Groundwater Quality Hydrogeological Assessments

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Preface

This report was developed as part of Victoria EPA's hydrogeological guidelines project, which started in 1998 with the engagement of Mr Anthony Lane of Lane Consulting (now Lane Piper) in association with Dr Tamie Weaver of University of Melbourne and Mr John Leonard of John Leonard Consulting Services . This long form of the guideline document was prepared in 1999, but was not published. The current Hydrogeological Assessment (Groundwater Quality) Guidelines (EPA Publication 668, August 2006) is an abridged version and supersedes this document. The published EPA guideline is available at http://www.epa.vic.gov.au/.

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1 INTRODUCTION

1.1 BACKGROUND AND PURPOSE OF GUIDELINES

Groundwater is a vital resource in Victoria. The Environment Protection Authority (EPA) and other authorities recognise the need to protect the quality of groundwater as a resource and as part of the natural environment. Hydrogeological Assessments (HAs) provide the necessary information to determine the status of groundwater quality or the effects of a proposal on the beneficial uses of groundwater. For example, a proponent of a new landfill or industrial development with potential to impact groundwater is likely to be required to perform a HA.

Specifically, the objectives of undertaking HAs for groundwater quality include assessment of the:

- potential of activities to cause groundwater contamination; or
- extent and degree of existing contamination; and
- transport and fate of groundwater contaminants.

The outcome of the HA should provide the basis for decision making.

These guidelines have been developed to provide an overview of HA methodologies, and the reasons for using different investigative techniques. **The guidelines are not intended as a "do-it-yourself" guidebook on hydrogeology or HA procedures. HAs require comprehensive understanding of geology, hydrogeology and hydrochemistry, and should be undertaken by qualified and experienced hydrogeologists**. The guidelines also recognise and reference the substantial body of technical guidance texts available to groundwater professionals and are intended only to provide general information for all stakeholders (general public, regulatory authorities, industry and groundwater professionals) in cases where HAs are required.

The **purpose of issuing these guidelines** is to provide guidance on the execution and reporting of HAs for groundwater quality protection purposes in order to:

1. Provide a consistent and appropriate approach to HA (commensurate with risk).
2. Encourage a consistent approach to HA data presentation (quality and validity).
3. Provide guidance to industry about EPA's requirements in HA.
4. Raise the level of public understanding of groundwater protection and HA.
5. Result in an appropriate level of assessment of groundwater vulnerability, pollution risk and impacts necessary for EPA to make sound decisions.

1.2 GROUNDWATER PROTECTION IN VICTORIA

Groundwater[1] occurs almost everywhere in the subsurface, and not only provides a source of water supply for human consumption, stock watering, irrigation and industrial use, but also discharges to wetlands and streams providing nature's "environmental base-flow" to sustain these aquatic ecosystems.

In Victoria over 50 communities derive their drinking water supply wholly or partly from groundwater – including Geelong, Portland, Sale, Elmore, etc. (Leonard, 1992a). Our significant streams including the Yarra River derive a large proportion of their flow from groundwater, especially between rain periods (Ronan, 1980, Shugg and O'Rourke, 1998).

Groundwater in some areas of Victoria has been contaminated by previous (and some recent) poorly controlled discharge of wastes to the environment. Some of these areas may be designated Polluted Groundwater Zones while others are being restored slowly. Once polluted it is usually very difficult to restore an aquifer to its former unpolluted state.

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[1] See Appendix B for definitions and glossary

The protection of groundwater resources and the quality of these resources are serious concerns to the community and protection authorities including EPA. Consequently, assessments of the existing contamination and potential risks to groundwater quality have become a common requirement of regulatory agencies when developments such as landfills, wastewater disposal or chemical storage facilities are proposed, or approvals for licensing of industrial premises are sought. Assessments of contaminated sites also include HAs.

In response to these concerns, and consistent with the general direction of environmental regulation in Victoria, the Government proclaimed a new State Environment Protection Policy (SEPP) in December 1997 entitled “Groundwaters of Victoria” (Victorian Government Gazette, 1997). This formalises the legal framework of groundwater quality protection in Victoria and identifies the need for systematic approaches to, amongst other activities, hydrogeological assessments.

1.3 WHAT ARE BEST PRACTICE ENVIRONMENT MANAGEMENT GUIDELINES (BPEMG)?

The Best Practice Environment Management Guideline (BPEMG) series outlines essential environmental objectives relevant to particular industries or activities, and provides suggested measures to achieve these objectives. However, operators should feel free to consider alternative ways to meet the objectives and to apply the best site-specific solutions equivalent to, or better than, the suggested measure. Consequently, innovation is not restricted and flexibility is provided. Those seeking greater direction can apply the measures suggested in these guidelines.

The underlying philosophy of BPEMG is to provide a forward-looking approach rather than to simply reflect what is presently the norm.

Implementation of best practice environmental management (BPEM) will benefit the community through sustainable improvements in environmental quality. Industry will benefit through minimising waste, avoiding environmental problems and liabilities, and streamlined management procedures.

Although the BPEMG is not itself mandatory, the potential exists for regulatory authorities to call up such a document in approvals, licenses or permits.

1.4 WHAT IS A HYDROGEOLOGICAL ASSESSMENT?

This section gives a brief outline of the content of a HA. Section 3 provides more detailed guidance.

A **Hydrogeological Assessment (Groundwater Quality)** is a systematic study of geology, hydrogeology and chemistry to evaluate contaminant occurrence and movement, using industry best practice methods.

For the purposes of these guidelines HAs have been separated into those containing only **Desk Studies** and those also containing **Field Investigations**. All HAs commence with a Desk Study, and the scale of Field Investigations will vary depending on the level of perceived risk to groundwater and the existing state of knowledge. Whatever the scope of the HA, it is necessary to do sufficient work to establish a ***Conceptual Hydrogeological Model*** (see Section 3.1.2) of the locality in order to evaluate risks to groundwater quality. The HA would typically evaluate:

- **Site History;** contaminants of concern/potential for contamination eg. contaminant use, site practices and locations of contamination sources, etc.,
- **Hydrogeological Setting;** hydrostratigraphy (single/multiple aquifer system), aquifer type and configuration, groundwater flow directions and rates, existing groundwater quality; vulnerability of the aquifer system to contamination,

- **Beneficial Uses** of groundwater and **potential receptors** (eg. streams, wetlands, bore users, etc.),

If groundwater is contaminated, further assessment is required to evaluate:

- **Movement and fate** of groundwater contaminants,
- **Potential risks** to human health and the environment.

The scope of each HA will need to be site-specific and "risk-based" ie. adjusted to suit the circumstances. HA Desk Studies or Field Investigations may have one of several outcomes, but would generally facilitate management decisions for:

- No further action (i.e. groundwater is unlikely to be polluted and there is no risk of future pollution), or;
- On-going management of groundwater contamination including containment or monitoring, or;
- Further hydrogeological assessment in addition to monitoring and possible aquifer restoration where significant groundwater contamination occurs, or;
- Groundwater clean up to restore or protect beneficial uses of groundwater.

1.5 WHO NEEDS THIS GUIDELINE?

The guideline is intended for use by a wide cross-section of stakeholders. These include:

- **Officers of regulatory and protection authorities** (EPA, DoI, Municipal Councils, DNRE, Community Services, Water Authorities, etc.). To provide guidance to clients and assist the agency to be confident that appropriate assessments have been undertaken to define the groundwater environment of the locality and the risks to groundwater and the wider environment.
- **Site owners/occupiers** conducting or specifying HAs (eg. as part of a Works Approval or licensing application/ requirement, land transfer "due diligence", and contaminated site investigations or in response to EPA Notices or audits). To provide some certainty about the requirements of the regulatory authority and a benchmark for consultants submitting fee proposals.
- **Consultants** undertaking HAs on behalf of site owners/occupiers requiring confirmation of the appropriate scope of HAs.
- **The wider community** with an interest in the protection of the groundwater environment.

1.6 LEGISLATIVE FRAMEWORK

1.6.1 EPA Legislation, Regulation and Policies

The principal legislation, policies and regulations administered by EPA that are directly relevant to groundwater protection in Victoria include:

- Environment Protection Act 1970,
- SEPP Groundwaters of Victoria 1997,
- SEPP Waters of Victoria 1988,
- SEPP Siting and Management of Landfills Receiving Municipal Waste 1991,
- Industrial Waste Management Policy (Waste Minimisation) 1990.

Other guidelines or publications of relevance include:

- SEPP Groundwater - Policy Impact Assessment 1997,
- NEPM Assessment of Contaminated Sites 1999,
- Guidelines for Auditors issuing Certificates of Environmental Audit (s.57AA) EP Act, 1998.

Examples of situations in which EPA may call for a HA under various sections of the Environment Protection Act include:

- Works Approval Applications (s.19B)
- Waste Discharge Licence (s.22)
- Clean Up Notices (s.62A)
- Environmental Improvement Plans (s.31C)

- Pollution Abatement Notices (s.31A)
- Environment Audit (s.57AA)

Local councils may require a HA in support of:

- Septic tank installations permits (s.53M)

SEPP Groundwaters of Victoria

In the SEPP Groundwaters of Victoria, government consolidated the groundwater protection philosophy of EPA and outlined objectives and mechanisms for their attainment.

The SEPP Groundwaters of Victoria:

"The goal of this policy is to maintain and where necessary improve groundwater quality sufficient to protect existing and potential beneficial uses of groundwaters throughout Victoria."

The policy defines five segments of the groundwater environment, based on Total Dissolved Solids (TDS), and assigns to each segment a number of Beneficial Uses (see Section 2 for more details on water quality). The policy recognises that groundwater may have a wide range of uses and that the eight beneficial uses defined may have a wide range of permissible water quality, depending on the particular use. Clause 16 of the SEPP Groundwaters of Victoria (Victoria Government Gazette, 1997) indicates that EPA may require a HA to determine existing or potential groundwater contamination and the resulting risk to beneficial uses of groundwater.

HAs may also be required by other government agencies (see Section 1.6.2) or they may be specified by non-government parties, such as in the case of a financier wishing to define the environmental liabilities of a site.

It must be appreciated that the Environment Protection Act (1970) protects all groundwater in Victoria from degradation, because even the most saline groundwater may play an ecological support role that should be protected.

1.6.2 Other Legislation, Regulations and Policies

Authorities apart from EPA may also have an interest in requesting HAs in the course of implementing other legislation and regulations.

These regulations and circumstances include:

- *Environment and Planning Act 1987:* Local councils have obligations to consider environmental protection, including groundwater, when considering planning applications.
- *Catchment and Land Protection Act 1994:* Regional Catchment Strategies required by Catchment Management Authorities may need to evaluate the impacts of groundwater base-flow on streams.
- *Water Act 1989:* The Rural Water Authorities and DNRE may wish to evaluate diffuse sources of contamination on water resources values: This Act also regulates the drilling of HA bores.

1.7 FURTHER READING

The remaining sections of the guidelines amplify/expand the concepts outlined in this introduction. Section 2 explains some basic hydro-geological concepts and illustrates why HA should be performed by appropriately qualified hydrogeologists. (Experienced hydrogeologists may wish to skip Section 2.) Section 3 elaborates on the HA methodology and process while Section 4 describes the technical methods necessary to obtain key data for HAs. Section 5 describes the information that should be included in a HA report. Section 6 lists the references cited while Appendix A provides further useful reading and Internet addresses.

2 UNDERSTANDING GROUNDWATER AND CONTAMINATION

This section briefly describes the occurrence and movement of groundwater in natural systems and the processes that can lead to groundwater contamination. This is intended only as an introduction to assist non-hydrogeologists to more effectively use these guidelines to engage appropriately qualified hydrogeologists to undertake HAs, and to assist stakeholders to assess and evaluate the results of HAs and to make risk management decisions.

2.1 GENERAL CONCEPTS

Several aspects need to be considered when **evaluating groundwater contamination:**

1) the local geology and occurrence of groundwater,
2) movement of water in the groundwater flow system,
3) the background chemistry (quality) of the groundwater,
4) sources and types of contaminants entering the groundwater system,
5) the movement and fate of contaminants in the groundwater system,
6) the potential risks that groundwater contamination poses to human health and/or the environment **now or in the future.**

2.2 GEOLOGY AND AQUIFERS

2.2.1 General Principles

Understanding the occurrence and movement of groundwater and contaminants starts with an appreciation of general hydrogeological principles in the context of the geology, at a local and regional scale. At a local scale groundwater can occur in the soil, the unsaturated zone and in the saturated zone below the water table. Figure 2.1 shows a generalised view in cross-section of the vertical distribution of water in the ground.

The geology of the area largely determines whether surface water and rainfall can move downward to recharge groundwater. The geology also defines more permeable formations (*aquifers)* that contain and transmit groundwater and non-aquifer formations (*aquitards*) which restrict groundwater flow.

Simplistic diagrams of aquifer systems often show aquifers and aquitards as uniform, usually horizontal, geological units with abrupt interfaces between each. A more realistic but complex flow system is illustrated in Figure 2.2 that shows a cross-section of a groundwater basin flow system with regional, intermediate and local flow cells, groundwater recharge and discharge zones, cross-formation flow between aquifers, and saltwater intrusion in a coastal discharge area. (The length of the system in Figure 2.2 would be of the order of kilometres and the depth about 100 m or more.)

While Figure 2.2 is an idealised representation, aquifers are usually heterogeneous, and their properties often change over relatively short distances. These variations are significant and may result in:

- variations in aquifer permeability (*hydraulic conductivity*) and/or thickness from place to place;
- variations in the density and direction of fractures in fractured rock aquifers;
- gradational boundaries between overlying and underlying formations; and
- a variable degree of natural protection provided to deeper aquifers. Aquitards do not always provide protection to underlying aquifers.

These factors have significant consequences for the transport and ultimate fate of contaminants, and therefore the impacts on beneficial uses of groundwater.

There are many different types of aquifers and classification systems, however the principal divisions are based on:

a) Type of porosity:

- porous rock aquifers with inter-granular ground water flow (eg. sands in the Brighton Group),
- fractured and jointed rock aquifers (eg. basalt in the Newer Volcanics or sandstone, mudstone and siltstone sequence in the Silurian bedrock), or solution channel aquifers (eg. Port Campbell Limestone).

b) The degree of groundwater confinement:

- water table (unconfined) aquifers with the top boundary in connection with the atmosphere (see Figures 2.1 and 2.2) or,
- confined and semi-confined aquifers with an overlying aquitard (see Figure 2.2).

The important hydraulic parameters in assessing a groundwater system include:

- permeability (k) or hydraulic conductivity (K),
- aquifer thickness (b) or saturated thickness (h_o),
- hydraulic head distribution (horizontal and vertical),
- storage parameters (S_s, S, S_y), and
- aquifer porosity (n).

From these parameters, groundwater flow velocities and rates can be estimated and modelled.

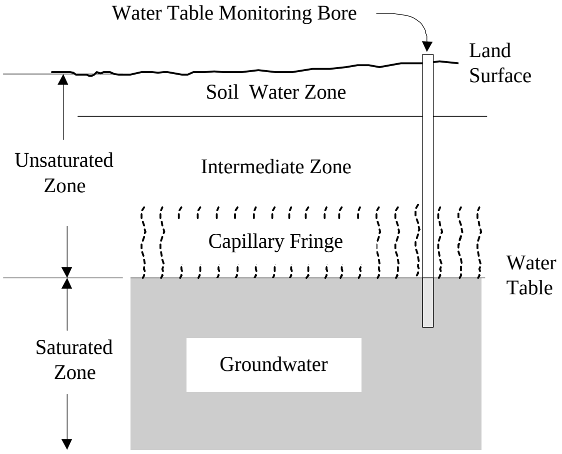

Figure 2.1 Subsurface Water

(Modified after Hazel, 1974; Heath, 1984)

2.2.2 Victoria’s Geology and Aquifers

The hydrogeology of Victoria is relatively complex and a comprehensive description of the main aquifer systems is beyond the scope of this guideline. However, Figure 2.3 shows the principal groundwater basins or provinces. Further information on Victoria’s groundwater basins is presented in Leonard (1992a, 1992b).

2.3 GROUNDWATER FLOW SYSTEMS

Groundwater moves in the landscape under the influence of hydraulic gradients, hydraulic conductivity, and porosity of aquifers and aquitards. Assessment of the pattern and rates of groundwater flow is critical in evaluating the hydrogeology of a region and the transport of contaminants in aquifers. ***"Groundwater flow systems"*** is the term used to describe groundwater movement in all aquifers and aquitards in a region.

Aspects of groundwater flow systems often not appreciated include:

- groundwater levels may vary with bore depth at any location, within or between aquifers resulting in vertical hydraulic gradients;
- all groundwater flow systems have recharge and discharge zones which are often very extensive and occur at different localities;
- groundwater often discharges to streams and wetlands.

Variations in hydraulic conductivity, both within and between geological strata, affect groundwater flow paths and rates and so must be evaluated if assessing contaminant migration pathways (Figure 2.2).

2.4 GROUNDWATER QUALITY

This section provides a concise discussion of natural or background groundwater quality and the beneficial use concept underpinning the SEPP Groundwaters of Victoria.

