GROUNDWATER ASSESSMENT TOOLBOX FOR SSD/SSI

Minimum Groundwater Modelling Requirements for SSD/SSI Projects

Technical guideline

January 2022

Published by NSW Department of Planning and Environment

dpie.nsw.gov.au

Title: Minimum Groundwater Modelling Requirements for SSD/SSI Projects

ISBN: 978-1-76058-519-8

First published: January 2022. Version 1

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Recommended citation:

DPE (2022). Minimum groundwater modelling requirements for Major Projects in NSW. Technical note prepared for the Water Division, NSW Department of Planning and Environment as part of the Groundwater Modelling Toolbox Project.

Acknowledgment of Country

The Department of Planning and Environment and Stantec acknowledge the Traditional Owners and Custodians of the land on which we live and work and pays respect to Elders past, present and future.

Executive summary

The Water Division of the New South Wales Department of Planning and Environment provides advice toward Major Projects to meet the requirements of the Water Management Act 2000 (WMA) and the Aquifer Interference Policy 2012 (AIP). Major Projects include projects declared State Significant Development (SSD) and State Significant Infrastructure (SSI). Major Project proponents are required to use groundwater models to estimate direct and induced surface and groundwater takes due to their proposed and/or ongoing activities. The assessment must clarify potential impacts to the aquifer and aquifer values.

Groundwater modelling guidelines already exist at the national level, principally the Australian groundwater modelling guidelines (AGMG; Barnett et al., 2012). The groundwater modelling guidelines presented in this document are intended to be complementary to the AGMG while incorporating elements from those developed by agencies in other countries at their state and federal levels as well as international standard-setting and scientific organisations. This document follows the general sequence of the AGMG, tracing the development of a groundwater modelling project from initial planning through conceptualisation, numerical model implementation, reporting, review, and archiving.

The AIP requires that a **Groundwater Monitoring and Modelling Plan** (**GMMP**) be prepared and submitted to the department's Water division prior to starting the modelling project. The modelling portion of the plan (Groundwater Modelling Plan; GMP) must include:

- A clear statement of model objectives;
- Identification of the required model complexity;
- A literature review of data and information in the project area;
- Geographic and temporal extent of the model;
- How potential cumulative impacts will be addressed;
- Climate change considerations;
- How uncertainty analysis will be addressed; and,
- Identification of independent reviewers and process.

A key component of the groundwater modelling project is development of a robust **conceptual model** of the site, the project, and other neighbouring projects. The conceptual model must include:

- Evaluation of data availability;
- Hydrostratigraphy;
- Geological and hydrogeological boundaries;
- Identification of sensitive receptors;
- Water quality and saltwater intrusion if applicable;
- Description of hydrogeological domain;
- Aquifer and aquitard properties;
- Assessment of groundwater-surface water interaction;
- Quantification of stresses and inputs; and,
- Uncertainty assessment of the conceptual model.

The conceptual model may be developed as a series of maps, cross-sections, block models, and tables of aquifer characteristics. It may be also developed and maintained in a digital format. The conceptual model must be checked through the use of simple analytical models and water balance calculations.

Once a conceptual model is in place, a **mathematical model** will be developed to provide quantitative predictions. The mathematical model must be closely tied to the conceptual model, with an iterative approach to overall development. Modelling objectives and the conceptual model must drive choices such as:

- Mathematical or numerical approach;
- Model resolution;
- Layering;
- Initial conditions;
- Code selection;
- Grid type;
- Boundary conditions;
- Discretisation in time and space; and,
- Inputs.

Calibration of a groundwater model is a complex process. The goal of calibration is to find model parameter values that are useful for predictions of future conditions, not just to reproduce past data. Calibration methods may be manual or automatic, with a combination of both often required for a successful calibration.

Calibration targets must be chosen to represent areas of concern within the model and must be spatially distributed both horizontally and vertically. Typical calibration targets include:

- Measured groundwater levels;
- Stream or river baseflow;
- Vertical gradients;
- Spring discharge rates;
- Lake levels; and,
- Horizontal gradients.

Calibration results must be evaluated both qualitatively and quantitively by graphical and statistical means. Minimum calibration criteria that must be calculated and reported include:

- Simulated vs interpreted potentiometric surfaces;
- Simulated vs measured head (tables and scatter plots);
- Simulated vs measured flow (tables and scatter plots);
- Hydrographs of simulated and measured heads for transient simulations;
- Minimum and maximum residuals;
- Histograms of residuals;
- Maps of residuals;
- Model mass balance;
- Root mean square (RMS) of residuals; and,
- Scaled RMS.

A **sensitivity analysis** must be conducted during calibration to evaluate the relative effect of different model input parameters and boundary conditions on both model calibration and predictive outputs. Typical parameters evaluated during the sensitivity analysis are horizontal and vertical hydraulic conductivity, aquifer recharge, and boundary condition level and conductance. Automated inverse modelling codes may provide parameter sensitivity statistics (**parameter identifiability**) in output files along with calibration results.

The AIP requires proponents to provide **estimates** of all water likely to be taken from any water source during or following the activity and all predicted impacts associated with the activity based on certain minimum standards. Key elements to **predict** include:

- Depletion of groundwater resources;
- Depletion of surface water resources;
- Potential water level, quality or pressure drawdown impacts on groundwater dependent ecosystems (GDEs);
- Potential to cause or enhance hydraulic connection between aquifers;
- Potential changes in water quality;
- Potential water level, quality, or pressure drawdown impacts on nearby water users;
- Potential for increased saline or contaminated water inflows to aquifers and highly connected river systems; and,
- Cumulative impacts.

In modelling studies where recharge and/or evapotranspiration are large components of the conceptual model water balance, predictive scenarios run over extended time periods may need to assess potential impacts due to **climate change**.

Particle tracking results may be used to predict flow paths, travel times, and areas of influence.

The AIP requires that an **uncertainty analysis** be included if predictive uncertainty may have a significant impact on the environment or other authorised water users. Under these conditions the AIP requires the following to be assessed:

- Any potential for causing or enhancing hydraulic connection between aquifers or between groundwater and surface water sources;
- Quantification of any other uncertainties in the groundwater or surface water impact modelling conducted for the activity; and,
- Strategies in place for monitoring actual and reassessing any predicted take of water and how any changes in these requirements will be accounted for.

Three basic types of uncertainty analysis are generally recognised:

- Scenario analysis with deterministic modelling;
- Linear uncertainty analysis with deterministic modelling; and,
- Bayesian analysis with stochastic modelling.

The type of uncertainty analysis used for a particular project must be based on the data available, sensitivity of decision alternatives to model predictions, and overall model complexity.

