Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development

CONSULTATION DRAFT – NOT FOR OFFICIAL USE

Consultation on Draft National Minimum Groundwater Monitoring Guidelines

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) is seeking comment on the *Draft National Minimum Groundwater Monitoring Guidelines*.

The IESC notes the draft nature of the Guidelines and welcomes feedback on the content, usability and applicability. In particular, views are sought on:

- **the technical content within the draft Guidelines. Are there any areas that are missing or not captured adequately?**
- **the relevance to your specific area of work and any views on its uptake and adoption; and**
- **potential options to increase uptake and adoption.**

The IESC and the National Minimum Groundwater Monitoring Guidelines

The IESC is a statutory body under the Environment Protection and Biodiversity Conservation Act 1999 (Cth). One of the IESC's key legislative functions is to provide independent scientific advice to the Australian Government Environment Minister and relevant state ministers in relation to coal seam gas (CSG) and large coal mining (LCM) development proposals that are likely to have a significant impact on water resources.

The IESC has identified a need to improve the understanding of groundwater monitoring requirements and recommended that OWS commission the development of "strawman" guidance material that reviews and standardises groundwater monitoring requirements across Australia.

National Minimum Groundwater Monitoring Guidelines

Groundwater monitoring plays an essential role in impact assessment and timely detection of impacts for a wide variety of projects from road construction, industry and agriculture to mineral and petroleum exploration and extraction. In Australia, the risk of potential impacts on groundwater from these project activities is managed under several state/territory and Commonwealth regulatory processes. While mandatory requirements may vary between states/territories and activities, there is a need for a shared, nationally consistent understanding of minimum groundwater monitoring requirements relative to the risks of the activities involved. The purpose of these guidelines is to recommend minimum requirements for groundwater monitoring and related field investigation programs. These guidelines adopt a risk-based approach.

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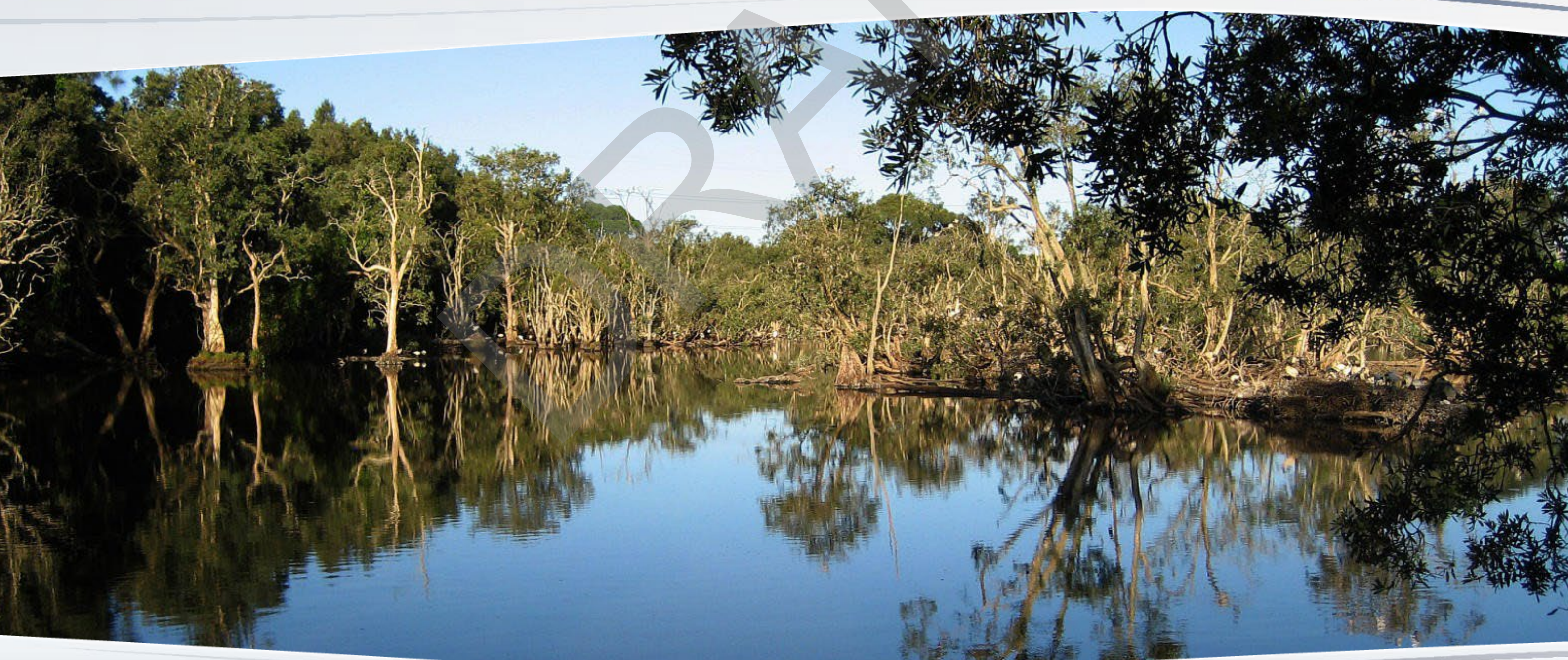
Draft National Minimum Groundwater Monitoring Guidelines



This report should be attributed as '*Draft National Minimum Groundwater Monitoring Guidelines'*, Commonwealth of Australia, 2023'.

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Images

Draft National Minimum Groundwater Monitoring Guidelines

Acknowledgements

These guidelines were commissioned by the Department of Climate Change, Energy, the Environment and Water on the advice of the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) to improve the understanding and clarity of groundwater monitoring requirements in Australia. The Fenner School of Environment & Society and Institute for Water Futures at the Australian National University were commissioned by the Office of Water Science (OWS), on behalf of the IESC, to develop overarching guidance material that reviews and standardises minimum groundwater monitoring requirements across Australia.

Members of the National Groundwater sub-Committee (NGSC) formed the Steering Committee for this project and, along with the IESC, provided comments and guidance on throughout the project.

Once these guidelines are approved by the Steering Committee and IESC, the NGSC will submit them to the National Water Reform Committee for endorsement.

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Executive summary

Groundwater monitoring plays an essential role in impact assessment and timely detection of impacts for a wide variety of projects from road construction, industry and agriculture to mineral and petroleum exploration and extraction. In Australia, the risk of potential impacts on groundwater from these project activities is managed under several state/territory and Commonwealth regulatory processes. While mandatory requirements may vary between states/territories and activities, there is a need for a shared, nationally consistent understanding of minimum groundwater monitoring requirements relative to the risks of the activities involved. The purpose of these guidelines is to recommend minimum requirements for groundwater monitoring and related field investigation programs. These guidelines adopt a risk-based approach.

Monitoring design (Section 2): Pre-approval monitoring

For projects in the pre-approval phase, groundwater monitoring and other related field investigations are undertaken to inform a groundwater impact assessment that will be submitted to government to seek approval for the proposed project.

Groundwater monitoring should be undertaken prior to project approval where a desktop assessment indicates there are potential adverse impacts to groundwater resources and related assets and ecosystems associated with the proposed project, there is uncertainty about the potential risks, or additional data are needed for impact assessment. The desktop assessment should include:

- a review of available information on the proposed project, the project site, the geological and hydrogeological environment, groundwater-related assets and ecosystems, and the regulatory context;
- a review of existing groundwater monitoring networks, data, modelling, and reports;
- an initial site inspection;
- development of an ecohydrological conceptual model and risk assessment for the proposed project; and
- development of a groundwater monitoring plan where groundwater monitoring and other related field investigations are planned.

Pre-approval groundwater monitoring should be undertaken to characterise the groundwater system and its key processes, identify and describe groundwater-related assets and ecosystems and assess their groundwater needs, and assess connectivity between groundwater systems and between groundwater and surface water systems. Baseline groundwater levels/pressures and groundwater quality should be established to inform impact assessment and allow for detection of impacts post-approval. A risk-based approach should be used to decide the duration of baseline monitoring and, at a minimum, baseline monitoring should be undertaken for a period of at least two years prior to numerical groundwater modelling and preparation of a groundwater impact assessment where there is potential for material risks to groundwater resources and related assets. While these guidelines do not recommend specific requirements for ecological monitoring, it is recommended that a multi-disciplinary approach be adopted, working closely with ecologists and other relevant experts.

Monitoring design (Section 2): Post-approval monitoring

For projects in the post-approval phase (including construction, operation, and post-operation/closure), groundwater monitoring should comply with any conditions of approval for the project and aim to provide for early detection of impacts on groundwater resources or related assets and ecosystems and further investigate uncertainties about the groundwater system and related assets and ecosystems, updating the conceptual model as necessary.

Post-approval groundwater monitoring should continue for the duration of the construction, operation and post-operation (including decommissioning, rehabilitation and closure) phases of the project until impacts on groundwater resources and related assets and ecosystems are unlikely.

The groundwater monitoring plan should be updated after project approval and as new information arises or new project activities are planned and may include trigger values for groundwater levels/pressures or guideline values for groundwater quality parameters.

Monitoring network design (Chapter 3)

The design of a groundwater monitoring network will be unique for each project and should be based on the monitoring objectives, risk assessment and uncertainties informed by the ecohydrological conceptual model.

Groundwater monitoring should be undertaken in dedicated installations such as monitoring bores or vibrating wire piezometers, with the type and design of monitoring installation governed by the purpose for which the data are being collected. Monitoring bores (or other installations) should be located to target groundwater-related assets and ecosystems and areas of high uncertainty or risk. Where it is necessary to establish groundwater flow direction and hydraulic gradients, a minimum of three monitoring bores completed within each aquifer are required for triangulation. Nested installations should be used to target all aquifers through the profile with the potential to be impacted by the project and be designed to detect vertical variation within and between aquifers.

Monitoring bores should be drilled, constructed, maintained and developed, and records should be kept, in accordance with the Minimum Construction Requirements for Water Bores in Australia, with additional considerations for monitoring bores to ensure data collected from the bore are representative of groundwater conditions in the aquifer targeted by the monitoring bore. Downhole geophysics should be used during construction in circumstances where lithological complexity may impact the construction of monitoring installations and therefore interpretation of monitoring data and resulting risk assessments.

Drilling and construction of monitoring installations should be undertaken by an appropriately licensed and experienced driller and an appropriately experienced field hydrogeologist. When deciding whether an existing bore is appropriate to use in a monitoring network, the location, construction and condition of the bore should be assessed. All monitoring installations should have a unique number or name and the location and elevation of the bore should be surveyed.

Groundwater level/pressure monitoring (Chapter 4)

Groundwater level/pressure monitoring provides the fundamental data needed to characterise groundwater resources, understand how groundwater systems behave over time, and detect impacts, and should be undertaken for all projects with the potential to impact on groundwater resources and related assets and ecosystems.

The frequency of groundwater level/pressure measurements should be adequate to detect short-term and seasonal groundwater level/pressure fluctuations of interest and to discriminate between the effects of short- and long-term hydrologic stresses. Automatic monitoring is recommended and should be undertaken for all projects requiring numerical groundwater modelling to predict impacts.

Groundwater level/pressure measurement should be undertaken in accordance with the Bureau of Meteorology National Industry Guidelines for hydrometric monitoring and other relevant standards and guidelines. The location and elevation of all groundwater monitoring bores should be accurately surveyed to establish horizontal and vertical datums. Groundwater level/pressure data should be corrected for well fluid-column density effects (including temperature and salinity) and natural external stresses (including changes in atmospheric pressure and mechanical loading/unloading) where appropriate.

Groundwater quality monitoring (Chapter 5)

Groundwater quality monitoring is undertaken for numerous reasons including characterising groundwater systems, improving conceptual understanding of groundwater systems, establishing baseline groundwater quality conditions, and detecting impacts to groundwater. The overarching objective of groundwater quality monitoring is the protection of environmental values (the values and uses of the groundwater for ecosystems and people). Groundwater quality monitoring should be undertaken for all projects with the potential to impact on groundwater resources and related assets and ecosystems.

Groundwater quality monitoring should be undertaken in accordance with The Australian and New Zealand Guidelines for Fresh and Marine Water Quality and other relevant standards and guidelines. Baseline monitoring programs should include monitoring for major ions, physical parameters, and contaminants that are relevant to the site and proposed project. The frequency of groundwater quality measurements should depend on the risks but should, at a minimum, occur quarterly unless there are risk-based reasons to differ.

Sampling methods and equipment should be selected for each individual bore to take a representative sample of the groundwater in the formation of interest. Sample preparation, storage, and transport procedures should ensure the chemical composition of samples is not affected during transport to the laboratory and that the laboratory receives a sample that is suitable for analysis for the parameters of interest. Sampling equipment and instruments should be maintained, stored, serviced, and calibrated as specified in the operating manual. Samples should be sent to an analytical laboratory that is accredited by the National Association of Testing Authorities (NATA), except in special circumstances where justified.

Quality management should be implemented including quality assurance (QA) procedures to minimise errors and a quality control (QC) program to identify and quantify potential quality issues that have arisen during the sampling, handling, storage and transport process. Field blank samples, field duplicate samples, and field spike samples (where appropriate) should be prepared and analysed as part of the monitoring program.

Other field investigation methods (Chapter 6)

Other field investigation methods (in addition to groundwater level/pressure and quality monitoring) may be necessary to characterise the groundwater system and assess potential adverse impacts associated with the proposed project. The appropriate investigation methods will be unique to each project and should be selected and designed based on the ecohydrological environment, project risks, and areas of scientific uncertainty.

Most projects will require field assessment of aquifer hydraulic properties to provide an informed assessment of potential adverse impacts to groundwater resources and related assets and ecosystems. Test pumping of productive formations at risk of adverse impacts should be undertaken for all proposed projects where numerical groundwater modelling is being used for impact assessment. Surface water monitoring should be undertaken for proposed projects where it is important to assess and characterise surface water-groundwater connectivity. A bore census survey should be undertaken for all projects with the potential to impact on water supply bores. Other field investigation methods to be considered to improve characterisation of the groundwater system and assessment of risks include hydrochemistry and environmental tracers, remote sensing and geophysical methods, and surface outcrop mapping.

Recording and reporting data (Chapter 7)

All data and metadata gathered during a groundwater monitoring program should be recorded in a consistent and logical manner using data collection sheets or similar and stored securely in a backed-up computer-based data management system. Primary measured data and associated metadata should be permanently retained, archived in an unedited form, and locked to prevent editing. Where data have been edited, details of the processes used to edit, correct, or analyse the data should be documented. Structured data should be stored and transferred in machine-readable formats compatible with the vocabulary defined by the National Groundwater Information System.

All groundwater monitoring programs should include quality management processes. Quality assurance procedures should be put in place to prevent errors occurring, including following standard procedures for groundwater monitoring, using qualified, trained and experienced staff, subcontractors and subconsultants, maintaining, servicing, and calibrating instruments, following data management procedures, and peer review of data analysis and interpretation. A quality control plan should be implemented to detect and quantify errors.

Groundwater monitoring reports should be standalone documents and include all relevant information needed to interpret the data presented.

1 Introduction

Groundwater monitoring plays an essential role in impact assessment and timely detection and response to impacts for a wide variety of projects from road construction, industry and agriculture to mineral and petroleum exploration and extraction. In Australia, the risk of potential impacts on groundwater from these project activities is managed under several state/territory and Commonwealth regulatory processes. While mandatory requirements may vary between states/territories and activities, there is a need for a shared, nationally consistent understanding of minimum groundwater monitoring requirements relative to the risks of the activities involved.

1.1 Purpose of these guidelines

The purpose of these guidelines is to recommend minimum requirements for groundwater monitoring and related field investigation programs. The recommended minimum requirements are intended for use by project proponents, government, consultants, and the community, for:

- project managers and experts to appropriately resource, design and deliver monitoring programs
- technical experts and regulators to evaluate proposed monitoring programs, recommend improvements, and inform approvals; and
- consultants, the community, and interested parties to help articulate and discuss expectations and results for any given project.

Emphasis is on providing normative information about what needs to be done, why, and in what circumstances, rather than descriptive information about how to do it. Some prior knowledge is assumed about aquifers and their basic properties, statistical analysis, project and risk management, and project approval processes. Wherever possible, the guidelines do provide illustrative worked examples and suggestions for further resources.

The guidelines are therefore positioned to have a specific role within a broader ecosystem of guidelines about groundwater monitoring. They specify recommended minimums to be applied at the discretion of regulators with consideration of the specific risks and circumstances of the proposed project. The recommended minimum guidelines are not prescribed by law (though some provisions may be separately enforced by state/territory or Commonwealth legislation).

The guidelines are written to complement:

- current or future guidelines on related groundwater impact management topics, including risk assessment and groundwater modelling;
- field guides, standard operating procedures, and best practice industry guidelines for specific monitoring or project activities, which tend to provide more detail on implementation of monitoring; and
- current or future guidelines in related areas, including international and Australian standards.

In particular, these guidelines refer to and complement:

- Geoscience Australia Groundwater Sampling and Analysis – A Field Guide[1], which provides specific instructions without stating impact assessment-specific minimum requirements;
- Bureau of Meteorology National Industry Guidelines for hydrometric monitoring[2], which tend to provide universally applicable rather than risk-based requirements;
- Australian and New Zealand Guidelines for Fresh and Marine Water Quality[3], which cover an expansive scope without a specific focus on groundwater;
- multiple Independent Expert Scientific Committee (IESC) Explanatory Notes[4] covering specific topics; and
- multiple Australian/New Zealand Standards covering specific topics.

A list of identified existing guidelines is provided in Appendix B.

It is expected that these minimum groundwater monitoring guidelines will need to be updated in future as practice continues to mature.

1.2 Scope of the guidelines

The guidelines focus on impact assessment of projects affecting groundwater. This includes a broad range of activities involving penetration of an aquifer, interference with water in an aquifer, obstruction of flow, taking of water (outside of a water allocation planning context) or disposal of water. At the discretion of the respective regulator, all state/territory and Commonwealth impact assessment processes related to groundwater are considered to be within scope. To keep the scope broad, the guidelines avoid referring to specific project approval processes.

The guidelines are not intended for state/territory or Commonwealth long-term ambient monitoring programs. They also do not address specific requirements prescribed by state/territory water allocation plans, such as assessing impacts of trading water entitlements or taking water under new entitlements.

The guidelines are focused on design of monitoring and therefore will primarily be used pre-development, but this includes consideration of post-approval monitoring, i.e. the guidelines include baseline monitoring, and monitoring to characterise groundwater systems for impact assessment, and impact detection monitoring during the construction, operation, and post-closure phases of a project.

In these guidelines, baseline monitoring is repeated monitoring of groundwater, over a period of time, to establish groundwater conditions. Monitoring for groundwater system characterisation includes drilling investigations, groundwater monitoring, and other field investigations to characterise the groundwater system, its key processes, and its associated groundwater-related assets and ecosystems. Impact detection monitoring (also known as surveillance monitoring) is intended to anticipate and catch potential impacts as early as possible. Impact detection monitoring includes monitoring for compliance with conditions of approval (compliance monitoring).

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[1] Sundaram B 2009. *Groundwater Sampling and Analysis - A Field Guide.* Record 2009/027. Geoscience Australia, Canberra. Available [online]: http://pid.geoscience.gov.au/dataset/ga/68901.

[2] Bureau of Meteorology 2021. *National Industry Guidelines for hydrometric monitoring.* Available [online]: http://www.bom.gov.au/water/standards/niGuidelinesHyd.shtml.

[3] ANZG 2018. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality.* Canberra, ACT, Australia, 2018. Available [online]: https://www.waterquality.gov.au/anz-guidelines.

[4] IESC 2022. *Information Guidelines.* Available [online]: https://iesc.environment.gov.au/information-guidelines.

The guidelines should not be used for contaminated sites groundwater investigations or monitoring of regulated industrial sites, for which other processes exist, i.e. the National Environmental Protection (Assessment of Site Contamination) Measure.[5]

These guidelines do include minimum requirements for monitoring that will be used for modelling and risk assessment, and emphasise the importance of conceptual modelling and risk assessment in designing monitoring. However, as noted above, these guidelines do not cover and are intended to be complementary to other guidelines on groundwater modelling and risk assessment specifically.

Health and safety are not discussed in these guidelines. It should be understood that all activities undertaken for groundwater monitoring should be in accordance with state/territory requirements for Occupational Health and Safety. Groundwater monitoring commonly includes high-risk activities, such as working around drill rigs, working with air compressors, working with chemicals, and driving off-road to remote locations. Risk assessments should be conducted and occupational health and safety protocols should be established, including considering the potential hazards for each fieldwork trip. Monitoring teams should be trained in the safety protocols and use of the equipment and have appropriate personal protective equipment.

1.3 Principles

1.3.1 Risk-based minimum requirements

These guidelines adopt a risk-based approach to minimum monitoring requirements. Consistent with the breadth of contexts and activities to which the guidelines are intended to apply, emphasis is not on a single set of universal requirements or on requirements specific to each possible project activity. Instead, monitoring requirements depend on the risk that proponents, regulators and the community are willing to accept, which also depends not just on the activities involved, but also on the characteristics of the groundwater system and the risk mitigation measures put in place. Higher risks may require a greater weight of evidence drawing on multiple lines of evidence, and greater effort to reduce uncertainty.

1.3.2 Explicit and iterative planning and improvement

The guidelines start from the premise that there will always be uncertainty around the behaviour of each unique groundwater system, as the subsurface environment is complex, heterogeneous, and difficult to directly observe, characterise or measure. Understanding of how a project may impact a groundwater system should be expected to progressively improve over time. Provision should be made for risk assessments to be updated over time as new information arises or new project activities are planned. Monitoring should track changes to the system due to external drivers, such as climatic conditions, not just impacts due to project activities. Project members should aim to be able to anticipate changes and to resolve any discrepancies between anticipated and actual system behaviour.

As an unseen resource, stewardship of groundwater resources requires special attention to transparency and collaboration in monitoring and risk assessment. Monitoring objectives and processes should be made explicit in a groundwater monitoring plan, which needs to be informed by an explicit risk assessment that draws on a clearly communicated and site-specific conceptual model of the ecohydrological system (a "ecohydrological conceptual model"), describing the project activities, groundwater system, and groundwater-related assets and ecosystems (which include water supply bores, groundwater-dependent ecosystems, connected groundwater and surface water resources and culturally significant sites, as defined in Section 2.1 of this guideline). Explicit reasoning about the role

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[5] National Environment Protection Council 2013. *National Environment Protection (Assessment of Site Contamination) Measure*. Available [online]: http://www.nepc.gov.au/nepms/assessment-site-contamination.

and design of monitoring is necessary in order to facilitate conversations about management of residual risk with regulators and other stakeholders, and to provide opportunities for regulators and other experts to help identify potential gaps and guide interpretation of monitoring data, which may be evidence to support or refute hypotheses of links in the conceptual model.

The minimum requirements recommended in these guidelines are therefore designed to provide the minimum information needed to inform risk assessment, ecohydrological conceptual model development, hypothesis testing, necessary analyses for impact assessment, as well as post-approval monitoring. Requirements increase where groundwater resources are more valued (e.g., an extensive fresh groundwater system with high yields compared with a saline system with low yields) and risks to groundwater dependent assets and ecosystems are higher.

1.3.3 Shared responsibility and objectives

It is recognised that monitoring and design of a fit-for-purpose monitoring program for project approval and compliance are non-trivial tasks to which significant resources need to be devoted. The recommended minimum requirements should be read as a collective goal to be achieved through collaboration between government, project proponents, and the community, rather than a prescription for a specific party to follow. A collaborative approach is needed to share responsibility and costs fairly and efficiently, including costs of planning, field investigations and monitoring, regulatory review, compliance monitoring, and community review and scrutiny. The guidelines also do not recommend any processes for dispute resolution, but recognise the need for sufficient transparency (consistent with the principle of explicit and iterative planning and improvement) and need to acknowledge potential for real or perceived conflicts of interest.

The objectives of groundwater monitoring are considered to be a shared concern with regard to supporting sustainable development. Namely, monitoring involves collecting data over time with the purpose of meeting specific objectives. The objective of groundwater monitoring is to provide the information needed to assess and mitigate risks that may arise from potential impacts associated with a project, to reduce uncertainty in the assessment and mitigation of risks, and to provide early warning of potential impacts to groundwater resources and related assets and ecosystems.

1.3.4 Feedback loops for impact assessment/monitoring and continuous improvement

There are two key feedback loops at play that underpin the success of monitoring. The first is a decision cycle for impact assessment/monitoring driven by data collection (Figure 1.1). Similarly to the observe-orient-decide-act loop well known in a military context, the aim is to stay ahead of unfolding events. Observed data are oriented for decision making by understanding how they fit in how the system works, as described by an ecohydrological conceptual model, while noting that the model also has associated uncertainty and the model may also be refined using the data. Risk assessment of anticipated or detected impacts determines risk treatments, including possible further monitoring or investigation activities, which are then put in action.

The second feedback loop provides for continuous improvement of risk management, roughly following a plan–do–check–adjust loop (Figure 1.2). Project risk assessment identifies further improvement required in risk management planning, which is operationalised through data collection. Discrepancies between observed system behaviour and expected behaviour according to the ecohydrological conceptual model feed into updated understanding of project risks (and refinement of the model).

In both feedback loops, anticipation of risks plays an important role due to delays in observing impacts, particularly in groundwater. Specific care is needed to ensure monitoring is able to provide timely detection of impending impacts. In the learning process, there should be awareness of changes in the hydrological cycle, including those related to climate change.

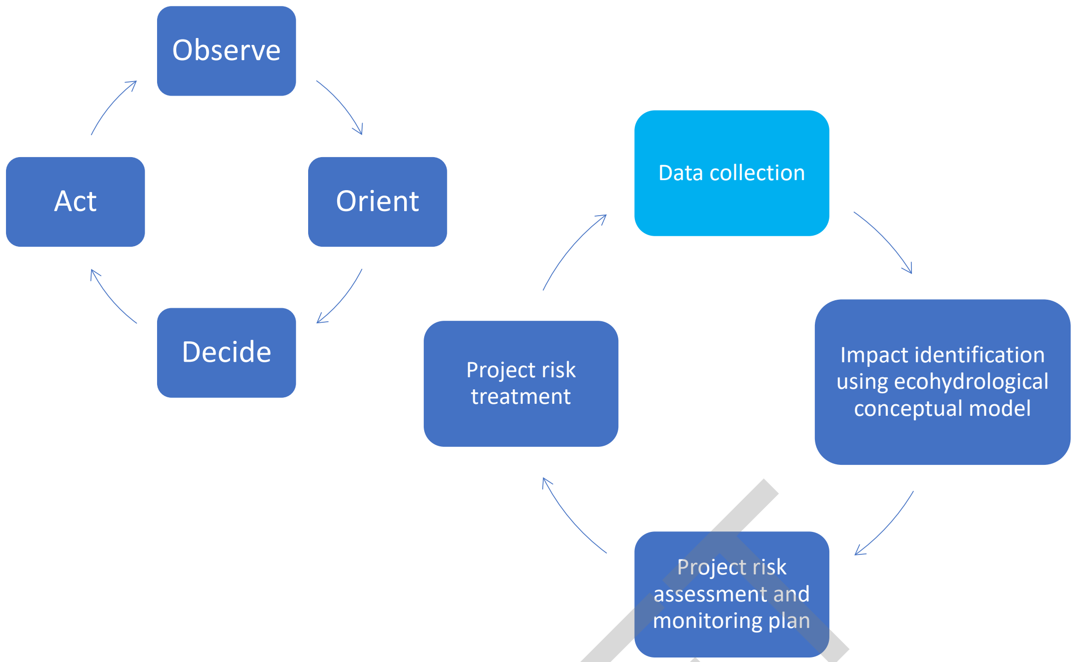

Figure 1.1 Decision cycle for impact assessment/detection

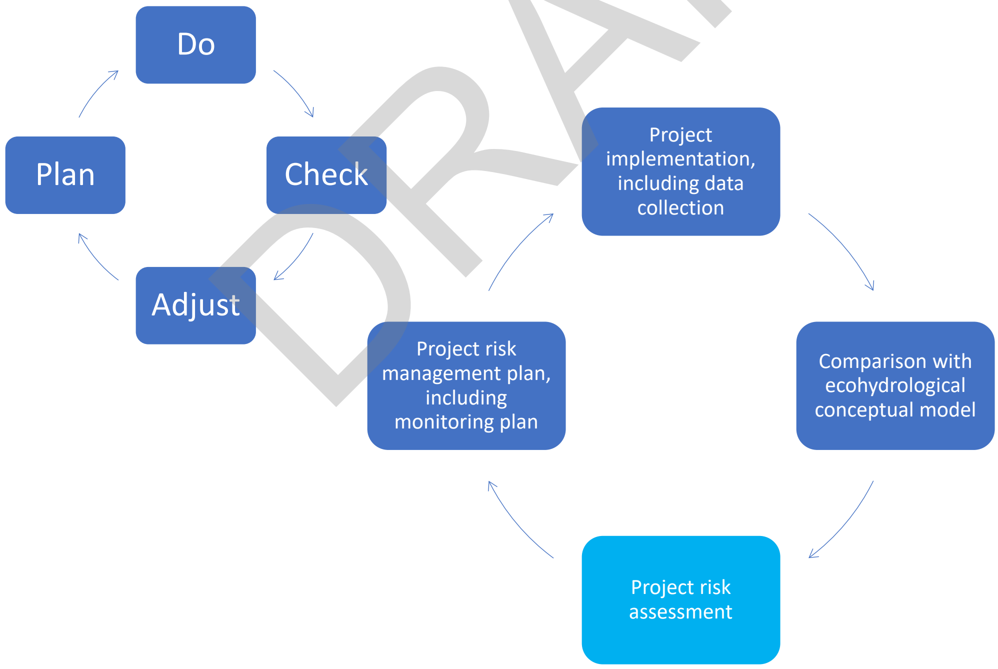

Figure 1.2 Continuous improvement loop for risk management

Concretely, monitoring therefore helps identify or characterise both the ecohydrological system itself and changes or impacts within that system. The broad objectives of groundwater monitoring will depend on what phase the project is in (pre-approval or post-approval) and may include:

- identifying and characterising groundwater resources and groundwater-related assets and ecosystems, including connected surface water systems, to inform an assessment of risks associated with a proposed project or a proposed modification of an existing development project (pre-approval);

- establishing baseline groundwater conditions prior to commencement of development a project (pre- and post-approval); and
- providing for early detection of impacts to groundwater resources and groundwater-related assets and ecosystems at risk due to a project (post-approval).

1.4 Overview of guidelines

Consistent with the principle of iterative planning and improvement, monitoring involves the repeated use of a similar set of methods in different contexts, e.g., water level/pressure monitoring in pre-approval monitoring, baseline monitoring, and post-approval impact monitoring. Similarly, other field investigation methods are potentially used in development and refinement of ecohydrological conceptual models, risk assessment, and in interpretation of results post-approval.

The guidelines are therefore split into two parts, with Part I specifying overall requirements for the monitoring process, and Part II providing requirements for specific methods or activities.

Part I Monitoring process

- Chapter 2 Monitoring design
- Chapter 3 Monitoring network

Part II Methods

- Chapter 4 Groundwater level/pressure monitoring
- Chapter 5 Groundwater quality monitoring
- Chapter 6 Other field investigation methods
- Chapter 7 Recording and reporting data

- Glossary
- Appendix A List of information to record
- Appendix B List of related guidelines

2 Monitoring design

2.1 Problem definition and terminology

Groundwater monitoring may be undertaken for a variety of reasons. The focus of these guidelines is groundwater monitoring for projects with the potential to impact on groundwater resources, water supply bores, and connected ecosystems. Groundwater monitoring for these projects must be undertaken in accordance with the requirements of the relevant state/territory government and any applicable Commonwealth government requirements. Recommended minimum requirements are included in this guideline for groundwater monitoring undertaken as part of:

- a groundwater impact assessment report submitted to government to seek approval for a proposed project (pre-approval); and
- a groundwater monitoring report submitted to government for compliance with conditions for an approved project (post-approval).

Figure 2.1 summarises the problem of groundwater monitoring design, as conceptualised in this guideline. A 'project' involves project activities at a project site that have potential impacts within a broader 'study area' either on one or more 'groundwater resources' or 'groundwater-related assets and ecosystems'. This system is described by a 'ecohydrological conceptual model' (Section 2.2.2), which is used to guide a risk assessment (Section 2.2.3), and hence develop a monitoring plan (Section 2.2.4) for data collection, which is expected to help update the ecohydrological conceptual model and therefore improve the risk assessment over time (see Chapter 1). The conceptual model may also be used to plan and justify risk mitigation strategies and associated monitoring of their effectiveness.

The pre-approval phase (Section 2.2) starts this feedback loop with a desktop study and initial site inspection (Section 2.2.1) and is responsible for a large part of the development of the ecohydrological conceptual model, including groundwater system characterisation, groundwater-related assets and ecosystems, their connectivity, and set-up of baseline monitoring. The post-approval phase (Section 2.3) is expected to continue to improve the conceptual model, risk assessment, and monitoring plan as new information arises (Section 2.3.1), but also implements impact monitoring in conjunction with project activities, intended to anticipate and catch potential impacts as early as possible to allow timely action, including exceedance of trigger thresholds (Section 2.3.2) and impacts on groundwater-related assets and ecosystems (Section 2.3.3).

As summarised in Figure 2.2, monitoring is therefore an iterative process across pre-approval and post-approval phases of a project that involves developing and implementing groundwater level/pressure and groundwater quality monitoring across a monitoring network, along with other supporting field investigations. For low risk projects, monitoring requirements may be quite modest – the principle remains that the minimum requirements are modest because the current risk assessment suggests that risks are low, and the mechanisms should be established to revisit the monitoring plan and risk assessment if new information arises.

Further definitions are given below.

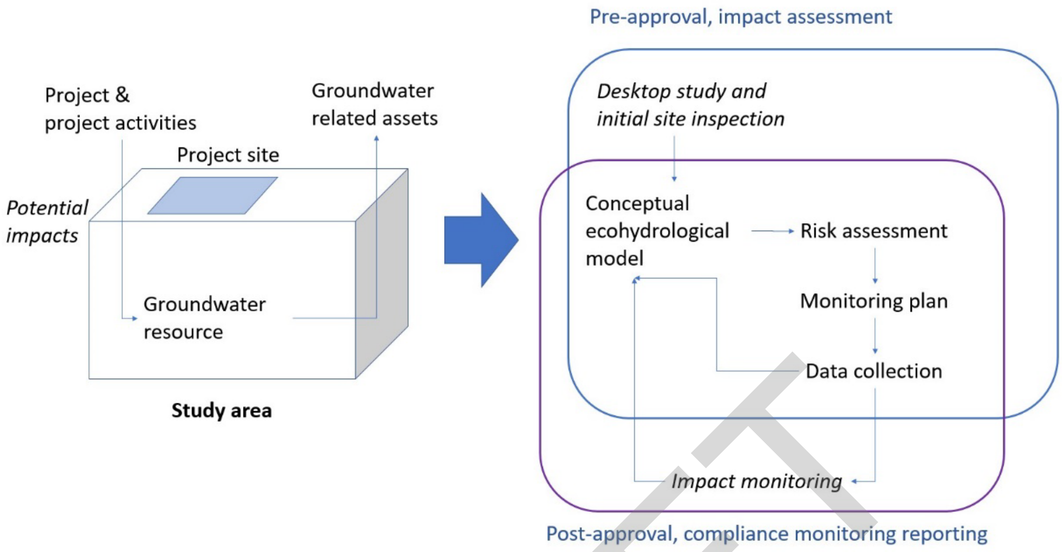

Figure 2.1 Conceptualisation of groundwater monitoring design problem

A 'project' involves project activities at a project site that have potential impacts within a broader 'study area' either on one or more 'groundwater resources' or 'groundwater-related assets and ecosystems'.

This system is described by an 'ecohydrological conceptual model,' which is used to guide a risk assessment, and hence develop a monitoring plan for data collection, which is expected to help update the ecohydrological conceptual model and therefore improve the risk assessment over time.

Monitoring is an iterative process across pre-approval and post-approval phases of a project.

'Project'

A 'project', for the purposes of this guideline, is any development, activity, series of activities, or modification of existing development or activities that may impact on groundwater resources and groundwater-related assets and ecosystems and requires approval from government prior. Examples of projects include:

- dewatering for mining or quarrying activities;
- other projects that require dewatering such as construction and maintenance of buildings, roads, or rail and other civil works;
- extraction of groundwater as a by-product of oil or coal seam gas production;
- extraction of groundwater for water supply;
- managed aquifer recharge;
- landfills;

- brine, saline water, or wastewater disposal schemes;
- storage (at the surface and underground) or transport of hazardous materials;
- mineral and petroleum resource exploration;
- carbon sequestration;
- underground hydrogen storage;
- Underground thermal energy storage; and
- agricultural activities such as irrigation.

'Study area'

A 'study area' for the purposes of this guideline, is the project site and the surrounding area where there is potential for impacts to groundwater resources and groundwater-related assets and ecosystems associated with the project.

A study area is three dimensional and includes all hydrostratigraphic units with the potential to be impacted by the project. This may include formations underlying the formation where activities are occurring. For example, formations underlying a coal seam may experience depressurisation or water quality impacts associated with mining. It also includes surface-expression groundwater-dependent ecosystems such as forests tapping groundwater via plant roots or rivers and lakes receiving baseflow from groundwater.

'Groundwater resource'

A 'groundwater resource' for the purposes of this guideline, is water stored in an aquifer or other water-bearing formation (hereafter aquifer) that can be transmitted and accessed by a 'groundwater-related asset or ecosystem'.

'Groundwater-related assets and ecosystems'

'Groundwater-related assets and ecosystems' for the purposes of this guideline, refers to:

- water supply bores;
- groundwater-dependent ecosystems (GDEs);
- connected groundwater resources; and
- connected surface water resources.

Groundwater-related assets and ecosystems may also be referred to as 'sensitive receptors' or 'groundwater-dependent assets' in this document. It is important to note that groundwater-related assets and ecosystems may be culturally significant sites (CSSs).

A water supply bore is a bore (otherwise known as a well) used for town water supply, an Aboriginal community, irrigation, intensive agriculture, aquaculture, mining, commercial, industrial, livestock, or domestic purposes. Monitoring bores, exploration bores, and gas or petroleum extraction wells are not considered to be water supply bores. Bores that have been decommissioned or destroyed are also not considered to be water supply bores as they cannot be used in future.

A groundwater-dependent ecosystem (GDE) is an ecosystem for which groundwater meets all or part of its water requirements. Examples of GDEs include[6]:

- aquifer and cave ecosystems (subterranean GDEs); and
- ecosystems dependent on the surface expression of groundwater (aquatic GDEs, including river baseflow systems, springs and swamps); and
- ecosystems dependent on the subsurface presence of groundwater (terrestrial GDEs, including some riparian vegetation communities).

A connected groundwater resource is a groundwater system that is hydraulically connected to the groundwater resource of interest. A connected surface water resource is a surface water system that interacts hydraulically, or is hydraulically connected, to the groundwater resource of interest.

A culturally significant site (CSS) is a place that is significant for Indigenous Australians in relation to their cultural and spiritual values and traditions. For the purpose of these guidelines, it includes groundwater-related environmental features and processes that are culturally or spiritually significant, such as streams that receive baseflow or groundwater-dependent ecosystems.

'Ecohydrological Conceptual model'

An ecohydrological conceptual model for the purposes of this guideline, is a descriptive representation of a groundwater system, its key processes, and its associated groundwater-related assets and ecosystems. An ecohydrological conceptual model is a hydrogeological model which shows linkages between the groundwater system and the groundwater-related assets and ecosystems that need to be protected and provides a structure within which to reason about causal pathways. Where possible, these linkages should be quantitative rather than qualitative. The model should include a narrative that describes the evidence for, and confidence in, each linkage.

Ecohydrological conceptual models are used at all stages of the groundwater assessment process and provide the basis for identifying causal pathways, constructing impact pathway diagrams, assessing risks to groundwater resources and connected water resources, water supply bores, GDEs, and CSSs and identifying areas of scientific uncertainty. Plans should be made for ecohydrological conceptual models to be refined when more data become available through groundwater monitoring and other field investigations, and when new project activities are planned.

[6] Doody TM, Hancock PJ, Pritchard JL 2019. Information Guidelines Explanatory Note: Assessing groundwater-dependent ecosystems. Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy, Commonwealth of Australia. Available [online]: https://iesc.environment.gov.au/publications/information-guidelines-explanatory-note-assessing-groundwater-dependent-ecosystems.

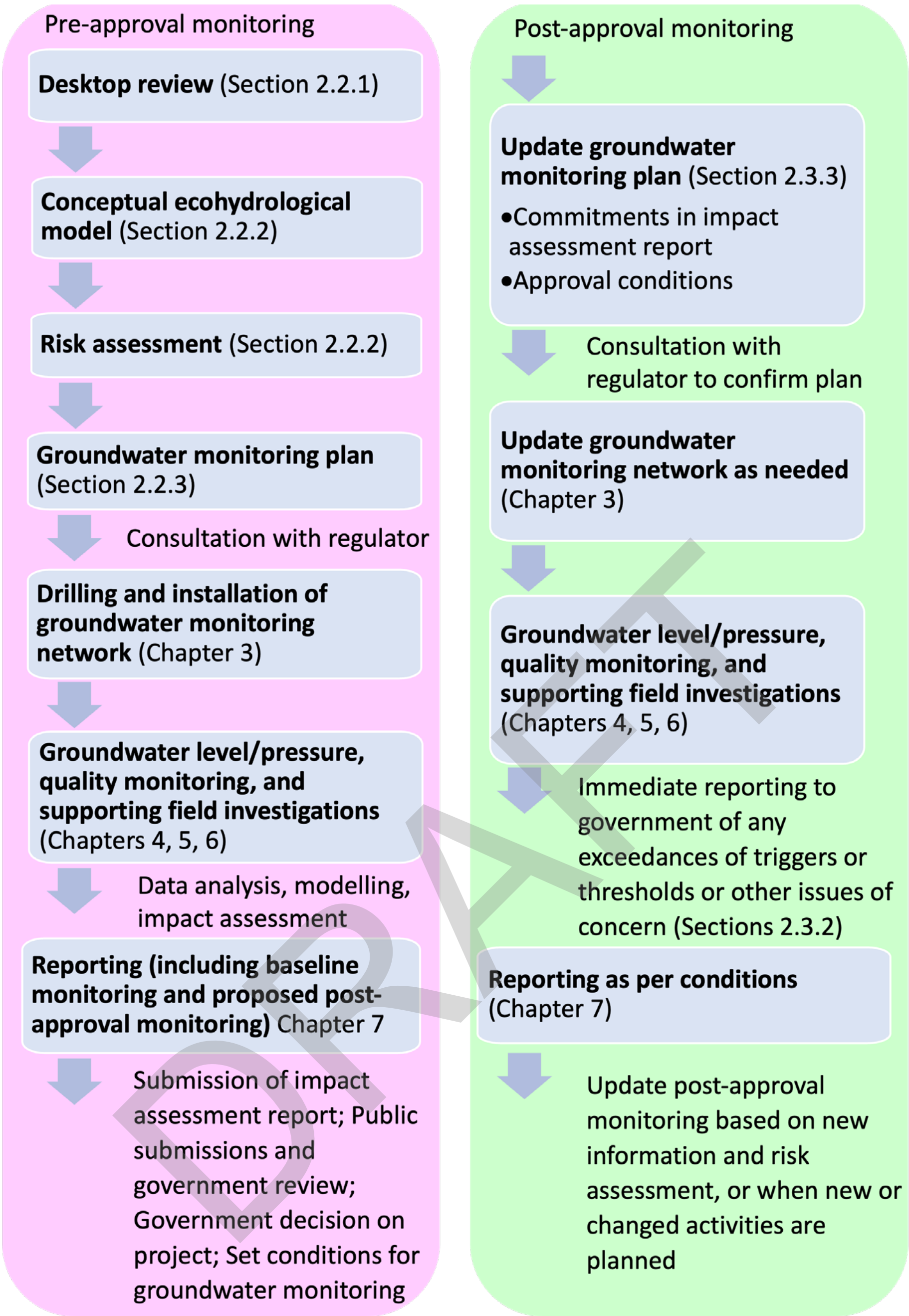

Figure 2.2 Groundwater monitoring process

2.2 Pre-approval

For projects in the pre-approval phase, groundwater monitoring is undertaken to inform a groundwater impact assessment report that will be submitted to government to seek approval for a proposed project. Groundwater monitoring for pre-approval typically comprises:

- drilling investigations, groundwater monitoring and other field investigations to characterise the groundwater system, its key processes (including groundwater flow, recharge, discharge, aquifer properties, connectivity with surface water and groundwater systems), and its associated groundwater-related assets and ecosystems (including water supply bores, groundwater-dependent ecosystems and connected surface water and groundwater systems); and

- baseline monitoring to establish pre-project groundwater levels/pressures and groundwater quality.

Pre-approval groundwater monitoring should be undertaken in accordance with a groundwater monitoring plan (Section 2.2.4). The groundwater monitoring plan should be developed based on the findings of an initial desktop study (Section 2.2.1), the ecohydrological conceptual model (Section 2.2.2) and an assessment of risks to groundwater resources and related assets and ecosystems (Section 2.2.3). Groundwater monitoring should be undertaken where there is potential for adverse impacts to groundwater resources and related assets and ecosystems due to project activities or where uncertainty about the potential risks to groundwater resources and related assets and ecosystems needs to be reduced.

> Groundwater monitoring should be undertaken where there is potential for adverse impacts to groundwater resources and related assets and ecosystems due to project activities or where there is uncertainty about the potential risks to groundwater resources and related assets and ecosystems.

2.2.1 Desktop study and initial site inspection

Every groundwater monitoring program should commence with a desktop study and an initial site inspection. This is sometimes referred to as a preliminary assessment but should be considered the start of the iterative monitoring design process and may undergo multiple iterations. The desktop study should involve developing an understanding of the proposed project and reviewing available information for the site, including groundwater monitoring data and the findings of hydrogeological investigations previously undertaken.

2.2.1.1 Project description

The first step in designing a groundwater monitoring program is to establish a clear understanding of the project to be assessed and the aspects of the project that may pose a risk to groundwater resources and related assets or ecosystems (project-related stressors). While some aspects may be covered in other reports required in the assessment/approvals process, the description here should be tailored specifically to the context of groundwater. A description sourced from other reports could also be included as an appendix. As not all details may be available in the early stages of work for a proposed project, the project description, risk assessment (Section 2.2.3), and the groundwater monitoring plan (Section 2.2.4) should be updated to reflect what is proposed as new information about the project comes to light.

Key aspects of the project description include:

- details of all activities to be undertaken during each phase of the project, including site preparation and construction, operation and maintenance, and closure and completion, as well as alterations or modifications to existing infrastructure;
- details of any current or intended groundwater extraction, groundwater use, dewatering, or groundwater injection or recharge;
- location of the project including a detailed site layout showing the surface and subsurface disturbance area;
- the proposed timing and duration of each phase of the project and its associated activities;
- how the activities and disturbance area may change throughout the course of the project, e.g., mine pit progression;
- identification of activities that may have an impact on groundwater resources and related assets or ecosystems, including a detailed description of the activity and its location, e.g., location, depth, and dimensions of a proposed tailings storage facility including the characteristics of materials to be stored; and

- for modifications or expansions of existing projects, details of which components of the project are existing and which components would be new.

Examples of project activities with the potential to impact on groundwater levels/pressures and groundwater quality are included in Table 2.1.

Any design features to be implemented as part of the project to minimise impacts to groundwater resources and groundwater-related assets and ecosystems should be documented in detail so they can be considered as part of the risk assessment in Section 2.2.3.

All project activities with the potential to impact on groundwater resources and related assets and ecosystems should be identified and described in detail.

Table 2.1 Examples of types of activities with potential to impact on groundwater levels/pressures and groundwater quality

Action	Examples of activities	Examples of potential impacts to groundwater resources
Groundwater extraction	• Extraction via a bore or bore field for water supply • Extraction as a by-product of oil or gas extraction • Dewatering for mines, or construction of buildings, roads, sewerage or other civil projects • Aquifer thermal energy storage	• Declining groundwater levels/pressures • Changes in groundwater flow regime (flow direction and gradients) • Changes to aquifer connectivity and the behaviour of aquitards • Changes in aquifer connectivity leading to mixing of groundwaters of different quality • Compaction of aquifers and subsidence
Groundwater infiltration or injection	• Managed aquifer recharge • Aquifer thermal energy storage • Enhanced recharge due to irrigation	• Rising water tables • Waterlogging and salinisation • Impacts on aquifer integrity (e.g. fracturing) • Water quality changes associated with injected water quality and aquifer reactions • Altering groundwater flow including contaminant plumes • Leaching of nutrients or pesticides to shallow groundwater systems
Heavy loading over an aquifer	• Road or rail project	• Physical compaction of an aquifer resulting in loss of storage • Changes in flow regime (hydraulic loading)

Action	Examples of activities	Examples of potential impacts to groundwater resources
Removal of material underlying an aquifer	• Underground mining	• Changes to aquifer properties (increased hydraulic conductivity) • Changes in flow regime and aquifer connectivity • Fracturing of aquitards and aquicludes • Mixing of groundwaters of different quality due to changes in flow regime or aquifer connectivity
Removal of material overlying an aquifer	• Quarrying or mining leading to unloading of underlying strata	• Changes to aquifer properties (increased hydraulic conductivity)
Removal of aquifer material	• Quarrying • Mining • Final voids/pit lakes	• Declining groundwater levels/pressures • Changes in flow regime • Loss of storage
Construction within an aquifer	• Tunnel • Road or rail cutting • Underground car park • Foundations • Pilings	• Dewatering • Interruption of groundwater flow regime • Contamination of aquifer during construction through spills
Disposal of brine, saline water, or other wastewater to groundwater systems	• Brine disposal associated with coal seam gas operations • Saline or wastewater disposal scheme • Water storage and evaporation ponds • Flare pits for petroleum drilling	• Changes to groundwater quality associated with injected water quality and aquifer reactions • Changes to groundwater quality in connected formations due to over pressurisation of target formation
Storage of chemicals and other materials at the surface	• Tailings storage facilities • Brine storage dams • Landfill • Chemical storage	• Contamination of aquifer due to leaks, dam failure or containment system failure
Storage of chemicals and other materials underground	• Underground storage tanks at service stations, fuel depots and industrial plants	• Contamination of aquifer due to leaking storage tanks
Energy storage/use	• Heating or cooling a building	• Temperature effects on groundwater-dependent ecosystems

2.2.1.2 Site setting

A comprehensive review of available information for the project site and surrounding area (study area) should be undertaken to establish the regional context, environmental and hydrogeological setting, and to identify surrounding activities. An understanding of the site setting is required to understand potential impacts associated with the project. The review should gather information on the following for the study area:

- the nearest population centres, properties, and projects (including proposed projects);
- climatic conditions;
- topography and land use;
- geology and structural geology (identifying key structural features that may be conduits or barriers to groundwater flow);
- surface water environment (catchments, waterways, dams and weirs, floodplains, wetlands);
- groundwater environment (hydrogeological units, connected groundwater and surface water systems and their ecology, groundwater users, groundwater-dependent ecosystems and springs); and
- protected areas, ecosystems and species (state forests, national parks, nature reserves, or other areas under statutory protection, and protected GDEs and any associated protected plant and animal species).

The available information will vary for individual projects depending on whether the project is a new development on previously undeveloped land (referred to as a greenfield project in this guideline) or a modification or expansion of an existing operation or development on previously developed land (referred to as a brownfield project in this guideline). Key sources of information include:

- existing project information;
- available information for nearby projects;
- aerial photography and satellite images;
- state/territory and Commonwealth government databases on groundwater resources, licensed water supply bores, stock and domestic bores, and monitoring bores, including the Bureau of Meteorology National Groundwater Information System (NGIS);
- state/territory and Commonwealth government information on the allocation and management of groundwater and surface water resources in the study area (e.g., water resource management plans);
- the bioregional assessment for the study area, if available;
- geological, geophysical, and aquifer mapping data available through Geoscience Australia;
- climate data available through the Bureau of Meteorology;
- information on groundwater-dependent ecosystems available through the Bureau of Meteorology Groundwater Dependent Ecosystems Atlas and any state/territory government databases including vegetation mapping;
- remote sensing data;
- state/territory government databases on contaminated sites; and
- literature review for geological formations in the study area.

The results of any previous groundwater or surface water monitoring (Section 2.2.1.6) or hydrogeological investigations (Section 2.2.1.7) undertaken at the site or for other projects in surrounding areas is of key importance for understanding the hydrogeological setting and any impacts to groundwater resources and groundwater-related assets and ecosystems associated with existing project activities or activities in surrounding areas.

The findings of the review will be used to develop or update the preliminary ecohydrological conceptual model (Section 2.2.2) and risk assessment (Section 2.2.3) and identify and justify data that may need to be collected through the groundwater monitoring program.

> A comprehensive review of available information for the project site and surrounding areas should be undertaken to understand the hydrogeological environment and identify groundwater-related assets and ecosystems.

2.2.1.3 Groundwater-related assets and ecosystems

Groundwater-related assets and ecosystems (also known as 'sensitive receptors' or 'groundwater-dependent assets') in the study area need to be identified and their significance under state/territory, and Commonwealth legislation documented. Groundwater-related assets and ecosystems may include:

- groundwater users (including town water supply bores, private water supply bores, stock and domestic bores, and Aboriginal community bores);
- groundwater-dependent ecosystems (GDEs); and
- connected groundwater and surface water sources.