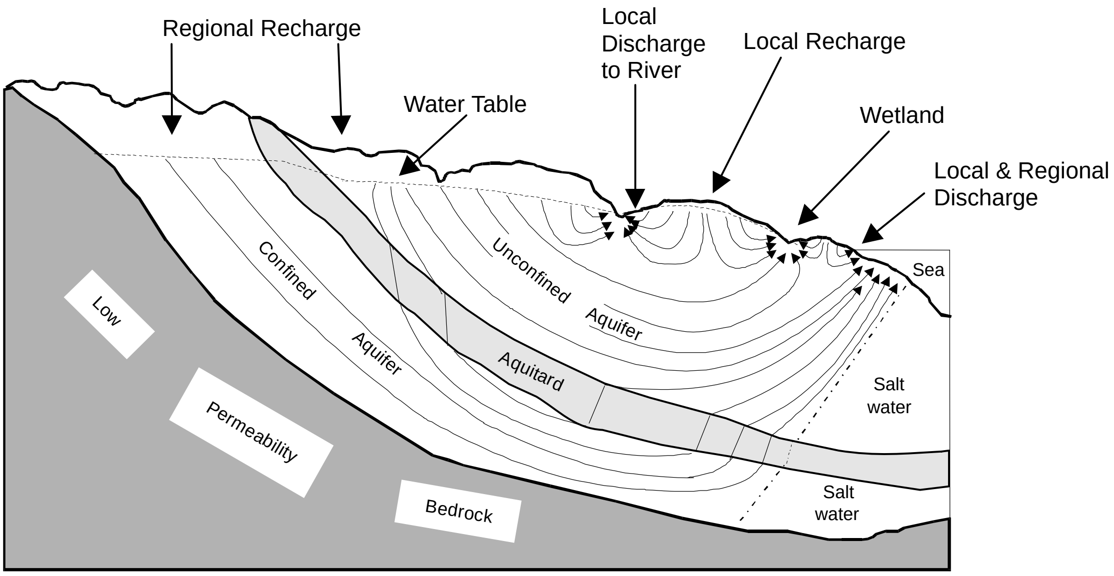

FIGURE 2.2 A cross-section of a groundwater flow system

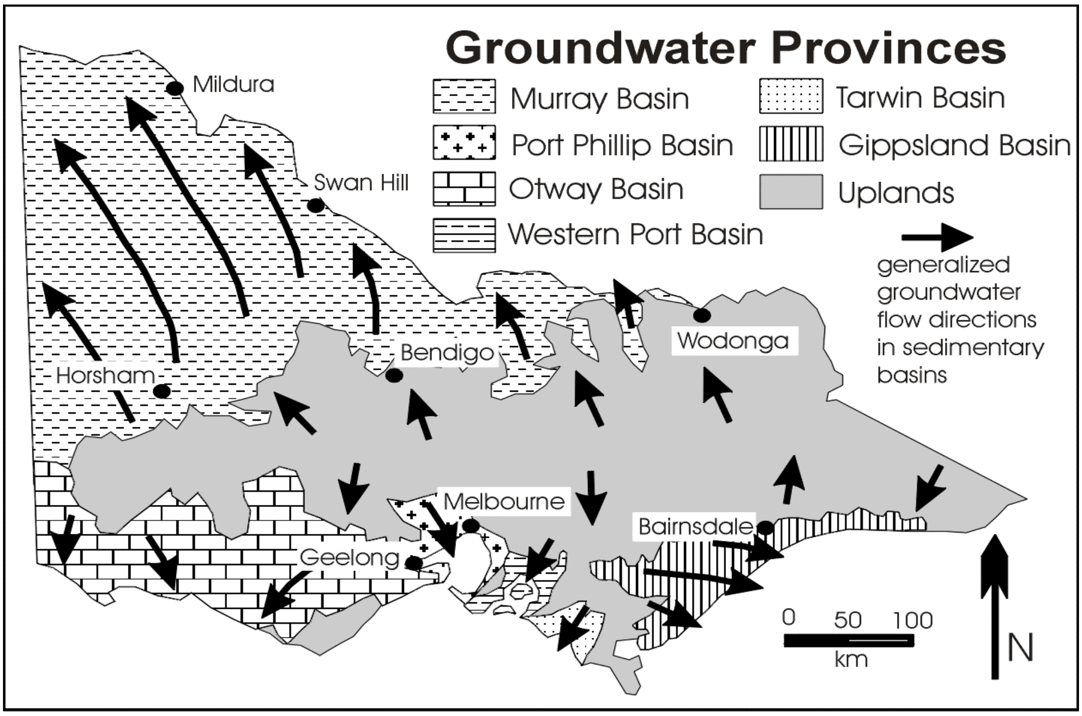

Figure 2.3 Groundwater Basins of Victoria
(modified from Leonard, 1992b)

Knowledge of groundwater chemistry is important in any HA because water quality parameters are required when assessing the background conditions of an aquifer and may also indicate the degree to which an aquifer must be protected from contamination (ie. its beneficial uses). Hydrochemical interpretation is also required in understanding interactions within and between aquifers in groundwater flow systems and between surface processes and groundwater.

While the electrical conductivity (EC) or total dissolved solids (TDS) of groundwater is often used to indicate its quality, several other parameters are needed to fully characterise groundwater quality. These include:

- major ions (calcium, magnesium, sodium, potassium, chloride, carbonate/bicarbonate and sulphate),
- pH, Eh, and dissolved oxygen (DO) which are best measured in the field,
- minor or trace ions and metals (eg. iron).

Some groundwater systems contain unusually high concentrations of metals and minor ions such as nitrate (NO_3^-) from natural sources (eg. Harrington et al, 1998).

The SEPP Groundwaters of Victoria established five segments of the environment and eight beneficial uses that may be relevant to those segments (see Table 2 of the SEPP). Beneficial use maps, based on background TDS, for most of Victoria's water table (unconfined) aquifer systems are available from DNRE. While the SEPP segments are classified by TDS it is recognised in the policy that other water quality criteria may determine the actual beneficial uses appropriate in any particular case (see Table 3 of the SEPP).

2.5 GROUNDWATER CONTAMINATION

Groundwater contamination has occurred widely in many countries and the study of contaminant hydrogeology is well advanced to assist communities to prevent, manage and restore polluted aquifer systems. Common causes and sources of groundwater contamination are listed in Table 2.1. A more detailed listing of contaminants from various sources can be found in Appendix I of Australian Standard AS4482.1 (Standards Australia, 1997).

Contaminant sources may include sudden releases (instantaneous source) resulting from spills or accidents, or gradual releases (continuous sources) as a result of long-term leaks, industrial or agricultural practices. Figure 2.4 shows an example of plumes resulting from continuous and instantaneous releases of contaminants in an idealised (homogeneous and isotropic) aquifer. This shows the growth and movement of the plume with time.

When contaminants enter the groundwater flow system, they tend to spread out (disperse) and often move more slowly than the groundwater. Their migration is determined by factors including; hydraulic gradient, hydraulic conductivity and porosity of the aquifer, physiochemical properties of the contaminants, and reactions between the contaminant and the aquifer.

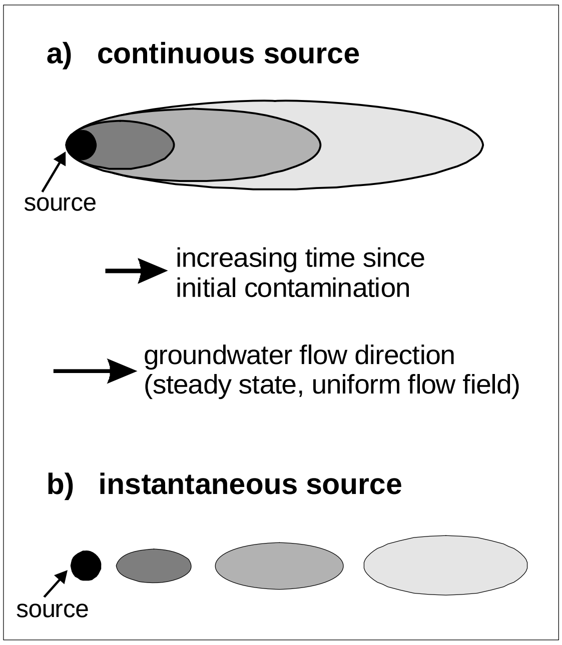

Figure 2.4 Contaminant Plumes in Plan View

Table 2.1 Sources of Groundwater Contamination

Sources /Industry	Activity	Typical Contaminants
Solid waste management	Waste landfill	Nitrate and ammonia, sulphate, chloride, metals and petroleum hydrocarbons
Liquid waste treatment	Storage and treatment of hazardous wastes	Wide range of organic and inorganic chemicals including metals, monocyclic aromatic hydrocarbons (MAHs), petroleum hydrocarbons, chlorinated organics, PCBs, strong acids and bases
Town gasworks (coal gasification)	Former sites of coal-gas manufacturing	Ammonia, polycyclic aromatic hydrocarbons (PAHs), monocyclic aromatic hydrocarbons (MAHs), cyanide, phenols and metals
Petroleum and transport	Petroleum storage and distribution	MAHs, petroleum hydrocarbons
Manufacturing and chemical industry	Storage of chemicals and wastes	Wide range of organic and inorganic chemicals (see Appendix I of AS4482.1)
Agriculture/horticulture	Pesticide mixing and application; fertilising	Pesticides, solvents, nitrate and ammonium, phosphorous and potassium
Food processing	Solid and liquid waste handling and disposal	TDS, nitrogen and bacteria
Mining and mineral processing	Mine tailings disposal, acid mine drainage	Metals, surfactants, hydrocarbons, radionuclides
Contaminated surface water	Wastewater treatment, polluted stream	Nitrogen, bacteria, virus; wide range of chemicals
Water and wastewater	Sewage treatment and disposal	Nitrate, ammonia, phosphorus, pathogenic microorganisms, metals, and ammonium.

See Appendix I AS 4482.1 (Standards Australia, 1997) for a detailed listing of contamination sources.

Contaminants may also be lost or transformed from the contaminant plume as a result of:

- Biodegradation of the contaminants (such as breakdown of petroleum hydrocarbons),
- Chemical reactions that transform the contaminant,
- Volatilisation of the contaminant to the gas phase,
- Decay of radioactive contaminants.

The original contaminant may be present in a plume in lower concentrations due to the above processes. However, “daughter” products, especially in the case of biodegradation or radioactive decay, may have formed producing “new” contaminants with different (sometimes more toxic or more mobile) properties. For example, the daughter products radon and vinyl chloride derived from radium and trichloroethylene respectively, are more toxic than their precursors.

Contaminants with low water solubility can also be present in sufficient concentration that they occur separately (undissolved) in water. These are called non-aqueous phase liquids (NAPLs) and can be lighter (LNAPLs; eg. petroleum products, etc.) or denser (DNAPLs; eg. chlorinated solvents, PCBs, etc.) than the groundwater in which they occur. The typical behaviour of LNAPLs is illustrated in Figure 2.5 and DNAPLs in Figure 2.6. It should be noted that the direction of migration of DNAPLs may be different to the direction of bulk groundwater flow (Figure 2.6). Note also the gas and dissolved phases associated with LNAPL and DNAPL plumes.

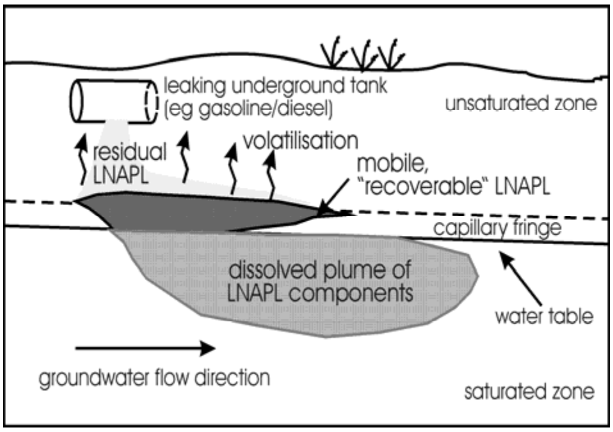

Figure 2.5 Light Non-Aqueous Phase Liquid (LNAPL) (After Fetter, 1993)

Groundwater contaminated with LNAPLs or DNAPLs requires extreme care in assessment, monitoring, and remediation, and is not fully addressed in this guideline. The occurrence of NAPLs will be discussed briefly to the extent necessary to inform stakeholders, particularly land owners/occupiers, of the need for specialized investigation techniques and assessment by qualified professionals.

It should be noted that EPA considers NAPLs to be “uncontrolled sources”. These should be removed, to the extent practicable, unless it can be demonstrated to the EPA’s satisfaction that they do not pose a risk to the beneficial use of groundwater.

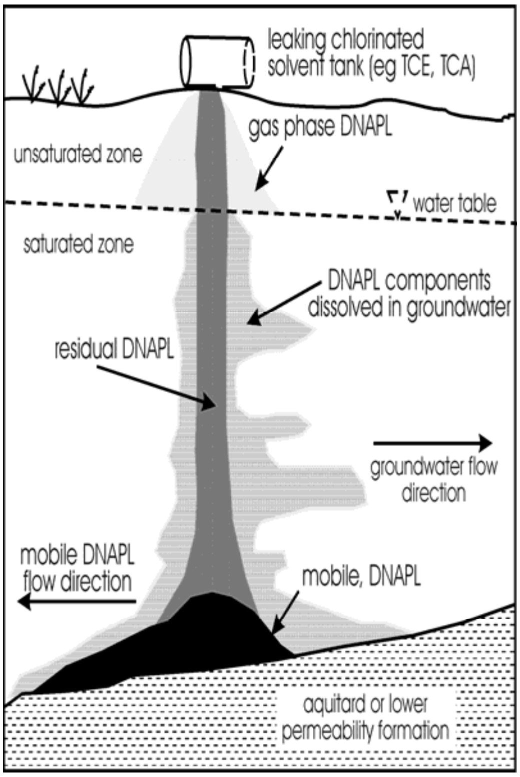

Figure 2.6 Dense Non-Aqueous Phase Liquid (DNAPL) (After Fetter, 1993)

2.6 AQUIFER VULNERABILITY AND IMPACT ASSESSMENT

Some aquifers are more vulnerable than others to contamination originating from the land surface. For example, a permeable aquifer with a shallow water table is more vulnerable to a surface contamination release than an aquifer with an overlying clayey soil or a confined aquifer.

All aquifers, regardless of their vulnerability with respect to surface contamination, are at risk from intentional or accidental contamination via subsurface structures such as bores (mine shafts are classified as bores under the Water Act 1989); the EPA generally prohibits disposal of wastes down bores. The exchange of groundwater from different aquifers via poorly constructed boreholes can also cause contamination of groundwater if one of the aquifers is contaminated. Industry “best practice” procedures should be used in drilling, installing and/or abandoning HA bores (see Section 4).

The culmination of HAs, where contamination is identified, should be an impact assessment (or a qualitative risk assessment) that evaluates the significance of the contamination (see Section 3.3.9).

3 COMPONENTS OF HYDROGEOLOGICAL ASSESSMENTS

HAs can be short and simple or more lengthy and complex studies, depending on the extent of groundwater contamination and the risks of environmental impact. However, all have common components and a common methodology is proposed in this section of the guidelines.

3.1 SCOPE AND AIMS OF HYDROGEOLOGICAL ASSESSMENTS

3.1.1 Aims and Objectives of HAs

Hydrogeological assessments vary both in their general scope and detail, however, the reasons for undertaking a HA include assessment of the:

- potential for activities to cause groundwater contamination;
- distribution and concentration of existing contamination; and
- transport and fate of groundwater contaminants.

Another fundamental aim of a HA conducted for the purposes of an environmental audit of contaminated land (under s.57AA of the Environment Protection Act 1970) is to determine whether or not groundwater is likely to be polluted at a site, or off site. (While "contamination" is a general term defined in the attached glossary, "pollution" is defined in s.39 of the Environment Protection Act (1970).)

Before any assessment begins, clear objectives must be developed. The specific objectives of any particular HA are dictated by the nature of the problem and the local conditions. The level of detail of any assessment will depend on the level of risk posed to a groundwater system: where the perceived risk is high, a more detailed HA may be justified. The risks to groundwater depend on the types of contaminants at a site, the vulnerability of the aquifer to contamination, the complexity of the hydrogeology, proposed future activities at the site and existing and potential beneficial uses of groundwater.

3.1.2 Conceptual Hydrogeological Model

A fundamental prerequisite for a competent HA is the early development of a ***conceptual hydrogeological model.*** The term ***model*** is used for any representation of a real system. Examples include physical models such as sand boxes (scaled down versions of the physical system), mathematical models (analytical or numerical), and conceptual models.

A **conceptual hydrogeological model** represents the geological framework and the movement of groundwater and contaminants within that framework. A conceptual model includes descriptions of the aquifer/aquitard distribution and properties, and explains the groundwater flow and contamination migration pathways. It also includes an explanation of the interactions between surface water and groundwater. Potential receptors (eg. users of a bore or a local wetland receiving groundwater inflow) may also be identified in the conceptual model. The conceptual hydrogeological model should be developed early in the HA and modified as more information becomes available.

3.1.3 General Method of HA

The key components of any HA and the relationships between them are presented as a flow-chart in Figure 3.1.

These guidelines propose a simplified approach to HA which includes two main activities common to most HAs, a ***desk study*** and ***field investigation(s)***.

The conceptual hydrogeological model should be established during the desk study and refined as further data are collected during the field investigation phase, if required. The lack of a cogent conceptual hydrogeological model implies the need for further work to establish such a model.

The following section provides a discussion of the different scales of hydrogeological investigation that may be required to adequately assess the hydrogeological conditions at a site.

A summary checklist for the contents of HAs is included in Appendix C.

