water;
- degassing and exposure to air may bias sensitive chemicals such as VOCs; and
- interaction with lysimeter materials could produce bias through leaching and/or sorption.

In situ samplers probably cannot produce representative pore water samples. Use these samplers only for a qualitative assessment of non-volatile pore water constituents. Coring and subsequent water extraction is the preferred approach.

For perched water zones, sample using wells as outlined for groundwater. Alternate methods are outlined in Everett *et al.* (1988).

If you suspect that volatile contaminants (e.g., methane and VOCs) are present, you will need to define their distribution in the soil vapour. Sampling and analysis of soil vapours have already been discussed in this section as a screening tool. Now you will probably require a more thorough study of soil vapours. The objectives of the assessment will dictate the design of the vapour monitoring study.

Select either a passive or active sampling approach. In the passive sampling approach you leave accumulator devices in shallow holes for several days. You then collect the devices and submit them to a laboratory for analysis. Use passive sampling only for monitoring the flux (mass per time) of contaminants going from the soil to the atmosphere. You will use active sampling most often because you usually want to define both the aerial and vertical extent of contaminants. Active sampling gathers information more rapidly. You can install and sample additional devices quickly, as required; therefore, the investigation is flexible and efficient. Locate sampling points in a regular grid pattern, but put additional sampling points along the most permeable pathways for vapours. At many sites, these pathways are sand- and gravel-backfilled service lines for underground piping and drains. Install each sampling tube into its own boring. Tillman *et al.* (1989) reviewed installation procedures. In shallow, unconsolidated, non-gravelly materials, driving the sampling tubes is recommended. For deeper depths and where driving is not possible, drill as narrow a diameter boring as feasible. Install the sampling tube into a permeable filter pack material like sand, seal the boring with bentonite or grout, and backfill.

Establish, follow, and document field procedures as part of the QA program. Vapour samples should be drawn from stainless steel probes open to the soil vapour at the desired depth. Samples

should be taken in glass, Teflon®, or SS gas-tight syringes, and injected into the GC system through a gas sample loop held at constant temperature. Re-using syringes demands careful cleaning and frequent analysis of blank samples (contaminant-free gas) to demonstrate that carry-over does not occur. On-site analyses provide rapid data and should be used whenever possible. Kerfoot (1990) found that portable GCs could produce data quality comparable with laboratory instruments, and therefore recommended establishing QA programs that would ensure field analyses were of comparable reliability.

The vertical distribution of temperature and soil moisture should be established for at least one location. Changes in the temperature and water content of soils can produce a change in soil vapour concentration that might otherwise be considered true temporal variation. Also, high soil-moisture zones can block soil vapour migration. These zones must be identified and considered when you interpret the vapour concentration data. Variation in barometric pressure, soil temperature, and soil moisture content, and variations in the flux of vapours from the source of contamination, can produce variations in temporal soil vapour concentration data. These factors are likely to complicate the interpretation of long-term monitoring data.

Although this section has isolated the subsurface assessment of saturated and unsaturated zones, you should remember that contaminants move across these zones. Your interpretation of both groundwater and soil vapour data must recognize this possibility. Vapours can contaminate groundwater, and volatile contaminants in groundwater can migrate into the overlying soil vapour.

5.8 *Additional Information*

Chemical assessment of the subsurface requires considerable skill and experience. This section provides guidance, but many readers, especially those doing chemical assessments, need access to broader resources. This section identifies sources of these resources.

Numerous professional short courses and conferences deal with chemical sampling of the subsurface, usually with broader hydrogeological methods. To see what is offered, consult newsletters such as:

- *Resilog* (Technology Development Branch, Environment Canada); and
- *The Association of Ground Water Scientists and Engineers Newsletter* (Ground Water Publishing Co., 6375 Riverside Drive, Dublin, OH 43017).

Journals such as *Ground Water* and *Ground Water Monitoring Review* often advertise such short courses. Also contact the organizations currently providing such courses:

- The National Water Well Association, 6375 Riverside Drive, Dublin, Ohio 43017; and
- Waterloo Centre for Groundwater Research, University of Waterloo, Waterloo, Ontario N2L 3G1.

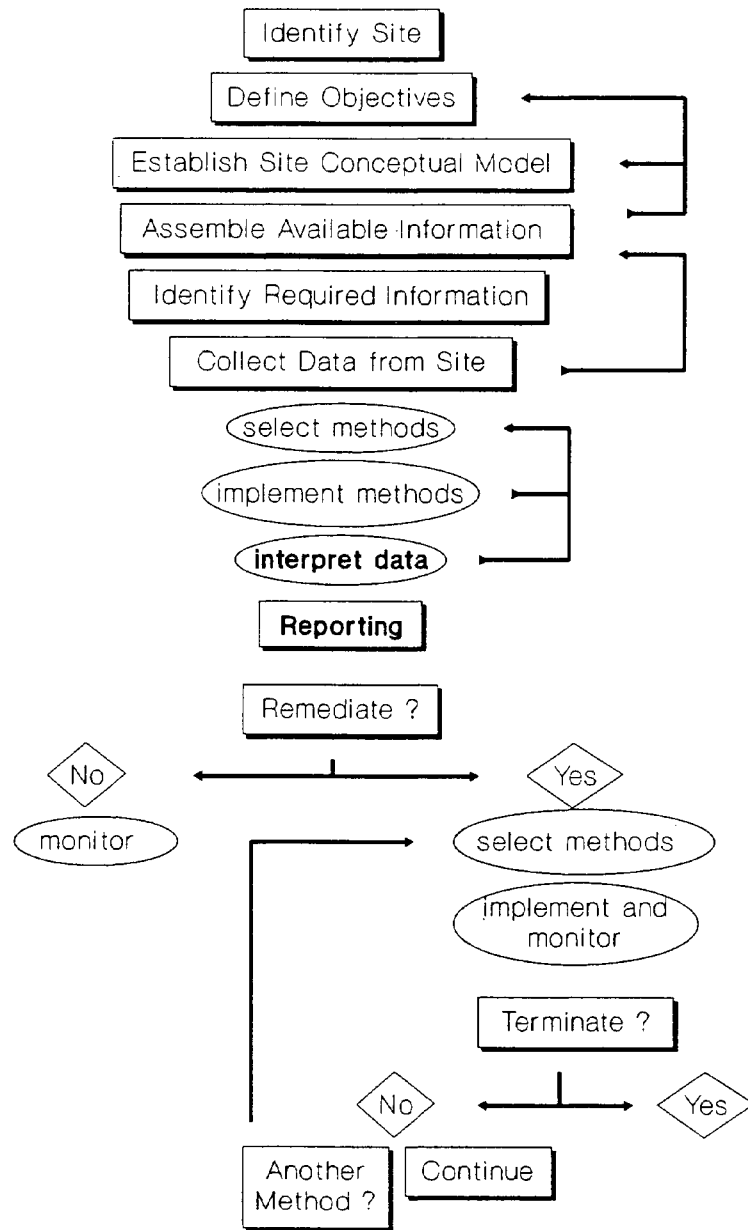
Readers may want additional information beyond that provided in this section. Good sources of additional information are these books:

- Nielsen, D.M. (ed.), *Practical Handbook of Ground-water Monitoring*, Lewis Publishers, Chelsea, Michigan (1991), (ISBN 0-87371-124-6).
- Emphasizes groundwater monitoring in response to U.S. regulations and covers most aspects of subsurface assessment. About half of the sections deal with aspects of chemical assessment. This book also references studies that form the basis for recommendations and that provide specific methods and procedures.
- CCME, *Guidance Manual on Sampling, Analysis, and Data Management for Contaminated Sites*, Canadian Council of Ministers of the Environment (CCME), Winnipeg, Manitoba (1993).
- Provides general sampling guidance and emphasizes QA/QC and analytical methods.
- Garrett, P., *How to Sample Ground Water and Soils*, National Water Well Association, 6375 Riverside Drive, Dublin, Ohio 43017 (1988).
- This “manual for the back pocket” tells how to plan and conduct actual sampling in the field. It is very practical and particularly useful for those actually doing the sampling.

Equipment is commonly available from major supply companies. Most advertise in the journals. *Ground Water Monitoring Review* publishes an annual buyers’ guide issue.

Contractors, laboratories, and consultants offer most of the services discussed in this section. Many advertise in these journals and, locally, in the yellow pages, (under Environmental Consultants or Laboratories). If you have not dealt with these firms before, talk to a few to determine the different services and approaches, and then talk with some of their clients. Cost, alone, should not be the deciding factor.

Chemical aspects of subsurface assessment are rapidly evolving and keeping abreast with new developments may require attending some short courses and reading journals.



Section 6

Groundwater Flow and Contaminant Transport Models

(J. Molson, E. Frind, and E. Sudicky)

This section provides an overview of the basic principles behind groundwater flow and contaminant transport modelling. It includes examples of their application to commonly encountered contaminated site situations. You may find this section useful if you have limited or no previous modelling experience and wish to understand the capabilities and limitations of modelling, different modelling approaches, and the effort involved in developing a site-specific model.

We begin by introducing the purpose of modelling and the modelling process. Next, the most common processes governing flow and transport are reviewed from a modelling perspective, using simulations to illustrate the concepts. Various solution techniques are then presented with a focus on analytical, finite difference, finite element, and particle tracking methods. We outline the process of developing a site-specific model and follow it with a discussion on model performance, focusing on model calibration and predictive uncertainty.

Throughout the section, we have approached the problem from the perspective of a user or decision-maker. References are provided where additional theoretical development or examples may be of interest. The Glossary provides definitions of all technical terms. We hope this section leaves you with a useful introduction to the hydrogeological modelling process and an impression of the purpose of using models to solve subsurface contamination problems.

6.1 Introduction

The following section contains an introduction to using groundwater flow and contaminant transport models.

6.1.1 Modelling in Perspective

Among the various techniques used to evaluate subsurface contamination, modelling is perhaps the most complex and misunderstood. Hydrogeological models can offer insights not otherwise obtainable, but they also offer ample opportunities for misuse or misinterpretation. These opportunities arise because of the conflict between the fully quantitative nature of the technique itself and the partly descriptive nature of the geologic information.

We define a hydrogeological **model** as a “physically-based mathematical model” (a term first coined by Allan Freeze in the late 1960s). A model mathematically represents the physical conditions in a hydrogeologic system. Often, the term *model* is misused, and interpreted as being only the **computer code**. A model, in its full meaning, includes the conceptual framework, a definition of the geometry and structure of the site, assumptions and limitations, processes, governing equations, boundary conditions, and solution method.

Models are tools that help us understand the physical, chemical, and biochemical processes taking place in groundwater systems. They help us understand and interpret the complex interactions between these processes, and they help provide the information we need to manage, protect, and remediate our groundwater resources.

Today, virtually all branches of science and engineering use models. In engineering, for example, a model can be used to predict the behaviour of a structure, such as a bridge, under various loading conditions. The dimensions of the structure and its members, the material properties, and the expected loading are input into the model. The dimensions and material properties are usually known quite accurately. There may be some uncertainty in describing the loading, but this can be dealt with by assuming some worst-case scenarios, and by applying a safety factor. The end result is a highly accurate assessment of the performance of the structure.

In hydrogeology, by contrast, we deal with systems that were designed by nature. These natural systems nearly always have a highly complex composition and arrangement of component materials. We can test these systems and materials by drilling holes, testing cores, analyzing water samples, measuring water levels, and applying geophysical techniques. However, these tests can only give us a limited picture of the real world that extends beneath our feet. The vast expanse of earth material that is situated between the measuring points will remain unknown, and because we cannot drill an infinite number of holes, it will always be “unknowable”. Unfortunately, the components of a groundwater system that cannot be observed will affect, and may even control, the behaviour of the contaminants that may be present in the groundwater. Naturally, we try to quantify the system as accurately as possible to be able to “predict” the future behaviour of the contaminants. If we use a model to make predictions, we must have some understanding of what the predictions mean.

It is tempting to take these simulations at face value and to predict on this basis that, for example, some remedial measure will clean up a contaminated aquifer in approximately 5 years. Disappointment often follows when nature fails to cooperate and the system behaves differently than predicted by the model. Often the conclusion drawn is that the model is worthless. What we need, therefore, is a realistic sense of what a model can do and what it cannot do.

A model *can* provide a highly precise solution to a given mathematical problem; however, a model *cannot* predict the future behaviour of a hydrogeologic system in a precise and definitive way, simply because the system itself cannot be known in a precise and definitive way.

If the predictive capability of groundwater models is limited, then how can they be useful? The answer is that modelling is the only practical way we can gain insight into, and hope to understand, the multitude of processes that can take place in a natural groundwater system. The number of processes or mechanisms that can affect the migration of a contaminant, or the success of a remediation program, is not only large; the processes can also produce unexpected effects by interacting in complex ways. Laboratory and field experiments can only provide results for the specific conditions of the experiment, and the range of conditions that can be explored is generally limited due to cost.

The power of a mathematical model is its ability to analyze a wide range of conditions rapidly and inexpensively. The hydrogeologist gains insight by posing various “what if” scenarios and letting the model respond to these scenarios. Normally we do not know the exact value of a certain parameter, but we can obtain most of the information we need by testing a range of values, or even only one value at each end of the range. It is this ability to “play with the system” that provides the insight needed to predict the behaviour of the system or to plan remedial measures.

Mathematical models can be set up fairly inexpensively, compared with laboratory or field experiments. Models can incorporate the physical, chemical, or biochemical processes that are likely to play a role in a given situation and they can be run under a variety of conditions. For parameters that are not well known, the model can be run with several choices of the unknown parameter covering its expected range. This **parametric sensitivity analysis** reveals how the system responds to changes in the parameter. Observing these changes gives us insight and understanding of the expected behaviour of the system. We can also turn certain processes on or off to learn how important the process is in the overall scheme. Mathematical models allow us to perform such sensitivity analyses rapidly and efficiently.

6.1.2 *Hydrogeological Processes*

The most common hydrogeological processes were introduced in Section 1.3 and are discussed from a modelling perspective here. Let us start with **advective** transport (in which particles of the dissolved contaminant are simply carried along with the flowing groundwater). To describe this process we must be able to describe the flow system with reasonable accuracy.

Complications can arise because many aquifer parameters (e.g., those obtained from aquifer testing) represent spatially averaged characteristics. The actual aquifer characteristics can vary considerably from those averages. For example, if the hydraulic conductivity in a layer exceeds the average by an order of magnitude, a contaminant may arrive at some critical point in one tenth the time that would be predicted on the basis of average properties. An order-of-magnitude variation in hydraulic conductivities is not unusual.

The second basic transport process is dispersion. On a small scale, this process describes the spreading of the dissolved contaminant due to the **tortuous** flow paths in the pore space of the aquifer material. On a larger scale, it also describes the spreading due to geologic lenses, stratification, and other irregularities in the material. The dispersion process, therefore, depends on the spatial scale of the problem. Usually the largest dispersion scale is assumed dominant. Unfortunately, dispersive parameters cannot be measured directly, except by highly sophisticated and expensive techniques. In routine investigations, the dispersion parameters are usually estimated, which requires some experience and judgement.

Other basic processes are sorption and transformation, which are described in more detail later in this section. These processes can be incorporated fairly easily into transport models and, in most cases, the data needed to quantify these processes can be obtained. The model can then be run to test the sensitivity with respect to these parameters.

Beyond these basic processes, however, a host of other processes may occur in a groundwater system. As a rule, at least some of these depend on other processes. Systems where such

interdependence occurs are known as **nonlinear systems**. A common example of non-linearity is a case in which a contaminant occurs at a concentration high enough that the fluid density is noticeably greater than the density of the resident groundwater. The denser fluid will sink and the lighter fluid will rise in the aquifer. The degree of motion depends on the relative concentration contrast. Density coupling is just one example within a common group of coupled process that are the rule rather than the exception in natural systems.

In the case of organic contaminants, we must be concerned with the non-aqueous phase, the dissolved phase, and possibly the gaseous phase of the contaminant. Models have been developed, or are being developed, to deal with multiphase flow, dissolution, biodegradation, volatilization, vapour transport, and other related processes. Most of these processes are nonlinear and models are correspondingly complex and relatively expensive to develop. Fortunately, the complexity of the model can often be reduced by judiciously selecting the relevant processes. For example, if we wish to simulate the effects of a hydrocarbon spill, we may select to model only the LNAPL migration, independent of the plume of dissolved hydrocarbons, although the two are definitely interdependent. The decoupling may be logical in terms of the objectives, and would likely result in significant savings in both human and computational effort.

Another example of a highly nonlinear system is the transport of reacting contaminants, which occurs within and downstream of mine tailings impoundments. In such a system, the various chemicals are continually exposed to new chemical environments while they are transported. This causes a continual re-equilibration and redistribution of mass among the various phases. For example, the precipitation of CaSO_4 depends on the concentration of both Ca and SO_4 in the groundwater. Therefore, the fate of every component of the system depends on the behaviour of every other component.

For such coupled processes we can perform laboratory and field experiments to identify the fundamental processes, to help us understand some of these interactions, and to validate models. Performing experiments for all possible conditions would be very expensive and time consuming. Modelling can be highly informative and cost-effective when used to address these types of problems.

6.1.3 The Modelling Process

Figure 86 lists the steps in the hydrogeological modelling process. The process starts with identifying and defining the problem and setting the modelling objectives. The objectives in contaminated site assessment often focus on determining the chances of a contaminant plume reaching a critical point, or on a comparative evaluation of various remediation strategies. Typical questions to be answered include:

- What is the relative importance of the various processes and parameters on the system?
- What is the possible worst-case scenario?
- How effective might natural or artificial remediation processes be in removing contaminants?

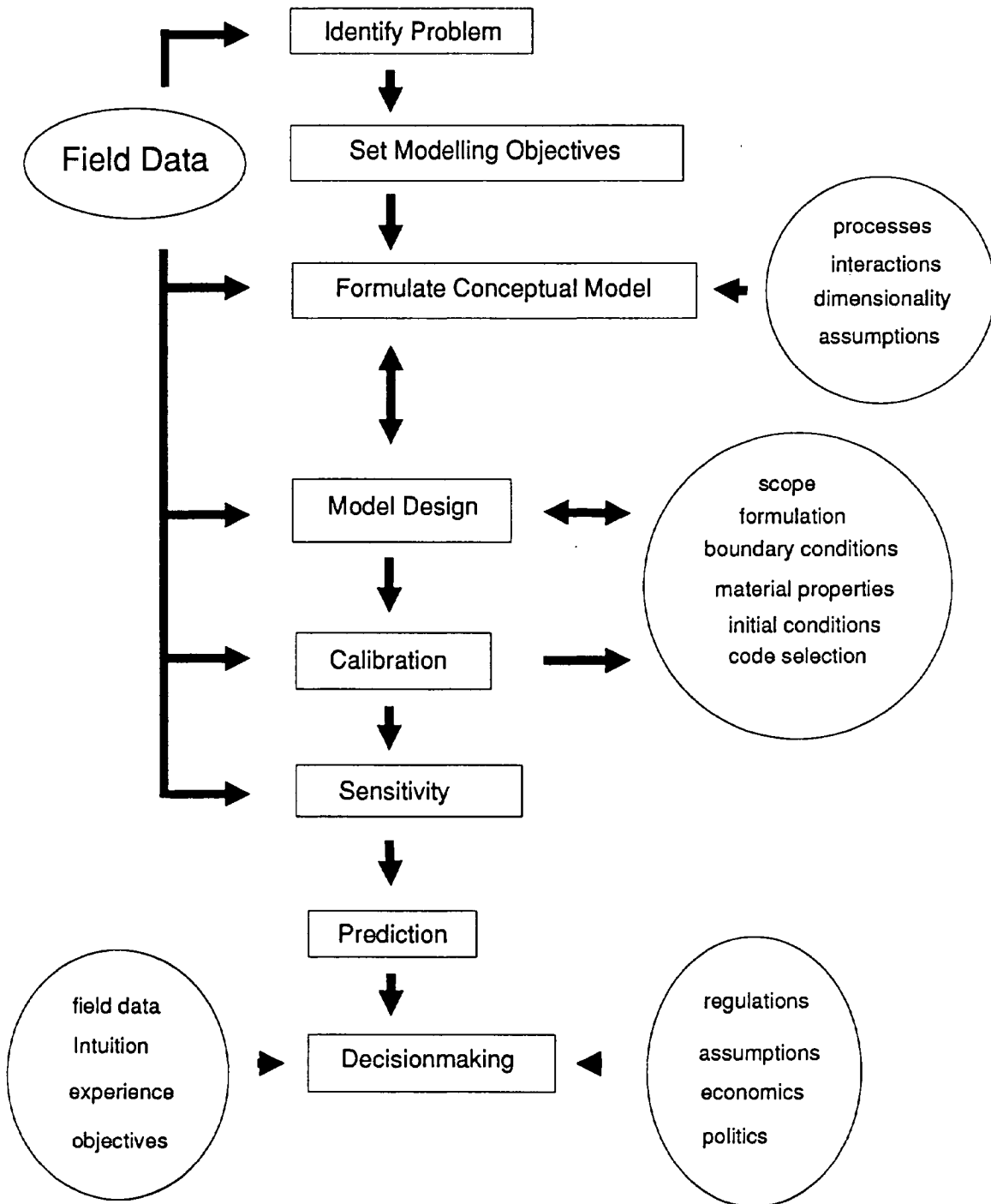


Figure 86 The Modelling Process

- What are the possible migration paths and travel times of contaminants?
- Are there limitations to the existing field data, and if so, what additional data are required, and from where should they be obtained?