Some groundwater systems, surface water sources and GDEs may also be culturally significant sites (CSSs).

Water supply bores (including town water supply bores, private water supply bores, Aboriginal community bores, and stock and domestic bores) in the study area can be identified from state/territory databases and the NGIS and supplemented with bore census survey data from any previous investigations at the site or for nearby projects. Relevant information for each bore includes bore owner (where available, this may be confidential), location, distance from project, status, purpose, depth, target formation, construction, standing water level, water quality, yield, extraction volumes, and associated licences or volumetric allocations.

Potential GDEs in the study area can be identified from the Bureau of Meteorology GDE Atlas, state/territory mapping, state/territory and Commonwealth water resource plans, bioregional assessments and previous studies conducted at the site or for nearby projects. Potential GDEs can include aquifer ecosystems (and their stygofauna), 'wet' cave and karst ecosystems, mound springs, baseflow stream ecosystems, riparian and terrestrial vegetation where the roots extend below the water table (phreatophytes), groundwater-dependent wetlands, and groundwater-dependent estuarine and marine ecosystems. Remote sensing data, such as MODIS or Landsat imagery, can be used to identify potential groundwater-dependent vegetation[7] and Water Observations from Space (WOfS) can be used to

[7] Doody TM, Hancock PJ, Pritchard JL 2019. Information Guidelines Explanatory Note: Assessing groundwater-dependent ecosystems. Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy, Commonwealth of Australia. Available [online]: https://iesc.environment.gov.au/publications/information-guidelines-explanatory-note-assessing-groundwater-dependent-ecosystems.

identify potential groundwater-dependent wetlands.[8] Ecologists who have worked at the site for previous investigations or are working at the site as part of the current project should be consulted to understand the condition and significance of potential GDEs and the nature of dependence on groundwater, which may vary from seasonal or episodic to continual. Vegetation mapping can be an important source of information for the identification of potential GDEs.

All surface water systems in the study area should be identified and characterised. Important information includes stream order, whether the stream is ephemeral or perennial or it varies, whether the stream is regulated or unregulated, the capacity and nature of any storages on the stream (dams, weirs, farm dams), whether the stream is connected to groundwater and if so whether it is gaining, losing, or it varies, any available information on aquatic and riparian ecosystems, the condition and location of waterholes, surface water quality, and surface water users. Stream flow data should be gathered where possible from state/territory government gauges or gauges installed for previous phases of the project and basic analyses undertaken to consider potential for connectivity between groundwater and surface water sources. These analyses could include consideration of the geology underlying the stream, riparian vegetation species, and the depth to groundwater and baseflow separation analysis (see Sections 2.2.4.3 and 6.2).

Indigenous cultural values associated with groundwater-related environmental features and processes should be identified. Culturally significant sites can be identified from state/territory registers of Indigenous heritage sites, although it is important to note that state/territory registers may not be comprehensive records of all Indigenous sites that are protected under state/territory laws. Other resources on CSSs include state/territory and Commonwealth water resource plans, bioregional assessments and previous studies conducted at the site or for nearby projects. Indigenous cultural heritage specialists who have worked at the site for previous investigations, as well as specialists working on the current project, should be consulted where possible. Large parts of arid and semi-arid Australia are under native title or Indigenous tenure and in-depth consideration of cultural and spiritual values is particularly important in these areas.

Where a project will involve ongoing activities, consideration of Indigenous cultural values should be approached through establishment of a long-term relationship with local First Nations. This engagement process should be guided by an Indigenous cultural heritage specialist to ensure cultural sensitivities are respected. Given that monitoring should be approached in the spirit of collaborative stewardship of groundwater, the long-term custodianship of the land by First Peoples should be recognised and opportunities should be sought for First Nations to engage actively in design and implementation of monitoring programs. Where a project involves one-off or short-term activities, opportunity should be sought to strengthen relationships between First Nations and existing government or civil society groups working in the region, with a view to ensuring that project monitoring activities integrate well with long-term stewardship activities and build rather than fracture long-term capabilities.

Groundwater-related assets and ecosystems in the study area need to be identified and their significance under state/territory, and Commonwealth legislation documented. These include groundwater users, groundwater-dependent ecosystems (GDEs) and connected groundwater and surface water sources. Indigenous cultural values and culturally significant sites associated with groundwater-related environmental features and processes should be identified.

[8] Harding C, Herpich D, Cranswick RH 2018. Examining temporal and spatial changes in surface water hydrology of groundwater dependent wetlands using WOfS (Water Observations from Space): Southern Border Groundwaters Agreement area, South East South Australia. DEW Technical report 2018/08. Government of South Australia, Department for Environment and Water, Adelaide. Available [online]: http://www.waterconnect.sa.gov.au.

2.2.1.4 Regulatory context

The project's status within the regulatory assessment process needs to be understood so that an appropriate groundwater monitoring plan can be developed. For example, projects in the pre-approval phase may require baseline monitoring whereas projects in the post-approval phase may require impact detection (or surveillance) monitoring. An appreciation of the groundwater monitoring requirements associated with any existing approvals (compliance monitoring) should also be obtained by engaging early with the relevant regulatory authorities so they can be incorporated as part of the groundwater monitoring plan or adapted as appropriate.

It is important to develop an understanding of how potentially impacted groundwater resources and groundwater-related assets and ecosystems are currently regulated under state/territory and Commonwealth legislation, policies and regulations. Any proposed development needs to comply with the requirements of these statutory instruments. For example, installation of groundwater monitoring bores will need to follow state/territory requirements for construction and licensing. Water management policies and regulations may provide important information to inform the assessment of risks (Section 2.2.3) and design of a groundwater monitoring plan (Section 2.2.4). For example, water plans will identify the key groundwater resources and groundwater-dependent ecosystems that require protection and environmental values will identify the uses of groundwater in the study area.

Water plans

State/territory governments have developed water plans that aim to sustainably manage water resources in accordance with the National Water Initiative. Typically, separate water plans are developed for groundwater and surface water resources except where groundwater and surface water systems are highly connected.

Water plans specify the water resources to be managed and define water management areas. They also identify water-related assets and ecosystems to be protected, including water users and water-dependent ecosystems, and establish rules on how much water can be taken from the system to maintain these consumptive and non-consumptive uses. Applicable water plans, groundwater and surface water management areas, water supply schemes, and water-related assets and ecosystems should be identified and shown on a map of the study area. Water entitlement data, including volumetric allocations or limits, should also be provided for each groundwater and surface water management area, and linked to bore data where possible.

In some parts of the country, water plans may form part of a broader plan for water management, such as in the Murray-Darling Basin where state/territory water plans need to meet the requirements of the Murray-Darling Basin Plan. Other relevant plans for water management should also be identified. For example, in the Great Artesian Basin, the Great Artesian Basin Strategic Management Plan provides a framework for identifying and responding to the risks, issues, challenges and opportunities associated with use of Basin water.

Protected areas, ecosystems, communities and species

Protected areas within the study area, such as state/territory forests, national parks, nature reserves, and wetlands should be identified, and their locations shown on a map. Protected GDEs and any associated protected plant and animal species should also be identified and located on a map. Protected areas, GDEs, and plant and animal species may be protected under:

- International treaties or conventions, such as the Ramsar Convention on Wetlands;
- Commonwealth legislation, such as the Environment Protection and Biodiversity Conservation Act 1999;
- state/territory legislation, such as The Nature Conservation Act 1992 (Qld); and
- state/territory regulations and policies, such as the National Parks and Wildlife Regulation 2019 (NSW).

Environmental values and water quality objectives

State/territory governments are progressively determining environmental values and water quality objectives for waters in accordance with the National Water Quality Management Strategy. Environmental values (also known as 'community values' or 'beneficial uses') are values or uses of water that support aquatic ecosystems, primary industries, recreation, and aesthetics, drinking water, industrial water, and cultural and spiritual values. Water quality objectives are the locally specific guideline values for relevant indicators that are intended to protect the environmental values. The environmental values and water quality objectives associated with groundwater and connected surface water systems in the study area should be identified. Where environmental values have not been determined by states/territories, a similar process to that in the National Water Quality Management Strategy[9] should be followed to identify potential environmental values associated with groundwater and connected systems that may be impacted by the project.

With regard to water quality, environmental values are established by comparing pre-development water quality parameters for the groundwater or surface water system to guideline values in the Australian and New Zealand Fresh and Marine Water Quality Guidelines[10] and the Australian Drinking Water Guidelines[11] or other locally developed guideline values to determine which environmental value category is appropriate. The IESC provides guidance on developing site-specific guideline values.[12] The natural properties of groundwater might preclude some environmental value categories; for example, brackish or saline groundwater may not be suitable for drinking or irrigation. Other water quality parameters are also considered in addition to salinity, including natural geogenic contaminants such as arsenic, fluoride or radionuclides which may exceed guideline values and therefore preclude certain environmental value categories.

Physical constraints on groundwater extraction are considered when identifying environmental value categories for groundwater. For example, low aquifer yields may preclude groundwater extraction for industrial or agricultural use. However, location, remoteness, and depth to groundwater are not reasons to disregard certain environmental value categories as water resource development may change over time and potential future use of the groundwater should be considered.

Bioregional assessments

The Commonwealth government completed the Bioregional Assessment Program in 2018.[13] The Program assessed the potential impacts of coal seam gas and large coal mining developments on groundwater and surface water and related assets and ecosystems in six bioregions across Queensland, New South Wales, Victoria, and South Australia.

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[9] Department of Agriculture and Water Resources 2013. *Guidelines for groundwater quality protection in Australia: National Water Quality Management Strategy*. Canberra. Available [online]: https://www.waterquality.gov.au/sites/default/files/documents/guidelines-groundwater-quality-protection.pdf.

[10] ANZG 2018. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality.* Canberra, ACT, Australia, 2018. Available [online]: https://www.waterquality.gov.au/anz-guidelines.

[11] National Health and Medical Research Council (NHMRC) 2011. *Australian Drinking Water Guidelines.* Available [online]: https://www.nhmrc.gov.au/about-us/publications/australian-drinking-water-guidelines.

[12] Huynh T and Hobbs D 2019. *Deriving site-specific guideline values for physico-chemical parameters and toxicants.* Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy. Available [online]: https://iesc.environment.gov.au/publications/information-guidelines-explanatory-note-deriving-site-specific-guidelines-values.

[13] Commonwealth of Australia 2018. *Bioregional Assessment Program.* Available [online]: https://www.bioregionalassessments.gov.au/bioregional-assessment-program.

For projects located within these bioregions, the findings of the bioregional assessments should be reviewed and the relevance for the risk assessment considered.

The findings of the Geological and Bioregional Assessment Program[14] to assess the potential impacts of shale and tight gas development on water and the environment should also be considered for projects located in regions where these assessments have been undertaken.

> The project's status within the regulatory assessment process needs to be understood, as well as any applicable legislation, regulations, guidelines, or studies relating to groundwater resources and groundwater related assets and ecosystems within the study area including water plans, protected areas, ecosystems, communities and species; state/territory government environmental values and water quality objectives; and bioregional assessments.

2.2.1.5 Site history: current and historic activities

An understanding of the site history and surrounding land uses is required to interpret existing monitoring data and establish baseline (pre-project) groundwater conditions. Current and historic activities at the site should be identified and located on a site plan, in particular any land uses that have or had the potential to affect groundwater levels/pressures or quality. Relevant activities could include urban development, agriculture, mining, industrial, or commercial land uses. Surrounding land uses should also be identified as these have the potential to contribute to changes in groundwater levels/pressures and quality or be impacted by the proposed project. Relevant contaminated sites databases should be reviewed to determine if there are any known contaminated sites in the vicinity of the proposed activities.

> Current and historic activities at the site and surrounding land uses should be described in detail and clearly shown on plans.

2.2.1.6 Existing monitoring data

Any existing groundwater monitoring data for the study area should be gathered and analysed as part of the initial desktop review with the aim of:

- understanding the hydrostratigraphy;
- characterising groundwater levels and pressures and groundwater chemistry prior to the proposed project, including identifying any historical impacts to groundwater resources in the area;
- identifying groundwater monitoring sites and data that are suitable for use in the baseline monitoring program; and
- identifying water supply bores that need to be protected and require baseline monitoring (e.g., town water supply bores, private bores, Aboriginal community bores, and stock and domestic bores).

An assessment of the suitability of existing bores for monitoring should be undertaken, by reviewing the location, construction and condition of the bore as discussed in Section 3.6.

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[14] Commonwealth of Australia 2020. *Geological and Bioregional Assessment Program.* Available [online]: https://www.bioregionalassessments.gov.au/gba.

Any existing surface water monitoring data for the study area should also be collated, particularly where there is potential that groundwater and surface water systems are connected. Climate data for the study area can also be useful to provide context for the historical data gathered.

> Monitoring data for any existing operations at the project site and for other projects in the study area should be collated and reviewed to develop an understanding of groundwater conditions in the study area.

2.2.1.7 Results of previous hydrogeological investigations

For brownfield projects, an assessment of impacts to groundwater resources and groundwater-related assets and ecosystems was likely undertaken for approval of the existing project, and ongoing operations have likely involved groundwater and surface water monitoring to detect impacts. All previous hydrogeological investigations undertaken for the existing operation should be reviewed, including:

- ecohydrological conceptual models developed for the study area;
- impacts predicted for the existing operation, including results of any numerical groundwater flow modelling undertaken;
- cumulative impacts predicted for the existing operation and surrounding operations;
- the results of baseline and impact detection monitoring; and
- reports to government agencies on impact detection monitoring and any breaches of conditions.

A detailed review of predicted impacts against the impacts that occurred during project operation should be undertaken to assess the accuracy of previous models and identify areas of uncertainty that may require further investigation.

The results of hydrogeological investigations for any existing operations at the project site, and for other projects in the study area, should be reviewed to develop an understanding of groundwater conditions in the study area.

> For brownfield projects, all previous hydrogeological investigations undertaken for the existing operation should be reviewed and likewise for any projects in the study area.

2.2.1.8 Site inspection

Following the desktop review, an initial site inspection should be undertaken, involving a visit to the project site and surrounding area (study area). The purpose of the initial site inspection is to gain a first-hand appreciation of the project site and the site setting to inform development of the ecohydrological conceptual model. Key locations identified through the desktop review, including potential groundwater-dependent ecosystems and culturally significant sites, should be visited where access allows. Photographs should be taken to assist staff working on the project that could not attend the site inspection.

The site visit provides an opportunity to meet with any key staff working on the project to discuss the project site. For brownfield sites, it is a chance to observe existing site operations and any groundwater–related management issues such as rising water tables or pit dewatering, visit groundwater dependent assets and ecosystems, and visit existing groundwater monitoring bores.

An initial site inspection can be useful to assist with planning of the groundwater monitoring network. It is important to understand land ownership and the status of land access agreements as this may restrict the locations where groundwater monitoring bores can be installed. For greenfield sites, site access may be difficult, and earthworks or vegetation clearance may be required to provide for drill rig access. For brownfield sites, site operations may need to be considered when planning drilling and groundwater monitoring.

An initial site inspection should be undertaken following the desktop review. Key locations identified through the desktop review should be visited where access allows.

2.2.2 Conceptual model

The information gathered through the desktop study, together with expert advice, scientific literature, and other appropriate information sources, should be used to develop a preliminary ecohydrological conceptual model for the study area. The purpose of the model is to consolidate current understanding of the groundwater system, its key processes, and groundwater-related assets and ecosystems to provide the basis for identifying causal pathways, constructing impact pathway diagrams, and assessing risks (Section 2.2.3) and identifying areas of scientific uncertainty. Where possible, these processes should be quantitative rather than qualitative.

An ecohydrological conceptual model is a descriptive representation of a groundwater system and associated ecosystems that should typically include the following information:

- hydrogeological domain, consisting of distinctive groups of formations, e.g., Surat Basin;
- hydrostratigraphy;
- aquifer properties;
- physical boundaries (e.g., formation contacts, faults), hydraulic boundaries (e.g., a regional recharge divide) and conceptual boundaries (e.g., extent of potential impacts) ;
- groundwater flow and hydrodynamics (e.g., groundwater flow direction, hydraulic gradient);
- recharge and discharge processes;
- connectivity with surface water systems and between hydrostratigraphic units;
- structural controls on groundwater flow;
- hydrochemistry;
- environmental values of groundwater and connected water resources;
- water supply bores;
- groundwater-related assets and ecosystems and at least a qualitative assessment of their water needs (e.g., riparian vegetation on ephemeral systems are likely to use more groundwater than those where the surface water flows more regularly); and
- stressors on the groundwater system including climate (e.g. rainfall and evapotranspiration) and human and natural water use.

Ecohydrological conceptual models should be used at all stages of the groundwater assessment process and refined through an iterative process as more data becomes available through groundwater monitoring and other field investigations.

The Australian Groundwater Modelling Guidelines[15] provides further explanation of how to develop a conceptual model for the purposes of developing a numerical groundwater flow model and the principles are also relevant to developing an ecohydrological conceptual model for the purposes of developing a groundwater monitoring plan. Note that a numerical model may not be necessary if monitoring based on a well-constructed ecohydrological conceptual model and risk assessment is sufficient to show that project risk is acceptably low.

> An ecohydrological conceptual model that consolidates current understanding of the groundwater system, its key processes, and groundwater-related assets and ecosystems should be developed to provide the basis for the risk assessment and to identify areas of scientific uncertainty where groundwater monitoring may be required.

2.2.3 Risk assessment

A comprehensive risk assessment, based on the available information, should be undertaken to evaluate the potential for the proposed project to adversely impact groundwater resources and connected groundwater and surface water systems, water supply bores, GDEs, CSSs, and the environmental values of groundwater resources and connected systems. Where potential risks are identified, groundwater monitoring should be undertaken to better understand and quantify the risks.

All projects involving disturbance to land, water, or the sub-surface are expected to have some impact on groundwater. The nature and magnitude of impacts will depend on the groundwater system and the proposed project, and the material risk of impacts will depend on the groundwater-related assets and ecosystems affected and the likelihood of adverse events and their propagation through the system. The preliminary ecohydrological conceptual model developed under Section 2.2.2 consolidates current understanding of the groundwater system, its key processes, and groundwater-related assets and ecosystems, and should form the basis for assessing risks.

The risk assessment will identify key areas of interest for monitoring. For example, if the risk assessment indicates that there is a material risk that a tailings storage facility (TSF) could contaminate groundwater resources, then baseline groundwater quality monitoring should be undertaken at groundwater monitoring bores up- and down-hydraulic gradient of the TSF prior to the start of development, and impact detection monitoring should be undertaken at the bores during the construction, operational and post-operational phases. The risk assessment will also define specific questions that need to be answered through the groundwater monitoring program. For example, if a risk assessment indicates that there is material risk for drawdown to occur at the location of a potential GDE, then the groundwater monitoring program should investigate whether the potential GDE is accessing groundwater and whether this varies over time under different climatic conditions.

Selection of a suitable risk assessment approach should consider the complexity of the project, and the probability and potential consequences of risks. Risk assessment should be based around causal pathways informed by the ecohydrological conceptual model. A causal pathway is a logical chain of events – either planned or unplanned – that links activities associated with, for example resource development with potential impacts on groundwater resources

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[15] Barnett B, Townley LR, Post V, Evans RE, Hunt RJ, Peeters L, Richardson S, Werner AD, Knapton A and Boronkay A 2012. *Australian groundwater modelling guidelines*. Waterlines report. National Water Commission, Canberra. Available [online]: https://www.researchgate.net/publication/258245391_Australian_Groundwater_Modelling_Guidelines.

and related assets and ecosystems.[16] Causal pathways can be visualised in an impact pathway diagram, which specifies material pathways by which impacts may be propagated from activities and associated stressors to end-points. The level of risk associated with each causal pathway should be determined by considering its scope, likelihood and consequences, and the significance of the impact should be assessed by considering the value and condition of the potentially impacted groundwater resources and related assets and ecosystems and any legislated environmental values and water quality objectives. Groundwater monitoring is expected to focus on those groundwater resources and related assets and ecosystems that are at greatest risk.

Projects that involve expanding or modifying existing operations should clearly identify any impacts to groundwater resources and related assets and ecosystems from existing operations based on historical monitoring data. The impacts from the existing project should be considered together with the potential impacts of the project expansion and any surrounding projects to assess the potential cumulative impacts[17] of the project. The assessment of potential cumulative impacts may identify additional groundwater resources and related assets and ecosystems that require monitoring.

In areas where a bioregional assessment is available, it should be used to assist with risk analyses for coal seam gas and large coal mining development proposals. The bioregional assessments used a modification of the failure modes and effects analysis (FMEA) method[18] to identify and rank hazards associated with whole-of-life-cycle operations. The method is an example of an approach that can be used to assess risks to groundwater resources and related assets and ecosystems.

It should be noted that risk assessment is an iterative process, with new information obtained through groundwater monitoring used to continually refine the ecohydrological conceptual model, causal pathways and risk assessment and update the requirements for groundwater monitoring.

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[16] The Bioregional Assessment Program used conceptual models of causal pathways to summarise the potential linkages between coal resource development and impacts on water and water-dependent assets and the methodology developed is a useful reference.

Peeters LJM, Holland KL, Huddlestone-Holmes C and Boulton AJ 2022. *A spatial causal network approach for multi-stressor risk analysis and mapping for environmental impact assessments.* Science of The Total Environment, 802. Available [online]: https://doi.org/10.1016/j.scitotenv.2021.149845.

[17] For further reading on cumulative impact assessment, see: Blakley J and Franks D 2021. *Handbook of Cumulative Impact Assessment*. Edward Elgar Publishing, Cheltenham, UK, Northampton, USA. Available [online]: https://doi.org/10.4337/9781783474028.

Franks DM, Brereton D, Moran CJ, Sarker T and Cohen T 2010. *Cumulative Impacts – A good practice guide for the Australian coal mining industry.* Centre for Social Responsibility in the Minerals Industry, Sustainable Research Institute Program, Brisbane. Available [online]: https://www.csrm.uq.edu.au/publications/cumulative-impacts-guide.

Walker LJ and Johnston J 1999. *Guidelines for the assessment of indirect and cumulative impacts as well as impact interactions.* European Commission DG XI Environment, Nuclear Safety & Civil Protection. Office for Official Publications of the European Communities, Luxembourg. Available [online]: https://tethys.pnnl.gov/sites/default/files/publications/European-Commission-1999.pdf.

Nelson R 2019. Water Data and the Legitimacy Deficit: A Regulatory Review and Nationwide Survey of Challenges Considering Cumulative Environmental Effects of Coal and Coal Seam Gas Developments. *Australasian Journal of Water Resources* 24-34. Available [online]: https://doi.org/10.1080/13241583.2019.1600393.

[18] Ford EC, Smith K, Terezakis S, Croog V, Gollamudi S, Gage I, Keck J, DeWeese T and Sibley G 2014. A Streamlined Failure Mode and Effects Analysis. *Medical Physics* 41, no. 6, Part 1. Available [online]: http://doi.org/10.1118/1.4875687.

A risk assessment should be undertaken to identify groundwater resources and groundwater-related assets and ecosystems that are at risk of adverse impacts due to project activities and evaluate the causal pathways to identify material risks.

2.2.4 Groundwater monitoring plan

Groundwater monitoring and other related field investigations should be undertaken for projects where the ecohydrological conceptual model and subsequent risk assessment identifies potential adverse impacts to groundwater resources and related assets and ecosystems due to project activities. Groundwater monitoring should also be undertaken where there is uncertainty about the potential risks to groundwater resources and related assets and ecosystems, and where additional data are needed for impact assessment for project approval; e.g., for parameterisation or history matching of a numerical groundwater flow model. Groundwater monitoring may not be required if the risks to groundwater resources and related assets and ecosystems are acceptably low and there is sufficient information available to make this assessment. Rules on what constitutes acceptable risk, sufficient information, and whether groundwater monitoring is needed may be defined by state/territory and Commonwealth governments.

A groundwater monitoring plan should be developed where groundwater monitoring and other related field investigations are planned. The groundwater monitoring plan should be developed prior to the commencement of monitoring to ensure the monitoring program is undertaken in an organised and considered manner. Where state/territory governments have requirements for the preparation of a groundwater monitoring plan, or other similar document, these requirements must be met. Additional recommended minimum requirements for groundwater monitoring plans are included in this section.

A groundwater monitoring plan should be developed where groundwater monitoring and other related field investigations are planned.

For projects in the pre-approval phase, groundwater monitoring and other related field investigations are undertaken to inform a groundwater impact assessment that will be submitted to government to seek approval for a proposed project. Groundwater monitoring for projects in the pre-approval phase should comprise investigations to:

- characterise the groundwater system and its key processes;
- identify and describe groundwater-related assets and ecosystems and assess their groundwater needs;
- assess connectivity between groundwater systems and between groundwater and surface water systems; and
- establish pre-project baseline groundwater levels/pressures and groundwater quality (baseline monitoring).

The types of groundwater monitoring and other field investigations that could be undertaken to achieve these objectives is discussed in Sections 2.2.4.1, 2.2.4.2, 2.24.3 and 2.2.4.4 below.

The scope of the groundwater monitoring to be undertaken should be commensurate with the level of risk and focus on the groundwater resources and related assets and ecosystems that are at risk of materially adverse impacts due to project activities, areas of scientific uncertainty, and where data are needed for impact assessment. A groundwater monitoring plan should detail the findings of the desktop review (Section 2.2.1) and risk assessment (Section 2.2.3) and provide details of the proposed groundwater monitoring to be undertaken.

Guidance on the design of a groundwater monitoring network is provided in Chapter 3, guidance on the design of a groundwater level/pressure monitoring program is provided in Chapter 4, and guidance on the design of groundwater quality monitoring program is provided in Chapter 5.

For projects involving modification or expansion of an existing project (brownfield projects), a groundwater monitoring network may already be in place and groundwater monitoring data may be available. An assessment of the suitability of existing bores for monitoring should be undertaken during design of the groundwater monitoring network, as discussed in Section 3.6. The suitability of existing monitoring data for use in establishing baseline conditions or characterising the groundwater system should also be undertaken.

For large projects or projects with substantial potential impacts, groundwater monitoring networks will typically be installed in several phases over many years. The design of the groundwater monitoring network will evolve as new information comes to hand through groundwater monitoring and the ecohydrological conceptual model is refined and risk assessment is updated. In this situation, the groundwater monitoring plan should be updated to reflect the additional monitoring locations as the project progresses.

> Groundwater monitoring should focus on groundwater resources and related assets and ecosystems that are at risk of material adverse impacts due to project activities, and areas of scientific uncertainty identified through the ecohydrological conceptual model.

2.2.4.1 Groundwater system characterisation

Understanding the groundwater system in the study area and its key processes is essential to assess potential impacts to groundwater resources associated with the project. Groundwater monitoring plans for projects in the pre-approval phase should include field investigations to improve characterisation of the groundwater system. The focus of the investigations should be the areas of scientific uncertainty identified through development of the preliminary ecohydrological conceptual model.

Table 2.2 provides examples of the types of information that should be gathered for groundwater system characterisation, and the monitoring methods that could be used. Information on connectivity with surface water systems and between hydrostratigraphic units, and structural controls on groundwater flow, should also be gathered and is addressed in Section 2.2.4.3.

> Groundwater monitoring plans for projects in the pre-approval phase should include field investigations to characterise the groundwater system, focusing on areas of scientific uncertainty identified through the preliminary ecohydrological conceptual model.

Table 2.2 Examples of monitoring methods for groundwater system characterisation

Types of information	Examples of monitoring methods
Geology and structure	• Drilling (Section 3.4) • Downhole geophysics (Section 3.4.4) • Remote sensing and geophysical methods (Section 6.5) • Surface outcrop mapping (Section 6.6)
Hydrostratigraphy	• Drilling (Section 3.4) • Downhole geophysics (Section 3.4.4) • Groundwater level/pressure monitoring (Chapter 4) • Packer testing (Section 6.1.3.2)
Groundwater levels/pressure, flow, and hydrodynamics	• Drilling and installation of groundwater monitoring bores (Section 3.4) • Groundwater level/pressure monitoring (Chapter 4) • Groundwater quality monitoring (Chapter 5) • Hydrochemistry and environmental tracers (Section 6.4)
Hydrogeochemistry	• Drilling and installation of groundwater monitoring bores (Section 3.4) • Groundwater quality monitoring (Chapter 5) • Hydrochemistry and environmental tracers (Section 6.4)
Aquifer hydraulic properties	• Drilling (Section 3.4) • Downhole geophysics (Section 3.4.4) • Installation of test bores (Section 3.3.1.5 and 3.4.5) • Laboratory core permeability testing (Section 6.1.2) • Packer testing (Section 6.1.3.2) • Test pumping (Section 6.1.3.3) • Constant head testing (Section 6.1.3.4) • Earth tides and barometric pressure (Section 6.1.4)
Recharge and discharge processes	• Groundwater level/pressure monitoring (Chapter 4) • Groundwater quality monitoring (Chapter 5) • Aquifer hydraulic testing (Section 6.1) • Surface water monitoring (Section 6.2)

2.2.4.2 Groundwater-related assets and ecosystems

Groundwater monitoring plans for projects in the pre-approval phase should include field investigations to identify, locate, describe, and improve understanding of groundwater-related assets and ecosystems and their hydrological connectivity. It is important to locate groundwater-related assets and ecosystems in the study area so that an accurate assessment of potential impacts associated with the project can be made.

The types of information that should be gathered for water supply bores and GDEs, and the monitoring methods that could be used, are discussed below, and summarised in Table 2.3.

Groundwater monitoring plans for projects in the pre-approval phase should include field investigations to identify, locate, describe, and improve understanding of groundwater-related assets and ecosystems and their hydrological connectivity.

Water supply bores

Water supply bores include town water supply bores, stock and domestic bores, Aboriginal community bores, and bores used for irrigation, intensive agriculture, aquaculture, mining, commercial, and industrial purposes. Risks to water supply bores associated with project activities include impacts on the quantity, quality, and reliability of water supplied by the bore. Water supply bores that access water from a different aquifer to the aquifer that will be directly impacted by the project may experience indirect impacts due to inter-aquifer connectivity (see Section 2.2.4.3).

Therefore, data should be collected on all water supply bores that could be impacted by the project. This should include an initial desktop study (see Section 2.2.1.3) and subsequently a bore census survey (see Section 6.3) involving groundwater level/pressure and quality monitoring where possible. Downhole geophysics could be used to establish the bore construction if required (Section 3.4.4). Some bores may not be registered with state/territory governments and therefore the survey should include visits to all properties in the study area.

Groundwater dependent ecosystems

A groundwater-dependent ecosystem (GDE) is an ecosystem for which groundwater meets all or part of its water requirements. Examples of GDEs include aquifer ecosystems (including their stygofauna), 'wet' cave and karst ecosystems, mound springs, groundwater-dependent wetlands, baseflow stream ecosystems, riparian and terrestrial vegetation where the roots extend below the water table (known as phreatophytes), and groundwater-dependent estuarine and marine ecosystems. Any change in groundwater flow regime or chemistry may impact a GDE. For example, a GDE may be adversely impacted if there is a decline in groundwater level or change in groundwater salinity due to project activities.

Groundwater monitoring for GDEs during the pre-approval phase of a project should:

- assess whether the ecosystems identified as 'potential GDEs' in the study area through the desktop study are likely to be dependent on groundwater;
- assess the nature of the dependence on groundwater (e.g., obligate, with a continuous or entire dependence on groundwater, or facultative, with an infrequent or partial dependence on groundwater); and
- establish baseline groundwater levels/pressures and quality at the location of the GDE and collect any other data which may assist with assessment of which aquifers the GDE may be using.

Design of a groundwater monitoring program for GDEs should be undertaken using the guidance in the IESC Information Guidelines Explanatory Note: Assessing groundwater-dependent ecosystems.[19] The GDE Toolbox is another useful resource and should be referred to in developing a groundwater monitoring program for GDEs.[20]

Investigation and monitoring of GDEs requires a multidisciplinary approach and hydrogeologists need to work closely with other experts, including ecologists and surface water hydrologists. For example, identification of potential GDEs and assessment of their distribution and condition will need to be undertaken by specialised ecologists. The groundwater monitoring plan should be developed collaboratively to align with other relevant monitoring being undertaken at the site so that data may be collected concurrently if required. Assessments of dependence on groundwater should use 'multiple lines of evidence'. This means that multiple different methods may need to be used, and multiple different types of data may need to be gathered, to assess whether an ecosystem is groundwater-dependent. Examples of the types of groundwater monitoring field methods that can be used to assess GDEs are provided in Table 2.3. This list is not intended to be comprehensive. Specific recommendations for monitoring of GDEs is out of the scope of these guidelines, other than recommending inclusion of relevant experts.

Investigation and monitoring of GDEs requires a multidisciplinary approach and hydrogeologists need to work closely with other experts, including ecologists and surface water hydrologists.

Groundwater level monitoring (see Chapter 4) near GDEs can provide information on depth to the water table and temporal and spatial variation in groundwater levels, which can be used to assess the nature of any potential dependence on groundwater. For example, monitoring the depth to the water table in an area of terrestrial vegetation will provide information that can be used by an ecologist to consider whether the vegetation species in the area can access the groundwater (based on rooting depth). Also, by monitoring groundwater levels over an extended period of time, it may become evident that groundwater levels rise sufficiently in some seasons to reach the root zones of vegetation and therefore groundwater may have a role in the survival of that vegetation.

Groundwater quality monitoring (see Chapter 5) and environmental tracers (see Section 6.4) are also useful for assessing whether an ecosystem identified as a 'potential GDE' is dependent on groundwater. For example, comparing the chemistry of surface water in a riverine waterhole with the chemistry of groundwater in an underlying aquifer can provide information on whether the stream might receive baseflow. Measurements in soil and plants may also be useful.[21]

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[19] Doody TM, Hancock PJ, Pritchard JL 2019. Information Guidelines Explanatory Note: Assessing groundwater-dependent ecosystems. Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy, Commonwealth of Australia. Available [online]: https://iesc.environment.gov.au/publications/information-guidelines-explanatory-note-assessing-groundwater-dependent-ecosystems.

[20] Richardson S, Irvine E, Froend R, Boon P, Barber S, Bonneville B 2011. *Australian groundwater-dependent ecosystems toolbox part 1: assessment framework*. Waterlines report, National Water Commission, Canberra. Available [online]: http://www.bom.gov.au/water/groundwater/gde/GDEToolbox_PartOne_Assessment-Framework.pdf.

Richardson S, Irvine E, Froend R, Boon P, Barber S, Bonneville B 2011. *Australian groundwater-dependent ecosystems toolbox part 2: assessment tools*. Waterlines report, National Water Commission, Canberra. Available [online]: http://www.bom.gov.au/water/groundwater/gde/GDEToolbox_PartTwo_Assessment-Tools.pdf.

[21] Doody TM, Hancock PJ, Pritchard JL 2019. Information Guidelines Explanatory Note: Assessing groundwater-dependent ecosystems. Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy, Commonwealth of Australia. Available [online]: https://iesc.environment.gov.au/publications/information-guidelines-explanatory-note-assessing-groundwater-dependent-ecosystems.

Other methods can also be useful for assessing groundwater dependent ecosystems including surface water monitoring (Section 6.2) and remote sensing (Section 6.5).

Special consideration should be given to karst systems. Due to fast transmission, karst systems have a relatively poor buffer against changes in water volumes or quality, including the introduction of pollutants. Ecosystems in karst systems are typically adapted to stable conditions and therefore have limited tolerance for the changes that a project could introduce. Karst systems should be mapped, which often requires a field visit and the use of remote sensing (see Section 6.5). Stygofauna, which are animals living in groundwater, should not be forgotten, and an expert may need to be consulted if the risks to stygofauna are high or unknown. Environmental DNA (eDNA), which is DNA released by organisms into their environment, may be useful in assessing stygofauna. [22] For example, eDNA can be used to identify whether protected species are present in some areas.

Where a GDE is identified, groundwater monitoring will typically be required to support its management. Baseline monitoring at the location of the GDE should be undertaken and the data may need to be used to establish trigger levels or thresholds for groundwater levels or quality. Impact detection monitoring will also be necessary.

Table 2.3 Examples of groundwater monitoring methods for groundwater-related assets and ecosystems

Purpose	Examples of useful groundwater monitoring methods
Private water supply bores	• Bore census survey (Section 6.3) • Downhole geophysics (Section 3.4.4) • Groundwater level/pressure monitoring (Chapter 4) • Groundwater quality monitoring (Chapter 5)
Groundwater-dependent ecosystems	• Drilling (Section 3.4) • Downhole geophysics (Section 3.4.4) • Installation of groundwater monitoring bores (Section 3.4.5) • Groundwater level/pressure monitoring (Chapter 4) • Groundwater quality monitoring (Chapter 5) • Hydraulic testing (Section 6.1) • Surface water monitoring (Section 6.2) • Hydrochemistry and environmental tracers (Section 6.3) • Remote sensing (Section 6.5)

Groundwater monitoring should be undertaken to identify and verify potential GDEs in the study area and assess the nature of their dependence on groundwater. Monitoring should be undertaken in accordance with the IESC Information Guidelines Explanatory Note: Assessing groundwater-dependent ecosystems (Doody, Hancock and Pritchard, 2019) and the GDE Toolbox and use a multidisciplinary approach.

[22] Ibid.

2.2.4.3 Hydraulic connectivity studies

Direct impacts to groundwater levels/pressures or groundwater quality in an aquifer have the potential for indirect impacts on other water resources and any ecosystems they may support, depending on the degree of hydraulic interaction (or connectivity) between the water resources. Understanding the connectivity between groundwater systems and between groundwater and surface water systems (including springs) in the study area is therefore essential to assess potential impacts associated with the project.

Connectivity between water resources will depend on the lithology, and the integrity and spatial continuity of geological strata. Faults, fractures, and poorly sealed boreholes can form preferential flow paths that can influence connectivity. Local and regional hydraulic pressures will also influence the degree of connectivity and the rate of water flow between groundwater systems and between groundwater and surface water systems.

Groundwater monitoring plans for projects in the pre-approval phase should include field investigations to investigate connectivity between water resources. The focus of the investigations should be the areas of scientific uncertainty identified though development of the preliminary ecohydrological conceptual model. The investigations should include assessing the hydraulic behaviour of faults and aquitards as this is key to understanding connectivity.

As for GDEs, assessments of connectivity should use 'multiple lines of evidence'. This means that multiple different methods should be used, and multiple different types of data should be gathered, to assess whether water resources are connected and understand the nature of the connection, including how it may vary over time. Examples of the types of field methods that can be used to assess connectivity between water resources are provided in Table 2.4.

Inter-aquifer connectivity

Inter-aquifer connectivity refers to the degree of hydraulic interaction between aquifers. Inter-aquifer connectivity can be assessed using a range of methods including:

- groundwater level monitoring to assess groundwater flow direction and hydraulic gradients;
- hydraulic testing to assess aquifer hydraulic parameters, and to detect and analyse responses in adjacent aquifers;
- geochemistry to identify potential flow paths between aquifers;
- inspection of outcropping strata to assess primary porosity and degree of fracturing; and
- aerial geophysics (e.g., magnetics), surface geophysics (e.g., seismic) or downhole geophysics to identify rock properties and geological structures.

Recommended minimum requirements are discussed below for fault studies and aquitard studies.

Surface water-groundwater connectivity

Surface water-groundwater connectivity refers to the degree of hydraulic interaction between surface water systems (including streams, wetlands, and estuaries) and groundwater systems. The direction and magnitude of flow between surface water systems and groundwater systems may vary. For example, a watercourse may be:

- a gaining stream, which receives inflow of groundwater;
- a losing stream, which loses water to the groundwater system by leakage; or
- a stream that does both, for example gaining in some parts and losing in others or alternating between gaining and losing depending on periodic changes in relative stream and groundwater levels.

A surface water system can be connected to a groundwater system either intermittently, seasonally, or permanently.

Surface water-groundwater connectivity can be assessed using a range of methods including:

- groundwater and surface water level monitoring to identify hydraulic head differences and assess flow rates using measured or assumed rock properties;
- drilling investigations and laboratory core permeability testing to assess the hydraulic properties of the formation underlying the stream;
- stream gauging to detect differences in stream flow rates between stations, and identify possible losses to or gains from groundwater; and
- geochemistry and temperature monitoring to detect flow between surface water and groundwater systems.

These methods are discussed in Section 6.2.

Source aquifer for springs

Springs occur where groundwater pressure causes water to be discharged at the surface, including where groundwater enters a stream. They often support a GDE and/or have cultural value. Any change in groundwater properties in the source aquifer(s) of the spring water could have detrimental impacts on the spring and its ecosystem. In particular, a decline in groundwater level/pressure in the source aquifer may cause a spring to dry up, with potentially irreversible impacts to the dependent ecosystem. It is therefore important to identify any springs in the study area and identify their source aquifer(s).

The source aquifer may be in the same geological unit as the spring or may be a deeper aquifer, with water moving from the aquifer to the spring through a fault. Where there is connectivity between aquifers, or the potential for groundwater pathways to form during the project, multiple aquifers may affect the spring. For more complex geology, a model should be developed with surface and groundwater data to understand the factors that control flows from the spring.

Identifying the source aquifer first requires an understanding of the geology underlying the spring by drilling at or near the spring. Second, groundwater pressure should be measured in all underlying aquifers (see Chapter 4). Aquifers with sufficient pressure for water to reach the surface will be potential source aquifers. Third, appropriate techniques should then be used to determine if there are similarities in the hydrochemistry between the aquifers and surface water, such as repeat measurements of environmental tracers in both systems (see Section 6.4 for further details on environmental tracers). Multiple parameters should be measured, and measurements should be repeated over multiple seasons since there may be seasonal differences in connectivity to springs. This will allow for one or more aquifers to be identified as the source of the spring. The monitoring plan for impact detection will need to continue to assess the spring and underlying aquifers.

Fault studies

Faults are displacements in rock that is otherwise intact. They differ from fractures, which do not involve displacement. Faults can affect groundwater flow by forming a barrier to flow, creating a preferential pathway for groundwater flow, or both since the impacts on groundwater flow may vary at different parts of a fault. Faults often occur in networks and multiple faults may have cumulative impacts on groundwater, while some faults will have no noticeable effect on groundwater.

Faults can create groundwater flow paths where they would not otherwise be expected and therefore it is important to identify faults in the study area and characterise their hydraulic behaviour. The design of field investigations to identify and characterise faults should follow a risk-based approach and the recommendations in the most recent version of the IESC Information Guidelines Explanatory Note, *Characterisation and modelling of Geological Fault Zones.*[23] Hydrogeologists may benefit from collaborating with geologists or geotechnical engineers who are working on the project or engaging a geophysicist for projects where significant risks are identified. Faults are typically identified and characterised using a range of methods which may include:

- aerial photography, topography and LiDAR;
- surface outcrop mapping;
- interpretation of borehole core and downhole geophysical logging data;
- seismic surveys;
- electromagnetic surveys;
- hydraulic testing to detect and analyse responses across faults;
- groundwater level/pressure monitoring across faults; and
- hydrochemistry environmental tracer studies.

The ecohydrological conceptual model will need to include sufficient detail to be able to relate information from these studies to three-dimensional understanding of the subsurface, groundwater flow, and causal pathways used for risk assessment. Low-risk projects may infer faults from limited data, e.g., aerial imagery and drilling data. For example, a change in the level of the subsurface or unexplained differences in groundwater level between two points may indicate a fault. Where groundwater flow prediction is required, data sources should be selected based on modelling requirements.

Project activities may alter the hydraulic behaviour of a fault (for example, a fault which was previously a barrier to flow may become an active groundwater flow path) and the potential for this should be considered during field investigations and impact assessment.

Aquitard studies

Aquitards are layers of material that have low hydraulic conductivity and act as a barrier to groundwater flow from adjacent (typically overlying or underlying) aquifers. The hydraulic properties and integrity of aquitards should be investigated. It should not be assumed that an aquitard will create a reliable barrier to groundwater flow that is consistent across the study area.

Reasons that an aquitard may lack integrity include faults, fractures, discontinuities in the geology (e.g. macropores), or poorly constructed or maintained boreholes that leak groundwater across the aquitard. Aquitards with integrity will be a thick, continuous layer or multiple thin layers.

[23] Murray TA, Power WL 2021. Information Guidelines Explanatory Note: Characterisation and modelling of geological fault zones. Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of Agriculture, Water and the Environment, Commonwealth of Australia 2021. Available [online]: https://iesc.environment.gov.au/publications/information-guidelines-explanatory-note-characterisation-modelling-geological-fault-zones.

Where an aquitard is represented in the ecohydrological conceptual model, evidence should be provided to support that it is continuous in the relevant area and has low hydraulic connectivity, with the level of evidence commensurate with the risks. A selection of appropriate methods may be used.[24] The thickness and spatial extent of the layer may be mapped using data from the drilling program. Laboratory core permeability testing of the aquitard material may be undertaken to confirm that the layer has low hydraulic conductivity. Potential flow paths through aquitards may be assessed using downhole geophysics, bore log, and fault mapping data. Test pumping (otherwise known as a pumping test) may also be used to assess the integrity of aquitards.

Project activities may alter the hydraulic behaviour of an aquitard (for example, an aquitard which was previously a barrier to flow may become fractured). The possibility that aquitard integrity may be compromised by project activities needs to be considered during field investigations and impact assessment.

Table 2.4 Examples of monitoring methods for connectivity studies

Purpose	Examples of useful monitoring methods
Inter-aquifer connectivity	*See fault studies and aquitard studies below*
Surface water – groundwater connectivity	• Groundwater and surface water level monitoring (Chapter 4) • Drilling investigations (Chapter 3) • Laboratory core permeability testing (Section 6.1.2) • Stream gauging (Section 6.2.1) • Hydrochemistry and environmental tracer studies (Chapter 5 and Section 6.4) • Temperature monitoring (Section 6.2.4)
Source aquifer for springs	• Drilling to determine the geology (Chapter 3) • Groundwater pressure measurements (Chapter 4) • Environmental tracer studies (Chapter 6.4)
Fault studies	• Surface outcrop mapping (Section 6.6) • Geophysical surveys and remote sensing (see Section 6.5) • Hydrogeological tests (see Section 6.1) • Groundwater level/pressure monitoring (Chapter 5) • Environmental tracer studies (see Section 6.4)

[24] See for example Timms W, Acworth R, Hartland A and Laurence D 2012. *Leading practices for assessing the integrity of confining strata: application to mining and coal-seam gas extraction.* In: McCullough CD, Lund MA, Wyse L. Proceedings of International Mine Water Association, September 29-October 4, 2012, Bunbury, Western Australia. Bunbury, Western Australia: International Mine Water Association. Available [online]: https://www.researchgate.net/publication/263555780_Leading_practices_for_assessing_the_integrity_of_confining_strata_application_to_mining_and_coal-seam_gas_extraction.

Purpose	Examples of useful monitoring methods
Aquitard studies	• Laboratory core permeability testing (Section 6.1.2) • Groundwater/level pressure measurements (Chapter 4) • Test pumping (Section 6.1.3.3)

Design of the groundwater monitoring program should be based on the risk assessment and should consider whether field investigations to assess inter-aquifer connectivity, connectivity between surface water and groundwater systems, and the hydraulic behaviour of faults and aquitards are required to adequately assess risks to groundwater resources and groundwater-dependent assets and ecosystems associated with the project.

2.2.4.4 Baseline monitoring

Baseline monitoring should occur before a project commences. The objective of baseline monitoring is to establish typical groundwater conditions at the site prior to the project and variations in those conditions due to natural influences and any existing human activities in the area such as groundwater extraction, pollutants, and land and water management practices. For the purposes of this guideline, baseline monitoring is repeated monitoring of groundwater levels/pressures and groundwater quality at a groundwater monitoring location, over a period of time, to establish groundwater conditions prior to the commencement of a project.

In the pre-approval stage, baseline monitoring supports the development of models, anticipating potential groundwater impacts from the project and creating a monitoring plan for impact detection (see Section 2.3). In the post-approval stage, baseline data are critical to interpreting data to differentiate impacts from the project from background conditions. Monitoring may follow a multiple before-after-control-impact (mBACI) type design (see Section 2.2.4.5).

The baseline monitoring should include monitoring of groundwater level/pressure (Chapter 4), groundwater quality (Chapter 5) and other observations and monitoring, such as surface water monitoring and remote sensing (Chapter 6). Within the mBACI design, baseline monitoring should include the parameters and locations that are expected to be monitored in impact detection monitoring to allow for comparison. However, the monitoring plan should be updated as necessary to add or change monitoring locations and parameters to be monitored.

Duration of baseline monitoring

The duration of baseline monitoring should be determined using a risk-based approach in consultation with regulators and should be based on aquifer characteristics (including connectivity to surface water systems), the frequency and timing of changes in environmental stressors and associated variability in parameters, the availability and suitability of historical data in the study area, and project risks, including the information required for numerical groundwater modelling where applicable.

If baseline monitoring only occurs briefly before the project commences, it may not be representative of the usual variations in the system and may be misleading. For example, if monitoring occurs at a particularly wet or dry time, or if an activity in the area is not occurring at that particular time, an impact assessment using that data may not adequately represent the relevant stressors.

In general, baseline monitoring should be undertaken for a period of at least two years prior to preparation of a groundwater impact assessment, with ideally three years of monitoring completed prior to the commencement of project construction. This is important since it covers multiple seasons, which may be associated with major differences in rainfall and land use. For projects requiring numerical groundwater modelling to predict impacts, a minimum of two years of baseline data is recommended prior to development of the model. The duration of baseline monitoring should be extended if high-risk conditions were not observed during the monitoring period, e.g., a wet period for a shallow aquifer at risk of rising water tables, or a period of high water extraction connected with a prolonged drought with risks that may be compounded by project activities. The baseline monitoring period should ideally be extended where groundwater and surface water systems are connected to capture baseflow during dry years that may be critical for dependent ecosystems, e.g., streams in areas with high interannual variability in rainfall and alluvial aquifer recharge, or streams with persistent pools that depend upon bank storage return flows from an alluvial aquifer (which may continue to support pools even in multiple subsequent dry years). The Australian and New Zealand guidelines for fresh and marine water quality recommend at least three years of baseline data for biological indicators and water quality in temporary (ephemeral) waters.[25]

It is recognised that the duration of monitoring required to capture these variations may not be possible in the context of timelines for pre-approval monitoring, particularly within the context of land access or Indigenous cultural heritage matters. Justification should be provided if the duration of groundwater monitoring prior to submission of a project impact assessment is less than what is outlined above. Wherever possible, monitoring data gathered for the project should be supplemented with other available data to increase the period of available data and provide an insight into how the groundwater parameters may vary over longer timescales, e.g., monitoring data collected for nearby developments or monitoring data gathered by state/territory government networks. When using data collected for other projects, consideration needs to be given to the monitoring bore construction, purpose of monitoring, and local impacts that may influence the parameters (see Section 3.6).

A risk-based approach should be used to decide the duration of baseline monitoring based on aquifer characteristics (including connectivity to surface water systems), the frequency and timing of environmental stressors, the availability of historical data for the groundwater system, and project risks. At a minimum, baseline monitoring should be undertaken for a period of at least two years prior to numerical groundwater modelling and preparation of a groundwater impact assessment where there is potential for material risks to groundwater resources and related assets. Baseline monitoring should include the parameters and locations that are expected to be monitored in impact detection monitoring to allow for comparison.

2.2.4.5 Before-after-control-impact (BACI) design

The before- after-control-impact (BACI) design is useful in determining how groundwater changes in response to a project and differentiating those changes from other influences and background variation. In its simplest form, BACI involves a control site and an impact site. The two sites are as similar as possible except that only the impact site is within the area that could be impacted by a project activity. Groundwater measurements are taken at both sites before and after the activity. If there are differences between the data from the two sites, they are likely to be due to

[25] ANZG 2018. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Canberra, ACT, Australia, 2018. Available [online]: https://www.waterquality.gov.au/anz-guidelines.

the activity. In most cases multiple control sites should be used, which is referred to as Beyond BACI[26] or multiple BACI (mBACI).[27] Using multiple control sites strengthens the ability to determine if the activity had a statistically significant impact.

Data should be collected at both control and impact sites 'before' the project commences and then 'after' the project commences. The data collected 'before' a project commences is essentially baseline monitoring and the data collected 'after' a project commences is essentially impact detection monitoring. The number of locations and frequency of monitoring in an mBACI design should be risk-based and reflect the inherent spatial variance of the data. Monitoring should focus on high-risk activities and occur in all aquifers with the potential to be impacted (as discussed in Chapter 3). Using an mBACI design can provide early warning of potential impacts as it is focused on the activity. Additional monitoring of sensitive receptors should also be undertaken as discussed in Section 2.2.

It can be helpful to know the layout of a project before design of the groundwater monitoring network so that control and impact sites can be identified. For example, if the location of a tailings storage facility is known, a monitoring bore can be installed up-hydraulic gradient of the dam (control site) and another bore down-hydraulic gradient of the dam (impact site). However, a project layout may change during the pre-approval phase and therefore control and impact sites may need to change during the course of a monitoring program. In this instance, it may be adequate to collect baseline data for all aquifers in the study area with the potential to be impacted by the project.