3.2 HYDROGEOLOGICAL DESK STUDY

All HAs require some form of Desk Study. This provides a review of current and historical information on a site as well as a review of any hydrogeological data that are relevant to the assessment.

The initial outcome of a **Desk Study** is generally a conceptual hydrogeological model of the site, sufficient to answer the question ***"Is the risk to groundwater quality acceptable?"***. If there is no contamination or the contamination represents no risk of pollution then no further work is justified.

3.2.1 Site History and Review of Existing Hydrogeological Information

Reviewing existing information can provide an indication of the potential for groundwater contamination, even if no site-specific hydrogeological data are available.

Critical components of a Desk Study include:

- Identify current and past land uses and operations including chemical storage and use, effluent disposal, water supply, and waste disposal practices.
- Identify current and past impacts on the land including quarrying, filling, dredging, mine shafts, and abandoned and lost bores.
- Review existing geological and hydrogeological information and describe local hydrogeological conditions such as aquifers and aquitards, depth to groundwater, and background groundwater quality.
- Identify the beneficial uses of groundwater and surface water in the vicinity of the site.
- Identify any current users of groundwater or surface water and the type of water usage.
- Identify any sensitive environmental factors such as rare flora or fauna or sensitive adjacent land such as wetlands, and sensitive adjacent land uses such as schools, residences or market gardens.

Useful sources of information for developing a site history include:

- aerial photographs (available for the 1940s onward in the Melbourne region);
- records and reports from government agencies (including local government);
- anecdotal information from current or previous site owners or operators, employees, and local residents;
- historical records available from local libraries and historical societies;
- topographic, geological and hydrogeological maps and reports;
- groundwater information, including water quality data, the State Groundwater Data Base (www.dce.vic.gov.au/dnre/grndwtr…).

Preliminary Site Inspection and Field observations

In addition to the site history and review of existing hydrogeological information, the Desk Study may include a preliminary inspection of the site. This provides an opportunity to further refine the conceptual hydrogeological model and to assess the likelihood that groundwater at a site has become contaminated. Inspections typically involve:

- Hydrogeological reconnaissance mapping (see Section 4.3).
- Identifying current land uses and any evidence of filling or dredging.
- Identifying of potential sources of contamination not evident in documentation.
- Locating any existing or abandoned bores.
- Identifying potential receptors of groundwater flow, runoff, or surface water such as rivers, wetlands, shafts, old bores, etc.

If bores have existed on the site, bore logs and any hydrogeological data should be obtained and used in the discussion of site hydrogeology. Bore logs should be included in the desk study report. Water levels should be measured if possible. If no further hydrogeological assessment is to be carried out at the site, a program for bore restoration and maintenance may be required or bores should be abandoned according to regulations. (see Section 4.3.9).

Outcome of Desk Study

The Desk Study should either result in a HA Desk Study report (see Figure 3.1) or provide input to the work plan for the field investigation. If no further investigation is necessary, the Desk Study report should incorporate the site history and site inspection information, a conceptual hydrogeological model and a defensible argument that groundwater is not contaminated or polluted and is unlikely to become so.

If a conceptual hydrogeological model cannot be developed due to a lack of data, or if groundwater at the site is suspected of being contaminated or of becoming contaminated in the future, then a hydrogeological Field Investigation is necessary.

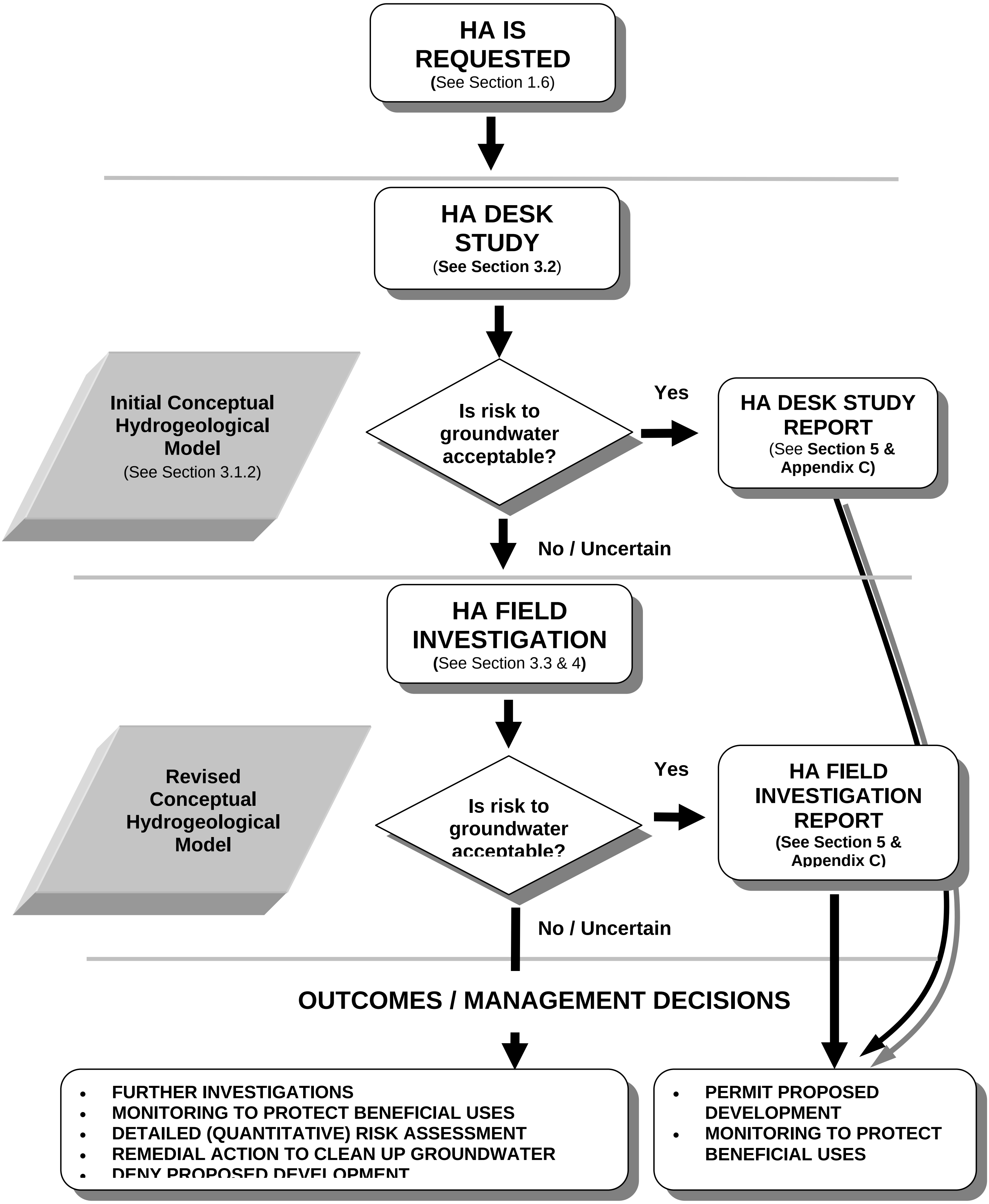

Figure 3.1 Flow Chart of Hydrogeological Assessment Process

3.3 HYDROGEOLOGICAL FIELD INVESTIGATION

The results of the Desk Study provide the basis for designing hydrogeological field investigations. Hydrogeological field investigations provide the opportunity to obtain site-specific and problem-specific data.

> The scale and detail of the field investigations will vary depending on the hydrogeological setting, the type of problem being addressed, and the overall risk that the contamination at the site may pose to groundwater and the surrounding environment.

3.3.1 Field Investigation Work Plan

Before any assessment begins, clear objectives and a work plan must be developed. The work plan should account for special physical features at a site and for the characteristics of the contaminants of concern. Specific issues to be addressed include (CCME, 1994):

- Suitability of the overall approach to the site.
- Suitability of non-drilling monitoring techniques.
- Compatibility between suspected contaminants and proposed monitoring bore construction materials.
- Suitability of drilling and monitoring bore installation techniques.

All drilling, sampling and monitoring should be carried out to avoid expanding the contaminated zone. Specific situations requiring great care are where DNAPLs may be present and where there is potential for cross-contamination of aquifer zones and water samples.

Field investigation at industrial sites and/or in urban environments can present logistical problems. Access may be difficult, and noise, dust, water, and mud must be carefully controlled. Underground utilities and overhead power lines must be accurately located prior to drilling. Disposal of drilling fluids and cuttings, site cleanup, and bore headwork completion require special attention. Special permits or agreements may be required to discharge or dispose of water collected during sampling and/or aquifer testing into the sewer system or to stormwater drains. Highly contaminated groundwater may need to be treated before disposal.

The project work plan or quality plan should specify:

- Project purpose and objectives.
- Project management and personnel.
- Site details and access.
- Drilling and bore construction plan.
- Groundwater sampling and testing plan.
- Field records.
- Reporting standards or requirments.

> The field investigation can involve drilling into potentially hazardous materials. As with all field work, **Occupational Health and Safety** considerations are of paramount importance and should be considered fully when designing and costing the field investigation.

The conceptual hydrogeological model developed during the desk study must be verified in the field, or must be refined to reflect actual site conditions. This is usually accomplished by (CCME, 1994):

- Obtaining sufficient subsurface information to characterise the site geology and to identify strata that act as aquifers or aquitards (hydrostratigraphic analysis).
- Measuring water levels (to estimate hydraulic head distribution) within the saturated zone to determine the actual rate and direction of groundwater movement in the subsurface.
- Collecting and analysing groundwater samples to map the lateral and vertical extent of groundwater chemistry and contaminants within the groundwater flow system.

3.3.2 Installing Groundwater Monitoring Bores

The objectives of the field investigation are achieved by intercepting the contaminant plume in bores, and sometimes by indirect geophysical methods. Bore installation and groundwater sampling programs are crucial aspects of the field investigation phase. Section 4.3 provides details on the techniques of bore installation.

Information gained during initial drilling and monitoring can be used to establish lateral and vertical variations in groundwater elevations and chemistry, the occurrence of NAPLs, and the configuration of the subsurface geology. This will also help determine the locations, depths, and screen settings (depth and length) of additional bores. The possibility of retaining bores for long term monitoring should also be considered when designing a bore network. All bores that are not maintained must be properly abandoned (see Section 4.3.9).

> Great care must be taken when drilling into deeper aquifers. A “golden rule” of field investigations is to **not make the contamination worse** by introducing pathways from the surface to groundwater or between different aquifers. Particular care is required where NAPLs are suspected.

In the first stages of a field investigation, monitoring bores would generally be:

- shallow (at or near the water table) and close to the contamination source(s),
- screened within the same aquifer, usually the water table aquifer,
- installed using similar construction techniques to minimise sources of variation in the monitoring data.

A more comprehensive drilling program may be needed to investigate the unsaturated zone, monitor multiple aquifers or monitor different depths within one aquifer depending on the nature of the problem and the site hydrogeology.

The choice of bore numbers and locations, depths and screen intervals, is site-specific. Hydrogeological site investigations require at least:

- one bore located up-gradient of the site to indicate the water quality entering the site;
- two to three bores to monitor the aquifer located near, but down-gradient of, the contaminant source;
- recording all relevant data during drilling and preparation of detailed bore logs describing the geology, contamination observations, water intersection and levels, and soil sample intervals;
- recording bore construction details for all completed and failed bores;
- level survey of the top of casing and ground surface to be incorporated in the bore log information.

Although three bores may often be sufficient to indicate groundwater flow directions, if groundwater mounds or sinks are present, using only three bores can provide a false picture of the flow system (Figure 3.2). More bores may be required even for an initial

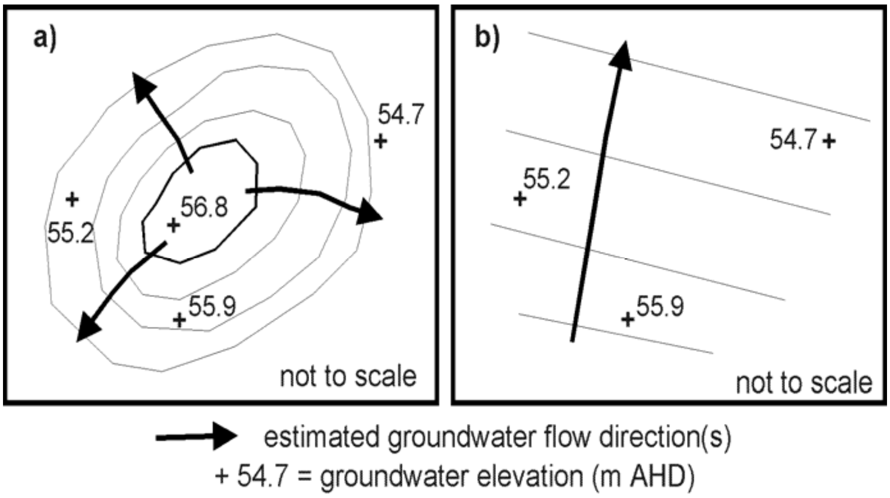

Figure 3.2 “Three Bore Problem”

Predicted water level contours with a) four and b) only three bores.

investigation particularly where the extent of a contamination plume is to be delineated.

The depth of each bore and the location of its screened interval can be critical. **Figure 3.3** shows how the vertical distribution of contaminants can affect the validity of some monitoring bore results. While all four bores in this example are down gradient of the source, bores C and D would not intersect the plume. Bore A would cause mixing of uncontaminated and contaminated water, but bore B would more accurately characterize contaminant concentrations in the plume.

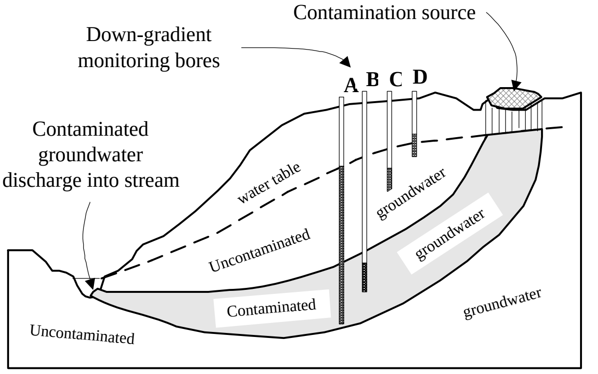

Figure 3.3 Bore Design and Location Affect Results

3.3.3 Aquifer Testing Program

In all but the most basic of HAs it is necessary to obtain data on the hydraulic properties of the aquifer system unless such data already exist.

Knowledge of aquifer hydraulic properties is necessary to estimate groundwater flow velocities, flow volumes, and travel times. This becomes more critical in cases where computer modelling is used. Section 4 discusses available aquifer testing techniques in more detail.

It may be necessary in more detailed site investigations to obtain undisturbed samples of the aquifer and aquitard material to measure mechanical and chemical properties of the material. A wide range of physio-chemical properties can be determined in this way (eg. bulk density, porosity, permeability, cation exchange capacity, distribution coefficient, etc.).

3.3.4 Groundwater Level Measurements

Groundwater level measurements are essential to determine groundwater and contaminant flow directions and rates within aquifers. Depending on monitoring bore design and location these measurements can provide information on lateral and/or vertical head distribution and hydraulic gradients within individual aquifers and between aquifers in layered aquifer systems. Long-term groundwater monitoring programs provide information on the temporal responses of groundwater levels and therefore flow directions and rates, due to the effects of drought, high rainfall events, and groundwater pumping.

Some important factors to be considered when collecting and evaluating water level data include:

- water levels in new bores may take some time to stabilise after installation and development (in low permeability formations this may require several days or longer);
- levels need to be measured relative to ground level and reduced to a common datum (usually AHD);
- all water levels should be measured on the same day (time should also be recorded);
- in some environments (such as tidally affected areas or areas with extensive groundwater pumping), water levels may fluctuate rapidly, and frequent (hourly) measurement may be required. Where levels are affected by pumping, tides, etc., data on these stresses are required to interpret the levels and can provide information on aquifer hydraulic properties.

3.3.5 Groundwater Sampling and Testing Program

These guidelines do not provide detailed guidance on groundwater sampling protocols. **Separate guidelines are being prepared by the EPA**. However, several aspects relevant to planning a HA are discussed.

The scope of the water quality sampling and testing program will depend on whether the purpose is to identify background groundwater quality or specific groundwater contaminants, or both. The design of the sampling and testing program should consider;

- the type of contaminants being analysed,
- the design of the boreholes,
- the hydraulic conductivity of the monitored zone, and
- the logistics of disposing of contaminated groundwater.

Background water quality information is required for all HAs. The background water quality data must include TDS and pH, and should include major and minor ions (eg. Ca, Mg, Na, K, Cl, HCO_3^-, SO_4^{2-} ± NO_3^-, NH_4^+, Fe, CO_3^{2-}, H_2S^-, etc.). In addition to background water quality data, the HA should include a sampling program targeting specific contaminants and degradation products identified in the Desk Study.

All sampling programs should include field measurements of parameters including electrical conductivity (EC), temperature, pH, Eh, and dissolved oxygen (DO). Field observations should always be made during sampling to indicate sample odour, colour, turbidity and sheen.

Groundwater monitoring should provide an indication of **water quality within the aquifer** rather than water that has been standing in the bore casing - groundwater must be removed and analysed with minimum physical disturbance, temperature change, and exposure to the atmosphere.