The key step is to formulate a **conceptual model**. Because the real hydrogeological system is invariably complex, we create an idealization of this system, which, in essence, incorporates whatever we know about it. The information consists of the extent, configuration, and properties of the hydrogeological units, as well as the processes relevant to our objectives. The coupling and interactions among these processes are particularly important, as are the assumptions that justify excluding certain processes or interactions. We must consider the spatial dimensions that are necessary to properly represent the selected processes in the system. As a rule, we choose the fewest dimensions that will satisfy the objectives.

On the basis of the conceptual model, we can design the physically based mathematical model. This step involves: identifying the governing physical principles and the corresponding equations that express these principles; defining the boundary and initial conditions and material properties; and selecting and implementing the solution method. The solution domain must be defined, and depending on the chosen solution method, made discrete in some way. The hydrogeologic information must also be processed in a way that is compatible with the chosen computer code.

When the resulting **computational algorithm** (computer program) is complete, it must be verified against an established solution to ensure that it is error-free. The model must also be validated by applying the solution to a compatible laboratory or field experiment. This step ensures that the selection and representation of the processes in the model are valid.

In most cases, the development, **verification**, and **validation** stages will have been completed by the authors of the code. Indeed, codes that have been developed to solve a wide variety of the most common hydrogeological processes (refer to software supplier list in Section 6.8) are now available on the market. The user must choose the most suitable code for the given problem, be familiar with the basic design of the code and its limitations, and ascertain that the code has been properly verified and validated.

Often, the first application of a model is **calibration**. In cases where one of the model parameters (e.g., dispersivity) is unknown, calibration can be used to estimate this parameter from the model by fitting a simulation to an observed response under controlled conditions. Often, only one parameter can be determined uniquely by calibration. If more than one parameter is unknown, fits may be obtained with different combinations of the fitted parameters; however the parameter selection will then be **non-unique**.

The model should then be ready for use. One of the most important uses of models is to determine the sensitivity of the system with respect to the various parameters. A **sensitivity analysis** is usually done by defining a base case, and then varying the parameters (one at a time) within their respective ranges. These ranges are generally known to an experienced hydrogeologist and are fairly well-defined, although the actual parameter values may not be

accurately known. Sensitivity analyses provide the hydrogeologist with insight about the behaviour of the system under various conditions, and about the importance of the individual parameters and processes.

Throughout conceptualization, design, validation and calibration, gaps in the available data can be identified and remedied, and new data can be incorporated. This process also gives insight into the value of new data in relation to the corresponding improvement in the simulation results.

When the sensitivity of the model is sufficiently understood, the model can be used for predictive purposes. Remember that the model is not the real system. It is only an idealization of the system and it is subject to many assumptions and simplifications. Always interpret model predictions on the basis of the underlying uncertainty.

Some advanced models, based on probabilistic equations, address the issue of uncertainty by making predictions in terms of mean values as well as expected deviations from these mean values. Simpler deterministic models can also provide predictions if they are run with selected parameter values — including those at the extremes of their respective range. A similar but more systematic approach is the so-called **Monte-Carlo analysis**. In this analysis, parameter values are chosen at random from their respective ranges, the model is run, and the distribution of key results is examined. In either case, it is understood that any future prediction of system behaviour is subject to some uncertainty.

Model predictions form one component in the decision-making process related to the original problem. The process also involves regulatory, economic, environmental, and political components. The integration of all these aspects requires, above all, an understanding of the “big picture”. A sound modelling process can contribute to this understanding.

6.1.4 Errors and Misconceptions in Modelling

A model can bring valuable insight and understanding to site investigations. If used incorrectly, however, model results can be misleading. Interpretive errors and misconceptions can result from: losing sight of the underlying assumptions; using a model in situations for which it is unsuited; using inappropriate or grossly incomplete data; and placing undue faith in the computational precision of the model. Consider:

- **Structural Limitations** — The model can only handle processes for which it has been designed. The user should remain alert to the possibility that a processes that is significant in a particular application (e.g., biodegradation) is not accounted for in the model. This possibility exists if the model response differs significantly from the response observed in the field.
- **Dimensionality** — Are the dimensions of the chosen model compatible with the real problem? For example, the likely presence of density effects indicates that the vertical dimension is essential; therefore, a two-dimensional cross-sectional model may be necessary. However, if, in addition, the source is small in extent and the flow field is complex, a three-dimensional model may be needed.

- **Data Limitations** — Have all significant hydrogeologic characteristics been identified? For example, a “window” in an aquitard could mean that the contaminant enters a different aquifer than expected. A low-permeability lens missed in the site investigation can retain contaminant mass and thereby increase cleanup times in remediation schemes. Data limitations can also have serious consequences regarding non-uniqueness and uncertainty of model predictions.
- **Non-uniqueness** — This problem can arise when more than one parameter is unknown. For example, in studies of existing contamination, original source conditions are often unknown, and model calibration against the observed plume can be used to determine the most likely source conditions. However, if an additional parameter, such as the biodegradation rate, is also unknown, the model calibration against the observed plume may be non-unique and the source condition will be defined with much less certainty.
- **Undue Faith in Numerical Precision** — Numerical results can be impressive when printed out to many significant figures, or plotted in the form of smooth curves and contours. The modeller must keep in mind, however, that the accuracy of the results is no better than the accuracy of the data that went into the model.

Above all, the user must realize that the model is merely a conceptual model, never the real world. Any prediction, therefore, is valid only under the condition that the conceptual model is a reasonable and valid representation of the real system.

6.2 *Groundwater Flow and Contaminant Transport Processes*

The fundamental processes of groundwater flow and contaminant transport in hydrogeologic media are governed by natural laws that can be expressed in simplified form using mathematical equations. These equations form the fundamental basis of all mathematical models. Although the focus of Section 6 is directed toward model application, a user or decision-maker should possess at least a working knowledge of the theory and governing equations to fully understand the site-specific requirements for model development, to avoid misuse, and to apply a correct interpretation to the results.

This section will briefly review the primary flow and transport processes that are important from a modelling perspective. References are provided where the theory and formulations become more complex. Several examples of typical applications of the theory are also included. Refer to Luckner and Schestakow (1991), de Marsily (1986), and Domenico and Schwartz (1990) for a more thorough treatment of quantitative hydrogeology.

6.2.1 *Groundwater Flow*

The most basic measured quantity in groundwater flow is hydraulic head (h), which has dimensions of length (L):

$$h = \frac{P}{\rho g} + z \quad [15]$$

This equation describes the potential energy of the groundwater at a point in the aquifer, where ρ is the density of the water and g is the acceleration due to gravity. The first term in equation [15] represents the energy due to the pore pressure at the point. The second term (z) represents the potential energy with respect to some datum elevation.

We have assumed in equation [15] that the density (ρ) of the water is constant. This assumption is generally valid for dilute solutions (e.g., one originating through dissolution of a substance with low solubility such as gasoline). In other circumstances (e.g., saltwater intrusion or brine contamination) the assumption may not be valid.

The gradient in the potential energy between two points in the system provides the driving force for the flowing groundwater. The relationship between the gradient dh/dl and the groundwater flow is expressed by the Darcy equation:

$$q = -K \frac{dh}{dl} \quad [16]$$

where q is the **specific discharge** (L/T , also known as the Darcy flux) and K is the hydraulic conductivity (L/T). The hydraulic conductivity is further defined as $k\rho g/\mu$, where k is the intrinsic permeability of the porous medium and μ is the viscosity of the fluid. The negative sign in equation [16] indicates that flow is in the direction of the decreasing hydraulic head. Equation [16] is the simplest form of the Darcy equation and it assumes that the porous medium is **homogeneous** and **isotropic** (hydraulic conductivity is the same in any direction). In an isotropic system, the water flows exactly in the direction of the driving force, the hydraulic gradient.

The Darcy flux (q) is related to the average linear groundwater flow velocity (v) according to the following equation:

$$v = \frac{q}{\theta} \quad [17]$$

where θ is the aquifer porosity.

In real aquifers or aquifer-aquitard systems, the hydraulic conductivity likely differs in the horizontal and the vertical directions. Sandy aquifers, for example, are rarely homogeneous, rather they contain many different thin layers or lenses of less permeable material. In that case, the horizontal conductivity will be dominated by the more permeable layers; whereas, the vertical conductivity will be dominated by the less permeable layers. Therefore, the horizontal flow component is, as a rule, larger.

Under these conditions, equation [16] is still valid provided the layering of the material follows one of the principal coordinate directions (i.e., the horizontal). In the cross-sectional case, the flow components (q_x , q_z) are conveniently expressed as:

$$\begin{aligned} q_x &= -K_{xx} \frac{\partial h}{\partial x} \\ q_z &= -K_{zz} \frac{\partial h}{\partial z} \end{aligned} \quad [18]$$

where K_{xx} , K_{zz} , are the hydraulic conductivity components in the horizontal and vertical direction, respectively, and $\partial h/\partial x$ and $\partial h/\partial z$ are the corresponding components of the hydraulic gradient. In three-dimensional flow, we add a third flow component. If the direction of the layering does not coincide with the coordinate directions, a more general form of the Darcy equation should be used (see Bear 1979).

Saturated Flow in Confined/Unconfined Aquifers. Saturated flow conditions exist beneath the watertable where the pores are completely filled with water. Under **transient** conditions in a three-dimensional homogeneous, isotropic groundwater system, saturated groundwater flow is represented by the equation:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) = S_s \frac{\partial h}{\partial t} \quad [19]$$

assuming x , y , and z follow the principal directions of K_{ij} . Equation [19] is the mathematical statement of the law of conservation of fluid mass. It equates the change in the water flowing through volume (left-hand side) to the change in the water stored in the volume during a unit of time (t) (right-hand side).

The parameter S_s is the specific storage, which represents the volume of water that is stored (mainly due to elastic compression of the soil skeleton and expansion of water) under a unit increase in head. The equation is based on the assumption that the stratification in the aquifer coincides with the coordinate directions. A more general form valid for arbitrary directions can be found in Bear (1979). The **steady state** form of equation [19] is obtained by setting the right-hand side to zero.

Equation [19] is valid for a fully three-dimensional system. Often, the dimensionality of the system can be reduced to the two-dimensional areal or vertical plane, or even to a one-dimensional system (see Subsection 6.4.2 for further discussion on dimensionality). Because information on the vertical dimension is lost, depth-dependent processes cannot be modelled in the two-dimensional areal plane.

A two-dimensional areal plane flow model may be appropriate if:

- the contaminated aquifer is extensive in the horizontal plane and vertically thin (the length:thickness ratio is of the order of 100:1);
- the contaminants are dilute and well dispersed throughout the vertical thickness;
- the vertical flow velocities are small relative to horizontal velocities; and

- any pumping wells are screened throughout the aquifer thickness.

Areal flow models that allow hydraulic connection with adjoining aquifers are known as “multi-aquifer models” or as “quasi-three-dimensional aquifer models” (see Chorley and Frind, 1978; Rudolph and Sudicky, 1990). The simplest system consists of two aquifers separated by one aquitard (Figure 87). Flow is assumed to be horizontal in the aquifers and vertical through the aquitards. These models can be used to represent confined and/or unconfined systems. They are generally valid if a permeability contrast of at least two orders of magnitude exists between the aquifers and aquitards.

A horizontal two-dimensional formulation is obtained by integrating equation [19] over the thickness of an aquifer. This leads to the two-dimensional aquifer flow equation:

$$\frac{\partial}{\partial x} \left(T_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(T_{yy} \frac{\partial h}{\partial y} \right) + \frac{K'}{b'} (h_0 - h) + Q\delta(x_w, y_w) = S \frac{\partial h}{\partial t} \quad [20]$$

where the first two terms are analogous to the corresponding terms in equation [19], and T_{xx} , T_{yy} are the components of transmissivity (hydraulic conductivity \times aquifer thickness). The third term represents **leakage** through an aquitard with vertical hydraulic conductivity (K') and thickness (b'); and h_0 is the head in the neighbouring aquifer. The next term is the source–sink term representing pumping or injection wells — where Q is the injection rate (withdrawal is considered to be negative injection) and $\delta(x_w, y_w)$ is a function that conveys the coordinates of the well (x_w, y_w) into the equation system. On the right-hand side, the parameter (S) is the “storativity” (specific storage \times aquifer thickness). In equation [20] we assume that the aquitard thickness is relatively small and that the contribution to leakage from water stored in the aquitard is negligible.

In the case of an **unconfined aquifer**, the equation becomes:

$$\frac{\partial}{\partial x} \left(K_{xx}b \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy}b \frac{\partial h}{\partial y} \right) + R + Q\delta(x_w, y_w) = S_y \frac{\partial h}{\partial t} \quad [21]$$

where R is the recharge to the aquifer per unit area and b is the saturated thickness. The quantities $K_{xx}b$ and $K_{yy}b$ represent “transmissivity”, which in this case depends on the variable aquifer thickness. The unconfined problem then becomes nonlinear. The term S_y on the right-hand side is the specific yield. This equation assumes that storage occurs only through raising or lowering of the watertable, and neglects elastic storage in the aquifer. The assumption is generally valid except at “early” time (e.g., immediately following the start-up of a pumping well). A further assumption is to neglect well bore storage, which may be important in large diameter wells.

To develop a two-dimensional areal plane flow model, we must know the geometry of the aquifer base or its thickness where it is confined (Table 22). The hydraulic conductivity distribution in the areal plane must be defined as well as the recharge distribution and well

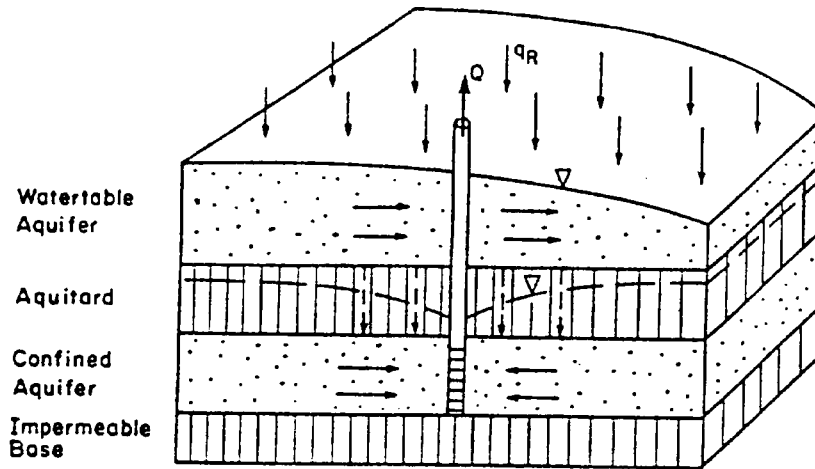


Figure 87 The Multiaquifer Model

Table 22 Summary of Data Requirements for a Two-dimensional Areal Flow Model

Input Data	Aquifer geometry (basal elevations or thickness if confined) Recharge distribution in the areal plane Well locations, pumping rates K_x , K_y (areal hydraulic conductivity distribution) Specific yield or storage coefficient if confined Boundary conditions (river elevations, flow divides)
Calibration Data	Observed water table elevations (transient or long-term average for steady state) Observed response of pumping wells Observed discharge to surface water

locations and pumping rates. Suitable boundary conditions including river elevations or locations of flow divides must also be defined.

Two-dimensional Steady State Saturated Flow in the Vertical Section. At many contaminated sites, flow in the vertical dimension may be of prime concern because there may be potential for vertical contaminant migration to underlying aquifers. In the vertical dimension, however, a simulation of the hydraulic head distribution alone may not provide adequate insight into the transport of contaminants because travel paths are not computed directly.

A powerful alternate method of solving steady state, saturated groundwater flow problems involves the use of both hydraulic heads and **stream functions** (known as the “dual formulation”). Although presently restricted to two-dimensional vertical sections, the technique is useful at many sites because it defines groundwater travel paths directly (Figure 88). Groundwater flow velocities are also more accurate when determined using stream functions.

The dual formulation generates an accurate **flownet**, which can be used to evaluate groundwater flux and to study the advective transport of a groundwater contaminant. A full theoretical development using **finite elements** is given by Frind and Matanga (1985), and field-scale applications are provided by Frind *et al.* (1985) and Molson *et al.* (1987). A method to compute stream functions using the steady-state, two-dimensional form of equation [19] is given by Anderson and Woessner (1992). Bramlett and Borden (1990), present a finite difference flownet model.

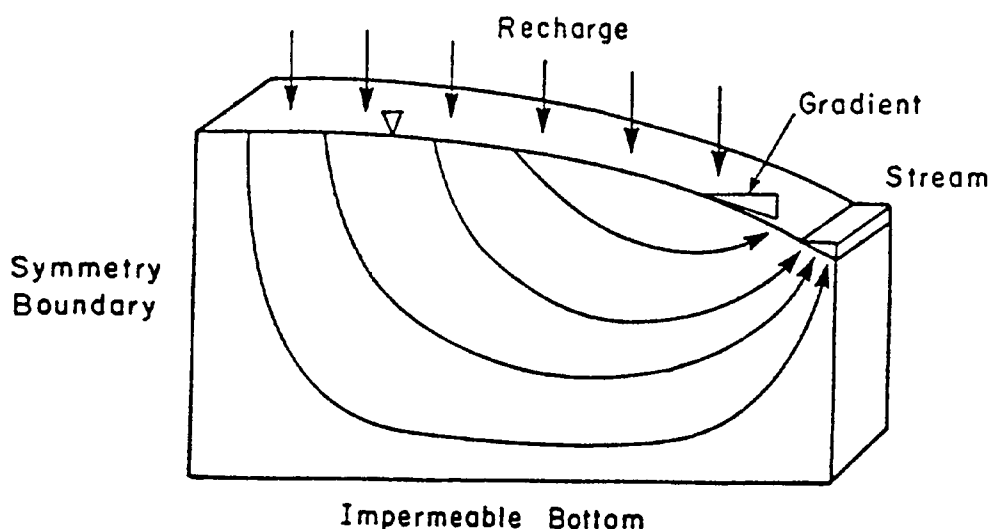


Figure 88 **A Typical Cross-sectional Flow System**

Table 23 Summary of Data Requirements for a Two-dimensional Vertical Section Flownet Model

Input Data	Geometry of aquifer base along the section Steady state recharge distribution K_x , K_z (hydraulic conductivity distribution) Boundary conditions (river elevations, flow divides)
Calibration Data	Observed long-term average water table elevations Observed long-term average potentials in piezometers Observed or estimated groundwater velocity Observed steady state discharge to surface water

The data required to run a two-dimensional flownet model are outlined in Table 23. Observed hydraulic head data in the vertical section, including the position of the watertable, are used as constraints for model calibration. In a flownet model, hydraulic conductivity and surface recharge are common calibration parameters because the estimated or observed range of these variables can be quite large.

Important assumptions and limitations in this modelling approach include:

- transverse flow is neglected and the section is assumed to correspond to a flowline in the areal plane;
- flownet models assume steady state, **isothermal** conditions, and neglect aquifer deformation due to dewatering; and
- if the streamlines are used to interpret advective contaminant transport, the dispersion process is assumed not to be significant.

Boundary conditions for a flownet model are discussed in Subsection 6.4.4.

Flownet Application. Figure 89 shows an application of a two-dimensional flownet model. The system consists of a watertable aquifer separated from an underlying, partially confined water-supply aquifer by a discontinuous clay aquitard (Figure 89a). The hydraulic conductivities are 0.1 m/day for the sand aquifer, and 0.01 m/day for the clay. The domain is 100 m long by 20 m high. Assume that a waste disposal site is located at ground surface 20 m downgradient

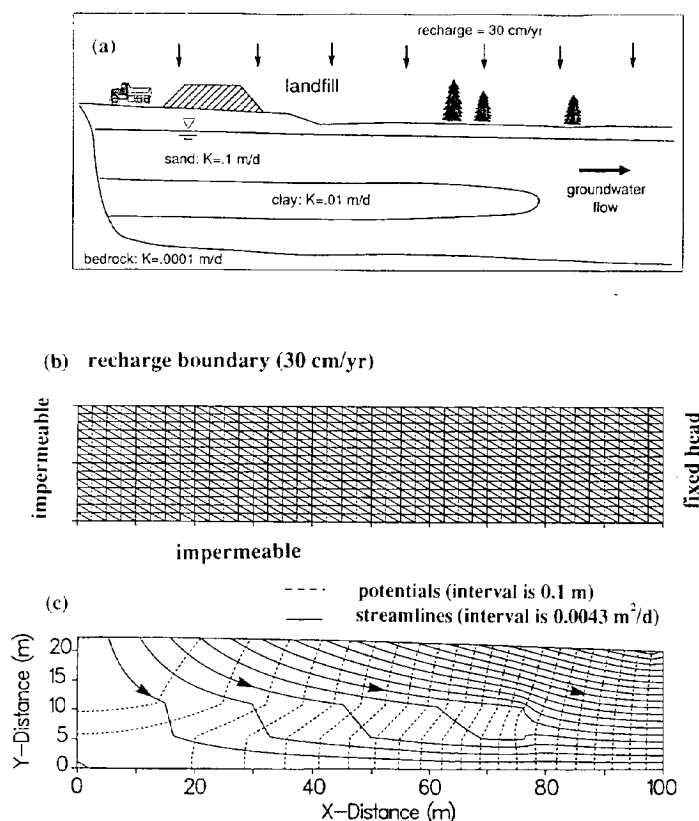


Figure 89 An Example Flownet Application: (a) Conceptual Domain; (b) Boundary Conditions and Finite Element Grid; and (c) Flownet Solution

from a bedrock **outcrop** and that contaminants have been found immediately below the source. The objective is to determine if the contaminants may reach the lower aquifer.