As an alternative to an mBACI approach, a gradient approach may be used, particularly where it is not practical to have a control site. Monitoring locations should be set along a gradient where values of a parameter increase or decrease with distance from the project. This approach also allows for analysis in which any impacts from the project are differentiated.

A multiple BACI monitoring design is recommended for impact detection, involving data collection at both control and impact sites before and after the project commences.

[26] Underwood AJ 1992. *Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world.* Journal of Experimental Marine Biology and Ecology, 161. Available [online]: https://doi.org/10.1016/0022-0981(92)90094-Q.

[27] Downes B, Barmuta L, Fairweather P, Faith D, Keough M, Mapstone B and Quinn G 2002. *Monitoring Ecological Impacts: Concepts and Practice in Flowing Waters.* 10.1017/CBO9780511542015. Available [online]: https://doi.org/10.1017/CBO9780511542015.

Variability and non-stationarity

When creating a groundwater monitoring plan, it is important to consider temporal variability in the parameters and underlying processes. If measurements are taken in particular conditions, those results and conclusions about system behaviour are not necessarily representative of other times. Unaccounted for or unexpected system behaviour may limit the ability to anticipate and detect potential impacts. While these guidelines do provide a recommended minimum duration of baseline monitoring, the minimum duration for a particular project needs to be risk-based because it is influenced by the information content of the data. The conditions and behaviours need to have been observed with sufficient certainty and confidence to be able to assess project risk. A key consideration when deciding whether to collect more data for a model of the groundwater system is the extent to which adding data will reduce uncertainty.

In general, groundwater parameters are slower to change than surface water parameters because they contain water that is stored for many years. However, groundwater parameters may be influenced by seasonal changes in rainfall, evaporation, vegetation and runoff, which affect groundwater recharge, and seasonal changes in groundwater pumping from the aquifer (e.g., the timing of irrigation). They are also likely to be influenced by interannual variation in rainfall, for example due to climate drivers such as ENSO, and changes in land use and groundwater extraction. The impact of these changes will be specific to the aquifer being monitored.

For monitoring programs spanning longer time periods, stationarity should not be assumed. Stationarity is the assumption that variability in parameter values in the future will be statistically similar to the past. For example, they will generally stay within the range as observed, include the same seasonal patterns, and events (such as floods) will have the same distribution. Instead, with non-stationarity due to climate change, changes in system behaviour, and other factors, directional change is expected and droughts and floods may have frequencies, magnitudes and lengths that differ from what is observed.

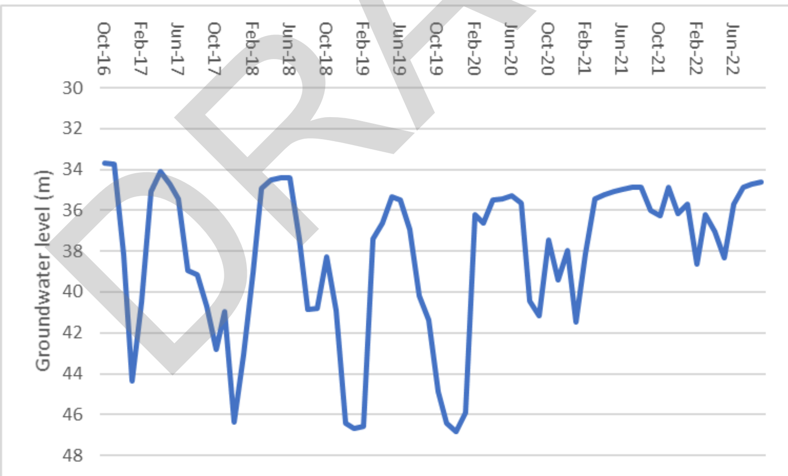

Figure 2.3. Example hydrograph showing changing water level behaviour over time
Groundwater levels over seven years in the Lower Namoi in northern NSW show variation between seasons and years, influenced by rainfall, groundwater extraction and regulation of the Namoi River and its catchments. Data from https://waterinsights.waternsw.com.au/11887-lower-namoi-groundwater/river-data#.

2.3 Post-approval

Groundwater monitoring after a project has been approved (post-approval monitoring) refers to groundwater monitoring undertaken during the construction, operation, and post-operation (including decommissioning, rehabilitation, closure) phases of a project with the objective of detecting impacts to groundwater resources associated with project activities and protecting groundwater-related assets and ecosystems. Post-approval monitoring is generally undertaken to comply with the conditions of approval for the project, as set by the relevant Commonwealth, state/territory government. There may also be monitoring to meet commitments made in the impact assessment for project approval or through community consultation, or to investigate areas of uncertainty in the ecohydrological conceptual model.

Post-approval monitoring should continue for the duration of the construction, operation, and post-operation phases of any project activity where potential risks to groundwater resources and related assets and ecosystems have been identified and as required by Commonwealth or state/territory government approval or licence conditions. Monitoring after project operation should continue until impacts on groundwater resources and related assets and ecosystems from the project and post-operation activities are unlikely and no further monitoring is required by approval or licence conditions.

> Impact detection monitoring should comply with any conditions of approval for the project, aim to detect impacts on groundwater resources and related assets and ecosystems and further investigate uncertainties about the groundwater system and groundwater resources and related assets and ecosystems. Impact detection monitoring should continue for the duration of the construction, operation, and post-operation phases of the project until legacy impacts are unlikely.

2.3.1 Monitoring program design

Design of the post-approval monitoring program should be based on the risks identified through the impact assessment undertaken for project approval. Post-approval monitoring should aim to detect impacts to groundwater resources and groundwater-related assets and ecosystems due to project activities as early as possible.

The design should consider the most appropriate locations and target aquifers for monitoring installations. The use of an mBACI design may be desirable as the control location can allow for the effects of other stressors to be considered in the analysis of impacts. The groundwater monitoring network used during the pre-approval investigations may need to be changed or augmented with additional monitoring locations that target key infrastructure or sensitive receptors. Selection of appropriate monitoring locations is further discussed in Section 3.3.3.

Design of the post-approval monitoring program should also consider the most appropriate frequency and duration of monitoring at each monitoring bore. The frequency of monitoring should be risk-based and consider the aquifer response time, the proximity of sensitive receptors to project activities and the temporal scales of variation in the parameters. For high-risk activities and high-value assets and ecosystems, telemetered data loggers may be most appropriate so that real-time data can be obtained. The duration of monitoring should include the duration of the project activity being monitored, taking into consideration any time lag associated with potential impacts and continuing until approval conditions are met. The frequency and duration of monitoring is further discussed in Sections 4.2.2 and 4.2.3 (groundwater level/pressure monitoring) and Sections 5.5 and 5.6 (groundwater quality monitoring). Monitoring network design is further discussed in Chapter 3.

Design of the post-approval monitoring program should be based on the risks identified through the impact assessment undertaken for project approval. Post-approval monitoring should aim to detect impacts to groundwater resources and groundwater-related assets and ecosystems due to project activities as early as possible.

2.3.2 Trigger values, threshold values and guideline values

The conditions of project approval may require that trigger values and/or threshold values be established for groundwater levels/pressures and guideline values be established for groundwater quality parameters at particular monitoring locations. State and territory governments may use different terminology and may have their own guidance for deriving and applying trigger values, threshold values, or guideline values, and should always be consulted at the outset to determine appropriate methods.

2.3.2.1 Groundwater levels/pressures

A trigger value is a groundwater level/pressure that, when exceeded, alerts water managers to a potential impact, and triggers a management response, which may include further investigation or some agreed action. These actions may be specified in a Trigger Action Response Plan (TARP).

A threshold value is a groundwater level/pressure that is the lower (or upper) limit that will be accepted by the regulator and may result in cessation of project activities, a fine, and/or the requirement to conduct remedial activities.

Establishing trigger values can be a useful way to provide an early warning of potential impacts to a groundwater-related asset or ecosystem. Trigger values should be set at appropriately conservative levels and the frequency of monitoring should be suitable to providing an early warning. A band of values could be used to act as a warning of impending change as levels approach a trigger value.

There is a range of different approaches that can be used to establish guideline values, trigger values and thresholds. The most common approach for groundwater levels/pressures is to use results from the numerical groundwater flow model used for the impact assessment for project approval.

Trigger values should be established for groundwater level/pressure in monitoring bores located between a project predicted to cause drawdown/depressurisation and a groundwater-related asset or ecosystem at risk of impacts to provide an early warning of potential impacts. Monitoring data should be reviewed soon after they are collected and compared with trigger values. Exceedance of a trigger value should trigger a management response.

2.3.2.2 Groundwater quality

Guideline values are measurable quantities of an indicator (analyte concentration) that support and maintain the community values (otherwise known as environmental values) of a water body. A community value is a particular value or use of the environment that is important for a healthy ecosystem or for public benefit, health, safety, or welfare, and requires protection from the effects of stressors. Where concentrations are below guideline values, there is considered a low risk of unacceptable effects occurring.

The community (environmental) values of aquifers and connected water resources should be identified and used to establish guideline values. [28] The Australian and New Zealand Guidelines for Fresh and Marine Water Quality [29] provide guidance on the use of default guideline values and the derivation and application of site-specific guideline values for water quality parameters. State and territory governments may have their own guidance for deriving and applying site-specific guideline values, and they should be consulted at the outset on appropriate methods. It should be noted that it may be necessary to develop site-specific guideline values for individual monitoring locations or target aquifers. Water quality guideline values are discussed further in Section 5.3.

It is important that groundwater monitoring targets the necessary parameters and value ranges to detect whether a guideline value is exceeded. Monitoring data should be reviewed soon after they are collected and compared with guideline values. Exceedance of a guideline value alerts water managers to a potential impact, and triggers a management response, which may include further investigation or some agreed action. These actions may be specified in a Trigger Action Response Plan (TARP).

> Guideline values should be established for groundwater quality monitoring to provide an early warning of potential impacts. Monitoring data should be reviewed soon after they are collected and compared with guideline values. Exceedance of a guideline value should trigger a management response.

2.3.3 Updated groundwater monitoring plan after approval

Post-approval monitoring should be described in a new or updated groundwater monitoring plan. It should include all monitoring required under legislation or approval conditions and any commitments to additional monitoring, for example through community consultation.

The monitoring plan should then be updated as necessary during the project. At a minimum, the monitoring plan should be assessed during an annual reporting process (see Section 7.3) and updated if there is reason to do so. The monitoring plan should also be updated as soon as possible to respond to any issues where a change in the monitoring plan is necessary to meet objectives or new objectives are established. Reasons for updating a monitoring plan may include a revision to the ecohydrological conceptual model due to new hydrogeological information, exceeding guideline/trigger levels (see Section 2.3.2) or finding quality issues through quality assurance and quality control (QA/QC) procedures (see Section 7.3).

> Post-approval monitoring should be described in a new or updated groundwater monitoring plan and updated as necessary during the project.

2.3.4 Monitoring after project operation (post-operation)

Monitoring should continue after a project has finished (post-operation) while there are still potential impacts on groundwater resources and related assets and ecosystems from the project or from post-operation activities such as decommissioning, rehabilitation, and closure. Post-operation monitoring is essential because there may be risks associated with ceasing operations as well as lags associated with some project impacts, i.e., some impacts may occur gradually or with a delay, meaning they are not apparent until after the project. The duration of post-operation

[28] National Health and Medical Research Council (NHMRC) 2011. *Australian Drinking Water Guidelines.* Available [online]: https://www.nhmrc.gov.au/about-us/publications/australian-drinking-water-guidelines.

[29] ANZG 2018. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality.* Canberra, ACT, Australia, 2018. Available [online]: https://www.waterquality.gov.au/anz-guidelines.

monitoring should be risk-based, continue until negative impacts on groundwater are unlikely to be detected and expected outcomes of remediation activities have been observed, and be in adherence with approval or licence conditions of the project.

The groundwater monitoring plan should be updated as part of planning for project closure. The project description should be updated to include details of post-operation activities which may include decommissioning and removal of infrastructure, regrading, revegetation, changing land use, removing waste, recovery of water levels, decommissioning of bores, management of tailings, and backfilling excavations. The ecohydrological conceptual model should be updated to reflect the post-operation hydrogeological environment, which may include features such as pit lakes. Risks should be re-evaluated and, where applicable, quantitative models updated. The locations and frequency of groundwater monitoring may be adjusted accordingly. For example, additional monitoring bores may be added to the monitoring network to correspond to new activities or predicted pathways of solutes. For projects where monitoring will continue for many years, particular consideration should be given to variations in climate that may occur in that time.

There may be additional monitoring, not addressed in detail in these guidelines, to deal with the specific objectives of post-closure monitoring, such as evaluating rehabilitation activities. In these cases, monitoring objectives are no longer centred exclusively on characterising the groundwater system and detecting negative impacts but also to detecting progress towards objectives such as improving groundwater quality and restoring groundwater levels. These guidelines do not cover monitoring at contaminated sites.

Reporting during the post-operation phase should be continued as outlined in Chapter 7.

> Monitoring should continue after a project has finished (post-operation) while there are still potential impacts on groundwater resources and related assets and ecosystems from the project or from post-operation activities such as decommissioning, rehabilitation, and closure. A new or updated groundwater monitoring plan should be prepared as part of planning for project closure.

3. Monitoring Network

3.1 Objectives

A groundwater monitoring network comprises a collection of monitoring installations, such as monitoring bores and vibrating wire piezometers, through which a groundwater system can be monitored. It should be designed to suit the monitoring objectives and the site-specific geology and hydrogeology. As a groundwater system is not observed directly but instead monitored through a limited number of points, the spatial and vertical distribution of the monitoring installations and their design is critical to achieving monitoring objectives.

3.2 Existing standards

The siting, design, drilling, and construction of groundwater monitoring installations should be undertaken in accordance with the provisions of this section and relevant sections of the most recent version of the Bureau of Meteorology National Industry Guidelines for hydrometric monitoring.[30] The Guidelines contain Australian industry recommended practice for the collection, analysis, and reporting of hydrometric data, including site establishment, with the aim of ensuring the quality of data gathered is suitable for the intended use.

Relevant sections of the Minimum Construction Requirements for Water Bores in Australia,[31] developed by the National Uniform Drillers Licensing Committee (NUDLC), should also be adopted. The NUDLC document provides minimum requirements for constructing, maintaining, rehabilitating, and decommissioning water bores in Australia with a focus on bores for water supply. Monitoring bores differ from water supply bores in several ways and this needs to be considered when referring to the NUDLC document.

Additional guidance on the siting, design, drilling, and construction of groundwater monitoring bores is also provided by Geoscience Australia.[32]

> The Bureau of Meteorology National Industry Guidelines for hydrometric monitoring, the Minimum Construction Requirements for Water Bores in Australia developed by the National Uniform Drillers Licensing Committee, and the Geoscience Australia field guide should be referenced for the siting, design, drilling, and construction of groundwater monitoring installations.

3.3 Monitoring network design

The design of a groundwater monitoring network will be unique for each project and will be based on the outcomes of the preliminary assessment (see Chapter 2). The preliminary assessment will define the hydrostratigraphy, groundwater-related assets and ecosystems and risks associated with proposed project activities. It will identify

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[30] Bureau of Meteorology 2021. *National Industry Guidelines for hydrometric monitoring.* Available [online]: http://www.bom.gov.au/water/standards/niGuidelinesHyd.shtml.

[31] National Uniform Drillers Licensing Committee 2020. *Minimum Construction Requirements for Water Bores in Australia.* Available [online]: https://adia.com.au/wp-content/uploads/2020/09/Minimum-Construction-Requirements-for-Water-Bores-in-Australia.pdf.

[32] Sundaram B 2009. *Groundwater Sampling and Analysis - A Field Guide.* Record 2009/027. Geoscience Australia, Canberra. Available [online]: http://pid.geoscience.gov.au/dataset/ga/68901.

available information for groundwater in the study area and any gaps in the data that need to be addressed. The risks and data gaps identified through the preliminary assessment will inform the groundwater monitoring network design, which will be detailed in the groundwater monitoring plan for the project (see Section 2.2.4).

Benefits of baseline monitoring are maximised if the groundwater monitoring network installed during pre-approval is used throughout the construction, operation, and post-operation phases of the project for the purposes of impact detection. Development of the initial monitoring plan should consider and try to anticipate where monitoring bores will be useful later.

However, this may not always be possible as the design of a groundwater monitoring network may need to evolve over time as new information becomes available through field investigations, the project plan evolves, and the project moves through different phases of development and operation. The ecohydrological conceptual model and risk assessment should be updated as new groundwater monitoring information becomes available, and the groundwater monitoring network should be reviewed to assess whether it adequately addresses the key data gaps and risks to groundwater resources and related assets and ecosystems. The groundwater monitoring plan should be updated every time there is a change to the groundwater monitoring network or groundwater monitoring program so that there is a record of changes and the rationale for changes.

The design of a groundwater monitoring network will need to consider the types of monitoring installations suitable for gathering the data needed, the number and location of monitoring installations, and the spatial and vertical distribution of monitoring locations. These considerations are discussed in the following sections.

> The design of a groundwater monitoring network will be unique for each project, based on the outcomes of the preliminary assessment and will change over time.

3.3.1 Types of groundwater monitoring installations

Groundwater monitoring should be undertaken in dedicated installations that have been designed, drilled, and constructed for the intended purpose. This may be supplemented with existing installations, such as private bores. As detailed below, the type and design of monitoring installation should be governed by the purpose for which the data are being collected. There are numerous options for how groundwater can be monitored, some of which are described in this section.

> Groundwater monitoring should be undertaken in dedicated installations, with the type and design of monitoring installation governed by the purpose for which the data are being collected.

3.3.1.1 Monitoring bores

Monitoring bores have the advantage that they can be used to collect both groundwater level/pressure and groundwater quality data. They can also be used for sampling of stygofauna and eDNA and for rising and falling head tests to gather data on hydraulic conductivity of the formation at the screened interval of the bore.

Monitoring bores are comparatively reliable, long-lasting installations and are suitable for unconfined and sub-artesian groundwater systems where the depth to the potentiometric surface is less than 150 m (the estimated limit of manual groundwater measurement), and also artesian groundwater systems.

The simplest monitoring bores are open boreholes that consist of a hole drilled into rock (Figure 3.1A). They may be suitable in stable, consolidated formations. A bore casing may be necessary for parts of the bore that are in unconsolidated material, typically near the surface. Groundwater will enter the bore in all parts that are not cased.

The most common type of monitoring bore is a bore that is entirely cased except at specific depths where the casing is slotted or perforated or where a screen exists instead of a casing (Figure 3.1B). Groundwater will enter the bore through the bore screen or slotted interval.

Care should be taken when constructing monitoring bores to ensure the open area or screened interval of the bore does not connect geologically separate aquifers or other water-bearing zones (hereafter aquifers) as this could result in mixing of waters between aquifers. If the monitoring bore is appropriately constructed (see Section 3.4) and maintained (see Section 3.7), groundwater level measurements and water quality samples collected from the bore will be representative of the depth at which the bore is open for an open hole or screened or slotted for a cased monitoring bore.

> Monitoring bores should be installed at locations where groundwater level/pressure and groundwater quality data are required.

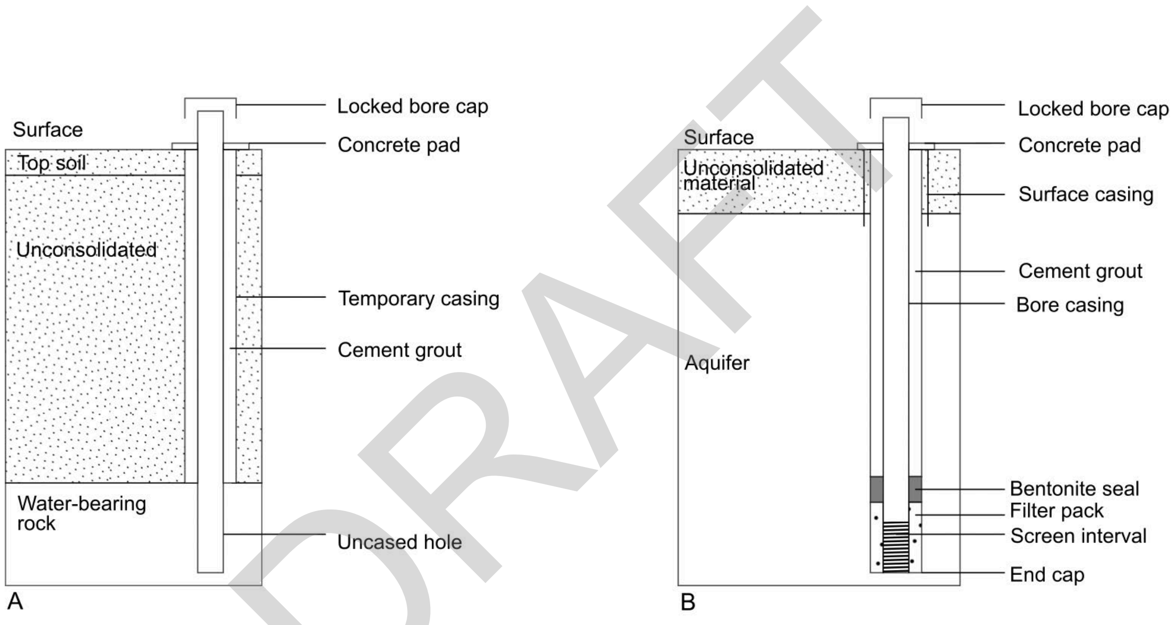


Figure 3.1 (A) Open hole monitoring bore (B) Cased monitoring bore

3.3.1.2 Conventional piezometers

Conventional piezometers are similar to screened bores but are smaller in diameter (usually around 25 mm) and are specifically designed for monitoring groundwater levels. Due to their small diameter, they cannot be used to collect groundwater samples.

> Piezometers should be installed where groundwater level data are needed but not groundwater samples.

3.3.1.3 Nested installations

Nested installations should be used where data on groundwater levels/pressure and/or groundwater quality are required at different depths at the same location; for example, where multiple different aquifers occur in a stacked aquifer system, or where groundwater quality varies with depth within an aquifer. Nested sites can provide data on vertical hydraulic gradients, vertical variation in groundwater quality, and connectivity between different aquifers.

Types of nested installations include clusters of monitoring bores or piezometers, multiple screened bores, multiport samplers and bundled mini-piezometers. A cluster of monitoring bores or piezometers is where individual monitoring bores or piezometers with screens at different depths are constructed in close proximity (Figure 3.2A). A multiple screened bore consists of multiple bore casings with screens at different depths in one large borehole (Figure 3.2B). Multiple screened bores can be time-consuming to install due to the large borehole required and the need to wait for bentonite to cure in between installing each pipe. Clusters of monitoring bores are usually preferred as they are safer completion-wise; however, care must be taken to drill the deepest bore first to ensure drilling does not compromise the screened interval of other bores in the cluster.

Multiport samplers (Figure 3.3A) and bundled mini-piezometers (Figure 3.3B) comprise multiple small diameter tubes within a borehole. They are typically used in shallow unconsolidated sand or gravel aquifers and installed using hollow auger drilling. Tubes in a multiport sampler include sampling ports at different depths. Groundwater samples are collected by vacuum or suction, or alternatively using pressure or positive displacement pumps installed in the bore. Tubes in bundled mini-piezometers are usually installed outside a central pipe and have a short screen length at different depths to provide a vertical profile of hydraulic head.

Nested installations should be installed where data on groundwater level/pressure and/or groundwater quality are required at different depths at the same location

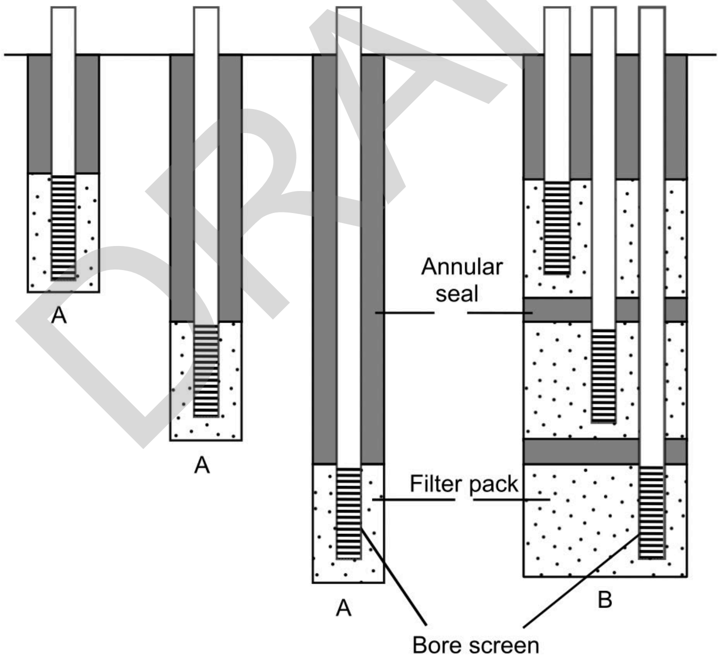


Figure 3.2 (A) Clustered bores (B) Multiple screened bore

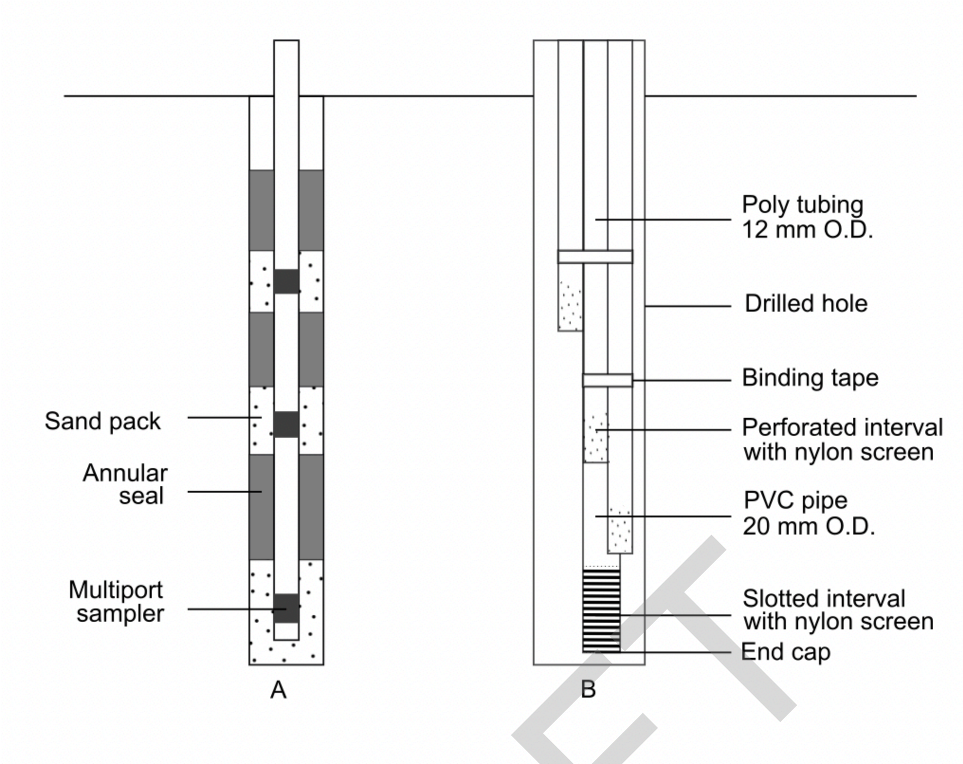


Figure 3.3 (A) Multiport sampler (B) Bundle mini-piezometer

3.3.1.4 Vibrating wire piezometers

Vibrating wire piezometers (VWPs) are instruments used to continuously measure groundwater pore pressures. They may be used in monitoring bores in a similar way to a submersible pressure sensor; however, typically most VWPs are permanently installed in the ground in backfilled or grouted boreholes and connected to a data logger in a control box at the surface that stores continuous pressure readings (Figure 3.4). Several sensors may be placed in a single borehole, collecting high-frequency pore pressure data at discrete intervals through the profile. A VWP array may therefore be a cost-effective alternative to nested monitoring bores. Data from the sensors are accessed via either manual download from the data logger or telemetry.

One of the benefits of VWPs is that they can be installed in exploration boreholes, which are not suitable for monitoring bore installation due to their small diameter (typically 96 mm). Also, VWPs can measure pressures in deep formations and in aquitards and other formations that are not productive.

However, these installations have several disadvantages, including that they can be unreliable compared with standard monitoring bores because individual sensors cannot be replaced if they fail, and they do not enable groundwater quality monitoring.

Further guidelines for installation of VWPs are provided in Section 3.4.6.

> Vibrating wire piezometers should be installed at locations where continuous groundwater pressure data are required.

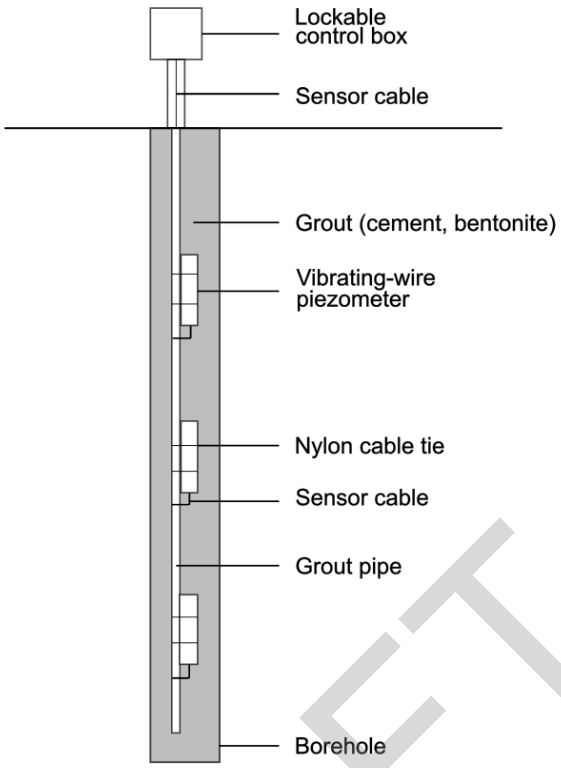


Figure 3.4 Vibrating wire piezometer array

3.3.1.5 Test pumping bore

Projects that require numerical groundwater flow modelling to assess impacts will usually require assessment of site-specific hydraulic properties for aquifers, including hydraulic conductivity, transmissivity, and storage. These properties can be estimated in the field using test pumping (otherwise known as a pumping test). Guidance on aquifer test pumping is included in Section 6.1.3.3.

Some projects may also have specific questions about the groundwater system in the study area that arose from the preliminary ecohydrological conceptualisation and that need to be investigated to provide for a robust impact assessment. Some of these questions may include whether an aquitard is leaking, whether there is connectivity between formations, whether there is connectivity between surface water and groundwater, and the role of a fault in groundwater flow. These questions can be investigated in the field using test pumping.

Monitoring bores are not suitable for test pumping due to their small diameter compared to the diameter of the submersible pump, submersible pressure sensor and manual dipper that need to be used inside the bore during test pumping. For this reason, bores intended for test pumping should be installed at suitable locations within the study area. These bores will target the aquifer of interest and will have an internal diameter of around 150-200 mm to accommodate the equipment. Monitoring bores may be installed close to the test bore to gather data during test pumping.

Test pumping bores should be installed at locations where aquifer test pumping is required.

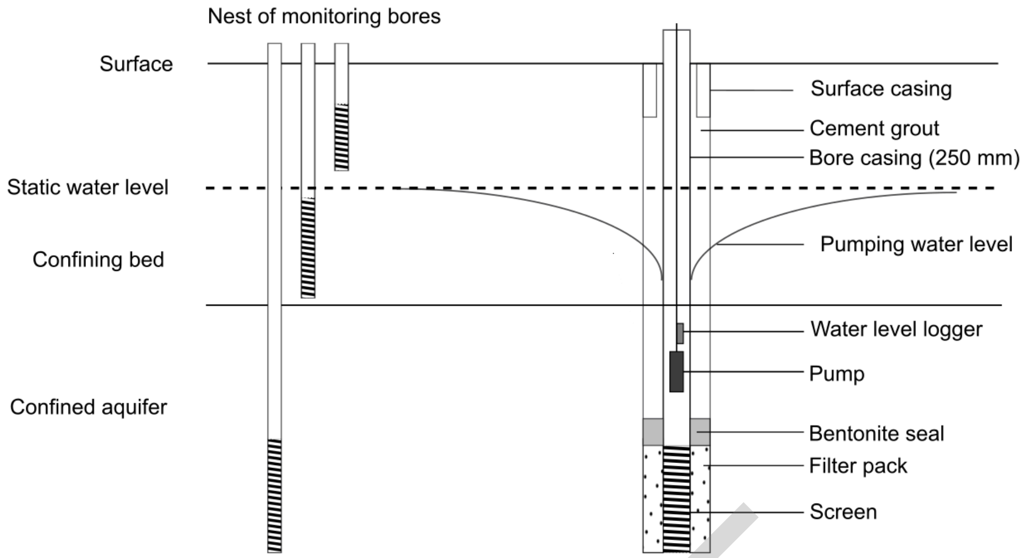


Figure 3.5 Test pumping bore and nearby monitoring bores

3.3.2 Complementary monitoring

Contextual information supports the understanding of the groundwater system and is required for the interpretation of groundwater data. This information includes climate (e.g., rainfall and evapotranspiration), surface water, soil water, land use, irrigation, vegetation cover, and ecosystem condition. While design of complementary installations is out of scope of this guideline, groundwater monitoring will generally need to be designed with their locations in mind. Groundwater use data should be collected for metered bores in and around the project area. The type of metering and level of precision should be commensurate to risk and telemetry should be used where appropriate. Irrigation data should be gathered from the bore census survey (see Section 6.3), although it may also be necessary to visit properties that do not have bores. A monitoring plan may also integrate with remote sensing and field investigations with minimal physical infrastructure, e.g., geophysics studies. Further discussion on complementary monitoring that is typically undertaken together with groundwater monitoring is included in Chapter 6.

> Installations for complementary monitoring should be included in the monitoring network as necessary to support interpretation of groundwater monitoring data. For groundwater use monitoring, the type of metering and level of precision should be commensurate to risk and telemetry should be used where appropriate.

3.3.3 Number and location of monitoring sites

The number and location of monitoring sites will be unique for each project. They should be selected to meet the monitoring objectives and address the risks and areas of scientific uncertainty identified through the preliminary assessment (see Section 2.2). Monitoring locations should support improvement of the conceptualisation of the groundwater system (pre-approval), establishment of baseline conditions for the groundwater system (pre-approval), characterisation of variation among different parts of the study area (pre-approval) and provide early warning of potential impacts to groundwater (post-approval). The frequency of monitoring will be specific to each monitoring location and the parameters being measured, therefore allowing for a broader coverage of locations without the cost of higher frequency monitoring at all locations.

The monitoring locations should allow for the detection of spatial and vertical variation in the groundwater properties that will be monitored. They should target all aquifers and groundwater-related assets and ecosystems in the study area with the potential to be impacted by the project and any other formations relevant to the ecohydrological conceptualisation and risk assessment, such as aquitards. Ideally, the monitoring locations will provide data representative of various topographic, geologic, climatic, and land use environments within the study area.

Monitoring bores for impact detection should be located between the proposed development and groundwater-related assets and ecosystems (such as town water supply bores and groundwater-dependent ecosystems) to give timely warning of impacts. Monitoring bores should also be located outside the area of impact as a control to understand natural variation in groundwater level/pressure in the region (see Section 2.2.4.5).

Additional monitoring sites may be added to the monitoring network later in the monitoring program as the conceptualisation and risk assessment are refined based on the groundwater monitoring and other field investigations. However, initial decisions on monitoring locations are important since they will affect what baseline data are available.

A monitoring program should be resourced to meet these needs, as existing bores in an area may have been constructed for other purposes (such as private water supply) and may not be suitable for use for groundwater monitoring (see Section 3.6).

> The number and location of monitoring bores should be based on the monitoring objectives, risk assessment and uncertainties informed by the ecohydrological conceptual model.

3.3.2.1 Spatial coverage

The monitoring locations should be distributed across the study area (the area in which groundwater could be affected by a proposed project) and be governed by the purpose for which data are being collected. For example, for projects in the pre-approval phase, monitoring bores may be located to allow for assessment of the groundwater flow direction in each aquifer. An mBACI approach should be used (see Section 2.2.4.5).

The monitoring locations should address any gaps in conceptual understanding of the groundwater system identified through the preliminary assessment; for example, the direction of groundwater flow or the interaction between surface water and groundwater systems. Where it is necessary to establish groundwater flow direction and hydraulic gradients, at least three bores or piezometers (hereafter bores) in each aquifer are necessary for triangulation. The bores should be equidistant and spread across the study areas and must not be in line. If the data suggest that the groundwater flow is not uniform, more than three bores will be necessary to characterise groundwater flow.

The monitoring network should also be designed to target groundwater-related assets and ecosystems and address risks identified through the preliminary assessment where a causal pathway is identified; for example, monitoring of groundwater near tailings storage facilities or monitoring of source aquifers for springs with the potential to be impacted by depressurisation.

If a potential point source for contaminants is known and considered a risk, there should be at least one bore down-gradient of it. It should be sufficiently far away that the contaminants will have mixed with the groundwater but not so far away that the contaminants would have dispersed. Preferably, there should be multiple bores along the potential contaminant flow path: up-gradient and down-gradient at multiple points. Up-gradient bores may be useful in differentiating the impact of a contaminant source on the groundwater from up-gradient effects. Where there are multiple bores, they should typically be concentrated close to a potential disturbance with fewer bores further away where the expectation is to measure no impact.

In addition to the considerations above, monitoring sites should specifically target areas of high risk or with potential confounding factors:

- locations where there is groundwater extraction;
- land uses that may affect the groundwater; and
- areas with higher risks of contaminant transmission, such as fault lines or a weathered zone in a consolidated aquifer.

Where the monitoring network is used to provide a statistically representative reference condition assessment of a region, survey sites should be far enough apart to reduce spatial auto-correlation where measurements are similar due to the small distance between the locations where they were taken. High spatial auto-correlation generally reduces the information content of the data and would need to be specifically addressed in statistical analyses.

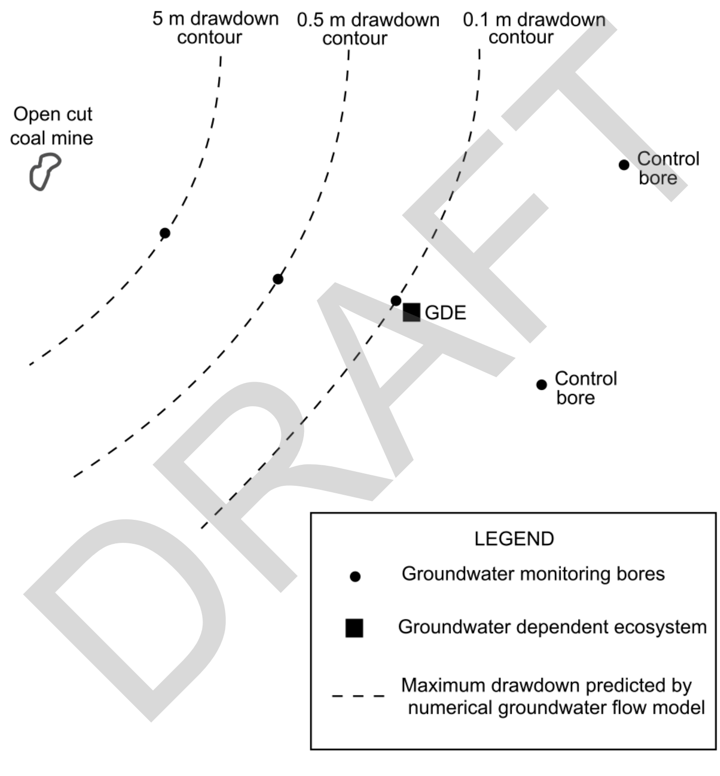
Monitoring sites should be located to be safe and practical to access in all conditions and for the duration of the project. If bores are located on private property, there may be access constraints or restrictions if the property changes ownership. If a monitoring site cannot be accessed at certain times (e.g., if flooding prevents access to a bore during the wet season), it may lead to bias in the data. Bores should also be located to reduce potential for damage due to vandalism, flooding, erosion, or usual activities on a property such as farming or earthworks.

> Where it is necessary to establish groundwater flow direction and hydraulic gradients, a minimum of three monitoring bores completed within each aquifer are required for triangulation. Bores should be located to target groundwater-related assets and ecosystems and areas of high risk.

Case study example

Post-approval groundwater monitoring for an open cut coal mine will typically involve groundwater level/pressure and groundwater quality monitoring at the mine site, as well as off-site between the mine and sensitive receptors, such as groundwater-dependent ecosystems (GDEs) and water supply bores.

The below diagram provides an example of a groundwater monitoring network design that could be used to provide early warning of potential drawdown impacts to a GDE located near an open cut coal mine. In this example, multiple groundwater monitoring bores are located between the coal mine and the GDE, and one in close proximity to the GDE. This example also includes control sites located outside the area of predicted drawdown impact from the mine. Control bores may be needed if there is potential for drawdown impacts from another source to impact on the GDE.



3.3.2.2 Vertical coverage

Vertical variation in groundwater level/pressure and quality can occur within aquifers, such as within a sand or gravel aquifer, and between aquifers, such as where multiple different aquifers occur in a geological sequence and are separated by lower permeability formations or aquitards. Therefore, monitoring installations should be designed to allow for the detection of vertical variation within and between aquifers in the study area. Nested installations and vibrating wire piezometer arrays are most suitable for this.

Monitoring should target all aquifers through the profile with the potential to be impacted by the project. This should include aquifers where development is not occurring because it cannot be assumed that aquitards will prevent impacts to those aquifers. For example, if groundwater extraction from a confined aquifer is proposed, monitoring of shallow aquifers above the confining bed should be undertaken as the confining bed may not be continuous and the shallow aquifer may be connected to the confined aquifer via a fault or similar. Monitoring of hydraulic head in low-permeability formations and aquitards should also be undertaken to provide for improved conceptualisation of the groundwater system. The maximum depth of monitoring should be below the maximum depth of any planned activities, such as the lowest level of construction planned on the site. The depth of monitoring should also be suitable for the range of groundwater level/pressure fluctuations expected, the measurement method, and the transmissivity of the formation.

In addition to targeting each aquifer, monitoring should target the depths at which potential contaminants are likely to occur, particularly for contaminants that do not mix with groundwater. If dense non-aqueous phase liquids (DNAPLs) may be present, they will sink to the lowest part of the aquifer and therefore bore screens may need to extend slightly into the aquitard beneath although the bore design should not enable the DNAPLs to move further downwards. If light non-aqueous phase liquids (LNAPLs) may be present, they will float near the top of the saturated zone and therefore the bore screen should extend above that into the area where groundwater levels fluctuate.

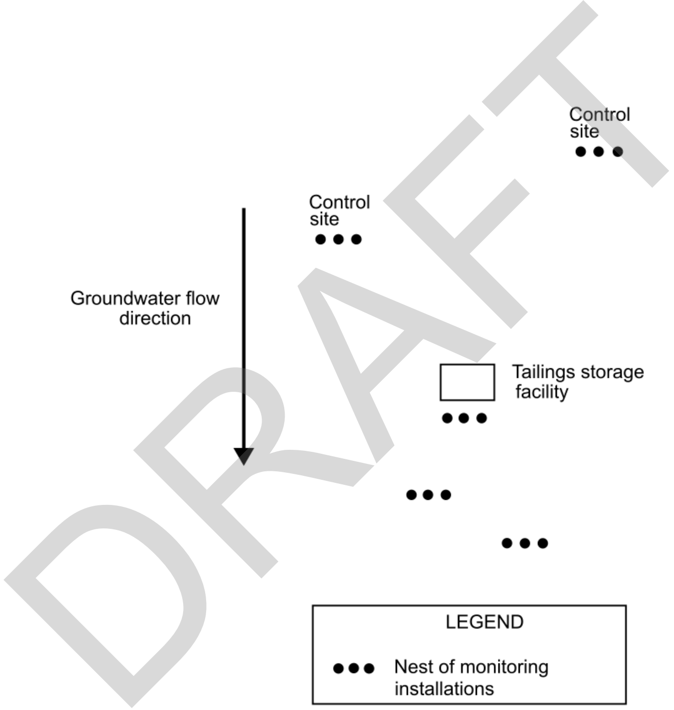
> Monitoring installations should target all aquifers through the profile with the potential to be impacted by the project and be designed to detect vertical variation within and between aquifers.

Case study example

Post-approval groundwater monitoring for a tailings storage facility (TSF) will typically involve groundwater level/pressure and groundwater quality monitoring at the mine site, as well as off-site between the TSF and sensitive receptors, such as groundwater-dependent ecosystems and water supply bores.

The below diagram provides an example of a groundwater monitoring network design that could be used to detect leaks from a TSF. The design follows an mBACI design, where multiple impact sites are located down-hydraulic gradient of the TSF, and multiple control sites are located up-hydraulic gradient of the TSF. Groundwater level/pressure and quality monitoring is undertaken at the monitoring bores for two years prior to construction of the TSF to establish baseline conditions, and then impact detection monitoring is undertaken throughout construction and use of the TSF (and, ideally, after operations cease).

Each monitoring location is a nest of three monitoring bores, with a shallow bore constructed in the same formation as the TSF, and deeper bores in underlying formations which may potentially be affected by seepage.



3.4 Monitoring bore design and installation

Monitoring bores should be designed and constructed in accordance with the NUDLC Minimum Construction Requirements for Water Bores in Australia[33] and any state/territory requirements. Most of the NUDLC document is focused on bores for water supply but requirements for monitoring bores differ in several ways. Additional considerations for monitoring bores are outlined in this section.

Monitoring bores should be appropriate for the site-specific geology and hydrogeology and should enable measurements that are representative of the target aquifer. Monitoring bore design should be appropriate for the monitoring objectives, including the analytes that will be monitored and the depths of the target aquifer.

Poor bore design can have irreversible effects on the representativeness and reliability of measurements from a bore. Later actions, such as purging the bore, do not substitute for inappropriate bore design, construction, and development.

Approval may be required prior to the drilling and installation of monitoring bores under state/territory legislation.

> Monitoring bores should be constructed in accordance with the Minimum Construction Requirements for Water Bores in Australia with additional considerations for monitoring bores to ensure measurements taken and samples collected from the bore are representative of groundwater conditions in the aquifer targeted by the monitoring bore.

3.4.1 Record keeping

Records of monitoring bore design and installation may be essential for data interpretation later. They should be kept in accordance with the Minimum Construction Requirements for Water Bores in Australia and should include:

- location and datum of the bore, including the elevation in mAHD (see Section 3.5);
- bore identification number;
- dates of bore construction;
- diameter and depth of the bore;
- details of any slotted sections or screens, including type, length and depth;
- drilling method and equipment;
- details of the strata, aquifers, yield, and water quality;
- details of the casing, pipe, wall, grouting, and gravel pack; and
- bore development procedure and record of bore development.

Records should also be kept of any failed or dry bores.

Drilling and construction records for monitoring bores may need to be provided to states/territories under state/territory legislation.

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[33] National Uniform Drillers Licensing Committee 2020. *Minimum Construction Requirements for Water Bores in Australia*. Available [online]: https://adia.com.au/wp-content/uploads/2020/09/Minimum-Construction-Requirements-for-Water-Bores-in-Australia.pdf.

Records of bore construction should be kept in accordance with the Minimum Construction Requirements for Water Bores in Australia.

3.4.2 Planning

Planning is key to a successful drilling program and an early site visit should be conducted prior to mobilisation of the drill rig to inspect each proposed monitoring bore location. It may be necessary to conduct services location, earthworks, or vegetation clearance to provide for drill rig access and approvals may be required for this, for example if the proposed vegetation clearance will impact protected vegetation. Indigenous cultural heritage specialists should be consulted prior to mobilisation of the drill rig where appropriate and engaged in the planning of any drilling investigation as there is potential for the heavy equipment to cause damage to artefacts.

Site visits should be conducted prior to mobilisation of the drill rig to inspect each proposed monitoring bore location and ensure necessary approvals are obtained, including any approvals needed for monitoring bore installation, site access, vegetation clearance, or cultural heritage clearance.

3.4.3 Drilling

Drilling for the installation of a monitoring bore is a highly specialised field and requires the engagement of an appropriately licensed and experienced driller. There is a broad range of drilling methods available, such as auger drilling, rotary air drilling and rotary mud drilling. However, the choice of method will usually be limited for a project by the nature of the subsurface environment and the proposed depth of drilling. It is important to consult with the driller on the options and select a method that will ensure representative groundwater level/pressure measurements and groundwater samples can be obtained.

The drilling method should aim to minimise smearing or compaction of the walls of the borehole, as this can affect groundwater flow into the bore and therefore the representativeness of future measurements. Reduced flow to the bore can also make purging and sampling difficult.

The use of drilling fluids such as muds, and other substances such as polymers to stabilise the walls of the borehole, should be minimised. These substances may contaminate the groundwater or affect flow into the bore. Where they are used, they should be selected to minimise impacts and to avoid those that leave toxic residues. The details of the fluids used and depths at which they were used should be recorded. These records can be used to assist with interpretation of downhole geophysics or packer testing if undertaken. Drilling methods that temporarily case the bore during drilling and construction (e.g., hollow-stem auger and sonic methods) may be preferred for monitoring bores.

Drilling equipment should be cleaned prior to use. If there is already a high level of a particular analyte present in the groundwater, bore construction should be planned to minimise cross-contamination.

When drilling a cluster of monitoring bores, the deepest bore should be drilled and constructed first. This is to prevent drilling interference with screened intervals of shallow bores in the cluster.

Drilling methods should be selected to minimise impacts on groundwater and ensure that representative measurements can be taken in future.

3.4.4 Downhole geophysical logging

Downhole geophysics should be used during construction in circumstances where lithological complexity may impact interpretation of monitoring data and resulting risk assessments. Downhole geophysics is routinely undertaken for resources exploration; however, it also provides useful data for hydrogeological investigations. Geophysical logs are useful for accurately determining the depth to different lithological units so that groundwater monitoring bores can be designed to target specific formations, and for providing information on fractures, permeability, porosity and water quality. Due to the value of this information, when deeper bores, such as those greater than 300 metres in depth, are being constructed in areas with a low density of data for those depths, downhole geophysics should be undertaken and the data should be contributed to public databases.

Downhole geophysics involves lowering probes that measure different physical properties into a borehole. The probes collect different types of continuous or point data which are graphically displayed as a geophysical log. Multiple logs are usually collected and interpreted together to provide information on rock lithology, fractures, permeability, porosity, and water quality. Common geophysical logs include calliper, gamma, single-point resistance, spontaneous potential, normal resistivity, electromagnetic induction, fluid resistivity, neutron-density, temperature, flowmeter, television, and acoustic televiewer.

> Downhole geophysics should be used during construction in circumstances where lithological complexity may impact interpretation of monitoring data and resulting risk assessments or when constructing bores greater than 300 metres depth in areas with limited availability of geophysical data.

3.4.5 Monitoring bore installation

3.4.5.1 Bore dimensions

Monitoring bores are typically smaller in diameter than water supply bores. The internal diameter of the monitoring bore casing should be at least 50 mm. If it is expected that geophysical logging may be useful after construction of the bore, the diameter should be at least 80 mm. The bore should have sufficient space for equipment that may be used in it, such as pumps for sampling.

The depth of the bore will relate to the target depths for monitoring, following guidance from Section 3.3.2.2.

> The internal diameter of the monitoring bore casing should be at least 50 mm and have sufficient space for equipment that may be used in it.

3.4.5.2 Materials

The materials for the bore casing and bore screen should be selected for durability, protection from corrosion, and to minimise impacts on the groundwater, particularly where the bore will be used for groundwater quality measurements. The current groundwater quality (e.g., salinity, pH) and potential future contaminants should be considered as they will affect the likely interactions with bore materials, such as oxidation, sorption or leaching. The materials chosen need to retain their structural integrity within the subterranean environment for the duration of the groundwater monitoring program.

Typical options for bore casings are:

- unplasticised polyvinyl chloride (PVC-U) – suitable for monitoring most organic analytes and suitable for saline conditions. Casing thickness should suit soil pressures linked to the bore depth;

- stainless steel – suitable for monitoring most organic analytes and most inorganic substances; and
- fibreglass – suitable for monitoring most organic analytes and most inorganic substances, including in corrosive groundwater.

Selection of a suitable bore casing should be site-specific. PVC is often chosen because of its comparatively low cost, however there are circumstances where its use is not appropriate, such as for deep monitoring bores.

Screwed casing joints or welded joints should be used for monitoring bores where possible. The use of solvent-based or organic-based glues on joints should be avoided, particularly if the monitoring program includes sampling for organic substances.

> The materials for the bore casing and bore screen should be selected for durability, protection from corrosion, and to minimise impacts on the groundwater.

3.4.5.3 Screens and annulus

Bore screens in monitoring bores are typically three metres in length. Longer screen lengths should be avoided as they may allow for mixing of groundwater and they may affect the natural flow of groundwater. Exceptions may be made for shallow monitoring bores that are intended to monitor the water table level. The screens on these bores should span the range of likely depths of the water table.

The aperture size of the screen should be appropriate for the geology and selected to minimise silt entering the bore and accumulating. There will typically be a sand or gravel pack in the annulus between the screen and borehole for stabilisation and to minimise solid material entering the bore. Further details on selection of screen aperture size and gravel pack grading are provided in the Minimum Construction Requirements for Water Bores in Australia.