The final step in groundwater flow modelling is **reporting**. The written technical report must describe the basis for the model, key assumptions, modelling approach, limitations, and the study findings, conclusions, and recommendations. Modelling reports or consultation with the department's Water division and other stakeholders must be considered after each of the following stages:

- Conceptualisation and model design;
- Calibration and sensitivity analysis; and,
- Predictive modelling and uncertainty.

Modelling archives must include documented data analysis, modelling data and software program files if they can be provided in accordance with copyright or distribution agreements.

The AIP requires that models submitted in support of Major Project development undergo **independent review**, be consistent with the AGMG, and that they be determined to be **fit for purpose** to the satisfaction of the Minister. The department's Water division will review the modelling reports to evaluate whether they are consistent with AIP requirements, Secretary Environmental Assessment Requirements (SEARs) and/or Conditions of Approval (COA) that relate to the water related aspects of the project.

The AGMG suggests three levels of independent review:

- Appraisal by a non-technical reviewer to evaluate model results;
- Peer review by one or more experienced hydrogeologists and modellers; and,
- Post audit after new data are available or model objectives change.

Appraisal and peer reviews generally occur periodically during the modelling project. Post audits may occur well after the modelling project is complete.

Contents

Acknowledgment of Country .... Error! Bookmark not defined.

Executive summary iv

Acronyms ix

1 Introduction 1

1.1 Purpose and objectives 1

1.2 Regulatory framework 2

1.3 Other relevant guidance 2

2 Planning the model 4

2.1 Groundwater modelling plan 4

2.1.1 Model objectives 7

2.1.2 Model complexity 7

2.1.3 Literature review 8

2.1.4 Geographic and temporal extent 8

2.1.5 Inclusion of potential cumulative impacts 9

2.1.6 Climate change considerations 9

2.1.7 Planning for uncertainty analysis 10

2.1.8 Independent review 10

2.2 Agency engagement 10

3 Conceptual hydrogeological model 11

3.1 Data availability 11

3.2 Contents of the conceptual model 12

3.2.1 Hydrogeological domain 13

3.2.2 Hydrostratigraphy 14

3.2.3 Aquifer and aquitard properties 14

3.2.4 Geological and hydrological boundary conditions 14

3.2.5 Water sources 14

3.2.6 Groundwater-surface water interaction 15

3.2.7 Sensitive receptors 15

3.2.8 Stresses and inputs 15

3.2.9 Water quality and saltwater intrusion 15

3.3 Conceptual model uncertainty 16

3.4 Format and contents of the conceptual Model 16

3.5 Checking the conceptual model 17

4 Mathematical model development 18

4.1 Modelling approach 18

4.2 Model complexity 18

4.3 Code selection 20

4.4 Horizontal and vertical extent ... 20
4.5 Model layering ... 21
4.6 Discretisation in space and time ... 21
4.6.1 Spatial ... 21
4.6.2 Temporal ... 22
4.7 Boundary conditions ... 22
4.8 Initial conditions ... 23
4.9 Inputs ... 23
5 Calibration and sensitivity analysis ... 24
5.1 Purpose of calibration ... 24
5.2 Calibration targets ... 24
5.3 Calibration methods ... 25
5.4 Minimum calibration criteria ... 25
5.5 Sensitivity analysis ... 26
6 Model predictions ... 27
6.1 Predictions required by the AIP ... 27
6.2 Cumulative impacts ... 28
6.3 Timeframe for predictions ... 28
6.4 Incorporating climate change ... 29
6.5 Particle tracking ... 29
7 Uncertainty analysis ... 30
7.1 Goal of uncertainty analysis ... 30
7.2 Causes of model uncertainty ... 30
7.3 Type of uncertainty analysis ... 31
8 Groundwater model report ... 32
8.1 Timing of reports ... 32
8.2 Target audience ... 32
8.3 Structure and minimum contents ... 33
8.4 SEARs and COA ... 35
8.5 Model file archive ... 35
9 Model review ... 36
9.1 Independent review ... 36
9.2 Agency review ... 36
10 References ... 38
Appendix A: Model review checklists ... 40
Appendix B: Assessment criteria for low to medium complexity groundwater models for low to medium environmental sensitivity projects ... 50

Tables

Table 1: Potentially relevant guidance documents. 2
Table 2: Recommended content of a Groundwater Modelling Plan (GMP)........ 5
Table 3: Example model objectives........ 7
Table 4: Major elements of the conceptual hydrogeological model. 12
Table 5: Minimum calibration criteria........ 25
Table 6: Typical sensitivity testing ranges for individual model parameters. 26
Table 7: Model predictions required by the AIP. 27
Table 8: Sources of model uncertainty (after Middlemis and Peeters, 2018). 31
Table 9: Example model report structure (compiled from ASTM, 2013; Barnett et al., 2012)........ 34

Figures

Figure 1: Typical groundwater modelling workflow. 6
Figure 2: Example of a hydrological conceptual Model (sourced from EMM, 2021)........ 13
Figure 3: Environmental sensitivity and model complexity........ 19

Acronyms

Acronym	Explanation
1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
ACT	Australian Capital Territory
AGMG	Australian Groundwater Modelling Guidelines
AIP	NSW Aquifer Interference Policy 2012
ASTM	American Society for Testing and Materials
BLM	Bureau of Land Management [USA]
BSAL	Biophysical Strategic Agricultural Land
CLC	Confidence level class [for groundwater models]
COA	Conditions of Approval
CSG	Coal Seam Gas
CSS	Culturally Significant Sites
DPE	Department of Planning and Environment
e.g.	For example
EIS	Environmental Impact Statement
EP&A	Environmental Planning and Assessment [Act, USA]
ET	Evapotranspiration
et al.	and others
etc.	and others, and so forth, and so on
GDEs	Groundwater dependent ecosystems
GIA	Groundwater Impact Assessments
GMMP	Groundwater Monitoring and Modelling Plan
GMP	Groundwater Modelling Plan
GMT	Groundwater Modelling Toolbox Project
GUI	Graphical user interfaces [for modelling software]
GW-PET	Groundwater model assessment procedures and evaluation tool report

Acronym	Explanation
HCM	High complexity [groundwater] model
HES	High environmental sensitivity [project]
i.e.	That is
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
LMCM	Low to medium complexity [groundwater] model
LMES	Low to medium environmental sensitivity [project]
m	metre
MDBC	Murray-Darling Basin Commission
NARCliM	NSW/ACT Regional Climate Modelling
NDEP	Nevada Department of Environmental Protection
NSW	New South Wales
PEST	Parameter Estimation and Uncertainty Analysis [software]
RMS	Root mean square
SEARs	Secretary’s Environmental Assessment Requirements
SSD	State Significant Development
SSI	State Significant Infrastructure
TSF	Tailings storage facilities
USGS	United States Geological Survey
vs	Versus
WMA	Water Management Act 2000
WRDMAP	Water Resources Demand Management Assistance Project (China – UK)

1 Introduction

The Water Division in the New South Wales (NSW) Department of Planning and Environment provides advice toward Major Projects to meet the requirements of the Water Management Act 2000 (WMA) and the Aquifer Interference Policy 2012 (AIP). The department's Water Division conceived the Groundwater Modelling Toolbox (GMT) Project to create a collaborative, transparent, and enabling environment for the preparation and reviewing of groundwater models in NSW.