Other considerations in a groundwater sampling of testing programs include:

- **Type and composition of sampling equipment:** Choices include bailers, bladder pumps, inertia-lift pumps, down-hole bladder pumps and peristaltic pumps. The choice depends on the flow rate into the bore, the parameters being analysed, depth to water and the overall water quality of the bore. Common materials employed in sampling equipment include polyethylene, Teflon, and stainless steel. The choice of sampling equipment should be determined based on the contaminants expected to occur in the groundwater.
- **Volume and timing of purging:** Where bore yield is high, it may be possible to pump bores until field parameters stabilise. In some low permeability formations, bores may have to be emptied and then sampled when the water level recovers.

Whichever method is used to **purge** a specific bore, the **same method** should be used **each time** it is sampled. This eliminates a source of error in the data.

- **Identification of sampling, preservation and treatment protocols:** Most groundwater quality parameters require specific treatment in the field such as filtration, acidification, addition of base, or precipitation of sulphides, or will need to be collected in specific bottles and vials. These requirements may vary with field measured water quality parameters, bore construction, and analytical techniques detection limits, so good planning is required significantly before sample collection (see EPA, 1995, Publication 441).

At contaminated sites, the treatment and **disposal of contaminated groundwater** removed during purging and sampling requires care to avoid Occupational Health and Safety risks or pollution of surface water, land, or uncontaminated groundwater.

- **Laboratory Testing Methods and Limits:** The choice of laboratory test method and the specified reporting limit requires definition in the project planning stage. All tests should be undertaken by laboratories that are NATA certified for the specified analysis. Care is required to ensure that reporting limits are sufficiently low to enable a sensible risk assessment to be performed (for example by comparison with ecosystem protection water quality criteria).

3.3.6 Unsaturated Zone Monitoring

Monitoring of the unsaturated zone may also be used to provide data on contaminant transport. Where the contamination source is above the water table, contaminants must migrate through the unsaturated zone to the water table. Sampling fluids, soils, and vapours in the unsaturated zone can therefore provide information on the potential for groundwater contamination long before contamination is detected in groundwater monitoring bores. In addition, the gas phase in the unsaturated zone may provide a significant pathway for migration of volatile contaminants to, or from, groundwater.

3.3.7 Data Analysis and Interpretation

The analysis and interpretation of hydrogeological data (aquifer properties, flow direction and rates, and groundwater quality) is the most critical step in any HA. Generally, however, this step is the most poorly understood and is often inadequately carried out. Proper data analysis and interpretation can result in significant cost savings by, for example, demonstrating that no further analysis is necessary, demonstrating due diligence, or identifying contamination thus limiting future liabilities.

As with any formal scientific assessment, this should only be undertaken by appropriately qualified personnel (ie. hydrogeologists).

Data analysis and interpretation is the key to developing an understanding of the hydrogeology of a site **(the Conceptual Hydrogeological Model*),*** the likelihood of groundwater contamination, and potential health or environmental risks from contamination. The extent and means of data analysis will vary substantially depending on the site hydrogeology and the potential risk posed by the contamination. All data interpretation requires the collation, presentation and quality review of geological information, groundwater level measurements, and groundwater chemistry data. Key questions that hydrogeological investigations of potentially contaminated sites should try to answer include:

- Is the existing conceptual hydrogeological model still valid?
- What are groundwater flow directions and flow rates in the aquifer(s)?
- To what extent are different aquifers interconnected?
- What is the “background” groundwater quality?
- What is the extent of the contaminated groundwater?
- Which aquifers are affected by contamination?
- How and where did contaminants enter the aquifer system?
- How do different contaminants behave within the aquifer?
- What are the actual and potential beneficial uses that may be at risk?
- What and where are the groundwater receptors?

Methods that can be used to answer these questions include potentiometric surface and water table maps, hydrogeological cross sections, hydrographs (groundwater level charts), calculation of groundwater flow rates, geochemical distributions (eg. Piper and Schoeller diagrams – see Section 5), contaminant distribution maps and groundwater flow and cross sections, mass balance calculations and contaminant transport estimates by analytical and numerical models.

3.3.8 Groundwater Impact/Qualitative Risk Assessment

As the objective of the HA is to determine whether the groundwater is contaminated or polluted, or is likely to become polluted, it follows that some form of risk assessment should be carried out as part of the HA. This would initially occur as part of the Desk Study, and should be revised during the Field Investigation.

Impact or risk assessment can be performed at many levels. For the purposes of these guidelines, impact assessment is a qualitative analysis of the potential for undesirable effects caused by groundwater contamination. Risk assessment on the other hand is a more rigorous quantitative process involving detailed analysis of the transport and fate of contaminants, their interaction with receptor organisms, the toxicity of chemicals of concern and then a detailed characterisation of the significance of the calculated risks. Discussion of the methodology of quantitative risk assessment is beyond the scope of this guideline.

A groundwater impact (qualitative risk) assessment involves:

- Assessing the source of the contaminant and nature (solubility, mobility, toxicity, etc.) of the chemicals of concern.
- Identifying the actual and potential beneficial uses of the local groundwater and therefore the "receptors" that may be affected.
- Estimating likely groundwater flow paths and actual or potential exposure of the receptors to the contaminants.
- Assessing the likely degradation of water quality and beneficial uses of the groundwater by reference to water quality criteria.

This form of analysis is sometimes referred to as the "Source-Pathway-Receptor" model and should be performed in all HAs.

In cases where beneficial uses include sensitive uses such as drinking water, evidence of groundwater pollution derived from the HA is likely to result in a requirement for additional action to further assess contamination and to clean-up groundwater. This often justifies the need for a more detailed quantitative risk assessment.

In cases where ecosystem maintenance is the principal beneficial use, and where contamination has been identified on site, it may be necessary to undertake more detailed assessment of the potential impact on the ecosystem.

3.3.9 Further Hydrogeological Investigations

The level of detail of hydrogeological assessments will vary depending on the specific case conditions. A conventional HA may lead to the conclusion that the uncertainties or potential risks are such that a more detailed assessment is required.

Additional tools that may be used to better define contaminant migration and fate at a site include:

- geophysics (surface and down-hole) (see Section 4),
- unsaturated zone or soil gas monitoring,
- environmental isotopes (oxygen-18, deuterium, tritium, nitrogen-15, carbon-14) to trace, date or “fingerprint” groundwater or contaminants,
- detailed, site-specific, groundwater flow and solute transport modelling,
- separate phase (LNAPL or DNAPL) identification, sampling, and monitoring,
- innovative techniques for monitoring such as in-situ monitors and loggers, cone penetrometers, etc.

Wherever groundwater remediation is required (eg. pump and treat, reactive walls, barrier systems), or where monitoring of "natural attenuation" is the approved management option, site hydrogeology and contaminant behaviour must be very well understood so that the feasibility of remedial or management strategies can be determined and demonstrated, and to ensure that situations are improved and not worsened by remediation or management.

4 HYDROGEOLOGICAL INVESTIGATION TECHNIQUES

4.1 INTRODUCTION

This section discusses field methods for the acquisition of data commonly required for hydrogeological assessments. Emphasis is on the more conventional and commonly used techniques. Key references are provided on the applications and limitations of the techniques mentioned. All of the techniques discussed below can be applied to site-specific, local, or regional scale hydrogeological assessments.

Figure 4.1 is a flowchart that illustrates the possible sequence for using various techniques during HAs.

4.2 HYDROGEOLOGICAL RECONNAISSANCE MAPPING

Hydrogeological reconnaissance mapping can be undertaken as part of the Desk Study or to confirm findings of the Desk Study and to plan the Field Investigation. Reconnaissance surveys involve field mapping techniques and can be used to estimate general groundwater flow directions, relative depth to the water table, and soil or water contamination sources. They involve evaluating:

- geological maps and aerial photographs;
- geology exposed in quarries and road cuttings on or near the site;
- topography and surface drainage;
- stream flow, springs, and seeps;
- vegetation patterns.

Accessibility for drilling rigs and related safety issues should be assessed during the initial reconnaissance.

4.3 MONITORING BORES

Installation of monitoring bores that provide representative samples of the groundwater of interest, is critical to a successful HA. The main success factors are:

- Choice of bore design to suit the site-specific conditions and the HA objectives.
- Choice of drilling techniques that allow the chosen bore design to be implemented.
- Placement of proper seals in the bore annulus and at the surface.
- Proper installation procedures for placement of casing and screens and development of the bore.
- Protection and identification of the bore to preserve a valuable asset and to maintain its integrity .

Failure to adhere to these factors may result in invalid groundwater quality data and a misleading interpretation of the nature, extent and significance of contamination.

All groundwater bores drilled in Victoria, except those on Commonwealth land, require a **bore construction licence** from the relevant Rural Water Authority (see Appendix A).

Detailed guidance on design criteria for monitoring bores and installation procedures are presented in hydrogeology textbooks and other publications. Useful references include Driscoll (1986), Aller et al. (1989), Nielsen (1991), CCME (1994), Bedient et al. (1994) and Fetter (1993, 1994).

4.3.1 Bore Design

The purpose of each bore must be determined before it is designed and completed. Monitoring bores are installed for one or a combination of the following purposes:

- Measuring groundwater level (elevation or potential);
- Collecting water samples for chemical analysis;
- Measuring hydraulic conductivity in the aquifer or aquitard;
- Providing access for geophysical instruments;
- Collecting samples of a non-aqueous phase liquid (usually LNAPL);
- Collecting soil/sediment or rock samples for physical and chemical analysis.

In addition to the final purpose of the bore, parameters that affect the choice of monitoring bore design, construction and development techniques include:

- site-specific subsurface geology;
- drilling methods available;
- number of vertical monitoring points required per borehole;
- types of contaminants to be monitored.
- Bore design components that should be considered are shown in Figure 4.2 and include (modified after Bedient et al. 1994):

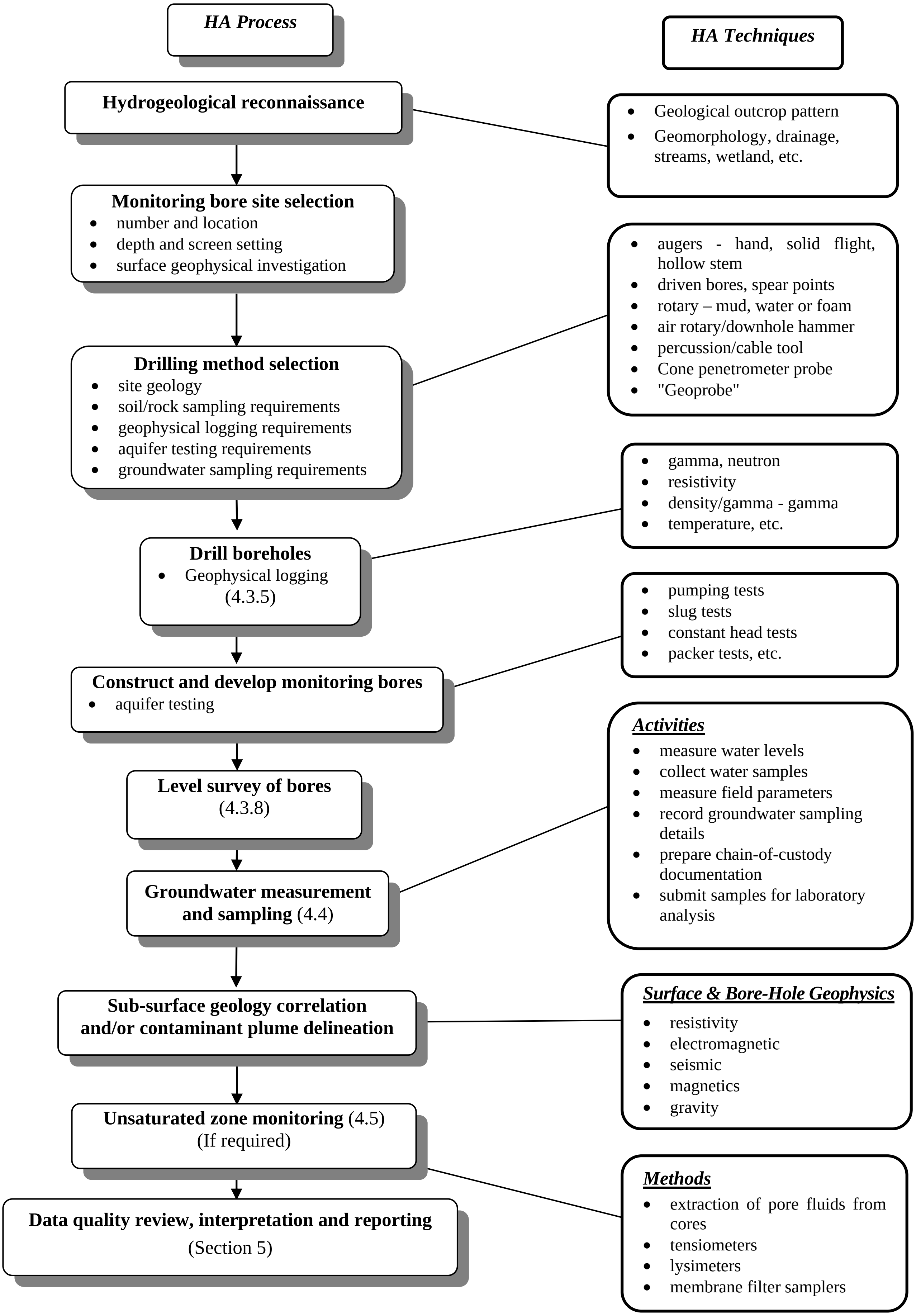

Figure 4.1 Flowchart of HA Process & Techniques

- bore hole depth,
- depth, length and diameter of bore screen or open interval,
- length, diameter and type of casing
- type of material for screen and slot opening,
- length and need for silt trap or sump,
- filter pack (gravel pack) requirements and location,
- method of casing and screen installation,
- material and method of sealing annular space between casing and borehole wall,
- location and length of annual seal,
- protective surface casing or bore vault.

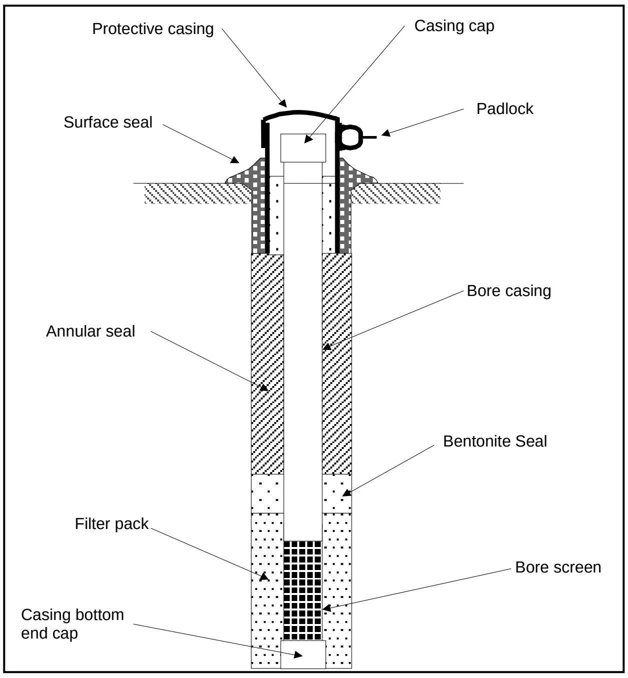

Figure 4.2

Typical monitoring bore components

4.3.2 Seals

The annular space in the borehole above the filter pack must be sealed to prevent the movement of surface water downward to the filter pack where it could affect the quality of water sampled. Seals also prevent vertical movement of groundwater from one zone to another, isolating a discrete sampling zone. Materials typically used for annular seals are bentonite pellets, granular bentonite slurry, neat cement grout, bentonite-sand slurry, or neat cement grout with a powdered bentonite additive. In some saline environments, a proprietary seal ring gasket may be used in place of bentonite (Senger and Perpich, 1983) because bentonite will not swell when exposed to water in highly saline environments such as occur in parts of northern Victoria. Ideally, sealant materials should not interfere with the groundwater chemistry of the monitored zone.

A surface seal is required to prevent contaminated surface water entering the bore annulus.

4.3.3 Screen Length and Depth

Different screen lengths and depths are required for various purposes:

- monitoring the position of the water table,
- measuring the potentiometric head at specific depths in the aquifer,
- collecting representative water samples from various depths in the aquifer,
- detecting LNAPLs or DNAPLs,
- detecting groundwater contaminants entering an aquifer,
- evaluating the effectiveness of groundwater remediation programs.

In more detailed investigations, some bores would be installed at more than one depth in an aquifer to access the extent of vertical groundwater flow and the distribution of contaminants with depth (see Figure 4.3).