> Bore screens longer than three metres should be avoided with the exception of bores screening the water table. The aperture size of the screen should be appropriate for the geology and selected to minimise silt entering the bore and accumulating.

3.4.5.4 Preventing contamination or mixing between aquifers

The bore should be designed to reduce the risks of creating a pathway for groundwater and contaminants between aquifers that would not naturally exist due to the presence of an aquitard. When a bore intersects multiple aquifers, any screened, slotted, or open parts of the bore and gravel packs should be contained within one aquifer. All other parts of the bore should be cased, the bore should be properly sealed and the bottom of the bore should also be sealed with an end cap.

> The bore should be designed to reduce the risks of creating a pathway for groundwater and contaminants between aquifers.

3.4.5.4 Bore development

Bore development is a process that removes suspended sediment from the bore and ensures it is operational. Bore development should always be completed after bore construction. The chosen method should minimise impacts on the groundwater from introducing air, water, or other material. Chemical methods of bore development should not be used for monitoring bores unless a clear need can be justified and the effects on collected data are clearly described. After drilling and development, a bore should not be used for groundwater quality measurements until the chemistry has stabilised, which may take several days.

> Bore development should always be completed after bore construction to remove suspended sediment from the bore and ensure it is operational using a method that minimises impacts on the groundwater.

3.4.5.5 Bore completion

Monitoring bores should be completed by installing headworks around the bore and sealing and capping the bore casing. This is to protect the bore from damage and prevent surface runoff and other substances from entering the bore. Ideally, the headworks or bore cap should be lockable to prevent vandalism.

If the bore casing extends above the surface, a steel monument should be installed around the bore. In areas where a monument would not be appropriate, the bore casing may extend to just below the surface and be sealed with a lockable surface cover, such as a Gatic® cover or similar that is flush with the ground surface. In all cases, the bore casing should include a lockable well cap to seal the bore casing and prevent the ingress of water and other substances.

Well-head completion for artesian monitoring bores (where the groundwater level/pressure is above the surface) should ensure that water flow from the bore can always be controlled.

The bore should be labelled with a unique bore identification number. A mark should be placed on the rim of the bore casing to provide for consistent groundwater level measurements when multiple monitoring rounds are undertaken (see Section 3.5).

> Monitoring bores should be completed by installing headworks around the bore and sealing and capping the bore casing.

3.4.6 Vibrating wire piezometer installation

Installation of a vibrating wire piezometer (VWP) or an array of VWPs is technical and requires the engagement of an appropriately licensed and experienced driller and an appropriately experienced field hydrogeologist.

The VWPs selected for installation should be designed for the anticipated temperatures, pressures and saturation and include thermistors for temperature monitoring.

During installation, the depth of each sensor from the reference point should be recorded so that potentiometric head can be inferred from pressure sensor readings. It is important that the cable from each sensor is clearly labelled so the depth of each sensor at the control panel is known.

In the past, the most common method of installation for VWPs was to surround the VWP sensors with a sand pack and seal with bentonite. However, a more contemporary approach is to fully grout the borehole.[34] A fully grouted completion makes installation easier and faster and minimises the risks of incorrect placement of sand packs and bentonite seals. Selection of a suitable grout mix is complex. A balance between the proportions of bentonite and cement in the mix needs to be achieved such that the permeability of the cured grout is lower than the formation permeability yet the grout is also of a consistency suitable for pumping into the borehole.

VWPs should be completed with the control box at the surface encased in a lockable weatherproof enclosure.

> Installation of VWPs requires the engagement of an appropriately licensed and experienced driller and an appropriately experienced field hydrogeologist.

3.5 Site identification

Each monitoring site should have a unique identifier and name that is clearly identified on the bore or other monitoring installation. The groundwater monitoring plan should include protocols for numbering and naming sites in accordance with state/territory numbering protocols associated with the drilling permit.

A qualified surveyor should record the location and elevation of the bore and record them as horizontal and vertical datums. The elevation of the ground surface should also be recorded. Regular surveys of bore locations should be undertaken because human activities and environmental factors can cause monitoring bores to move.

The vertical datum may be a local datum or the national datum, namely the Australian Height Datum (AHD) or AHD Tasmania. A reference point may be the same as the datum point or different (e.g., the datum point may be the ground surface while the reference point is the top of the casing of a bore).

The elevation is typically recorded at the top of the inner PVC casing and this should be done by marking a reference point on the rim of the bore casing (using permanent marker or making a notch) to reduce errors that may be introduced by an uneven bore rim height. For flowing bores, the reference point is usually the monitoring port.

The most accurate results are obtained using a surveyor's level, with the potential for elevations to be found to within one centimetre. Monitoring bore elevation data may be obtained using global positioning system (GPS) readings, contour lines on topographic maps, remotely sensed land-surface elevation data or barometric altimeters. However, the accuracy of these methods is typically in the order of metres and so they shall only be used 1) where the uncertainty in the datum measurement is demonstrated not to impact analyses, or 2) where despite best efforts, the datum has not been surveyed and groundwater level measurements would otherwise need to be disregarded. The precision of the datum should be recorded in the field notes and provided for consideration of

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[34] Contreras IA, Grosser AT, and Ver Strate RH 2008. The Use of the Fully-Grouted Method for Piezometer Installation. *Geotechnical Instrumentation News* 26. Available [online]: https://doi.org/10.1061/40940(307)67.

McKenna GT 1995. Grouted-in Installation of Piezometers in Boreholes. *Canadian Geotechnical Journal* 32, no. 2, 355-63. Available [online]: https://doi.org/10.1139/t95-035.

Mikkelsen PE 2002. Cement-Bentonite Grout Backfill for Borehole Instruments. *Geotechnical Instrumentation News.* Available [online]: https://www.researchgate.net/publication/242148889_Cement-Bentonite_Grout_Backfill_for_Borehole_Instruments.

Vaughan PR 1969. A Note on Sealing Piezometers in Boreholes. *Géotechnique* 19, no. 3, 405-13. Available [online]: https://doi.org/10.1680/geot.1969.19.3.405.

uncertainty in analyses. Uncertainty values and observations should be recorded in field notes and provided to the monitoring team if surveying is undertaken by a third party.

The National Industry Guidelines for hydrometric monitoring[35] provides details on what should be recorded for each monitoring location.

> The groundwater monitoring plan should include protocols for numbering and naming sites. The location and elevation of the bore should be recorded.

3.6 Using existing bores for monitoring

A groundwater monitoring network may already be in place for some projects. Examples include projects involving an expansion or modification of an existing operation, or projects moving from the pre-approval phase to the post-approval phase. Before installation of a groundwater monitoring network, review of the existing groundwater monitoring network should be undertaken to understand whether some of the locations may be suitable for inclusion. The use of existing bores can be advantageous in that it reduces impacts on the groundwater from further bore construction and may allow for the use of any previous data from the bore as baseline data. The location, construction and condition of the bore should be assessed when deciding whether an existing bore is appropriate to use in a monitoring network (see Section 3.6.1). New bores should be constructed at locations where existing monitoring bores are unable to meet the requirements.

For some projects, although there may be no existing groundwater monitoring bores in the study area, local landholders may have water supply bores. Private water supply bores are not recommended for monitoring but may need to be monitored for an impact assessment. They may also be used to provide additional data to augment data from a groundwater monitoring network. Assessment of their suitability for monitoring is discussed in Section 3.6.2.

The ability to access a bore for the duration of the monitoring program should be considered when deciding whether a bore is suitable for inclusion in a monitoring network. It may be necessary to negotiate an access agreement with a state/territory government or a private landholder to provide for ongoing access arrangements.

> The location, construction and condition of the bore should be assessed when deciding whether an existing bore is appropriate to use in a monitoring network. New bores should be constructed at locations where existing monitoring bores are unable to meet the requirements.

3.6.1 Existing monitoring bores

Assessment of the suitability of a bore for inclusion in a monitoring network should start with review of the drilling records, lithological logs, bore construction logs, and geophysical logs to understand the drilling method, bore construction, target formation and method of bore development. Bores constructed in accordance with Section 3.4 of this document may be suitable for inclusion in a monitoring network. Bores that do not have drilling records or construction details available are not recommended for inclusion. Where bore logs exist, consideration should be given to their reliability. Post-construction geophysics may help with assessing bore screen locations and lithology.

[35] Bureau of Meteorology 2021. National Industry Guidelines for hydrometric monitoring. Available [online]: http://www.bom.gov.au/water/standards/niGuidelinesHyd.shtml.

A review of monitoring data collected for the bore should be undertaken. The review should consider any changes in groundwater level/pressure or quality and whether this may suggest deterioration in bore condition. For example, a sharp increase in groundwater levels in a deep bore may indicate the bentonite seal has failed and the bore annulus is providing a pathway connecting a shallow groundwater system with the deep groundwater system. In this instance, the bore should not be included in the groundwater monitoring network and should be decommissioned as soon as possible.

A site visit should be conducted to check the condition of the bore. The identification of the bore should first be confirmed using markings on the bore, GPS location, and the depth of the bore. The bore should then be inspected for construction defects and signs of deterioration. Even bores that have been carefully constructed may at some point lose their value as a reliable measurement instrument. Cracks in the bore casing or displaced joints may form due to subtle ground movements or casing may corrode over time. The integrity of the casing and screen should be inspected using a downhole video camera. Downhole geophysics may also be used to provide information on the construction and integrity of the bore.

Another issue that may occur is clogging of the bore screen. This can occur during construction of the bore, for example by bentonite due to an error in filter pack placement, or over time due to mineral precipitation (e.g., iron hydroxides), settlement of organic or sediment fines from the water column and biofouling or bio-clogging (bacterial growth). Clogging is known to significantly affect water production rates in pumping wells and is likely to negatively impact the accuracy of monitoring bores. The depth of the bore may indicate whether siltation has occurred. Hydraulic testing (e.g., slug tested as discussed in Section 6.1.3.1) may indicate whether other types of clogging have occurred. Hydraulic testing should be undertaken for all bores selected for inclusion in the monitoring network to confirm that there is good hydraulic communication between the monitoring bore and the aquifer and the hydraulic response of the bore accurately reflects groundwater level/pressure fluctuations in the aquifer. Hydraulic tests should be repeated periodically, and bores cleaned out, particularly if low purging rates suggest that clogging of the screens has occurred.

Existing bores should be assessed for inclusion in a monitoring network by reviewing any drilling records, lithological logs, bore construction logs, geophysical logs, and monitoring data and conducting a site visit. The quality of available data should be considered. Post-construction downhole geophysics may be required to assess the bore construction and target formation.

3.6.2 Private water supply bores

Private water supply (production) bores are generally not recommended for monitoring. These bores typically have a longer screen or open area than monitoring bores, which can make it difficult to interpret results within the context of the monitoring network. Also, as these bores are used for groundwater extraction, groundwater level/pressure data from the bore may not be representative of aquifer conditions.

Private water supply bores may need to be monitored where there is potential that they may be impacted by a project. They may also be used to provide additional data to supplement a groundwater monitoring network. In these instances, pre-development data should be collected, comparable monitoring bores should be available, and the condition of the bore at the time of measurement should be documented along with anticipated impact on accuracy of measurement, with an emphasis on what is and is not known about the construction of the bore and presence and use of pumping.

Private water supply (production) bores are generally not recommended for monitoring but should be monitored where there is potential that they may be impacted by a project. They may be used to provide additional monitoring data if the bore is not in use, depending on the bore construction and how recently pumping occurred.

3.7 Maintaining bores

Bores should be protected and maintained as outlined in the Minimum Construction Requirements for Water Bores in Australia.[36]

This includes keeping the area around the bore clear, preventing surface water from collecting around the bore, protecting the bore headworks and casing from damage, and checking the seal of the bore cap.

A downhole video camera can be used to inspect the bore if low purging rates suggest clogging or fouling, instruments cannot easily be deployed down the bore, or review of the monitoring data suggests that there may be an issue with the bore. Issues may include clogging due to sedimentation of the bore, displaced casing joints or cracks in the casing, biological, chemical, or physical fouling of the screen, or corrosion of the bore.

Bores should be cleaned out periodically to avoid clogging or fouling. Pumping water from the bore is the preferred method. Air lifting may be required if pumping is ineffective at clearing the bore. Chemical methods should be avoided and only used where absolutely necessary. Records of all maintenance should be kept to understand any potential issues with interpretation of monitoring data.

The datum points of the bore should also be surveyed periodically to ensure they remain valid.

Faulty bores that can no longer be used for monitoring should be decommissioned as outlined in the Minimum Construction Requirements for Water Bores in Australia.

Bores should be protected and maintained as outlined in the Minimum Construction Requirements for Water Bores in Australia.

[36] National Uniform Drillers Licensing Committee 2020. *Minimum Construction Requirements for Water Bores in Australia*. Available [online]: https://adia.com.au/wp-content/uploads/2020/09/Minimum-Construction-Requirements-for-Water-Bores-in-Australia.pdf.

4. Groundwater level/pressure monitoring

4.1 Introduction

Groundwater systems are dynamic and in constant flux in response to short-term and long-term changes in climate, groundwater extraction, and land use. Groundwater level/pressure measurements provide the fundamental data needed to characterise groundwater resources, including lateral and vertical head distribution and hydraulic gradients within individual aquifers and between aquifers in layered aquifer systems. They are used to determine the response of an aquifer to stresses such as pumping or recharge, to characterise interactions with surface-water bodies, to identify hydrogeologic units and to determine aquifer properties such as transmissivity and storativity. Long-term, systematic measurement of groundwater levels/pressures (baseline monitoring) can provide the data needed to understand how groundwater systems behave over time, undertake history matching when developing groundwater flow models and detect impacts to groundwater-related assets and ecosystems during construction and operation of a project. As such, groundwater level/pressure monitoring should be undertaken for all projects with the potential to impact on groundwater resources and related assets and ecosystems.

Throughout this section, the term 'groundwater level' is used to refer to the water level measured in a monitoring bore screened across the water table or a subartesian monitoring bore and the term 'groundwater pressure' is used to refer to the water level measured in an artesian monitoring bore. Hydraulic head (or potentiometric head) is a measure of water pressure above a vertical datum. It can be calculated for a formation by measuring the groundwater level or pressure in a groundwater monitoring bore that is screened across that formation where the elevation of the groundwater monitoring bore is known. Hydraulic head measured at different groundwater monitoring bores can be used to interpret the direction and magnitude of groundwater flow and changes over time provided all heads are expressed with respect to the same reference datum and corrected for any variation in density.

Groundwater level/pressure monitoring should be undertaken for all projects with the potential to impact on groundwater resources and related assets and ecosystems.

4.1.1 Failure points and sources of uncertainty

Although water table elevations and hydraulic heads may seem like simple metrics to obtain in hydrogeology, their measurement is prone to error and the true values are inherently uncertain. Whether this uncertainty is acceptable will depend on the nature of the investigation and the purpose of the measurements. It is important to appreciate the limitations and imperfections of the instruments and measurement procedures to minimise errors in groundwater level or pressure data.

The main sources of error when measuring groundwater levels/pressures are related to[37]:

- the measurement instruments, discussed in Sections 4.3.1, 4.3.2, 4.3.3 and 4.3.4;
- the conversion from pressure to heads, discussed in Section 4.4;
- time-lag effects, discussed in Section 4.3.1; and

[37] Post, V., H. Kooi, and C. Simmons 2007. Using Hydraulic Head Measurements in Variable-Density Ground Water Flow Analyses. *Ground Water* 45, no. 6. Available [online]: http://doi.org/10.1111/j.1745-6584.2007.00339.x.

- monitoring bore defects, discussed in Section 3.6.1.

Good quality-assurance practices help to maintain the accuracy and precision of groundwater level/pressure measurements, ensure that monitoring bores reflect conditions in the aquifer being monitored, and provide data that can be relied upon for its intended use. The following sections provide details of field and office practices that, if consistently applied, will provide the needed levels of quality assurance for groundwater level/pressure data.

4.1.2 Existing standards

Groundwater level or pressure monitoring should be undertaken in accordance with the provisions of this section and relevant sections of the most recent version of the Bureau of Meteorology National Industry Guidelines for hydrometric monitoring.[38] The Guidelines contain Australian industry recommended practice for the collection, analysis and reporting of hydrometric data, with the aim of ensuring the quality of data gathered is suitable for the intended use.

Additional guidance on groundwater level/pressure monitoring is also provided in the following documents:

- Geoscience Australia, Groundwater sampling and analysis – A field guide;[39]
- International Organization for Standardization, Hydrometry - Measuring the water level in a well using automated pressure transducer methods, ISO/TR 23211:2009; and
- International Organization for Standardization, Manual methods for the measurement of a groundwater level in a well, ISO 21413:2005; and
- Post and von Asmuth (2013). [40]

> Groundwater level/pressure measurement should be undertaken in accordance with the Bureau of Meteorology National Industry Guidelines for hydrometric monitoring and other relevant standards and guidelines.

4.2 Monitoring plan

A groundwater monitoring plan developed under Section 2.6 should include details of the groundwater level/pressure monitoring to be undertaken. The plan should specify:

- the monitoring locations where groundwater levels/pressures will be measured (Section 4.2.1);
- the frequency of monitoring at each location (Section 4.2.2);
- the duration of monitoring at each location (Section 4.2.3);

[38] Bureau of Meteorology 2021. *National Industry Guidelines for hydrometric monitoring.* Available [online]: http://www.bom.gov.au/water/standards/niGuidelinesHyd.shtml.

[39] Sundaram B 2009. *Groundwater Sampling and Analysis - A Field Guide.* Record 2009/027. Geoscience Australia, Canberra. Available [online]: http://pid.geoscience.gov.au/dataset/ga/68901.

[40] Post VEA and von Asmuth JR 2013. Review: Hydraulic Head Measurements—New Technologies, Classic Pitfalls. *Hydrogeology Journal* 21, no. 4, 737-50. Available [online]: http://doi.org/10.1007/s10040-013-0969-0.

- the methods and instruments that will be used to measure groundwater levels/pressures at each location (Section 4.3);
- additional data to be collected for data correction at each location, such as temperature or salinity (Section 4.4.3); and
- the locations and collection methods for other types of meteorological or hydrological data needed for interpretation of the groundwater level/pressure data (Section 4.2.4).

4.2.1 Monitoring locations

The locations selected for groundwater level/pressure monitoring will depend on the objectives of monitoring and whether the project is pre-approval or post-approval. Projects in the pre-approval phase may require characterisation of the hydrogeological environment and therefore require groundwater level/pressure monitoring across a broad study area and in all water-bearing formations that may potentially be impacted by the proposed development. Projects in the post-approval phase may require more targeted groundwater level/pressure monitoring, such as impact detection monitoring of groundwater pressures in the source aquifer of a spring.

Groundwater level/pressure monitoring should be undertaken in dedicated groundwater monitoring bores, piezometers or vibrating wire piezometers that have been appropriately designed, drilled, constructed, and maintained as outlined in Chapter 3. Groundwater level/pressure monitoring should not rely on measurements from private water supply bores as groundwater level/pressure will be directly affected by pumping of the bore and will not be representative of conditions in the aquifer. Nested locations should be monitored where groundwater level/pressure data are required for multilayer systems and where data on vertical hydraulic gradients are required. To characterise horizontal groundwater flow directions, a minimum of three bores completed within each aquifer (or other water-bearing formation) is required (see Section 3.3.2.1). The formations targeted for groundwater level/pressure monitoring should include all water-bearing formations that may potentially be impacted by the development, as well as potentially connected formations.

> Groundwater level/pressure monitoring should be undertaken for all formations that may be impacted by the project, as well as potentially connected formations

4.2.2 Frequency of monitoring

The frequency of measurement should be determined with regard to the variability of groundwater level/pressure fluctuations in monitoring installations if known and/or the data resolution or amount of detail needed to fully characterise the hydrologic behaviour of the aquifer in relation to project risks. There should be evidence that the frequency of measurement is adequate to detect short-term and seasonal groundwater level/pressure fluctuations of interest and to discriminate between the effects of short- and long-term hydrologic stresses. This may involve statistical analysis or be informed by modelling.

For aquifers that have not previously been monitored, frequent or continuous water-level monitoring should initially be undertaken to identify the magnitude and frequency of aquifer fluctuations and determine the appropriate frequency of ongoing monitoring. For aquifers where monitoring has previously been undertaken, the frequency of measurement should be determined based on groundwater level/pressure fluctuations in existing monitoring installations (see Section 2.3.5). More frequent groundwater level/pressure monitoring (hourly, daily, weekly, monthly) is generally required for aquifers if they are: shallow or unconfined, have a high through-flow or recharge rate, have a higher level of extraction, or show a strong response to weather conditions or link to surface water features. Less frequent groundwater level/pressure monitoring (seasonally or annually) may be suitable for large, stable (usually confined) aquifers provided that stresses associated with the project can be detected at suitable timescales.

Groundwater level/pressure monitoring may involve automatic or manual measurements. Automatic monitoring is undertaken with either submersible pressure sensors (commonly referred to as data loggers) in monitoring bores (see Section 4.3.1) or vibrating wire piezometers (see Section 4.3.2) that are programmed to make measurements at a specified frequency, providing the highest level of resolution of groundwater level/pressure fluctuations. The frequency of measurements selected as part of the monitoring plan design should ensure that the effects of various stresses on the aquifer system can be accurately identified and accurate estimates of maximum and minimum groundwater level/pressure fluctuations in aquifers can be obtained.

Where the hydraulic response of an aquifer to stresses is slow and the frequency and magnitude of groundwater level/pressure changes is small, automatic monitoring may not be required and manual measurements may be adequate. Manual groundwater level/pressure measurements are those made at scheduled intervals (weeks, months, or years), most typically using electronic-sensor tapes or acoustic sounding devices. Manual monitoring should not be used when project risks involve potential for hydraulic responses to short-term stresses to occur between measurements and be missed, extreme groundwater level/pressure fluctuations need to be determined with high confidence, or apparent trends in groundwater levels/pressures may be biased by the coarse measurement frequency. For example, manual measurement of groundwater levels once a quarter may miss tidal influences on a groundwater system that may confound impact detection.

To provide representative data for model history matching, automatic monitoring should be undertaken for all projects requiring numerical groundwater modelling to predict impacts. The frequency of pressure sensor readings should consider the dynamics of the groundwater system and battery life and memory of the logger. Four- to six-hourly pressure readings are recommended to capture variation that may occur at a sub-daily scale, such as pumping impacts from nearby bores or tidal influences, whilst minimising data loss. To validate the automatic readings and provide for sensors to be checked so that data loss is minimised, manual groundwater level measurements should be undertaken in monitoring bores with pressure sensors at least once a year, and ideally quarterly (four times a year and once in each season).

Where manual groundwater level measurements are undertaken, measurements would ideally be undertaken weekly to monthly, but as a minimum should be undertaken quarterly (four times a year and once in each season or period relevant for the study area) to capture seasonal variability in groundwater level.

Near real-time data collection can be accomplished using an automatic recording device and telecommunication or radio transmitter equipment (telemetry). Telemetered groundwater level/pressure monitoring should be used in impact detection monitoring where high risks to a groundwater-related asset have been identified and early warning of potential impacts is required, where the gap caused by loss of data logger measurements would be unacceptable, access to timely data or needs to be independent of logistics constraints. Telemetry is also recommended for other applications as it can minimise data loss, as issues with pressure sensors (e.g., battery failure) can be detected early and a field visit can be scheduled to fix or replace the pressure sensor. Telemetry also allows remote data access for projects in remote areas where field visits are costly and logistically complex.

> There should be evidence that the frequency of measurement is adequate to detect short-term and seasonal groundwater level/pressure fluctuations of interest and to discriminate between the effects of short- and long-term hydrologic stresses. Automatic monitoring should be undertaken for all projects requiring numerical groundwater modelling to predict impacts.

4.2.3 Duration of monitoring

Long-term groundwater level/pressure records for aquifers in the study area prior to commencement of a project (baseline monitoring data) greatly enhance the ability to predict future groundwater levels/pressures and reduce uncertainty in numerical groundwater modelling. Ideally, baseline groundwater level/pressure monitoring should span a range of groundwater level fluctuations in a monitoring bore and represent aquifer behaviour in response to seasonal climatic variation, longer-term climatic changes, and land and water management practices and water extraction in the study area. The duration of baseline monitoring should be as outlined in Section 2.2.4.4 and the duration of impact detection monitoring as outlined in Section 2.3.

4.2.4 Other types of data

Other types of hydrologic information should also be collected as part of a groundwater-level monitoring program if not available from other reliable sources. Meteorological data, such as precipitation data, are required in the interpretation of groundwater level/pressure changes in monitoring bores and should be collected in accordance with the Bureau of Meteorology National Industry Guidelines for hydrometric monitoring[41]. Groundwater temperature and salinity data should also be collected (see Chapter 5). Where monitoring bores are in alluvial aquifers or other aquifers with a strong hydraulic connection to a stream or lake, hydrologic data, such as stream discharge or stage (in mAHD), are useful in examining the interaction between groundwater and surface water (see Section 6.2). Meteorological and streamflow data are typically available from government sources; however, additional monitoring of variables such as precipitation or streamflow may be needed in remote areas or small catchments. Groundwater extraction data, such as pumping rates and volumes of pumped water, can also be useful for the interpretation of trends observed in groundwater levels.

> Meteorological data, hydrologic data, groundwater temperature and salinity data, and groundwater extraction data should be collected or obtained from reliable sources as needed to interpret groundwater level/pressure data.

4.3 Monitoring methods

4.3.1 Groundwater monitoring bores

Manual measurement

Manual measurement of groundwater levels is undertaken in monitoring bores to validate continuous readings and to measure groundwater level where continuous monitoring is not being undertaken.

Manual measurement of the depth to groundwater should be undertaken before submersible pressure sensors are removed from the bore to download and before purging and sampling of the bore so that an undisturbed groundwater level is recorded. Groundwater levels in the monitoring bore should be allowed to equilibrate prior to measurement after removing sealing caps, with the procedure for the given monitoring bore documented along with justification. Appropriate equilibration times can range from minutes to hours depending on bore recharge rates.

Field records of the depth to groundwater should be maintained, indicating the point on the bore from which groundwater levels were measured. Typically, a reference point is marked on the rim of the bore casing so that groundwater level is consistently measured from the same point during every monitoring round (see Section 4.4.1).

[41] Bureau of Meteorology 2021. *National Industry Guidelines for hydrometric monitoring.* Available [online]: http://www.bom.gov.au/water/standards/niGuidelinesHyd.shtml.

Various factors can affect the accuracy of groundwater level measurements and their ability to represent hydraulic head. These include external stress effects, such as atmospheric pressure changes, and the density of the fluid-column within the bore by changes in groundwater temperature and/or salinity. These factors should be considered prior to groundwater monitoring as it may be necessary to collect additional data to allow for the correction of groundwater level data. Types of additional data that may need to be collected include barometric pressure data, water temperature data, and salinity data. Data correction is further discussed in section 4.4.3. Correction of water level observations for density effects is particularly important for deep confined aquifer systems (>500 m) where geothermal gradients lead to higher water temperatures and lower water density within the well. Disregarding the effect of temperature in such cases may overestimate heads.[42] Further guidance is provided in the case study in Section 4.3.3 and in Bekesi et al.[43] Observations of factors that may influence groundwater level readings, such as pumping at a nearby bore, should also be included in field records.

Manual groundwater level measurement is most typically undertaken using an electric probe attached to a graduated measurement tape, which is often referred to as a water level meter, a dip meter, or a dipper. Other options for groundwater level measurement include the plopper, or popper, a metal (e.g., brass) cylinder which makes an audible plopping noise when it hits the water, and the wetted chalk tape method, which submerges part of the tape to avoid ambiguity as to the position of the lower end of the tape. The method used should be recorded as it may affect accuracy of the measurement, as discussed in Table 4.1 below.

Measurement tapes should be calibrated against a reference tape of the highest accuracy class at least once a year to ensure comparability of measurements and account for general wear and development of bends and kinks. Tapes not manufactured to any standard can be out by more than 5 cm over 30 m. Field records should include an estimate of the expected accuracy of the tape used based on the most recent calibration.

Measurement method should be selected to ensure that accuracy is sufficient to identify and diagnose changes in groundwater level relevant to project risks. Further discussion of accuracy of water level measurement can be found in Post and von Asmuth.[44]

Manual measurement of the depth to groundwater should be undertaken prior to removing the logger from the bore or conducting purging or sampling so that an undisturbed and equilibrated groundwater level is measured where possible. Measurements should be taken from a reference point marked on the rim of the bore casing so that groundwater level is consistently measured from the same point during every monitoring round.

Automatic measurement

Automatic measurement of groundwater levels in monitoring bores is typically undertaken using a submersible pressure sensor/transducer/logger. A submersible pressure sensor measures hydrostatic pressure above the sensor. Alternatively, a vibrating wire piezometer may be used; however, these are more typically used in backfilled or grouted boreholes (see Section 4.3.2).

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[42] Bekesi G, Tyler M and Waterhouse J 2013. Groundwater head in high-temperature aquifers. Q*uarterly Journal of Engineering Geology and Hydrogeology* 46, no.1, 87-94. Available [online]: https://doi.org/10.1144/qjegh2012-035.

[43] Bekesi G, Tyler M and Waterhouse J 2012. Lessons from the use of an active production well for compliance monitoring in the Great Artesian Basin, Australia. Mine Water Environ 31, no.3, 225-232. Available [online]: https://doi.org/10.1007/s10230-012-0183-7.

[44] Post VEA and von Asmuth JR 2013. Review: Hydraulic Head Measurements—New Technologies, Classic Pitfalls. Hydrogeology Journal 21, no. 4, 737-50. Available [online]: https://doi.org/10.1007/s10040-013-0969-0.

Submersible pressure sensors with built-in data loggers provide a cost-effective means of collecting time-series groundwater level/pressure data. Data from the sensor are accessed via either manual download or telemetry. To avoid data loss, a data logger with sufficient memory capacity and battery life should be selected in consideration of the frequency of groundwater level/pressure measurement and the frequency of download.

The pressure sensors used for monitoring need to be carefully selected. The accuracy of different pressure sensors varies and an increase in measurement range comes with a reduction in accuracy. Selection of an appropriate sensor should consider the depth to groundwater, fluctuations in groundwater level/pressure, bore construction and head of groundwater above the sensor. Differences between vented and non-vented pressure sensors must be taken into consideration. The chamber of a vented pressure sensor is open to the atmosphere whereas a non-vented pressure sensor is sealed. When using vented pressure sensors with a hollow tube, a desiccating agent should be used to prevent condensation in the tube. When using non-vented pressure sensors, appropriate barometric compensation should be applied to estimate the groundwater elevation (see Section 4.4.3).

The distance of the sensor from the marked reference point on the bore rim (suspension wire length) should be measured and recorded so that groundwater level/pressure can be inferred from pressure sensor readings. The suspension wire will stretch under strain and heat and therefore the length of the suspension wire is best calculated from a manual measurement of the groundwater level taken at the same time as the first measurement by the sensor in the monitoring bore, particularly for longer wires which can be expected to stretch further. Any change to the suspension wire length should be recorded in the field notes so that an accurate groundwater elevation can be calculated.

Pressure transducers are prone to various types of errors, including instrument drift and sensitivity to temperature variations, which may amount to a measurement error of several centimetres or even decimetres. To address this issue, regular manual groundwater level/pressure measurements should be standard practice to identify any drift of the pressure transducer and provide a means to correct for this effect. Regular manual checks of automatic data should be undertaken to detect instrument malfunctioning and drift. The date and time of manual readings should be recorded in the field notes so that comparison to automatic data can be made. Errors interpreting groundwater level/pressure data can also be introduced if the internal clocks of the loggers are inaccurate, with deviations of up to 30 min/year not uncommon. Checks and synchronisation of the internal clocks of loggers against a consistent, reputable source should be undertaken when the logger is set up and when it is downloaded as asynchronicity between loggers can introduce errors, e.g., if recording water and air pressures to allow for barometric pressure correction (see Section 4.4.3) or interpreting pressures recorded in different monitoring bores. Pressure transducers should undergo column tests in a water vessel before use.

When undertaking automatic measurements during test pumping or where rapid changes in head are occurring, it is important to be aware of time-lag effects. Groundwater level in a monitoring bore always needs some time to equilibrate with the groundwater pressure at the screen. The response time of a monitoring bore will depend on the transmissivity and storativity of the aquifer, the volume of the bore, the screen length, and the local permeability of the strata adjacent to the screen. This will be in the order of seconds to minutes for permeable formations and may be days or more for impermeable strata such as silt, peat and clay. Measurement conditions and any precautions to account for time-lag effects should be documented to allow for its consideration in subsequent data analysis.

Submersible pressure sensors should be selected and installed based on the depth to groundwater, expected fluctuations in groundwater level/pressure, frequency of measurement, and frequency of download. Regular manual checks of automatic groundwater level data should be undertaken to detect instrument malfunctioning and drift. Internal clocks of loggers should be checked and synchronised to a consistent reputable source.

Table 4.1 Data accuracy and limitations of methods for measuring groundwater level/pressure in subartesian bores[45]

Method	Data accuracy and limitations
Wetted chalk method (graduated steel tape)	• Can be accurate to ± 1 cm for depths less than 60 m and to ± 2 cm for depths between 60 m and 150 m. • Errors can be introduced due to the effects of thermal expansion and stretch due to the suspended weight of the tape and plumbing weight, particularly in bores where the water level is greater than 300 m. • Requires calibration against a dedicated steel reference tape at least once a year to check the accuracy is not affected by tape wear or kinks. • Results may be unreliable if water is dripping into the bore or condensing on the well casing. • Not recommended for use in pumping wells due to turbulence and risk of lowering tape into pump impellers. • Not suitable for use where multiple readings need to be taken in quick succession, such as during test pumping, as the steel tape needs to be removed from the bore after each measurement. • Depth to water will need to be corrected if the well casing is angled instead of vertical.

[45] International Organization for Standardization. Manual methods for the measurement of a groundwater level in a well. ISO 21413:2005

Cunningham, William L., and Charles W. Schalk. "Groundwater Technical Procedures of the U.S. Geological Survey." U.S. Geological Survey, 2011

Post, Vincent E. A., and Jos R. von Asmuth. "Review: Hydraulic Head Measurements—New Technologies, Classic Pitfalls." Hydrogeology Journal 21, no. 4 (2013/06/01 2013): 737-50.

Method	Data accuracy and limitations
Water level meter (electric probe)	• Can be accurate to ± 1 cm for depths less than 60 m, ± 3 cm for depths of around 150 m and to ± 15 cm for depths in the 500-m range. • Requires calibration against a dedicated steel reference tape at least once a year to check the accuracy is not affected by tape wear or kinks. • May not give an accurate reading if water in the bore has very low electrical conductivity, if there is material on the water surface such as oil, ice or debris, or if water in the bore has very high electrical conductivity where water films can form bridges between the co-axial elements of the sensing tip. • Tape expansion and stretch is an additional consideration when measuring deep water levels or in water with a temperature greater than 20 degrees Celsius. • A stilling well may be required for taking measurements during test pumping. • Depth to water will need to be corrected if the bore casing is angled instead of vertical.
Submersible pressure sensor	• Accuracy differs with the manufacturer, measurement range, and depth to water. Accuracy is generally the highest of 3 mm, 0.1 percent of range in water level fluctuation, or 0.01 percent of depth to water. • Pressure sensors are subject to drift, offset and stretch of the suspension wire. Readings should be checked against manual water level measurements, which should be made to the nearest 3 mm, at every visit. Pressure sensors should also be checked against the date and time and recalibrated periodically. Hysteresis may occur. • An appropriate pressure sensor needs to be selected for the depth to groundwater and the range of level/pressure fluctuations in each bore. Pressure sensors in bores with a large range in water level/pressure will have reduced resolution or may require frequent resetting of the depth of the sensor.

4.3.2 Vibrating wire piezometers

VWPs are instruments used to continuously measure groundwater pore pressures. They can be used in monitoring bores in a similar way to a submersible pressure sensor. However, typically VWPs are permanently installed in the ground in backfilled or grouted boreholes and connected to a data logger in a control box at the surface that stores continuous pressure readings. Multiple sensors can be placed in a single borehole to measure pressures at different levels through the profile and provide information on vertical hydraulic gradients. The depth of each sensor from the reference point is recorded during installation so that the hydraulic head can be inferred from the pressure sensor readings. Further information on the installation of VWPs is included in Sections 3.3.1.4 and 3.4.6.

Drilling a borehole and backfilling it temporarily changes the pore pressure, so readings that are taken immediately after installation will not be representative of conditions in the formation. Recovery of the natural pore pressure may take a few hours to a few weeks, depending on the permeability of the formation. Pressure readings are considered representative once stable readings over a few days are recorded. Lead-time before data are available should be taken into account in planning of VWPs, and data prior to stabilisation should not be included in the required baseline period.

Readings from a VWP should be converted to units of pressure by applying the calibration factors unique to the sensor as per manufacturer instructions. The VWP should also provide temperature data. Temperature has some effect on the response of a VWP and therefore correction for temperature is recommended (see Section 4.4.3).

> Readings from a recently installed VWP are considered representative once stable readings over a few days are recorded. Readings from a VWP should be converted to units of pressure by applying the calibration factors unique to the sensor as per manufacturer instructions and correction for temperature is recommended.

4.3.3 Flowing artesian bores

An artesian bore is a bore tapping a confined groundwater system, where the groundwater is under pressure and the water level in the bore rises above the aquifer. A flowing artesian bore is where the water level in the bore is above the ground surface (shown on the left in Figure 4.1). A subartesian bore is where the water level in the bore is below the ground surface (shown on the right in Figure 4.1).

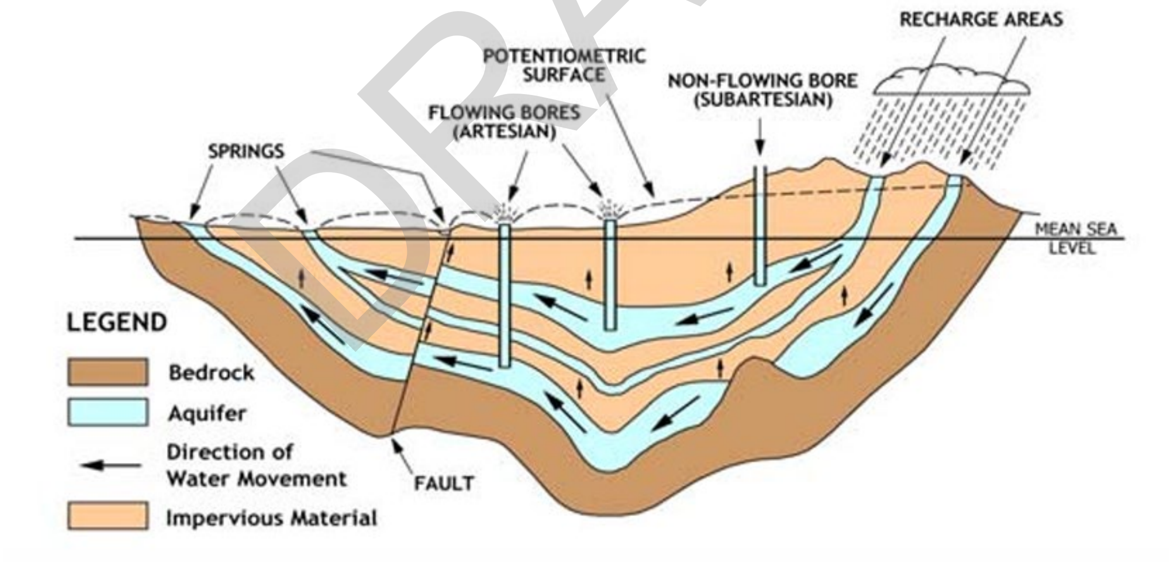

Figure 4.1 Subartesian and flowing artesian bores in the Great Artesian Basin, Australia

Source: Queensland Government, Department of Environment and Resource Management, 2011.

The preferred way to measure groundwater pressure is to use a dedicated shut-in monitoring bore. However, in some circumstances, a flowing artesian bore that is not shut-in may need to be used to measure groundwater pressure. To measure the head in a flowing artesian bore, the top of the bore either needs to be extended using transparent tubing (where the head is less than 2 m above ground level), or the head is derived from a shut-in test, during which the flow of water through the bore is stopped and the pressure at the land surface is recorded using a pressure gauge.

If measuring pressure head in low pressure flowing artesian bores using transparent tubing, the measuring scale should be placed on the reference point and the water level should be read by placing the hose against the measuring scale. For higher pressure flowing artesian bores, pressure head should be measured using a calibrated pressure gauge installed into the monitoring port on the bore. Selection of a suitable pressure gauge should be based on the expected pressure in the bore, with pressure gauges generally most accurate in the middle third of the gauge range. Prior to taking a pressure reading, it is important to ensure that all flow from the bore is shut down. All valves on the bore should be closed, apart from the monitoring valve, and there should be no leaks at joins of any of the pipe fittings as this will result in a false pressure reading. The height of the centre of the gauge relative to the reference point on the bore (generally the monitoring port but may be ground level) should be recorded in the field notes so that an accurate potentiometric elevation can be reported. When measuring groundwater pressure in a flowing artesian bore using a shut-in test, the time required for the water pressure to equilibrate after the bore is shut down may range from hours to days. The appropriate time to take the water pressure measurement after shut-in will vary and should be determined on a case-by-case basis. Adequate recovery times could be estimated from recovery tests or using standard methods such as the Theis equation. The time between shut-in and measurement of the water pressure should be recorded together with the rationale for the selected period and should be consistent between monitoring rounds.

When using a shut-in test to measure groundwater pressure for deep confined aquifer systems (>500 m) with high water temperatures, an initial rise in pressure may be observed, followed by a pressure decline. This is a density-related effect corresponding with cooling due to the annulus of rock surrounding the bore. In these situations, heads calculated from maximum pressures may underestimate heads by not allowing for adequate recovery times. Further guidance is provided in the case study below and Bekesi et al.[46]

The pressure of the groundwater at the bore screen is the sum of the recorded pressure and the pressure due to the water column between the pressure gauge and the bore screen. In this case, the hydraulic head is found by converting the pressure to pressure head and adding this to the elevation head.

Detailed information on measuring pressure head in flowing artesian bores is provided in International standard ISO 21413:2005.

> To measure the head in a flowing artesian bore, the top of the bore either should be extended using transparent tubing (where the head is less than 2 m above ground level), or the head should be derived from a shut-in test. Pressure head should be measured using a calibrated pressure gauge installed into the monitoring port on the bore.

[46] Bekesi G, Tyler M and Waterhouse J 2012. Lessons from the use of an active production well for compliance monitoring in the Great Artesian Basin, Australia. *Mine Water Environ* 31, no.3, 225-232. Available [online]: https://doi.org/10.1007/s10230-012-0183-7.

Bekesi G, Tyler M and Waterhouse J 2013. Groundwater head in high-temperature aquifers. Q*uarterly Journal of Engineering Geology and Hydrogeology* 46, no.1, 87-94. Available [online]: https://doi.org/10.1144/qjegh2012-035.

Case study: Density corrections for groundwater level and pressure measurements in deep bores and flowing artesian bores in the Great Artesian Basin

In the Great Artesian Basin (GAB), Australia, the depth of bores regularly exceeds 500 metres, with some bores drilled to 2000+ metres depth. Some bores are flowing, while others are sub-artesian. Water temperatures range from 30ºC in shallow areas to 100ºC in deeper regions and the salinity of the groundwater varies from 100 to over 25,000 milligrams per litre.

The combination of deep bores (>500 m), high temperatures and salinity make the calculation of groundwater heads in the GAB challenging. The typical assumptions, often made implicitly, regarding constant density of the water column within a bore may not apply, particularly with deep bores with higher water temperatures at depth. Accurate determination of head is particularly important where regulatory requirements set small drawdown trigger levels.

While the technology exists to measure pressure directly at depth using instruments such as quartz and sapphire gauges, that are routinely used in the oil and gas industry, these instruments are costly and may not be sufficiently stable for long term deployment. For hydrogeological investigations, pressure at the bore head is more typically measured.[2]

To correct for the error induced by temperature-related density changes, pressure measurements in deep bores should be accompanied by a thermal survey, with temperature measured just below the water level in the bore, or near the surface for flowing bores, and at the bore screens. Ideally near-surface temperature measurements should be taken at a depth <20 m using a dedicated temperature probe hung in the bore. If that is not practical, bore head temperatures may be used as a proxy. Temperatures at the bottom of the bore may be estimated from existing bore and temperature data or measured by geophysical logging.[2] Further guidance on this issue, including a methodology for calculating temperature-inclusive head using bore depth, elevation, and both near-surface and bottom-hole temperature, is provided in the references below.

[1] Bekesi G, Tyler M and Waterhouse J 2012. Lessons from the use of an active production well for compliance monitoring in the Great Artesian Basin, Australia. *Mine Water Environ* 31, no.3, 225-232. Available [online]: https://doi.org/10.1007/s10230-012-0183-7.

[2] Bekesi G, Tyler M and Waterhouse J 2013. Groundwater head in high-temperature aquifers. *Quarterly Journal of Engineering Geology and Hydrogeology* 46, no.1, 87-94. Available [online]: https://doi.org/10.1144/qjegh2012-035.

4.3.4 Private water supply bores

As discussed in Sections 3.6.2 and 4.2.1, private water supply (production) bores are not typically used for measuring groundwater levels/pressures as they are used to extract groundwater and levels in the bore may not be representative of aquifer levels/pressures. However, there may be circumstances where it is appropriate, for example as part of a bore survey to gather pre-development baseline data or to supplement data gathered through a dedicated groundwater monitoring network.

If the production bore is not operational and not equipped, it may be possible to measure groundwater level/pressure in the bore in the same manner as a groundwater monitoring bore by using a measurement tape or pressure sensor (see Section 4.3.1). If the production bore is equipped, groundwater level/pressure could be measured using the air-line method. This method involves inserting a pipe to a known depth into the well so that its lower end is submerged. Air is pumped into the pipe and the increasing air pressure is monitored until it stabilises at the value where it expels all the water from the pipe. The pressure is then converted into a water level by dividing it by an appropriate value of the specific weight of water inside the well.[47] Groundwater level/pressure in operational production bores should be measured when the pump is switched off. Ideally, the bore would be allowed to equilibrate to natural conditions but given practical constraints, measurement should be taken a minimum of 12 hours after the pump is switched off, noting that inability to check whether measurements have stabilised introduces uncertainty, and such measurements should therefore only be used to supplement data from a dedicated monitoring network. The time that the bore is switched off and the time that the measurements are taken should both be recorded in the field notes.

If measuring pressure head in a private flowing artesian bore, all flow from the bore should be shut down so that a static pressure measurement can be made. If the bore does not have a shut-down valve, or the bore owner objects to shutting down the flow, it can be shut-in by temporarily installing a soil-pipe test plug on the bore or discharge line. As discussed in Section 4.3.3, the time required to reach static pressure after the bore is shut down may range from hours to days. Since it may be impractical or impossible to reach true static conditions, measurement should be taken as long as practical after the pump is switched off or flow is shut down and involve recording recovery over a period such that the equilibrated level can be estimated. The shut-down time for each gauge reading and the time that the pressure reading was taken should be included in the field records and consistent shut-off times should be applied between monitoring rounds.

Some private bores may have a permanently installed gauge on the bore headworks that can be used for measurement. These gauges should only be used if records can demonstrate that they are well maintained and calibrated. Pressure head measured using a calibrated gauge installed into the monitoring port should be treated as a reference estimate and preferred over alternatives.

When measuring groundwater level/pressure in private bores, the bore would ideally be allowed to equilibrate to natural conditions, but given practical constraints, measurement should be taken as long as practical after the pump is switched off or flow is shut down and involve recording recovery over a period such that the equilibrated level can be estimated. If a production bore is equipped, groundwater level/pressure could be measured using the air-line method. For flowing artesian bores, pressure head could be measured with an installed gauge if it is well maintained and calibrated, but preferably would be measured using a calibrated gauge.

[47] Cunningham, W, and C Schalk 2011. *Groundwater Technical Procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods.* Available [online]: https://pubs.usgs.gov/tm/1a1/.

4.3.5 Terrestrial gravity methods

Terrestrial gravity measurement is a geophysical method that measures minute changes in the force of the Earth's gravity, for example due to changes in mass associated with flows of water and associated changes in storage. Subject to the limitations of available equipment, measurements of these changes in mass may be more representative of changes in aquifer water volume than water level measurements in single bores.[48]

In projects that involve substantial flows of groundwater either naturally or due to project activities, gravity methods should be considered. Where measurement accuracy is deemed sufficient, estimates of aquifer mass changes from gravity methods should be treated as reference estimates and preferred over alternatives. Justification is required where model predictions grossly differ from gravity measurements, or unexplained changes have occurred compared to pre-development benchmarks.

> In projects that involve substantial flows of groundwater either naturally or due to project activities, gravity methods should be considered. Justification is required where model predictions grossly differ from gravity measurements, or unexplained changes have occurred compared to pre-development benchmarks.

4.3.6 Surface deformation methods

Surface deformation or altimetry methods measure changes in the height of the ground surface which may be caused by elastic or inelastic deformation, e.g., due to temporary changes in water storage or irreversible subsidence due to compaction or removal of materials underground. Surface deformation methods should be considered in projects involving large-scale dewatering or injecting water or any risk of subsidence. Methods include point-wise measurements from permanent GPS sites, deformation across large regions from InSAR (Interferometric Synthetic Aperture Radar) and airborne/satellite measurements using lasers and radar pulses reflecting off the Earth's surface.[49] Analogously to gravity methods, where measurement accuracy is deemed sufficient, altimetry methods should be deemed the reference method for estimation of subsidence impacts. They may also provide independent estimates of change in mass. Justification is required where model predictions of subsidence grossly differ from

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[48] For examples of the method contributing to monitoring or conceptual understandings of a groundwater system, see: Aitken A, Adams C, Easton S, Miller B and Veneklaas E 2018. Using Microgravity to Characterise Water Storage and Usage at Kings Park, Perth, WA. *ASEG Extended Abstracts.* Available [online]: https://doi.org/10.1071/ASEG2018abM3_1H.

Pivetta T, Braitenberg C, Gabrovšek F, Gabriel G and Meurers B 2021. Gravity as a Tool to Improve the Hydrologic Mass Budget in Karstic Areas. *Hydrology and Earth System Sciences* 25, no. 11. Available [online]: https://doi.org/10.5194/hess-25-6001-2021.

Kennedy JR, Wildermuth L, Knight JE and Larsen J 2021. Improving Groundwater Model Calibration with Repeat Microgravity Measurements. *Groundwater.* Available [online]: https://doi.org/10.1111/gwat.13167.

For documented procedures, see: Kennedy JR, Pool DR and Carruth RL 2021. Procedures for field data collection, processing, quality assurance and quality control, and archiving of relative- and absolute-gravity surveys: U.S. Geological Survey Techniques and Methods, book 2, chap. D4, 50 p. Available [online]: https://doi.org/10.3133/tm2D4.

[49] For examples of this method being used, although not for project-scale groundwater monitoring, see: Castellazzi P and Schmid W 2021. Interpreting C-Band Insar Ground Deformation Data for Large-Scale Groundwater Management in Australia. *Journal of Hydrology: Regional Studies* 34. Available [online]: https://doi.org/10.1016/j.ejrh.2021.100774.

Chaussard E, Milillo P, Bürgmann R, Perissin D, Fielding EJ, and Baker B 2017. Remote Sensing of Ground Deformation for Monitoring Groundwater Management Practices: Application to the Santa Clara Valley During the 2012–2015 California Drought. *Journal of Geophysical Research: Solid Earth* 122, no. 10: 8566-82. Available [online]: https://doi.org/10.1002/2017JB014676.

altimetry measurements, or unpermitted changes have occurred compared to pre-development benchmarks. Where the risk of subsidence is high, baseline measurements are required of sufficient temporal extent and accuracy to differentiate project impacts from natural variation or non-project impacts. Separate subsidence assessments may also be required and may impose additional monitoring requirements.

> Surface deformation methods should be considered in projects involving large-scale dewatering or injecting water or any risk of subsidence. Justification is required where model predictions of subsidence grossly differ from altimetry measurements, or unpermitted changes have occurred compared to pre-development benchmarks. Separate subsidence assessments may also be required.

4.4 Monitoring data

4.4.1 Datum

If groundwater level/pressure data from multiple bores are being used to determine groundwater flow direction, or numerical groundwater flow modelling is to be undertaken, the locations and elevations of all groundwater monitoring bores should be accurately surveyed to establish horizontal and vertical datums (see Section 3.5). Inaccurate datums are a major source of error for groundwater level/pressure measurements used for contouring groundwater level or potentiometric surface maps and in the history matching and sensitivity analysis of numerical groundwater models.

Where baseline groundwater level data are being gathered for a non-flowing bore (a bore tapping an unconfined aquifer or a subartesian bore) over multiple monitoring rounds, groundwater-level measurements should be taken from a clearly marked reference point on the rim of the bore casing so that groundwater level is consistently measured from the same point during every monitoring round. Marking a reference point on the rim of the bore casing reduces errors that may be introduced by an uneven bore rim height. The reference point is usually identified at bore installation using a permanent marker for PVC wells, or by notching the top of casing with a chisel for stainless steel wells. For flowing bores, the reference point is usually the monitoring port. The height of the centre of the pressure gauge or the height of water in transparent tubing relative to the reference point should be recorded in the field notes so that an accurate piezometric elevation can be reported.