Figure 89b shows boundary conditions and the finite element grid for the flownet model application. A uniform background recharge of 30 cm/year exists across the surface. In practice, recharge estimates may be refined during model calibration by matching the observed watertable position. The left boundary is a no-flow boundary, and at the right boundary the head is fixed at $h = 0$ m. The lower boundary corresponds to the upper surface of bedrock and is assumed to be impermeable. The domain is resolved into 1120 triangular elements.

Figure 89c shows the steady state hydraulic head and stream function flow solution. In this case, the results suggest that a serious threat to the lower aquifer does indeed exist, and that immediate preventive or remedial measures seem necessary. In this analysis, the effect of dispersion is considered minor and has been ignored.

Unsaturated Flow. If groundwater contamination originates from a ground-surface source (e.g., a landfill or accidental spill) the contaminants will enter the unsaturated zone before reaching the watertable. In practice, it is common to neglect the unsaturated zone in a contaminant transport model if its depth is not significant relative to the aquifer thickness, and if

the areal extent of the site is large. However, you may have to include the unsaturated zone in the model if there are important transport processes occurring within it (e.g., vapour phase transport, volatilization, or degradation).

In the unsaturated zone, the hydraulic conductivity becomes a nonlinear function of moisture content, which can vary with depth. This variation must be well resolved by the model, which then requires much larger grids and a higher computational effort than is required for the saturated zone alone. A variably saturated flow model must be run in either the two-dimensional vertical section, or in a fully three-dimensional domain.

In addition to the data required to run a saturated flow model, the following data are also necessary:

- detailed vertical profiles of the pressure head; and
- field or laboratory data defining the variation of hydraulic conductivity with moisture content.

A fully three-dimensional model for simulating variably saturated flow is described by Huyakorn *et al.* (1986). Narasimhan (1982) and Therrien (1992) present a three-dimensional variable saturation model in fractured media.

6.2.2 Contaminant Transport

The behaviour of contaminants in the subsurface is affected by a variety of physical, chemical, and biological processes; the most common transport processes are summarized in Table 24.

When a dilute chemical contaminant enters a typical porous medium, it is transported by groundwater flow (**advection**). The chemical will disperse due to microscopic variations in the velocity field (mechanical dispersion) and it will disperse due to random motion in response to concentration gradients (molecular diffusion). A contaminant may also be retarded due to sorption, or it may **decay** due to chemical or radioactive processes.

In most porous media (because advective–dispersive transport is usually dominant) the flow system simulation is critical. In low permeability material, however, diffusion may become the primary mode of transport. In fractured or **heterogeneous** porous media, both advection and diffusion may be significant. The characterization of these different processes is important because it will often dictate the transport modelling approach or solution technique that is required.

Advective–Dispersive Transport. Techniques for modelling advective–dispersive transport have been studied intensively over the last 15 years. Assuming isothermal conditions, insignificant density differences, a non-deforming medium, and the absence of sources or sinks, the governing differential equation is given by equation [22] in Table 24, where x_i are the spatial coordinates, t is time, $c=c(x_i,t)$ is the concentration, v_i is the average linear pore water velocity, and D_{ij} is the hydrodynamic dispersion **tensor**. The boundary conditions on equation [22] can be either specified concentration, specified concentration gradient, or a concentration-dependent mass flux condition (see Subsection 6.4.4 for further discussion).

Table 24 Summary of Major Transport Processes

Transport Process	Mathematical Model	Physical Description
Advection–Dispersion	$\frac{\partial c}{\partial t} = -v_i \frac{\partial c}{\partial x_i} + \frac{\partial}{\partial x_i} \left[D_{ij} \frac{\partial c}{\partial x_j} \right] \quad (1)$	Advective transport because of ambient flow, and dispersive spreading of contaminants because of diffusion and microscopic changes in velocity
Molecular diffusion	$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x_i} \left[D_{ij}^* \frac{\partial c}{\partial x_j} \right] \quad (2)$	Spreading of contaminants because of random motion across a concentration gradient
Linear equilibrium adsorption	$\frac{\partial c}{\partial t} = -\frac{\rho_b}{\theta} \left(\frac{\partial S}{\partial t} \right) \quad (3)$	Retardation of contaminants because of sorption onto grains
Transformation or decay	$\frac{\partial c}{\partial t} = -\lambda c \quad (4)$	Loss of contaminants because of biological or radioactive processes

The hydrodynamic dispersion tensor (D_{ij}) in equation [22] is defined by Bear (1979), and is a function that depends on the groundwater velocity, aquifer dispersivities, and the effective molecular diffusion coefficient (D^*). In one dimension the dispersion term reduces to:

$$D_x = \alpha_L v + D^* \quad [26]$$

where α_L is the longitudinal **dispersivity**. In three dimensions, in addition to the longitudinal dispersivity, transverse horizontal (α_{TH}), and transverse vertical (α_{TV}) dispersivities are also required. Ranges of $\alpha_L = 1$ to 10 m, $\alpha_{TH} = 0.1$ to 1 m, and $\alpha_{TV} = 0.01$ to 0.001 m are typical for a sandy aquifer.

The dispersive parameters, which are related to the spatial variability of the porous material, are often obtained by calibrating an advection–dispersion model against an observed plume. When this is not possible, reasonable values can be obtained from the literature if the general aquifer structure is known. Conversely, this uncertainty can be avoided (but not removed) by neglecting dispersion and adopting a purely advective transport approach (e.g., using a **particle tracking model**).

An Example Advective–Dispersive Transport Problem. The sensitivity of a contaminant plume to longitudinal and transverse dispersion is illustrated by employing an analytical solution to the advective–dispersive transport problem. The base case parameters are: $V_x = 0.1$ m/day; $\alpha_L = 1.0$ m, $\alpha_T = 0.1$ m; $R = 1.0$ (no adsorption); $\lambda = 0$ (no decay); and the source is continuous. Concentration contours at $t = 2$ years are shown in Figure 90a and longitudinal profiles along the centreline of the plume are shown in Figure 90b. We see that increasing α_L (Figure 90c) produces a typical stretching of the profile; whereas, increasing α_T by the same proportion (Figure 90d) gives a much different response due to the increased transverse spreading that depresses the profile.

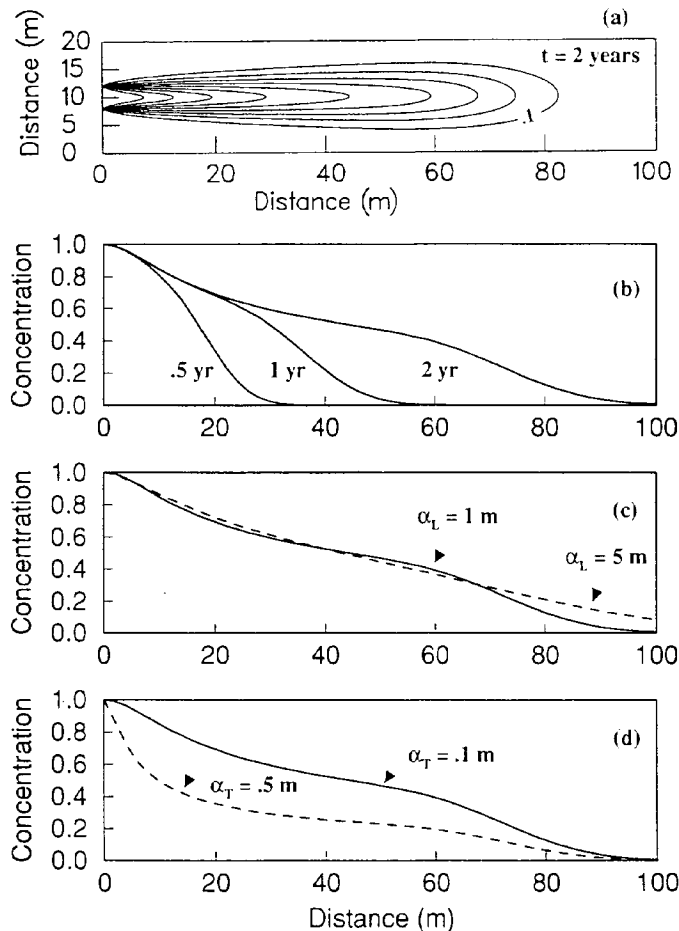


Figure 90 A Two-dimensional Analytical Simulation of Advective–Dispersive Transport in the Areal Plane: (a) Concentration Contours at $t = 2$ years; (b) Longitudinal Profiles; (c) Variable Longitudinal Dispersivity; and (d) Variable Transverse Dispersivity

Reactive Contaminant Transport. When contaminants migrate in groundwater, physical, chemical, or biogeochemical reactions can significantly alter both the concentration and form of the contaminant. Organic contaminants, for example, may biodegrade, or if they are volatile, they may partition into the gas phase. These, and many additional reactive processes, can be built into standard transport models.

Sorption and Decay. Sorption and first-order decay can be easily simulated using most standard advection–dispersion type models without a significant increase in computational effort. Sorption of a contaminant onto aquifer solids results in a retardation effect; whereas, decay (e.g., from radioactive wastes) decreases the mass. The transport equation in this case becomes:

$$\frac{\partial}{\partial x_i} \left(\frac{D_{ij}}{R} \frac{\partial c}{\partial x_j} \right) - \frac{v_i}{R} \frac{\partial c}{\partial x_i} - \lambda c = \frac{\partial c}{\partial t} \quad [27]$$

where $\lambda = (\ln 2)/t_{1/2}$ is the decay constant and $t_{1/2}$ is the **half-life**. The form of equation [27] assumes that the sorbed phase also decays, and that it decays at the same rate as the solution phase. Sorption is represented as a linear equilibrium partitioning process between the dissolved and adsorbed phases, where R is the retardation coefficient given by:

$$R = (1 + \frac{\rho_b}{\theta} K_d) \quad [28]$$

where ρ_b is the bulk density of the saturated porous medium, θ is the effective porosity, and K_d is the distribution coefficient that governs the partitioning of the **solute** into dissolved and adsorbed phases.

To illustrate the sensitivity of the advective–dispersive transport process to linear retardation and decay, we use the same problem domain of Figure 90a. The longitudinal profiles are provided at $t = 2$ years with the base case of $R = 1$ and no decay shown for comparison (Figure 91). Note that doubling R reduces both the advective advance and the dispersion by one-half (Figure 91a). Introducing a decay term with $t_{1/2} = 1$ year generates a profile that is dominated by the exponential decay component (Figure 91b).

This theory has been simplified to include only the linear processes of retardation and decay. In reality, these processes are often highly nonlinear. The relevant reaction terms not only depend on the concentration distribution of the species of interest, but often depend on additional species concentrations as well. In practice, these data may be difficult to obtain. In these cases, one might use a model to determine parameter sensitivity, or to make relative comparisons, rather than absolute predictions that would carry a large uncertainty.

For more complex **kinetic** and equilibrium reactions involving multiple species, powerful geochemical models are available (e.g., PHREEQE and MINTEQ; Bassett and Melchior, 1988). These types of models are, however, restricted to local geochemical processes and require coupling to a mass transport model to realistically simulate the geochemical transport process. This becomes a quite demanding problem to solve.

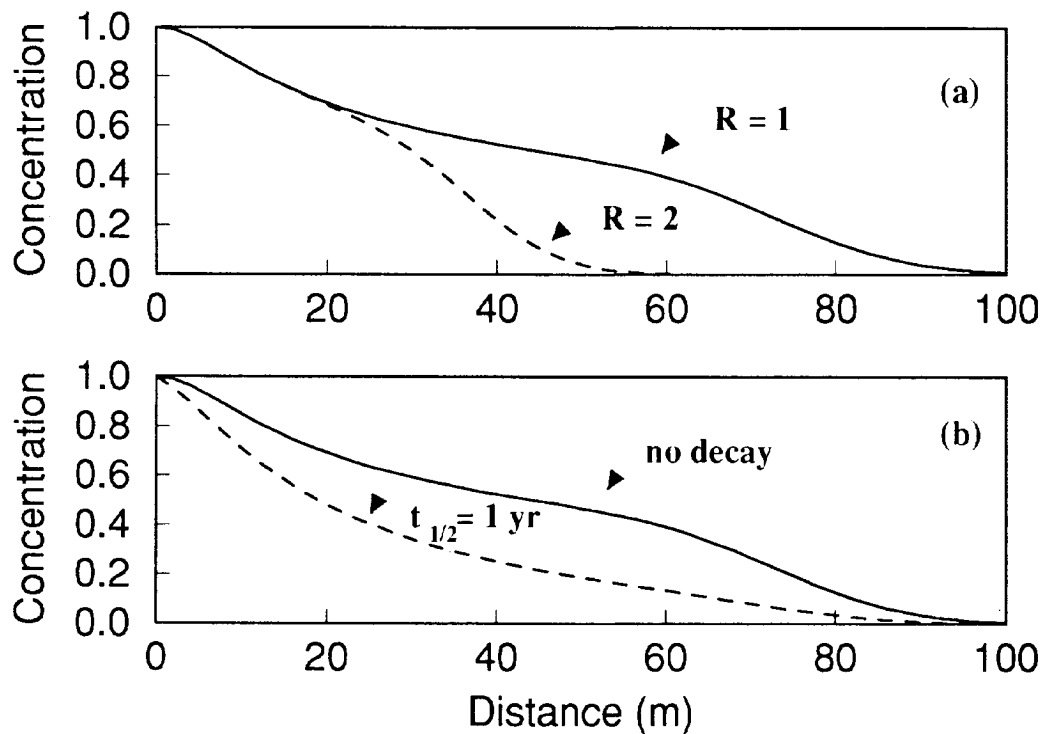


Figure 91 Two-dimensional Advective-Dispersive Transport: (a) Variable Retardation; and (b) Variable Linear Decay (see Figure 90a for Problem Domain)

In practice, a common approach is to first simulate transport of a conservative species (e.g., chloride) which will represent a worst-case scenario in terms of travel distance. More complex reactions can then be added depending on the scope of the investigation and on the availability of field data.

Biodegradation. Biodegradation is an example of a more complex reaction process in which dissolved organic contaminants are consumed by microbes. Biodegradation can, for example, occur under **aerobic** conditions.

Natural or enhanced biodegradation is often considered to remediate dissolved organic contamination (e.g., contamination caused by gasoline-derived hydrocarbons). Numerical simulation models can be valuable tools to study the behaviour and fate of organic contaminants. However, because of the complex processes involved, the required field data can be difficult to obtain in practice and non-uniqueness can become a serious problem.

The equations governing advective-dispersive transport of a biodegrading organic can be expressed in forms similar to equation [27]. The decay terms in this case, however, become nonlinear functions of the relevant species concentrations and also involve several reaction rate terms that are generally site- and species-specific. In general, one transport equation is required for each of the relevant species (e.g., the organic substrate, oxygen, and microbial population).

Rifai *et al.* (1987) and Frind *et al.* (1989) present two- and three-dimensional models, respectively. BIOPLUME II (Rifai *et al.*) is available from Department of Environmental Science and Engineering, Rice University, Houston, Texas, 77001.

6.2.3 *Flow and Transport in Fractured Media*

Transport in fracture networks is one of the most difficult problems in groundwater modelling. Both flow and transport processes depend on complex parameters (e.g., fracture spacing, **roughness**, and **connectivity**) that are difficult to determine in field situations. Furthermore, advanced numerical techniques are required to account realistically and efficiently for complex fracture geometry.

Within the individual fractures, transport is generally flow controlled, with dispersion in the fracture playing a minor role (see Figure 7). Within the matrix, contaminant diffusion will initially serve as a **sink** while the plume front invades the network. However, after the plume has passed, the contaminants in the matrix can act as a long-term source slowing remediation efforts. Numerical models can help illustrate these processes.

For networks of fractures of finite length, the connectivity between fractures determines the extent to which the system can conduct flow and transport contaminants. As the spacing of discrete fractures decreases and connectivity increases, the system behaves more like a porous medium. Long *et al.* (1982) and Schwartz and Smith (1988) outline the criteria that indicate when a fractured system can be approximated by an equivalent porous medium model. The **dual-porosity** concept (Coates and Smith, 1964; Bibby, 1981) is a useful simulation approach that avoids the complexities of treating discrete fractures.

Flow and contaminant transport through a fractured network can be simulated using analytical, semi-analytical, or numerical methods. Analytical solutions have been developed by Tang *et al.* (1981) and Sudicky and Frind (1982). Although these methods are restricted to simple fracture systems such as single or parallel fractures, they are simple to implement and can often provide a useful first approximation to the transport problem. More advanced numerical methods are required for more complex fracture systems.

A common approach to simulate mass transport within discrete fracture systems is to couple the advection–dispersion equation [22] describing transport in the fractures, with the diffusion equation [23] for the porous matrix. The coupling occurs at the fracture wall where the concentration determined from equation [22] forms the solute source boundary condition for equation [23]. More advanced numerical models also allow advection within the matrix and can include reactive processes such as contaminant adsorption onto fracture walls.

A common problem in the simulation of transport within discrete fractures arises from the highly detailed grid used to resolve the high concentration gradients that are common to contaminated fracture systems. With these large grids, the computational demands and computer storage requirements may become too excessive for practical application.

Using the Laplace Transform Galerkin (LTG) technique, Sudicky and McLaren (1992) developed a discrete fracture transport model that overcomes this problem and is well suited for

long-term simulations. Their model also accounts for advective–dispersive transport within the matrix blocks. This model was used in Figure 92 to simulate contaminant transport from a continuous source into a fractured till overlying a porous, non-fractured aquifer.

Because of the difficulty in obtaining the required field data to characterize the fracture network, model predictions of contaminant transport through fractured systems are uncertain. One common approach is to generate many random realizations of a fracture network using the statistical properties of the network (e.g., mean fracture spacing and its variability). A transport simulation is completed for each **realization** and the results interpreted using the average response and degree of variability. Although somewhat more difficult to implement, the use of fracture transport models is becoming more widespread because of the common occurrence of fractured media at contaminated sites.

6.2.4 Density-dependent Flow and Transport

If the total concentration of dissolved solutes is high relative to background levels, or if significant temperature differences of at least 5 to 10°C exist within the system, the fluid density in a contaminant transport model may become significant. Density contrasts as low as 0.1% can alter the behaviour of a contaminant and cause a plume to rise if its density is lower than the background level (e.g., if the plume is warmer) or to sink if its density is higher than the background level.

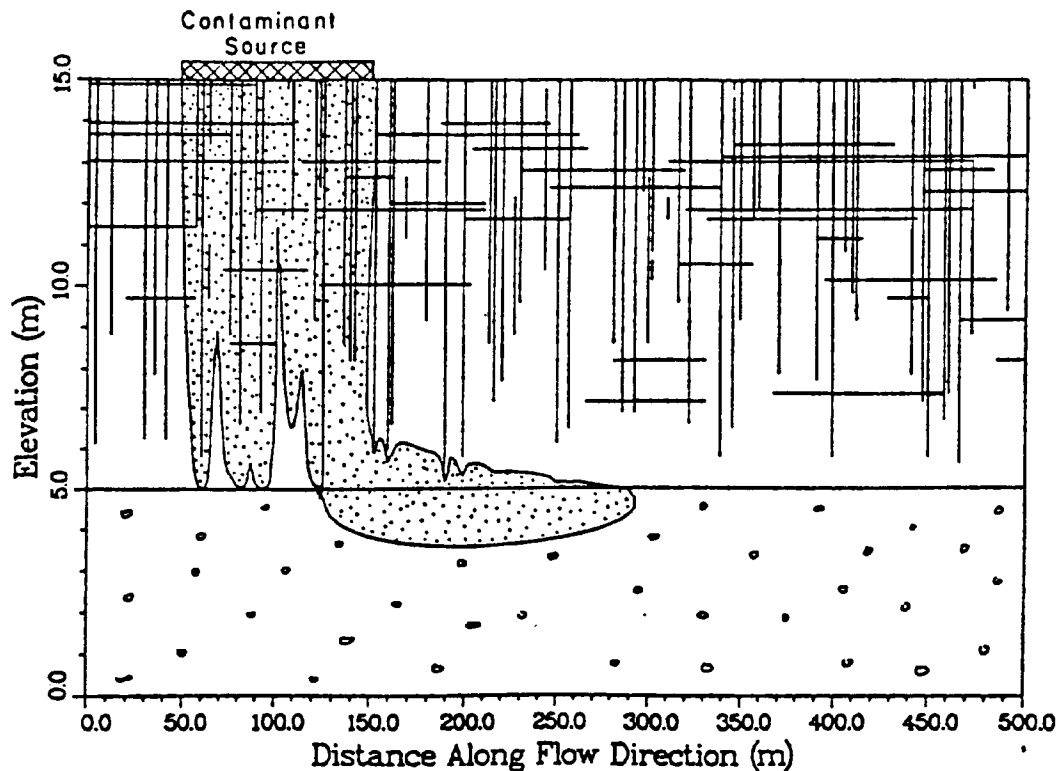


Figure 92 Contaminant Transport Simulation in a Fractured Till Overlying a Non-fractured Aquifer

Because the dynamics of the groundwater flow system depend on changes in fluid density, and that changes in density are determined by the concentration or the temperature distribution, the contaminant transport problem in this case becomes nonlinear. The groundwater flow equation must then be coupled to a mass or energy transport equation. These models are often computationally demanding. If both concentration and temperature changes are significant, separate equations must be included to define both mass and thermal energy transport processes. A two-dimensional vertical cross section or full three-dimensional simulation approach must be used if density contrasts are significant.