4.3.4 Bore Construction Materials

The range of available bore casing and screen materials and their advantages and disadvantages are indicated in Table D1, Appendix D. Site-specific and logistical factors will control the selection of monitoring bore casing and screen materials. Site-specific factors include the geologic environment, natural geochemical environment, anticipated bore depths, and types and concentrations of contaminants. Logistical factors include the bore drilling method, ease of handling and cleaning, availability and cost (for materials and shipping). The selection of monitoring bore

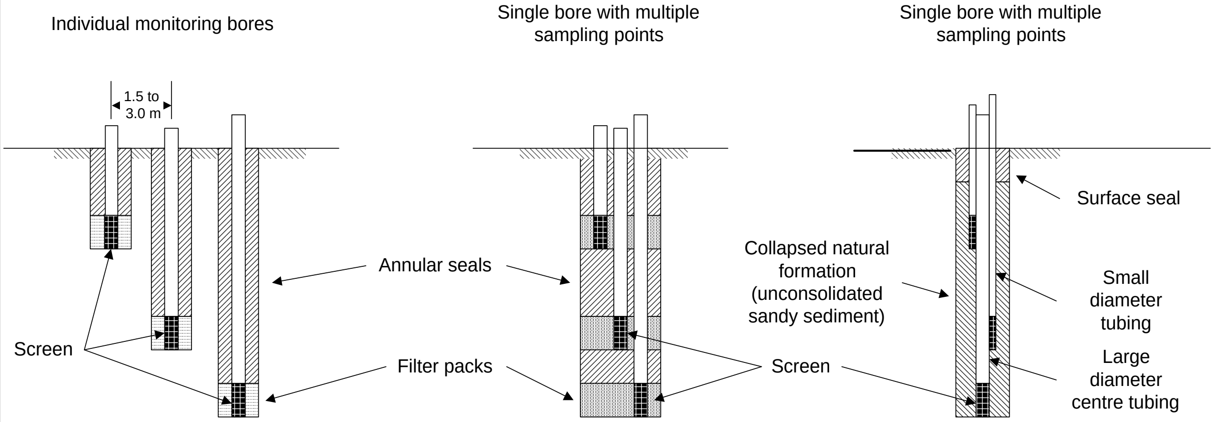

Figure 4.3 Cluster, nested and multilevel monitoring bores

(for measuring vertical head gradients and distribution of contaminants)

casing and screen materials should be based on three primary casing characteristics

- physical strength,
- chemical resistance, and
- chemical interference potential

to best meet the needs of the site-specific conditions (Nielsen and Schalla, 1991) and the objectives of the HA.

4.3.5 Drilling

Drilling methods that can be used for hydrogeological assessments include: hand auger, driven bores, jet percussion, solid flight auger, hollow stem auger, direct (mud or foam) rotary, air rotary, air rotary with casing driver, dual-wall rotary and cable tool (eg. Scalf et al., 1981; Driscoll, 1986; ADI, 1997). Drilling methods and their advantages and disadvantages are summarised in Table D2, Appendix D. As with all aspects of field investigations, the potential for cross contamination between aquifer zones during drilling should be assessed and minimised.

Drilling can alter the physical and/or chemical characteristics of both the aquifer and groundwater. Consequently, the drilling method that is least disruptive should be selected. Drilling fluids (air, mud, water, foam) should be carefully assessed as fluids can affect contaminant concentrations.

Health and Safety - When drilling at a contaminated or potentially contaminated site, separate health and safety plans specifically for hydrogeological assessment personnel and drillers must be in place before drilling begins. Drillers **MUST** be informed of all health and safety aspects of HAs prior to commencing field work.

Decontamination

Ensuring that contamination is not distributed between bores or introduced to uncontaminated bores is essential. Therefore a decontamination program for all downhole equipment, construction materials (casing, screens, etc.), and sampling equipment should be developed before drilling and bore installation (Aller et al., 1989). The level of effort for decontamination is a site- and project-specific issue and is relevant to uncontaminated as well as contaminated sites.

4.3.6 Bore Installation

In all monitoring bore installations it is crucial to ensure that:

- the bore screen is completely isolated in the borehole at the specified depth;
- the borehole wall near the screen is not severely altered by drilling operations, eg. smearing, mud impregnation, etc.;
- groundwater quality has not been significantly changed by drilling fluids (mud, water, foam, air);

- the diameter of the bore casing is large enough to permit access of water level, water sampling, and geophysical equipment, if required; and
- the material used to construct the bore is compatible with the contaminants present in the monitored zone.

Multiple Level Monitoring

In multi-level monitoring, bores are usually installed in nested configurations, with a water table piezometer/bore and one or more separate piezometers/bore screened below the water table (Figure 4.3).

Although installing individual bores in separate boreholes is preferred to ensure accurate and reliable sealing, multiple sampling points in a single borehole may be used in some circumstances. Cases where this is useful include deep installations in hard fractured rock aquifers where drilling costs are considerable. However, in most multiple installations in a single bore, the effectiveness of the seals may be difficult to test, and questions regarding data reliability may persist.

Isolation Casing

To establish the vertical extent of groundwater contamination, it is frequently necessary to drill monitoring bores through a contaminated upper zone into a potentially uncontaminated lower zone. In such cases, isolation casing must first be installed to prevent the movement of contaminants between the zones during drilling.

Protective Casing

All monitoring bores should be fitted with a lockable protective steel casing or bore vault at the surface to provide physical protection from accidental or intentional damage and/or the introduction of objects or fluids into the bore.

4.3.7 Bore Development

Bore development refers to the process of removing fine sand, silt, and clay from the aquifer around the bore screen, and breaking down any mud cake on the borehole wall. Development improves the quality of groundwater samples collected by:

- maximising the hydraulic connection between the bore and the formation,
- removing drill fluid residues,
- removing fine sediment from the bore, and therefore from the groundwater sample,
- minimising the potential for clogging and damaging pumping equipment.

Although a variety of development techniques exist, for monitoring bores, methods should be chosen that do not introduce foreign fluid or air into the borehole so that the groundwater chemistry is altered as little as possible (Aller et al., 1989). Such methods include surging and pumping.

Care must be taken to protect worker Health and Safety during development of a contaminated bore and to contain and properly dispose of contaminated groundwater removed from the bore.

4.3.8 Bore Identification and Surveying

All bores must be identified to ensure that the location of water-level measurements and groundwater samples will be recorded correctly. The identification should be clearly visible on the protective casing, on the bore casing, and on the cap.

Monitoring bore elevations must be surveyed in order to evaluate groundwater flow directions and hydraulic gradients, and bore locations need to be accurately plotted onto maps. A licensed surveyor should perform all surveying. Bore elevations should be surveyed to Australian Height Datum (AHD), and locations to the AMG co-ordinate system.

> The elevations of both the water level measuring point (generally the **top of casing**) and the **natural land surface** should be surveyed.

The measuring point should be permanently marked to ensure water levels are measured consistently from the same point.

Reporting bore details - Because the results of a groundwater monitoring program are directly related to monitoring bore construction, all construction information should be reported both on a bore log and in a summary table (see Section 5 and Appendix D), and included in HA reports.

4.3.9 Bore Abandonment

Bore abandonment (decommissioning) is the process of sealing boreholes, both drillholes and installed bores, to:

- prevent migration of contaminants within the bore,
- prevent drainage of surface water down the bore,
- eliminate the possibility of liquid waste disposal via the bore,
- remove potential safety hazards.

A number of different techniques can be used to abandon bores (see Driscoll, 1986; ADI, 1997; ARMCANZ, 1997). Records of all abandoned bores should be forwarded to the relevant Rural Water Authority (Appendix A).

4.4 WATER LEVEL MEASUREMENTS

Methods and instruments used to collect and record changes in groundwater levels vary substantially depending on the design of the monitoring program and the borehole construction. The more common instruments are fox whistles, electrical tapes, pressure transducers, and monometers or pressure gauges for flowing bores (Kraemer et al., 1991). Although many electronic methods exist, fox whistles are both accurate and extremely reliable.

Where an accurate record of temporal variations in water level is important, bores are commonly equipped with pressure transducers coupled to data loggers.

Special conditions in bores that affect the accuracy of levels include:

- The presence of **LNAPLs floating** on the water table. This requires special care in measuring the water table elevation and product thickness because of density differences.
- The presence of saline or hot groundwater requires measured groundwater elevations to be **corrected for density effects.**

4.5 THE UNSATURATED ZONE

4.5.1 Monitoring and Sampling the Unsaturated Zone

At some sites, it may be necessary to monitor the unsaturated zone. Because bore water in the unsaturated zone is under tension, standard monitoring bores or piezometers cannot be used to measure hydraulic head or to collect pore water samples. Porous cup tensiometers at different depths can be used to measure vertical pressure head gradients in the unsaturated zone (Morrison, 1983). The moisture content of unsaturated materials can be measured directly by gravimetric techniques or indirectly using calibrated neutron probes or time-domain reflectometry (TDR). Infiltration rates and field saturated hydraulic conductivity values can be measured in the field with a variety of devices, including single ring and double ring infiltrometers (CCME, 1994). Pore fluids in the unsaturated zone can be sampled by pore water extraction or by using vacuum or suction samplers including lysimeters (Wilson, 1990). Often sample volumes are small, so chemical analyses may be limited.

4.5.2 Sampling Perched Groundwater

Dedicated bores can be installed to sample perched groundwater. The construction techniques and bore designs are identical to those used for groundwater monitoring bores. Since perched groundwater systems can be ephemeral, unsaturated zone monitoring techniques may also be required.

4.6 GEOPHYSICAL METHODS

A variety of geophysical methods can be used during field investigations to obtain additional information on site hydrogeology and/or contaminant plume configuration. Geophysical methods are broadly divided into surface methods and borehole methods.

Surface geophysical techniques offer several advantages (Driscoll, 1986): (1) the investigation can proceed rapidly with little danger to health, (2) the near-surface physical characteristics of the aquifer can be determined, and (3) the limits of the plume can be generally defined. Several bores should be used to provide subsurface control data when interpreting geophysical data.

Geophysical borehole logs provide invaluable information for subsurface geological characterisation, and are a valuable tool for optimising the design of additional bores. Geophysical logging also allows information to be obtained from bores that have no record of subsurface geology or bore construction. Generally, a suite of geophysical logs of complimentary methods is made including gamma radiation and electrical logs. More details are presented in Appendix D**.**

4.7 AQUIFER PARAMETER DETERMINATIONS

Common techniques for determining the hydraulic properties of aquifers are usually based on solutions to groundwater flow equations simulating the response of an aquifer to pumping stress (Driscoll, 1986; Dawson & Istok, 1992; Kruseman & DeRidder, 1994; Walton, 1996; Butler, 1997).

Techniques include:

- multiple-bore pumping tests,
- single-bore pumping tests,
- slug tests (rising head, falling head, or displacement tests),
- constant-head tests,
- purge or recovery tests performed while purging,
- tracer tests,
- borehole dilution tests,
- packer tests,
- rock or sediment core testing for porosity and hydraulic conductivity in a laboratory.

When choosing a technique for estimating hydraulic conductivity at potentially contaminated sites, it is important to consider:

- the known, or expected, hydraulic conductivity range,
- the scale of information required,
- the treatment and/or disposal of water removed from the bore (eg. pumping, slug, and recovery tests),
- the impact of introducing different water or tracers to the aquifer or aquitard (eg. constant head, tracer, and borehole dilution tests) and,
- the appropriateness of the solution technique and all assumptions used in the solution technique.

Analysis of test data can be complex and requires a hydrogeologist trained in aquifer test analysis. A number of computer software programs are available for analysing aquifer test data; however, **extreme care is required when using aquifer test analysis software programs**. They do not readily recognise real hydrogeological features that impact on flow rates to bores in the field such as barriers, recharge boundaries, or variable flow conditions.

4.8 SAMPLING METHODS AND FIELD PARAMETER MEASUREMENTS

A large number of methods exist for removing groundwater samples from boreholes, however, the method will depend significantly upon:

- the type of contaminants being analysed,
- the design of the borehole,

- the hydraulic conductivity of the monitored zone, and
- the logistics of disposing of contaminated groundwater.

Regardless of the method chosen, water levels should be measured before either purging or sampling. It is also useful to measure water levels after purging and sampling to provide an indication of the hydraulic conductivity of the formation.

It is useful to sample water removed during aquifer tests to examine temporal changes that may occur due to capture of contamination plumes or leakage between aquifer zones.

Groundwater samples should be analysed for a wide range of chemical and physical parameters in both the field and the laboratory (see Section 3.3). Each chemical parameter may require different sampling techniques. This aspect is discussed in detail in the **Groundwater Sampling Guidelines** being prepared by the EPA. Guidance on sample preservation and storage is provided in EPA Publication 441 (EPA, 1995).

4.9 GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELLING

Groundwater flow and solute transport models are numerical or analytical solutions to the mathematical groundwater flow and advection-dispersion equations respectively. Groundwater flow models are typically used to estimate groundwater flow rates, actual groundwater velocities and groundwater flow paths. Solute transport models are used to assess the migration and fate of individual solutes or contaminants. All solute transport models require a groundwater flow model for the same aquifer system; solutes are then transported within the flow system.

As with all solutions to differential equations, assumptions and boundary conditions are required to solve the problem. Most groundwater flow and solute transport models assume that flow is through porous, not fractured, aquifers and require assumptions regarding:

- aquifer configuration (lateral and vertical extent and distribution),
- the distribution of hydraulic conductivity within each aquifer unit,
- head or groundwater flow estimates at all boundaries of the modelled domain,
- head distributions before stress, if transient,
- contaminant flux estimates at each boundary,
- initial contaminant concentrations throughout the modelled domain,
- contaminant source information (duration, concentration, and flow rate),
- contaminant transport parameters including diffusion and dispersivity, and
- chemical reactions such as degradation and sorption for each contaminant modelled.

Key data required for groundwater flow models are indicated in Appendix E.

Because of the large number of assumptions and the large amount of data required to calibrate and verify a model, one of the most common uses of groundwater models should be as a tool to test different scenarios. If predictive models are developed, significant additional field or laboratory data on hydraulic conductivity distribution, temporal variations in groundwater flow rates, and contaminant behaviour usually need to be gathered.

The amount of data required to produce an **adequately calibrated and verified solute transport model** that can be used to predict future contaminant distributions is usually beyond the scope of all but the most rigorous and complete hydrogeological assessments.

Where sufficient data exist for model calibration and verification, groundwater flow or solute transport models can be used in a more predictive mode to:

- design groundwater monitoring networks,
- design, evaluate, and optimise proposed remediation schemes,

- assess the impacts of pumping or injection schemes,
- estimate the possible fate and migration of contaminants for risk evaluation.

Numerical models should be designed and used so that they are relevant to the conceptual hydrogeological model and the nature of management decisions depending on the model results. In many cases, the basic data available and the scale of decisions do not warrant the use of complex numerical models, and analytical models may be the most efficient, appropriate, and economical approach to testing scenarios. A comparison of common solution methods is presented in Appendix E.

Additional information on the theory and practice of groundwater flow and solute transport modelling is available in Wang & Anderson (1982), Anderson & Woessner (1991), CCME (1994), Spitz and Moreno (1994), and Zheng and Bennett (1995), amongst others.

4.9.1 Model Reporting

The model, whether analytical or numerical, should be described in sufficient detail that a reviewer can determine the appropriateness of the model for the site or problem that is simulated. In addition, the model report, together with model journal, should provide sufficient information for another modeller/reviewer to develop the same model and generate the same output. This requires that all aspects of the model development and simulation runs be fully documented. Specific reporting requirements are presented in Section 5, and a checklist is included in Appendix E.

4.9.2 Errors, Misconceptions and Modelling Limitations

Modelling results should not be solely relied on to predict contaminant distribution, pumping rates, travel times, or capture of contaminant plumes. Any such predictions must be viewed as estimates, dependent upon the quality and uncertainty of the input data. Where models are used as predictive tools, however, field monitoring must be incorporated to verify model predictions.

Modelling results can be impressive when printed out, or plotted as smooth curves and contours in full colour graphics. However, the accuracy of the results is no better than the accuracy of the data that went into the model and the appropriateness of the original model design and the conceptual hydrogeological model.

A computer model can bring valuable insight and understanding to HAs even if the results are not used directly. If used incorrectly, model results can be misleading and expensive.

5 HYDROGEOLOGICAL ASSESSMENT REPORTS AND DATA PRESENTATION

5.1 INTRODUCTION

This section indicates the documentation and data presentation requirements, and provides further general guidance on the contents of a HA report. It is intended to encourage consistency of reporting and enable efficient review by regulatory authorities and/or independent third parties.

General guidance is provided on presenting information including; site description, site geology and hydrogeology, and geochemical data.

Specific guidance is also provided on numerical modelling reports and reporting of impact assessment.

Regardless of the type and scope of assessment, all hydrogeological assessments must be accurately and comprehensively reported. The reports have to be complete and detailed as they generally serve as the basis for management decisions with significant environmental and financial consequences, such as the design and implementation of monitoring programs or costly remedial action plans.

5.2 REPORT CONTENTS

5.2.1 Report Structure

The HA report should present an integrated geological, hydrogeological, and hydrochemical conceptual model of the site, including the stratigraphic profile, direction and rate of groundwater flow, lateral and vertical extent of groundwater contamination, and groundwater recharge and discharge zones as well as existing and potential receptors. The style and content of HA reports are determined by the type of study and can vary in as many ways as the investigations themselves. However, a general outline is presented below for HA reports. A more detailed checklist for reporting is presented in Appendix C.

5.2.2 Data Sources and Acknowledgement

Data sources, collection, compilation, correlation and interpretation methods should be fully described. All information and data sources such as text books, previous reports, company records, geological maps, database records, etc., used for the HA must be fully acknowledged. The reference list must include author(s) and title, and relevant details such as the type of report, publisher and publication date must be presented in the reference list. Information obtained from interviews or from anecdotal evidences must be indicated and, where possible, the source identified.

Introduction: Background; Objectives; and Scope of Work

Site Description, Setting and History: Location site description and features; climate; topography and drainage; regional geology and hydrogeology; land use and zoning; groundwater users (from database search and field observations); beneficial uses of regional groundwater.

Site History: Past and present site land use; potential contamination sources; chemicals of concern.