The accuracy of groundwater level measurements relative to the chosen datum will depend on the accuracy to which the elevation of the reference point on the bore (bore rim or monitoring port) with respect to the datum can be measured.

> The location and elevation of all groundwater monitoring bores should be accurately surveyed to establish horizontal and vertical datum and a reference point for measurements marked on the bore.

4.4.2 Site data

Primary measured groundwater level/pressure data gathered in the field should be permanently retained and archived in an unedited form in accordance with the minimum requirements in National Industry Guidelines for hydrometric monitoring Part 5: Data editing, estimation and management, NI GL 100.05–2019.

To help maintain quality assurance, a permanent file with the bore ID, state/territory government bore identification number, bore construction, location coordinates, the datum used for groundwater level measurements, and results of hydraulic tests should be established for each monitoring bore. Recent groundwater level/pressure measurements should be compared with previous measurements made under similar hydrologic conditions to identify potential anomalies in groundwater level/pressure fluctuations that may indicate a malfunction of measuring equipment or a defect in monitoring bore construction. Where an anomaly is detected, reasonable effort should be made to obtain new measurements, consistent with monitoring frequency requirements.

Primary measured groundwater level/pressure data gathered in the field should be permanently retained and archived in an unedited form in accordance with the minimum requirements in National Industry Guidelines for hydrometric monitoring.

4.4.3 Data correction

Various factors can affect the accuracy of groundwater level/pressure measurements and their ability to represent hydraulic head and to infer groundwater-flow conditions within an aquifer. These factors include well fluid-column density conditions and external stress effects.[50] Well fluid-column density conditions relate to factors that affect the height of a fluid column in a monitoring bore above a known datum, including fluid temperature, salinity, pressure, dissolved gas content multiphase conditions, and gravitational acceleration effects. Natural external stresses that can influence monitoring bore water level/pressure measurements include barometric effects, tidal or river-stage fluctuations, and Earth tides.

Some of the key methods for correcting groundwater level/pressure data are presented here.

Groundwater level/pressure data should be corrected for well fluid-column density effects (including temperature and salinity) and natural external stresses (including changes in atmospheric pressure and mechanical loading/unloading) where appropriate.

4.4.3.1 Aquifer loading

The total load exerted on an aquifer will vary over time, due to both atmospheric pressure changes and mechanical loading.

Atmospheric pressure changes

Water levels in bores will fluctuate as the atmospheric pressure changes. The main phenomena that influence groundwater levels are diurnal pressure fluctuations (pressure increases slightly at night) and passing weather systems such as barometric highs and lows that typically take several days to pass over. The change in water level in semi-confined and confined aquifers is caused by a change in the loading applied to the Earth's surface by the atmospheric pressure and is related to compressible properties of the formation. In unconfined aquifers, the response is due to the difference in air movement through the bore compared with the unsaturated zone.

The relationship between groundwater levels and atmospheric pressure is inverse: water levels will rise whenever the barometric pressure falls, and vice versa. The barometric efficiency (*BE*) is used to describe how changes in water levels in wells (ΔW) fluctuate in response to changes in atmospheric pressure (ΔB):

$$BE = -\frac{\Delta W}{\Delta B}$$

[50] Spane F 1999. Effects of Barometric Fluctuations on Well Water-Level Measurements and Aquifer Test Data. US Department of Energy. Available [online]: https://doi.org/10.2172/15125.

where consistent units are used for both water levels and barometric pressure (e.g., m of water or hPa). Barometric efficiency will be specific to each individual bore and will generally be within the range 20 to 70% for confined aquifers, and 80 to 100% for unconfined aquifers.

The effect of barometric pressure changes on groundwater levels can be significant. For example, a 30-mbar fluctuation in atmospheric pressure, which could occur due to a passing weather system, could cause 20 to 30 cm of change in a bore hydrograph. Groundwater level/pressure data should therefore be corrected for barometric pressure to remove the effects of atmospheric pressure changes on groundwater level/pressure and decipher the underlying trend. Failure to account for changes in atmospheric pressure could result in misinterpretation of changes in groundwater level/pressure, e.g., a decline in groundwater levels in a monitoring bore could be interpreted as a drawdown impact associated with a project when it was actually related to a high-pressure system passing through the area. Failure to account for changes in atmospheric pressure could also result in misinterpretation of the groundwater flow direction and hydraulic gradient.

Correction of groundwater level/pressure data for atmospheric pressure changes should be undertaken using the change in barometric pressure and the barometric efficiency of the target formation of the bore. The barometric pressure data used for the correction and for the calculation of barometric efficiency should be obtained using a barometric pressure logger located within the study area and within 30 km and 300 m elevation of the monitoring bores for which the data are being used for correction. For large study areas, multiple barometric pressure loggers may be required to account for differences in atmospheric pressure that may occur across the area. Barometric pressure data may be obtained from a local weather station provided it is located within 30 km and 300 m elevation of the monitoring bores and any offset or normalisation applied to the data is accounted for. It should be noted that local differences in air pressure will translate into errors in the inferred hydraulic heads, with errors increasing with distance between the pressure sensor and barometer.

The barometric pressure logger should be suspended above the water column in at least one of the monitoring bores in the network (the bore must be vented). It is important that the barometric pressure logger is never submerged but is installed deep enough that it is in a similar thermal environment to the groundwater and large temperature fluctuations are avoided. The barometric pressure logger should be set to collect barometric pressure data at approximately the same timing and frequency as the submersible pressure sensors in the monitoring bores and should cover the full duration of groundwater monitoring. Data from the barometric pressure logger should be downloaded at the end of each monitoring round and used to correct the groundwater level data collected.

Correction of groundwater level/pressure data for atmospheric pressure changes can be undertaken using data analysis packages, such as the free software available through the manufacturers of data logging equipment or through programming languages such as Python. The package will calculate barometric efficiency for the bore and correct the groundwater level/pressure data. Groundwater level/pressure and barometric pressure data may need to be provided in consistent units (e.g., m of water or hPa). If correcting manually, the calculation of general barometric efficiency should be undertaken on a statistically significant number of events. It may take a month or more of data to determine barometric efficiency and time lag.

> Groundwater level/pressure data should be corrected for barometric pressure using the barometric efficiency of the target formation of the bore.

Mechanical loading and unloading of confined aquifers

Confined aquifer water levels measured in the field should be corrected for mechanical loading/unloading effects prior to any analysis and interpretation. This is because confined-aquifer water levels can be influenced by hydraulic loading and unloading caused by water table fluctuations in overlying unconfined aquifers. If confined-aquifer water levels are not corrected for loading/unloading effects, there is potential that groundwater models may overestimate inter-aquifer leakage or other hydraulic fluxes to explain observed confined aquifer water levels.

Harrington and Cook (2011)[51] review the literature on mechanical loading and unloading of confined aquifers and recommend that corrections be made by determining an appropriate loading efficiency and multiplying it with observed changes in water storage at the water table. Loading efficiency should ideally be measured in the field using time-series barometric responses or specially designed experiments that can precisely monitor individual natural (e.g. rainfall, tides) or artificial (e.g. freight trains) loading effects. Alternatively, a more sophisticated approach may be to use coupled flow-stress numerical models such as DIANA or SEEPW-SIGMAW, although the use of those codes will require geotechnical expertise and intensive parameterisation.

Selection of an appropriate correction method for local conditions is the responsibility of the hydrogeologist. Corrected and uncorrected data should be provided along with documentation of the method used. The correction method selected by the hydrogeologist will determine what additional data need to be collected. Details on methods for determining the importance of mechanical loading and unloading of confined aquifers due to water table fluctuations and making corrections are provided in Harrington and Cook (see example below).

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[51] Harrington G and Cook P 2011. *Mechanical Loading and Unloading of Confined Aquifers: Implications for the Assessment of Long-Term Trends in Potentiometric Levels*. Waterlines Report Series No 51, National Water Commission, Canberra. Available [online]: http://hdl.handle.net/102.100.100/104239?index=1.

Worked example: Data correction for mechanical loading

AGL Hunter Gas Project: Groundwater Monitoring Status Report - 2012

An increase in groundwater levels was noted in deep coal and bedrock water-bearing zones in June 2011 and into 2012. The increase in groundwater levels was assessed to consider whether it was due to mechanical loading by overlying shallow unconfined aquifers, applying the method in Harrington and Cook (2011).

Barometric efficiency (BE) was determined by comparing observed groundwater level changes in the deep bores with the change in barometric pressure over numerous 1-day periods. Loading efficiency (LE) was calculated as 1 - BE. The loading correction was calculated as follows:

$$\Delta WL_{conf} = \Delta WL_{unconf} \times LE \times Sy$$

where

ΔWL_{conf} is the change in water level of the confined aquifer

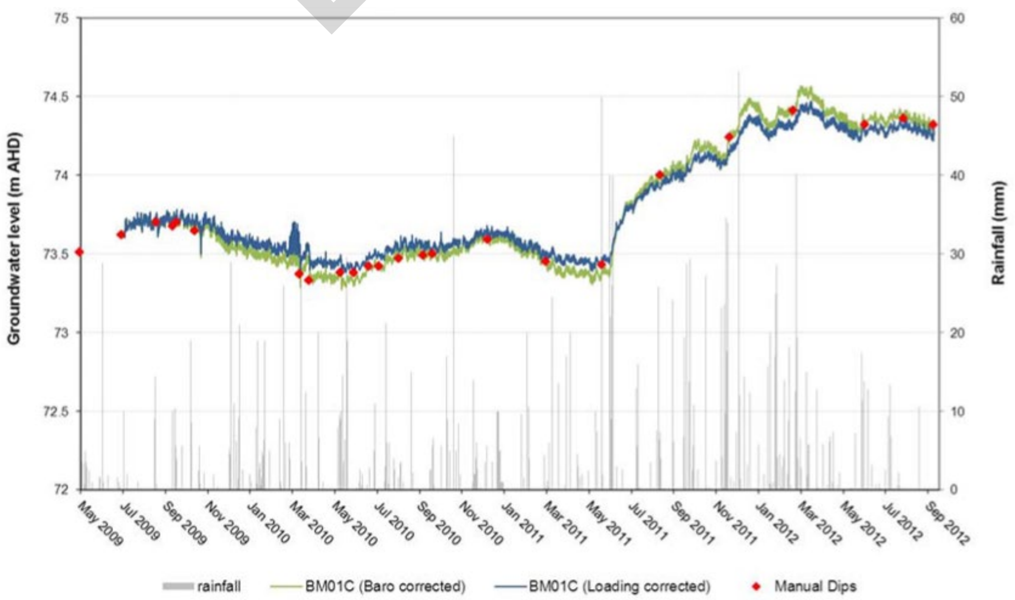
ΔWL_{unconf} is the change in water level of the unconfined aquifer

Sy is the specific yield of the unconfined aquifer.

A groundwater hydrograph with the loading efficiency-corrected groundwater levels is plotted with the barometrically corrected groundwater levels in the figure below.

Based on the specific yield used (taken from the literature) and the calculated LE for the deep aquifer zones, the maximum possible loading efficiency correction was calculated to be approximately 5% of the magnitude of groundwater fluctuations in the shallow aquifers. This amounts to a maximum loading effect of approximately 13 cm in the deeper aquifers. The figure below confirms a minimal difference between the loading corrected hydrograph and the barometrically corrected hydrograph.

The study concluded that the increase in the deeper groundwater levels from June 2011 onwards was in excess of the potential loading effects and could be explained by another process (in this instance, hydraulic connection between the shallow aquifers and deeper coal measures).



4.4.3.2 Density correction

The flow of groundwater is governed by the hydraulic properties of the subsurface as well as the viscosity and density of the groundwater. If fluid density in a groundwater system is variable, this needs to be taken into account when calculating hydraulic heads.

Fluid-density variations in groundwater systems most typically occur due to variations in temperature and the concentration of dissolved solids (salinity). Density variations can also occur due to the presence of non-aqueous liquids or dissolved gases and the increase of water pressure with depth.

Corrections for variations in temperature and salinity should be made in variable-density groundwater systems so that hydraulic head can be accurately assessed. These influences can be accounted for by correcting or normalising hydraulic head measurements to a reference density. An assessment of whether variable-density effects need to be taken into account should be undertaken in the initial stages of a monitoring program so that temperature and salinity data can be gathered if required. Post, Kooi and Simmons[52] provide guidance on when a hydrogeologic analysis should be treated in a density-dependent or density-independent manner and suggest appropriate methodologies for correcting hydraulic heads. An example is given below.

Temperature

Density stratification develops in monitoring bores in confined systems as the temperature of water from the target formation equilibrates with the subsurface surrounding the bore above the screen. To correct for the error induced by temperature-related density changes, head measurements in deep bores should be accompanied by a thermal survey, with temperature measured just below the water level in the bore and at the bore screens. Temperature measurements in shallow wells may be required if small head differences are important for the investigation, as density variations can occur due to seasonal temperature variations in the upper 10–20 m of the subsurface and may result in an error of up to 3 mm/m of water column.[53] Fluid density should also be considered when measuring water levels by the air-line method. ISO 21413 provides a table quantifying the change in density of distilled water over a wide temperature range.

Salinity

Some groundwater systems have large vertical and lateral variations in salinity. These systems can occur in coastal areas (e.g., where seawater intrusion is occurring or where brackish water is present at the surface such as near estuaries) or in inland groundwater systems (e.g., where agricultural development or irrigation is occurring). Variable-salinity groundwater systems are also common in sedimentary basins and where dense contaminant plumes are present.

To correct for the error induced by salinity-related density changes, all head measurements in variable-salinity groundwater systems should be carried out in conjunction with measurements of electrical conductivity (EC). As salinity can vary with depth, particularly where salt water overlies fresh water or where brackish surface water is present, a salinity survey which measures EC with depth in the bore, should be undertaken. The salinity of groundwater just below the water level in the bore and at the bore screens should be measured as a minimum.

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[52] Post V, Kooi H and Simmons C 2007. Using Hydraulic Head Measurements in Variable-Density Ground Water Flow Analyses. *Ground Water* 45, no. 6. Available [online]: http://doi.org/10.1111/j.1745-6584.2007.00339.x.

[53] Post VEA and von Asmuth JR 2013. Review: Hydraulic Head Measurements—New Technologies, Classic Pitfalls. *Hydrogeology Journal* 21, no. 4, 737-50. Available [online]: http://doi.org/10.1007/s10040-013-0969-0.

Worked example: Density corrections for water level observations

Office of Groundwater Impact Assessment - Surat Underground Water Impact Report 2021

A commonly applied equation used to analyse groundwater flow is Darcy's Law. This equation assumes uniform density and therefore corrections are necessary in variable-density environments. Density corrections were applied to correct measured water levels in monitoring bores accessing the Surat and Bowen basins, Queensland.[1] The application of these corrections allowed for measured water levels in monitoring bores to be analysed so that potentiometric surface mapping could be undertaken, and groundwater flow direction and hydraulic gradients determined.

Density corrections are necessary as temperature and salinity can vary across individual aquifers. Additionally, bore construction and measurement method vary considerably, which dictates the length of the water column to be corrected due to temperature variations resulting from the geothermal gradient. This is addressed through a water column correction and conversion of measured water levels to a common freshwater reference density of temperature (20°C) and salinity (0 mg/L total dissolved solids (TDS)).

McCutcheon et al.[2] provides an equation to correct for the influence of temperature and salinity on fluid density. The following method applies to bores where a pressure transducer is located within the water column above a screen interval:

$$Pressure\ head\ (h1) = measured\ pressure\ (kPa)\ \times\ GWDB\ conversion\ factor$$

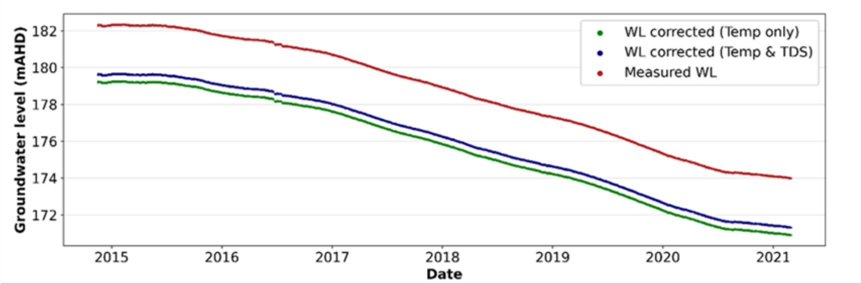
$$Pressure\ head\ (h2) = WC\ length\ \times \frac{\rho_A}{\rho_R}$$

$$h_f =\ z + h1 + h2$$

where
Pressure head (h1 & h2) = corrected water column above and below the pressure transducer (m), respectively
GWDB conversion factor of 1 kPa = 0.10215507 m, relating pressure to head (20°C & 0 mg/L TDS)
WC length = water column length at the pressure transducer relative to the mid-screen depth (m)
ρ_A = average water column density (kg/m^3)
ρ_R = density of freshwater or reference density (kg/m^3)
h_f = equivalent freshwater hydraulic head or reference head (m)
z = elevation head at the screen mid-point.

To facilitate these corrections, OGIA have calculated a geothermal gradient within the Surat and Bowen Basins from available bore and well temperature data, as given by $T(°C) =\ 0.023x\ +\ 28.797$, where *x* is the mid-screen depth.

The below figure illustrates the correction applied to a bore with a pressure transducer located at 708 mbgl, which is above a mid-screen intake of 1,020 mbgl with a TDS of 1,720 mg/L. For this bore, temperature accounts for a 1.5% reduction in corrected groundwater levels. Salinity increases fluid density and thereby raises the water column relative to fresh water. However, the influence of this correlation is significantly less compared to temperature alone.



[1] Queensland Office of Groundwater Impact Assessment (OGIA) 2016. *Hydrogeological Conceptualisation Report for the Surat Cumulative Management Area*. Department of Regional Development, Manufacturing and Water, Brisbane. Available [online]: https://www.rdmw.qld.gov.au/__data/assets/pdf_file/0003/1577820/2016-conceptualisation-report.pdf.

[2] McCutcheon SC, Martin JL, Barnwell Jr TO and Maidment DR 1992. Water quality. *Handbook of hydrology*. pp. 11.1. Available [online]: https://www.mheducation.com.au/handbook-of-hydrology-9780070397323-aus.

4.4.3.3 Other corrections

Vibrating Wire Piezometers

Temperature has some effect on the response of a VWP and therefore correction for temperature is recommended. Given that VWPS usually include thermistors, this is usually possible. The importance of correcting for temperature varies with the application. If the VWP is sealed in a borehole, there is usually little variation in temperature, so temperature effects will be small and corrections less important than if the VWP is in a shallow monitoring bore that is likely to be affected by day-to-day and seasonal changes in temperature. Temperature correction should be applied if temperature in the borehole varies or if small head differences are important for the investigation.

Barometric pressure corrections would not typically be applied for VWPs in a sealed borehole; however, they would be applied for a VWP in a monitoring bore as the pressure seen at the piezometer is the combined pressure of water and the air above the surface of the water.

Land subsidence

In areas where there is a risk of land subsidence, e.g., where coal seam gas and associated water extraction is occurring, the elevation of the measuring point (top of casing) could change over time. This could be problematic for interpretation of groundwater levels/pressures, groundwater flow direction and hydraulic gradients.

In areas where there is potential for land subsidence, results of subsidence monitoring should be checked prior to each groundwater monitoring round. If the results of the subsidence monitoring indicate that there has been a change since the last groundwater monitoring round, the monitoring bores should be re-surveyed close to the time of monitoring.

Where surveying indicates a change in elevation of the bore and submersible pressure sensors are collecting groundwater level/pressure data, a methodology should be developed to estimate the elevation of the top of casing over the monitoring period so that groundwater levels/pressures may be corrected. For example, a regression between download events could be used, taking into consideration the location of the bore relative to the location of impacts and the timing of impacts.

5. Groundwater quality monitoring

5.1 Introduction

Groundwater quality monitoring is undertaken for numerous reasons including characterising groundwater systems, improving conceptual understanding of groundwater systems, establishing baseline groundwater quality conditions and detecting impacts to groundwater. The overarching objective of groundwater quality monitoring is the protection of environmental values. In this context, environmental values are the values and uses of the groundwater for ecosystems and people, including values for aquatic ecosystems, industries, health and safety, drinking water, recreation and aesthetics, and cultural and spiritual values.

The chemical composition of groundwaters has the potential to be impacted by human activities. Therefore, prior to any new development, it is important that baseline groundwater quality conditions are established so that impacts to groundwater quality can be detected during the construction and operational phases of the development and distinguished from natural groundwater conditions and impacts from any previous activities. Groundwater quality monitoring can also assist with understanding and modelling the groundwater system.

Monitoring of groundwater quality typically includes setting objectives, selecting locations for monitoring, selecting parameters to analyse, deciding on the duration and frequency of monitoring, sampling using appropriate methods, and analysis in the field and laboratory. Figure 5.1 outlines the process for groundwater quality monitoring, as covered in this chapter.

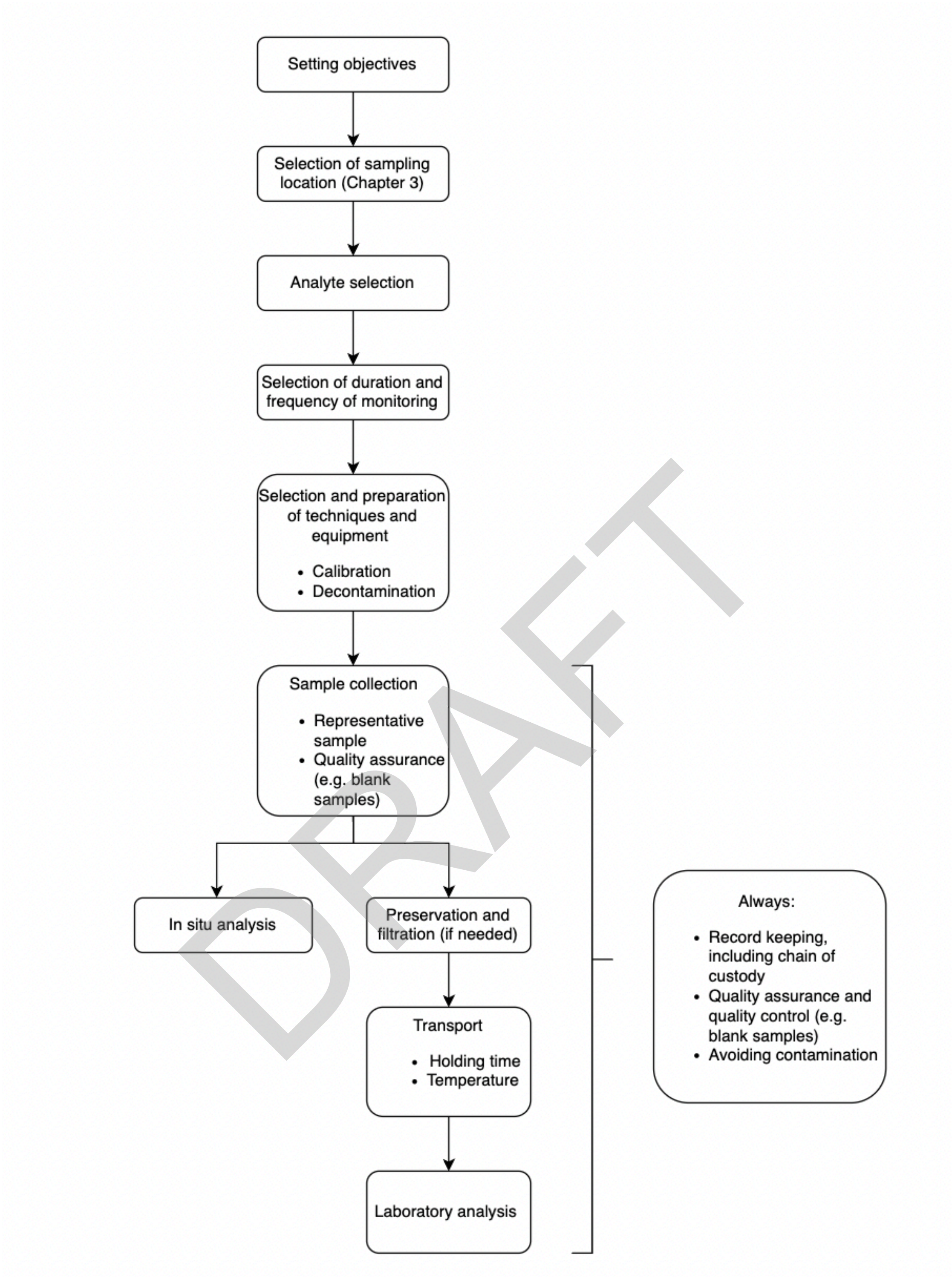


Figure 5.1 The groundwater quality monitoring process, as covered in this chapter.

Groundwater quality samples should be collected by qualified staff, following documented protocols. Sampling staff should have training and should be able to demonstrate their competence in following sampling protocols, avoiding contamination of samples, calibrating instruments, and making field observations. Samples should be collected by or in consultation with hydrogeologists, particularly if there is complex hydrogeology. Analytical chemists should also be consulted before sampling.

The sample at the time of analysis should be representative of the groundwater system from which it came. This requires procedures throughout the monitoring process to minimise changes to the sample, for example due to contamination or chemical processes. Quality assurance and quality control are essential to reduce and quantify these errors.

There is a range of possible failure points in groundwater quality sampling identified in this chapter. In all cases, the priority is to follow best-practice requirements, but where it is not possible all available data should still be recorded, including any problems that arose and any errors and uncertainty in the data. This will assist with later analysis.

5.2 Existing standards

Monitoring of groundwater quality should adhere to:

- relevant legislation;
- The Australian and New Zealand Guidelines for Fresh and Marine Water Quality;[54]
- relevant standards, particularly;
  - AS/NZS 5667.11-1998 Water quality – Sampling;
  - ISO 5667-11:2009 Water quality – Sampling Part 11: Guidance on Sampling of groundwaters;
- Guidelines for Groundwater Quality Protection in Australia (2013);[55] and
- National Industry Guidelines for hydrometric monitoring (2019).[56]

If the groundwater is a drinking water source or is of a quality and yield that it could be used as a drinking water source in future, the Australian Drinking Water Guidelines should also be referred to.

Guideline values should be derived, or default guideline values (DGVs) used as per the Australian and New Zealand Guidelines for Fresh and Marine Water Quality or, where applicable, the Australian Drinking Water Guidelines.[57]

For detailed advice on how to implement monitoring methods, refer to Geoscience Australia Groundwater Sampling and Analysis – A Field Guide.[58] State/territory and federal legislation and guidelines may also apply.

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[54] ANZG 2018. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Canberra, ACT, Australia, 2018. Available [online]: https://www.waterquality.gov.au/anz-guidelines.

[55] Department of Agriculture and Water Resources 2013. *Guidelines for groundwater quality protection in Australia: National Water Quality Management Strategy*. Canberra. Available [online]: https://www.waterquality.gov.au/sites/default/files/documents/guidelines-groundwater-quality-protection.pdf.

[56] Bureau of Meteorology 2021. *National Industry Guidelines for hydrometric monitoring*. Available [online]: http://www.bom.gov.au/water/standards/niGuidelinesHyd.shtml.

[57] National Health and Medical Research Council (NHMRC) 2011. *Australian Drinking Water Guidelines*. Available [online]: https://www.nhmrc.gov.au/about-us/publications/australian-drinking-water-guidelines.

[58] Sundaram B 2009. *Groundwater Sampling and Analysis - A Field Guide*. Record 2009/027. Geoscience Australia, Canberra. Available [online]: http://pid.geoscience.gov.au/dataset/ga/68901.

5.3 Groundwater quality monitoring objectives

All water quality monitoring programs should define tolerable levels of error that are appropriate given the risks of harm due to changes in a parameter.

All water quality monitoring programs should aim to minimise disturbance or contamination of the groundwater and surrounding environment, for example through the selection of sampling procedures.

Water quality sampling may be targeted at one of more of the following objectives.

Pre-approval monitoring may:

- Characterise the chemical composition of aquifers (or other water-bearing zones) in the groundwater system, including identifying the presence of any contaminants associated with current or previous activities at the site.
- Improve conceptual understanding of the groundwater system, including connectivity between aquifers, connectivity to surface water systems, and the location of recharge zones. The data gathered can be used to calibrate groundwater flow and quality models, and improve understanding of flow paths, transport and aquifer reactions, including through tracers and groundwater age.
- Baseline monitoring to determine the background variation in groundwater quality prior to a proposed activity. This will assist with differentiating any impacts from natural variation, following a multiple before-after-control-impact (mBACI) type model (see Section 2.2.4.5).
- Establish the environmental values that the groundwater can support. This is generally undertaken by comparison to guideline values (discussed further below).

Post-approval monitoring may:

- Detect and quantify impacts from an activity. This is generally undertaken by comparison to guideline values. Impact detection monitoring may include understanding the movement, extent and sources of pollutants and attributing the observed changes. The monitoring may aim to provide evidence that would be admissible in court.

Guideline values are measurable quantities, thresholds or conditions for an indicator. Comparison of groundwater quality with guideline values can provide information on the environmental values that the groundwater can support. Where concentrations in groundwater exceed guideline values, it is considered that there is a risk of unacceptable impacts for the relevant environmental value. Exceeding guideline values does not necessarily mean that there is problem, but it will usually trigger follow-up action. The Water Quality Guidelines for Drinking Water should be considered if the groundwater is or could be used for human consumption. For all other situations, site-specific or catchment-specific guidelines values are preferred, as outlined in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality. The IESC provides information on how to develop site-specific guideline values.[59] Where necessary, default guideline values (DGVs) may be used from the Australian and New Zealand Guidelines for Fresh and Marine Water Quality.

[59] Huynh T and Hobbs D 2019. *Deriving site-specific guideline values for physico-chemical parameters and toxicants.* Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy. Available [online]: https://iesc.environment.gov.au/publications/information-guidelines-explanatory-note-deriving-site-specific-guidelines-values.

Groundwater quality monitoring objectives should be specific and clearly stated. These may include establishing a baseline of groundwater quality conditions, assessing connectivity between aquifers or with surface water systems, identifying the environmental values that the groundwater could support, and detecting impacts to groundwater quality associated with development.

5.4. Analyte selection

The major dissolved components of natural groundwaters include the anions bicarbonate, chloride and sulphate, and the cations sodium, calcium, magnesium and potassium (major ions), which typically comprise more than 90% of the total dissolved solids (TDS). The concentrations of these constituents are related to the aquifer materials, duration of contact with aquifer minerals, connectivity to surface waters, connectivity to other aquifers and recharge rates, and they provide important information to conceptualise groundwater systems.

The chemical composition of groundwaters may be affected by anthropogenic activities where there is a source of contamination and a pathway for contamination of an aquifer. For example:

- a sewage treatment plant may leak and contaminate an aquifer with nutrients and microbial contaminants;
- stormwater runoff from an urban area may infiltrate the surface and contaminate an aquifer with metals and nutrients;
- a tailings storage facility at a mine may leak and contaminate an aquifer with metals;
- cattle grazing may provide a source of nutrients to a shallow groundwater system; or
- irrigated cropping may provide a source of pesticides or nutrients to a shallow groundwater system.

The physical properties of groundwaters, i.e., temperature, pH, oxidation-reduction (redox) potential, can influence the concentrations of dissolved constituents and are therefore also important for understanding the chemistry of groundwaters.

Baseline groundwater quality monitoring programs should always include major ions, physical parameters, and contaminants that are relevant to the site. This includes contaminants associated with historic and current activities at the site and its surroundings, as well as future activities associated with any proposed development. There may be naturally occurring high concentrations of some analytes. When selecting the analytes for groundwater monitoring, consideration should be given to:

- current and potential future environmental values of the groundwater system and connected surface water systems and the quality of groundwater needed to support these environmental values;
- potential risks to groundwater quality associated with the proposed development, in particular parameters that are potentially harmful to people, animals or ecosystems;
- parameters that can improve understanding of the groundwater system, e.g., monitoring for natural isotopes can improve understanding of recharge and discharge processes, groundwater flow and interaction with surface water;
- parameters for which guideline values are defined, or that may be mandatory for a development or environmental authority; and

- parameters such as dissolved organic carbon (DOC) that can control the bioavailability of metals and other chemicals.

Groundwater quality monitoring for impact detection should include major ions, physical parameters and contaminants associated with the construction and operational phases of the approved development.

A parameter may be measured directly or measured indirectly through surrogates or indicators, e.g. electrical conductivity as a physical measure indicative of chemical composition. Where a particular contaminant may be present and it could degrade into a different analyte, it may also be important to measure the degraded product.

Analytes that will be monitored during impact detection should also be monitored during baseline monitoring. For example, if the project proposes storage of hydrocarbons, then analysis for hydrocarbons should be undertaken during baseline monitoring to establish background levels, and during impact detection monitoring to identify any leaks. Baseline monitoring should be undertaken using the same design as impact detection monitoring. Using an mBACI design (see Section 2.2.4.5), baseline monitoring to establish background levels should be undertaken at the control site(s) (up-hydraulic gradient of the project area) and at the potentially impacted site(s), and then impact detection monitoring should be undertaken at the same locations. Following this design, and assuming sufficient duration of baseline monitoring, statistical methods can be used to establish natural background levels of contaminants and provide the basis for impact detection. The analytical method chosen for impact detection monitoring should have sufficient sensitivity to distinguish impacts from natural variation. Selected analysis methods should be documented along with limits of reporting and other associated data collection requirements.

Monitoring of surface water (see Section 6.2) and the unsaturated zone should be undertaken as this may detect potential contamination before it reaches the groundwater. Water level/pressure should also be measured at the time of water quality measurements at a site (see Chapter 4) to support interpretation of changes over time.

Table 5.1 lists the analytes, beginning with those recommended for all monitoring programs, along with the rationale for monitoring or potential sources that may be reason to include that analyte in the monitoring. In addition to the analytes in this table, other analytes may also be necessary depending on the local hydrogeology and ecological processes, historic, current and future proposed activities and risks. New chemical constituents of concern may emerge with time, as was seen with per- and polyfluoroalkyl substances (PFAS) compounds, and this may necessitate monitoring additional analytes for some projects.

Site-specific analytes should be selected that will allow the monitoring objectives to be met, and supporting rationale should be documented.

Table 5.1 Mandatory analytes and other potential analytes

Analyte category	Analytes	Rationale for monitoring
Analytes recommended for all monitoring programs		
Field parameters (these parameters are best measured in the field using a calibrated water quality meter as values may change during sample transport to the laboratory)	Temperature, electrical conductivity (EC), pH, redox potential (ORP), dissolved oxygen (DO)	Basic properties and properties of groundwater that can influence concentrations of dissolved constituents and may be required to normalise or interpret data
Physical parameters	Total dissolved solids (TDS), total suspended solids (TSS), total alkalinity (as $CaCO_3$), acidity	Physical properties of groundwater can influence concentrations of dissolved constituents and may be required to normalise or interpret data
Major ions	Calcium, magnesium, sodium, potassium, sulphate, chloride, bicarbonate, and silica	Provide important information for characterisation and conceptualisation of groundwater systems and identification of changes in groundwater quality
Dissolved organic carbon (DOC)	Quantity and quality of DOC	Ecologically important and affects bioavailability of many chemicals and some contaminants
Potential contaminants and other indicator analytes		
Physical parameters	Turbidity	Many potential sources and it can affect other measurements
Dissolved and total metals	Aluminium, antimony, arsenic, barium, boron, cadmium, chromium, cobalt, copper, fluoride, iron, ferrous iron, lead, magnesium, manganese,	Potential sources include mining, landfill, urban development, and being naturally present (e.g. nitrate and uranium in some areas)

Analyte category	Analytes	Rationale for monitoring
	molybdenum, nickel, selenium, strontium, zinc, vanadium, uranium, tungsten, antimony	
Nutrients	Ammonia as N, nitrite as N, nitrate as N, total N, reactive phosphorous, phosphorous, total as P	Potential sources include grazing, cultivation/cropping, sewage treatment, landfill, urban development
Pesticides and herbicides	Organochlorine pesticides (OCPs), organophosphate pesticides (OPPs)	Potential sources include cultivation/cropping, urban development
Hydrocarbons	Total petroleum hydrocarbons (TPH), benzene, toluene, ethylbenzene, xylene (BTEX), polycyclic aromatic hydrocarbons (PAHs), semi-volatile organic hydrocarbons (SVOCs), volatile organic hydrocarbons (VOCs),	Potential sources include fuel storage facilities and workshops associated with a range of different types of developments
Microbial	Faecal indicator bacteria, faecal streptococci, *Escherichia coli*, other microbiology (bacteria, fungi and protozoa), biochemical oxygen demand (BOD), carbonaceous biochemical oxygen demand (CBOD), eDNA	Potential sources include sewage treatment plants and landfill and naturally occurring
Radioisotopes	Isotopes of uranium, tritium and carbon	Potential sources include mining activity and naturally occurring
Other contaminants	Polychlorinated biphenyls (PCBs), perfluoroalkyl and polyfluoroalkyl substances (PFAS)	Potential sources include workshops, landfill and historical activities

5.5 Duration of monitoring

The duration of monitoring should be as specified in Section 2.2.4.4 for baseline monitoring and Section 2.3 for impact detection monitoring in order to characterise the groundwater system and capture variation over time.

5.6 Frequency of monitoring

Monitoring may be either continuous or periodic (see Sections 5.4.6.1 and 5.4.6.2).

The frequency of monitoring should depend on site-specific characteristics, including the natural conditions of the groundwater and the nature of any proposed activity. The frequency of monitoring should also consider the analyte. For example, highly water-soluble chemicals (including salts) are mobile in groundwater and will generally require monthly monitoring, whereas insoluble or soil-binding chemicals (including hydrocarbons and persistent chemicals) may be less variable over time and half-yearly monitoring may be acceptable. As in Section 4.2.2, deciding on the frequency of monitoring may involve statistical analysis or be informed by modelling.

In baseline monitoring, the frequency should be sufficient to characterise natural variability. For example, there may be changes between seasons, particularly in unconfined aquifers, and there may be tidal influences in coastal areas.

In impact detection monitoring, the frequency should be sufficient to detect a change in water quality within a time frame that is appropriate for the risk levels. The frequency of impact detection monitoring will be determined by the risk assessment undertaken for project approval, which will identify the activities with potential to contaminate groundwater resources, and the likelihood and consequence of impacts. The frequency of monitoring may be refined as the understanding of the groundwater system develops further. For activities with a high risk of impacting on groundwater quality and associated environmental values, monitoring should be more frequent.

The frequency may be established after initial monitoring to better understand the groundwater system, possibly including short term continuous monitoring to assist in identifying the value of more frequent monitoring. The frequency of monitoring should be appropriate for the planned data analysis. The rationale for the frequency of monitoring should be documented, including consideration of allowing for lead-time for follow-up monitoring and action.

Risk factors that affect the monitoring requirements include:

- The activity has a high risk of contaminating the groundwater and/or there is significant uncertainty.
- The groundwater has social, cultural or economic value, for example it is used as stock water or to provide drinking water.
- The activity will occur in proximity to a drinking water source, a groundwater-dependent ecosystem, a culturally significant area, a populated area, a waterway, or a protected area.
- The area has geology such as faults or karst geology that may cause contaminants to be mobilised faster than otherwise, particularly after rainfall, or the groundwater is in a shallow, unconfined aquifer.
- There is a high level of extraction from the groundwater.
- The groundwater is connected to surface water or the groundwater quality responds strongly to weather conditions.
- There has been a recent extreme weather event or a failure of site infrastructure that may impact groundwater. For example, rainfall may lead to dams storing contaminated material overflowing or failing and contaminants being released to a shallow groundwater system.

It is possible that the intended frequency of monitoring will not be achieved due to missing data or errors. For example, a landholder may restrict access to a monitoring bore, or a monitoring bore may yield too little groundwater to provide a sufficient volume for water quality analysis. Plans should be made to address these types of risks, including collecting more samples shortly after discovering an error if necessary to meet objectives.

The frequency of baseline and ongoing monitoring for groundwater quality monitoring should depend on the risks but will, at a minimum, occur quarterly unless there are risk-based reasons to differ.

5.6.1 Continuous monitoring

Automatic data loggers, potentially with transmission by telemetry, may be used to collect data at a greater frequency than periodic manual measurements. Automatic data loggers are used to monitor field parameters including electrical conductivity (EC), pH and temperature.

Continuous monitoring should be undertaken where early detection of impacts to groundwater quality is required to provide adequate protection of environmental values. Continuous monitoring should also be undertaken to characterise baseline groundwater quality where the quality characteristics are dynamic.

Equipment for continuous monitoring should be spot-checked using a calibrated field water quality meter and calibrated every time data loggers are downloaded and at least once a year. Data loggers should be downloaded sufficiently frequently to allow for any necessary lead-time to respond. Telemetry should be used where a fast response to water quality changes or measurement failures is required. There should be data verification such as duplicate transducers, visits by independent observers, and remote cameras.

Continuous groundwater quality monitoring should be undertaken where early detection of impacts to groundwater quality is required to adequately protect environmental values. Equipment should be checked and calibrated every time data loggers are downloaded and at least once a year.

5.6.2 Periodic monitoring

Periodic water quality monitoring is monitoring that is undertaken at defined intervals and does not use automatic data loggers to provide continuous data. Periodic monitoring should occur quarterly at a minimum, with more frequent monitoring sometimes required due to the risk levels and inherent variability.

The frequency of baseline monitoring may vary for different analytes, with a lower frequency of monitoring appropriate for analytes that are not basic indicators or analytes (see Section 5.4.4) and do not generally change in shorter time periods. The frequency of impact detection monitoring may also vary for different analytes depending on the findings of the risk assessment. When a set monitoring frequency for an analyte is not adopted, triggers for additional sampling should be defined, e.g. between project phases, or in response to observed changes in other parameters.

5.7 Record keeping during sample collection

Record keeping is a key component of any groundwater quality field program (see Section 7.1 for more information). Field records should be maintained for each monitoring bore using a template so that consistent data are recorded for every bore and important data and observations are not missed. Field records are important for the data analysis, as they can help with interpreting unusual data that may be related to the field conditions or methods.

Field records should include at a minimum:

- date and time of sampling;
- exact locations of sampling sites, including coordinates and the bore/pipe identification possibly same as the state/territory drilling permit numbering system to be able to feedback data consistently;

- depth to groundwater level, 'stickup' height of bore casing above ground level;
- depth of sampling;
- field measurement techniques and equipment;
- if purging the bore, the volume removed and pumping rates;
- identification of the sampling team;
- details of equipment;
- calibration procedures for meters, including the date, temperature and calibration reading;
- any issues with equipment and any repairs;
- field measurements, including potential sources of error;
- procedures used for decontamination;
- procedures used for preservation and filtration of samples;
- number and volume of samples, including quality control samples;
- procedures used for collecting, labelling, transporting and storing samples and data;
- types of storage containers and sample preservation procedures;
- weather conditions before sampling; and
- other field observations or comments, possibly including the turbidity, odour and colour of the groundwater, and descriptions and photographs of the site.

For further information on good recording-keeping practices, see Chapter 7.

> Field records should be maintained using a template that covers information that is critical to later data analysis.

5.8 Maintaining equipment

Reasonable care should be taken to ensure measurements can be taken reliably, minimising the risk of missing or inaccurate data. Before sampling, equipment should be checked for issues that will cause delays or affect data quality. Any repairs or incidents that may affect the equipment should be recorded.

The equipment should be reliable, meaning that it is usually capable of collecting data without breaking down or causing unexpected changes to the sample. There should also be procedures to clean and maintain equipment to minimise equipment failure. Equipment may require greater attention to maintenance if it is exposed for long periods of time to groundwater with chemistry that causes corrosion or degradation of its materials.

Where the risk of equipment failure is high despite reasonable care being taken, there should be contingency plans in place. For example, pumps are known to fail (despite regular maintenance) and therefore contingency plans need to be in place if a pump fails during fieldwork. These contingency plans may include carrying spare parts for the pump so that simple repairs can be made in the field and ensuring alternative sampling equipment is available as the priority is to for data to be collected even if conditions are not ideal. The method used for sampling should be recorded so that potential issues can be identified during data quality review. Equipment that is easier to maintain and clean may be preferred, particularly if it can be serviced in the field.

> Equipment should be maintained and stored as specified in the operating manual, and records of equipment maintenance, servicing, and repairs should be kept. Where the risk of equipment failure is high despite reasonable care being taken, there should be contingency plans in place.

5.9 Calibrating equipment

Instruments that require calibration (such as water quality meters used for field measurements) should be calibrated regularly. Meters for in-situ measurements should be calibrated on the day of sampling. The meters should preferably also be calibrated after measurements or repeatedly if taking measurements over several hours.

Records of the instruments used should be maintained as described in the National Industry Guidelines for hydrometric monitoring Part 3. Calibration procedures should be documented, including the time and date, the standard solutions used, and the calibration readings. Procedures should adhere to manufacturer instructions and National Association of Testing Authorities (NATA) requirements, including storage and handling of standard solutions. An appropriate range of concentrations should be used for calibration, reflecting what is likely to be measured in the field.

> Instruments should be calibrated as specified in their operating manual and records should be kept. Calibration should occur before use and, where necessary, regularly while in the field.

5.10 Material of equipment

Sampling equipment made of relatively inert materials such as glass, stainless steel, Teflon ®, polyethylene, polypropylene, or polycarbonate will reduce contamination and changes to the chemical composition of the sample. Flexible parts of the equipment may be made of PVC or polyethylene but will preferably have an inert coating. The cords for bailers should not be made of cotton or cloth. If a sample container has cardboard, cork or rubber in the container cap, it should be removed. Specific care in selection of material should be taken where it may affect the required detection limit or contaminate the sample.

For sample containers, the cap should close well to avoid leaks. As sunlight can affect biological and chemical characteristics, sample containers should be opaque or otherwise protected from sunlight if this is relevant to the parameters of interest. Sample containers of different materials will be needed for different analytes. It is typical for the analytical laboratory to supply the appropriate sample containers for the selected analytes prior to fieldwork.

> Sampling equipment and containers should be made of an appropriate material that will not affect the parameter being measured.

5.11 Decontamination of equipment

Contamination is a common problem. Efforts should be made to minimise it to ensure that the sample is representative of the groundwater being monitored. Decontamination of equipment ensures that it is clean and prevents cross-contamination from one bore to the next. Equipment used in the bore (e.g., pumps) should be decontaminated before entering a bore.

Sample containers should be decontaminated before use either by the laboratory or by the sampling team. The decontamination procedures should be suitable for the parameters that will be measured and the material that the equipment is made of. For example, a specific cleaning solution may be appropriate, followed by deionised water, or the laboratory may provide sterilised bottles with preservative. For microbiological samples, sterilisation is required.

Blank samples should be taken during the final rinsing of equipment to assist with quality control (see Section 5.13). Equipment should not be decontaminated too close to the sampling site and wastewater should be disposed of in a way that minimises impact to the environment, particularly if contaminants are likely.

> Appropriate procedures should be followed to minimise the risk of contamination of samples from equipment or other samples.

5.12 Sample collection

When collecting groundwater samples, the primary objective is to obtain a sample that is representative of groundwater in the formation screened by the bore and for the laboratory to receive a sample that is suitable for analysis for the parameters of interest. To achieve this:

- the most appropriate sampling method for each individual bore should be carefully selected to ensure samples are representative of groundwater in the formation of interest, not stagnant water that has been sitting in the bore for an extended time;
- sampling methods should be selected to ensure minimal disturbance to the groundwater to reduce physical, chemical and temperature changes related to exposure to sunlight and the atmosphere or the introduction of water or air;
- the volume of sample taken should be sufficient for the laboratory analysis to meet the required detection limits;
- sample preparation, storage, and transport procedures should ensure the chemical composition of samples is not affected during transport to the laboratory and that the laboratory receives a sample that is suitable for analysis for the parameters of interest; and
- procedures to avoid contamination of samples need to be put in place.

The monitoring should be designed to allow for each parameter to be detected at the lowest concentration at which it is of interest. This concentration should be below any relevant guideline value. The ability of laboratory analysis to detect low concentrations will be limited by sampling methods and errors. Accuracy is more important if the measurement results are close to the chosen guideline value.

Further detail on sampling methods and equipment are provided below, and in Geoscience Australia Sampling and Analysis – A Field Guide.[60]

> Sampling methods and equipment should be selected to take a representative sample of the groundwater in the formation of interest with minimal disturbance and within the appropriate detection limits.

5.12.1 Avoiding contamination during sampling

There are numerous ways that a sample may be contaminated in the field. Sources of contamination include equipment, people and dust. Sampling procedures need to be implemented to minimise changes to the sample due to contamination.

Equipment should be decontaminated as described in Section 5.11. Risks of contamination may be further reduced by using different equipment for different uses and different sites if possible.

Sampling should start with bores that are likely to have the lowest levels of contaminants and finish with those with the highest levels.

While in the field, equipment should be kept in a relatively clean environment. Exposure to dust, dirt and fumes should be minimised. For example, sample containers should be open for minimal amounts of time. Contact with the insides of sample containers or their lids should be avoided, and sampling staff should wear disposable gloves.

Additional protocols are required when sampling for trace metals, nutrients, organic compounds, microbes or eDNA to minimise contamination, including from dust, skin and hair. Reagents and calibration solutions should be stored in decontaminated containers and transported separately from the samples in sealed plastic bags. Containers should be capped and stored in bags except for the minimum required time for sampling.

After sampling, the samples should be stored and transported according to the guidelines in Section 5.17.

> Sampling procedures should minimise the risk of contamination with the level of care being appropriate for the sampling objectives, including detection limits.

5.12.2 Obtaining representative samples of groundwater

It is important for samples to be representative of the groundwater in the aquifer of interest, not of the water that has been sitting in the borehole for an extended time. Stagnant water is likely to have different properties from the surrounding groundwater, for example due to contact with the bore casing and atmosphere, and to have chemical gradients. If the water has been in the bore for even a few hours, levels of volatile organic compounds and dissolved gases may differ from the surrounding groundwater. This may also impact biology, e.g., detected stygofauna may also differ.

Therefore, it is necessary to either (a) use a low-flow sampling method, (b) use a passive sampling technique, or (c) purge the borehole before taking the sample.

It is important to select the most appropriate sampling technique for each monitoring bore to ensure that a sample representative of the target formation is collected. It is common for different sampling techniques to be used at

[60] Sundaram B 2009. *Groundwater Sampling and Analysis - A Field Guide.* Record 2009/027. Geoscience Australia, Canberra. Available [online]: http://pid.geoscience.gov.au/dataset/ga/68901.

different bores within the one monitoring network. Some of the considerations when selecting the most appropriate sampling technique for a monitoring bore include the depth of the bore, the length of the standing water column in the bore and the bore yield. Details of each sampling technique and the circumstances where the technique should be used are provided in the sections below. Each technique requires the use of specific types of sampling equipment.

It can be challenging to obtain a representative groundwater sample at some monitoring bores. If sampling is occurring in a formation with low hydraulic conductivity (e.g., clay), purging may not be feasible as the monitoring bore may purge dry and recover slowly. The low-flow method is preferred over purging but may also be difficult due to drawdown. Bores should not be pumped below the screened level because it will cause aeration of the geological formation. In these circumstances, efforts should be made to take the most representative sample possible. Options include purging the bore until the water level is at the top of the bore screen and then sampling the water flowing through the bore screen, or a passive sampling technique as described below.

> The sampling method should be designed to take water that has been flowing through the formation, not water that has been sitting in the bore. This requires either a low-flow sampling method, a passive sampling technique, or purging the borehole before taking the sample.

Low-flow method

The low-flow method takes a representative sample from the aquifer with minimal disturbance to the water in the borehole. The method is typically used for deep bores with a long-standing water column where purging would take a long time and produce large volumes of water, which may be problematic at some locations, particularly if the water is contaminated. The method can also be useful for bores with a low yield that would be difficult to purge.

In the low-flow method, water is extracted from the depth of the bore screen at the same rate as the flow rate through the formation. The method requires a pump with low-flow rates that can be adjusted. If the pumping rate is appropriate, there will be minimal drawdown.

The low-flow method can lead to a representative sample because water moving through the bore screen does not mix with the stagnant water in the rest of the bore. It minimises disturbance to the bore, mixing, turbidity, and vaporisation of volatile organic compounds.

Parameters such as pH, electrical conductivity, and temperature should be measured during pumping. When they have stabilised, the sample can be taken using a similar flow rate.

Passive sampling

In passive sampling, a sampling device is permanently installed in a bore with the inlet of the sampling device at the depth of the bore screen. The sampling device remains in the bore between sampling rounds so that water in the device can equilibrate with water flowing from the target formation through the screened part of the bore. The method is typically used for deep bores with a long-standing water column where purging would take a long time and produce large volumes of water. The method can also be useful for bores with a low yield that would be difficult to purge.

Purging

The bore-purge method involves removing stagnant water from the monitoring bore prior to sampling. The method is used at productive (moderate- to high-yield) monitoring bores and involves removing water with a pump, bailer, or tubing with foot valve before sampling. When assessing the suitability of the purge and sample method, purge volumes and associated purge times are important considerations, particularly if the water is contaminated.