The effect of density on the advective-dispersive transport of a dissolved-phase contaminant is illustrated in Figure 93. The problem domain consists of a continuous source located at the watertable about 20 m down gradient from a flow divide. A steady-state background flow field was obtained using a hydraulic conductivity of 0.2 m/day and a uniform aquifer recharge of 15 cm/year (Figure 93a). The transport simulations used a longitudinal dispersivity of 10 m and a transverse dispersivity of 0.05 m.

The steady-state flow field of Figure 93a was first used to simulate transport of a dilute plume in two dimensions, with no density contrast, over a 6000-day period (Figure 93b). Because in this case, the groundwater flow field is not affected by the concentration distribution, the plume contours closely follow the streamlines.

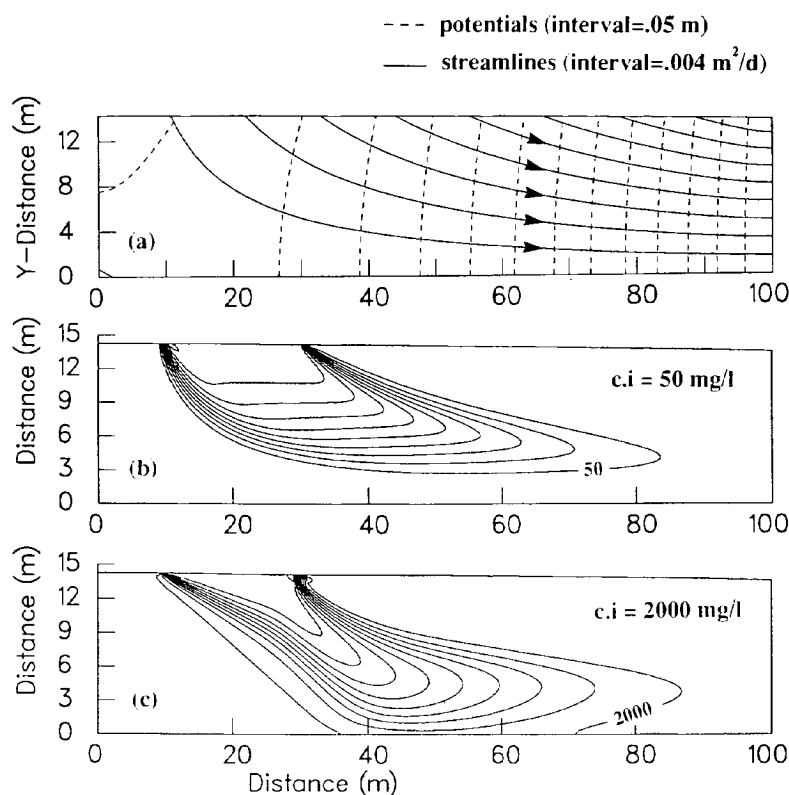


Figure 93 Effect of Density on the Migration of a Contaminant Plume: (a) Background Flownet; (b) Dilute Plume, 6000 days; and (c) Dense Plume, 6000 days

In comparison, when the source concentration is assumed to be that of seawater chloride (approximately 2×10^3 mg/L), with a relative contrast of 1.025, the plume no longer follows the initial streamlines, but sinks deeper into the aquifer and reaches the lower model boundary (Figure 93c). The two plumes migrate through different segments of the aquifer and therefore may show different migration and attenuation rates.

6.2.5 *Transport of Vapours and Non-aqueous Phase Liquids*

Researchers are currently developing models that simulate the transport of vapours and non-aqueous phase liquids (NAPLs) within the subsurface. The demand for these types of models is growing rapidly because of widespread groundwater contamination by volatile organics and by NAPLs such as PCB oils, gasoline, and chlorinated solvents.

Multi-phase and multi-component processes are difficult to simulate because of strong nonlinearities in the governing equations and because many of the relevant processes occur at widely different spatial and temporal scales. Component concentrations, for example, can vary from the pure phase (with concentrations in the order of 10^6 ppm) to the dissolved or vapour phase (with concentrations in the order of 1 ppb). To simplify the simulation problem, the processes are often decoupled, i.e., the transport of one phase (e.g., the vapour phase or dissolved phase) is simulated separately from the other phases.

Vapour Transport. Vapour transport is similar to density-dependent contaminant transport in the saturated zone. Depending on the site conditions, the vapour transport problem can be further simplified by neglecting density effects and by assuming ideal gas behaviour. This approach permits the use of standard groundwater flow models to predict vapour phase transport.

More advanced vapour transport models fully account for density-dependent advective–dispersive transport, including phase-partitioning to soil moisture (Sleep and Sykes, 1989; Mendoza and Frind, 1990).

Figure 94 provides an example of a vapour transport simulation. This figure illustrates a vapour plume caused by a 200-L spill of trichloroethane in a coarse sand. The domain extends vertically from the surface of the ground down to the capillary fringe. The upper boundary is open to the atmosphere. In this example, the effect of density-dependent, advective–dispersive vapour transport causes the vapour to sink and increases the extent and concentration of the vapour along the contact area with the capillary fringe, which increases the likelihood of contamination of the underlying aquifer. Further details are provided by Mendoza and Frind (1990).

Transport of Non-aqueous Phase Liquids (NAPLs). Models that simulate the transport of NAPLs are becoming more common; however, they are still not widely used because of high computational costs, the demand for detailed input data, and the difficulties in validating these models. An overview of the processes involved can be found in Parker (1989). Allen (1985) provides a review of multiphase flow modelling. Currently, models provide useful insight into NAPL flow in the subsurface, but predictions must be treated very cautiously.

Advanced finite difference multiphase flow models have been developed by Faust (1985), Forsyth (1988), and Kueper and Frind (1991). The finite element method was used by Osbourne

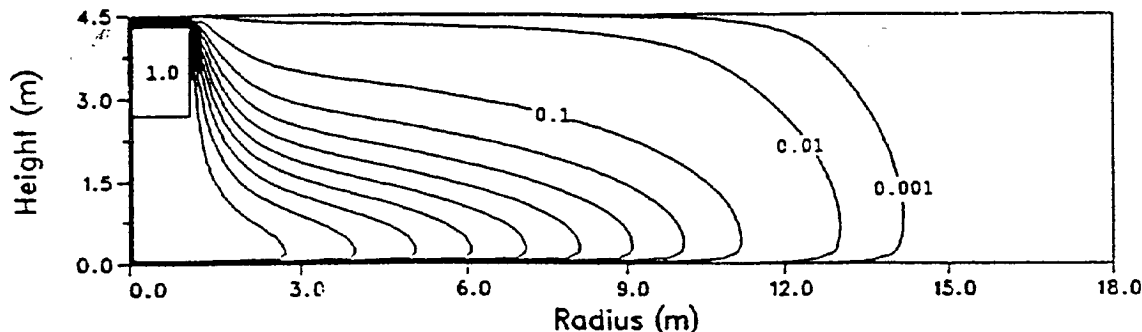


Figure 94 **An Example of Vapour Transport Simulation.** Contours are trichloroethane concentrations in the vapour phase, expressed relative to the trichloroethane-saturated vapour concentration found in the spill area. The spill area is in the upper left, where relative concentrations are 1.0. The upper boundary represents ground surface and the lower boundary represents the watertable.

and Sykes (1986) to simulate immiscible organic transport at the Hyde Park landfill, and by Kaluarachchi and Parker (1989) to develop a three-phase simulation model.

6.3 *Solution Techniques*

The partial differential equations that describe groundwater flow and mass transport can be solved using a variety of methods that include the analytical, particle tracking, numerical finite difference, and finite element techniques. The options available for a particular problem depend on the form of the governing equation and the complexity of the solution domain. Table 25 provides a summary of advantages and disadvantages of the most common methods.

6.3.1 *Analytical Solutions*

Analytical solutions to groundwater flow and transport equations serve useful roles in conceptual and sensitivity analyses, and in preliminary design prior to development of a more advanced numerical model. They provide effectively exact solutions to given equations. Because of their high accuracy, analytical solutions are often used to verify the solution of numerical models.

Because all analytical solutions are exact, the specific solution method employed is usually not important to the user. Reviews are provided by Javandel (1982) and van Genuchten and Alves (1982). Wexler (1989) provides a wide range of one-, two-, and three-dimensional analytical solutions for solute transport problems.

Table 25 Comparison of Common Solution Methods

Solution Method	Advantages	Disadvantages
Analytical	Provides an exact solution Simple and fast Computationally less demanding No numerical dispersion	Less realistic Less versatile Restricted to linear systems Properties must be uniform
Particle Tracking	Often low computational demands No numerical dispersion Well-suited for advective problems, pathlines, capture zones No matrix solution required	Sophisticated velocity interpolation required Local concentrations are difficult to define Complex processes difficult to include
Finite Difference Method (FDM)	Relatively simple compared with FEM May require less memory than FEM Versatile Coupled systems can be solved	Computationally demanding Geometry must be simple Grid layout less flexible Susceptible to numerical dispersion
Finite Element Method (FEM)	Geometry can be complex Realistic and versatile Coupled systems allowed Grid layouts very flexible	Computationally demanding Susceptible to numerical dispersion

6.3.2 Numerical Solutions

Numerical solutions include the techniques of finite difference, finite element, and particle tracking. Solution theory for these, and additional numerical methods, is provided in standard groundwater modelling textbooks (see Section 6.8). Variations on these conventional methods include the Principal Direction (Frind, 1982), Boundary Element (Huyakorn and Pinder, 1983), and Laplace Transform Galerkin (Sudicky, 1989) techniques.

In contrast to analytical methods, numerical techniques solve a problem by establishing the relevant mass or energy conservation relationships between many smaller blocks or elements within the larger domain. These relationships are statements of the original partial differential equation but are developed on a local, subdomain level. In contrast to analytical methods that solve a single, relatively complex equation, numerical methods solve many simpler equations either sequentially (one at a time) or simultaneously (in matrix form).

Dividing a model domain into smaller subdomains is called **discretization**. This subject is discussed more fully in Subsection 6.4.5. Discretization allows numerical models to incorporate spatially variable material properties. With numerical models, domain geometry and boundary conditions are also very flexible.

Whereas analytical solutions are exact, numerical solutions are only approximate. However, you can increase the accuracy of a given numerical model by choosing the most suitable element type and matrix solution technique, and by providing sufficient spatial and/or temporal resolution (by adding more subdivisions or elements or by decreasing the time step). As the element size decreases, a numerical solution will approach the exact solution, although the number of elements is in practice limited by the available computer memory. Most numerical techniques also have accuracy constraints (see Subsection 6.4.5).

Two of the most common numerical techniques are the finite difference and finite element methods. The finite difference method approximates the differential terms in the governing equations using corresponding difference terms. The resulting equation is then written at a finite number of points in the domain. Spatially variable material properties can be accommodated; however, the geometry of a finite difference model must be relatively simple because the blocks or elements must be rectangular.

The finite element method is more advanced than the finite difference method. The finite element method generates a spatially integrated, or spatially averaged, approximation to the partial differential equation. Compared with the finite difference method, which considers the solution only at the grid nodes, the finite element method considers a continuous solution of the unknown variable. The finite element technique also allows for more complex geometry because of the greater geometric flexibility of the grid elements. Several excellent references are listed in Section 6.8, in particular Pinder and Gray (1977) and Huyakorn and Pinder (1983).

Particle Tracking. The region of groundwater contamination is represented by a finite number of particles, and each particle carries a given concentration or a fraction of the total contaminant mass. The particles are tracked through a pre-computed velocity field that is usually defined using finite difference or finite element methods. Advanced interpolation schemes are used to create a continuous velocity field from the discrete elemental values generated from most numerical flow models. Particle tracking is most often applied in the two-dimensional areal plane.

Particle tracking methods can be subdivided into the Method of Characteristics (MOC) and the Random Walk method. A review of the theory is provided by Huyakorn and Pinder (1983) and Kinzelbach (1986). Their advantages are: they are simple to formulate, they are conceptually easier to understand; and they are free from numerical dispersion.

Although most useful for advective-dominated systems, particle tracking methods can also be applied to simulate advective-dispersive transport in either porous or fractured media with a nonporous matrix. Particle tracking techniques are particularly well suited to determine pathlines and zones of groundwater “captured” by pumping wells.

Figure 95 illustrates the use of the particle tracking method to define the capture zone of a pumping well in a uniform groundwater flow field. The capture zone is the region of an aquifer that supplies water to a well over a given period.

With the particle tracking method, it is difficult to incorporate more complex transport processes and to define local concentrations. Because a finite number of discrete particles is used, mass distributions and **breakthrough curves** will often have an erratic appearance.

6.4 *Developing a Numerical Model*

The development of a numerical model requires foresight and planning. First the problem must be defined, and the objectives set (see Figure 86). A suitable code must then be selected and developed into a complete model by defining the model domain and **boundary conditions**, and

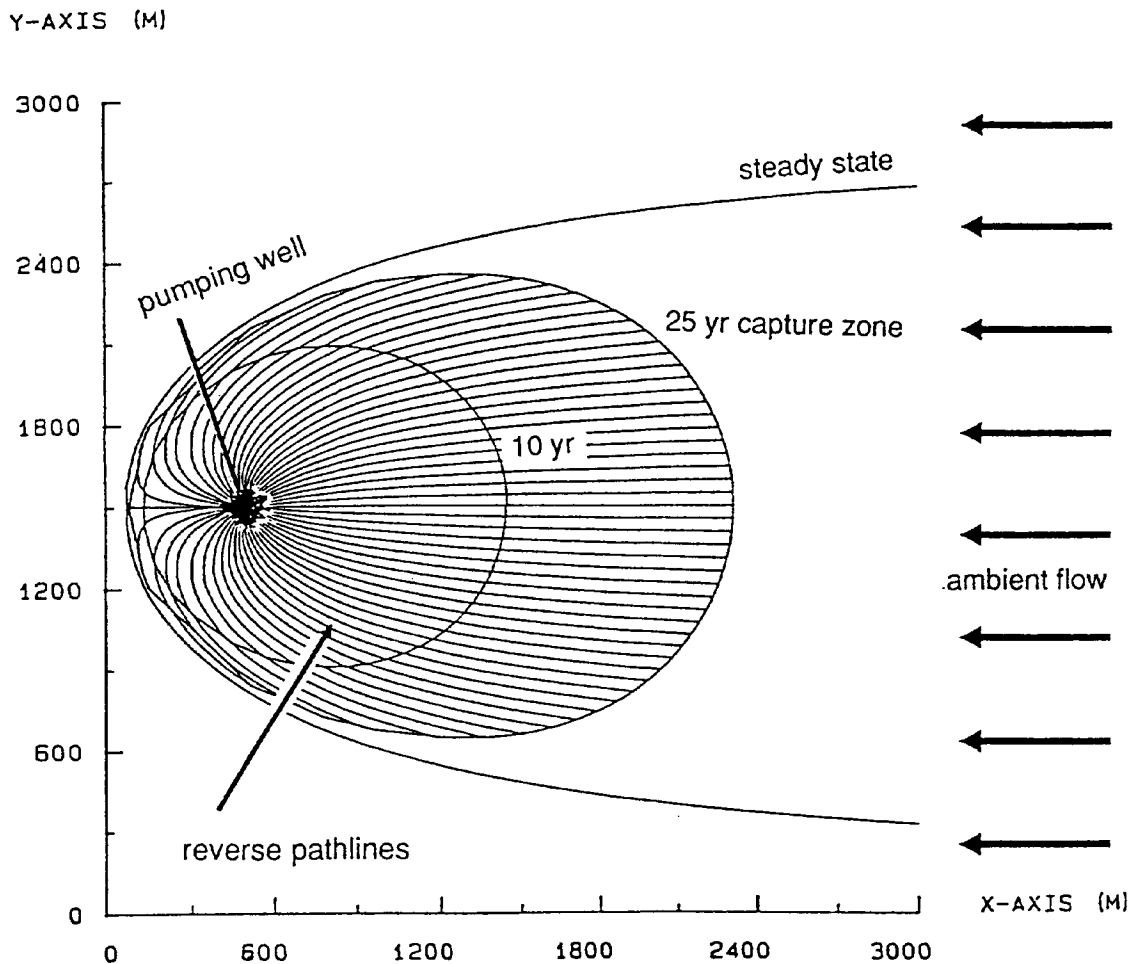


Figure 95 Sample Application of the Particle Tracking Method to Determine a Capture Zone Model that Shows the Expansion Over Time of the Areal Extent of Groundwater Flow Captured by a Pumping Well

by defining the relevant input parameters. After the model is developed, it can be calibrated to the observed data of the site-specific problem, used to perform sensitivity analyses, and used to make predictions.

This section presents the important factors that influence code selection and model development, including goals and objectives, site conditions, dimensionality, site domain, and boundary conditions. The section concludes with definitions of various constraints that affect the accuracy and stability of a model.

We assume that suitable codes are already available and that the user is faced only with choosing the code and developing it into a model. We also assume that the human and computational resources required to run common commercially available codes are available.

6.4.1 Code Selection

The most important factors governing code selection are the goals and objectives of the proposed modelling study. You must also establish how the model results will assist in the decision-making process.

The most common objectives in modelling are:

- to identify the source of contamination;
- to predict future migration; and
- to evaluate proposed remediation methods.

Within these broad objectives, the simulation approach may vary considerably because different codes can satisfy different goals. The effectiveness of a proposed purge well, for example, can be determined by a particle-tracking capture-zone model (an analysis based solely on the flow system); whereas, a more complex advective-dispersive transport model would be required to obtain realistic contaminant concentrations in the extracted water. The **capture zone** model addresses the concern about the duration of pumping; whereas, the transport model helps those who are designing the treatment system for the extracted groundwater.

The solution approach is important as well. A one-dimensional analytical solution, for example, may be adequate to quickly estimate the travel time from a suspected source to a water supply well. At the same site, however, a full three-dimensional transport model incorporating the full aquifer geometry and structure may provide a better estimate. Each approach has advantages and disadvantages (see Section 6.3).

Many issues must be addressed in your choice and application of a suitable code. The following list summarizes the major questions to be answered:

- What is the relevant study area?
- Which chemical species are of most concern?

- What contaminant phases are present [i.e., solid, liquid (pure), dissolved, or gaseous]?
- Which processes are dominant at the site, and which should be included in the model (i.e., advection, dispersion, diffusion, density, retardation, biodegradation, chemistry, volatilization, and DNAPLs.)?
- Which real or potential sources will be included?
- Should an analytical or numerical solution be used?
- Is a one-dimensional, two-dimensional (radial, areal plane, or vertical section), or three-dimensional analysis required?
- Is a flow solution sufficient (e.g., flownets or capture zones), or must mass transport be simulated?
- Can the flow field be simulated assuming steady state conditions or is a transient flow analysis required? and
- Should the unsaturated zone be included?

Choosing the best code for a given site depends on the goals and objectives of the study, and on the actual site conditions (including the physical definition and processes involved). The user or decision-maker must choose a suitable code and a modelling approach that will best solve the given problem without going beyond what is necessary or exceeding the scope of the study. In addition to code selection, proper development of the model, and correct interpretation and presentation of the results, acknowledging the assumptions and limitations of the model is of equal importance to the success of the modelling effort.

6.4.2 Dimensionality

Within natural hydrogeologic systems, contaminant transport is inherently a three-dimensional process. Contaminants advect through complex three-dimensional groundwater flow systems, and disperse and diffuse in three dimensions. When considering a site to be modelled, however, you can simplify the real system to one or two dimensions, or include the complete three-dimensional domain. The choice of **dimensionality** will significantly affect the computational effort required and the realism of the results. Table 26 summarizes the primary applications for a variety of dimensional approaches and also presents some of their limitations.

In many situations, groundwater flow can be analyzed in two dimensions rather than three. If we are interested, for example, in the migration of a contaminant plume originating at a source of fairly large extent (e.g., a landfill) we might analyze a cross-section that follows the watertable gradient downstream from the source. The advantage of a cross-sectional analysis is that it can correctly incorporate depth-dependent transport processes or depth-dependent chemical transformations, while avoiding the greater expense of the full three-dimensional analysis. A cross-sectional analysis is not well suited for point sources because horizontal spreading of a contaminant cannot be represented and the best cross-section may be difficult to choose.