This technical note on the minimum requirements in groundwater modelling for Major Projects in NSW has been prepared as part of the GMT Project.

As described in the AIP, the WMA defines an aquifer interference activity as that which involves any of the following:

- The penetration of an aquifer.
- The interference with water in an aquifer.
- The obstruction of the flow of water in an aquifer.
- The taking of water from an aquifer in the course of carrying out mining or any other activity prescribed by the regulations.
- The disposal of water taken from an aquifer in the course of carrying out mining or any other activity prescribed by the regulations.

Examples of aquifer interference activities described in the AIP include mining; coal seam gas (CSG) extraction; injection of water; and commercial, industrial, agricultural, and residential activities that intercept the water table or interfere with aquifers. The Water Management (General) Regulation 2011 (NSW Government, 2011) states that an aquifer interference activity also includes the extraction of sand and the extraction of road base material.

Major Project proponents are required to use groundwater models to estimate direct and induced surface and groundwater takes due to their proposed and/or ongoing activities. The assessment must clarify potential impacts to the aquifer and aquifer values. This technical note clarifies the department's Water division's minimum requirements of Major Projects groundwater models, serving as a guide that complements but does not replace existing best practice guidelines.

1.1 Purpose and objectives

Groundwater modelling guidelines already exist at the national level, principally the Australian groundwater modelling guidelines (AGMG; Barnett et al., 2012). The groundwater modelling guidelines presented in this document are intended to be complementary to the current Australian best practice guidelines while incorporating elements from those developed by agencies in other countries at their state and federal levels as well as international standard-setting and scientific organisations.

The objectives of this guidance document are to:

- Clarify the requirements for groundwater models developed specifically for evaluation of groundwater and connected surface impacts anticipated to result from Major Projects.
- Ensure that Major Project proponents are aware of the groundwater modelling requirements in the context of governing regulations.
- Provide transparency and consistency to the broader community related to how models are used to assess potential groundwater impacts of proposed Major Projects.

1.2 Regulatory framework

Groundwater modelling to support SSD and SSI project assessments is conducted within the regulatory framework of several statutes and policies, the principal of which are:

- Environmental Planning and Assessment Act 1979: The Environmental Planning and Assessment Act 1979 (EP&A Act) and the corresponding Environmental Planning and Assessment Regulation 2000 (EP&A Regulation) together set out the foundation for general land-use planning and development in NSW. They govern the management, development, and protection of natural and other resources in NSW, including water resources.
- Water Management Act 2000: The Water Management Act 2000 (WMA) is the primary law covering water allocation, management and licensing in NSW. The WMA provides a framework for balancing varied factors in water management decisions.
- NSW Aquifer Interference Policy 2012: The NSW Aquifer Interference Policy 2012 (AIP) describes how to implement the water assessment and licensing processes for aquifer interference activities that required by the WMA. The AIP describes what Major Project proponents must provide so that an assessment can be made by the department's Water division.

1.3 Other relevant guidance

This document is intended to complement guidance already in place from other sources. Potentially relevant guidance on development of groundwater models for assessment of Major Projects is summarised in **Error! Reference source not found.**.

Table 1: Potentially relevant guidance documents.

Reference	Comment
Australian groundwater modelling guidelines (AGMG) (Barnett et al., 2012)	Principal guidance document for groundwater modelling projects undertaken in Australia. The AIP requires that groundwater models used to assess Major Projects be developed in accordance with the AGMG.
Guidelines for groundwater documentation for SSD/SSI Projects (EMM, 2021)	Describes requirements of the NSW Government for the assessment of groundwater related matters and consideration of potential water-related impacts from Major Projects in NSW. This guideline provides important context for how groundwater models fit into the overall framework of documentation for Major Projects.
Groundwater monitoring and modelling plans – information for prospective mining and petroleum exploration activities (NSW, 2014)	Recommendations are relevant to similar plans for Major Projects.

Reference	Comment
Groundwater modelling fact sheet (NSW, 2018)	Describes key elements of groundwater models used to assess proposed water resource plans, relevant to similar modelling projects developed for Major Projects.
Information guidelines explanatory note: Uncertainty analysis – guidance for groundwater modelling within a risk management framework (Middlemis and Peeters, 2018)	Prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coals Mining Development (IESC). Provides guidelines related to uncertainty analysis as applied to groundwater modelling. While directly applicable to CSG and coal mining, the concepts may be relevant to other Major Projects.
Coal seam gas extraction: modelling groundwater impacts (Commonwealth of Australia, 2014)	Prepared by IESC. Describes how groundwater models can be applied to simulate groundwater impacts from coal seam gas extraction.

Other guidelines related to development of groundwater models have been prepared by national and state/provincial agencies outside Australia as well as scientific and non-governmental standard-setting organisations. An extensive scientific literature exists related to the development, calibration, and application of groundwater models in general. While it is outside the scope of the GMT Project to summarise this body of work, relevant publications are cited where applicable.

2 Planning the model

In this section: Planning the groundwater model and agency engagement.

Key references consulted:

- *AGMG* (Barnett et al., 2012).
- *Murray-Darling Basin Commission groundwater flow modelling guideline* (Middlemis et al., 2001).
- *Groundwater Monitoring and Modelling Plans - Information for prospective mining and petroleum exploration activities* (NSW Office of Water, 2014).
- *Guidelines for groundwater documentation for SSD/SSI projects* (EMM, 2021).

The groundwater modelling approach for an individual project must be planned carefully to make the best use of resources and ensure that the model will be fit for purpose when developed. The AIP requires that a Groundwater Monitoring and Modelling Plan (GMMP) be prepared and submitted to the department's Water division prior to starting the modelling project.

Groundwater modelling is a structured process. Figure 1 illustrates a general framework for model development, calibration, and application. Groundwater modelling is usually an iterative process, whereby the mathematical model results often help refine the conceptual model and additional data can be used to update both. Each groundwater model is unique. Not all steps in **Error! Reference source not found.** may be applicable to every model but the systematic and iterative process is useful.