The necessary purge volume varies between sites. Purging should continue until the water quality stabilises and the purge water is considered representative of water in the formation as there is otherwise a risk that the sample will be or include stagnant water. In some cases due to low hydraulic conductivity, it will not be possible to purge the necessary volumes and the alternative methods described above should be used. Water quality during purging should be assessed using a calibrated water quality meter, which can include the use of a flow-through cell for continuous readings. The physical parameters that should be assessed include pH, electrical conductivity, and temperature. Additional parameters should be measured when there is reason to believe they may show variation even when these basic parameters are stable. Parameters should be deemed to be stable if they show variation less than 10% in mass or unit volume or 0.2^{o}C in temperature, with more stringent requirements applied if risk assessment deems it necessary.

Purging may be done with a pump or a bailer, but it should be considered that a bailer may leave some stagnant water in the bore. High purging rates should be avoided as they can lead to changes to the groundwater chemistry. For example, high pumping rates may lead to the formation of iron oxyhydroxide mineral precipitates, which can adsorb dissolved metals and result in anomalously low concentrations of dissolved metals in the groundwater sample. In circumstances such as this, purging should be avoided and sampling should be undertaken using a low-flow method. High pumping rates should also be avoided to avoid disturbance to the formation and sometimes collapse of the bore screen interval in old bores. The pump intake should be placed above the screen level if possible and, if not, at least one metre above the bottom of the bore to avoid disturbing fines. Water quality samples taken from a bore that has been purged may be less representative of the groundwater depending on the equipment and techniques used.

Purged water should be disposed of in accordance with relevant legislation for the jurisdiction, for example by storing it onsite until it can be removed, particularly if there are likely to be contaminants that should not go into the soil.

When sampling from a private/production bore, purging is only necessary if the bore has not recently been used.

5.12.3 Obtaining a sample from a specific depth

Where groundwater quality varies with depth, samples may be taken from a nest of monitoring bores, where multiple bores are drilled in close proximity and screened at specific depths. Alternatively, if the bore is an open hole in a consolidated aquifer (i.e., not cased), samples may be pumped from a sealed section of the bore using a packer-pump assembly.

Production bores often have long open or screened sections and water in the bore may be a mix of water from different depths. Therefore, these samples should only be taken where there is vertical uniformity (e.g., where only one formation is screened and the water quality of the formation does not vary with depth) or where the monitoring objectives can be met with average groundwater quality across the depth of the bore.

5.12.4 Selection of sampling equipment

There is a range of equipment available for taking a groundwater sample. The options include:

- **Pumps:** A pump is used to sample groundwater in the low-flow and purge and sample methods. Where possible, the same device should be used for both purging and sampling to minimise disturbance and contamination. When sampling with a pump, the pumping rate should be slower or equal to the pumping rate while purging to avoid mobilising particles that were not released during purging. For sensitive parameters (e.g. VOCs and trace metals), a lower pumping rate should be used than for other parameters. A permanent pump may be installed in the bore in some circumstances to reduce the need for decontamination and set-up.

- **Passive sampling devices:** Passive sampling devices are designed to close before being removed from the bore. This is to prevent stagnant and stratified water in the upper part of the bore mixing with the water sample collected from the screened part of the bore.

- **Grab sampling devices:** Grab sampling devices include bailers and hydrasleeves. These devices are best used for groundwater sampling immediately after a bore has been purged and groundwater in the bore is considered representative of water in the target formation. Bailers and hydrasleeves should not be used for grab sampling without purging.

- **In-situ sampling devices:** In-situ sampling devices are typically used for sampling shallow groundwater and include porous cups and piezometer points. Groundwater is extracted using vacuum or gas displacement. Some devices are only suitable in the unsaturated zone.

Groundwater samples can also be obtained by extracting pore water from samples of soil or rock in the laboratory.

Samples should be taken from a depth that is as close as possible to the bore screen. The equipment must be able to reach this depth. Sampling equipment and methods should be chosen to minimise disturbance to the groundwater system and the samples being collected as changes will affect the accuracy and precision of results. Some methods are not suitable for some analytes. Processes and equipment that can affect analyte concentrations in groundwater samples include the following:

- **Degassing:** Degassing is the loss of dissolved gas due to a temperature increase or pressure decrease. It affects pH and parameters that are sensitive to pH, e.g., alkalinity and metals. It also causes a decrease in total dissolved solids (TDS) and total organic carbon (TOC). Equipment that can cause degassing includes air-lift pumps, suction-lift pumps, bailers, and gas-operated piston pumps.

- **Aeration:** Aeration is the introduction of air into the sample. Equipment that can cause aeration includes air-lift pumps, suction-lift pumps, bailers and gas-operated pumps (if air or oxygen is used as the driving gas).

- **Volatilisation:** Volatilisation causes dissolved gases to be lost through evaporation. It is affected by vapour pressure of the solute or solvent. It is particularly important when sampling for volatile organic compounds (VOCs). Bladder pumps may be suitable for VOCs. Equipment that can cause aeration includes air-lift pumps, gas-operated pumps, and bailers. Additionally, sample containers should be filled slowly at less than 250 ml/min for VOCs and less than 500 ml/min for other samples.

- **Precipitation:** Precipitation causes solids to form for dissolved constituents. It may be caused by changes in temperature, pH, chemical concentrations, or the presence of seed particles (small particles that provide a surface for precipitation to occur).

- **Oxidation:** Oxidation occurs when oxygen is introduced to a sample. It affects dissolved oxygen (DO), pH, redox and many other parameters.

- **Sorption:** Sorption is when dissolved constituents are attached to the surface of solids. It is affected by the suspended solids in the sample. It causes changes in various parameters.

- **Introduction of suspended solids:** Some methods may cause fines to be disturbed and to enter the water column. This may occur with bailers or inertial lift pumps. It may also occur with any pump used at a high pumping rate, i.e. over 1 litre per minute. It is important to ensure sampling does not disturb the fine sediments that accumulate in the bottom of the bore. Filtration (see Section 5.14) may be necessary if suspended solids are high.

- **Contamination from other samples and equipment:** See Section 5.11 on decontamination of equipment. Additionally, when using pumps that are fuelled by petrol or diesel, hydrocarbon contamination of the sample is possible.
- **Temperature changes:** A change in temperature will affect the rate of chemical processes. Some pumps may cause an increase in temperature in the bore or sample, such as helical-rotor pumps. Once samples have been taken, they should be cooled (see Section 5.17.3).

> Sampling equipment should be selected that allows for a sample to be taken that meets the monitoring objectives for accuracy and precision. Methods should avoid degassing, aeration, volatilisation, precipitation, oxidation, sorption, introduction of suspended solids, contamination or temperature changes.

5.12.5 Gas sampling equipment and methods

Monitoring of gas concentrations in groundwater is required for projects where proposed activities may change the concentrations of gases in groundwaters. A change in gas concentrations in groundwaters is a potential safety risk for groundwater users as some gases are flammable or dangerous to human health.

Projects where monitoring of gas concentrations in groundwater may be required include unconventional gas extraction, coal mining and landfills. For example, unconventional gas extraction involves depressurisation of coal seams for gas extraction, and this may lead to migration of methane into overlying or underlying formations that are used by local residents for water supply.

Monitoring for gases may be undertaken either by analysing dissolved gases from a water sample or by collecting gases at the bore and analysing the gases in the field or a laboratory.

When collecting a water sample for gas analysis, the container should be filled completely and tapped lightly to minimise bubbles in the sample. The container should have a tight seal to prevent loss of gases to the atmosphere and underestimation of the gas content of the sample. If monitoring evolving gases by passing bore water through a separator, a calibrated gas meter must be used.

Detailed information on the options for monitoring of gas concentrations in groundwater is provided in the Geoscience Australia Field Guide.[61] Monitoring of soil gas may also be undertaken but is not covered in these guidelines.

> Gas monitoring of groundwater should be undertaken where there is potential for project activities to change concentrations in groundwater.

5.12.6 Sampling non-aqueous phase liquids

Non-aqueous phase liquids (NAPLs) are organic liquids that do not mix with water. They may collect above the water table or above a less-permeable part of the formation. NAPLs may be lighter than water (LNAPLs) or more dense (DNAPLs). NAPLs may move in different directions to the groundwater.

The presence of LNAPLs and DNAPLs can be detected using an interface meter, which is a type of manual water level meter that can indicate the depth of NAPLs and the depth of water in the bore, thereby allowing the thickness

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[61] Sundaram B 2009. *Groundwater Sampling and Analysis - A Field Guide.* Record 2009/027. Geoscience Australia, Canberra. Available [online]: http://pid.geoscience.gov.au/dataset/ga/68901.

and location of NAPLs to be assessed. An interface meter should be used for all bores where there is potential for NAPLs to be present prior to any purging or sampling.

NAPLs should be sampled prior to any purging or other sampling techniques. This is because purging and groundwater sampling may affect the distribution of NAPLs in the bore. LNAPLs can be sampled using a bailer, with care taken to only sample the surface where the LNAPLs float above the groundwater. Sampling of DNAPLs is more complex and will require additional expertise.

Disposable equipment should be used to sample NAPLs and groundwater in bores with NAPLs as equipment exposed to NAPLs is difficult to decontaminate.

> An interface meter should be used to detect NAPLs in all bores where there is potential for NAPLs to be present prior to sampling. NAPLs should be sampled prior to the commencement of purging or other sampling techniques.

5.12.7 Sampling from private bores

Collection of groundwater quality samples from private bores will involve using the existing pump infrastructure associated with the bore. Sampling will therefore be undertaken using the purge and sample method. It is best to ask the landholder to operate the bore if you cannot do so safely and with their consent.

If the bore has been used by the landholder on the day of sampling, additional purging may not be required prior to collection of a sample. This is provided that the volume pumped by the landholder is sufficient and pumping was within a few hours of sampling. In any case, field parameters should be measured using a calibrated water quality meter prior to sampling to assess stabilisation and confirm the groundwater is representative of conditions in the target formation.

Water samples will typically be collected at the outlet of the bore infrastructure to the water storage infrastructure. Samples should not be collected from the water storages into which the bore pumps, such as water tanks or turkey's nest dams, as the water in these storages may have been there for long periods of time and is not representative of the groundwater.

The pumping history of the bore should be recorded in the field notes. The type of pumping infrastructure should also be recorded, as the type of pump may affect the water quality of the sample. Photographs of the bore and associated pumping equipment should be included as part of the field records.

> Samples may be collected from private bores through the purge and sample method, with additional purging unnecessary if a sufficient volume has been pumped within a few hours of sampling. Samples should be taken from the outlet of the bore infrastructure, not from stored water.

5.13 Quality assurance/quality control for sampling

As discussed in Section 5.12, the objective of groundwater sampling is to obtain a sample that is representative of groundwater in the formation screened by the bore and for the laboratory to receive a sample that is suitable for analysis for the parameters of interest. There are numerous ways that the chemical composition of groundwaters can be altered during the sampling, handling, storage, and transport process. These include cross-contamination of samples if sampling equipment is not properly decontaminated between bores, volatilisation of organic compounds or loss of gases if sample bottles are not filled and tightly sealed, and changes in the physical properties and chemical composition of samples if samples are not stored and transported at appropriate temperatures. It is therefore important that groundwater quality monitoring programs incorporate quality management. This includes quality assurance (QA) procedures to minimise errors and produce data that are accurate and reliable. Groundwater quality monitoring programs should also include a quality control (QC) program to identify and quantify potential quality issues that have arisen during the sampling, handling, storage and transport process. Records of QA/QC processes for sampling should be kept.

The quality control program should ensure that any significant changes to a sample are detected. Any contamination of samples or changes to the chemical composition of samples should be within acceptable limits determined as part of development of the QA/QC plan for the monitoring program. If acceptable limits are exceeded, there should be procedures in place to investigate the cause or source of the exceedance, and resampling may need to be undertaken. If the quality of the data collected is poor and the reason is unknown, it may affect the usefulness of the data.

Quality control samples are used to assess the accuracy and precision of the data gathered through a groundwater quality monitoring program and include field and laboratory quality control samples. This section addresses field quality control samples (see Section 5.18.2 for laboratory QA/QC). These samples are prepared to assess the effectiveness of the field methods in minimising contamination and avoiding changes in the chemical composition of samples. They include blank, duplicate (or replicate), and spike samples. They are analysed using the same methods as other samples so that the results can be compared.

The number of field quality control sampleswill depend on the sampling objectives, including the required confidence in results. At least one site out of every 10 to 15 should be sampled in triplicate to obtain original, duplicate and spike (where appropriate) samples.

> Quality management should be implemented to control errors in the field and identify and measure errors in the sampling, handling, storage, and transport of samples. Field blank samples, field duplicate samples and field spike samples (where appropriate) should be prepared and analysed.

5.13.1 Blank samples

Field blank samples (blanks) are used to identify whether contamination or cross-contamination of water samples is occurring during the sampling process. They are samples of deionised or highly purified water that undergo parts of the sampling, transport, and analysis process along with the groundwater samples collected. As they initially contain very low concentrations of any analyte, if higher concentrations are detected during analysis, it is likely that the samples have been contaminated. This should trigger an investigation into the source of contamination and consideration of whether the samples collected are representative of groundwater conditions.

Blank samples should always be collected where there is a risk of contamination. Different types of blank samples assess contamination during different parts of the sampling and transport process (see Table 5.2). Blank samples of each type relevant to the sampling process should be prepared for every monitoring round.

The number of blank samples should be appropriate for the monitoring objectives. Typically, there is one field blank for every ten samples, container blanks for a random selection of 10% of the container types and at least one per trip, and at least one rinsate blank for each type of sampling equipment per trip.

The results of field blank analysis should be considered together with the results of laboratory blank analysis to consider whether any differences may be attributed to field or laboratory practices.

Table 5.2 Types of blank samples

Type of blank sample	Contamination that it monitors	How to sample	Processes that the blank sample undergoes in the same way as the original sample
Field blanks	Contamination during sampling, for example from sample handling, dust and atmosphere	Fill sample containers with deionised water, typically while in the field.	All opening and closing of sample bottles, handling, preservation, storage and transport.
Filter blanks	Contamination during sampling and field filtration, for example from sample handling, dust on filters and atmosphere.	Filter a sample of deionised water and store in sample containers that filtered samples are stored in.	All opening and closing of sample bottles, handling, filtration, preservation, storage and transport.
Container blanks	Contamination from the sample container	Fill an empty container with deionised water.	These blank samples can be prepared in the laboratory, including preservation, and stored there for the same length of time before analysis.
Equipment or rinsate blanks	Contamination from the sampling equipment	Fill sample containers with deionised water that has been used to rinse decontaminated sampling equipment.	Contact with equipment used for sampling, opening and closing of sample bottles, transport and storage
Trip or transport blanks	Contamination during transport and storage.	Provided by the laboratory in closed containers and not opened in the field.	Transport and storage

5.13.2 Duplicate samples

Field replicate or duplicate samples are used to assess the precision of sampling and analysis, including the effect of rapid changes between samples. Two or more samples are taken at the same time and location, or a sample is split into two samples, although the former is preferred. Both samples undergo the same sampling, filtering, storage, transport, and analysis processes. If the concentrations of analytes between duplicate samples differ outside of tolerances for the analytical methods, the possibility of contamination or other errors should be investigated.

The number of duplicates will depend on the requirements of data quality given the monitoring objectives. Duplicate samples should be taken for five to ten percent of samples and analysed for the analytes that are most likely to be affected by the sampling method or be subject to change during sample handling, storage and transport.

Field duplicates may be sent to the same laboratory as the original samples or to a different laboratory. Records must be kept of which duplicates correspond to which samples. However, the laboratory should not know which samples are duplicates, i.e., blind duplicates.

The results of field duplicate analysis should be considered together with the results of laboratory duplicate analysis to consider whether any differences may be attributed to field or laboratory practices.

5.13.3 Spike samples

Spike samples are used to detect degradation or chemical adsorption or alteration during the sample storage and transport process. Spike samples are most typically used for volatile compounds such as hydrocarbons or dissolved gases such as methane or carbon dioxide.

Field spike samples are created by adding known amounts of an analyte to a sample in the laboratory or field. The resulting concentration of analyte should be within the range that is likely to be found in the sampled groundwater. Multiple spikes at different concentrations can be used if there is a range of concentrations in the sampled groundwater. When samples are being analysed for volatile compounds, there should be at least one spike sample per trip. Geoscience Australia provides recommendations for the preparation of spike samples in the field.[62] Spike samples from a certified laboratory may alternatively be used.

When analysed, the concentration of analyte in the field spike sample should be within specified tolerances. The results of field spike sample analysis should be considered together with the results of laboratory spike sample analysis to consider whether differences may be attributed to field or laboratory practices. Depending on the results, possible errors in the sampling and analysis process should be investigated, and resampling may be required.

5.14 Filtration

Sampling procedures and bore design should be designed to avoid high concentrations of suspended solids. However, some groundwater samples will require filtration, which is a physical process to separate the particulate and aqueous fractions of a water sample. It involves forcing water through a membrane with tiny holes (which can vary in size) to remove suspended solids from the water. Filtration can reduce changes to a sample that would otherwise occur during the period of time between sample collection and analysis (holding time). When developing a groundwater sampling plan, it is important to get instructions from the laboratory on when filtration is required, and what sample bottles and preservation are needed for filtered samples.

Filtration of groundwater samples is required when sampling to determine dissolved concentrations of analytes or mobile concentrations of analytes (dissolved and colloidal) that may be subject to sorption by suspended particles. For example, dissolved metals and hydrophobic contaminants such as PBCs and organochlorine pesticides in a water sample will tend to sorb to particulate matter during storage and transport if the sample is not immediately filtered. Filtration of samples for other analytes may also be required if it is not possible or practical to obtain a sample with low turbidity (i.e., visually clear) because preservatives may interact with suspended solids. Sampling procedures should aim to reduce turbidity, for example by using a low-flow sampling method or purging with a low pumping rate (see Section 5.12.2) as well as avoiding disturbing the fine sediments that have settled in the bottom of the bore

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[62] Sundaram B 2009. *Groundwater Sampling and Analysis - A Field Guide.* Record 2009/027. Geoscience Australia, Canberra. Available [online]: http://pid.geoscience.gov.au/dataset/ga/68901.

during sampling. Monitoring bores should be designed and constructed to minimise turbidity and therefore the need for filtration by using appropriately graded filter packs and screens with suitable aperture sizes for the geology.

Samples should be filtered at the field site as soon as possible after sampling to minimise changes to groundwater chemistry associated with the presence of particulate matter. Exceptions may be made where the conditions in the field would affect the representativeness of the sample. In that case, the laboratory should be notified that filtration is needed as soon as they receive the sample.

Field filtration may use a range of techniques and equipment, including syringe filters, vacuum pumps, and pressure pumps. A new filter membrane should be used for each sample and the selected filtration technique should ensure a high surface area to volume of water ratio to minimise pore clogging. The technique for filtration should be recorded and should be consistent within the monitoring program when sampling for the same analyte. Vacuum filtration should be avoided when analysing nutrients since it may remove some nutrients; pressure filtration is preferred.

The type of filtration membrane should be selected to minimise impacts on the parameters. Filters may be cellulose-based, glass or polycarbonate. Pore sizes must be appropriate for the parameter being analysed and should be on the advice of the laboratory conducting the analysis.

The filtration process has the potential to change the chemistry of the sample through exposure to air or adsorption of iron and metals to the filter. Filtration should be completed in an environment that minimises contamination (for example dust), filtration equipment should be rinsed with sample water before use, and sample container caps should not remain open for longer than necessary. When sampling for trace metals, filters should be rinsed first with dilute acid and then with Milli-Q water (ultrapure water) before being rinsed with sample water. If the groundwater is anaerobic, filtration must occur in anaerobic conditions.

If a sample has been filtered, this should be noted on the chain of custody documentation and the sample bottle for the advice of the laboratory.

> Filtration should be undertaken when determining dissolved concentrations of analytes. Bore construction and sampling techniques should be designed to avoid the need for additional filtration by minimising turbidity in samples.

5.15 Sample preservation

Sample preservation involves adding a reagent to a sample to reduce physical and chemical changes to the sample during the period between sample collection and analysis. The type and quantity of reagent will depend on the analyte and whether filtration has occurred. For example, acid may be added to a sample to reduce adsorption of metals or precipitation of salts. When developing a groundwater sampling plan, it is important to get instructions from the laboratory on what sample bottles and preservation are needed for the selected analytes. Some chemical preservatives, such as formaldehyde and mercury, should not be used as they may interfere with analysis and are harmful to people.

Where preservation is necessary, it should occur as soon as possible after sampling. Records of the type, concentration and volume of preservative added to samples should be kept and provided to the laboratory and made available to contextualise analysis. Cross-contamination between samples when adding preservatives should be avoided.

It is common practice for the laboratory to provide sample bottles with preservative already added. In these instances, care needs to be taken not to overfill bottles as this will result in loss of preservative. Care should also be taken to fill the bottle to the top so that the volume of preservative is correct for the volume of water sample in the bottle. Sample bottles should be ordered immediately prior to the sampling program rather than using bottles that have been stored for long periods.

Samples should be preserved where necessary to reduce changes to the sample over time.

5.16 Field (in situ) analysis

Some physical and chemical parameters may change rapidly after sampling and therefore should be measured in the field as soon as possible after collection. These parameters include temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), and redox potential (referred to as field parameters). Alkalinity and turbidity are also commonly measured in the field. Some parameters may be measured in the field using ion specific probes or field colorimetric methods; however, laboratory analysis is considered more accurate for these.

Field parameters are measured during every groundwater quality monitoring round. Field parameters are measured during the low-flow and purge and sample methods to assess whether stagnant water in the bore or water in the target formation is being sampled. Field parameters are also measured immediately prior to sample collection so that data are obtained for parameters that may change rapidly following collection (e.g., DO and redox potential) or will change as part of the storage and transport process (e.g., temperature). Some of the parameters measured in the field will also be measured in the laboratory, including pH, EC and turbidity.

Measurements of field parameters should be made within the bore where possible using a water quality meter. Otherwise, measurements may be taken from sampled water, preferably using a flow-through cell to avoid contact with the atmosphere.

Where the parameter being measured is affected by secondary parameters (e.g., temperature, salinity, altitude, and air pressure), that parameter must be measured at the same time. This may be done manually or automatically within the meter being used. Field measurements may be affected by other factors that cannot be compensated for. Possible interferences with the measurements beyond normal field conditions should be documented.

Measurements of temperature, pH, EC and DO should use a water quality meter (including the option of a multiparameter meter) that is calibrated as outlined in Section 5.9. Field readings should be compared with past measurements at the site or typical values to assess whether the results are within expected ranges. If the readings are substantially different, the equipment should be checked and calibrated before further measurements are taken.

If despite appropriate maintenance and calibration, an instrument is found to be not operating or is operating outside tolerance limits, a record should still be made of the actual reading, noting the observed issues with the water quality meter and any actions taken such as sending samples to the laboratory for analysis; poor data in context is more valuable than no data at all.

Table 5.3 provides some guidance on measuring field parameters. However, this is not intended to be comprehensive. The Geoscience Australia Field Guide[63] may be referred to for further information.

[63] Sundaram B 2009. *Groundwater Sampling and Analysis - A Field Guide.* Record 2009/027. Geoscience Australia, Canberra. Available [online]: http://pid.geoscience.gov.au/dataset/ga/68901.

Parameters should be measured in the field if there is a risk of substantial change during the period between sample collection and analysis (e.g. temperature, pH, EC, dissolved oxygen). Field measurements should be undertaken using a calibrated water quality meter. Conditions with potential to introduce errors should be documented.

Table 5.3. Minimum requirements for measurement of field parameters

Parameter	Minimum requirements for field measurements
Temperature	Use a calibrated field thermometer.
pH	Use a calibrated pH meter (not a chemical process). Temperature must be measured at the same time as pH changes with temperature. Accuracy should be at least ±0.1 pH unit.
Electrical conductivity (EC)	Use a calibrated EC meter. Results should be normalised to 25^{o}C because EC changes with temperature. Typically, the user manual can be used to confirm that the meter is doing this automatically. Alternatively, record both EC and temperature measurements so that it can be calculated manually. Accuracy should be at least ±10 µS/cm.
Dissolved oxygen (DO)	Use a calibrated optical or electrochemical DO sensor or an automated titrator. DO is affected by temperature, salinity, and atmospheric pressure. If using a typical multi-parameter instrument, the user manual should be used to confirm that dissolved oxygen is being recirculated around the instrument and is compensating for temperature and salinity and that atmospheric pressure is considered during calibration procedures. Results should be reported in mg/L and % saturation.
Redox potential	Use a calibrated oxidation reduction potential (ORP) sensor.

Parameter	Minimum requirements for field measurements
Total alkalinity	Total alkalinity may be measured in the laboratory but field measurements are preferred, particularly if the sample contains high levels of dissolved gases which may cause the alkalinity to change quickly. Use burette titration or a digital alkalinity titrator.
Total acidity **(Recommended for groundwater that is vulnerable to acidification)**	Use a titrimetric method.
Turbidity	Use a calibrated nephelometer (turbidity meter).

5.17 Sample storage and transport

The physical and chemical properties of groundwater samples may change during storage and transport due to effects of temperature and exposure to the atmosphere. Samples may also be contaminated during transport or degrade because they are not appropriately stored.

Appropriate procedures can ensure that samples are representative of the original groundwater at the time of analysis. This includes analysing some parameters in the field (see Section 5.16) and using appropriate procedures for samples that will be stored and transported as described below.

> Sample storage and transport should be undertaken to minimise physical, chemical and biological changes and contamination of samples, and documented with consideration of effect on uncertainty on results.

5.17.1 Holding time

Holding time refers to the period between sample collection and sample analysis. Different analytes will have different maximum holding times. If analysis occurs after the maximum holding time for an analyte, the sample is more likely to have undergone changes that will affect the concentration of that analyte. Appropriate procedures for filtration (Section 5.14), preservation (Section 5.15), and storage at low temperatures (Section 5.17.3) will reduce the rate of change within a sample; however, some changes will still occur.

The maximum holding time for an analyte may range from hours to years. Parameters with holding times in the range of hours are typically measured in the field (see Section 5.16). However, other parameters with short holding times may need to be analysed in the laboratory. This is an important consideration when planning the transport of samples to the laboratory. Arrangements should be made to ensure samples arrive at the laboratory within maximum holding times, and that laboratories are aware of any samples that may be close to expiry of their maximum holding times. Couriers may need to be arranged to pick up and transport samples to the laboratory during the monitoring program, in some cases at the end of each day of sampling.

If samples are delivered to the laboratory beyond the maximum holding time, for example due to the distance from a laboratory or because of unexpected problems with transport, the samples may still provide useful results, albeit with greater uncertainty. Samples should not be disposed of without being analysed unless there is strong justification.

> Plans should be made to ensure a sample is analysed within the maximum holding time. However, samples should be retained and analysed even if the holding time has expired, with appropriate documentation.

5.17.2 Sample identification

Sample bottles should be labelled as soon as possible after sample collection to prevent samples getting mixed up.

Sample labels should be durable. If samples will be stored in ice, it is particularly important that labels are waterproof. To avoid contamination of the sample, the labels should be stick-on labels and preferably use waterproof pre-printed labels but may use ink pen or biro. Permanent marker should not be used.

Labels should include all information that is necessary for sample identification and analysis, including the bore from which the sample was taken, the date and time of sampling, any filtration or preservation, and whether the sample may be hazardous or have high concentrations of the analyte.

The details on the sample labels should be the same as the details in the chain-of-custody documentation.

> All samples should be labelled as soon as possible during sampling in a way that ensures that they remain distinguishable from other samples.

5.17.3 Temperature during storage and transport

Samples will typically need to be refrigerated or frozen and protected from sunlight. An appropriate temperature should be chosen depending on the analytes and the maximum holding times. Information on appropriate storage temperature can be provided by the laboratory and must be consistent with AS/NZS 5667.1:1998, AS/NZS 2031:2012 or superseding standards.

The samples should be cooled to the specified temperature as soon as possible after sampling and should not be allowed to increase in temperature before analysis. Samples are usually stored in fridges and transported in cooler boxes. Any fridges or cooler boxes should be cleaned before use, particularly if their previous use could cause contamination. Samples stored and transported in cooler boxes should be cooled using ice bricks. It is acceptable to use ice if the samples are protected from contamination from the ice, for example using double-sealed bags around the samples and keeping the container lids above the ice.

Frozen samples will typically have longer holding times. However, freezing temperatures will affect some analytes and may not be a suitable option.

> Samples should be kept at a low temperature and protected from direct sunlight during storage and transport to minimise changes in parameters.

5.17.4 Chain of custody

It must be clear at all times who has custody of a sample and is responsible for it. Having custody of the sample includes limiting access to it, for example by having it in an individual's physical possession or by keeping it in an area with restricted access. Tamper seals, locks, or tape should be used on the samples or cooler boxes commensurate with the importance of maintaining the integrity of the chain of custody.

Documentation of the chain of custody should include who has custody at which times, and other information such as identification numbers for samples, the dates and times of sampling, transport, storage, sample preparation, and sample analysis, and the names of the technicians and laboratories involved.

The chain of custody documentation will provide evidence that the sample was treated appropriately and not tampered with. It should remain with the sample from the time of sample collection to disposal and be signed by each person who has custody of the samples.

> Documentation of the chain of custody should include who has custody at which times, and other information such as identification numbers for samples, the dates and times of sampling, transport, storage, sample preparation, and sample analysis, and the names of the technicians and laboratories involved. It should remain with the sample from the time of sample collection to disposal and be signed by each person who has custody of the samples.

5.17.5 Transport

Samples should be packaged in a way that avoids cross-contamination of samples or contamination of samples from packaging or ice. Packaging may also be designed to minimise damage to sample labels from vibrations. For example, samples may be kept in bubble wrap, snap-lock bags or in air-tight plastic tubes with screw caps. Any space between sample containers should be filled to ensure that they stay upright and that glass containers do not break.

Transport containers such as cooler boxes should be sealed, for example with packing tape and a tamper-proof seal provided by the laboratory. Sample containers may also have sample seals.

Samples may be delivered personally by the sampling team, or a courier may be used only if they are able to meet the requirements, such as time frames, holding samples at cool temperatures and keeping the package secure.

Samples with different preservation requirements may need to be in separate transport containers. Couriers should be made aware of the temperature requirements, whether the samples are fragile, and any potential toxicity.

Couriers should be made aware of the maximum time at which the samples can be delivered to the laboratory (which will be based on the maximum holding time). The monitoring team should check whether transport is proceeding on schedule and take appropriate action to either ensure delivery or collect additional samples.

> Samples should be transported within the holding times and without causing substantial changes to the samples or breaking the chain of custody. Samples should be packaged and transported in a way that avoids contamination, minimises damage and is sealed.

5.18 Laboratory analysis

The aim of laboratory analyses is to provide accurate and precise data on groundwater quality that meet the monitoring objectives.

Analysis should be conducted by a laboratory that is accredited by the National Association of Testing Authorities (NATA) or ISO or AS and NZ accredited laboratories. Accreditation ensures that certain standards will be met, including QA/QC. However, it does not guarantee that results will be accurate. Even when a laboratory is accredited, it is still important to check that the laboratory has experience with the methods to be used and has access to the necessary equipment. Some analysis, such as analysis for certain statutory purposes, can only be completed by a NATA-accredited laboratory.

Exceptions to using accredited laboratories may be made for novel techniques that are not available through accredited laboratories, where there is good reason to use those techniques and where they meet any applicable requirements.

Relevant information should be communicated to the laboratory in advance, including the type of analysis, when they will receive the samples and what their holding times will be, and if there are likely to be high concentrations of analytes in the samples. Plans with the laboratory should be made in advance to ensure that there are sufficient resources to complete the analysis within the holding times for samples.

> Laboratories should be accredited by the National Association of Testing Authorities (NATA) except in special circumstances where justified. The monitoring team should verify that the laboratory has experience with the methods to be used and has access to the necessary equipment, and that it has the resources and advance notice necessary to complete the analysis within maximum holding times for samples.

5.18.1 Choice of analytical methods

Laboratory analytical methods will vary in complexity and cost. Standard analytical methods should be used unless there is technical justification for the use of an alternative method. Any changes to laboratory procedures must be documented and, where possible, quality control procedures should be used to demonstrate the performance of the alternative method, such as through analysis of a standard reference material. The choice of analytical method should also take into account the holding times for samples and when the end user requires the data.

Different analytical methods may have different limits of reporting for an analyte. The limit of reporting is the level at which an analyte can be measured with acceptable accuracy and precision. It is important that the laboratory understands the limits of reporting needed prior to analysing samples. Appropriate limits of reporting for a project should be below the relevant guideline values for the analyte of interest.

The method should also minimise damage to the environment, including having consideration for waste disposal.

Procedures for analysis of water samples are referenced in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality and Groundwater Sampling and Analysis – A Field Guide.[64]

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[64] Sundaram B 2009. *Groundwater Sampling and Analysis - A Field Guide.* Record 2009/027. Geoscience Australia, Canberra. Available [online]: http://pid.geoscience.gov.au/dataset/ga/68901.

The analytical methods used should be suitable for the detection limits, accuracy, precision, and timeframes targeted under the monitoring objectives.

5.18.2 Laboratory QA/QC

Procedures for quality assurance and quality control (QA/QC) for groundwater sampling aim to deliver a sample to the laboratory that is representative of groundwater in the formation screened by the bore and is suitable for analysis for the parameters of interest. Once samples reach the laboratory, there is potential that the chemical composition of samples may be altered due to the laboratory procedures. NATA-accredited laboratories are required to implement QA/QC procedures to minimise errors and produce data that are accurate and reliable. NATA-accredited laboratories are also required to undertake quality assurance to identify and quantify potential quality issues that have arisen during sample handling and analysis.

The Australian and New Zealand Guidelines for Fresh and Marine Water Quality provide details of what should be included in laboratory QA/QC. When using a NATA-accredited laboratory, QA/QC procedures will be in place, including blanks, duplicates, spikes and laboratory control samples. The QA/QC procedures to be implemented should be confirmed and agreed during development of the groundwater quality monitoring plan for the project.

The laboratory should report quality control data for each batch of samples. This should include data from blanks, duplicates, spikes and laboratory control samples. Data on precision (e.g. standard deviation, relative standard deviation or error) and accuracy (e.g. bias and the methods for establishing accuracy) should also be provided.

The data and quality control report should be reviewed as soon as possible after it is received to check for any deviations from expected values or acceptable ranges. Possible issues that could occur include anomalously high concentrations of an analyte in a groundwater sample that would typically have low concentrations, blank samples with high concentrations of an analyte or spike samples that do not have the expected recovery. Where problems are identified, they should be followed up with the laboratory as soon as possible, and reanalysis of the sample should be considered. It may be necessary to investigate sources of error in the sampling and transport procedures or seek a replacement sample; measurement should be approached as an iterative process of seeking timely, representative and fit-for-purpose information rather than simply accepting possible failures of data collection and analysis.

The monitoring team should require evidence of laboratory QA/QC procedures and should follow up within appropriate timeframes if there are errors that are outside of tolerances.

6. Other field investigation methods

Hydrogeological investigations are studies undertaken by hydrogeologists to improve knowledge of groundwater systems. They are usually undertaken as part of groundwater study for a project approval and are in addition to baseline groundwater level/pressure and quality monitoring.

The aim of hydrogeological investigations is to improve conceptualisation of a groundwater system by answering specific questions that arise through the initial desktop review or baseline monitoring program, for example questions about connectivity between aquifers or connectivity between aquifers and streams or the role of faults in groundwater flow. Hydrogeological investigations are also undertaken to gather site-specific hydraulic property data for parameterisation of geological formations in a numerical groundwater flow model.

Other field investigation methods (e.g., surface water monitoring) may also play a role in post-approval impact monitoring, in diagnosis of monitoring discrepancies, or attribution of impact.

As discussed in Chapter 2, before any hydrogeological investigation is undertaken, it is important to clearly define the project being assessed, gather background information on the hydrogeological setting and conduct a preliminary risk assessment to identify and assess all potential risks to groundwater resources and sensitive receptors. Based on the findings of the risk assessment, a groundwater monitoring plan should be developed for the project that includes the details of hydrogeological investigations needed to improve assessment of the risks to groundwater resources and sensitive receptors. Every hydrogeological investigation is site-specific, and the methods used should be tailored accordingly.

This section describes some of the methods that can be used in hydrogeological investigations and provides recommended minimum requirements for hydrogeological investigations for project approvals.

6.1 Hydraulic testing

Hydraulic properties are estimated in the field using methods that record changes to hydraulic head as a result of natural or artificial stresses applied to a groundwater system. Hydraulic parameters, including hydraulic conductivity, storativity, and leakage from adjacent aquitards, can be estimated using mathematical methods from data collected in the field. Hydraulic parameters cannot be measured directly and their quantification is an estimate with accuracy dependent on the testing methods used and the data analysis and interpretation. These guidelines focus on data collection needed to support analysis. Specific analyses may also impose additional requirements on data collection.

The data collection methods described in this section are most typically undertaken to:

- estimate hydraulic parameters for parameterisation of a numerical groundwater model, for example packer testing may be undertaken at boreholes across a groundwater system to characterise variability in hydraulic conductivity for model parameterisation;
- improve conceptualisation of a groundwater system, for example test pumping (otherwise known as a pumping test) may be designed to assess whether a fault acts as a barrier or conduit to groundwater flow; and
- assess risks to groundwater resources and sensitive receptors, for example test pumping may be designed to assess leakage through an aquitard and improve understanding of connectivity between aquifers.

Most projects will require field assessment of aquifer hydraulic properties to provide an informed assessment of potential adverse impacts to groundwater resources and related assets and ecosystems. These include laboratory, active and passive methods.

6.1.1 Overview of methods for estimating hydraulic properties

Methods for estimating hydraulic parameters include laboratory, active and passive methods. Active methods involve applying a stress to a bore and recording changes in hydraulic head in one or more observation bores. Examples include slug tests, drill stem tests (packer tests), pumping tests and constant head tests. Passive methods involve recording hydraulic head responses to natural stresses such as barometric pressure, Earth tides or seasonal water level fluctuations. Hydraulic parameters can also be estimated from laboratory core testing.

Table 6.1 summarises the methods for estimating hydraulic parameters, including the parameters that can be estimated from the data collected and conditions in which they are or are not recommended. Details of each method and when they should be used in a hydrogeological investigation are provided in the sections below.

Table 6.1 Methods for estimating hydraulic properties

Test	Use/purpose	Recommended contexts	Contra-indications
Laboratory methods			
Core permeability tests	Testing is conducted on a small sample (approximately 0.1 m long) and therefore provides information on the hydraulic properties of the rock mass at a specific point in the subsurface.	Results can be obtained for horizontal and vertical permeability if samples are appropriately prepared. Characterising hydraulic properties of aquitards. Using core samples collected during exploration.	Provides data on the primary permeability of the rock mass (matrix flow) but does not account for the effects of secondary permeability that may be associated with joints and fractures. Best used for consolidated rock samples and less reliable for unconsolidated sediments.
Active methods			
Slug tests	Provides an indication of the hydraulic properties of the formation in the immediate vicinity of the screened interval of the monitoring bore. Typically provides data for estimating horizontal hydraulic conductivity (kh).	Existing monitoring bores can be used for testing if the geology and construction are known. Tests are comparatively short duration.	Limited in area of impact, testing only a small part of the formation around the monitoring bore. Susceptible to borehole skin effects (changes to the hydraulic properties of the formation in the borehole wall associated with the drilling process such as smearing) and may not be representative of conditions in the formation.
Packer hydraulic conductivity tests	Provides information on the hydraulic properties of the rock mass at discrete depth-intervals down the borehole (generally in intervals between 1 and 12 m long). Typically provides data for estimating horizontal hydraulic conductivity (kh).	The results are indicative of the primary permeability of the rock mass as well as secondary permeability that may be associated with joints and fractures.	Highly fractured zones cannot be tested and so results may underestimate hydraulic conductivity.
Passive methods			
Passive methods	Provides information on aquifer properties	Does not impact on the groundwater system Can use groundwater level measurements collected for other purposes, if good quality data	Estimates may need to be confirmed with other methods May be confounded by pumping activities in the area

6.1.2 Laboratory methods

Laboratory methods may be used to obtain data on the hydraulic properties of an aquifer or aquitard sample. Testing is conducted on small samples collected during drilling, and thus represent point values. Laboratory methods provide an indication of the primary permeability of the sample, i.e., the flow of water through the matrix of the sample, but are less suitable for characterising in situ conditions where fractures and other forms of heterogeneity influence groundwater flow. For this reason, laboratory methods should be used in combination with field methods to determine whether such heterogeneities exist.

There is a number of different laboratory methods that can be used to estimate the hydraulic properties of sediment and rock samples. IESC (2014)[65] provide a discussion of the different methods available which include constant head permeameter tests, falling head permeameter tests and air permeameter tests. Air permeameter tests are not recommended as they tend to result in an overestimation of hydraulic properties. Water permeameter tests can also overestimate hydraulic properties; however, the accuracy can be increased by conducting the experiments under in situ effective stress, which can be simulated in the laboratory using a triaxial cell, an apparatus that applies stress to a core in three dimensions.

Laboratory testing of very low-permeability materials characteristic of aquitards can be achieved using a centrifuge permeameter, which uses accelerated gravity to drive fluid flow through the sample. The method simulates the flow of water through the material over thousands of years in a period of weeks to months.

Other methods discussed in IESC (2014) that can be used to estimate the hydraulic permeability of porous media include high-resolution X-ray tomography, scanning electron microscopes and mercury-injection porosimetry. X-ray tomography can be used to digitally reconstruct the 3D porous system of a small sample of rock to simulate pore-scale flow and allow for the identification of the principal components and direction of hydraulic permeability for the sample. Scanning electron microscopes (SEM) can be used to image pore spaces down to the nano-scale (1 µm to 1 nm), and allow the visualisation of microstructures in fine-grained rocks. Mercury-injection porosimetry is a standard method used in the petroleum industry to measure the pore volume of a sample by forcing mercury into the pore spaces at increasing pressures.

6.1.3 Active methods (aquifer testing)

Active testing methods, which involve applying a stress to a bore and recording changes in hydraulic head, include:

- single well tests, where a stress is applied to, and response is recorded in the same well; and
- multiple well tests, where a stress is applied to one well and the response is recorded at one or more observation wells.

Slug tests and packer tests are single well tests. Pumping tests and constant head tests may be single or multiple well tests, depending on the test design. Details of each type of test are provided below.

6.1.3.1 Slug tests

The simplest type of single well test is the slug test, where an instantaneous change in hydraulic head is applied to a monitoring bore. Slug tests are limited in their area of impact, testing only a small part of the formation around a monitoring bore, and typically only provide information on hydraulic conductivity. Slug tests can be useful for

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[65] Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development 2014. *Connectivity between water systems – fact sheet.* Available [online]: https://iesc.environment.gov.au/publications/connectivity-between-water-systems/.

characterising variability in the hydraulic conductivity of a formation across an area in addition to broader scale testing such as pumping tests. Slug tests can also be useful for providing an indicator of bore performance.

There are two types of slug tests:

- a rising head test, where a known volume of water is removed from the well and the head recovery is recorded; and
- a falling head test, where a known volume of water is added to the well and the head decline back to normal is recorded.

Requirements of the selected analysis method should be confirmed. Analysis commonly relies on making an instantaneous change in head, which can be difficult to achieve. Often a falling head test is undertaken using a physical slug – a solid cylinder that is lowered into the well causing a rapid change in hydraulic head. A rising head test can be undertaken by air-pressurisation of a well with the rising water level recorded when the pressure is released. The change and recovery in water level during a slug test should be measured using a pressure transducer set to record pressure at small intervals (e.g. 1-second intervals) to avoid loss of data as the changes occurring can be rapid depending on the hydraulic conductivity of the formation. Slug tests should be undertaken at least three times at each monitoring bore to allow assessment of uncertainty.

Slug tests can be interpreted using a number of mathematical methods which can account for the aquifer conditions (confined, unconfined), borehole skin effects (increased or decreased permeability caused by the drilling process) and length of well screen (screen partly or fully penetrating the aquifer).

6.1.3.2 Packer tests

The term "packer test" is widely used to describe hydraulic conductivity testing that uses inflatable packers to isolate a section of a borehole for controlled injection or withdrawal of water and analysis of the pressure/flow rate response. Packer tests are a routine component of many geotechnical investigations to provide parameters for design in rock where groundwater flow is a key consideration, for example seepage below retaining walls, slope stability, tunnel seepage, construction dewatering. Packer tests also have applications for hydrogeological investigations because they can be used to characterise variation in the hydraulic properties of the rock mass. Packer testing and data analysis should be undertaken by experienced personnel in accordance with ISO 22282-3:2012 Geotechnical investigation and testing — Geohydraulic testing — Part 3: Water pressure tests in rock.

Packer testing is typically carried out in cored boreholes in rock, where unlined sections of the borehole are stable enough to stand unsupported. The testing is undertaken during or immediately following drilling and before monitoring bore casing is installed. It involves isolating a section of a borehole using either a single- or double- (straddle) packer system (Figure 6.1) and then testing the hydraulic properties of the sealed part of the formation. Testing typically involves multiple phases of controlled injection of water at different pressures into the sealed section of the borehole via the drill string. Each phase is effectively a constant head water injection test. The horizontal hydraulic conductivity of the formation isolated by the packers is estimated by analysis of the pressure-flow rate response.

The packer test program should be planned to ensure useful and representative data are obtained. Prior to testing, it is important to confirm that the equipment can achieve the estimated flow rate/water volume requirements based on the anticipated rock hydraulic conductivity. Packer testing of highly permeable zones (with conductivities higher than around 10-4 m/s) generally cannot be undertaken with standard equipment as it can be difficult to achieve the injection pressures needed for the test. Any zones where testing was unable to be undertaken due to high permeabilities should be identified in the field notes so that they can be considered in the conceptual ecohydrological model.

The depth and length of test sections should be specified based on the monitoring objectives and borehole lithology. Downhole geophysical logging should be undertaken prior to packer testing so that the data can be used to specify the packer intervals. Downhole geophysics will provide data on lithology/stratigraphy, fracture zones, and borehole width, which are important for positioning the packers. For example, if an objective of the packer testing is to gather hydraulic conductivity data for an aquifer and an overlying aquitard, then the packer test interval should not cross the boundary/contact between the two formations but should be above and below the boundary/contact. The packers should be positioned on smooth sections of the borehole to avoid bursting the packers and provide a seal on borehole wall. If the packers do not create a seal on the borehole wall, water may leak past the packers and the results will not be representative of the formation being tested.

Boreholes that required the use of drilling fluids such as muds to remain open should not be packer-tested as the muds will change the hydraulic properties of the formation and the results will not be representative. If substances such as polymers were used at particular intervals during drilling to stabilise the walls of the borehole, these intervals should not be packer-tested as the polymer will reduce the conductivity of the formation and give a false result. Highly fractured sections that have been stabilised with polymers should be clearly identified in field notes so that these high-conductivity zones can be considered in the conceptual ecohydrological model. The injected water should be clean and free from suspended solids to reduce the risk of clogging or plugging of the test section.

Packer tests are limited in scale, testing a maximum zone of 10 m from the borehole, and of short duration, with a typical test time of 50 to 75 minutes. The test provides information about the horizontal hydraulic conductivity of the formation but cannot provide information about vertical conductivity. In addition, the hydraulic properties derived from the test relate to water being injected into rock, which may differ from water flowing out of rock, e.g., as tunnel seepage, or for construction dewatering.

Packers can also be used for other types of testing, including collecting groundwater samples for water quality analysis from a defined interval. These other types of testing using packers have not been addressed here.

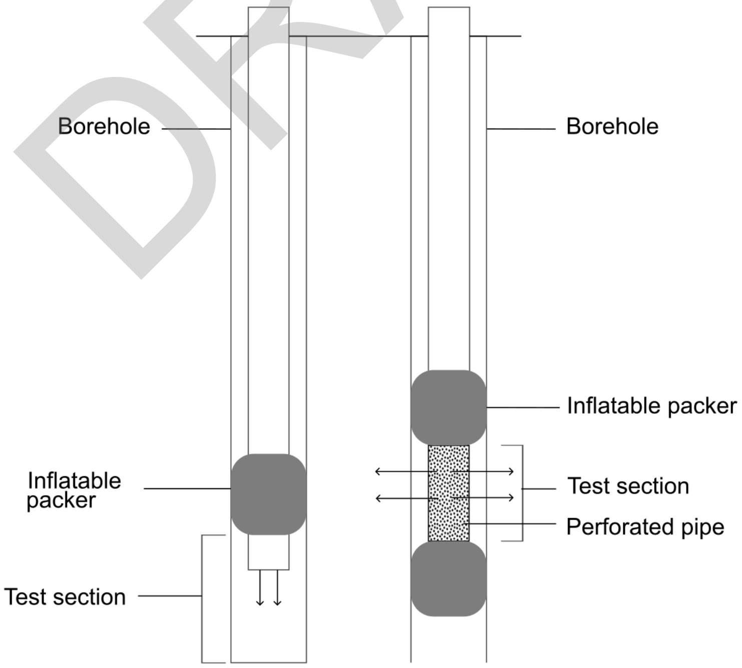

Figure 6.1 (a) Single-packer test, open borehole and (b) Double-packer test, open borehole

6.1.3.3 Test pumping

Test pumping (otherwise known as a pumping test) is conducted by pumping water from an aquifer at a controlled rate and measuring the response in groundwater level/pressure as it declines during pumping and subsequently recovers. The data are typically represented as a plot of time and drawdown. These data can be used to estimate hydraulic properties because these properties determine how groundwater levels respond to pumping. They may also be used to determine the aquifer boundaries because groundwater levels in bores outside of the pumped aquifer will not respond or will respond differently if there is limited connectivity.

Test pumping will be necessary for projects involving a numerical model because they require quantification of hydraulic properties. Compared to slug tests, pumping tests impact the aquifer for a longer period of time, causing drawdown across a larger area and therefore provide data that are representative of average hydraulic properties across that area.

The location and number of pumping tests should be selected to provide necessary information for the conceptual and/or numerical models of the groundwater system. As outlined in Section 3.3.1.5, bores used in test pumping should have a sufficient internal diameter to accommodate equipment and should have monitoring bores in the vicinity. Therefore, it will likely be necessary to install new bores once the location of test pumping has been planned rather than relying on existing bores. If there is surface-groundwater interaction, the test pumping design should either deliberately assess recharge and include surface water measurements, or the test pumping should be conducted away from those areas if possible to represent typical properties in the aquifer.

The intended rate and duration of pumping should be carefully selected for the site conditions. Longer pumping causes a larger cone of depression. Preliminary tests with different pumping rates may be used to assist with selecting a suitable pumping rate. The intended pumping rate may be constant or it may be varied according to predetermined requirements of the analysis method. For example, a step-drawdown test involves an increasing series of pumping rates, each used for the same length of time. It is common for test pumping to have multiple stages, such as a step-drawdown and then a constant rate test.

The intended pumping rate may not always be possible. For this reason, the actual discharge rate should be recorded each time that a groundwater level measurement is taken or more frequently. This may be less than the pump capacity. Unplanned variations in pumping rates may be due to fast drawdown or a failure of the pump. If the variation from the intended rate is above 5%, groundwater levels should be monitored until they recover to initial levels. The pumping test should then be restarted, using a lower pumping rate if drawdown was too fast with the original rate.

Pumped water should be discharged as far as possible from the bores to minimise its impact on groundwater levels through recharge. The risks of pollution should be minimised, for example by considering the groundwater quality properties before allowing pumped water to enter surface water bodies. Risks of saltwater intrusion due to pumping should be assessed and, where relevant, electrical conductivity should be monitored and the test stopped if there is evidence of intrusion.

Groundwater levels should be monitored in the pumped bore and in at least one nearby bore before, during and after pumping. There should preferably be several days of monitoring before the pumping test to assess normal variations in groundwater levels, particularly in coastal areas with tidal influences. The duration of monitoring after pumping has ceased should be sufficient to characterise the response, typically with recovery of at least 90% of the decline in groundwater levels. Depending on the analysis method, measurements may be required more frequently towards the start of the test when there will be rapid changes in groundwater levels and less frequently in later stages of the test.

Measurements should be taken in the same aquifer and, in some cases, also in other aquifers to assess aquitard integrity. Packers may be used to monitor a specific depth interval. Monitoring bores should be located within the area where groundwater levels are expected to be impacted, which may be based on preliminary data and testing. In some cases, it will also be important not to place the monitoring bores too close to the pumped bore because of vertical groundwater flow. As the cone of depression may be asymmetrical, monitoring at multiple bores distributed around the pumped bore will provide more information. Four monitoring bores may be typical, with more included if there are complexities in the aquifer, such as faults.

If possible, test pumping should be completed when there is no pumping at bores in the vicinity. If this is not possible, details of nearby pumping should be recorded. Test pumping should not be conducted during or after heavy rainfall since it may affect groundwater levels. Other factors that may affect groundwater levels should also be recorded. Refer to Chapter 4 for more details on groundwater level measurements and corrections.

Approval may be required prior to test pumping under state/territory legislation.

> Test pumping of productive formations at risk of adverse impacts should be undertaken for all proposed projects requiring numerical groundwater modelling to predict impacts to obtain site-specific hydraulic parameters and improve conceptual understanding of aquifer connectivity.