Table 26 Analysis of Model Dimensionality

	Typical Applications	Assumptions/Limitations
One dimension	Preliminary concept evaluation Vertical migration from a large source Darcy's Law applications Migration through landfill liners Local scale processes, sensitivity analyses Unsaturated zone modelling	Transverse flow neglected Transverse dispersion neglected No geometry Highly simplified
Two dimension, areal	Areal extensive, vertically thin aquifers Capture zones, purge well networks Multi-aquifer models, leaky aquifers Transport from a laterally wide source	Vertical flow neglected Vertical dispersion neglected Fully screened wells No depth-dependent processes
Two dimension, vertical	Flownet simulations Depth-dependent processes Vertically heterogeneous aquifers Laterally extensive sources	Horizontal dispersion neglected Horizontal flow neglected Lateral continuity assumed
Two dimension, radial	Radially symmetric problems Single source well or purge well	Restrictive geometry Radially symmetric Homogeneous flow properties
Three dimension	Depth-dependent processes within three-dimensional heterogeneous systems Complex aquifer geometry and structure Multiple, partially screened wells Long-term transport from small source	High computational demands (memory/execution time) Large effort: field data collection; model development and calibration.

A two-dimensional vertical section transport model neglects transverse horizontal gradients, and therefore only applies along the selected vertical flow plane. It is most realistic for plumes that are extensive in the horizontal plane. The vertical flow plane must pass through the source and should approximately coincide with the symmetry plane of the plume if one exists. Because transverse horizontal dispersion is neglected, two-dimensional vertical section models tend to be conservative in predicting transport migration rates. Field concentration data must be depth-specific for use in calibrating a vertical two-dimensional, or three-dimensional transport model.

A two-dimensional areal plane model by contrast, neglects vertical gradients and is therefore most realistic for really extensive but vertically thin aquifers. Because this approach integrates over the vertical dimension, wells are assumed to be fully penetrating and the contaminants are assumed to be well dispersed vertically throughout the aquifer. A two-dimensional areal transport model must use depth-averaged field concentration data for calibration.

The most realistic approach in contaminant transport modelling will always be in three dimensions. A three-dimensional approach is most important if, for example, the source area is small relative to the plume, the contaminant distribution is localized within the aquifer, the structural geometry is clearly three-dimensional, and partially screened pumping wells are present. If high vertical and transverse flow gradients are present, a full three-dimensional approach becomes very important.

With a three-dimensional approach, however, more effort is needed to develop the site-specific model. The field characterization and calibration data are also required in the vertical as well as the areal dimensions and must be depth-specific, not vertically averaged.

6.4.3 *Defining the Model Domain*

A model **domain** is defined by its boundaries and interior geometry, its hydrostratigraphy, and its material property variations (porosity, hydraulic conductivity). Because groundwater flow is the primary control on contaminant transport, it is the flow system that dictates the definition of the model domain. The domain must encompass the anticipated maximum extent of the contamination.

Two boundaries are needed for every dimension included in the model. In the vertical dimension, the upper domain most commonly corresponds to the water table when the unsaturated zone is neglected. For domains that include the unsaturated zone, the upper boundary is usually the surface of the ground.

Choosing a suitable lower boundary depends on the vertical distribution of contaminants and on the hydrostratigraphy. The upper surface of a unit of low permeability is usually the most favoured choice for the lower domain boundary. A common rule of thumb states that a stratigraphic unit is effectively an impermeable boundary if its hydraulic conductivity is at least two orders of magnitude less than the adjacent units.

Because the vertical dimension of a two-dimensional areal plane model is lost through vertical integration, this type of model represents the total thickness of the aquifer containing the

contaminants. If the aquifer is unconfined, its thickness is determined by the solution. If it is confined, the thickness must be specified. In either case, you must know the geometry of the lower aquifer boundary. Within a two-dimensional areal plane model, you cannot incorporate hydrostratigraphic variation, but you can define lateral variations in aquifer thickness and material properties.

In the areal plane, natural flow boundaries (e.g., rivers, lakes, or impermeable bedrock outcrops) are preferred wherever present or suspected. If artificial boundaries are necessary, put them at a sufficient distance — where they will not interfere with the simulated migration of the contaminants under study, and where they do not impose any unnatural conditions on the system.

6.4.4 Boundary Conditions

Boundary conditions are required for both groundwater flow and contaminant transport domains. Table 27 summarizes the most common types of boundary conditions.

Table 27 Summary of Flow and Transport Boundary Conditions

Boundary Type	Groundwater Flow	Contaminant Transport
First (Dirichlet)	$h = h_0$ <p>Fixed head boundary (e.g., river or lake boundary)</p>	$C = C_0$ <p>Fixed concentration boundary (e.g., a large, well-mixed source)</p>
Second (Neumann)	$q_n = q_0 = K \frac{\partial h}{\partial n}$ <p>Specified flux boundary (e.g., recharge across watertable, inflow or outflow, or no-flow $q=0$)</p>	$\frac{\partial C}{\partial n} = 0$ <p>Zero-concentration gradient (e.g., outflow or impermeable boundary)</p>
Third (Cauchy)	$q_n = K' \frac{(h^* - h)}{b'}$ <p>A "leaky boundary" (see text) — represents leakage flux from an adjoining aquifer or from an aquifer-connected river</p>	$\frac{q_0 C_0}{\theta} = vC - D \frac{\partial C}{\partial x_i}$ <p>Dispersive flux boundary (e.g., source with known influx q_0 and concentration C_0)</p>

Groundwater Flow Boundary Conditions. Flow boundary conditions may be either a first type or Dirichlet flow boundary (at which the hydraulic head is fixed) or a second type or Neumann flow boundary (which represents a groundwater flux).

The first type boundary condition may be appropriate at locations such as river or lake boundaries, and at wells for which the head is known. You can assign fixed heads to artificial boundaries if the boundary is sufficiently distant from the area of concern, and if realistic values are known.

It is generally poor practice to use observed heads as a first type condition at the watertable in a two-dimensional vertical or three-dimensional model. Small measurement errors or variation over time may induce unrealistic gradients that can have damaging effects on subsequent transport simulations. You should also avoid a fixed head (or other artificial boundary) near an active source or sink because it may induce an unrealistic response. An abnormal hydraulic head response near a boundary often indicates the poor choice of a boundary condition.

The second type or Neumann flow boundary condition represents groundwater flux. Use of this boundary condition is appropriate, for example, across the upper domain of a model where it represents recharge to an aquifer system, or at artificial, lateral boundaries where a flux is known or estimated to occur. A Neumann condition with a zero flux is used to represent an **impermeable boundary or groundwater divide**.

In an areal two-dimensional flow model, a special condition known as a leakage type boundary represents aquifer connections to rivers, lakes, or adjoining aquifers. Although not a true boundary condition, it often appears as a boundary to the user. This condition represents a head-dependent flux and is most commonly applied in two-dimensional areal flow models to represent leaky rivers or to represent leakage through an upper or lower semi-permeable aquitard. The exact form is given in Table 27 where K' is the hydraulic conductivity of the semi-permeable layer, b is its thickness, h^* is the given fixed head, and h is the unknown aquifer head.

The leakage boundary allows flux into or out of the primary aquifer and depends on the head gradient as defined by the computed aquifer head and the given fixed head. For example, during a single transient flow simulation, a river may initially receive groundwater from an aquifer but may subsequently begin to lose water to the aquifer after a purge well becomes active. If the aquifer head drops below the aquitard or river base, the flux becomes constant (defined by the fixed hydraulic gradient across the semi-permeable base).

Transport Boundary Conditions. There are three types of transport boundary conditions:

- a specified concentration (Dirichlet condition);
- a specified gradient (Neumann); and
- a concentration-dependent flux (Cauchy) boundary.

Another transport boundary condition is the “free-exit condition”, although it has not yet appeared in any public-domain codes.

The most critical boundary condition in a transport simulation is a boundary condition imposed to represent an external source. In this case, a third type, or Cauchy condition, is most realistic because it allows a gradual build-up of contaminant concentration at the source with both advective and dispersive flux across the boundary. If the early time behaviour is not of interest, or if advection is much greater than dispersion, a first type or fixed concentration source can be used (see Figure 96).

The second type transport boundary condition represents a fixed gradient that in practice is most commonly set equal to zero. The zero-gradient boundary condition is applicable along impermeable flow boundaries, or at outflow boundaries distant from the plume where it forces the concentration contours to meet the boundary at right angles. A second type condition should never be used at or near a source because the fixed gradient will erroneously allow mass to spread away from the source along the boundary.

At down-gradient boundaries, a “free-exit” condition is most realistic because it allows mass to leave the system naturally. If the contaminants remain distant from the boundaries, the specific exit boundary condition for the transport problem becomes less relevant.

6.4.5 Domain Discretization and Constraints on Accuracy

Numerical simulation models require that the subsurface domains be resolved into a finite number of blocks or elements that are joined at nodes, and form a spatial grid. Most numerical models must also resolve the time domain; exceptions include steady state problems, and models

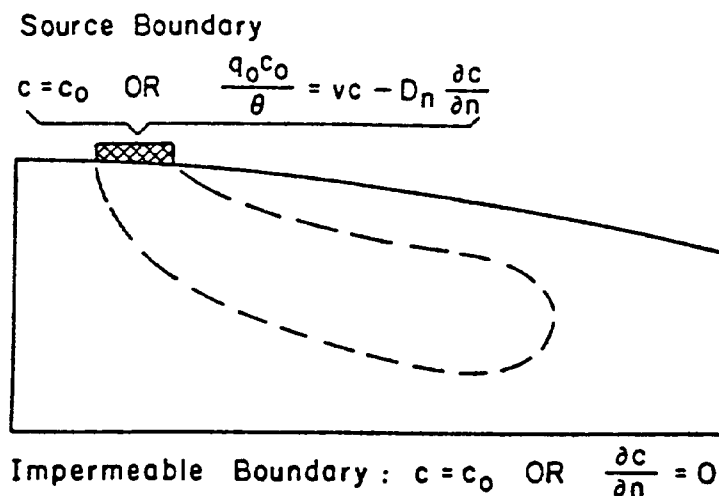


Figure 96 **Typical Transport Boundary Conditions**

using the Laplace Transform technique (for which the time domain is continuous). The degree of resolution in both the spatial and temporal domains can have a significant effect on the accuracy and computational effort of the simulations and can affect their stability.

Discretization methods vary considerably depending on the type of model and the solution method. Figure 97 shows some common element types. Finite element methods tend to favour triangles, or tetrahedra and triangular prisms in three dimensions, because of their simplicity and versatility in defining irregular geometry. Deformed quadrilaterals or deformed brick elements are also common in finite element models. Finite difference methods most commonly use rectangular-based cells (either node or block centred). Figure 98 illustrates an example of a plan-view domain resolved using: (a) triangular finite elements; and (b) rectangular finite difference cells. Note that the finite element method provides a more accurate definition of the boundaries, and with triangles, is more efficient in resolving local-scale features (e.g., pumping wells).

The accuracy of a numerical model is partially governed by the grid spacing and time step constraints. In the spatial domain, the grid spacing should satisfy the aspect ratios given by:

$$\frac{K_x}{\Delta x^2} \approx \frac{K_y}{\Delta y^2} \approx \frac{K_z}{\Delta z^2} \quad [29]$$

where Δx , Δy , and Δz are the grid spacings in the x, y, and z directions, respectively.

The spacing should also satisfy the grid Peclet constraints given by:

$$P_x = \frac{v_x \Delta x}{D_{xx}} \leq 2; \quad P_y = \frac{v_y \Delta y}{D_{yy}} \leq 2; \quad P_z = \frac{v_z \Delta z}{D_{zz}} \leq 2 \quad [30]$$

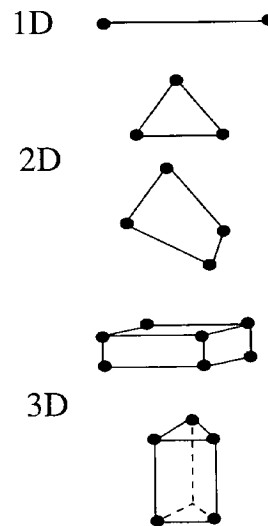
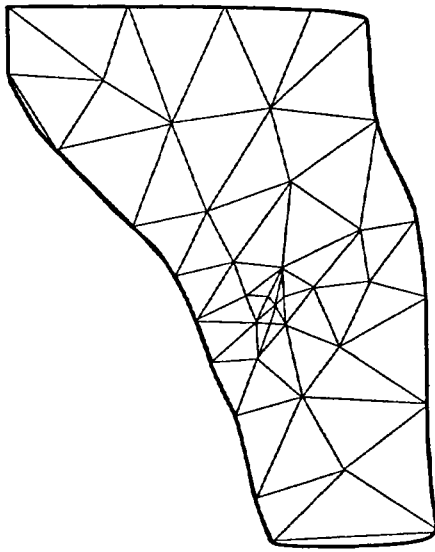
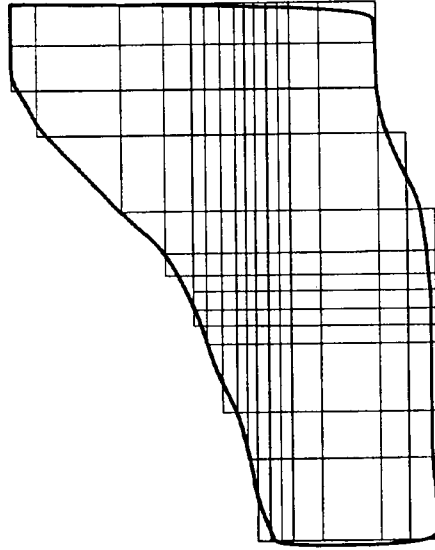


Figure 97 Some Common Element Types Used in Numerical Models. 1D = one dimension; 2D = two dimensions; and 3D = three dimensions.



Finite Element Grid



Finite Difference Grid

Figure 98 An Example of a Plan-view Domain Resolved Using: (a) Triangular Finite Elements; and (b) Rectangular Finite Difference Cells. Note the more efficient manner in which the high-resolution area (a proposed pumping well location) is resolved in the finite element grid.

In the temporal domain, the time step should satisfy the Courant criteria given by:

$$C_x = \frac{v_x \Delta t}{\Delta x} \leq 1; \quad C_y = \frac{v_y \Delta t}{\Delta y} \leq 1; \quad C_z = \frac{v_z \Delta t}{\Delta z} \leq 1; \quad [31]$$

where Δt is the time step. Transport problems involving decay must also satisfy a mass-loss criteria given by:

$$\Delta t \leq 1/\lambda \quad [32]$$

that restricts the amount of mass allowed to decay within one time step. Two additional guidelines for designing grids are:

- The grid should be oriented, wherever possible, along the principal directions of transport. Element boundaries or diagonals for example, should follow the velocity field as close as

possible. For transient flow, a principal direction grid corresponding to the average flow field is suggested.

- The plume should be resolved into an adequate number of elements in both the transverse and the longitudinal directions to provide resolution of the dispersive components.

In practice, the above constraints can be relaxed as time increases and concentration gradients diminish. As a general rule, you need a higher grid resolution to define irregular changes in material properties, and where gradients are high (e.g., near pumping wells and near contaminant sources).

Although the above criteria can always be met with a sufficiently fine grid, a grid designed with excess elements may require more computer memory than is available, or may require an impractically long time to complete. A well-designed grid is therefore critical to a successful modelling effort. Interactive grid generators, available with many commercial models or as separate software packages, can help immensely in this regard.

6.5 *Model Reliability*

The reliability of a model refers to its accuracy in solving the differential equations on which it is based, and to its ability to realistically simulate observed physical, chemical, or biological processes. Van der Heijde (1990) provides a review of definitions and guidelines relevant to model reliability.

6.5.1 *Verification*

Before it can be used, a new groundwater simulation code must first be verified (or proven) to solve the differential equations for which it was developed. Verification is most often accomplished by comparing the model with an analytical solution to the same problem. Verification examples for commercially available codes should be provided, either within the user manual or in the published literature.

A given code needs to be verified only once. It is good practice, however, after installing a new code on a system, to run the verification, or a test case, to verify that the code is running properly on that system. Factors such as computer precision, non-standard compilers, and intrinsic functions such as random number generators can vary among different computer systems and can adversely affect model results. For reasons of liability, commercial codes are never guaranteed to be error-free and, therefore, the responsibility always lies with the user to ensure that the code is running accurately.

A successful verification proves only that the code is running correctly and that it solves the given equations. It implies nothing about the suitability of the code to any natural or conceptual hydrogeological system. The user must decide if the code is suitable for the given problem.

6.5.2 Validation

Whereas verification ensures the computational accuracy of a code, validation ensures the physical realism of the developed model. Models are validated by simulating the results of a controlled laboratory or field experiment for which the parameters and processes are well-known. The model input parameters in this case are obtained directly from the experimental data. Because these parameters and processes have been defined independently of the model, an accurate reproduction indicates that the model is physically realistic and can be applied with a high degree of confidence to field-scale contaminant problems, provided the physical system is similar to that upon which the model was validated.

Be aware, however, of the potential to apply a model to simulate a physical system for which the model has not been validated. The limitations and assumptions of the developed model must be recognized. Konikow and Bredehoeft (1992) provide a very thoughtful discussion on the philosophy of model validation.

6.5.3 Calibration, Sensitivity, and Prediction

After a code has been verified and validated, it can be applied to the site-specific problem. The first step, calibration, reproduces an observed set of data by varying the model input parameters within acceptable limits. However, if these limits are too large, the calibration may be non-unique.

In a flow model, the primary calibration parameters are hydraulic conductivity, porosity, and aquifer recharge distribution. Boundary conditions and the **storage coefficient** in transient models are also calibration variables. Observed water table elevations, and the vertical head distribution in a two-dimensional vertical or three-dimensional flow model provide good constraints for model calibration. If steady-state flow is assumed in the approach, the flow simulation need only match an average of the observed transient head distributions. Apparent groundwater velocities can constrain the calibration even further.

Often, the best calibration data for a flow model are given by an observed distribution of contaminants, if one exists, because this will be an excellent reflection of the long-term average flow system. In the vertical dimension, for example, streamlines from a flownet model can be calibrated to the observed concentration contours. A transport simulation using this flow field should then be able to reproduce the observed plume with high accuracy.

An example of this calibration approach is provided in Figure 99 in which a two-dimensional advective-dispersive transport model is calibrated to the Canadian Forces Base Borden landfill chloride plume. The observed chloride plume (Figure 99a) extends approximately 800 m downgradient from the landfill and is constrained below by a continuous clay aquitard. The aquifer material is a sand with a hydraulic conductivity of approximately 5×10^{-5} m/s.

By adjusting the lateral flow boundary conditions, and varying the aquifer recharge distribution across the surface, a flownet model was successfully calibrated to the concentration contours (Figure 99b). Using this steady state flow field, a two-dimensional advective-dispersive numerical transport model was applied using a third type source boundary to represent the

landfill (Figure 99c). Internal concentration peaks were simulated by varying the source concentration with time. The simulated plume appears to match the observed plume very well, verifying the calibration. This transport simulation could then be extended in time to predict future behaviour.

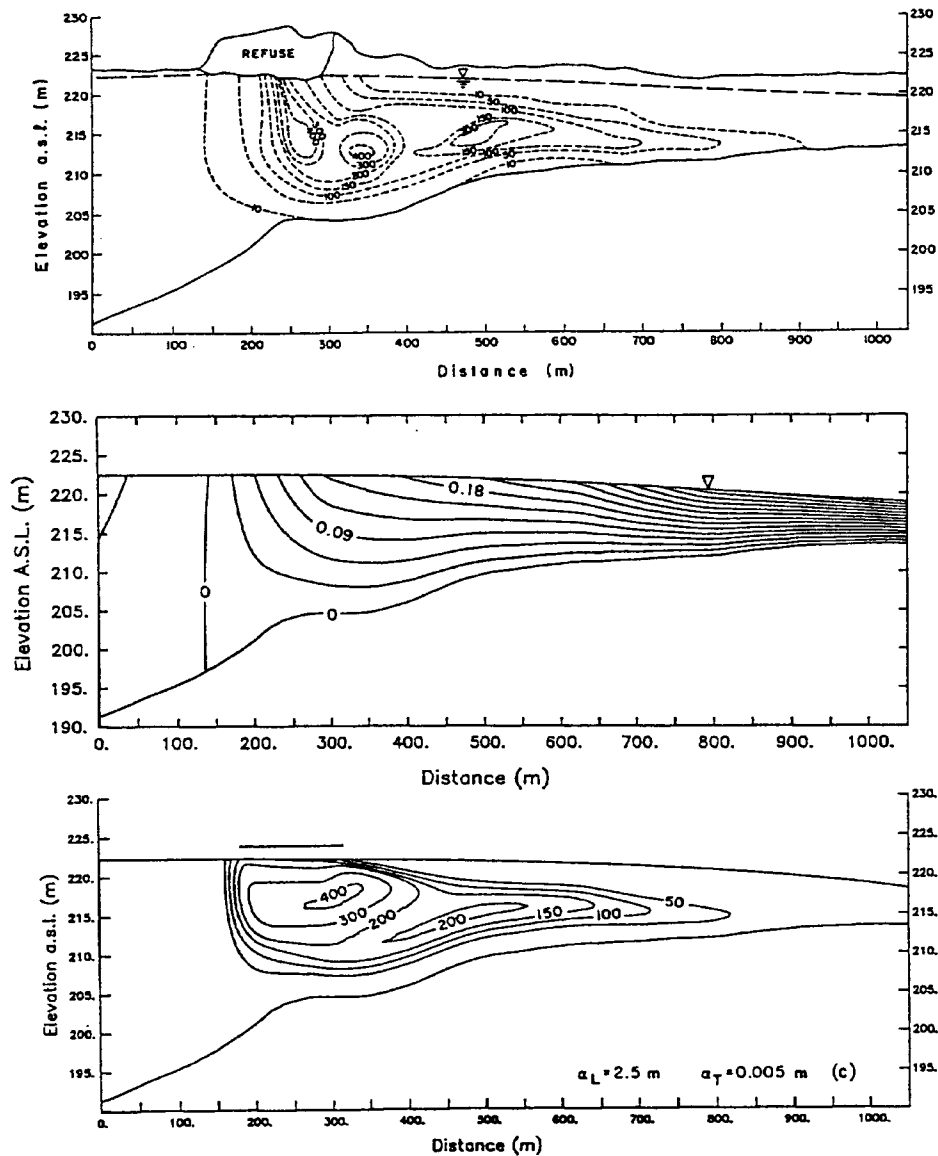


Figure 99 An Example of Model Calibration (The Canadian Forces Base Borden Case):
 (a) Observed Contaminant Distribution; (b) Calibrated Steady State
 Streamline Flow Solution; and (c) Simulated Plume

To reduce uncertainty and to avoid the non-uniqueness problem, use independently derived original field data whenever possible in the calibration process. Without independent data, however, models are often calibrated using a trial and error approach, whereby one or more parameters are varied until a reasonable match with the observed data is obtained. Inverse and optimization methods have been developed to improve the calibration process, but because of their complexity they are not often used in practice.