2.1 Groundwater modelling plan

A Groundwater Modelling Plan (GMP) must be developed early in the project and reviewed with the department's Water division. Early engagement with the department's Water division is encouraged to gain agreement on the groundwater modelling approach, key metrics for evaluating the model, output that is needed to satisfy project requirements, and how the model will be documented. The GMP may be provided as a standalone document or may be incorporated into a broader GMMP as described in NSW Office of Water (2014).

The recommended contents of the GMP are summarised in Table 2 and described below.

Table 2: Recommended content of a Groundwater Modelling Plan (GMP).

Groundwater modelling plan content	Description
Model objectives	Objectives of the groundwater model and how they fit the larger project requirements.
Model complexity	Determine the target level of complexity for the model.
Literature review	Review of relevant literature including existing data sources and previous modelling reports in the area.
Geographic and temporal extent	Geographic and temporal extent of the conceptual and mathematical models.
Cumulative impacts	How the proposed project and other existing or reasonably foreseeable future projects may cumulatively impact water resources.
Climate change	Whether and how climate change may be incorporated into the model. Climate change should be taken into consideration for Major Projects that have a lifespan of more than 50 years or are located in areas where considerable changes to the hydrological cycle are predicted.
Uncertainty analysis	How predictive uncertainty will be assessed.
Independent review	Plans for independent model review as required by AIP.

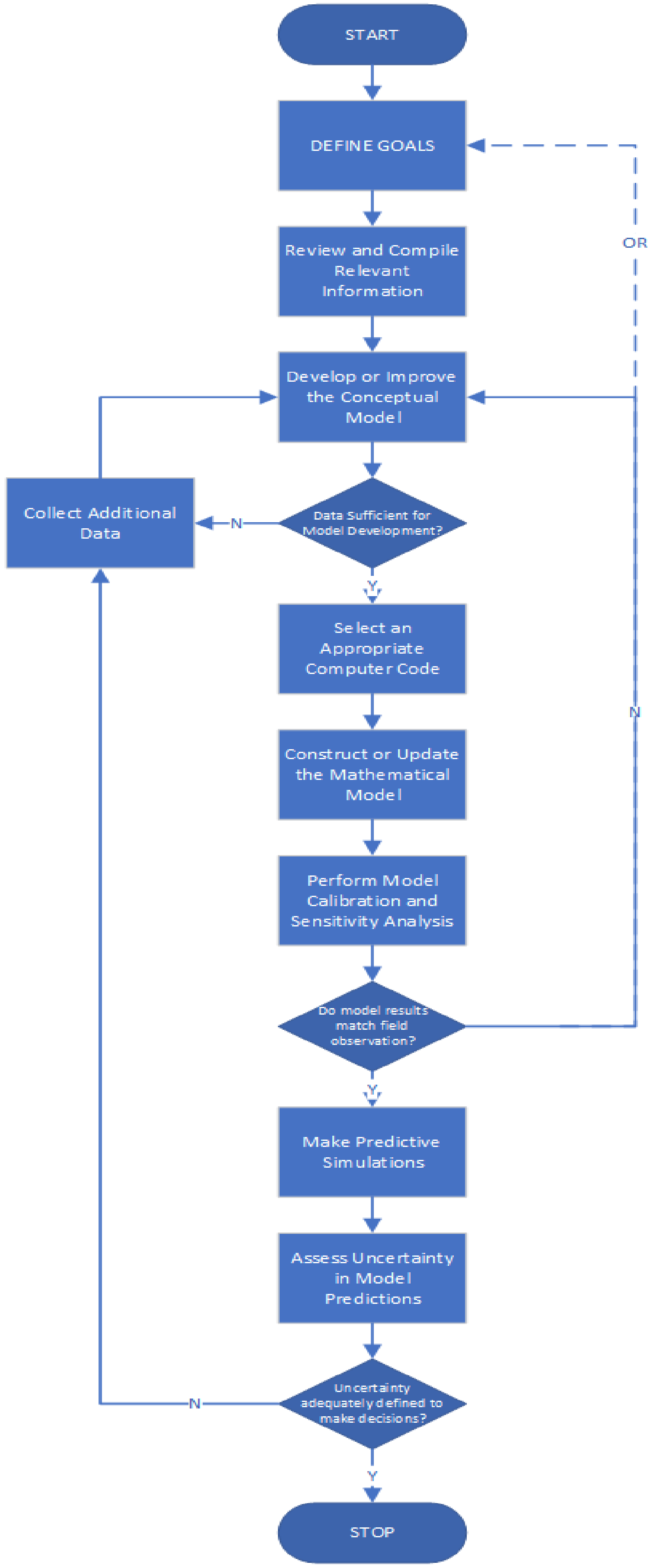

Figure 1: Typical groundwater modelling workflow.

2.1.1 Model objectives

Groundwater models must be fit for purpose. 'Fit for purpose' means that the model is designed and constructed to satisfy relevant project objectives and that model predictions are sufficiently robust and reliable. For example, a groundwater model that is developed and operated to design a mine dewatering system may not have sufficient geographic extent to evaluate potential impacts on groundwater dependent ecosystems (GDEs) or nearby water users. It may use a fine grid spacing to estimate drawdown and flow rates near the pit, but a coarser spacing would be needed to evaluate drawdown further from the proposed operation without excessive run times. The dewatering model would be fit for the purpose of dewatering system design but would not be fit for the purpose of evaluating potential impacts further away from the pit.

The model objectives must be clearly stated before model development begins to provide confidence that the resulting model will be fit for purpose. Examples of common model objectives are shown in Table 3. Model objectives for a particular project may include some or all of these, or others as appropriate.

Table 3: Example model objectives.

Objective	Rationale
Evaluate drawdown at nearby water users	Determine if the proposed project will have minimal impacts or greater than minimal impacts as describes in the AIP.
Evaluate potential impacts on GDEs	Assess magnitude and duration of potential impacts from proposed project on GDEs.
Evaluate flow directions and travel times	Determine if the proposed project may cause changes in groundwater flow directions or travel times compared to baseline conditions.
Assess SEARs and COAs	Evaluate whether the proposed project will be in compliance with water-related Secretary's Environmental Assessment Requirements (SEARs) and Ministerial Conditions of Approval (COAs).

Modelling objectives must be:

- Reviewed regularly throughout the model development and application process.
- Updated as new information is gathered or new evaluation targets are identified.
- Clearly communicated between the project proponent and the department's Water division.