6.1.3.4 Constant head tests

A constant head test is a variation of a pumping test. It involves pumping water from a bore at a rate that is adjusted to ensure the groundwater level/pressure remains the same. Groundwater levels should be monitored at the pumped bore and preferably at multiple bores in the same aquifer. The intended analysis method should inform which type of test is used.

6.1.4 Passive methods

Passive methods provide information about groundwater properties in-situ, and without the costs of active hydraulic test methods. In particular, measurements of groundwater level fluctuations due to Earth tides and atmospheric tides can be utilised to estimate hydraulic and geomechanical properties of aquifers and aquitards.

Earth tides are movements of the subsurface due to gravitational forces from the Moon and Sun. In confined aquifers, pore pressure will change in response to dilation and contraction of the subsurface. Atmospheric tides are changes in atmospheric pressure due to heating from the Sun and gravitational forces from the Moon. There will be localised changes in atmospheric pressure in addition to this, for example due to a weather system.

To use this method, groundwater levels and barometric pressure should be monitored continuously or at short intervals for a period of time with sufficient vertical measurement resolution. These data along with knowledge of the theoretical tides at those times can be used to calculate hydraulic properties, such as specific storage.[66] Passive methods are worth considering for cost-effective and in-situ measurement of hydraulic properties at many bore locations. Bores with both barometric and earth tide signals provide the most hydraulic data, if good quality data is

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[66] Acworth RI, Rau GC, Halloran LJS and Timms WA 2017. Vertical Groundwater Storage Properties and Changes in Confinement Determined Using Hydraulic Head Response to Atmospheric Tides. *Water Resources Research* 53, no. 4, 2983-97. Available [online]: https://doi.org/10.1002/2016WR020311.

Rau GC, Cuthbert MO, Acworth RI and Blum P 2020. Technical Note: Disentangling the Groundwater Response to Earth and Atmospheric Tides to Improve Subsurface Characterisation. *Hydrology and Earth Systems Sciences* 24, no. 12, 6033-46. Available [online]: https://doi.org/10.5194/hess-24-6033-2020.

Valois R, Rau GC, Vouillamoz JM and Derode B 2022. Estimating Hydraulic Properties of the Shallow Subsurface Using the Groundwater Response to Earth and Atmospheric Tides: A Comparison with Pumping Tests. *Water Resources Research* 58, no. 5. Available [online]: https://doi.org/10.1029/2021WR031666.

available for analysis. For passive methods, groundwater head time series should be available with appropriate temporal resolution (≥8 samples per day) and duration (≥1 month) and should also have an appropriate pressure resolution (< 1 mm head).[67] Multiple lines of evidence (i.e., different hydraulic testing methods) are recommended for sites that are considered to be high risk or where modelling outcomes indicate a sensitivity to hydraulic parameters.

6.1.5 Failure points and sources of uncertainty

As with all scientific methods, there are limitations associated with these hydraulic testing methods. The mathematical methods that are commonly applied to the interpretation of these tests have to make a series of simplifying assumptions. These introduce some uncertainty into the interpretation of the data. The volume of material being tested varies depending on the test (near borehole for single well slug tests to larger volumes for large-scale test pumping) and may limit the usability of the data. There is also a well-known limitation, and knowledge gap, associated with using field-scale tests to represent regional-scale aquifer or aquitard properties. The processes that are important at the small scale may not be important at the large scale, and processes that are important at the large scale, such as the presence of preferential flow paths (e.g., fracture, faults), may not be observed in the small-scale measurements. The use of hydraulic methods in combination with other methods (e.g., geophysics, geochemical) together can provide better estimates of regional processes.

6.2 Surface water monitoring

Surface water monitoring is essential for assessing and characterising surface water-groundwater connectivity (see Section 2.2.4.3). Understanding surface water-groundwater connectivity is required to predict impacts to surface water resources, surface water users, and groundwater-dependent ecosystems such as in-stream aquatic ecosystems that rely on groundwater-fed pools that persist over the dry season. An overview of four surface water monitoring methods that can be used to assess connectivity is provided below: stream gauging (Section 6.2.1), seepage monitoring (Section 6.2.2), surface water quality monitoring (Section 6.2.3) and temperature profiling (Section 6.2.4). For more details on these methods, as well as other methods, refer to *An Overview of Tools for Assessing Groundwater-Surface Water Connectivity*.[68] Simultaneous application of multiple methods of assessing groundwater-surface water connectivity is recommended to reduce uncertainties.[69]

There may be a specialist surface water monitoring program for the project, which could include a geomorphology assessment, stream gauging, water quality sampling, and ecology surveys in-stream, under the stream bed (hyporheic) and within the bank sediments (parafluvial). These guidelines focus on monitoring related to surface water-groundwater connectivity; however, it should be recognised that there may be opportunities for synergies between the two programs. Understanding the hydrology of streams in the study area is important for understanding connectivity, for example whether streams are regulated (flow is controlled by releases from instream structures such as dams or weirs) or unregulated (flow is natural and not disrupted by instream structures), or whether streams are

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[67] McMillan T, Rau G, Timms W, Andersen M 2019. Utilizing the Impact of Earth and Atmospheric Tides on Groundwater Systems: A Review Reveals the Future Potential. *Review of Geophysics*. 57. 281-315. Available [online]: https://doi.org/10.1029/2018RG000630.

[68] Brodie R, Sundaram B, Tottenham R, Hostetler S, and Ransley T 2007. *An Overview of Tools for Assessing Groundwater-Surface Water Connectivity*. Bureau of Rural Sciences, Canberra. Available [online]: https://www.researchgate.net/publication/266472444_An_Overview_of_Tools_for_Assessing_Groundwater-Surface_Water_Connectivity.

[69] McCallum JL, Cook PG., Berhane D, Rumpf C and McMahon G 2012. Quantifying groundwater flows to streams using differential flow gaugings and water chemistry. *Journal of Hydrology*. 118–132. Available [online]: http://doi.org/10.1016/j.jhydrol.2011.11.040.

perennial (continuous flow throughout the year) or ephemeral (flows for a period after rain). It is also important to identify surface water users in the study area so that potential impacts to these users associated with impacts to groundwater can be considered.

Following a risk-based approach to address gaps in the ecohydrological conceptual model and prioritise surface water bodies of significant value, a combination of monitoring methods should be used when risks associated with surface water-groundwater connectivity are high. At a minimum, data should be collected or existing data should be accessed for all streams, rivers, lakes, wetlands, estuaries and other surface water bodies in the study area. Available remote sensing datasets should be assessed in terms of spatial resolution, temporal availability, and ability to assess surface water dynamics and the presence and health of fringing riparian vegetation relevant to the ecohydrological conceptual model. Field visits to significant water bodies should note any discrepancy and provide ground truth for comparison with desktop and remote sensing analyses. The community composition and vertical distribution of stygofauna under the stream bed (hyporheic) and within the bank sediments (parafluvial) can also be used to assess connectivity.

Monitoring data should span multiple seasons because surface water–groundwater connectivity may change over time, for example in response to rainfall and water extraction. Targeted data collection may also obtain data on hydrological response during conditions relevant to the ecohydrological conceptual model, e.g. targeting typical flow conditions, low flow, or flood flows.

> Surface water monitoring should be undertaken for proposed projects where it is important to assess and characterise surface water-groundwater connectivity. At a minimum, data should be collected or existing data should be accessed for all streams, rivers, lakes, wetlands, estuaries and other surface water bodies in the study area.

6.2.1 Stream gauging

Gauging points along a river or stream are used to collect water level (stage) and flow rate (discharge) data. Gauging points/stations can also be used to collect water level data for lakes, wetlands and estuaries. Existing gauges should not be relied on exclusively unless they can meet the monitoring objectives. Stream gauging should be undertaken in accordance with the Bureau of Meteorology National Industry Guidelines for hydrometric monitoring. A skilled hydrologist should be engaged to choose the location of the gauges, survey a suitable cross section so that flow rates can be calculated, and install equipment.

The design of the monitoring network should ensure that surface water gauges and groundwater monitoring bores that target the shallow aquifer are in close proximity. This will allow for comparison of surface water and groundwater levels (elevations) to consider whether connection is likely (e.g., connected, disconnected) and what the nature of connection might be (e.g., gaining stream, losing stream). It may be appropriate to place mini-piezometers directly in a streambed to take groundwater level measurements at the same location as surface water measurements.

Surface water-level measurements are typically taken automatically at intervals at a gauging station. They may also be taken using a graduated marker. Comparisons of surface water levels and groundwater levels (preferably a potentiometric surface generated from multiple bores, as in Chapter 4) can indicate the vertical direction and magnitude of flow between them, if any. The measurements should be adjusted to use the same reference datum (typically mAHD) and corrections should be made, which is particularly important where there are substantial differences in salinity. In addition, a time series of surface water level data (a hydrograph) may be analysed to estimate baseflow coming from groundwater.

Stream discharge is defined as the volume of water passing through a cross section in a unit of time. At gauging stations, discharge can be calculated from water level data provided the cross-section of the stream at the location of the gauging station has been surveyed. The relationship between the two parameters will be specific to each gauging station because of the characteristics of the channel at that cross-section. Discharge should also be measured more directly at regular intervals and during high-flow conditions. Where possible, the velocity should be measured within the stream along a perpendicular transect using appropriate equipment. Discharge can then be calculated from velocity and depth measurements. For streams with very low discharge, it may be possible to collect all of the stream flow and record the length of time taken to collect a given volume. Other methods include measuring velocity of an object floating an object down the stream, measuring the dilution of an environmental tracer, or estimating flow from other parameters using Manning's Equation. However, methods should not be used if the measurement errors may be greater than the loss or gain to groundwater and therefore do not meet the objective of assessing connectivity.

Differences in stream flow rates between gauging stations may indicate losses or gains to groundwater. For example, an increase in flow at the downstream gauge may indicate that the reach is a gaining stream. Stream flow data along with estimates of all other inputs, such as rainfall and connected surface water, and outputs, such as evaporation and water use, may be used to calculate the contribution of groundwater to a water budget. When designing the stream gauging network, the distance between the gauging stations needs to be sufficient for the groundwater inflow to be greater than the error in measurements but may also be confounded by inflow from ungauged tributaries or surface water extraction[70].

6.2.2 Seepage monitoring

Seepage meters directly measure the rate of water infiltrating into groundwater (downwards seepage) or entering the surface water body (upwards seepage). In this method, a rigid chamber with an open base is pushed into the sediment-water interface, with the top of the container about two centimetres above the sediment. This isolates an area of the sediment-water interface and allows for any seepage there to be measured. The method is not appropriate for some conditions, such as a gravel stream bed or a strong current.

A flexible bag containing a known volume of water is attached to the chamber. After an interval of time, the volume of water in the bag is measured. If there is upwards seepage, water will move into the chamber and water will be displaced into the bag causing an increase in the volume of water in the bag. If there is downwards seepage, the volume of water in the bag will decline. The seepage flux can be calculated based on the change in volume.

The duration of the test should allow for a change in the volume of water in the bag of at least 50 mL but not completely empty or fill the bag. It will depend on site-specific conditions and may be up to several days if there is low hydraulic conductivity.

Alternatively, a seepage meter may be used instead of a bag to measure the rate of flow from an outlet tube attached to the chamber. This method has the advantage of creating a time series of data instead of determining an aggregate seepage flux.

There are uncertainties associated with extrapolating small-scale seepage measurements to a stream reach. Seepage varies spatially depending on factors including distance to the stream bank, hydraulic conductivity of stream bed material and confounding processes other than groundwater inflow such as hyporheic exchange. Interpretation of measurements depends on both the ecohydrological conceptual model and any data analysis methods used. Although absolute estimates of seepage may be uncertain, direct seepage measurement should be considered a reference method for determining direction of flow, and discrepancies in whether the stream is gaining or losing at a particular

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[70] Cook PG 2015. Quantifying River Gain and Loss at Regional Scales. *Journal of hydrology*, 531(3): 749-758. Available [online]: https://doi.org/10.1016/j.jhydrol.2015.10.052.

time and place should be explained, drawing on additional monitoring or modelling if needed. Cook[71] discusses methods available for estimating surface water–groundwater exchange flux at regional scales.

6.2.3 Surface water quality monitoring

Surface water quality data can be useful for assessing connectivity when the data are compared with groundwater quality data from nearby bores targeting the upper aquifer. Surface water quality should initially be measured in the field using a calibrated water quality meter, at multiple locations along or around the surface water body. Field water quality measurements may provide immediate indications of groundwater discharge, for example at locations where there is higher salinity due to relatively saline groundwater entering a freshwater stream. These quick measurements can support the selection of sites for further monitoring.

Laboratory analysis of surface water samples may also provide useful data for assessing connectivity. For example, analysis of surface water and groundwater from a nearby bore may indicate similar major ion composition and therefore that a stream is losing at this location. Environmental tracers (see Section 6.4) can also be useful to assess and, in some cases, quantify connectivity.

Surface water quality sampling methods and equipment should be in accordance with the Australian and New Zealand Guidelines for Fresh and Marine Water Quality, any relevant Australian, New Zealand and International Organization for Standardization (ISO) standards, as well as any applicable local standards. Many of the same considerations will apply as with groundwater quality measurements (see Chapter 5). For example, there should be procedures for calibrating and decontaminating equipment, taking quality control samples, and transporting samples.

6.2.4 Temperature profiling

The temperature of groundwater at a particular location will typically be relatively constant while the temperature of surface water will typically have a strong diurnal pattern, responding to changes in solar radiation and air temperature. If there is no connectivity between surface water and groundwater, the temperature in the sediment (stream bed) will gradually transition with depth from the surface water temperature to the groundwater temperature. In gaining stream reaches, there is minimal temperature variation with depth in the sediment and over time because water with a stable temperature is moving up through the sediment. In losing stream reaches, the diurnal variations in temperature associated with surface water may be detected deeper into the subsurface.

For this method, temperature measurements should be taken at multiple depths within the surface water and underlying sediment. Groundwater temperatures may be collected from a piezometer in the streambed or from a nearby monitoring bore in the shallow aquifer. A variety of instruments may be used to measure temperature, including temperature probes, thermistor ropes, fibre-optic distributed temperature sensing, and thermal infrared imagery.

This method should be used to supplement rather than replace other methods for assessing connectivity due to confounding factors in interpretation. However, it has an advantage in that it is relatively easy to collect a time series of temperature data from automatic data loggers at multiple locations and can therefore detect variations in flow at a smaller scale than other methods.

6.3 Bore census surveys

A bore census survey should be undertaken for all projects with the potential to impact on water supply bores, as identified through the preliminary assessment or other impact assessment. Water supply bores include town water

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[71] Ibid.

supply bores, stock and domestic bores, Aboriginal community bores, and bores used for irrigation, intensive agriculture, aquaculture, mining, commercial, and industrial purposes. They may be registered with state/territory government authorities and may have an associated water licence or tradeable water allocation.

A bore census survey involves a qualified hydrogeologist visiting properties in the area surrounding the project to meet with the property owner, tenant, or property manager (hereafter referred to as landholder) and gather data on bores on the property. The purpose of the survey is to gather information about the condition and pumping capacity of the bore and to obtain baseline data to inform any future assessment of impacts associated with the project. The survey should be conducted prior to project approvals to gather data for all private bores that are in use or could potentially be used in future. Follow-up surveys should be undertaken during project operations as required by project approvals and where impacts to a private bore greater than predicted or approved are indicated.

All properties in the area of potential impacts to groundwater should be visited, even if government databases do not have a record of a bore on the property. This is because bores may be unregistered or bore details in databases may be incorrect, e.g., incorrect location coordinates. Effort should be made to contact the landholder prior to the survey to arrange a suitable time. Every effort should be made to interview all landholders in the area of potential impacts to groundwater and to visit all bores that are in use or could potentially be used in future.

Prior to the survey, a desktop review should be undertaken to identify bores that are recorded in government databases. During the survey, efforts should be made to relate the bores on the properties visited to the bores recorded in government databases. Information about private bores recorded in government databases may be inaccurate or outdated. For example, a bore may be recorded as 300 m deep on the database but only be 80 m deep, or a bore may be recorded as functional on the database but has been decommissioned. The landholder may be able to assist with identifying registered bores if it is unclear during the field visit.

Data should be gathered through interview with the landholder and by visiting the bore. The visit to the bore should include taking photographs, inspecting the bore, measuring groundwater levels, operating the bore, and collecting a groundwater sample for analysis. The source of data gathered during the survey should be recorded in the field notes, e.g., the field notes should indicate if the depth of the bore recorded was measured in the field, was provided by the landholder, or was obtained from government databases. If there are any uncertainties with the data collected, these should also be recorded in the field notes, e.g., if the target formation of the bore is uncertain. Table 6.2 provides a summary of the data that should be collected for each bore during a bore census survey.

Table 6.2 Bore census survey data

Data	Methods of data collection
Bore identification details	
Bore ID, bore name, registered number, associated water licence or water allocation	Database searches (state/territory government and NGIS) Interview with landholder during field visit
Bore location referenced to GDA94	Global Positioning System (GPS) or GPS-ready camera during field visit High resolution aerial photographs or satellite data
Bore construction details	
Name of drilling contractor, date of construction	

Data	Methods of data collection
Bore construction - type of casing, casing diameter, perforated or screened intervals, seals and cement grouting in bore annulus	Any information on bore construction obtained from government databases should be checked with the landholder during the interview and notes on any differences made
Lithology – bore log, geology, target formation for the bore (source aquifer)	
Bore yield assessed at time of drilling	
Bore equipment and condition details	
Bore status (e.g., functional and equipped, not equipped, or decommissioned) and reasons bore is used or not used	Landholder interview
Pump type and make	Landholder interview and bore inspection
Pump setting depth	Landholder interview
Power source (e.g., diesel, solar, electricity, windmill)	Landholder interview and bore inspection
Details on the riser and on the headworks	Landholder interview and bore inspection
Any repairs or maintenance undertaken on the bore	Landholder interview
Photographs of the bore and associated equipment	Digital camera
Bore supply information	
Authorised bore purpose	Database searches, check with landholder
Bore use	Landholder interview
How often the bore is used (hours pumped per day or per week) and any seasonal variation in use	Landholder interview
Operating capacity of the bore and peak extraction expected	Landholder interview
Water level information	
Groundwater level	See Section 4.3.4 Where not possible to measure groundwater level, reason should be recorded, e.g., equipped bore, no access to measure water level

Data	Methods of data collection
Height of datum (point from which water level was measured) above ground level	Tape measure
Date and time of groundwater level measurement, date and time of most recent pumping event and pumping rate and duration of most recent pumping event	Landholder interview
Water quality information	
Purge volume	Estimated based on flow rate and duration of pumping (see Chapter 5)
Location of sampling point	Samples should be collected as close to the bore as possible
Field parameters	Calibrated water quality meter
Water quality analysis	Analytical laboratory

A bore census survey should be undertaken for all projects with the potential to impact on private water supply bores. All properties in the area of potential impacts to groundwater should be visited. Data should be collected from government databases, landholder interviews, and by visiting the bore.

6.4 Hydrochemistry and environmental tracers

Environmental tracers are measurable substances or properties in groundwater or surface water that occur naturally or are added to the water.[72] They are usually non-reactive and decay at a predictable rate or only react in specific circumstances. Therefore, concentrations or ratios of tracers will reflect the sources of water that mixed together and the duration of time since mixing occurred.

Where there is significant and ongoing mixing between two systems (e.g. an aquifer, surface water, precipitation), measurements of environmental tracers will be similar in both. If there is limited mixing, there will be greater differences. For example, if two aquifers are separated by an aquitard with high integrity, measurements of environmental tracers in the shallow aquifer may resemble those in precipitation or surface water from which there is

[72] Office of Water Science 2020. Environmental water tracers in environmental impact assessments for coal seam gas and large coal mining developments – fact sheet. Prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development. Available [online]: https://iesc.environment.gov.au/publications/environmental-water-tracers.

Kurukulasuriya D, Howcroft W, Moon E, Meredith K and Timms W 2022. Selecting Environmental Water Tracers to Understand Groundwater around Mines: Opportunities.1 and Limitations. *Mine Water and the Environment,* https://doi.org/10.1007/s10230-022-00845-y.

recharge. Measurements of environmental tracers in the deeper aquifer may be different if there is very limited connectivity.

Environmental tracers may be used to assess groundwater flow directions and rates and connectivity between surface water and groundwater, between a spring and its source aquifer, or between a project and a groundwater-dependent asset or ecosystem (see Section 2.2.4.3). This method can contribute towards a conceptual or numerical model of the groundwater system and towards understanding the risks to groundwater-dependent assets and ecosystems.

Environmental tracers may also allow for quantification of the degree of mixing, as long as all other factors that could affect the environmental tracers are taken into account. Some environmental tracers (radioisotopes) decay at predictable rates and therefore allow for dating of when mixing occurred.

It is important to remember that environmental tracers provide information about current and past groundwater flow paths. Flow paths may change as a result of the project or other factors such as unusual rainfall. Therefore, a lack of connectivity in baseline measurements of environmental tracers should not be interpreted as implying absence of potential connectivity in future.

Environmental tracers used in preliminary measurements to develop a conceptual model may include field parameters (e.g. temperature, pH, dissolved oxygen, electrical conductivity) and major and trace ions. Additional tracers should be selected as necessary to address monitoring objectives and should be measured at appropriate locations, preferably across different seasonal conditions. Some options for environmental tracers are summarised in Table 6.3.

The use of tracers should follow a risk-based approach. The ecohydrological conceptual model should identify common potential tracers that may be applicable to the specific case. Application of tracers will depend on their anticipated value in reducing uncertainty. Where material risk warrants it, there should be a greater number of types of tracers, more repeated measurements of each tracer, and other evidence should be used to address the objective (e.g., using a combination of remote sensing and environmental tracers for fault mapping). If unexpected changes are observed through other monitoring processes, collection of data on pre-identified tracers should be considered to help reduce uncertainty.

> Environmental tracers may be used to assess groundwater flow directions and rates and connectivity between surface water and groundwater, between a spring and its source aquifer, or between a project and a groundwater-dependent asset or ecosystem.

Table 6.3. Types of environmental tracers and examples

Type	About
Physico-chemical properties	These properties of the water are usually easy to measure. Examples include electrical conductivity and temperature. Temperature and depth profiles can assist with understanding groundwater recharge and discharge.
Major and trace ions	Ion concentrations are influenced by rainfall and dissolution of minerals. Ratios of ions should be reviewed using a Piper plot.
Environmental isotopes	Ratios of stable isotopes of hydrogen and oxygen are typically used. They are especially useful as tracers since they change in predictable ways in groundwater.
Radioisotopes	Radioisotopes allow for the dating of groundwater, specifically the mean residency time, as their concentration reduces at a rate determined by known half-lives. They can therefore be used to determine the recharge and flow rates. Radioisotopes may be produced in the atmosphere by interaction with cosmic rays, by human activities, or by a combination.
Anthropogenic tracers	These are chemicals produced by human activities where the atmospheric concentrations at a given point in history are known. In conditions where they do not degrade, their concentrations will depend only on the atmospheric concentrations at the time of infiltration and mixing. Examples include CFCs and sulphur hexafluoride.

6.5 Remote sensing and geophysical methods

Remote sensing is observing or measuring properties from a distance. It can be used to collect data about the surface and subsurface using satellites, aircrafts or ground-based measurements. Remote sensing data may be used to detect features related to groundwater processes, for example identify potential recharge and discharge of groundwater, detect the presence of and changes in GDEs (e.g., the extent of vegetation[73]) and surface water, and to map faults and alluvium.

Geophysical methods measure properties of the rock or soil. Some methods passively detect a property while others transmit a signal and measure the response. Geophysical surveys typically take measurements continuously or at intervals along a line or grid. Where high spatial variation is expected, continuous methods or higher resolution are preferred because they may detect small features or variations that would be missed otherwise.

Remote sensing and geophysical methods can assist with characterising the groundwater system and developing a three-dimensional model of the site. For example, ground surface geophysics (electrical and electromagnetic methods in particular) can be used to identify fractures that are potential seepage conduits from a proposed tailings storage facility. Remote sensing and geophysical methods can also be used to observe changes in groundwater, surface water and GDEs for baseline and impact detection monitoring. These methods should not replace direct measurements of groundwater level/pressure and groundwater quality (see Chapter 4) but they are a valuable addition and some will be essential to achieving monitoring objectives, as outlined below.

There are many methods available. Examples include satellite imagery (with options to detect different parts of the electromagnetic spectrum), aerial photography, ground-penetrating radar, seismic methods, electromagnetic methods (resistivity/conductivity), magnetic methods (nuclear magnetic resonance, NMR), radiometric methods, gravity methods (see Section 4.3.5), altimetric or surface deformation methods (see Section 4.3.6).

At a minimum, there should be recent aerial imagery of the study area to provide an overview of surface features within the study area that may be relevant to groundwater. Satellite data, such as Landsat, MODIS or Sentinel data, will often be readily available although other data sources may be needed to achieve the target spatial resolution. Aerial imagery data should be considered in the selection of monitoring locations (see Section 3.3.2) and may be integrated with Geographic Information Systems (GIS) to identify and map key features in the study area.

Downhole geophysical logging is useful to identify which formations are present and the depths and properties of aquifers and aquitards, and it can be used to develop a geological model of the study area if undertaken at multiple boreholes spatially distributed across the area (see Section 3.4.4). However, downhole logging only provides information about a narrow area around the bore. Other methods, such as airborne or surface geophysics, may be useful to provide broader-scale information, for example to identify faults or the extent of alluvium.

The methods selected should be appropriate to the site and the monitoring objectives. Important considerations include:

- spatial resolution;
- area covered – for some methods, the feasibility of covering large areas will depend on the speed at which a sensor can move while collecting data;

[73] See example in Doody TM, Hancock PJ, Pritchard JL 2019. Information Guidelines Explanatory Note: Assessing groundwater-dependent ecosystems. Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy, Commonwealth of Australia. Available [online]: https://iesc.environment.gov.au/publications/information-guidelines-explanatory-note-assessing-groundwater-dependent-ecosystems, p. 28.

- depths covered and any loss of resolution with depth or limitations when penetrating certain materials;
- spacing between measurements, with continuous measurements preferable where possible;
- the level of contrast – the method should clearly contrast the feature of interest from background conditions or distinguish between geological layers; and
- interference from objects such as metal fences or buried pipelines.

> Remote sensing and geophysical methods can assist with characterising the groundwater system and developing a three-dimensional model of the site. At a minimum, there should be recent aerial imagery of the study area.

6.6 Surface outcrop mapping

Surface outcrop mapping can be useful for hydrogeological assessments including:

- to map the geology of the study area to provide the basis for the ecohydrological conceptual model;
- identifying likely recharge areas within the study area;
- identifying hydrogeological units that may be connected to surface water systems, for example by mapping the surface geology along stream beds or along cliff faces near incised streams; and
- identifying hydrogeological units that may be connected to groundwater-dependent ecosystems such as hanging swamps.

Surface outcrop mapping should be undertaken by a qualified geologist. The information gathered should be used together with data from the drilling program (see Chapter 3) to develop an interpretation of the geology and hydrogeology of the study area.

> Surface outcrop mapping can be useful for hydrogeological assessments and should be undertaken by a qualified geologist.

7. Recording and reporting data

7.1 Data management

Data management procedures should be established for all groundwater monitoring programs to ensure that data are recorded and handled in a consistent and organised manner and stored securely. Data management procedures should cover all phases of a groundwater monitoring program, including the desktop, fieldwork, data entry, data analysis, and reporting components. Recommendations for recording and storing data are provided in Sections 7.1 and 7.2 below.

7.1.1 Recording data

Recording data is critical for any scientific investigation and a key component of groundwater monitoring. Data are all information gathered during a groundwater monitoring investigation, including the desktop, field, laboratory, and data analysis components of a study, and include all information that will be considered or used for review, analysis, interpretation, or decision making. Types of data collected during a groundwater monitoring investigation include:

- facts (e.g., the date and time a measurement was made);
- observations (e.g., a private water supply bore had uncontrolled headworks and was flowing);
- numbers (e.g., the depth to groundwater in the bore from the top of casing, or the Geographical Positioning System coordinates of a bore);
- units of measurement (e.g., L/s);
- photos (e.g., a photo of drill cuttings);
- findings of other studies (e.g., mapped locations of private water supply bores in the study area based on the National Groundwater Information System); and
- references or data sources (e.g., Bureau of Meteorology (2022), Groundwater Dependent Ecosystems Atlas, URL http://www.bom.gov.au/water/groundwater/gde/, date accessed 3 March 2022)

Metadata are data which describe the data collected. Metadata should be recorded and stored with all data collected as they are essential for data interpretation. Examples of metadata include the location of data collection, the data and time of data collection, the method of data collection, and the units of measurement.

Data should be recorded throughout a groundwater monitoring investigation and stored securely to ensure the data are not lost. It is critical that data are recorded at the time they are collected to reduce loss of data and ensure that they are accurately recorded – it can be easy to forget to record things later or forget the details of what needed to be recorded.

Data should be recorded in a consistent and logical manner to ensure all required information is gathered. Data collection sheets, databases, or tools should be used for all field and laboratory work. These may be in hard or soft copy and typically comprise a worksheet that helps the practitioner to collect data by prompting them for the information that needs to be recorded. Data collection sheets are important to ensure that the data gathered are consistent between monitoring rounds and between different practitioners. Different data collection sheets should be used for the different components of a groundwater monitoring investigation to avoid confusion about when the data were collected, e.g., one data collection sheet should be used for drilling and another data collection sheet should be used for a later groundwater monitoring round. If hard copy data collection sheets are used, they should be scanned electronically and stored in a secure database as soon as possible to reduce the potential for data loss. Databases or other electronic tools used to collect data should similarly be saved in a secure and backed up database as soon as possible.

All data recorded should be clear and legible so it can easily be read by others. The location, date, and time that the data were recorded, and the name of the person who recorded the data, should be included on all data collection sheets. Any measurements recorded should include the units of measurement, the reference point for the measurement (where appropriate), and details of how the measurement was taken. For example, a groundwater level measurement could be recorded as 14.52 metres below the top of casing, measured from the black survey mark on the top of casing, and measured with an electronic water level dip meter. If equipment error is suspected during groundwater monitoring, the reading from the instrument should be recorded and include associated metadata noting the suspected nature of the error and likely reasons. Any actions taken in response should also be recorded.

Data obtained from reference material, for example during desktop review, should be referenced. There are a range of referencing styles available, which detail how to record in-text citations and compile a reference list. Scientists in Australia most commonly use Author-Date citation styles such as Harvard or the American Psychological Association (APA). References should include the Digital Object Identifier (doi) or Uniform Resource Locator (URL) wherever possible, and the date that the data were accessed. References can be stored in a referencing database such as EndNote, Mendeley or similar.

Examples of data that should be recorded during a groundwater monitoring program are provided in the tables in Appendix A.

7.1.2 Data storage

Data gathered during groundwater monitoring should be stored in a computer-based data management system. The data management system should be backed up and secure to reduce the potential for data loss. Any data recorded on paper, such as field notes, should be scanned as soon as possible and stored in the data management system. When selecting a data management system, it is encouraged to consider how easy is to share data and metadata, for example for compliance reporting, and how easy is to integrate additional information, for example from other databases.

Data in the data management system should be stored in an organised manner. Folder structures and file naming can be important for locating data in a data management system. Standard protocols for folder structures and file naming should be developed for each groundwater monitoring program to make it easier to locate data. The data should be easy to find, download and search. Access to edit the data should be restricted to specified personnel to reduce the potential for mistaken data editing.

Primary measured data e.g., raw water level data downloaded from a logger, should be permanently retained, and archived in an unedited form. The data should be clearly marked and locked to prevent editing. It is important to have original copies of all data files for future reference and auditing. Primary measured data should be accompanied by metadata which describes the data in detail, including the purpose and method by which the data were collected. The metadata should be attached to the data at all times and should use a standard format. Data without sufficient metadata have less value and the use of such data could lead to errors in analysis. The metadata should include information on data provenance. Data provenance is an explanation of why and how the data was produced, where, when and by whom. Where data have been edited, details of the processes used to edit, correct, or analyse the data should be documented. This includes any transfers of data, validations, edits, corrections, or estimations. The author, date, and time should be recorded, as well as whether it is possible to undo or redo the action.

Databases may be used to store particular types of groundwater data, including structured data and data that are in text or narrative form. Databases for storing groundwater data include open source and commercial options.

For structured data, a formal, machine-readable data or database format should be adopted for ease of use and transfer. The intent is to allow the use of existing and new automated tools to support efficient analysis, minimising time needed for data preparation, as well as enabling greater transparency and collaboration.

The data format adopted should be compatible with the vocabulary used by the National Groundwater Information System (NGIS)[74], i.e., there should be a clear mapping between terminology used in the project database and terms defined in the NGIS. Inter-operability should be preferred over strict compliance to a rigid data format, i.e., it is essential that necessary data fields are collected using a shared vocabulary, but once the necessary data are available in a machine-readable format, they can be converted between file formats as necessary.

The data format adopted should support all data fields needed according to the monitoring plan even if they are not defined in an existing vocabulary or data format. Differences from existing standard data formats or vocabularies should be documented to allow their consideration in updates of those standards. Two recommended data formats for groundwater data include the Open Geospatial Consortium standard WaterML 2: Part 4 – GroundWaterML 2 (GWML2), or the latest version of this standard, and the Water Data Transfer Format (WDTF).[75]

The data are likely to have value beyond the specific purpose for which they were collected and therefore ease of use for future analysis should be a consideration. Open data that are freely available for anyone to use is preferable to maximise value and consideration should be given to making data publicly available. Data storage should continue beyond the timespan of the monitoring program because the data may have value for later monitoring or understanding of the groundwater system. Resources should be planned for this, including software requirements, licensing, and ensuring that someone is responsible for the data and can be a point of contact to those using the data in future.

All data and metadata gathered during a groundwater monitoring investigation should be recorded in an organised manner and stored securely in a computer-based data management system. Structured data should be stored and transferred in machine-readable formats compatible with the vocabulary defined by the NGIS.

7.2 Quality management

Quality management is key to providing confidence in the accuracy and reliability of the groundwater monitoring data collected. Quality management includes implementing quality assurance and quality control (QA/QC) measures to prevent, detect, quantify, and correct issues during groundwater monitoring that may cause errors. There are numerous potential sources of error during a groundwater monitoring program. Possible sources of error include:

- in the field - bore defects, malfunctioning or uncalibrated equipment, faulty operation of equipment, not following sampling procedures, cross-contamination of sampling equipment, incorrectly recording data, mislabelling samples, incorrect preservation of samples, incorrect storage of samples;
- in the laboratory - cross-contamination of instruments, failure to analyse samples within holding times, not following standard analytical procedures, broken sample containers, malfunctioning instrumentation; and

[74] Bureau of Meteorology 2022. *Documentation.* National Groundwater Information System. Available [online]: http://www.bom.gov.au/water/groundwater/ngis/documentation.shtml.

[75] Bureau of Meteorology 2013. *Water Data Transfer Format (WDTF).* Available [online]: http://www.bom.gov.au/water/standards/wdtf/index.shtml.

- in the office - editing or deleting raw data files, data entry errors, not following standard procedures for data quality review or data correction.

Quality assurance procedures are the processes put in place to prevent errors occurring. They include the organisational procedures, processes, resources and review necessary to ensure that the results of the groundwater monitoring program accurately reflect the groundwater system at the time of sampling. An example is ensuring that staff are suitably qualified, trained, and competent before undertaking groundwater monitoring.

Quality control procedures are the methods used to detect and quantify errors. They assess the quality of the groundwater monitoring data collected within the framework and system provided by the quality assurance procedures. An example is a trip blank sample to assess whether cross-contamination between groundwater samples has occurred during storage and transport to the laboratory.

Recommendations on the minimum requirements for quality management are provided below.

All groundwater monitoring programs should include quality management processes. Quality assurance procedures should be put in place to prevent errors occurring, including:

- following standard procedures for groundwater monitoring;

- using qualified, trained and experienced staff, subcontractors and subconsultants;

- maintaining, servicing, and calibrating instruments; following data management procedures;

- and peer review of data analysis and interpretation.

A quality control plan should be implemented to detect and quantify errors.

7.2.1 Standard procedures

Groundwater monitoring should involve developing and following standard procedures. The purpose of standard procedures is to provide clear direction on the monitoring methods to be used. The monitoring methods in the standard procedures should be in accordance with the recommended methods for groundwater monitoring in Chapters 3, 4, 5, and 6 of this guideline, which aim to reduce errors and improve the accuracy and reliability of data collected. Standard procedures should also be in accordance with any state/territory requirements.

In addition to providing details of the methods to be used for drilling and installation of groundwater monitoring bores (Chapter 3), groundwater level/pressure monitoring (Chapter 4), groundwater quality monitoring (Chapter 5), and other investigations (Chapter 6), the standard procedures should also cover relevant aspects of quality management to be applied during the groundwater monitoring program. This includes procedures for staff training (Section 7.2.2), instrument calibration and maintenance (Section 7.2.3), data management (Section 7.2.4), quality control (Section 7.2.5), data validation (Section 7.2.6), quality coding (Section 7.2.7), and peer review (Section 7.2.8). Any variation to the procedures, and the reason for the variation, should be documented and reported together with the data.

7.2.2 Staff training

All people involved in groundwater monitoring should have appropriate qualifications and training for their role and be skilled and competent for the tasks they are project managing or undertaking. Field staff should know how to use the specific equipment to be used for monitoring and be trained and verified as competent in the methods to be applied. More complex monitoring programs, such as those involving packer testing or pumping tests, will require additional skills and experience to manage and execute.

Any subcontractors providing specialist services as part of a groundwater monitoring program should also have appropriate qualifications, training, skills, and experience for the work that they will be undertaking.

7.2.3 Instrument calibration and maintenance

All instruments used for groundwater monitoring should be in good working order and regularly checked and maintained in accordance with manufacturer requirements.

Instruments that require calibration should be calibrated as recommended by the manufacturer or as indicated is necessary by spot checks of the instrument within calibration intervals. Field water quality meters would typically be calibrated at the start of each day and spot checked during the day to confirm that there has been no drift. Calibration of instruments should be undertaken by trained operators.

A register of all instruments used for groundwater monitoring, with their unique identification number and records of maintenance and calibration, should be maintained. If the instrument has been supplied by an equipment hire company, records of maintenance and calibration should be checked prior to use and kept on file.

The unique identification number of the instruments used to take measurements during groundwater monitoring should be recorded with the data collected.

7.2.4 Data management

Data management procedures should be established for all groundwater monitoring programs as outlined in Section 7.1. Data management procedures should be established for all phases of a groundwater monitoring program, including the desktop, fieldwork, data entry, data analysis, and reporting components, to ensure that data are recorded and handled in a consistent and organised manner and stored securely. Recommendations for recording data are outlined in Section 7.1.1 and recommendations for storing data are provided in Section 7.1.2. Of particular importance is that primary measured data should be permanently retained and archived in an unedited form to allow for future reference and auditing. Data management procedures should also include requirements for data validation and technical review. These requirements are outlined in Sections 7.2.6 and 7.2.8 below.

7.2.5 Quality control plan

Every groundwater monitoring program should have a quality control plan which outlines the number and type of quality control samples to be prepared in the field during the groundwater monitoring program. The analytical laboratory will have its own quality control plan for quality control samples prepared in the laboratory.

Quality control samples prepared in the field during the collection of samples for groundwater quality analysis include blank, duplicate, and spike samples. The appropriate number and type of quality control samples will depend on the number of groundwater samples being collected, the analytes of interest, and the expected concentrations of the analytes. Guidance on the appropriate number and type of quality control samples is provided in Section 5.13.

Quality control samples are used to assess the accuracy and precision of the data collected. Accuracy refers to how close a result is to its true value. An example of a quality control sample used to assess accuracy is a laboratory control sample (or reference material). Precision relates to the repeatability of a result. An example of a quality control sample used to assess precision is a duplicate sample. Quality control samples are also used to assess whether contamination has been introduced into a sample during sample collection, sample transport, or in the laboratory analysis. The analytical method used for the quality control samples should be exactly the same as that used to analyse other samples from the monitoring program.

Quality control plans should include acceptance criteria that are determined prior to monitoring. Acceptance criteria are the acceptable limits for accuracy, precision and blank samples. The analytical laboratory will have their own acceptance criteria for quality control samples prepared in the laboratory, which will be reported together with the results for quality control samples prepared in the laboratory.

7.2.6 Data validation

Data validation involves checking the quality of data before using, correcting, or analysing the data. Data validation should be undertaken immediately upon having access to data. Checking data immediately will allow issues to be identified and rectified as soon as possible, reducing data loss. Data should be checked for missing data or unexpected values, differences from historical values under similar hydrological conditions where available, and differences from what was reported in the field notes.

Data should be checked in the field during data collection. For example, when downloading groundwater level data from a submersible pressure sensor in the field, the data should be checked using a laptop computer and compared to historical data for the bore. If, for example, data are missing from the logger, then potential causes should be considered. It may be determined that the logger battery had failed, in which case the logger should be replaced with a spare from the field kit.

Groundwater quality data received from the analytical laboratory should be checked as soon as possible after they are received as water samples have limited holding times for some analytes, and so if re-analysis of the sample is required, this should occur as soon as possible. For example, if a sample was reported to have high concentrations of total recoverable hydrocarbons (TRH) when there was no record of a hydrocarbon odour during sample collection, and no identified potential source of hydrocarbons near the monitoring bore, it may be suspected that cross-contamination has occurred in the laboratory during analysis. The laboratory should be contacted immediately, alerted to the issue, and asked to re-analyse the sample.

Graphical representations of data can be a useful way to identify features in the data that may indicate an error. A time series should be plotted for groundwater level and each water quality parameter for every monitoring location. Time-series graphs will clearly show any anomalies, such as shown in Figure 7.1 below. In this example, dissolved and total concentrations of metal *y* are plotted over a nine-year monitoring period. The concentration of dissolved metals should be less than total metals; however, during one sampling event the dissolved concentration was higher. Possible causes of the error should have been investigated at the time the analytical results were received. The field technician may have forgotten to filter the water sample prior to preservation, sample bottles may have been incorrectly labelled, or it may be a reporting error by the laboratory. Depending on the findings of the investigation, it may be necessary to go and re-sample the bore. This should be undertaken as soon as possible after the original sampling event.

It should be noted that in some cases, an extreme value will not be an error. Appropriate investigative and statistical techniques should be used to assess whether this is the case. Data should not be excluded from analysis simply because they were outside of the expected range because it may be an unexpected and important feature in the groundwater.

A key part of data validation is the review of results for quality control samples. This should be undertaken as soon as possible after laboratory reports are received. The results for quality control samples should be reviewed against the acceptance criteria in the quality control plan. Laboratory quality control reports should also be reviewed against laboratory acceptance criteria. Where results exceed the criteria, there should be procedures in place to investigate the cause or source of the exceedance. The monitoring procedures should be modified as necessary to reduce further errors from the same cause. The original data, potential causes of error and evidence for them, and modifications to the monitoring procedures should all be recorded. If the quality of the data collected is poor and the reason is unknown, it may affect the usefulness of the data.

Where anomalous data are identified, additional data should be collected to ensure there are reliable data at the frequency intended in the monitoring program. This may involve additional field measurements or re-analysing a groundwater sample in a laboratory. The original data should be recorded, reported, and investigated regardless of the presence of additional data. Information about the quality of the data should be included with any reporting of data as outlined in Section 7.2.7.

Data gaps should be identified, and the reason for the missing data recorded. Data may be missing for a range of reasons, including equipment malfunction or site access issues. Data analysis will need to consider what data are missing and whether the gaps are random. For example, if data are missing from a particular monitoring bore every December, January, and February due to access issues associated with wet season rains, it may be considered that the data are biased.

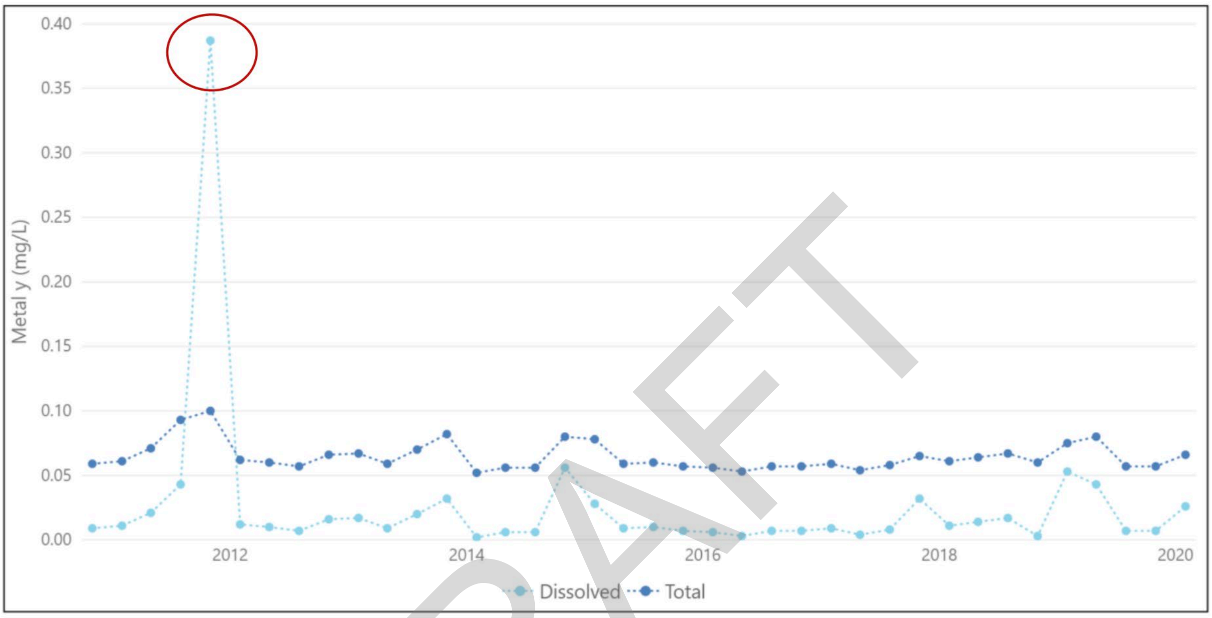

Figure 7.1 Example graphical inspection of data

Dissolved and total metal *y* concentrations in mg/L. An outlier in the data is circled. Source: Department of Environment and Science (DES) 2021. *Using monitoring data to assess groundwater quality and potential environmental impacts.* Version 2. DES, Queensland Government, Brisbane. Available [online]: https://www.publications.qld.gov.au/dataset/groundwater-quality-assessment-guideline/resource/472cc88a-000a-4bb8-a60d-204cfe7e0238. CC BY 4.0.

Data validation to check the accuracy and quality of data should occur as soon as possible after data are available. Any potential issues should be investigated and addressed as soon as they are identified and reported together with the data.

7.2.7 Quality coding

Data quality codes should be assigned to all checked, corrected, edited, and estimated data as specified in the National Industry Guidelines for hydrometric monitoring, Part 1: Primary Measured Data. These codes indicate the usefulness of the data for a specific purpose. Quality codes should be assigned that meet the needs for 1) documenting the corrections applied to raw data, 2) providing information needed for analysis methods to correctly make use of imperfect data, and 3) ensuring compatibility with the Water Data Transfer Format Quality Code System.[76]

Quality codes are expected to inform uncertainty quantification or understanding of uncertainty. Uncertainty quantification is encouraged, with the level of effort depending on risk and any state/territory requirements. Uncertainty quantification can support management of uncertainty in monitoring design and development of conceptual ecohydrological and numerical models. Refer to the IESC explanatory note on uncertainty analysis for further information.[77]

> Data quality codes should be assigned to all checked, corrected, edited, and estimated data as specified in the National Industry Guidelines for hydrometric monitoring. Uncertainty quantification is encouraged.

7.2.8 Peer review

Field and laboratory analytical data that have been manually entered or exported into an Excel spreadsheet, csv file, database, or programming language such as Python, should be independently verified against the original data set. The data validation process, and any post-processing or corrections applied to the data, should be reviewed by a suitably qualified and experienced professional to confirm the quality and integrity of the data before data analysis or reporting.

Independent audits should be undertaken at least once a year to confirm that staff are following standard procedures and meeting the requirements for data management and data validation.

The data validation process, and any post-processing or corrections applied to the data, should be reviewed by a suitably qualified and experienced professional. Independent audits should be undertaken at least once a year.

7.3 Reporting

Reporting on groundwater monitoring may be undertaken for a variety of reasons, for a variety of audiences, and in a variety of formats. Examples include:

- a report prepared by an organisation or individual for a government authority to seek approval for a proposed development or comply with conditions of approval associated with a development;
- submitting drilling logs and bore construction details to the government authority after drilling and installation of a groundwater monitoring bore;
- an online web portal which gives public access to groundwater level data for monitoring bores in an area;
- a document produced by a government authority to provide information to the public on the condition or status of a groundwater resource;
- a presentation to a community group on groundwater monitoring undertaken for a development.

[76] Bureau of Meteorology 2022. *Quality codes*. WTDF validator service. Available [online]: http://www.bom.gov.au/water/wdtf/documentation/schema-control-lists/quality-code.htm.

[77] Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development 2019. *Information Guidelines Explanatory Note - Uncertainty analysis–Guidance for groundwater modelling within a risk management framework*. Available [online]: https://www.iesc.gov.au/publications/information-guidelines-explanatory-note-uncertainty-analysis

The level of detail and types of information that should be included for these different reporting formats will vary and have not been addressed here. This section focuses on the reporting of groundwater monitoring data to government authorities for the following reasons:

- as part of a groundwater impact assessment report submitted to government to seek approval for a proposed project (pre-approval); and
- as part of a groundwater monitoring report submitted to government for compliance with approval conditions (post-approval).

A document that includes reporting on groundwater monitoring pre-approval or post-approval is referred to as a groundwater monitoring report throughout this section for ease of reference but may include other types of documents such as environmental impact statements or water management plans.

7.3.1 General reporting requirements

Reporting on groundwater monitoring must be undertaken in accordance with state/territory requirements. Additional recommended minimum requirements for reporting on groundwater monitoring are included in the sections below.

Groundwater monitoring reports should be standalone documents and include all relevant information needed to interpret the data presented. For example, if a report presents groundwater level/pressure data for a monitoring bore, then details of the location and construction of the monitoring bore, the method used to collect the groundwater level/pressure data, and any methods used to correct the data should also be included in the report.

The level of detail included in a groundwater monitoring report should be commensurate with the scale of the project, the level of risk to groundwater resources and related assets and ecosystems, the phase of the project (i.e., pre-approval or post approval, greenfield or brownfield), how much data is being reported, and the requirements of the relevant state/territory government.

Background information should be included as an appendix to the report to avoid detracting from the main content of the report. For example, a table summarising the construction of bores in the monitoring network could be included in the main body of the report and the detailed bore construction logs could be included as an appendix to the report. Reference to other documents for more detailed information can be provided; however, the key information needed to interpret the data presented should be included in the report.

Any changes since previous reports should be highlighted. For example, if a groundwater monitoring bore has been decommissioned and replaced since the previous report, this needs to be clearly stated and the new groundwater monitoring bore location and construction provided.

All groundwater monitoring reports should be accompanied by the raw and corrected data presented in the report in machine-readable format. This should follow the format requirements of state/territory governments and the NGIS.

Groundwater monitoring reports should include a glossary of key terms. A reference list should also be included to provide details of reports

> Groundwater monitoring reports should be standalone documents and include all relevant information needed to interpret the data presented.

7.3.2 Pre-approval reporting

Prior to project approval, groundwater monitoring data are usually reported as part of a groundwater impact assessment report submitted to government to seek approval for a proposed project. Groundwater impact assessment reports include a lot of different information to allow the regulator to assess the impacts to groundwater and related assets and ecosystems. This information includes:

- project description and study area definition;
- applicable regulations and approvals;
- characterisation of the geological, hydrogeological, and hydrological environment;
- identification of groundwater resources and related assets and ecosystems;
- ecohydrological conceptual model;
- baseline groundwater level/pressure and quality conditions;
- numerical groundwater flow modelling to predict impacts to groundwater resources and related assets and ecosystems;
- assessment of risks to groundwater resources and related assets and ecosystems associated with the project;
- proposed mitigation measures to manage risks to groundwater resources and related assets and ecosystems; and
- proposed monitoring to assess the effectiveness of mitigation measures and provide for early detection of impacts.

Most of the information included in a groundwater impact assessment report (including the ecohydrological conceptual model, numerical groundwater flow model, and risk assessment) is based on information gathered during a groundwater monitoring program. It is therefore critical that groundwater monitoring data are presented in the report as clearly and comprehensively as possible. Minimum requirements for how groundwater monitoring data should be reported are provided in Section 7.3.4.

The reporting of groundwater monitoring data prior to project approval is often more detailed and comprehensive than post-approval. This is because it may be the first time that groundwater monitoring data for the study area have been reported, particularly if it is a greenfield site. For brownfield sites, it is important to include results of monitoring undertaken for the previous phases of the project. This is because the data from this previous monitoring need to be considered in terms of cumulative impacts and should be used to assess the accuracy of impact predictions for the project.