A calibrated model does not imply it is valid for a given site because calibration is usually only a curve-fitting exercise. Many models, some based on non-valid assumptions, could be calibrated to the same data. Furthermore, if the model is not sensitive to the calibrated parameter, then an apparently good calibration may be misleading. Konikow (1978) discusses problems associated with the calibration process.

If the model input parameters are not well-defined, a parameter sensitivity analysis may help identify the parameters that require more accurate definition. By using the extremes of the parameter ranges, you can develop worst-case or conservative scenarios.

Finally, the model can be used to predict contaminant migration or estimate the effectiveness of proposed remediation measures. Predictions are usually made using the calibration simulation as the initial condition and extending the model in time. It is in this predictive mode that models are most useful, but also most susceptible to misuse. Take care to recognize all assumptions and uncertainties in the modelling process. Konikow (1986) for example, presents examples where model predictions have been seriously flawed in part due to improper calibration.

6.6 *Uncertainty and Non-uniqueness*

At field sites, there will always be some degree of hydrogeological uncertainty. Furthermore, there is future uncertainty in additional model parameters, including source concentration variation over time (e.g., river levels) that will affect predictions of contaminant transport.

Uncertainty in the model input parameters can produce non-uniqueness, where more than one set of input parameters will produce essentially the same result. To better illustrate the non-uniqueness problem, consider an unconfined aquifer, in which the hydraulic conductivity is only known within a factor of 10, and aquifer recharge is only known within a factor of 2. Because groundwater heads only depend on the ratio of aquifer recharge and hydraulic conductivity, and not on their magnitudes, a given observed head distribution may be reproduced using any combination of these two parameters that gives the same ratio as that determined from the model calibration. The predicted distance a contaminant could migrate could vary by an order of magnitude, depending upon the hydraulic conductivity value chosen in the model. This occurrence of non-uniqueness could be avoided, if, for example, the recharge rate was well-known. Other occurrences are less-easily avoided.

Non-uniqueness is not a fault of the model itself, but rather of the quality and quantity of the actual data. If simulation results are non-unique, perhaps the chosen model and/or scope of the study is too complex given the limited field data.

6.7 *Summary*

We have presented only a very brief outline of a very complex subject. Before engaging in a modelling project, we recommend further background reading (see Section 6.8). Modelling too often becomes a “black-box” exercise if either the physical system or the chosen model is not adequately understood.

In summary, we offer the following guidelines:

- Always acknowledge the inherent assumptions and limitations of the chosen modelling approach, and include them in your interpretation of the results.
- Hydrogeological models are best suited to assess the validity of conceptual models, to assess parameter sensitivity, or to make comparative predictions. They should not be used to make absolute predictions.
- Keep the modelling in perspective. The model parameters, boundary conditions, and material properties should all be realistic and be kept as simple as possible. Before attempting a complex numerical model of your site, perhaps an analytical solution would be useful in your preliminary conceptual analysis.
- Respect the model accuracy criteria, stability criteria, and mass balance requirements.

6.8 *Additional Information*

The following textbooks are recommended for those needing to improve their understanding of modelling and quantitative approaches in hydrogeology:

- Anderson, M.P. and W.W. Woessner, *Applied Groundwater Modelling*, Academic Press, New York, New York (1992).
- Bear, J., *Dynamics of Fluids in Porous Media*, Elsevier, New York, New York (1979).
- de Marsily, G., *Quantitative Hydrogeology*, Academic Press, New York, New York (1986).
- Domenico, P.A., and F.W. Schwartz, *Physical and Chemical Hydrogeology*, John Wiley & Sons, New York, New York (1990).
- Freeze, R.A. and J.A. Cherry, *Groundwater*, Prentice-Hall, New York, New York (1979).
- Huyakorn, P. and G. Pinder, *Computational Methods in Subsurface Flow*, Academic Press, New York, New York (1983).

- Luckner, L. and W.M. Schestakow, *Migration Processes in the Soil and Groundwater Zone*, (English translation), VEB Deutscher Verlag für Grundstoffindustrie, Leipzig, Lewis Publishers Inc., Chelsea, MI, 48118 (1991).
- Kinzelbach, W., *Groundwater Modelling*, Elsevier, Amsterdam (1986).
- Pinder, G. and W. Gray, *Finite Element Simulation in Surface and Subsurface Hydrology*, Academic Press, New York, New York (1977).
- Schwartz, F.W., (ed.), *Ground Water Models — Scientific and Regulatory Applications*, National Academy of Sciences, Washington, D.C. (1990).

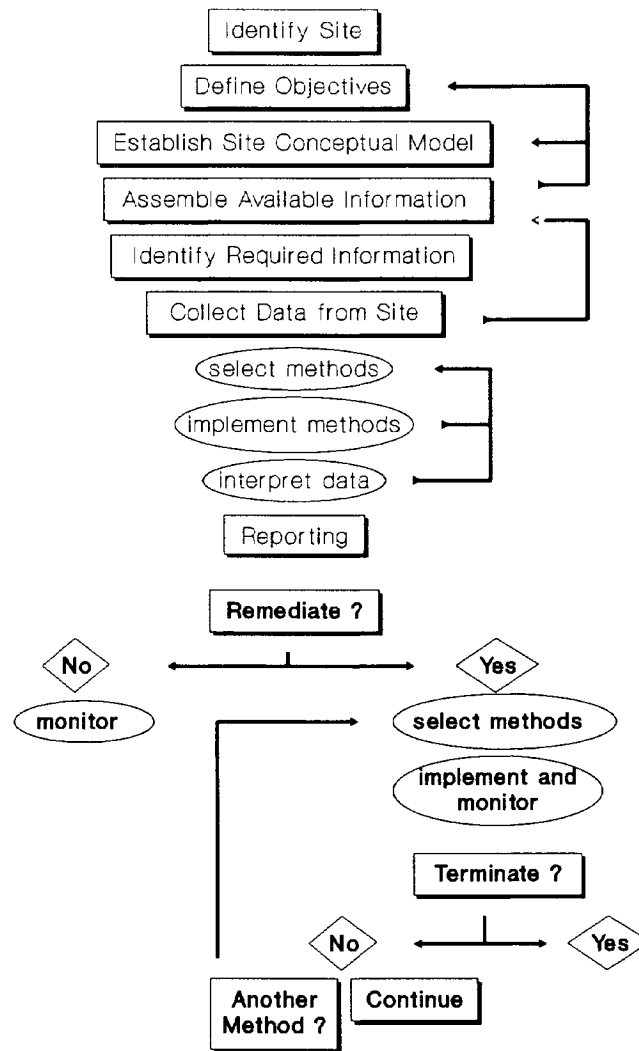
The following journals publish advances in modelling and are excellent sources of new ideas:

- *Water Resources Research* (American Geophysical Union, 2000 Florida Ave., NW, Washington, DC, 20009)
- *Ground Water* (Ground Water Publishing Co., 6375 Riverside Dr., Dublin, OH, 43017)
- *Journal of Contaminant Hydrology* (Elsevier Science Publishers, P.O. Box 211, 1000 AG, Amsterdam)
- *Advances in Water Resources* (Computational Mechanics Publications, Ashurst Lodge, Ashurst, Southampton, SO4 2AA UK)

A number of models are commercially available. Table 28 lists the major suppliers. In addition, new models are often advertised or referenced in journals. Short courses in most aspects of modelling, ranging from actual model operation to using results, are presented by a number of organizations. Advertisements appear in *Ground Water Monitoring Review* and in *Ground Water* and most model suppliers also are involved in short courses. Contact those offering the courses to decide which courses are best suited to your needs.

Table 28 Major Commercial Suppliers of Groundwater Flow and Contaminant Transport Models

International Ground Water Modelling Centre Colorado School of Mines Golden, Colorado 80401-1887 tel: (303) 273-3103 fax: (303) 273-3278	Geraghty & Miller Inc., Modelling Group 10700 Parkridge Blvd., Suite 600 Reston, Virginia 22091 tel: (703) 758-1200 fax: (703) 758-1201
Waterloo Centre for Groundwater Research University of Waterloo Waterloo, Ontario N2L 3G1 tel: (519) 885-1211 x 3960 fax: (519) 725-8720	GeoTrans Inc., Computer Model Sales 46050 Manekin Plaza, Suite 100 Sterling, Virginia 22170 tel: (703) 444-7000
NGWA Ground Water Bookstore P.O. Box 182039, Dept. 017 Columbus, Ohio 43218 tel: (614) 761-1711	HydroGeologic Inc. 1165 Herndon Parkway, Suite 900 Herndon, Virginia 22070 tel: (703) 478-5186 fax: (703) 471-4180
Waterloo Hydrogeologic Software 200 Candlewood Cr. Waterloo, Ontario N2L 5Y9 tel/fax: (519) 746-1798	Rockware 4251 Kipling St., Suite 595 Wheat Ridge, Colorado 80033
S.S. Papadopoulos and Assoc. Inc. 12250 Rockville Pike, Suite 290 Rockville, Maryland 20852 tel: (301) 468-5760	Scientific Software Group P.O. Box 23041 Washington, D.C. 20026-3041 tel: (703) 620-9214 fax: (703) 620-6793



Section 7

Assessment of Subsurface Remediation (J. Barker)

Contaminated sites are normally assessed with the intention of performing some clean up or remediation of the subsurface, if necessary. Previous sections have presented methods for assessing the subsurface at contaminated sites. This section discusses subsurface assessment of the remedial actions themselves. It does not discuss choosing or implementing remedial actions. Remedial actions can range from no action (if the contamination does not warrant action), through passive remediation (nothing except monitor the natural clean up), to complex and often expensive positive actions. Positive remedial actions include containing and isolating contaminants, *in situ* degradation of contaminants, and removal of contaminated soil, vapours, or groundwater. Treatment of contaminants after removal is not discussed because it does not involve subsurface assessment.

This section introduces the current and emerging remedial technologies, but emphasizes the subsurface assessment required to evaluate their success. Generally, subsurface assessment of site remediation must address two questions:

- Upon completion, has the remediation met the remedial objectives? and
- Was the remedial action responsible for the reduction in contamination?

The subsurface assessments required to answer these questions are identified for each technology. Most of the subsurface methods are presented in earlier sections.

Remedial technologies are rapidly evolving, with new approaches emerging. For example, multiple technologies will be commonly used at contaminated sites. The subsurface assessment requirements remain the same. How clean is the site and what was the contribution of the applied techniques? Therefore, the subsurface assessment approaches presented in this section will likely be followed even for new technologies.

7.1 Introduction

Subsurface assessment evaluates if the remediation has met some predetermined objectives, for example:

- removal of a specified portion (or all) of the contaminants; and
- reduction of contaminant concentrations to specific levels.

Clean up criteria and their development are discussed in other CCME documents (CCME, 1991a, 1991b) and are not discussed here.

Previous sections indicate how to assess the subsurface contamination and to determine if remediation is required. Subsurface assessment also helps in the design and operation of site remediation, if it is required. To judge the success of the remedial actions we must determine the post-remediation distribution of contaminants. Were the clean up criteria met? Another issue is whether the remediation was due to the remedial actions. For example, if expensive additives were used to help mobilize DNAPL, the effectiveness of that addition needs to be assessed. All evaluations will require some subsurface assessment.

7.2 *Remedial Technologies*

Table 29 summarizes various methods used to clean up or remediate subsurface contamination. Some methods are routinely employed; others are under development. Many are specific to certain contaminants, certain phases (soil, vapour, groundwater, NAPL), or certain hydrogeological settings. More technologies will emerge and more than one will likely be applied at most contaminated sites. Some technologies are patented; others require skilled contractors. All technologies need specific subsurface information for their design and implementation.

Remediation methods are considered for four approaches:

- passive remediation;
- containment and isolation;
- removal for subsequent on-site or off-site treatment or storage; and
- *in situ* treatment.

Landfarming, a method most commonly employed for on-site treatment of contaminated soils, is grouped with *in situ* treatment because the actual remediation occurs largely *in situ*. Each method is briefly described and the subsurface assessment required to evaluate its performance is identified.

7.2.1 *Passive Remediation*

Passive remediation requires that the natural processes currently acting on the subsurface contaminants continue to provide adequate environmental protection. For example, dissolved contaminants may be attenuated before an unacceptable risk to the environment occurs. To employ passive remediation, monitor the subsurface to:

- demonstrate that the natural attenuation processes continue to provide the desired protection; and
- alert us to unacceptable changes.

Table 29 Summary of Remedial Technologies

Technology	Basic Approach	Possible Applications or Examples
Passive Remediation	Monitor natural attenuation	Sites where likely impact is acceptable
Containment and Isolation	Isolate waste from the environment at risk	Capping landfills to prevent leaching by recharge waters
Physical	Prevent contaminant movement by preventing fluid flow	Landfill covers, slurry walls
Encapsulation	Create an inert waste form	Inject solidifying chemicals into waste
Vitrification	Apply electrical energy to vitrify contaminated material	Shallow metal-contaminated soils or waste
Removal for Treatment	Remove contaminants and treat on- or off-site	Groundwater, soil vapour pumping and soil excavation
Product Recovery	Pump NAPL	Always leaves a residual
Groundwater Extraction	Pump groundwaters for surface treatment	Most common approach for contaminated groundwaters
Soil Venting	Pump contaminated vapours	For volatile organics
Sparging	Inject gas bubbles to remove volatiles	For volatile organics
<i>In Situ</i> Soil Flushing	Add water to leach contaminants and collect this water	For soluble contaminants
Enhanced Solubilization	Add surfactants or solvents to solubilize contaminants for removal	Applied to sorbed contaminants or NAPL residuals
Excavation	Remove contaminated soils	Common practice for shallow, highly-contaminated soils
<i>In Situ</i> Treatment	Alter <i>in situ</i> conditions to create contaminant degradation	Common approach for volatile or biodegradable organics
Bioventing	As soil venting, above, but encourages biodegradation	Useful for aerobically degraded organics (e.g., gasoline)
Landfarming	Encourage natural degradation of wastes in surface soils or wastes spread on land	Currently used for aerobically degraded organics
<i>In Situ</i> Biodegradation	Alter groundwater environment to encourage biodegradation of dissolved or residual contaminants	Currently used for aerobically biodegraded organics (e.g., BTEX with oxygen and nutrients added to groundwater)
Reactive Barriers	Create conditions for contaminant attenuation in a permeable barrier	Groundwater flows through reactive barrier in which contaminants are sorbed or degraded

This monitoring must define contaminant distributions and changes. Thus, passive remediation requires subsurface sampling and chemical analysis (Section 5). Establish a basis, perhaps statistical, for identifying changes in quality (e.g., groundwater, soil vapour). As noted in Section 5, this is difficult and site-specific, but consistent sampling and analysis protocols are essential.

The processes restricting contaminant migration (see Section 1) must be understood, and possible changes in contaminant distributions must be anticipated. For example, if groundwater flow takes contaminants away from sensitive areas, it may be the critical process. Changes in site or regional conditions could cause groundwater flow toward the sensitive area and increase risk. Therefore, monitoring of groundwater flow direction and velocity (Section 4) is a critical requirement.

7.2.2 Containment and Isolation

Creating barriers or immobilizing contaminants can maintain the current contaminant distribution and prevent unacceptable contaminant movement.

Physical Barriers. You do not have to create barriers for contaminants that are sufficiently immobile. Passive remediation will be sufficient. Where required, barriers can either prevent the movement of contaminants or restrict the movement of fluids before they pick up the contaminants. Impermeable caps are typical restrictive barriers that prevent precipitation from leaching through contaminated soil (Figure 100).

Steel casing and “walls” of bentonite, cement, or grout (Figure 101) are typical subsurface barriers to groundwater or vapour migration. Barriers may be part of other treatment technologies. In any event, the effectiveness of the barrier is the critical issue.

Some barriers may react chemically with contaminants, especially NAPLs; therefore, resistant materials must be selected. Perhaps some laboratory compatibility tests will be required. Evaluate the effectiveness of the barrier in preventing water movement shortly after it is emplaced. Refer to the hydraulic performance field testing methods in Subsection 4.8.2. To test, pump from a well inside the barrier and measure the hydraulic response outside the barrier. Remember that the requirements for impermeability of contaminant barriers are usually orders of magnitude more strict than for geotechnical applications because even small amounts of water or vapour leakage is often unacceptable. Most barriers prevent lateral movement. Preventing movement of contaminants downward usually depends on the natural lateral or upward flow of groundwater, and/or on the presence at depth of some naturally low-permeability material. This natural barrier must also be assessed for permeability. Collecting core material for laboratory permeability testing, and conducting pumping tests (with pumping above the barrier and monitoring below the barrier) are suggested.

A pumping well is often operated inside the enclosed area to ensure that groundwater or vapour flow is from outside the barrier into the enclosed area. Under these conditions, only diffusion can move contaminants through the barrier. Measure hydraulic head, inside and outside the barrier, to confirm the desired performance of such a hydraulic control well.

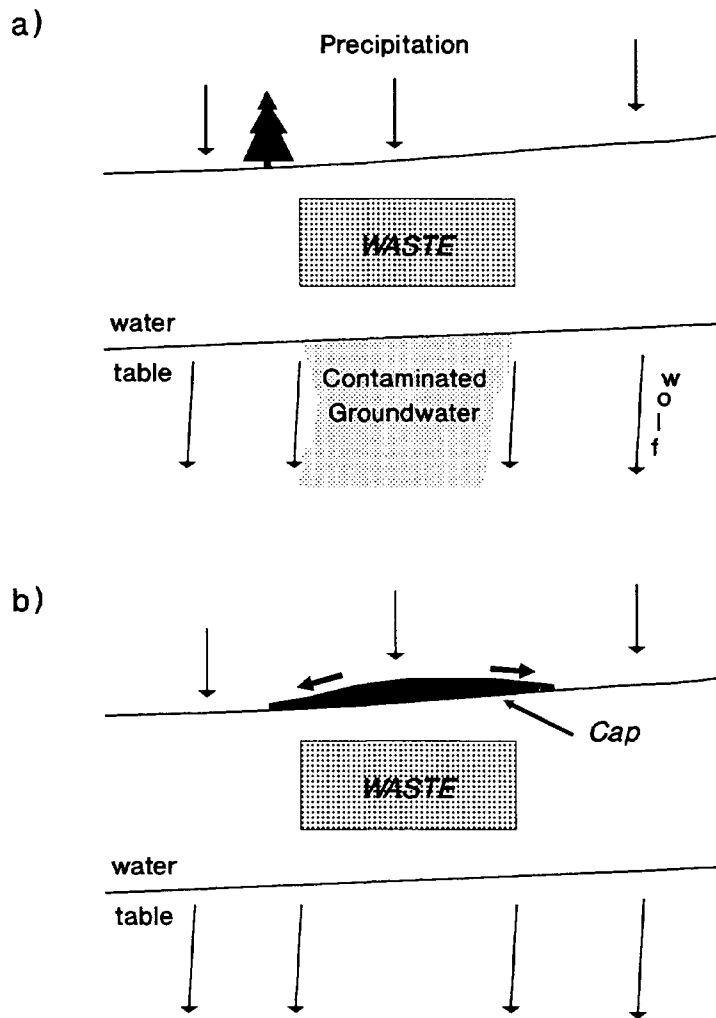


Figure 100 An Example of a Potential Barrier (A Low Permeability Cap): (a) Uncapped Waste with Contaminants Leaching into Groundwater (Section View); and (b) The Cap Prevents Leaching by Diverting Recharge Water Around the Waste

Diffusion through non-metal barriers may provide a pathway for contaminants. Evaluate this possibility using simple models of diffusion, and realistic, but conservative estimates of contaminant concentration within the isolated area. Figure 102 illustrates the type of plume that could develop from diffusion of contaminants through a barrier into an idealized, uniform, porous aquifer. A breach in the barrier would produce a similar, narrow contaminant plume. The contaminants would form such a narrow plume that groundwater or soil vapour monitoring networks would be unlikely to detect the plume. Perhaps a geophysical technique could be used. Consult Section 3 for advice.