2.1.2 Model complexity

The level of complexity for an individual model must be commensurate with the groundwater model objectives and potential impacts on water sources. Hill and Tiedeman (2007) provide a set of guidelines for groundwater model applications. Their Guideline 1 is entitled Apply the Principle of Parsimony, which suggests that a model be kept *'…as simple as possible while accounting for the system processes and characteristics that are evident in the observations and are important to the predictions, and while respecting all system information.'*

If the take of water may result in potentially significant impacts on water sources, the AIP requires that *'…the predictions should be based on complex groundwater modelling conducted in accordance with the Australian Groundwater Modelling Guidelines…'*

The AGMG describes three model confidence levels classes (CLC) based on a number of factors. The appropriate level of complexity for a particular model could be represented by the different CLCs described in the AGMG.

The GMP must describe the modelling approach and the complexity of that approach must be agreed upon in advance between the project proponents and the department's Water division. It must also clearly specify the target model CLC as defined in the AGMG. Assessment of model CLC without firstly specifying a target is meaningless.

2.1.3 Literature review

Planning for a groundwater model must include a review of the existing literature for the project and surrounding area. The literature review can provide important data and information related to both the conceptual and mathematical model components of the overall groundwater model.

Groundwater models developed for previous projects within the water source(s) that may be impacted by the proposed project must be identified. Review of existing models is critical to ensure consistent application of boundary conditions and hydraulic properties in a region. If an approach from an existing model is not employed for a subsequent model, the project proponent must justify the variation from the existing model and identify how those differences are related to achieving the model objectives. Notwithstanding, adopting elements and parameters from existing groundwater models must be justified and must be shown to be appropriate.

2.1.4 Geographic and temporal extent

The geographic and time scales of interest must be defined in the GMP. The geographic extent must allow the hydrogeological processes that control groundwater movement to be incorporated into the conceptual and mathematical model.

The geographic extent must be large enough to encompass:

- Locations of potential receptors such as GDEs, other water users, connected surface water sources, etc.;
- Extent of potential impacts;
- Key current and reasonably foreseeable future stressors on the hydrogeological system; and,
- Relevant hydrogeological boundaries.

The time scale of the groundwater model must be defined based on the model objectives and an initial assessment of potential impacts to be evaluated. The model time scale may be affected by:

- Project planning and development timeframes;
- Time for potential impacts to propagate to receptors;
- Time required for the groundwater system to recover after the proposed project is complete;
- Potential long-term, post-project impacts on water resources; and,
- Extent of historical and predicted effects of neighbouring projects.

In general, larger areas of expected impact and greater volume or rate of water takes will require longer time scales of assessment, often on the order of tens to hundreds of years. The geographic and time scales of the model must be agreed upon between the project proponent and the department's Water division prior to beginning the model. They must be revisited periodically while the model is being developed and applied to ensure that they remain aligned with the model objectives.

2.1.5 Inclusion of potential cumulative impacts

The AIP requires that evaluation of cumulative impacts be based on the combined impacts of all 'post-water sharing plan' activities within the water source. Existing and reasonably foreseeable future projects that generate aquifer interferences within each water source under consideration must be identified during the literature review as part of the model planning process.

Numerical models are commonly employed to assess cumulative impacts due to factors such as the large area to be simulated; long temporal scale to assess impacts; the presence of multiple aquifers, multiple groundwater users, and GDEs; surface and groundwater interactions; and coalescing data, impacts, and models from multiple projects. Recommended procedures for evaluating cumulative impacts are the subject of a companion publication to this document (Stantec, 2021a). Howe (2011) developed a framework for assessing potential local and cumulative effects of mining on groundwater resources.

The GMP must include the approach to assess cumulative impacts, such as defining the model area and discretisation and the methods to assign model inputs such as boundary conditions and hydraulic properties. Where possible, existing models in the same region must apply similar approaches to assign boundary conditions and hydraulic properties.

Predicted impacts from other projects may be included as boundary conditions. They may also be modelled explicitly by incorporating the inputs from the other projects' groundwater models. The approach for assessing cumulative impacts must be agreed upon between the project proponent and the department's Water division as part of the model planning process.

2.1.6 Climate change considerations

Changes in climate, including future changes in rainfall and recharge, are likely to impact groundwater resources throughout NSW. These changes will place additional pressure on water resources, particularly in certain parts of NSW, and require consideration for projects where groundwater modelling is undertaken into the future.

Understanding the predicted changes will help decision-makers manage the State's water supply in the long-term. Projections from the NSW/ACT[1] Regional Climate Modelling (NARCliM) project have been used to provide updated information on the projected impacts of climate change on groundwater recharge and surface runoff in the near future (2030) and far future (2070) (DPIE, 2021). By 2070, it is predicted that:

- Large changes are projected to occur in groundwater recharge and surface runoff.
- More recharge is likely across most of the state with increased runoff in autumn due to projected increases in autumn rainfall.
- The alpine areas and southern NSW are expected to experience considerable declines in both recharge and runoff.

The actual impact of predicted climate change on a Major Project will be highly variable depending on the type of project, duration of the activities, and the location. Therefore, the need for consideration of the potential impacts of climate change is complex.

There is a number of datasets on predicted climate scenarios available to proponents, such as the NARCliM predictions. These datasets must be taken into consideration for Major Projects that have a lifespan of more than 50 years or are located in areas where considerable changes to the hydrological cycle (rainfall, runoff) are predicted. Where appropriate, climate change prediction datasets can be used for scenario modelling to determine the impact of climate change on the activities, including the cumulative impact. In some instances, predicted changes in climate may reduce the impact of an activity on groundwater resources.

[1] ACT: Australian Capital Territory.

2.1.7 Planning for uncertainty analysis

A groundwater model is by necessity an imperfect representation of a natural hydrogeological system. As described in the AGMG, modelling results presented to decision-makers must include estimates of uncertainty. The AIP requires that an analysis of prediction uncertainties be included in a groundwater modelling project whenever such uncertainty may have a significant impact on the environment or other authorised water users.

Uncertainty analysis in the context of groundwater modelling is the subject of several publications and active scientific research. The Independent Expert Scientific Committee (IESC) on Coal Seam Gas and Large Coal Mining Development developed an explanatory note outlining three broad approaches to uncertainty analysis (Middlemis and Peeters, 2018). This was an outgrowth of a groundwater modelling uncertainty workshop that was held in 2017, a summary of which is provided in (Middlemis et al., 2019). Doherty (2015) and Anderson et al. (2015) also describe approaches to uncertainty analysis in groundwater modelling. Doherty and Moore (2020) present a framework for decision support modelling incorporating uncertainty quantification.

The GMP must describe the approach to uncertainty analysis that will be employed on the project. The approach must be related to the model objectives, the types of predictions required of the model, and the overall complexity of the model. The approach for analysing uncertainty must be agreed upon between the project proponent and the department's Water division as part of the model planning process.