It can be useful to include a summary of the objectives of groundwater monitoring and the methods used to achieve the objectives in the report. An example of a table summarising groundwater monitoring objectives is provided in Table 7.1 below.

Table 7.1 Example of groundwater monitoring objectives and planned methods where MB01-03 are bore numbers and SW01-03 are stream gauging sites

Groundwater monitoring objective	Methods used	Relevant section of this report
Identify water supply bores at risk of potential impacts in the study area	Search of NGIS Bore census survey	Section 6.4.1
Assess connectivity between streams and groundwater	Drilling and installation of groundwater monitoring bores MB01, MB02 and MB03 adjacent to streams Continuous monitoring of groundwater levels Stream gauging at SW01, SW02 and SW03 Cross-section analysis Baseflow separation analysis Water quality analysis (Piper plot)	Section 3.5.2, Figure 4.2, Appendix B Section 4.1.2 Section 5.2.2 Figure 4.7 Section 5.2.3, Figure 5.1 Section 4.3.1, Figure 4.3

7.3.3 Post-approval reporting

Following project approval, groundwater monitoring is generally undertaken to comply with the conditions of approval for the project, as set by the relevant state/territory or Commonwealth government. Additional groundwater monitoring may also be undertaken to meet commitments made through community consultation or to further investigate areas of uncertainty in conceptual understanding of the groundwater system and related assets and ecosystems.

Reporting to government on the results of groundwater monitoring in accordance with approval conditions (compliance reporting) must be undertaken in accordance with the relevant state/territory requirements and it is recommended to be at least once a year and as soon as possible following any breach of approval conditions. Additional recommended minimum requirements for reporting are provided in Section 7.434.

The objectives of compliance reporting include:

- present new data gathered through the groundwater monitoring program;
- evaluate the new data in the context of baseline data, predicted impacts, and relevant guideline/trigger values or thresholds;
- review the methods and data quality;
- document maintenance to the groundwater monitoring network, deviations from approved methods, and other unexpected conditions;
- draw conclusions and make recommendations as required; and
- evaluate the current groundwater monitoring plan (including locations, sampling methods, frequency of monitoring) and make recommendations for changes as required.

Compliance reporting is generally less detailed than pre-approval reporting; however, all relevant information needed to interpret the data presented should be included in compliance reports. It can be useful to include a summary of the approval conditions and how they were met in the report. An example is provided in Table 7.2 below.

Table 7.2 Example of approval conditions for groundwater monitoring and associated monitoring

Approval condition	Monitoring undertaken	Relevant section of report
2.3.5.1 Groundwater level monitoring	Continuous monitoring of groundwater pressure at MB04, MB05, MB06 and MB07 from Jan 2021 to Dec 2022	Section 4.1.2
2.3.5.2 Groundwater quality monitoring	Quarterly sampling and analysis at MB04, MB05, MB06 and MB07 between Jan 2021 and Dec 2022	Section 4.3.1

It is important to note that just because compliance reporting may only occur once a year, groundwater monitoring events may be more frequent, and review of the data should be undertaken as soon as possible following collection (as discussed in Section 7.2.6). If an exceedance of a guideline value, trigger level or threshold occurs, or anomalous readings or quality issues are noted, it is recommended that government be notified immediately and follow-up investigation is undertaken as soon as possible.

7.3.4 Reporting groundwater monitoring data

This section includes recommended minimum requirements for reporting of groundwater monitoring data. Specific requirements for pre-approval and post-approval monitoring are noted where relevant.

Groundwater monitoring reports should include details of the groundwater monitoring installations, including:

- locations on a map and construction details in a summary table and bore construction diagrams;

- details of the groundwater level/pressure monitoring that was undertaken, including time-series graphs;

- details of the groundwater quality monitoring that was undertaken, including Piper diagrams; and

- details of any other field investigations that were undertaken.

7.3.4.1 Groundwater monitoring installations

The groundwater monitoring report should include details of the groundwater monitoring installations. The locations of the monitoring installations should be shown on a map and clearly labelled with their unique IDs. The map should include the study area boundary, the project layout, and any groundwater-related assets and ecosystems.

A table summarising the monitoring installations should be included in the report for ease of cross-reference to the map. The table should include the following details:

- unique ID for the monitoring installation;
- bore name (if applicable);
- state/territory government bore ID;

- type of monitoring installation, e.g., groundwater monitoring bore, vibrating wire piezometer, nested groundwater monitoring bore);
- date installed;
- location (x and y coordinates as surveyed);
- elevation of the top of casing where groundwater levels are measured (in mAHD as surveyed);
- elevation of the ground at the location of the installation (in mAHD as surveyed)
- monitoring bore casing material and internal diameter, e.g., 50 mm PVC
- total depth of monitoring bore (in m below ground level);
- target lithology for the monitoring installation, e.g., alluvial silt, clay, sand and gravel
- target formation for the monitoring installation, e.g., Calivil Formation; and
- depth of screen (depth to top and bottom of screen in m below ground level) or depth of sensors for a vibrating wire piezometer

A bore construction diagram (bore log) which includes the lithology, and an installation diagram should be included in the report for each groundwater monitoring installation, typically as an appendix to the report. Ideally, one-page bore logs should be provided for ease of reference; however, more detailed logs can also be included if required. Where possible, the bore log should include the hydrogeological unit or formation names (e.g., instead of simply stating sandstone, the bore log should state Hawkesbury Sandstone), and information on water flows and quality assessed during drilling. A bore log should clearly indicate the bore ID, coordinates and survey levels, and the date of drilling. An example of a monitoring bore construction diagram is provided in Figure 7.2. An example of a construction diagram for a vibrating wire piezometer is provided in Figure 7.3.

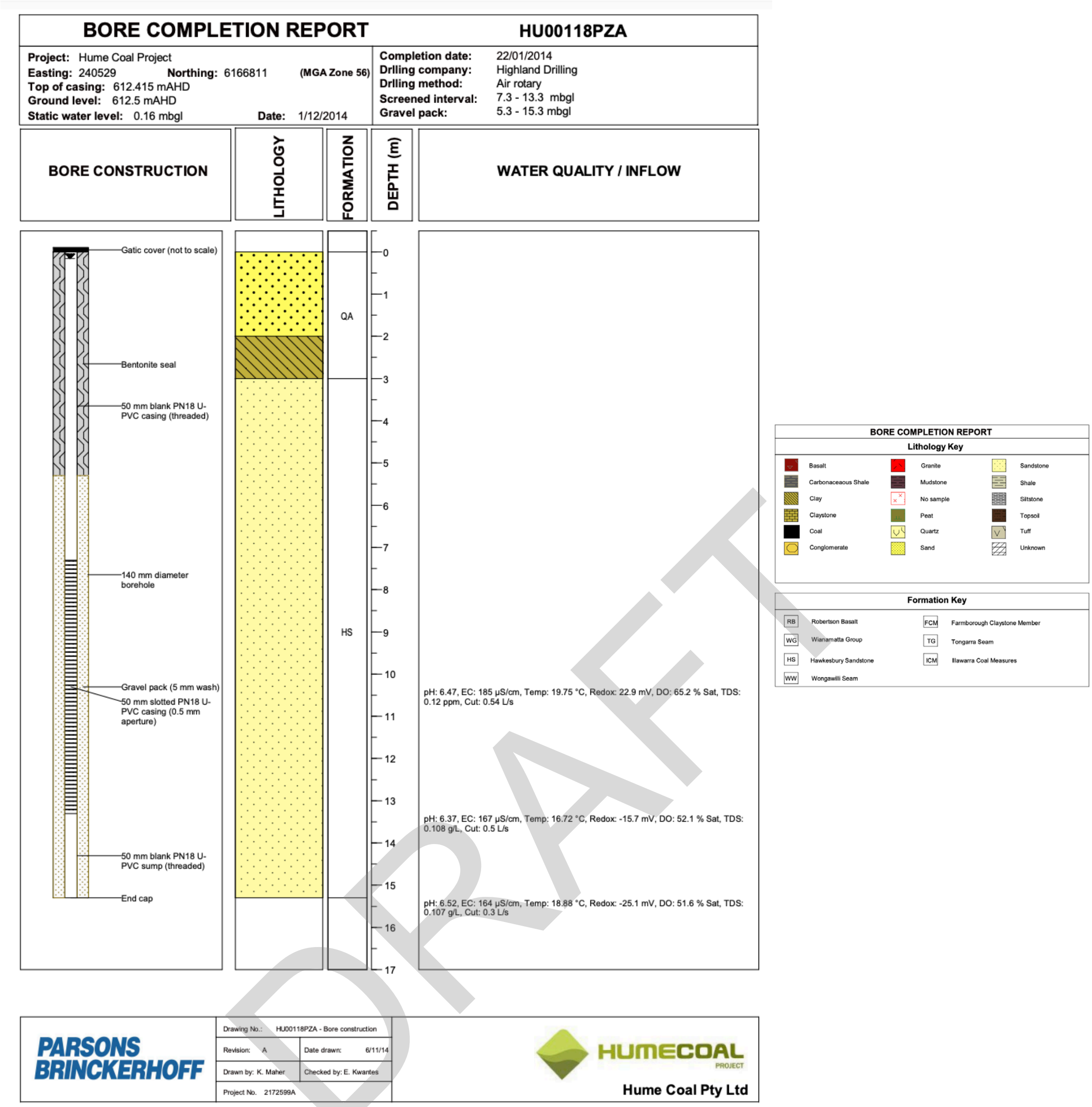

Figure 7.2 Monitoring bore construction diagram

Source: Hume Coal Project Environmental Impact Statement Appendix E: Water Part 21 (Appendix L) 2017. Available [online]: https://pp.planningportal.nsw.gov.au/major-projects/projects/hume-coal-mine.

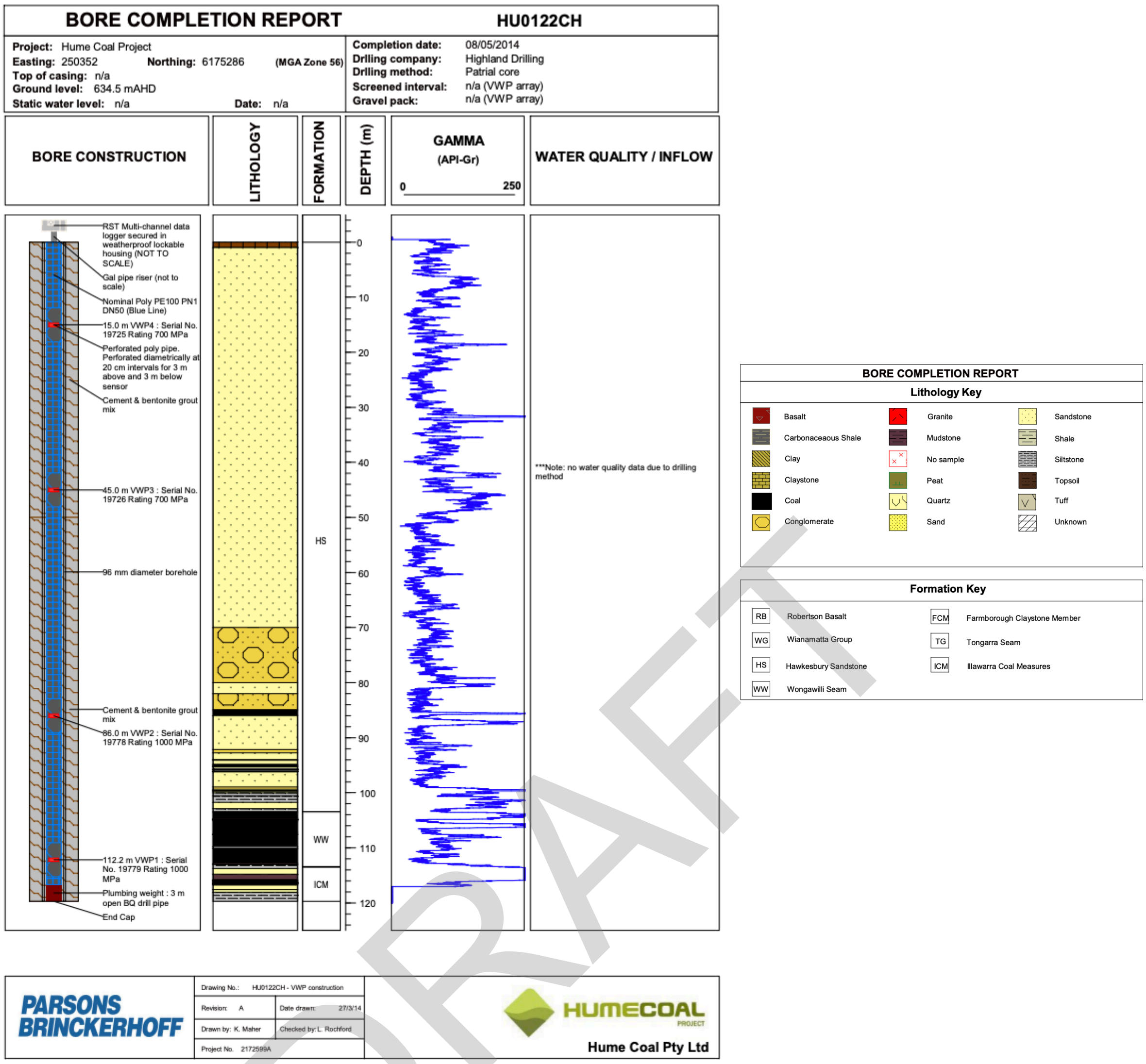

Figure 7.3 Vibrating wire piezometer construction diagram

Source: Hume Coal Project Environmental Impact Statement Appendix E: Water Part 21 (Appendix L) 2017. Available [online]: https://pp.planningportal.nsw.gov.au/major-projects/projects/hume-coal-mine.

7.3.4.2 Groundwater level/pressure monitoring

The groundwater monitoring report should include details of the groundwater level/pressure monitoring that was undertaken, including the locations, frequency, and duration (period of monitoring).

A description of the equipment and methods used to collect groundwater level/pressure data at each monitoring installation should be provided. Details of any corrections applied to the data should also be included.

Groundwater level/pressure monitoring data should be presented as a time-series graph (hydrograph) for each monitoring bore. If data were collected using a pressure sensor, the hydrograph should include the manual dips that were taken. Hydrographs should be presented in mAHD so that levels/pressures between bores can be compared. Additional hydrographs may also be prepared in m below ground level to aid with interpretation. Daily rainfall data or cumulative rainfall deviation from the mean can be useful to include on hydrographs to aid interpretation. It could also be useful to include stream, lake or wetland levels on the hydrograph if the bore is located near a stream, lake or wetland. An example of a hydrograph for a groundwater monitoring bore is provided in Figure 7.3.

Hydrographs should include any key events that may be needed to interpret the results. This may include purging and sampling events (as shown in Figure 7.3) or nearby activities such as dewatering a mine pit. For groundwater monitoring reports prepared post-approval, the period of baseline monitoring and the period of post-approval monitoring should be indicated on the graph. Any relevant trigger values or thresholds for the bore should be shown on the graph. All hydrographs in the report should be presented with consistent axes to make it easier for the reader to compare hydrographs for different bores.

It may be appropriate to present multiple hydrographs on one graph, for example the data for monitoring bores in a nest or cluster, or different sensors in a VWP, may all be presented on the one graph. In this instance, each hydrograph should be presented in a different colour with a legend included so that it is clear which hydrograph relates to which bore or sensor. Examples of a hydrograph for a vibrating wire piezometer with multiple sensors are provided in Figure 7.5.

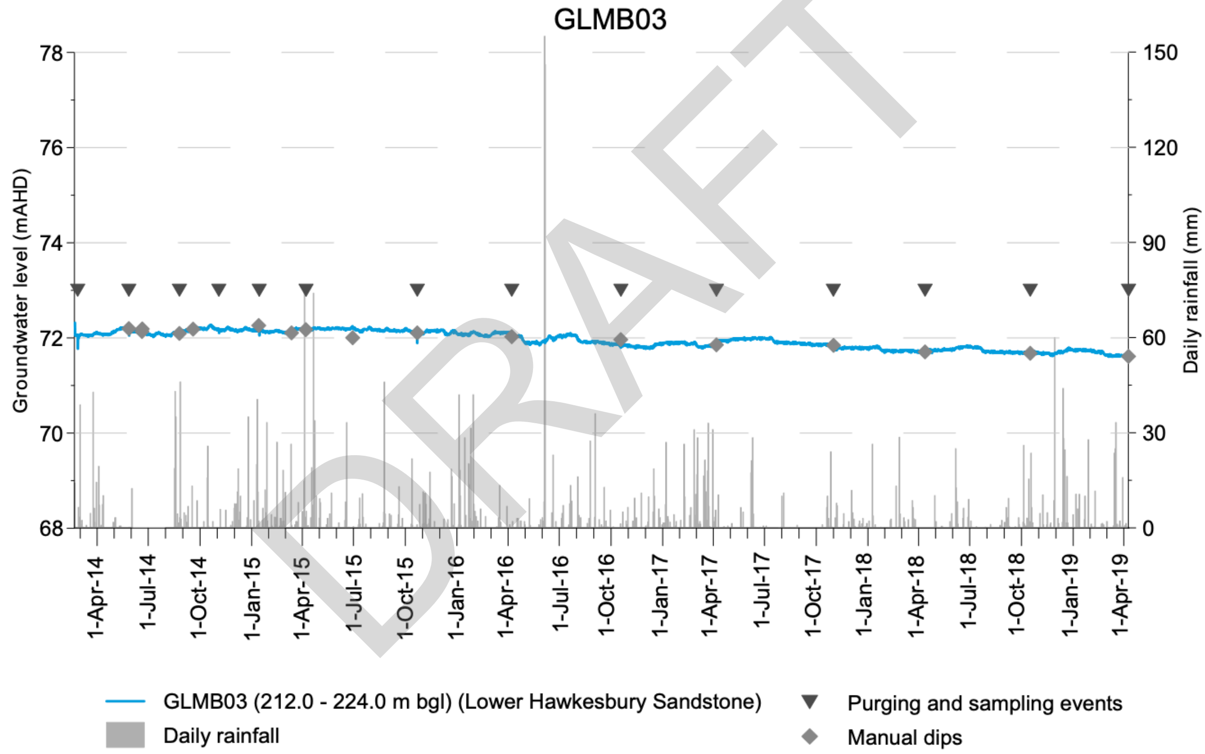

Figure 7.3 Hydrograph for a groundwater monitoring bore in the Camden Gas Project study area

Source: AGL Upstream Investments Pty Limited 2018-2019 Groundwater and Surface Water Monitoring Report: Camden Gas Project p.51. Available [online]: https://www.agl.com.au/content/dam/digital/agl/documents/about-agl/how-we-source-energy/camden-gas-project/agl-camden-gas-annual-water-monitoring-report-2019.pdf.

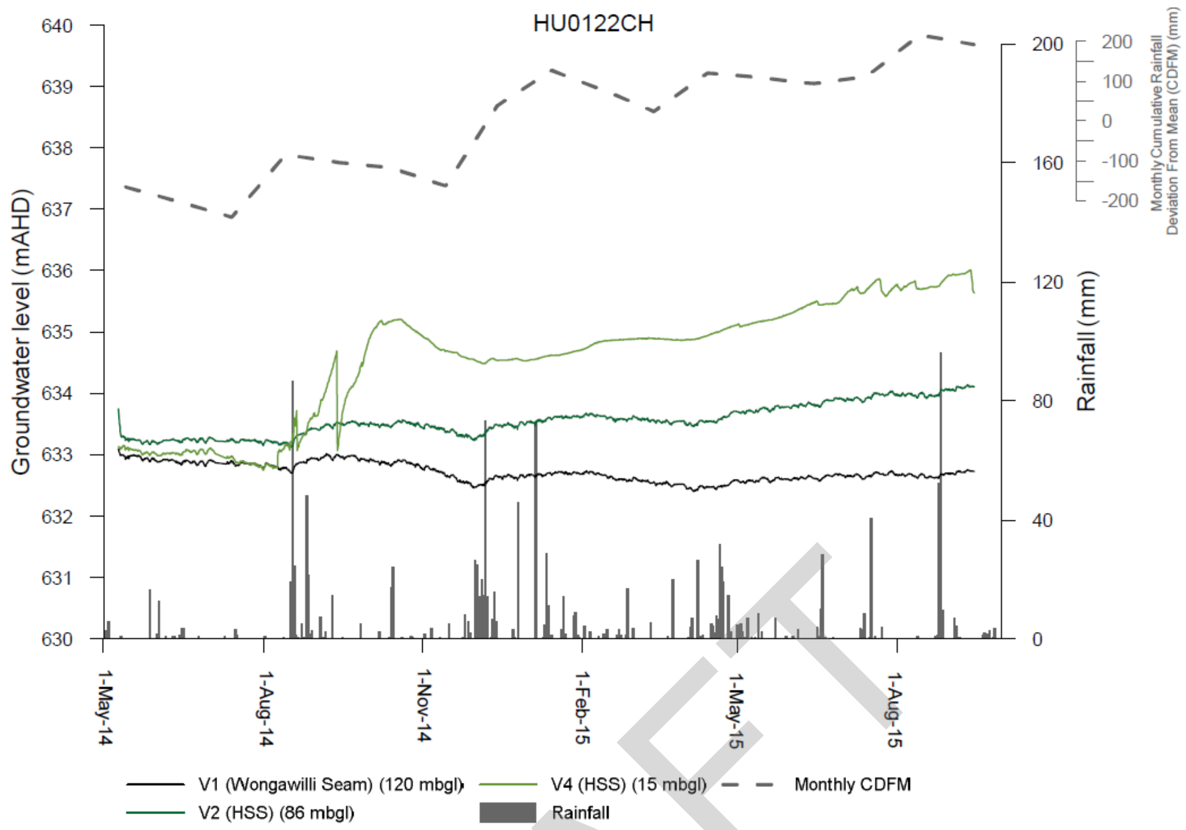

Figure 7.5 Hydrographs for three vibrating wire piezometers (V1, V2 and V4) located at different depths in borehole HU0122CH in the Hume Coal Project study area (baseline monitoring period). The dashed line shows the monthly cumulative rainfall deviation from the mean

Source: Hume Coal Project Environmental Impact Statement, March 2017. Available [online]: https://pp.planningportal.nsw.gov.au/major-projects/projects/hume-coal-mine.

7.3.4.3 Groundwater quality monitoring

The groundwater monitoring report should include details of the groundwater quality monitoring that was undertaken, including the locations, number and timing of sampling rounds, and analytical suite for each monitoring bore.

A description of the equipment and methods used to purge (where relevant) and collect samples for groundwater quality analysis should be provided for each monitoring bore. Details of how groundwater samples were filtered, preserved, stored, and transported should also be provided. Chain-of-custody documentation as received at the laboratory should be included as an appendix to demonstrate that samples were received by the laboratory as reported.

Groundwater quality monitoring data should be summarised in a table in the report. The name, unit of measurement, and limit of reporting or practical quantitation limit must be provided for each analyte. If data are to be compared to guideline values, these should also be included in the table, although this may not be possible where bore-specific trigger values have been derived. Values exceeding guideline values should be highlighted for ease of reference. The source of each guideline value should be noted in the table.

Field sheets with water quality parameters, laboratory analytical reports, and laboratory quality control reports should be included as appendices to the report. A summary of the quality review that was undertaken should be included in the main body of the report, including an assessment of how any quality issues identified may affect interpretation of the results.

Groundwater quality monitoring data can be presented in many different ways, including spatially on a map, or using bar graphs or box plots to show key parameters for each bore. Groundwater quality monitoring data for key parameters should ideally be presented as time-series graphs for each monitoring bore. Key parameters may include indicator parameters such as electrical conductivity (EC) or pH, or parameters with guideline values. Time-series water quality graphs should include any key events that may be needed to interpret the results. For example, if longwall mining occurred in the vicinity of a monitoring bore, then the start and finish of the longwall panel should be marked on the time-series water quality graph for the monitoring bore. For groundwater monitoring reports prepared post-approval, the period of baseline monitoring and the period of post-approval monitoring should be indicated on the graph. Any relevant guideline values or thresholds for the analyte should be shown on the graph. An example of a time-series graph for dissolved manganese showing relevant guideline values is provided in Figure 7.6. It is useful to present all graphs for the same parameter with consistent axes to make it easier for the reader to compare graphs for different bores.

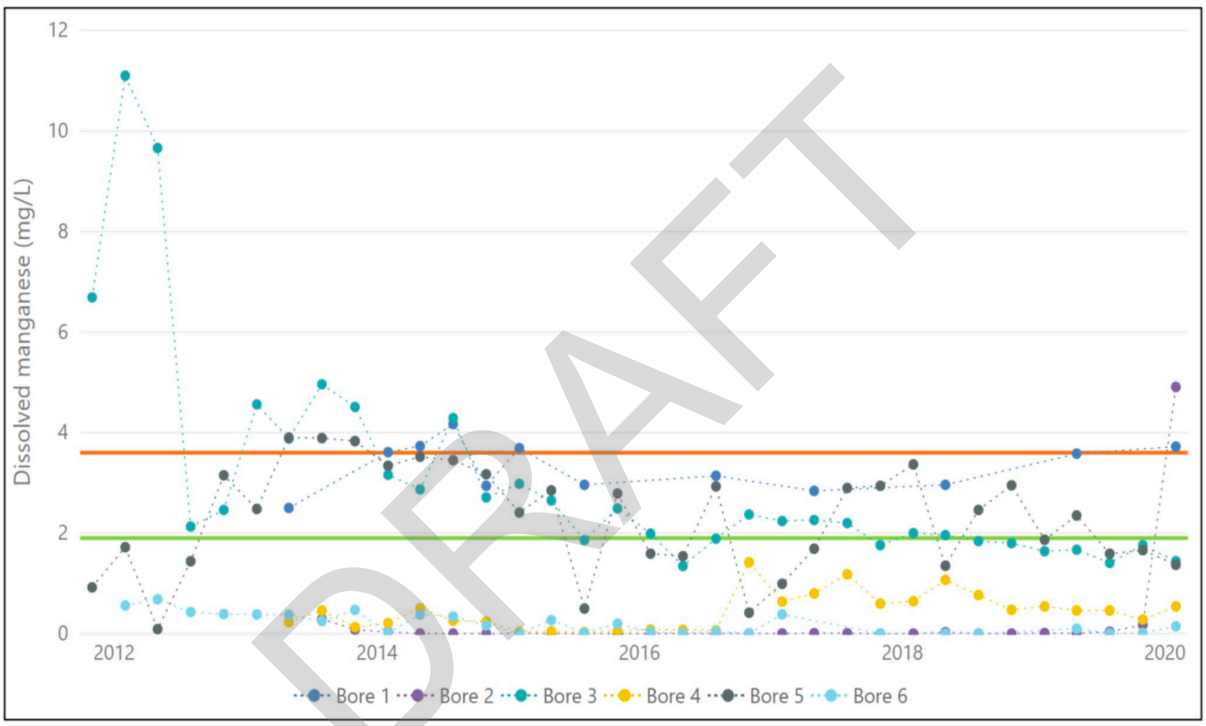

Figure 7.6 Time series water quality plots

The green line is the Australian Water Quality Guideline value, and the orange line is the site-specific trigger value derived using baseline water quality data. Source: Department of Environment and Science (DES) 2021. *Using monitoring data to assess groundwater quality and potential environmental impacts.* Version 2. DES, Queensland Government, Brisbane. Available [online]: https://www.publications.qld.gov.au/dataset/groundwater-quality-assessment-guideline/resource/472cc88a-000a-4bb8-a60d-204cfe7e0238. CC BY 4.0.

Groundwater quality monitoring data should also be presented using a Piper diagram. A Piper diagram is a way of visualising the chemistry of a groundwater sample. It provides a way to classify and compare water types based on the ionic composition of the groundwater samples plotted. Samples with similar major-ion chemistry are assumed to have undergone similar geochemical processes and be of the same or similar origins. In this way, a Piper diagram can provide useful information about the source aquifer of a groundwater sample, whether aquifers may be connected, and whether surface water and groundwater samples may be connected. An example of a Piper diagram is provided in Figure 7.7.

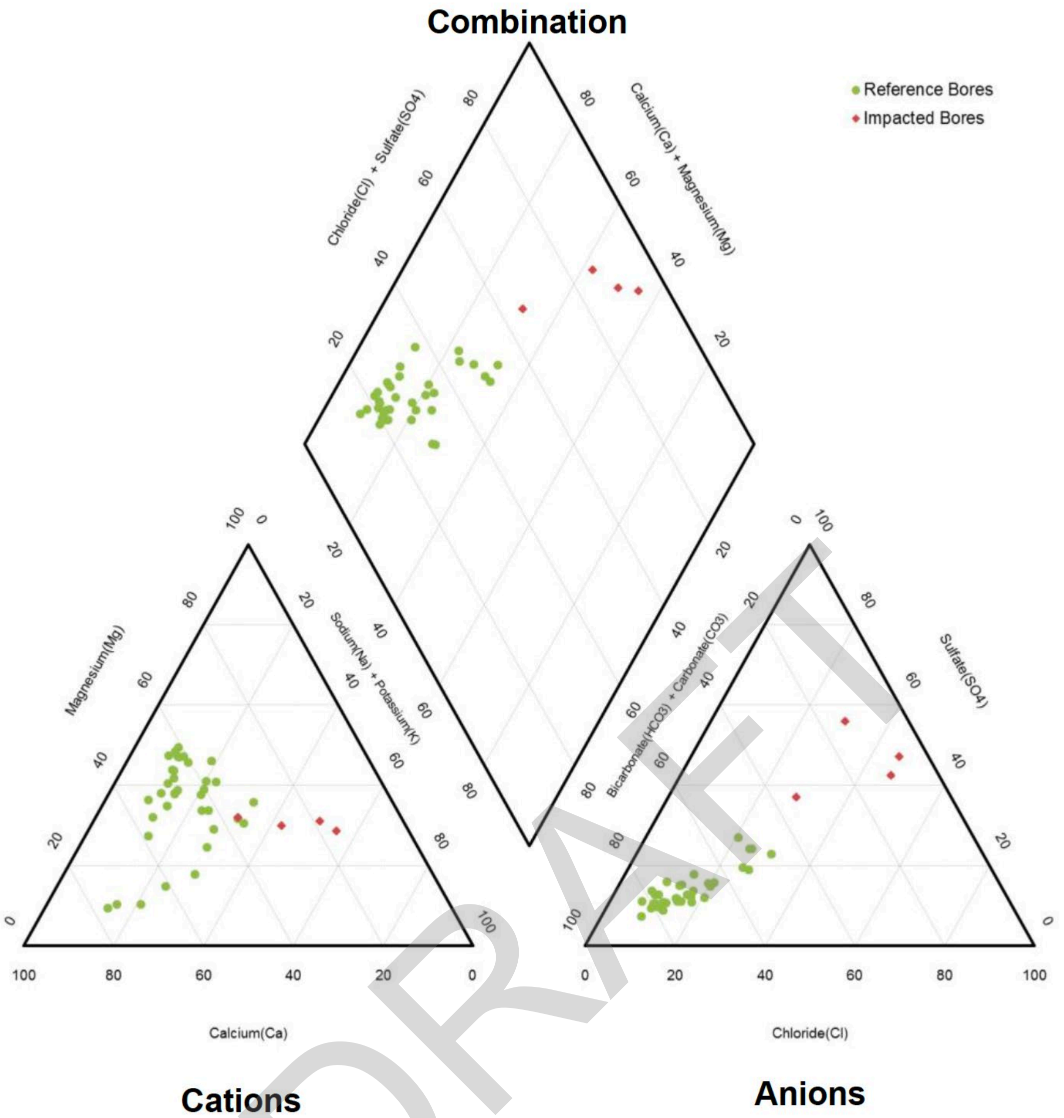

Figure 7.7 Piper diagram showing composition of groundwater samples from reference bores and impacted bores

Source: Department of Environment and Science (DES) 2021. *Using monitoring data to assess groundwater quality and potential environmental impacts*. Version 2. DES, Queensland Government, Brisbane. Available [online]: https://www.publications.qld.gov.au/dataset/groundwater-quality-assessment-guideline/resource/472cc88a-000a-4bb8-a60d-204cfe7e0238. CC BY 4.0.

7.3.4.4 Other hydrogeological investigations

The groundwater monitoring report should include details of any other field investigations that were undertaken, such as hydraulic testing, surface water monitoring, bore census surveys, hydrochemistry studies, remote sensing, geophysics, or surface outcrop mapping.

The report should outline the type of investigation that was undertaken, the objective of the investigation, and provide details of the location, date and any subcontractors involved. A description of the equipment and methods used should be provided. Details of any corrections applied to the data should be included.

The data should be summarised in a table in the report and raw data should be included as an appendix. Consideration should be given to how to best present the data in graphical form. An example of how packer test data may be presented using a box plot is provided in Figure 7.8. The plot shows how horizontal hydraulic conductivity varies with depth.

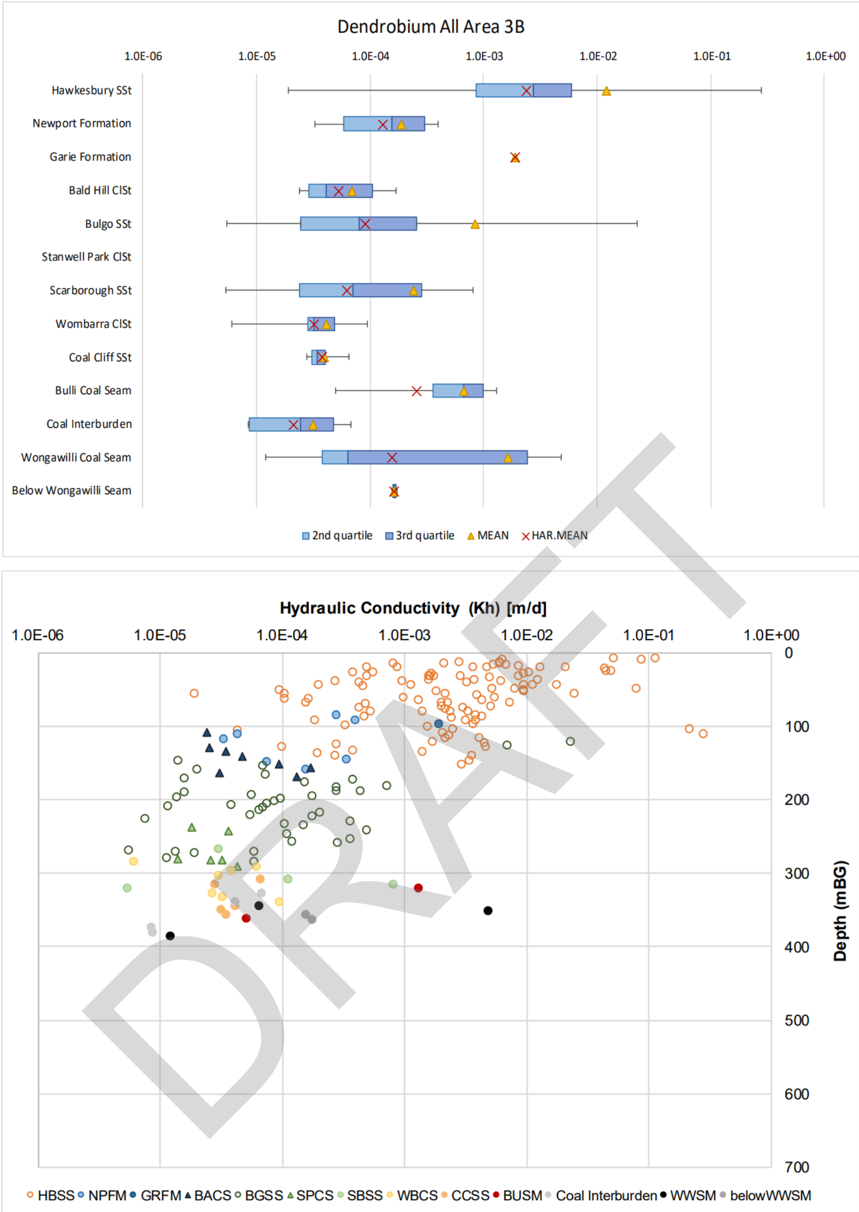

Figure 7.8 Spatial variation in horizontal permeability from packer test data

Source: HydroSimulations 2019. *Dendrobium Mine - Plan for the Future (GW Assessment).* Available [online]: https://pp.planningportal.nsw.gov.au/major-projects/projects/dendrobium-mine.

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Abbreviations

Short format	Meaning
eDNA	Environmental DNA (deoxyribonucleic acid)
GDE	Groundwater dependent ecosystem
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
InSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light detection and ranging
mAHD	Elevation in metres with respect to the Australian Height Datum.
NATA	National Association of Testing Authorities
NGIS	National Groundwater Information System
TARP	Trigger Action Response Plan
VWP	Vibrating wire piezometer

Glossary

These terms are defined in the context of this document.

Term	Description
Analyte	A parameter that is being analysed, such as an element or chemical.
Annulus (bore)	The space between a bore casing and borehole wall. It is typically filled with a filter pack of sand or gravel.
Aquifer	A formation of rock or sediment (or part of a formation or multiple formations) that has sufficient permeability to store and transmit water in significant quantities. Aquifers are separated from other aquifers by aquitards.
Aquitard	A formation of rock or sediment (or part of a formation or multiple formations) that has low permeability and does not transmit or store water in significant quantities.
Artesian aquifer	A confined aquifer where the hydraulic head is above the confining layer.
Artesian bore	A bore in an artesian aquifer.
Australian Height Datum	A datum with mean sea level at zero elevation.
mBACI design (multiple Before-After-Control-Impact)	An approach to monitoring in which data are collected multiple times before and after a potential impact to groundwater occurs and are collected at two sites, a control site and an impact site, or multiple control and impact sites.
Baseline monitoring	Monitoring that occurs before a potential impact to groundwater.
Baseflow	The component of flow in a river or stream that comes from groundwater.
Bore (also known as a well)	A hole artificially constructed in the ground that is used to take, store or monitor groundwater.
Calibration	A process where the output from measuring equipment is compared with a standard with known accuracy for a measurement range.

Term	Description
Brownfield project	A modification or expansion of an existing operation, or development of a previously developed site, where there is potential for previous impacts to groundwater resources and groundwater-related assets and ecosystems.
Casing (bore)	The tube lining a bore that prevents material from entering the bore. Groundwater can only enter the bore where there is a screen or an opening in the casing.
Catchment	The area of land that contributes to groundwater through rainfall.
Coal seam gas	Gas in coal or shale, usually methane.
Conceptual models	Descriptive representations of a system, typically illustrated with figures such as impact pathway diagrams and cross-section or block diagrams that show key features.
Confined aquifer	An aquifer between two aquitards where the pressure is greater than atmospheric pressure.
Connectivity	A measure or process of interaction between two systems, such as two aquifers or an aquifer and surface water.
Constituent	A substance that is part of the groundwater.
Contamination	A measurable change in water quality due to substances that are not normally present or are outside of naturally occurring levels, or that has the potential to harm human health or an environmental value.
Continuous monitoring	Collecting repeated measurements of a parameter, typically using automatic equipment
Control site	In the context of the mBACI design, a monitoring site that is unlikely to be impacted by a project activity. Data from the control site can be compared with data from an impact site.
Culturally significant site (CSS)	A place that is significant for Indigenous Australians in relation to their cultural and spiritual values and traditions. For the purposes of these guidelines, it includes groundwater-related environmental features and processes that are culturally significant, such as streams that receive baseflow.

Term	Description
Datum	A point or surface to which measurements can be referenced.
Depth to groundwater	The vertical distance from a datum to the surface of the groundwater in a bore.
Dewatering	Removing water from an aquifer.
Discharge	Water flowing from an aquifer through a spring or bore.
Discrete monitoring	Collecting measurements by hand using a sensor or instrument, at regular or irregular intervals
Drawdown	A decline in the potentiometric surface or water table due to groundwater extraction
Drinking water	Water intended for human consumption.
Ecohydrological conceptual model	A conceptual model that consolidates current understanding of the groundwater system, its key processes, and groundwater-related assets and ecosystems. The model integrates the hydrological (surface and groundwater) components with the ecological components (e.g. specific taxa, communities and ecosystems) to show the likely pathways by which a proposed project might impact on key aspects of water resources (e.g. water quality, flow regime, biota, ecological function).
Ecosystem	A community of living organisms, their physical environment and interactions between them.
Environmental tracers	Substances in water or properties of water that can be used to trace the source of the groundwater, discharge location and/or residence time.
Environmental values	Values or uses of groundwater that are important for ecosystems or people. (Also known as community values or beneficial uses)
Filter pack (also known as a gravel pack)	Sand or gravel in the annulus of the bore. It reduces sediment entering the bore and helps to stabilise the geological material around the bore.
Filtration	The process or removing solid material by passing water through a porous filter.

Term	Description
Flowing artesian aquifer	An artesian aquifer in which there is sufficient pressure for water to flow to the surface if a bore is screened in the aquifer. The potentiometric surface is above the ground surface.
Formation	Geological material that has some recognisable homogeneity.
Global Positioning System (GPS)	A system of satellites that receive and emit radio waves and are used to determine positions on earth at a GPS receiver.
Greenfield project	A new development on previously undeveloped land where previous impacts to groundwater resources and groundwater-related assets and ecosystems are unlikely.
Groundwater flow	The movement of groundwater through an aquifer.
Groundwater level	The water level measured in a monitoring bore screened across the water table.
Groundwater pressure	The water level measured in an artesian monitoring bore.
Groundwater quality	The chemical, physical, biological, and thermal properties of groundwater.
Groundwater system	Hydrogeological units and associated processes including groundwater flow, recharge and discharge.
Groundwater-dependent ecosystems	Ecosystems whose species and ecological processes rely on groundwater, either entirely or intermittently.
Groundwater	Water contained in rocks or sediment within the saturated zone.
Guideline value	With reference to water quality, a numerical concentration limit or narrative statement recommended to support and maintain a designated water use.
History matching	The process of calibrating a model to ensure it reproduces observed data.
Hydraulic conductivity	The ease with which groundwater can move through a material.
Hydraulic connection	A path in which groundwater can flow or a measure of how much a groundwater system can respond to changes in hydraulic head.

Term	Description
Hydraulic gradient	The slope between hydraulic head at two points in an aquifer.
Hydraulic head (potentiometric head)	A measure of water pressure above a vertical datum. It can be calculated for a formation by measuring the depth to groundwater in a monitoring bore that is screened across that formation and with information about the elevation of the monitoring bore and the screen depth.
Hydraulic properties	Measures of the ability of an aquifer to store and transmit water.
Hydrogeological unit	A geological formation that stores and transmits groundwater. Includes aquifers and other water-bearing formations.
Hydrogeology	The science of groundwater including its distribution, quality and movement.
Interferometric Synthetic Aperture Radar (InSAR)	A technique to observe movement in the Earth's surface using remotely sensed images.
Material risk	A risk that is of sufficient likelihood and consequence that it must be managed.
Metadata	Data that describes data and assists with interpreting the data.
Monitoring bore	A bore with the primary purpose of monitoring.
Monitoring location	A place where observations and measurements are made, typically the location of a bore.
Monitoring network	The collection of bores and other installations used in a monitoring program and their locations.
Monitoring plan	A plan that documents the activities that will be used to achieve monitoring objectives.
Monitoring program	The activities intended to achieve monitoring objectives, undertaken in accordance with the monitoring plan.
Monitoring	Collecting data to understand a system or evaluate potential impacts to it.

Term	Description
Nested bore	A bore with multiple casings or multiple nearby bores, with screens or openings at different levels to monitor different aquifers.
Non-aqueous phase liquids	Liquid with low solubility in water that forms discrete layers.
Non-flowing bore	A bore tapping an unconfined aquifer or a subartesian bore
Numerical models	Representations of a system that use equations.
Packer	Equipment that is placed in a bore to create a seal at a specific level and isolate some part of the bore.
Parameter	A measurable property of groundwater or substance in groundwater.
Permeability	The ability of a material to transmit a fluid, usually through connected pores and fractures.
pH	A representation of how basic or acidic a liquid is.
Piezometer	A bore that is used to measure groundwater level/pressure, typically with a small diameter.
Porosity	The proportion of volume of pores to solid rock.
Potentiometric surface	A representation of the level that standing water would be at in a bore in a confined aquifer.
Purging	Removing stagnant water from a bore.
Quality	The ability of an entity to satisfy needs.
Quality assurance	The processes put in place to prevent errors occurring and to ensure that the results of the groundwater monitoring program accurately reflect the groundwater system.
Quality control	The methods used to detect and quantify errors.

Term	Description
Quality management	Activities to improve confidence in the accuracy and reliability of the groundwater monitoring data collected. Quality management includes implementing quality assurance and quality control (QA/QC) measures to prevent, detect, quantify, and correct issues during groundwater monitoring that may cause errors.
Radionuclide	An isotope that is unstable and undergoes radioactive decay
Recharge	Water entering an aquifer.
Recovery	A measure of the return to the standing water level in a bore that has been purged.
Representative sample	A sample of groundwater with the same chemical and physical characteristics as the groundwater within the formation that is being monitored.
Risk assessment	The process of identifying and estimating the likelihood of harm from specified events and the magnitude of their consequences.
Risk	The likelihood and magnitude of consequences associated with a potentially harmful event.
Saturated zone	The area below-ground where water fills all available spaces, such as pores and fractures.
Screen interval	The depths at which a screen is positioned in a bore and therefore the depths from which groundwater in the bore originates.
Screen	A specially manufactured filter-like section of bore casing that allows groundwater to enter a bore. A screen has apertures of set sizes to allow water to enter the bore efficiently while blocking out sands and gravel as required.
Spot check	A single measurement, used to check if it is within tolerance or assist with verifying a measurement instrument through multiple spot checks.
Streamflow	The flow of water in a channel such as a stream or river.
Stygofauna	Animals that live in groundwater, usually for their entire life.

Term	Description
Subartesian bore	A bore that is in an artesian aquifer and has sufficient pressure for water in the bore to rise above the water table but not above the surface.
Surface water	Water that is naturally exposed to the atmosphere, flowing in or held in waterways at the surface such as rivers, streams, lakes and reservoirs.
Tolerance	The range of error that is permitted for a measurement.
Unconfined aquifer	An aquifer that does not have an aquitard above it. The upper boundary of an unconfined aquifer is the water table.
Unsaturated zone	The area below-ground where there is some air in void spaces as well as water.
Verification	The process of providing evidence to confirm that requirements are met.
Water balance	An expression of inputs, outputs and changes in water storage.
Water-bearing formation	Similar to an aquifer, but stores and transmits groundwater in lesser quantities and may be less extensive.
Water level	The vertical distance from a reference point to a water surface; for example, the depth to groundwater from the top of a bore casing.
Water table	The upper limit of the saturated zone in an unconfined aquifer. Groundwater pressure at the water table is the same as atmospheric pressure.

Appendix A List of information to record

A1. Monitoring installations

To record	Relevant section in these guidelines
The type of monitoring installation (e.g. bore, piezometer)	Section 3.3.1
For each bore, records should be kept in accordance with the Minimum Construction Requirements for Water Bores in Australia. This includes: • the location of the bore; • the dates of bore construction; • the bore identification number; • diameter and depth of the bore; • drilling method and equipment; • details of the strata, water-bearing formations, yield, and water quality; • details of the casing, pipe, wall, grouting, and gravel pack; • details of any slotted sections or screens, including type, length and location; • bore development procedure and record of bore development; and • drillers' logs and construction logs	Section 3.4.1
Geophysical logs	Section 3.4.4
Site identification including vertical datum, horizontal datum, and a reference point (e.g., on the rim of the bore)	Section 3.5
Where an existing bore will be used: • observations from a site visit, including any construction defects or signs of deterioration, photographs of the site; and • where relevant, data from hydraulic testing	Section 3.6
Details of any maintenance activities on the monitoring installation, such as cleaning	Section 3.7
Any observations of the monitoring installation, such as observations from a downhole camera to check for deterioration	Section 3.7
Relevant meteorological and hydrologic data at the time of groundwater monitoring, where available and relevant	Section 3.3.2 and 6.2

A2. To record in the field

	To record
General information	Date and time of each measurement and the time zone
	Location of monitoring: coordinates for the bore, bore identification and protocol for numbering the bore, and vertical datum of the reference point on the bore
	Name and contact details of person taking the measurements or samples
	Name and contact details of person responsible for the data and owner of the data
	Purpose for collecting the data
	Observations of factors that may affect measurements, e.g., pumping at a nearby bore
	Any issues with equipment and any repairs
	Procedures used for measurements, including specifications of the equipment used and a justification for the procedures
	Description of the parameter measured and the units
	Where applicable, the tolerance for each parameter, e.g., $\pm$ 10%
Manual groundwater level measurements	The groundwater level or pressure measurement
	Reference point for groundwater level measurements
	Time between removing the bore cap and taking the measurement (to allow for equilibration)
	An estimate of the expected accuracy of the measurement tape based on the most recent calibration
	Where necessary for density corrections, temperature and/or salinity measurements
	For flowing artesian bores, the distance from the reference point to the pressure gauge
	For equipped bores, the time when the bore was switched off prior to measurement
Automated groundwater level measurements	The distance from the reference point to the sensor, i.e., suspension wire length, and any changes to it Note: Manual groundwater level measurements should be taken regularly at the same location (see Section 4.3.1)
	Readings from loggers

	Logger specification
All groundwater quality measurements	The depth at which the measurement or sample is taken
	The analyte or parameter measured or to be analysed in the laboratory
	If purging the bore, the volume removed and pumping rates, and readings from a water quality meter demonstrating stabilisation of parameters
	Meter specification and servicing and calibration details
Groundwater quality field measurements	The measurement
	The parameter
	Calibration readings for water quality probes and the date and time of calibration. Additional records should be kept as outlined in the National Industry Guidelines for hydrometric monitoring Part 3
Groundwater quality samples – records to be kept with the sample at all times	Sample identification – to be recorded on a label on the sample as well as in field records
	The analyte to be measured or the type of quality control sample
	Details of any preservation of the sample, including the reagent and volume added
	Details of any filtration of the sample
	Chain-of-custody documentation, including the date and time at which the sample changed custody, who had custody, and the date and time of activities such transports and storage
	The number and volume of samples
	The holding time between sample collection and analysis and storage conditions, e.g., refrigerated, stored on ice
Automated groundwater quality measurements	The depth of the sensor Note: Equipment should be spot checked and calibrated at least once a year
	Readings from loggers
	Logger specification
Other data	Meteorological data
	Hydrologic data, where there is potential surface-groundwater interaction

A3. Desktop data

	To record
Preliminary data	Project description including: • details of all activities to be undertaken during each phase of the project, including site preparation and construction, operation and maintenance, and closure and completion, as well as alterations or modifications to existing infrastructure; • location of the project including a detailed site layout showing the disturbance area; • the proposed timing and duration of each phase of the project; • how the activities and disturbance area may change throughout the course of the project, e.g., mine pit progression; • location and nature of activities that may have an impact on groundwater resources and groundwater-related assets, e.g., location of tailings storage facilities; location, depth, and extent of excavations, location, depth; and target formation of groundwater extraction bores; and • for modifications or expansions of existing projects, details of which components of the project are existing and which components would be new.
	A review of available information about the project site and surrounding area. This should include the history of the site, the site setting including land use and vegetation cover, previous hydrogeological investigations, the regulatory context, and groundwater-related assets, including groundwater users, (known and potential) groundwater-dependent ecosystems, culturally significant sites, and connected surface water sources.
	An ecohydrological conceptual model
	A risk assessment
	The groundwater monitoring plan
	If an existing bore will be used: any available drilling records, lithological logs, and geophysical logs, any available monitoring data, observations from a site visit
	Relevant guideline values for groundwater quality
Procedures and people	Names, contact details, and qualifications of monitoring team
	Procedures and equipment for measurements, including justifications
	Procedures used for collecting, labelling, transporting and storing samples and data including types of storage containers
	Procedures for decontaminating equipment
	Reports from laboratories, including the name of the laboratory, details of its accreditation, their procedures and the results
	Any instances of data not being collected as per the monitoring plan, such as interruption to the frequency of monitoring a parameter

	An instrument management system as specified in the National Industry Guidelines for hydrometric monitoring which includes the current and historical status of all instruments in use
Telemetry, remote sensing and other measurements	Data from telemetry including the date, time and any information about the conditions at the site that could affect the measurements
	Barometric pressure data measured with a barometric pressure logger within 30 km of the study area – for correction of groundwater level measurements
	Any measurements from gravity methods or altimetry methods, and details of the methods and equipment used
	Results of land subsidence monitoring, where necessary for groundwater level corrections
	Data and methods for any remote sensing
	Surface outcrop mapping
	Data and methods for any hydraulic testing, such core permeability tests, slug tests, packer tests, and pumping tests

Appendix B List of related guidelines

The following guidelines provide further information about topics covered in this document and related topics. There may be additional guidelines not included here and some guidelines here contain information that is outdated and may be replaced with updated versions.

Key guidelines

ANZG 2018. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Canberra, ACT, Australia, 2018. Available [online]: https://www.waterquality.gov.au/anz-guidelines.

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Groundwater monitoring

State/territory Government guidelines

New South Wales Department of Primary Industries 2012. NSW Aquifer Interference Policy. Available [online]: https://www.industry.nsw.gov.au/__data/assets/pdf_file/0005/151772/NSW-Aquifer-Interference-Policy.pdf.

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