HA Methodology and Results: Reconnaissance mapping results; drilling and bore installation; geophysics; aquifer testing, etc.

Groundwater sampling and results: Groundwater sampling program; analytical program, laboratory methods and detection limits; analytical results; assessment guidelines and criteria (SEPP Groundwaters of Victoria); and notes and explainations of criteria exceedences.

Quality Assurance/Quality Control: Field protocol and procedures; laboratory protocols and procedures; quality control testing program and validation.

Conceptual Hydrogeological Model: This needs to be clearly stated and supported by data, figures, and interpretations. The model should describe the hydrogeological setting (aquifers and aquitards, their spatial relationship and hydraulic interconnection); groundwater flow direction, hydraulic gradient, flow rates and travel times; recharge and discharge zones and groundwater-surface water interaction; and soil profiles and the unsaturated zone characteristics.

Groundwater Contamination Assessment: Background groundwater quality; groundwater contamination; contamination sources; migration and fate of contaminants; impact on beneficial uses.

Qualitative assessment of impacts/risks to receptors (Sources-Pathways-Receptors model).

Groundwater modelling, if undertaken (see model reporting requirements).

Conclusions and Recommendations

References

Appendices

5.2.3 Data Quality

HA data can be in various forms and can range in quality depending on the data types, source, analysis methods, and the expertise of the hydrogeologist interpreting the data. The discussion on data quality should reference the Quality Plan used to guide the assessment and should include:

- Project scope and planning;
- Project staff, qualifications and supervisor (reviewer);
- Reference to standard operating procedures for key activities;
- Laboratory (and any other relevant) accreditation;
- Data quality objectives.

The HA should also include Quality Control activities carried out to verify that the results obtained are of acceptable quality. These activities include:

- field data quality control procedures including calibrations and standardisatory procedures; decontamination of field equipment; sample collection, storage and handling, including chain-of custody details, etc.
- field duplicate sampling (blind and "second laboratory")
- laboratory analytical methods, detection levels and quality control procedures and results.
- data validation – assessment of field and laboratory data against quality assurance requirements.
- reliability of the data - if data are not used, the reason for excluding particular data should be discussed.

5.3 DATA PRESENTATION

The key components of an HA are the hydrogeological and hydrochemical data that indicate the occurrence and movement of fluids in the subsurface and the movement and fate of contaminants in the groundwater flow system. Scientific, technically defensible interpretation of these data is required for a successful HA.

5.3.1 Site Description Information

The geography of the site should be described in the HA in sufficient detail to enable reviewers to accurately locate the site. Maps should be provided showing the site in its regional and local context. A site layout plan should also be included. Topography and drainage should also be described and shown in map form. A topographic map can generally be used to show the site location.

5.3.2 Geological Data

Geological data should be presented in such a way that relates the hydrogeological regime to surface and subsurface features including outcrop and fracture patterns.

Geological and Hydrogeological Maps

A geological map of the site at a sufficient scale to clearly show the geology of the site and surrounding area should be included in the report. The source of the geological map, generally the Geological Survey of Victoria, must be acknowledged.

> All maps should indicate north point and have a scale; geological and hydrogeological sections should show both the vertical and horizontal scales or the vertical scale and exaggeration.

Hydrogeological Cross-sections

Cross-sections should be drawn to illustrate the relationship of the identified aquifers and aquitards underlying the site, their lateral continuity and related groundwater quality and groundwater elevations. Given the extreme variability of geological strata, care should be taken in interpolating subsurface geology between widely spaced bores and/or extrapolating beyond the area of available geological logs.

Geological Structure Maps

Structure maps (contour maps of buried geological surfaces) and isopachs (equal thickness distribution maps) can also be used to characterise the physical constraints on groundwater or flow through the subsurface.

Geological Logs

Scaled geologic logs should be prepared for every bore on the site, including bores that were not constructed (cased). Individual logs should indicate information on:

- the bore location, ground surface elevation, drilling method, driller identification, and date of completion;
- lithological information on the type and thickness of each stratum encountered;
- groundwater occurrence information including water level and date;
- contamination observations including odour, colour or sheen;
- bore construction details.

5.3.3 Bore Data Presentation

Because the results of a groundwater monitoring program can be affected by the monitoring bore construction, construction information should be reported in detail for all monitoring bores. To facilitate review, details of all bores should be summarised in tables (see Table 5.1) together with as-built graphic bore logs (see Appendix F). Summary details are normally included in the main text with graphic logs presented as an appendix to the report.

Bore Log Contents Checklist

Bore and Project Identification Data

- Bore number with prefix
- Project, Site, Client identification
- Bore location, co-ordinates and level
- Driller's and hydrogeologist's names

Lithological Data

- Soil and rock descriptions
- Strata boundary depths
- Contamination observations

Groundwater Information

- Groundwater inflow intervals
- Groundwater levels and dates measured
- Groundwater quality data

Bore Construction details

- Approximate diameter of borehole
- Drilling methods for all intervals
- Diameter, schedule, and material type of casing
- Diameter, schedule, and material type of screen
- Screen length and setting depth
- Screen slot size (aperture)
- Length of casing
- Total depth drilled and constructed depth
- Filter pack setting and material description
- Type and depth setting of annular seals (bentonite, grout, cement, etc.)
- Location and description of casing and screen centralisers, if used
- Length and description of concrete surface seal
- Surface protective casing details (material, diameter, stick-up, seating depth).

(See Example Bore Log - Appendix F)

5.3.4 Hydrogeological Data

The hydrogeological data that is presented should describe the spatial and temporal distribution of aquifer properties, as well as groundwater elevation, flow direction, hydraulic gradients and velocities. Examples of hydrogeological data presentation include:

- Water level contour maps (with flow direction arrows) and cross-sections.
- Groundwater elevations versus time (hydrographs).
- Tabulations of water level data and hydraulic test data
- Tabulations of aquifer properties data.

Water Level Data

Measured water levels should be reduced to a common data (generally AHD) and plotted on a suitable scale map. To define lateral groundwater flow patterns, static water-level elevations measured within monitoring bores or piezometers screened within the same water-bearing stratum (measured at the same time) should be plotted on a scaled site plan, and the values contoured to indicate the water table or potentiometric surface configuration. Cross-sections may also be used to indicate groundwater flow directions and hydraulic gradients.

Erroneous interpretations of groundwater flow patterns may be obtained if static water-level data from different or discontinuous strata are used in contouring water level data, if water level data from different times are contoured together, or if water level measurements from different depths in thick units with significant **vertical hydraulic gradients** are used to characterise lateral flow.

Distortions in the potentiometric surface contours should be carefully evaluated in light of all available site data to determine whether apparent hydraulic head variations are indicative of actual aquifer conditions (eg. discharge or recharge features) or represent a possible measurement error or misinterpretation.

In summary, a great deal of hydrogeological judgement is needed in drawing groundwater contour maps and cross-sections. The number of data points may be limited and several interpretations possible; under such conditions, the groundwater contour map that makes the most sense hydrogeologically should be included in the HA report.

Computer generated contours should be used with great care – they are often invalidated by indiscriminate use of poor or incorrect data.

Aquifer Hydraulic Properties

The method used to obtain field data for aquifer parameter determination should be described, eg. pumping tests, slug tests, etc. The complete field test data should either be summarised as a table within the report or preferably included as an appendix.

Methods used to determine aquifer hydraulic parameters should be described including assumptions, limitations and applicability to the data sets. All computations should be included in the report.

It is recommended that **pumping test data should initially be analysed manually** as use of computer software can result in incorrect parameter values because of poor assumptions.

Groundwater Flow Calculation

If the lateral groundwater seepage velocity, travel times or flow rate (volumetric) within an aquifer are estimated using Darcy's Law, all input parameters (hydraulic conductivity, gradient, porosity, flow tube width) and the justification for their selection must be included together with relevant computations.

Table 5.1: Example of Tabular Presentation of Summary Bore Details

Bore	Depth (m)	RL Natural Surface (mAHD)	RL Top of Casing (mAHD)	Screen Depth (mbgl)	Filter Pack Depth (mbgl)	Annulus Seal Depth (mbgl)	Aquifer monitored	Standing Water Level (mbmp)	RWL Elevation (mAHD)
BH1A	7.5	67.50	67.80	4.5-7.5	4.0-7.5	3.5-4.0	Brighton Gp.	6.00	61.80
BH1B	15.0	67.50	67.90	12.0-15.0	11.5-15.0	11.0-11.5	Brighton Gp.	6.35	61.55
BH2	8.0	70.0	70.40	5.0-8.0	4.5-8.0	4.0-4.5	Brighton Gp.	6.00	64.40
BH2	9.5	73.00	73.55	6.5-9.5	6.0-6.5	5.5-6.0	Brighton Gp.	6.50	67.05
BH3	20.0	78.77	79.22	17.0-20.0	16.5-20.0	16.0-16.5	Fyansford Fn.	11.75	67.47

Notes:

BH1A and BH1B are different piezometers installed in bore BH1

mAHD; metres Australian Height Datum

RL: reduced level (m AHD) mbgl; metres below ground level

mbmp; meters below measuring point (top of bore casing)

5.3.5 Hydrochemical Data

The hydrochemical data required should described the spatial and temporal distribution of background groundwater quality as well as the concentration of contaminants in groundwater. Examples of hydrochemical data presentation include:

- Water quality contour maps and cross-sections (salinity, contaminant concentrations, etc.) for specific aquifers.
- Water quality time series plots.
- Tabulations of water quality data including statistical summaries.
- Water quality diagrams (Piper, Schoeller, etc.).
- Other map-based devices such as data summaries posted against bore locations; Stiff Diagrams, etc.

HA reports should include information on water sampling including equipment used, purging and field observations and measurements (water appearance, EC and pH, etc.) and sample preservation techniques. Methods used to measure field parameters including the meters and electrodes used, and calibration and standardisation details, should also be included.

Certified laboratory analytical reports, and the methods used, should be included in HA reports (generally in appendices). The results should be summarised in tabular form (see Table 5.2).

General procedures for laboratory data review and interpretation should be applied.

- **Data Validation Procedures:** Upon receipt from the laboratory, all test results should be carefully reviewed to confirm laboratory accuracy and precision, and compliance with relevant quality-control standards.
- **Data Interpretation:** Various statistical methods can be employed to characterise background conditions and to make comparisons between concentrations detected at individual sampling points.

Table 5.2: Field Parameters and Major Ion Water Quality Data

Sample	Date	pH **	EC @ 25 ºC µS/cm **	Temp ºC **	DO mg/L **	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	S as SO_4 mg/L	Alkalinity as HCO_3^- mg/L **	TDS (calc) mg/L$^{\#}$	**CBErr (%)≅**
MB A	24/02/99	6.3	1665	9.5	0.2	94	72	359	16.0	17.6	6.2	1030	2180	**-1.1**
MB 2 *	24/02/99	7.4	875	nm	nm	64	19	114	9.5	30	75	402	715	**+5.1**
Site C	24/02/99	5.95	nm	10.3	0.2	5990	2750	10900	445	31400	1240	328	53000	**+4.9**
BH 4 *	24/02/99	7.7	1200	nm	nm	49	18	168	nm	246	44	202	730	**+0.3**

Notes:

**Parameter measured in the field, calibration and standardization details included in report

CBErr= Charge Balance Error = ((∑ cations – ∑ anions) meq/L / (∑ cations + ∑ anions) meq/L) * 100

* Data from Hem (1985)

$^{\#}$ TDS calculated as sum of major ions (mg/L)

nm = not measured

HA report writers should ensure that:

- All units are indicated (eg. mg/L for aqueous concentrations, etc.).
- Consistent units are used.
- Methods used to average physical or chemical data are specified (eg. arithmetic versus geometric mean; vertical averaging of hydraulic head data, etc.).

Results of chemical analyses for groundwater samples should be plotted on scaled site plans and correlated with available geologic logs and cross sections to define the lateral and vertical limits of contaminant migration. Examples of water and soil quality data presentation on site plans are illustrated in DoEQ (1998).

Other devices commonly used for interpretation and presentation of hydrochemical data include Piper and Schoeller plots. These provide a form of "finger-printing" of the chemistry of the waters. Figure 5.1a shows an example of a Piper diagram and Figure 5.1b shows a simpler Schoeller plot.

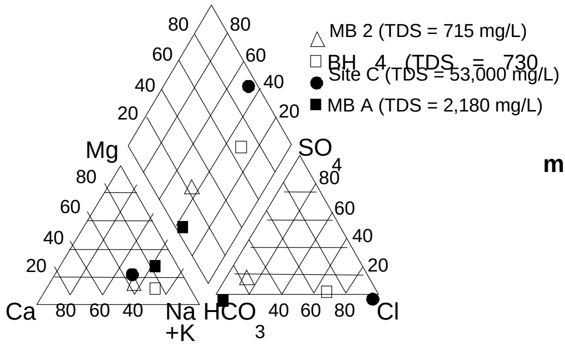

Figure 5.1a Piper Diagram

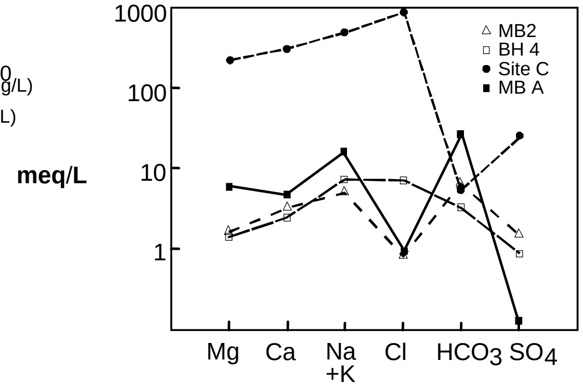

Figure 5.1b Schoeller Plot

5.3.6 Data Consistency and Correlation

The geological, hydrogeological, and chemical data collected during the site investigation should fit together as an overall picture that makes sense (Bedient et al., 1994). Structure contours, isopach maps and cross sections should describe the subsurface geological conditions. Derived hydraulic conductivity measurements should be generally consistent with the soil or rock types observed during the drilling program. The contoured groundwater flow patterns should correlate with observed stratigraphic variations or thickness changes, and/or with the locations of groundwater recharge or discharge features (eg. streams, lakes, wetlands, pumping bores, etc.). Dissolved contaminants should move in the direction of groundwater flow, diminishing in concentration with distance from the source area.

5.4 MODEL REPORTING REQUIREMENTS

All computer simulation models that are discussed in a hydrogeological assessment report must be adequately documented. The report must detail the process by which the model was selected, developed, calibrated, verified and utilised. The report should include:

- A clear statement of the objectives of the modelling task must be clearly stated (eg. scenario testing, flow behaviour, contaminant behaviour, etc.).
- Description (and diagram) of the conceptual hydrogeological model of the system to be simulated using numerical or analytical solutions.
- Description of the purpose and scope of the model application and discussion of the modelling approach.
- Discussion of the selected model and its applicability and limitations. This should include the model’s underlying equations and assumptions.
- Description of the model geometry (area discretization, grid orientation, layer number and type) and its relationship to the “real” system.
- Report and justification of all boundary conditions.
- Report and justification of all initial conditions (if transient flow or solute transport model).
- Presentation and justification of all data inputs for the model.
- Clear statement of all assumptions.
- Documentation of the source of all data used in the model, whether derived from published sources, or measured or calculated from field or laboratory tests.
- Description of model parameters; time, layer tops and bottoms, hydraulic conductivity and/or transmissivity, storativity, and effective porosity.
- Discussion of initial conditions and stresses modelled (recharge, evapotranspiration, bores, etc.).
- Documentation of all calculations.
- Description and discussion of simulation runs: model calibration and sensitivity analysis results and discussion of calibration procedure and data used.
- Details of final calibrated model.
- Results of model verification and data used for verification. In this case, verification is in the form of history matching, using historical data left out of the calibration process. In other cases, the verification step may require revisiting the model after new data have been collected.
- A discussion of the results of the modelling, including their reliability, likely accuracy, and appropriate application, and the use of the model results. In predictive models, all results should be presented as a range of probable results given the range of uncertainty in values of model parameters.

5.5 GROUNDWATER IMPACT ASSESSMENT REPORT

In cases where groundwater contamination is identified, the HA report should include a discussion of risks posed by the groundwater contamination to any existing or potential receptor. It must be recognised that such risk assessments are generally qualitative in nature and simply address the receptors, pathways, and sources of contamination in order to obtain an initial indication of the scale of risks to receptors (see Section 3.3.7). The qualitative groundwater risk assessment or impact assessment should define:

- sources or potential impact involved in terms of chemical and/or physical characteristics;
- potential migration pathways and processes affecting groundwater distribution within the groundwater flow system; and
- potential receptors (groundwater users, ecosystems, etc.) and the likely effects of groundwater contaminationon the receptors. Water quality criteria are often used as the basis for assessment of potential effects.

In cases where groundwater contamination is serious (and may constitute pollution), it may be necessary to undertake a more rigorous quantitative assessment of risk. This would generally involve detailed modelling to ascertain the exposure of each receptor, together with an assessment of the toxicity of each contaminant, and the acceptability of these exposures for the nominated effect or ‘end point’ experienced by the receptor. Discussion of such detailed risk assessments is beyond the scope of this guideline.

5.6 HA REPORT CONCLUSIONS AND RECOMMENDATIONS

The HA report needs to concisely answer the specific questions presented in the study brief, which often include:

- What is the potential of the site to cause groundwater contamination?
- What is the extent and degree of existing contamination?
- What is the extent and rate of transport and fate of groundwater contaminants?
- Is the information available sufficient to determine the acceptability of risks arising from groundwater contamination?