2.1.8 Independent review

The AIP requires independent review of groundwater models developed to support Major Projects approved under Division 4.1 of the EP&A Act 1979 or for any mining or Coal, CSG production activity not subject to the Gateway process. The independent review must take the form of a peer review as described in the AGMG. The GMP must identify the independent reviewers who will be engaged for the project and must clearly describe the independent review process. Actual and perceived conflict of interest must be clearly articulated and resolved.

2.2 Agency engagement

EMM (2021) provides a framework for early and continuing engagement by project proponents with the department's Water division. Consultation with the department's Water division must begin during project conceptualisation to define baseline data collection requirements through the development of an initial GMMP.

The GMMP is expected to be a stand-alone report submitted to the department's Water division. The initial GMMP may not include details of the groundwater modelling approach depending on the amount of data available for the project area. The GMP may be incorporated into the GMMP as the project evolves and the groundwater modelling approach is more clearly defined.

Engagement between project proponents and the department's Water division must continue throughout the model development, application, reporting, and review process. Discussions specific to the groundwater model must be incorporated into the overall workflow for groundwater documentation described in EMM (2021).

3 Conceptual hydrogeological model

In this section: Developing the conceptual hydrogeological model.

Key references consulted:

- *AGMG* (Barnett et al., 2012);
- *Groundwater Monitoring and Modelling Plans - Information for prospective mining and petroleum exploration activities* (NSW Office of Water, 2014);
- *Guidelines for groundwater documentation for SSD/SSI projects* (EMM, 2021); and,
- *Applied groundwater modelling - simulation of flow and advective transport* (1st ed Anderson and Woessner, 1991; 2nd ed Anderson et al., 2015).

A key component of the groundwater modelling project is development of a robust conceptual model of the site. A conceptual model is a descriptive representation that consolidates the current understanding of the key processes of the groundwater system. An extensive body of guidance and scientific literature exists regarding conceptual groundwater model development and application.

Conceptualisation of the groundwater system must start early in the overall Major Project timeline, with a preliminary conceptual model helping to guide baseline data collection well before mathematical modelling can begin. The key elements of the conceptual model must be guided early by the Major Project objectives and anticipated water related impacts, with refinements driven by the groundwater model objectives defined during the model planning stage.

The level of detail in the conceptual model must be based on data availability, modelling objectives, knowledge of the groundwater system, and the natural complexity of the system. The conceptual modelling process must be regarded as iterative, with the conceptual model being updated or even replaced as new data are developed and as mathematical model results are available to test the conceptual framework.

Conceptual hydrogeological models must be developed and updated:

- At the start of the project, to help guide baseline data collection.
- After baseline data collection is complete, to guide the mathematical model development.
- At the conclusion of mathematical modelling, incorporating any updates from model development.

Alternative conceptual models must be developed and evaluated to assess potential uncertainty in predictions due to different views of how the groundwater system functions. Bredehoeft (2005) and Ye et al. (2010) show that uncertainty in system conceptualisation produces greater uncertainties in mathematical model predictions than does uncertainty in parameterisation or model inputs.

3.1 Data availability

The conceptual model must be based on observed data of known quality wherever possible. A literature and data review must be undertaken early in the overall Major Project groundwater impacts assessment (GIA) development to identify available data, the potential existence of other models of the same water source(s), potential sensitive receptors (other water users, connected surface water bodies, GDEs, etc.), and data gaps that need to be addressed. A complete assembly of all relevant existing data, information and other knowledge sources will provide for a robust conceptual model that will in turn lead into a more defensible and useful mathematical model.

The initial conceptual model can help guide the baseline data collection program required by the AIP. Typically, two years of baseline data are required to assess potential impacts against. Nonetheless, this is not a target. Longer data records would be more useful.

The baseline data may provide important information to update or refine the conceptual model prior to starting the overall groundwater modelling program. Data quality must be assessed. Difficulties in mathematical model calibration or errors in system conceptualisation can occur due to poor quality observation data.

3.2 Contents of the conceptual model

The conceptual model must include the elements identified in Table 4 and described in the sections below. An example of a conceptual model is provided in Figure 2 (EMM, 2021).

Table 4: Major elements of the conceptual hydrogeological model.

Objective	Rationale
Hydrogeological domain	Vertical and horizontal extent of the conceptual and subsequent mathematical model, including resolution.
Hydrostratigraphy	Geologic and hydrogeologic units within the model domain, including vertical discretisation.
Aquifer and aquitard properties	Flow and storage properties of the hydrogeologic units.
Boundary conditions	Flow conditions defining the boundaries of the model domain.
Water sources	Groundwater and surface-water sources that may be affected and subject to permitting.
Surface water/groundwater interaction	Gaining and losing streams, interactions between groundwater and lakes, mine pits.
Sensitive receptors	Locations and magnitudes of receptors that may be affected.
Stresses and inputs	Water balance elements such as groundwater pumping, recharge through precipitation, etc.
Water quality, salt-water intrusion	Water quality based on dissolving constituents or salinity depending on the specifics of the location and project.