Encapsulation. This technology attempts to encapsulate the contaminants directly, reducing their leachability. In one approach, a liquid monomer is mixed with the contaminant, and then a catalyst is injected to polymerize the monomer and to encase the waste chemicals (Sanning and

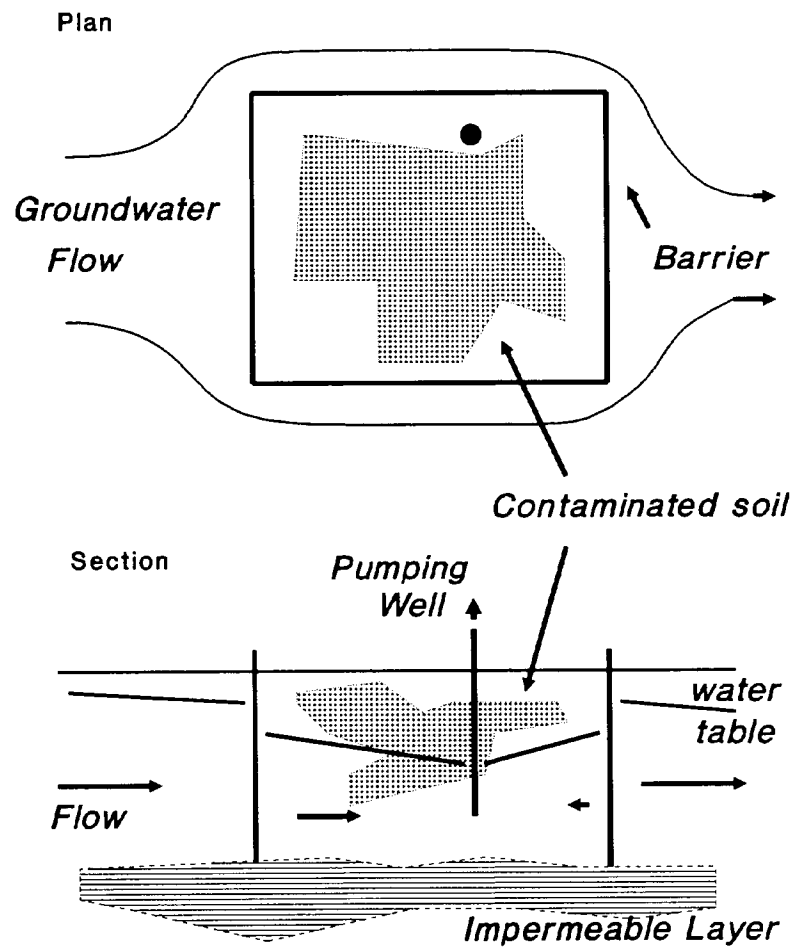


Figure 101 An Impermeable Wall of Steel Casing with an Underlying Impermeable Layer of Natural Material (e.g., Clay). The pumping well ensures that any groundwater leakage occurs inward through the barriers. The pumping well may also extract contaminants for treatment. Plan and section views shown.

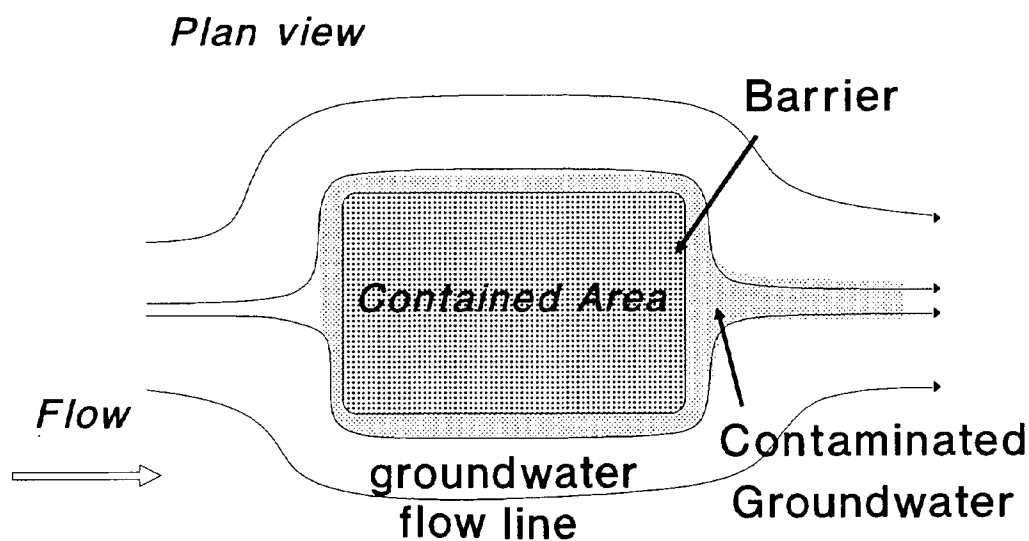


Figure 102 The Development of Contaminant Plumes by Contaminant Diffusion Through the Barrier. This is based on simple modelling of groundwater flow in sand.

Lewis, 1987). This technology may also be termed *in situ* solidification or stabilization. It differs from barrier technologies because the contaminants are encapsulated, not the contaminated area. The critical issues are:

- Did the desired reaction occur to create the encapsulated waste form?
- Did sufficient waste become encapsulated?
- Did the encapsulation reaction produce undesirable products? and
- Is the encapsulated form stable?

The first two issues can be addressed by coring and analyzing representative samples of the treated material. Methods are provided in Sections 4 and 5.

Consider laboratory tests to evaluate the products of the encapsulation reaction. Be prepared to monitor and control fugitive products, particularly vapours. Evaluate the potential for release of toxic encapsulating chemicals, either monomers or catalysts. Also test the stability of encapsulated contaminants in the laboratory. Remember that freeze-thaw cycles can break down the encapsulated wastes and release contaminants to water and/or soil vapours. Identify and evaluate any adverse chemical changes due to leaching of the injected chemicals (e.g., cement/grouts can raise pH to >10). Conduct laboratory leaching tests (e.g., the U.S. EPA Toxicity Characteristic Leaching Procedure TCLP, 1990) to identify leachable chemicals.

Long-term groundwater or soil water/vapour monitoring (Section 5) of readily leachable or volatilizable indicator chemicals is also recommended.

Vitrification. Vitrification incorporates the contaminants into a glassy solid. The critical issues and the recommended approaches for encapsulation apply here. Vitrification may create harmful products (especially gases); therefore, monitoring for such products is recommended.

7.2.3 *Removal for Treatment*

Contaminated groundwater, NAPLs, soil vapours, and soils can be removed and treated on-site or off-site, or disposed in some acceptable manner. Treatment approaches are preferred to methods that simply move the problem.

Product Recovery. Where NAPLs enter the subsurface, most organic contaminants usually remain as NAPL (either free product or residual). Usually LNAPL products are recovered with wells, interceptor trenches, or at surface water discharge points; DNAPLs are recovered in wells; however, with a low rate of success. Critical monitoring issues include:

- How much was present initially?
- How much has been removed? and
- How much remains and in what form (unrecovered but recoverable free product or unrecoverable residual)?

Usually subsurface monitoring is required to address these issues.

Soil gas surveys may help locate LNAPL products; whereas, core material analysis and sampling wells may be useful for locating DNAPLs. Unfortunately, the amount spilled or disposed is rarely known accurately. Initial volume can be measured in wells or in core samples (at least approximately) with the techniques recommended in Subsection 5.4.2. After free product recovery, the same techniques can be used to assess the volume and nature of the remaining NAPL. Collecting and analyzing cores is likely required because geophysical and well sampling methods will not be sensitive to low-levels of residual NAPL. Fractured media may frustrate core interpretation because the NAPL will be concentrated in small volumes of fractures, usually nonhomogeneously distributed in the core.

Groundwater Extraction. Dissolved contaminants are most commonly remediated by the “pump-and-treat” extraction method (Figure 103). Water re-injection wells are not always needed, but are usually used to optimize contaminant recovery. Usually, pump-and-treat is used for containment, rather than for efficient extraction of contaminants, especially if:

- sources of additional groundwater contamination (e.g., continuing leaks, NAPLs, recharge through contaminated soils) remain; and
- contaminants are highly sorbed to the solids (i.e., have high K_d s).

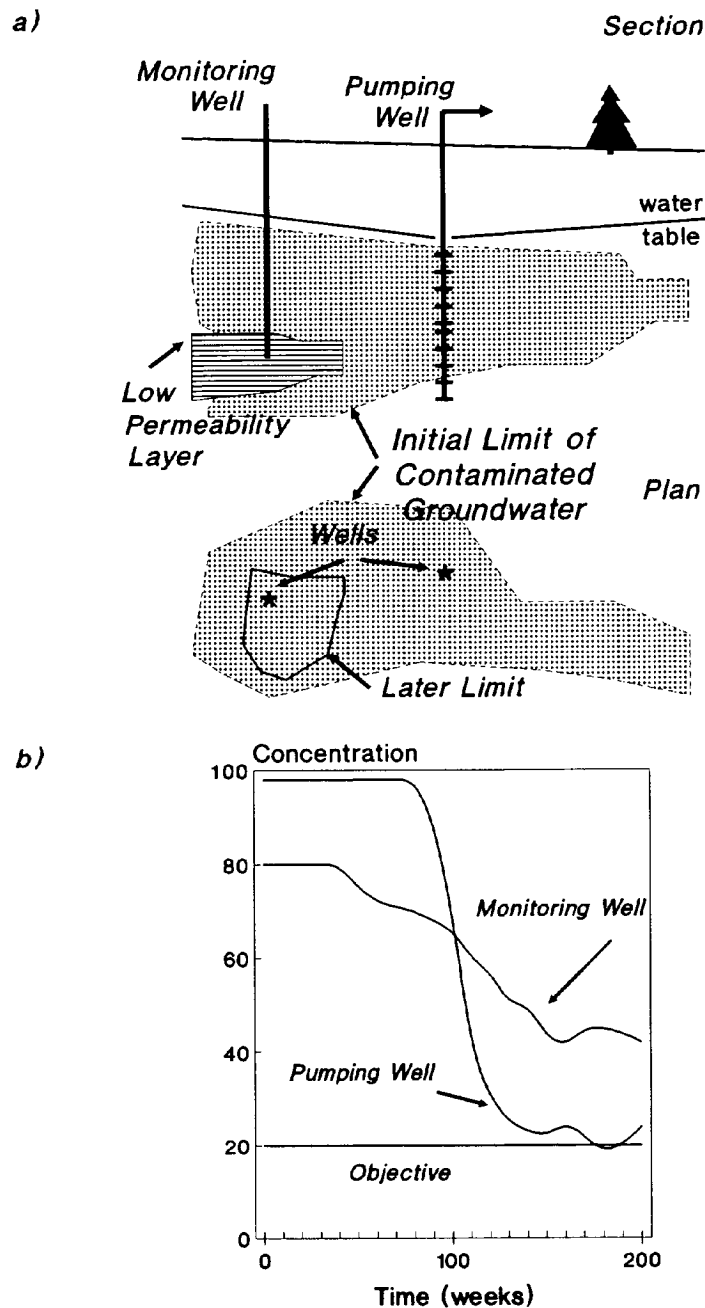


Figure 103 (a) Schematic of a Pump-and-treat System in Cross Section and Plan View Showing Shrinkage of the Contaminated Zone Over Time; and (b) Hypothetical Changes in Dissolved Concentration of a Containment Over Time, Measured from the Extraction Well and from a Monitoring Well Placed in a Lower Permeability Zone. Note that the extraction well concentration reaches the remedial objective; whereas, the monitoring well concentration does not.

Monitor the remediation progress to:

- determine if the extraction system is drawing in all contaminated groundwater; and
- determine the subsurface distribution of contaminants during, or at the end of, remediation.

Locate monitoring wells so that the response of the groundwater flow to extraction can be defined, and the design can be modified to capture the contaminated groundwater. Monitoring of groundwater flow is discussed in Section 4. Modelling (Section 6) is usually used to evaluate the hydraulic performance of the system. Both groundwater flow modelling and particle tracking modelling may be useful when evaluating pump-and-treat remedial success. Groundwater chemical sampling can also confirm the extent of extraction of contaminated groundwater (Figure 103b).

Conduct chemical sampling of the extraction wells to determine when concentrations drop to the point that extraction is no longer efficient. However, do not assume successful remediation when the extracted groundwater reaches acceptable concentrations. If residual sources exist, post-remedial groundwater concentrations will likely rebound. Contaminated groundwater will also persist in lower permeability zones after the more permeable zones have been flushed clean (Figure 103b). The remedial monitoring plan should include monitoring of water quality changes in the less-permeable materials if its continued contamination is unacceptable. Consider sampling less permeable materials using core samples.

Soil Venting. Soil venting is similar to groundwater extraction, but it removes vapours. This method can effectively remove volatile organics from residual NAPLs and even from LNAPL free products. Typically, soil vapours are drawn from extraction wells under vacuum. Air injection, steam injection, or soil heating (by *in situ* radio-frequency heating) can optimize contaminant evaporation (Figure 104).

Vapour monitoring wells must be sampled to determine the initial and final contaminant chemistry and distributions. Section 5 provides guidance. Identify zones of low permeability (e.g., zones of high water content) from which contaminated vapours can only slowly diffuse. These zones will clean up slowly and should be sampled to determine the progress and effectiveness of remediation. Note that vapours in long-contaminated soils (especially those with high f_{OC}) are likely to be difficult to desorb. Analyses that use purge-and-trap methods may greatly underestimate the concentration of volatile organics in the soil. Consider solvent extraction analyses (see Subsection 5.7.1).

Oxygen often enters the contaminated soil during venting. This enhances the biodegradation of certain organics such as monoaromatic hydrocarbons. This remedial mechanism must be considered when attempting to balance the mass of the contaminants initially present with the mass of the residual and extracted contaminants. In fact, bioventing (see Subsection 7.2.4) makes use of this biodegradation process.

In Situ Soil Flushing. Water (perhaps with the addition of solubilizers) can dissolve contaminants and flush them from the soil. Solubilizers include surfactants, complexing ligands

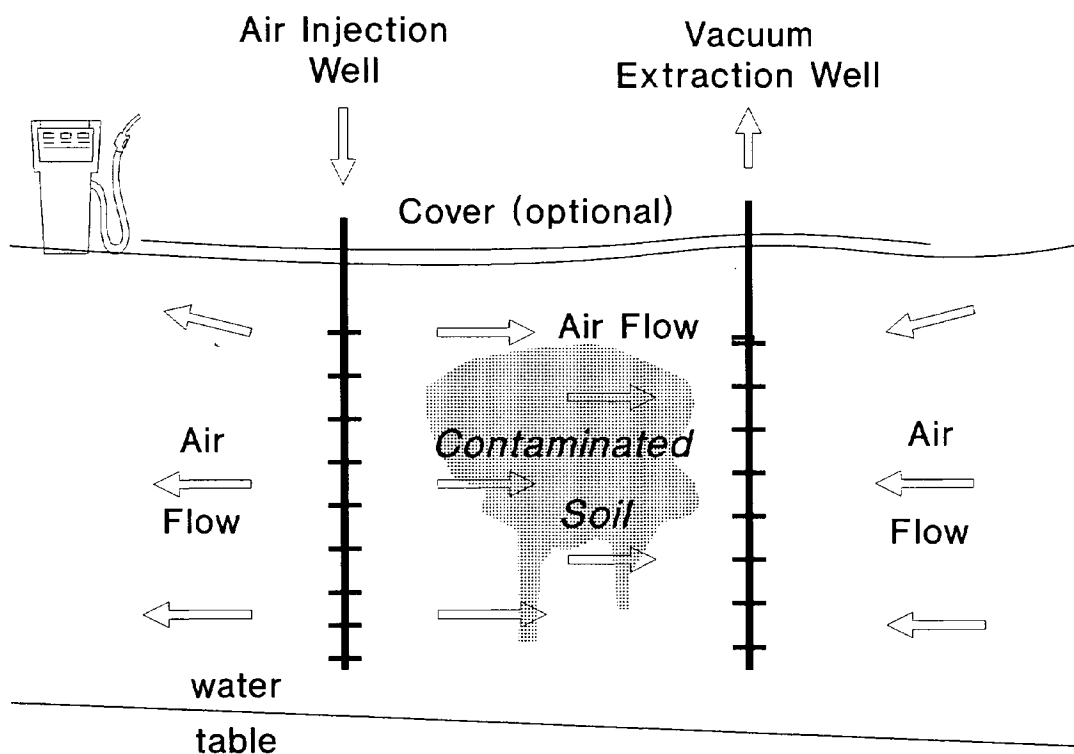


Figure 104 Schematic Section View Illustrating a Typical Soil Venting Operation with Air Injection and Vapour Extraction Wells

(e.g., EDTA and citrate), or water-soluble solvents (e.g., methanol). Pumping wells located below the water table can be used to collect the contaminated water for treatment (Figure 105).

Spatial variation in soil permeability probably causes the flushing solution to miss some of the soil contaminants. Monitoring must evaluate:

- the recovery of flushing water, especially if it contains environmentally harmful additives; and
- the removal and recovery of sufficient contaminant mass to meet the remedial objectives.

Evaluate the hydraulic properties of the soil to identify zones (of low permeability) where contaminants may be missed, and monitor these zones (probably by analyzing core samples). Establish a groundwater monitoring system and sample groundwaters for contaminants and additives to confirm that flushing fluids have been recovered. Consider performing a mass balance of additives (mass added *versus* mass recovered) to evaluate recovery success. Base the success of remediation on detailed soil coring and analysis before and after remediation. Leaching tests (e.g., TCLP, 1990) can help determine when you have mitigated subsequent adverse leaching into groundwater.

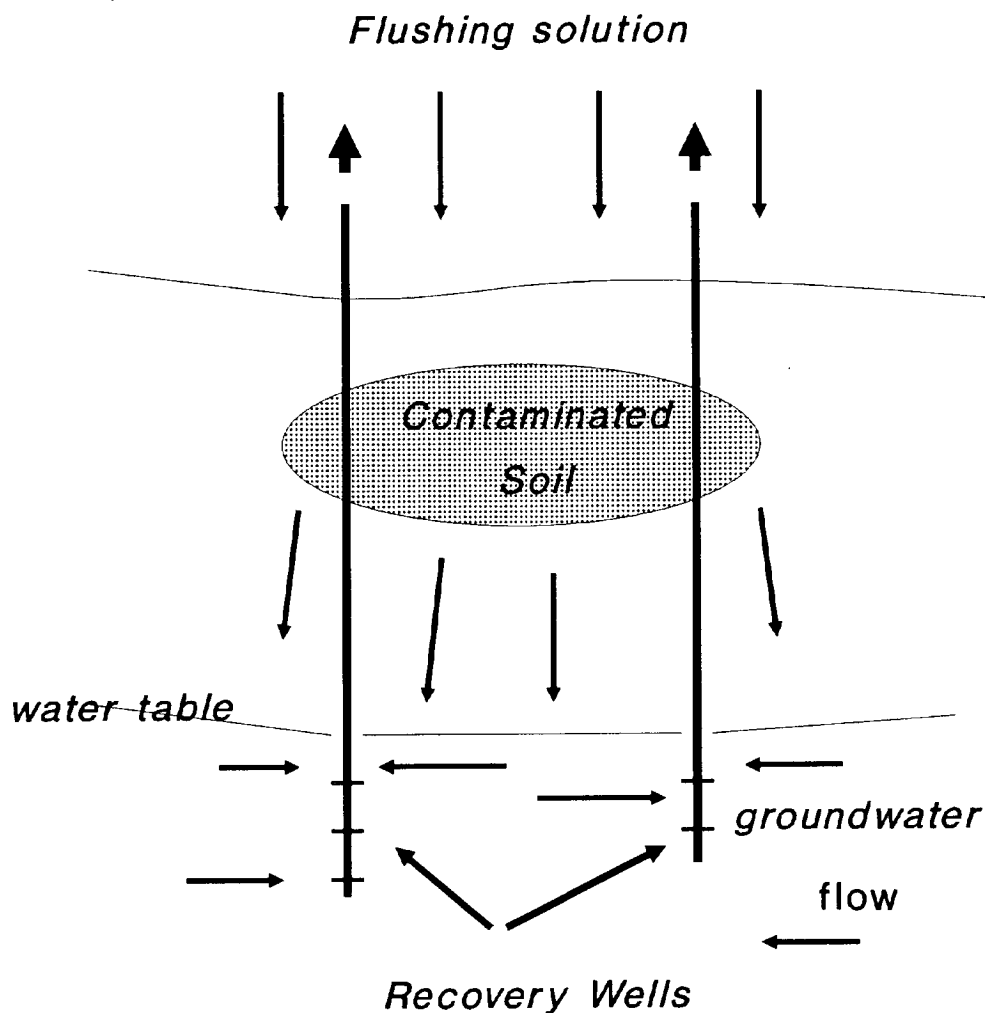


Figure 105 Schematic Cross Section of Soil Flushing Remediation Showing Addition of Flushing Solution and Groundwater Recovery Wells

Enhanced Solubilization. Solubilizers can also be added to groundwater to make sorbed, precipitated or NAPL contaminants more soluble and mobile and allow them to be recovered by groundwater extraction wells. This process is termed enhanced solubilization. Solubilizing chemicals include surfactants, chelating chemicals (e.g., EDTA), and water-soluble solvents (e.g., methanol). The NAPLs can also be mobilized, and displaced to extraction wells, by flooding techniques that are used to enhance crude oil production. For example, steam or solvent chemicals can be added through injection wells. Surfactants, solvents, or steam can mobilize residual DNAPL that, because of its high density, can migrate downward in the saturated zone and deepen the zone of contamination. This situation should be avoided.