In summary, the HA report should provide **accurate and comprehensive information** on background groundwater quality and occurrence, and the nature and extent of contamination. This information is required as the **basis for management decisions** in relation to the approval of works or implementation of on-going groundwater monitoring or clean up programs.

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APPENDIX A

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INTERNET RESOURCES

Environment Protection Authority, Victoria:

http://www.epa.vic.gov.au

Information on Environment Protection Authority programs, environmental quality and Environment Protection Authority publications including environmental legislation.

Department Natural Resources and Environment, Victoria:

http://www.dce.vic.gov.au/dnre/grndwtr

Information on Victoria's groundwater resources; bore licensing requirement; and groundwater beneficial use maps. Also provides details of the State Groundwater Data Base (SGDB) and access to the SGDB.

U.S. Environment Protection Agency, Subsurface Protection Remediation Division (formerly the Robert S Kerr Laboratory):

http://www.gov/ada/kerrlab

On-line issue papers about groundwater remediation, and fate and transport topics. Centre for Subsurface Modelling Support (CSMoS), which provides groundwater and vadose modelling software and services (software and documentation can be downloaded from this site).

U.S. Geological Survey Water Resources:

http://h2o.usgs.gov

Information on USGS projects and reports (many available for downloading); information on USGS groundwater software (most programs and source codes are available for downloading; links to other sites.

National Ground Water Association:

http://www.ngwa.org

Useful source of groundwater related information; bookshop for groundwater and environmental text book; literature searches; and links to related sites.

Ground-Water Remediation Technologies Analysis Centre:

http://www.GWRTAC.org

Information and reports on groundwater remediation technologies and projects. Listing of internet resources containing information on hydrogeology and groundwater remediation.

RURAL WATER AUTHORITIES CONTACT DETAILS

Southern Rural Water	03 5139 3100
Goulburn Murray Water	03 5833 5500
Wimmera Mallee Water	03 5362 0200
Sunraysia Water	water@srwa.org.au

APPENDIX B

GLOSSARY OF TERMS

(Modified from: EPA 1997 SEPP Groundwaters of Victoria)

Aquifer	means a geological structure or formation, or part thereof, permeated with water or capable of (a) being permeated with permanently or intermittently with water; and (b) transmitting water.
Background Level	means the level or range of levels (usually determined from a number of sites or a series of measurements from the same site) of an indicator measured in a manner and at a location specified by the Authority in waters outside the influence of any contamination.
Bore	means any bore, well or excavation or any artificially constructed or improved underground cavity used or to be used for the purpose of (a) the interception, collection, or storage of groundwater; or (b) groundwater observation or the collection of data
Contamination	means a change in water quality that produces a noticeable or measurable change in its characteristics.
Diffuse Source	means a source of contaminants which is not an identifiable single point of discharge.
Drillhole	means any hole drilled by a drilling rig but does not include other excavations such as backhoe pits, shafts and drives.
Groundwater	means, subject to Clause 6, any water contained in or occurring in a geological structure or formation or an artificial landfill.
Groundwater Protection Zone	means any area which (a) has groundwater of special environmental significance or vulnerability, or requires more stringent controls to protect groundwater than are otherwise prescribed by this policy; and (b) is prescribed in Schedule A.
Hydrogeology	means the geological science concerned with the occurrence, distribution, quality and movement of groundwater.
Indicator	means any physical, chemical or biological characteristic used as a measure of environmental quality, as described in Clause 10.
Non-Aqueous Phase Liquid	(NAPL) means a liquid which has a limited solubility in water and can form a discrete layer or separate phase. Either a light non-aqueous phase. Liquid (LNAPLs) or a dense non-aqueous phase liquid (DNAPL)
Permeability	means the ability of a porous or fractured medium to transmit a fluid.
Polluted Groundwater Zone	means an area the Authority identifies in accordance with Clause 19 as having an existing level of contamination of groundwater that precludes one or more beneficial uses that would otherwise apply to that groundwater.

Protection Agency	means any person or body, whether corporate or unincorporated, having powers or duties under any Act other than the Environment Protection Act 1970 with respect to the environment or any segment of the environment in any part of parts Victoria.
Recharge	means the process of water being added to a groundwater system.
Solution Channelling	means the process whereby cavities and channels are formed in rock by water dissolving the rock and forming conduits for water flow.
TDS	means total dissolved solids, measured by a method approved by the Authority.
Unconfined Aquifer	means the aquifer nearest the land surface where there is no overlying low permeability layer and in which the upper boundary of the saturated zone is at atmospheric pressure.
Vulnerable Aquifer	means an aquifer that is susceptible to contamination by seepage from sources of contaminants at or near the land surface. The degree of vulnerability is determined by factors including the type of contaminant, soil permeability and mineralogy and depth
Waste	includes (a) any matter whether solid, liquid, gaseous or radio-active which is discharged, emitted or deposited in the environment in such volume, constituency or manner as to cause an alternation in the environment; (b) any discarded, rejected, unwanted
Water Table	means the surface of saturation in an unconfined aquifer at which the water pressure is equal to atmospheric pressure.

APPENDIX C

HYDROGEOLOGICAL ASSESSMENT REPORT CONTENTS CHECKLIST

SECTION	TEXT CONTENT	SUPPORTING INFORMATION
SUMMARY	Concise description of purpose, activities, findings	
INTRODUCTION		
☐ **Purpose / Objective** ☐ **Background** ☐ **Scope**	The purpose of the HA and the parties with an interest in the HA Further information on the background to the HA and its relationship to other studies may be necessary. The **scope** of the assessment and whether it is based on a **desk study** includes information from a site inspection, or from more detailed field investigations and laboratory testing**.**	Locality Plan Site Plan Table that lists sequence of events and resources used. Appendix - Work Plan (for complex sites)
SITE OVERVIEW		
☐ **Description** ☐ **Setting** ☐ **History** ☐ **Previous Studies** ☐ **Summary**	A brief **description** of the site locality and features, the geographic **setting** in terms of climate, topography, surface water drainage, vegetation and land use (this is elaborated upon in discussion of conceptual hydrogeological model). Details on the **history** of the site and surrounds and potential contaminants of concern relevant to the HA. Identify any **previous studies** of groundwater or soil contamination relevant to the HA. A clear **summary statement** of the **potential** for groundwater contamination.	Plans showing setting and relevant features Plan and/or aerial photographs showing relevant historical features.
METHODOLOGY & RESULTS		
☐ **Desk Study** ➢ **Data sources** ➢ **Data quality** ➢ **Data summary**	HA Desk Study **Scope** of desk study, information **sources** and data sets discovered in the Desk Study, comment on **data quality** and present a data **summary**	Summary of desk study data, including statistical analysis. Appendix - Spreadsheets, data from State Groundwater Data Base, Climatic data
☐ **Field Study** ➢ **Scope** ➢ **Methods** ➢ **Results**	HA Field Study **Scope** of field investigation work, **methods** used (drilling, geophysical, water sampling, water level measurement, hydraulic testing, etc.) and any field **results** (factual) or observations. Bore construction details (summary table)	Plan showing bore locations Tabulation (detailed) of bore construction and survey data, tabulation of water level data Appendices – Bore logs, geophysical logs, pumping test data and analysis, water sampling field records, bore construction licence, elevation and location survey, equipment calibration detail

SECTION	TEXT CONTENT	SUPPORTING INFORMATION
	Laboratory testing of water samples, test methods and detection limits. Collation of results	Tabulated water quality results including field parameters. Laboratory test reports NATA-certified
	The means used to ensure q**uality assurance and quality control**, and a commentary on data validity.	Appendix – Work Plan, Tabulation of QC data, Data Validation Report
CONCEPTUAL HYDROGEOLOGICAL MODEL		
☐ **Setting** ☐ **Geology / Aquifers** ☐ **Groundwater Flow Systems** ☐ **Groundwater Chemistry** ☐ **Protected Beneficial Uses** ☐ **Groundwater Resource Utilisation** ☐ **Summary**	Local **setting** in terms of topography, surface water drainage, the position of the locality in the landscape, land use and vegetation. Climatic averages to identify potential recharge periods.	Topographic plan Tabulation of monthly rainfall and pan evaporation data Stream Stage / Flow hydrographs
	The **geology** and relationships between **aquifers** at the **regional and local scale**. Comment on whether aquifers are confined or unconfined. Comment on the protection potentially offered to aquifers by the soil profile, unsaturated zone and aquitards; or conversely the opportunity for downward seepage through soil fissures, permeable soil, etc.	Geological map. Tabulated geological column showing main aquifers, aquitards and properties (K, T, S, b, n) Hydrogeological cross-sections showing the levels of surface facilities, geology, aquifer / aquitard units, intervals monitored in bores and water level.
	The **groundwater flow systems** through the distribution of groundwater potentials, water table depth and morphology, directions and rates of groundwater flow, and seasonal fluctuations. Comment on vertical gradients. Describe any interpreted/inferred recharge, discharge and interactions between surface water and groundwater.	Figures showing the water table and/or potentiometric levels and principal flow lines (map view and cross-section) Tabulations and hydrographs of groundwater level data
	The natural water, **groundwater chemistry** / quality and relate to the interpreted geology and flow systems. Include a discussion on TDS and major ion chemistry, as a minimum.	Summary table of water chemistry data/statistics or ratios Contour and other plots of water chemistry data (Stiff Diagrams, Schoeller Plots, Piper Diagrams etc).
	Identify the groundwater segment and list the **protected beneficial uses** of the groundwater by reference to SEPP Groundwaters of Victoria.	Plan showing the location of the nearest existing receptors including known water supply bores.
	Discuss the development and **utilisation of the groundwater resource** and its potential for future development and use. Identify the location of receptors/users (such as bore owners, surface water bodies, wetlands).	Tabulate the protected beneficial uses.
	Conceptual Hydrogeological Model **(CHM) Summary**: A concise summary of the CHM. This can be useful for inclusion in site assessment and review or auditing reports by others.	Diagrams and tables as required

SECTION	TEXT CONTENT	SUPPORTING INFORMATION
GROUNDWATER CONTAMINATION ASSESSMENT		
☐ **Description of Contamination** ☐ **Impact Assessment** ☐ **Risk Assessment**	Discuss the results and any **interpretations of** groundwater contamination data. Include description of the processes leading to the observed containment distribution.	Tabulated and contoured data on contamination concentrations and/or ratios of contaminants. Appendix - Modelling report
	Impact Assessment (Source-Pathway-Receptor Model): Discuss the possible and likely impacts on receptors (beneficial uses) of groundwater by evaluating sources of contamination and the potential for an active pathways to exist between the sources and receptors. Discussion could include description of contaminant release mechanism, transport and attenuation, reversibility of attenuation reactions etc. Where a groundwater model is used this generally requires a separate report or appendix to adequately document the work. As a minimum, assess whether each of the protected beneficial uses of groundwater are protected or precluded by contamination.	Tabulate the sources in terms of location and chemical properties, the beneficial uses in terms of water quality criteria and the groundwater flow system (and travel times) providing the pathway. The data used in this discussion should already have been presented earlier in the report. Groundwater flow and solute transport model parameters. Appendix - Modelling report Tabulate protected beneficial uses and whether each is existing, likely or unlikely.
	In cases where contamination is serious and the risks may cause environmental harm, more detailed **Groundwater Risk Assessment** protocols may be appropriate at this stage. This may include site specific assessment of human health risk or ecological risks. This is generally beyond the scope of most HAs.	Appendix - Risk Assessment Data and Analyses
CONCLUSIONS AND RECOMMENDATIONS		
	Provide concise conclusions and where appropriate, corresponding recommendations in relation to the objectives of the study.	
REFERENCES		
	References may be provided in footers, as a separate section in the report, or as an appendix	Reference list

Notes:

1. *This is a suggested content for typical* ***detailed HA report****. As the scope of the HA and therefore the report is dependent on the “risk” presented to groundwater beneficial use a detailed assessment that does not include all of these aspects may be sufficient.*
2. *A report arising from a HA Desk Study would follow the same format, however the level of data available will be less than for a HA that includes field investigation.*
3. *The report for a HA that did not detect any contamination would not require detailed discussion of the "Groundwater Contamination Assessment".*
4. *The report should be signed by the Hydrogeologist responsible for the HA.*

APPENDIX D

USEFUL INFORMATION ON FIELD INVESTIGATION AND MODELLING TECHNIQUES

DRILLING AND MONITORING BORE CONSTRUCTION

Table D.1 - Bore Casing and Screen Materials

TYPE	ADVANTAGES	DISADVANTAGES
POLYVINYL CHLORIDE (PVC)	Lightweight. Excellent chemical resistance to weak alkalies, alcohols, aliphatic hydrocarbons, and oils. Good chemical resistance to strong mineral acids, concentrated oxidising acids, and strong alkalis. Readily available. Low priced compared to stainless steel and Teflon.	Weaker, less rigid, and more temperature sensitive than metallic materials. Can adsorb some constituents from groundwater. Can react with and leach some constituents from groundwater. Poor chemical resistance to ketones, esters, and aromatic hydrocarbons.
POLYPROPYLENE	Lightweight. Excellent chemical resistance to mineral acids. Good to excellent chemical resistance to alkalies, alcohols, ketones, and esters. Good chemical resistance to oils. Fair chemical resistance to concentrated oxidising acids, aliphatic hydrocarbons, and aromatic hydrocarbons. Low priced compared to stainless steel and Teflon.	Weaker, less rigid, and more temperature sensitive than metallic materials. May react with and leach some constituents into groundwater. Poor machinability - it cannot be slotted because it melts rather than cuts.
TEFLON	Lightweight. High impact strength. Outstanding resistance to chemical attack; insoluble in all organics except a few exotic fluorinated solvents.	Tensile strength and wear resistance low compared to other engineering plastics. Expensive relative to other plastics and stainless steel.
KYNAR	Greater strength and water resistance than Teflon. Resistant to most chemicals and solvents. Lower priced than Teflon	Not readily available. Poor chemical resistance to ketones and acetone.
MILD STEEL	Strong, rigid; temperature sensitivity not a problem. Readily available. Low priced relative to stainless steel and Teflon.	Heavier than plastics. May react with and leach some constituents into groundwater. Not as chemically resistant as stainless steel.
STAINLESS STEEL	High strength at a great range of temperatures. Excellent resistance to corrosion and oxidation. Readily available. Moderate price for casing.	Heavier than plastics. May corrode and leach some chromium in highly acidic waters. May act as a catalyst in some organic reactions. Screens are higher priced than plastic screens.

(After Driscoll, 1986)

Table D.2 - Applications and Limitation of Common Drilling Methods

METHOD	APPLICATIONS	LIMITATIONS
HAND AUGERS	• Shallow soils investigations • Soil samples • Piezometer, lysimeter and small-diameter monitoring bore installation • Piezometer, lysimeter and small-diameter monitoring bore installation • No casing material restrictions	• Limited to very shallow depths • Unable to penetrate extremely dense or rocky soil • Drillhole stability difficult to maintain • Labour intensive
DRIVEN BORES	• Water-level monitoring in shallow formations • Water samples can be collected • Dewatering • Water supply • Low cost encourages multiple sampling points	• Depth limited to approximately 15m (except in sandy material) • Small diameter casing • No soil samples • Steel casing interferes with some chemical analysis • Lack of stratigraphic detail creates uncertainty regarding screened zones and/or cross contamination • Cannot penetrate dense and/or some dry materials • No annular space for completion procedures
JET PERCUSSION	• Allows water-level measurement • Sample collection in form of cuttings to surface • Primary use in unconsolidated formations, but may be used in some softer consolidated rock • Best application is 100 mm diameter borehole with 50 mm diameter casing and screen installed, sealed and grouted	• Drilling mud may be needed to return cuttings to surface • Diameter limited to 50 mm • Installation slow in dense, bouldery clay/till or similar formations • Disturbance of the formation possible if borehole not cased immediately
SOLID FLIGHT AUGERS	• Shallow soils investigations • Soil samples • Vadose zone monitoring bores (lysimeters) • Monitoring bores in saturated. stable soils • Identification of depth to bedrock • Fast and mobile	• Unacceptable soil samples unless split-spoon or thin-wall samples are taken • Soil sample data limited to areas and depths where stable soils are predominant • Unable to install monitoring bores in most unconsolidated aquifers because of borehole caving upon auger removal • Depth capability decreases as diameter of auger increases • Monitoring bore diameter limited by auger diameter

METHOD	APPLICATIONS	LIMITATIONS
HOLLOW STEM AUGERS	• All types of soil investigations • Permits good soil sampling with split-spoon or thin-wall samplers • Water quality sampling • Monitoring bore installation in all unconsolidated formations • Can serve as temporary casing for coring rock • Can be used in stable formations to set surface casing (example: drill 300 mm diameter drillhole; remove augers; set 200 mm casing; drill185 mm borehole with 82.6 mm ID augers to rock; core rock with 75 mm tools; install 25 mm piezometer, pull augers)	• Difficulty in preserving sample integrity in heaving formations • Formation invasion by water or drilling mud if used to control heaving • Possible cross contamination of aquifers where annular space not positively controlled by water, drilling mud or surface casing • Limited diameter of augers limits casing size • Smearing of clays may seal off aquifer to be monitored
MUD ROTARY	• Rapid drilling of clay, silt and reasonably compacted sand and gravel • Allows split-spoon and thin-wail sampling in unconsolidated materials • Allows core sampling in consolidated rock • Drilling rigs widely available • Abundant and flexible range of tool sizes and depth capabilities • Very sophisticated drilling and mud programs available • Geophysical borehole logs	• Difficult to remove drilling mud and wall cake from outer perimeter of filter pack during development • Bentonite or other drilling fluid additives may influence quality of groundwater samples • Circulated (ditch) samples poor for monitoring bore screen selection • Split-spoon and thin-wall samplers are expensive and of questionable cost effectiveness at depths greater than about 45 m • Wireline coring techniques for sampling both unconsolidated and consolidated formations often not available locally • Difficult to identify aquifers • Drilling fluid invasion of permeable zones may compromise validity of subsequent monitoring bore samples
AIR ROTARY	• Rapid drilling of semi-consolidated and consolidated rock • Good quality/reliable formation samples (particularly if small quantities of water and surfactant are used) • Equipment generally available • Allows easy and quick identification of lithologic changes • Allows identification of most water-bearing zones • Allows estimation of yields in strong water-producing zones with short "down time"	• Surface casing frequently required to protect top of hole • Drifting restricted to semi-consolidated and consolidated formations • Samples reliable but occur as small particles that are difficult to interpret • Drying effect of air may mask lower yield water producing zones • Air stream requires contaminant filtration • Air may modify chemical or biological conditions. Recovery time is uncertain.