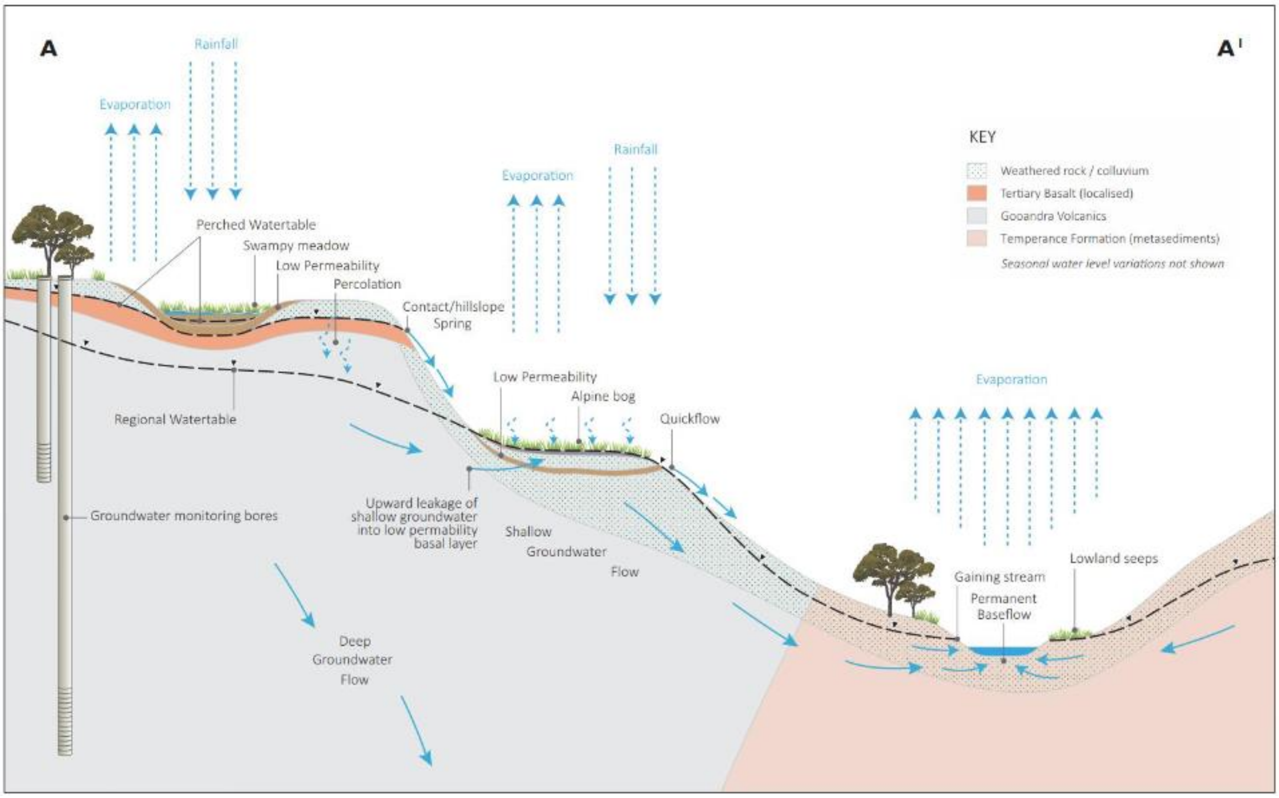

Figure 2: Example of a hydrological conceptual Model (sourced from EMM, 2021).

3.2.1 Hydrogeological domain

The horizontal and vertical hydrogeological domain of the conceptual model must be based on:

- Modelling objectives.
- Locations of potential sensitive receptors.
- Locations of possible cumulative impacts from other past, present or reasonably foreseeable future projects.

A qualitative risk assessment conducted during conceptual model development can be used to help determine the hydrogeological domain of the analysis. The risk assessment must provide an understanding of:

- The relative scale of potential spatial and temporal impacts.
- Whether there are receptors that may be affected by the project.
- The degree of anticipated uncertainty in the modelled system.
- Potential environmental effects.
- The potential for cumulative effects of the proposed project on effects due to other past, existing, or reasonably foreseeable future projects.

The hydrogeological domain of the conceptual model must feed directly into the domain of the mathematical model. It must be extensive enough to cover the locations of key stresses on the groundwater system, both in its pre-development state and in the reasonably foreseeable future conditions. It must also be large enough to capture the processes controlling groundwater behaviour in the project area. The model domain must extend to natural hydrogeological boundaries or be large enough such that potential effects of assumed boundary conditions do not impact the predictive power of the mathematical model.

3.2.2 Hydrostratigraphy

The hydrostratigraphy of the model domain must be described in the conceptual model. This will include information such as:

- Lateral and vertical extent of geological units;
- Stacked aquifer relationships;
- Presence or absence of aquitards between aquifers; and,
- Stratigraphic, structural, or geomorphological discontinuities such as:
  - Faults;
  - Fracture systems;
  - Facies changes or pinch-outs; and,
  - Karst areas.

The hydrostratigraphic elements of the conceptual model must inform the layering defined in the mathematical model. However, the mathematical model layers do not have to correspond exactly to the stratigraphic units. A model layer may lump more than a single stratigraphic unit, and a stratigraphic unit may be represented by multiple model layers (Section 4.5).

3.2.3 Aquifer and aquitard properties

Aquifer and aquitard properties control the movement of water and solutes in the subsurface and the responses of the hydrogeological system to stresses such as pumping and recharge. Quantified aquifer properties are necessary for mathematical model development and calibration. Key parameters and concepts to be considered in the conceptual model include:

- Saturated horizontal and vertical hydraulic conductivity properties.
- Specific yield or storativity (specific storage).
- Effective porosity if particle tracking is to be performed.
- If important to the assessment, relationships of unsaturated hydraulic conductivity with moisture content included hysteresis.
- Heterogeneity and anisotropy (vertical and horizontal).
- Scale upon which parameters are determined. For example, laboratory tests of hydraulic conductivity test the parameter at a different scale than long-term aquifer tests and may provide different information for parameterising a mathematical model.

3.2.4 Geological and hydrological boundary conditions

The conceptual model must include three-dimensional (3D) representations of the boundaries of the groundwater flow system. Boundary conditions are generally defined as no-flow, constant-head, or a mixed boundary condition.

Boundaries must be based on an understanding of the important flow processes in the area of interest, natural geological boundaries or hydrological divides, and the potential effects of future stresses to be imposed on the system. Defining boundary conditions may involve trade-offs between the existence of natural boundaries far from the area of interest and the practical extent of a mathematical model in terms of complexity and model run times.

3.2.5 Water sources

The conceptual model must identify the sources of water that are potentially affected and may need to be licensed per AIP requirements.

3.2.6 Groundwater-surface water interaction

Groundwater-surface water interaction may be an important factor if surface water sources are connected to groundwater systems that are potentially affected by the proposed action. They may also be important if GDEs are anticipated to be important receptors in the groundwater impact assessment.

The conceptual model must describe the nature of the interactions between surface water and groundwater such as the degree of connectedness and whether the surface water elements are gaining or losing reaches, and any changes in time in the relationships between groundwater and surface water. The nature and degree of groundwater-surface water interaction defined in the conceptual model must be represented in the mathematical model.

3.2.7 Sensitive receptors

The locations and magnitudes of sensitive receptors that may potentially be affected must be represented in the conceptual model. Such receptors may include:

- Culturally Significant Sites (CSS).
- Locations and magnitude of withdrawals from each water source by agricultural, industrial, and municipal water users.
- Locations of connected surface water sources.
- Locations and extents of GDEs.
- Locations of Biophysical Strategic Agricultural Land (BSAL).

Proper representation of sensitive receptors in the conceptual model will help identify the predictions needed from the mathematical model.

3.2.8 Stresses and inputs

The most common and obvious human-caused stresses to an aquifer system is groundwater extraction by pumping from wells. Other human-caused stresses could include passive drainage into mine workings or tunnels, or recharge through wells, basins such as a managed aquifer recharge system, or project components like mine tailings storage facilities (TSF).

Natural stresses to the aquifer system include recharge through precipitation and runoff, and discharge through evapotranspiration (ET). Discharge into surface water bodies may represent a stress to the groundwater system if groundwater-surface water interaction is not explicitly modelled.

3.2.9 Water quality and saltwater intrusion

Existing surface water and groundwater quality must be included in the conceptual model. Potential changes in water quality in the aquifer and connected surface water sources must be considered even if they are not explicitly included in a mathematical model.