The monitoring requirements are the same as for groundwater extraction, but the recovery of the additions must be evaluated. Consider analyzing core samples, as well as groundwater to assess remedial success, especially if target contaminants are strongly partitioned to the solid phase.

Excavation. Contaminated soil is commonly removed to clean up sites. Soil sampling and analysis (Section 5) are required to identify the soil to be removed, and to ensure that the remaining soil meets the remedial criteria. The problem is how to obtain a reasonably limited number of samples that are adequately representative of the site. Access is often restricted and time and budgets are limited. No sampling plan is adequate in general; the problem is site-specific. Expect on-site contaminant distributions to be heterogeneous and not amenable to statistical treatment. Expect “representativeness” uncertainty to far exceed sampling and analytical uncertainties. Only general advice can be offered: design and follow a sampling plan that considers the objectives and practical limitations, and acknowledge that representativeness uncertainty is likely large.

7.2.4 *In Situ Treatment*

In these technologies a significant portion of the treatment occurs *in situ*. Biological and chemical reactions decrease the target contaminant mass, which neither containment nor removal technologies can do.

Bioventing. During soil venting, biodegradation of organic contaminants can occur. Bioventing can enhance this process if organics that degrade under aerobic conditions are being remediated. Petroleum hydrocarbons are the best example.

Monitor as you would for soil venting, but also monitor the biodegradation process. As a minimum, check for decreasing O₂, increasing CO₂, and decreasing volatile organic concentrations in soil gas samples to confirm that biodegradation is likely occurring. To further demonstrate *in situ* biodegradation is at least likely, consider performing *in situ* respirometer tests (Dupont *et al.*, 1991). Remember to also assess non-volatile organics because they may biodegrade. Mass balance approaches may be useful to estimate the amount biodegraded (biodegraded mass = initial mass - residual mass - vented mass), if the required masses can be established by sampling. Madsen (1991) and Major and Cox (1992) provide advice on more extensive testing approaches. However, we do not recommend additional effort to establish the importance of biodegradation because little effort or expense is invested in its promotion.

Analyze soil samples, not just soil gases, for contaminants to satisfy remedial criteria. Remember that contaminated soils retain even volatile organics; therefore, simple purge-and-trap analyses are not reliable.

Landfarming. Landfarming usually involves shallow (<30 cm depth) organic wastes that are biodegradable and perhaps slightly volatile. Landfarming and related technologies (e.g., composting, bioreactors, and aeration piles) can also treat excavated soils on site. Cold temperatures and frozen soil severely limit its application.

For monitoring purposes, treat landfarmed wastes as potential sources of subsurface contamination. Monitoring of landfarming areas should:

- define the potential contaminants in the landfarming area (e.g., wastes, nutrients, especially nitrogen);

- identify and monitor the potential subsurface pathways for contaminants; and
- follow the extent of degradation of contaminants (possibly monitored as simple loss of contaminant, but preferably also defining the volatilization component) to provide assurance that mass loss does not represent loss to the subsurface.

Subsurface assessment methods appear in earlier sections. Most monitoring will be in the soil zone or in shallow groundwater. Use soil gas sampling to detect volatile organic contaminants in the soil zone because these contaminants are more mobile and more reliably detected in vapours than in recharging water. Reliable detection of non-volatile contaminants in the soil zone beneath landfarming operations will likely be difficult and expensive. Therefore, you should monitor groundwaters. However, subsurface contamination may be quite extensive before it is detected in the groundwater, especially if the water table is deep. Drilling through landfarming wastes may cause contamination. Follow the precautions recommended in Subsection 4.5.2. Geophysical methods, especially borehole monitoring techniques (Subsection 3.3.13), may be useful for detecting the depth of migration of high concentrations of ionic contaminants (e.g., chloride). Although the material is shallow and easily sampled, it is rarely homogeneous. Difficulties arise when collecting representative samples to define the contaminant distribution. Use systematic sampling (and combined and homogenized samples) to reduce analytical costs (Section 5). You may be able to reduce sampling numbers by using a random sampling approach and by combining and homogenizing samples. See CCME (1993) and Brunner (1986) for further advice.

In Situ Bioremediation. Chemicals (and sometimes bacteria) are added to groundwaters to alter the subsurface environment to enhance *in situ* biodegradation. Current technology enhances aerobic biodegradation by adding oxygen (and sometimes nutrients) into the subsurface. Some contractors also add bacteria specifically suited to conducting the desired biodegradation. *In situ* bioremediation is usually used on hydrocarbon contamination where both residuals and dissolved contaminants are present. A water recirculation system is usually used (Figure 106a); therefore, biodegradation occurs both *in situ* and on the surface. Nutrients are commonly added to speed up the biodegradation, especially of residual LNAPL. The changes in concentrations from an extraction well, and a monitoring well in low permeability material, are shown in Figure 106b.

When monitoring *in situ* bioremediation, focus primarily on the removal of contaminant and secondarily on establishing the mechanism of removal. Results from extraction wells *alone* provide unreliable evidence of successful *in situ* bioremediation. It is tempting to interpret the declining BTEX concentrations and the increasing O₂ concentrations in the withdrawal well (see Figure 106b) as such evidence. However, the well in the low permeability layer shows that oxygen has not been able to diffuse into the contaminated zone as fast as it has swept through the higher conductivity layer. These zones must be identified and monitored to evaluate the remedial effort. Sampling of these zones with wells may not be appropriate and you may need to collect core samples for subsequent analysis (Section 5). The fate of any added chemicals must also be determined if these chemicals pose a threat to the subsurface environment.

Biodegradation of some organic contaminants can create new, toxic compounds. For example, anaerobic biodegradation of trichloroethylene can produce vinyl chloride, a more hazardous

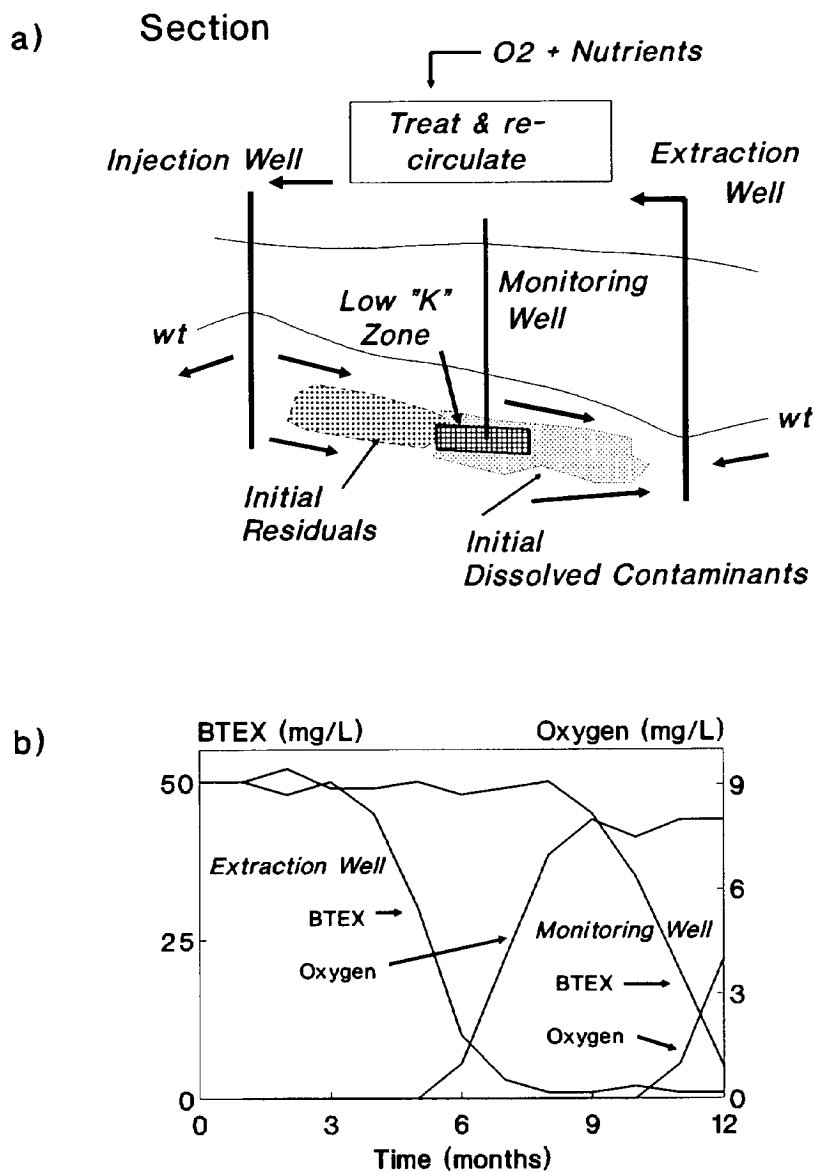


Figure 106 (a) Schematic Cross Section of an *In Situ* Bioremediation Scheme Where Residuals are Present; and (b) Hypothetical Concentrations in Groundwater Recovered from the Extraction Well and from a Monitoring Well in a Less Permeable (Low K) Zone. Note the apparent clean up in the extraction well and the lack of clean up in the monitoring well.

contaminant. Consider reviewing the pertinent biodegradation literature and perhaps performing some laboratory microcosm tests (Section 5.6) to determine which potentially hazardous biodegradation products should be included in the monitoring program.

Resources are often invested in a particular enhancement method; therefore, and the value of that expenditure must be determined. Select parameters to be monitored on a site- and contaminant-specific basis from the detailed reviews provided by Major and Cox (1992) and Madsen (1991).

Air sparging and subsurface volatilization and venting (SVVS) combine aspects of soil venting and bioremediation. Oxygen is sparged upward through the contaminated groundwater and both *in situ* biodegradation and volatilization occur. The volatilized contaminants are collected from the overlying unsaturated zone using vapour extraction wells. Monitoring requirements are essentially the same as for soil venting and *in situ* bioremediation. See Ardito and Billings (1990) for more information about this emerging technology.

Reactive Barriers. Rather than use impermeable barriers, this method uses a “barrier” that is permeable to groundwater or soil vapours and removes contaminants from the water or vapour. This reactive barrier encourages sorption, biodegradation, chemical degradation, or chemical precipitation reactions depending on the specific contaminants and site requirements. Figure 107 illustrates a reactive barrier.

Monitoring must evaluate:

- the interception of the groundwater by the barrier;
- the fate of contaminants and any potentially harmful products; and
- the ability of the barrier to continue to produce the desired *in situ* conditions.

The first issue will require monitoring of the subsurface flow system, specifically to define the fluid flow paths. Typically, water levels in wells will be monitored and mathematical models, especially those capable of tracking particles in the flow system (Section 6), will be used to evaluate the capture of contaminated groundwater. Chemical sampling and analysis should also be conducted to identify fluids that bypass the wall.

For barriers in which chemicals are periodically added through circulating water, assess barrier clogging and the performance of the circulation wells by comparing the flow rate with the hydraulic head measured during injection/circulation.

To evaluate the chemical performance of the barrier, sampling and analysis of fluids (most likely groundwater) is required to establish the distribution of the chemicals before and after the contaminated fluid passes through the barrier. You must also monitor potential products of the reaction to confirm that the reaction occurred and to evaluate the potential production of harmful products. If the barrier contains chemicals required to create the reaction, you must assess the continued presence and activity of these chemicals. Periodic coring and analysis of barrier

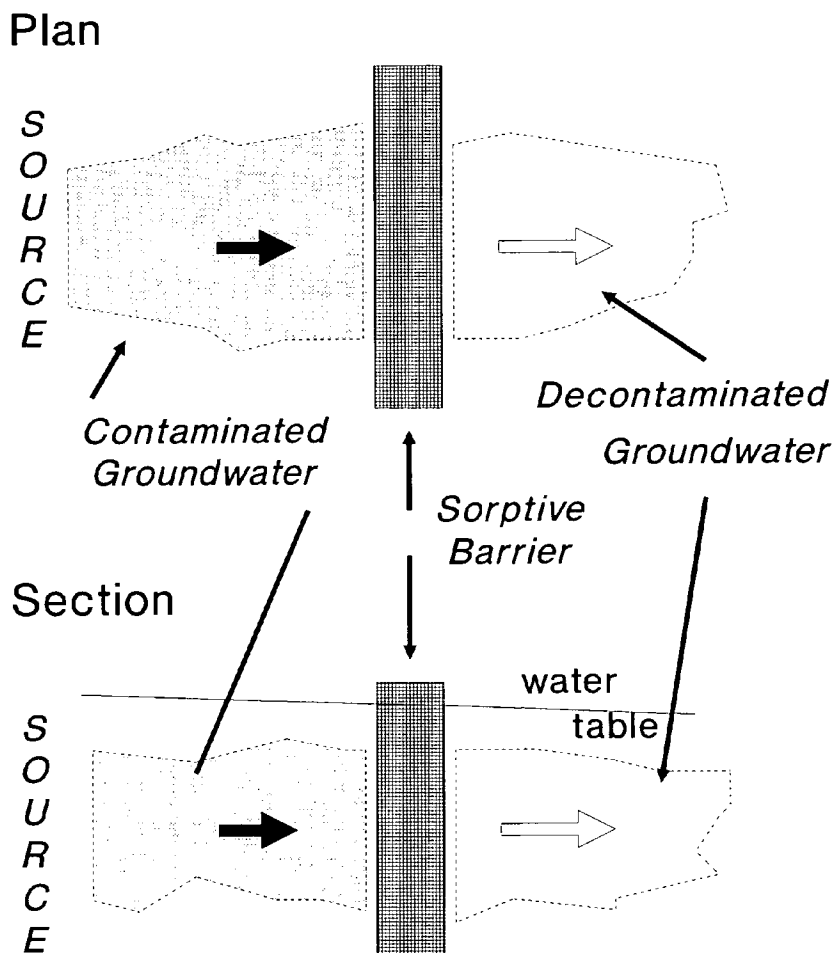


Figure 107 Groundwater Flows Through a Permeable Barrier in which Sorption Reduces Contaminant Concentrations. Plan (top) and cross section (bottom) views.

materials will define the status of the remaining active chemical. This sampling must not compromise barrier performance by adversely altering either the hydraulic or chemical functions. Long-term monitoring may be required if the reactive barrier is to treat the persistent contamination that typically emanates from contaminated sites.

7.3 *Status of Site Remediation*

Current technologies have not been demonstrated to remediate all subsurface contaminants. The DNAPL contaminants are particularly difficult. Give priority to determining if these contaminants are present at the site to ensure that remediation, which is unlikely to meet the remedial objectives, is not unwisely begun. In such situations, you may want to contain or reduce the environmental impacts until emerging, and hopefully more successful technologies, can be employed.

The priority objective of subsurface monitoring during remediation is to assess the reduction of contamination. Also, consider determining whether the technology is operating as planned. These will be the priorities even for new remedial technologies; therefore, the recommended subsurface assessment approaches will apply for new technologies. Use the methods presented in Sections 3 to 6 to meet these objectives, but be aware that subsurface assessment methods, like remedial technologies, are evolving. Practitioners, clients, and reviewers must update approaches and techniques as new information becomes available. Consult journals and seek courses mentioned in the “Additional Information” section of each Section.

7.4 Additional Information

A number of textbooks and reports discuss remedial technologies and include some discussion of subsurface assessments required for design and evaluation. Recommended texts include:

- Electric Power Research Institute/Edison Electric Institute, *Remedial Technologies for Leaking Underground Storage Tanks*, Lewis Publishers, Chelsea, Michigan (1988).
- Lemon, L.A., J.F. Barker, and B. Butler, *Review of Six Technologies for In Situ Bioremediation of Dissolved BTEX in Groundwater*, Report submitted to GASReP, Environment Canada CCIW, 867 Lakeshore Rd., Burlington, Ontario L7R 4A6 (1992).
- Major, D.W. and E.E. Cox, *Information Requirements for the Evaluation of Bioremediation Feasibility and for the Design of Monitoring Programs*, Report submitted to Ministry of the Environment and Energy, Toronto, Ontario (in press).
- Major, D.W. and J. Fitchko, *Emerging On-site and In Situ Hazardous Waste Treatment Technologies*, Pudvan Publishing Co., Northbrook, Illinois (1990).
- United States Environmental Protection Agency, *Site Characterization for Subsurface Remediation*, Seminar Publication, EPA 625/4-91/026, Office of Research and Development, Washington, D.C. (1991).

Articles on subsurface aspects of remediation appear in numerous journals including: *Ground Water* and *Ground Water Monitoring Review* (both published by the National Water Well Association) and *Remediation* (Executive Publications Co., New York, New York). Given the evolving nature of remediation, journals will be an important source of information in the future.

Some suggested reading about specific remediation technologies:

Physical Barriers

- Starr, R.C., J.A. Cherry, and E.S. Vales, “Sealable Joint Sheet Pile Cutoff Walls for Preventing and Remediating Groundwater Contamination”, In: *Proceedings of Conference on Technology Transfer*, Ministry of the Environment, Toronto, Ontario, p. 485–490 (1991).

Groundwater Extraction

- Mercer, J.W., D.C. Skipp, and D. Giffin, "Basics of Pump-and-test Ground-water Remediation Technology", U.S. EPA/600/8-90/003, United States Environmental Protection Agency, Washington, D.C. (1990).
- Haley, J.L., B. Hanson, C. Enfield, and J. Glass, "Evaluating the Effectiveness of Ground Water Extraction Systems", *Ground Water Monitoring Review*, 11(1): 119–124 (1991).
- Mackay, D.M. and J.A. Cherry, "Groundwater Contamination: Pump-and-treat Remediation", *Environmental Science and Technology*, 23: 630–636 (1989).

Soil Venting

- Johnson, P.C., C.C. Stanley, M.W. Kemblowski, D.L. Byers, and J.D. Colthart, "A Practical Approach to the Design, Operating and Monitoring of In Situ Soil-venting Systems", *Ground Water Monitoring Review*, 10(2): 159–178 (1990).

In Situ Soil Flushing

- Abdul, A.S., T.L. Gibson, C.A. Ang, J.C. Smith, and R.E. Sobcznski, "In Situ Surfactant Washing of Polychlorinated Biphenyls and Oils from a Contaminated Site", *Ground Water*, 30: 219–231 (1992).

Enhanced Solubilization

- Palmer, C.D. and W. Fish, "Chemical Enhancements to Pump-and-treat Remediation", EPA/540/S-92/001, United States Environmental Protection Agency, Washington, D.C. (1992).

Bioventing

- Hoeppel, R.E., R.E. Hinchee, and M.F. Arthur, "Bioventing Soils Contaminated With Petroleum Hydrocarbons", *Journal of Industrial Microbiology*, 8: 141–146 (1991).

Landfarming

- Sims, J.L., R.C. Sims, and J.E. Matthews, "Approach to Bioremediation of Contaminated Soil", *Hazardous Waste and Hazardous Materials*, 7: 117–149 (1990).

In Situ Bioremediation

- Thomas, J.M. and C.H. Ward, "In Situ Bioremediation of Organic Contaminants in the Subsurface", *Environmental Science and Technology*, 23: 760–766 (1989).

Reactive Barriers

- Gillham, R.W. and S.F. O'Hannesin, "Metal-catalyzed Abiotic Degradation of Halogenated Organic Compounds (Abstract)", *Ground Water*, 29: 752 (1991).

Numerous short courses, conferences, and workshops deal with remediation and the associated subsurface assessments. For current offerings, refer to journals such as *Ground Water* and *Ground Water Monitoring Review* and newsletters such as:

- *Resilog* (Technology Development Directorate, Environment Canada); and
- *The Association of Ground Water Scientists and Engineers Newsletter* (Ground Water Publishing Co., 6375 Riverside Drive, Dublin, OH 43017).

Contractors and consulting firms usually provide remedial technologies. Their services are advertised in the journals mentioned previously. Remember that remediation technologies are in their infancy. Look for experienced firms that include critical assessments of the remediation in their remediation plan.

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- Bassett, R.L. and D.C. Melchior, "Chemical Modeling of Aqueous Systems: An Overview", In: *Chemical Modeling Of Aqueous Systems*, Melchior, D.C. and R.L. Bassett (eds.), American Chemical Society, Los Angeles, California, ACS Symposium Series 416 (1988).

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