METHOD	APPLICATIONS	LIMITATIONS
AIR ROTARY WITH DRIVEN CASING	• Rapid drilling of unconsolidated sands, silts and clays • Drilling in alluvial material (including boulder formations) • Casing supports borehole thereby maintaining borehole integrity and minimising inter-aquifer cross contamination • Eliminates circulation problems common with direct mud rotary method • Good formation samples • Minimal formation damage as casing pulled back (smearing of clays and silts can be anticipated)	• Thin, low pressure water bearing zones easily overlooked if drilling not stopped at appropriate places to observe whether or not water levels are recovering • Samples pulverised, as in air rotary drilling may modify chemical or biological conditions. • Recovery time is uncertain
DUAL WALL REVERSE CIRCULATION ROTARY	• Very rapid drilling through both unconsolidated and consolidated formations • Allows continuous sampling in all types of formations • Very good representative samples can be obtained with minimal risk of contamination of sample and/or water-bearing zone • In stable formations, bores with diameters as large as 150 mm diameter can be installed in open hole completions	• Limited borehole size that limits diameter of monitoring wells • In unstable formations, well diameters are limited to about 100 mm Air may modify chemical or biological conditions; recovery time is uncertain • Unable to install filter pack unless completed open hole
CABLE TOOL (PERCUSSION)	• Drilling in all types of geologic formations • Almost any depth and diameter range • Ease of monitoring bore installation • Ease and practicality of bore development • Excellent samples of coarse-grained materials	• Drilling relatively slow • Heaving of unconsolidated materials must be controlled

(Modified after Aller et al, 1989)

SURFACE AND BOREHOLE GEOPHYSICS TECHNIQUES

Table D.3 - Summary of Main Geophysical Techniques for Environmental Applications

SURVEY TYPE	HOW METHOD WORKS	DETECT	COMMENTS
ELECTRICAL SURVEYS	A,C. current is introduced into ground; current and potential are measured at specific distances away from source.	Presence of conducting fluids, porosity	
MAGNETOMETER SURVEYS	Strength of magnetic field is measured at various locations on site.	Presence of different rock types: igneous rocks show response, while sedimentary rocks do not	Can also be used to detect buried metallic objects.
SEISMIC SURVEYS	Seismic waves are generated by energy source (hammer or explosive charge) and measured with geophones at various locations on site.	Differences in density and elasticity of soil or rock types	Pressure-wave (P-wave) methods are more common. Shear-wave (S-wave) may provide more resolution for shallow unconsolidated units.
BOREHOLE LOGS	*Measuring device ("sonde") is lowered downhole to measure various properties.*	*Electric log: properties of fluids in borehole* Spontaneous Potential: salinity contrasts between borehole fluids and formation fluids Resistance: Different types soil or rock column Gamma: Differences in radiation between clay/shale and sand Neutron: hydrogen ion content	Combined sondes can be employed to obtain several types of data.

(Modified after Bedient et al, 1994)

Table D.4 - Surface Geophysics Techniques used in Hydrogeological Assessments

METHOD	GENERAL APPLICATION	CONTINUOUS MEASUREMENT	PENETRATION DEPTH	MAJOR LIMITATIONS
RESISTIVITY	Soundings or profiling and mapping	No	No limit (commonly used to couple 100 m)	Requires good ground contact and long electrode arrays. Integrates a large volume of subsurface. Affected by cultural features (metal fences, pipes, buildings, vehicles, etc.).
EM (FREQUENCY DOMAIN)	Profiling and mapping; Very rapid measurements	Yes (to 15m)	60 m	Affected by cultural features (metal fences, pipes, buildings, vehicles).
EM (TIME DOMAIN)	Soundings	No	few 1000 m	Does not provide measurements shallower than about 50 m.
RADAR	Profiling and mapping; Highest resolution of any method	Yes	30 m (typically less than 10 m)	Penetration limited by soil conditions.
SEISMIC REFRACTION	Profiling and mapping soil and rock	No	No limit (commonly used to couple 100 m)	Requires considerable energy for deeper surveys. Sensitive to ground vibrations.
SEISMIC REFLECTION	Profiling and mapping soil and rock	No	Couple 100 m	Shallow surveys, < 30 m are most critical. Sensitive to ground vibrations.
MICRO GRAVITY	Profiling and mapping soil and rock	No	No limit (commonly used to couple 100 m)	Very slow, requires extensive data reduction. Sensitive to ground vibrations.
MAGNETICS	Profiling and mapping soil and rock	Yes	No limit (commonly couple 100 m)	Only applicable in certain rock environments. Limited by cultural ferrous metal features

(Modified after Nielson, 1991)

Table D.5 - Borehole Geophysics Methods

INFORMATION REQUIRED	LOGGING TECHNIQUES
Lithology and stratigraphic correlation of aquifers and associated rocks	Electric, sonic, or caliper logs made in open holes; nuclear logs made in open or cased holes
Total porosity or bulk density	Calibrated sonic logs in open holes, calibrated neutron or gamma-gamma logs in open or cased holes
Effective porosity or true resistivity	Calibrated long-normal resistivity logs
Clay or shale content	Gamma logs
Permeability	No direct measurement by logging. May be related to porosity, injectivity, sonic amplitude
Secondary permeability-fractures, solution openings	Caliper, sonic, or borehole televiewer or television logs
Specific yield of unconfined aquifers	Calibrated neutron logs
Grain size	Possible relation to formation factor derived from electric logs
Location of water level or saturated zones	Electric, temperature, or fluid conductivity in open hole or inside casing, neutron or gamma-gamma logs in open hole or outside casing
Moisture content	Calibrated neutron logs
Infiltration	Time-interval neutron logs under special circumstances or radioactive tracers
Direction, velocity, and path of groundwater flow	Single-bore tracer techniques-point dilution and single-bore pulse; multi-bore tracer techniques
Dispersion, dilution, and movement of leachate	Fluid conductivity and temperature logs, gamma logs for some radioactive wastes, fluid sampler
Source and movement of water in a bore	Injectivity profile; flowmeter or tracer logging during pumping or injection; temperature logs
Chemical and physical characteristics of water, including salinity, temperature, density, and viscosity	Calibrated fluid conductivity and temperature in the bore; neutron chloride logging outside casing; multi-electrode resistivity
Determining bore construction, diameter and position of casing, perforations, screen	Gamma-gamma, caliper, collar, and perforation locator; borehole television
Guide to screen setting	All logs providing data on the lithology, water-bearing characteristics, and correlation and thickness of aquifers
Cementing	Caliper, temperature, gamma-gamma; acoustic for cement bond
Casing corrosion	Under some conditions, caliper or collar locator
Casing leaks and/or plugged screen	Tracer and flowmeter

(Modified after Fetter, 1994)

Table D.6 - Borehole Geophysics Use/Limitations Matrix

Borehole Method	**Fluid**		**Casing/screen material**			**Perforations**		**Investigation radius (cm)**	**Comments**
	Air	**Water**	**Open**	**Metal**	**Plastic**	**Screen**	**None**		
Sonic	4	1	1	4	4	4	4	5-50	
Resistivity	4	1	1	4	3	3	4	5-400	
Induction	1	1	1	4	1	1	1	100-400	
Natural Gamma	2	2	2	2	*2*	1	1	5-30	
Gamma Density	2	2	2	2	2	1	1	5-15	
Neutron	2	2	*2*	2	2	1	1	5-15	Big effect with PVC
Caliper	1	1	1	1	1	1	1	0	
TV	1	2	1	1	1	1	1		Clear fluid only
Borehole Fluid Resistivity	4	1	1	1	1	1	1	0	
Vertical Flow	4	1	1	1	1	1	4	0	
Horizontal Flow	4	1	1	1	1	3	4	2-6	Screens strongly influence

1. Works (fluid property and/or bore construction does not adversely affect log)
2. Works (calibration affected)
3. Works qualitatively
4. Does not work

(Modified after Aller et al, 1989)

APPENDIX E

GROUNDWATER MODELLING GUIDANCE

Table E.1 - Comparison of Common Modelling 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	• Relatively simple compared with finite element method • May require less memory than finite element method • Coupled systems can be solved • Versatile	• Computationally demanding • Geometry must be simple • Grid layout less flexible • Susceptible to numerical dispersion
FINITE ELEMENT METHOD	• Geometry can be complex • Realistic and versatile • Coupled systems allowed • Grid layouts very flexible	• Computationally demanding • Susceptible to numerical dispersion

Table E.2 - Key Data Requirements for Groundwater Flow Models

AREAL FLOW MODE	**INPUT DATA**	• Aquifer geometry (areal extent, aquifer thickness, etc.) • Recharge distribution in the areal plane • Bore locations, pumping rates • Hydraulic conductivity distribution (Kx, Ky, Kz) • Storativity (specific yield for unconfined aquifers; storage coefficient for confined aquifers) • Boundary conditions (river elevations, flow divides)
	CALIBRATION DATA	• water table elevations (transient or long-term average for steady state) • Observed response of pumping bores • Observed discharge to surface water
VERTICAL SECTION (SLICE) MODEL	**INPUT DATA**	• Geometry of aquifer base along the section • Steady state recharge distribution • Horizontal and vertical hydraulic conductivity distribution • Boundary conditions (river elevations. flow divides)
	CALIBRATION DATA	• Recorded long-term average water table elevations • Observed long-term average potentials in piezometers • Groundwater velocity (observed or estimated) • Observed steady state discharge to surface water

Table E.3 - Analysis of Model Dimensionality

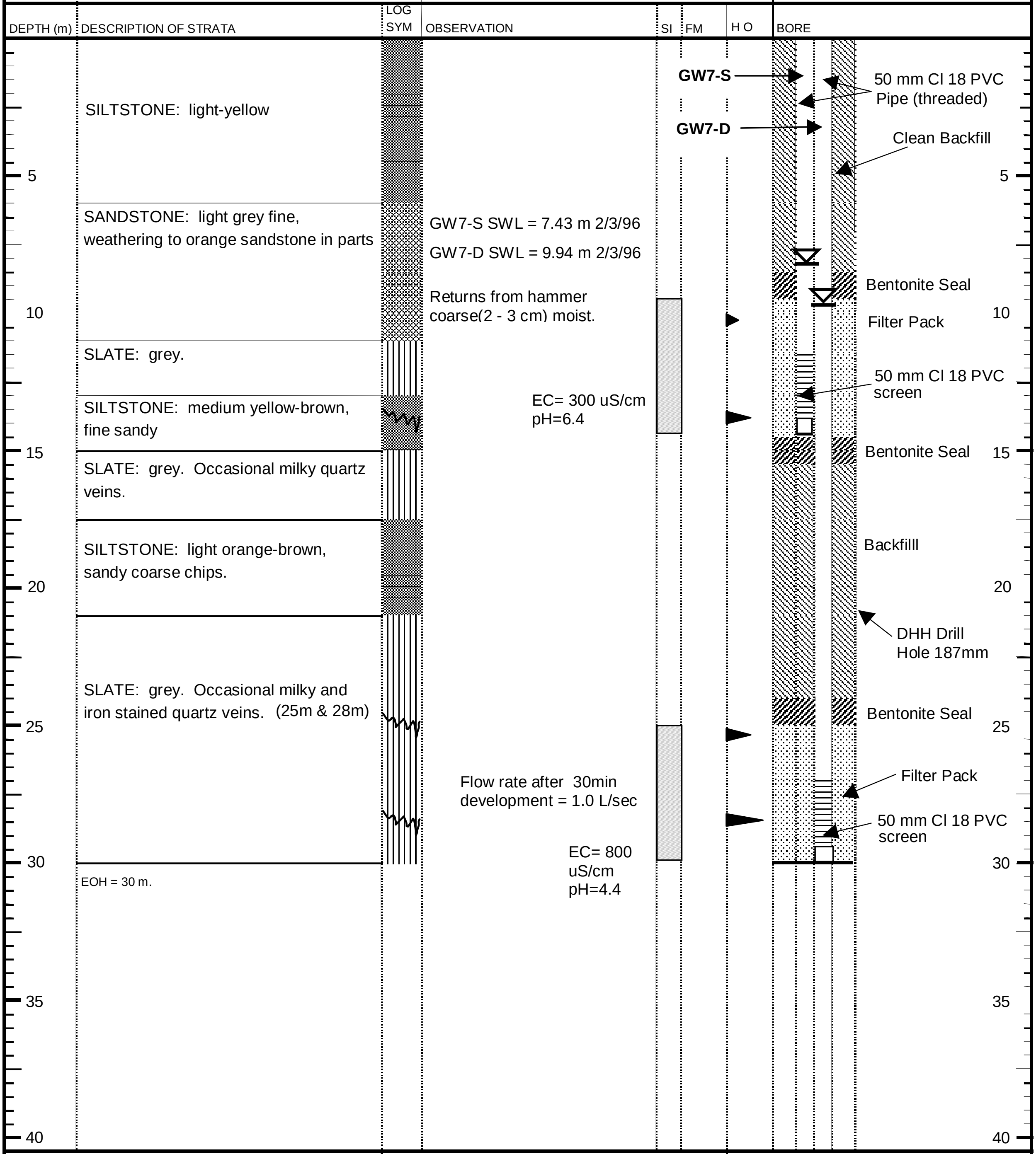
MODEL	TYPICAL APPLICATIONS	ASSUMPTIONS/LIMITATIONS
ONE DIMENSION	• Preliminary concept evaluation • Vertical migration from a large source Darcy's Law applications • Migration through landfill liners • Local scale processes, sensitivity analyses • Unsaturated zone modelling	• Transverse flow neglected • Transverse dispersion neglected • No geometry Highly simplified
TWO DIMENSION, AREAL	• Areal extensive, vertically thin aquifers • Capture zones, purge bore networks • Multi-aquifer models, leaky aquifers • Transport from a laterally wide source	• Vertical flow neglected • Vertical dispersion neglected • Fully screened bores • 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 bore or purge bore	• Restrictive geometry • Radially symmetric • Homogeneous flow properties
THREE DIMENSION	• Depth-dependent processes within 3-D heterogeneous systems • Complex aquifer geometry and structure • Multiple, partially screened bores • Long-term transport from small source	• High computational demands (memory and execution time) • Large effort: field data collection; model development and calibration.

APPENDIX F BORE LOG

BORE LOG

BORE NO: **GW7-S & GW7-D**

CLIENT:	BLOGGS AUSTRALIA PTY LTD	DATE DRILLED:	22-02-96	EASTING	413034.95
PROJECT	HYDROGEOLOGICAL INVESTIGATION	LOGGED/CHKD BY:	J.Brown	NORTHING	5450367.37
LOCATION:	Northbridge, Victora	DRILLED BY:	Acme Drill (D.Grey)	SURFACE RL (mAHD)	66.44
JOB NO:	0021/38	RIG TYPE:	PIONEER DHHammer		



SILTSTONE: light-yellow

SANDSTONE: light grey fine, weathering to orange sandstone in parts

SLATE: grey.

SILTSTONE: medium yellow-brown, fine sandy

SLATE: grey. Occasional milky quartz veins.

SILTSTONE: light orange-brown, sandy coarse chips.

SLATE: grey. Occasional milky and iron stained quartz veins. (25m & 28m)

EOH = 30 m.

GW7-S SWL = 7.43 m 2/3/96

GW7-D SWL = 9.94 m 2/3/96

Returns from hammer coarse(2 - 3 cm) moist.

EC= 300 uS/cm
pH=6.4

Flow rate after 30min development = 1.0 L/sec

EC= 800 uS/cm
pH=4.4

Sampling and Test Legend

H = hard, FB = friable, VS = very soft
S = soft, F = firm, ST = stiff, VST = very stiff
SI = sample interval, FM = field measurements
▶ Groundwater inflow
▽ Groundwater Level

Notes

Bore GW7-S constructed in this bore - screened 9.5 - 14.5 m.
Bore GW7-D constructed in this bore screened 25 - 30 m.
Bore fitted with a locked stand-pipe (150 mm steel)
Survey peg at ground level is measurement point

Author/s:
Lane, Mr Anthony;Leonard, Mr John;Weaver, Dr Tamie R

Title:
Groundwater Quality Hydrogeological Assessments

Date:
1999

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