In some projects near the coast or inland saline water bodes, saltwater intrusion may be a potential concern. In these areas, salinity or water density must be characterised and included in the conceptual model.

3.3 Conceptual model uncertainty

Conceptual models are inherently qualitative and uncertain. The full complexity of a given hydrogeological system cannot be completely represented. Field data are incomplete and carry their own uncertainties and approximations of true hydrogeological conditions.

Two approaches can be used to address uncertainty in the conceptual model (Anderson et al., 2015). First, the conceptual model must be updated and revised as new information becomes available. There must be an ongoing process of refinement as data are developed and as the mathematical model progresses. As illustrated in **Error! Reference source not found.**, the mathematical model calibration process can provide important insight into the conceptual model.

Second, alternative versions of the conceptual model can be developed early in the overall process. As new data are gathered, understanding of the groundwater system should improve and some alternative conceptualisations may be discarded while others may be proposed. Calibration of the mathematical model and evaluation of prediction uncertainties may help test the alternative conceptual models.

The model objectives and available resources will help determine the level of effort that goes into assessing conceptual model uncertainty. The final conceptual model can be considered adequate if the corresponding, calibrated mathematical model provides predictions of sufficient quality to meet the overall project needs.

3.4 Format and contents of the conceptual Model

The conceptual model may be developed as a series of maps, cross-sections, block models, and tables of aquifer and aquitard characteristics. It may be also developed and maintained in a digital format using 3D geological modelling tools, from which appropriate tables and figures can be abstracted for presentation purposes.

An advantage of using digital modelling tools is that the conceptual model parameters can be directly exported into the mathematical model framework and can then be more easily updated with results of the mathematical modelling calibration and prediction process. These tools may also include 3D visualisation capabilities that can facility communication and understanding of a conceptual hydrogeological model.

Whatever format is used, the contents of the final conceptual model must include at a minimum figures and maps showing:

- Water sources.
- Existing groundwater and surface water withdrawal locations.
- Expected groundwater and surface water withdrawal locations to support the proposed project.
- Groundwater monitoring locations (industry, private and government).
- Surface water monitoring locations (industry, private and government).
- Weather and climate monitoring locations.
- Mapped GDEs.
- Topography and drainage.
- Surface geology map at the regional and local scale, including geological structure (faults, folds, etc.).
- Depth to water table plan, identifying measurement locations and any depth information that has been inferred/estimated.
- Water table elevation contour plan, identifying measurement locations and any elevation information that has been inferred/estimated.

- Groundwater elevation/potentiometric surfaces for confined aquifers, identifying measurements points and any elevation information that has been estimated.
- Vertical gradients between layered aquifer units.
- Distribution of rainfall, estimated recharge, and estimated ET across the model domain.
- Time-series groundwater level and stream gauge data, at an appropriate and consistent scale to observe trends over time and between locations, presented with rainfall data.
- Hydrostratigraphic unit thickness and extent maps (where sufficient data is available).
- Spatial variation in groundwater salinity for each water source.

Tabulated information must include:

- Key aquifer and aquitard characteristics such as hydraulic conductivity, storage coefficient and specific yield, effective porosity.
- Climate and weather summaries from established monitoring locations.
- Summaries of groundwater and surface water withdrawals from all water sources identified in the conceptual model.
- Summaries of anticipated withdrawals from all water sources to support the proposed project.
- Water balance summarising major groundwater inflows and outflows in the model domain, such as.
  - Recharge due to precipitation, seepage from streams and lakes, irrigation return flows, etc.;
  - ET;
  - Groundwater pumping and surface water withdrawals related to use categories such as agriculture, industrial, municipal, mining, and CSG projects;
  - Groundwater discharges to gaining streams and lakes; and,
  - Surface water discharging from the model domain such as rivers and streams.

3.5 Checking the conceptual model

The conceptual model must be checked to evaluate its suitability and overcome errors. Simple checks that must be considered include:

- Development of a simple, preliminary water balance that will help evaluate later mathematical model results.
- Testing the conceptual model with simple analytical models to assess how well they represent the observed conditions.
- Reviewing the conceptual model with other professionals and stakeholders.

4 Mathematical model development

In this section: Developing the mathematical model from the conceptual model.

Key references consulted:

- *AGMG* (Barnett et al., 2012);
- *Guidelines for the assessment of groundwater abstraction effects on stream flow* (Environment Canterbury and Pattle Delamore Partners Ltd, 2000)*;*
- *ASTM D6170-17, D6170-17 Standard guide for selecting a ground-water modelling code* (ASTM, 2017);
- *ASTM D5609-16, Standard guide for defining boundary conditions in groundwater flow modelling* (ASTM, 2016);
- *D5610-94 Standard guide for defining initial conditions in ground-water flow modelling* (ASTM, 2014);
- *Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems - an introduction* (Franke et al., 1987);
- *Applied groundwater modelling - simulation of flow and advective transport* (1st ed Anderson and Woessner, 1991; 2nd ed Anderson et al., 2015); and,
- *Effective groundwater model calibration* (Hill and Tiedeman, 2007).

Once a conceptual model is in place, a mathematical model could be developed to provide quantitative predictions. The mathematical model must be closely tied to the conceptual model, with an iterative approach to overall development as described in Section 3.

4.1 Modelling approach

The mathematical model must be developed according to the model objectives, the GMP (Section 2) and conceptual model (Section 3), with each step in its development documented as it proceeds. Choices regarding aspects of the model such as analytical or numerical approach, grid type, model resolution, and boundary conditions must be based on the modelling objectives. The assumptions of the chosen approach must be valid for the groundwater system being modelled. The development phases of a groundwater model have direct impact on the success of model calibration and the accuracy of subsequent solutions.

It is reasonable and often necessary to modify the mathematical model design as model construction progresses, new insights to the groundwater system are developed, and limitations of available modelling tools are encountered. It is important to record all steps of model construction, but most important is the documentation of model aspects that either differ from standard procedure or have been changed from the original GMP.

4.2 Model complexity

The level to which a mathematical model appropriately represents the conceptual model impacts the CLC of model solutions. An effective model achieves an acceptable state of parsimony, in which the model is simple enough to be manageable, yet complex enough to represent the system at the desired level of detail.

Groundwater models are simplified representations of the natural hydrogeological systems they represent. The appropriate level of complexity depends on the environmental complexity and sensitivity of the natural system and the level of data available from which to develop the model. In general, less complex and environmentally sensitive groundwater systems, or those for which fewer data are available, may be represented adequately by a less complex groundwater model Figure 3 illustrates how model and environmental complexity can relate in a given project.

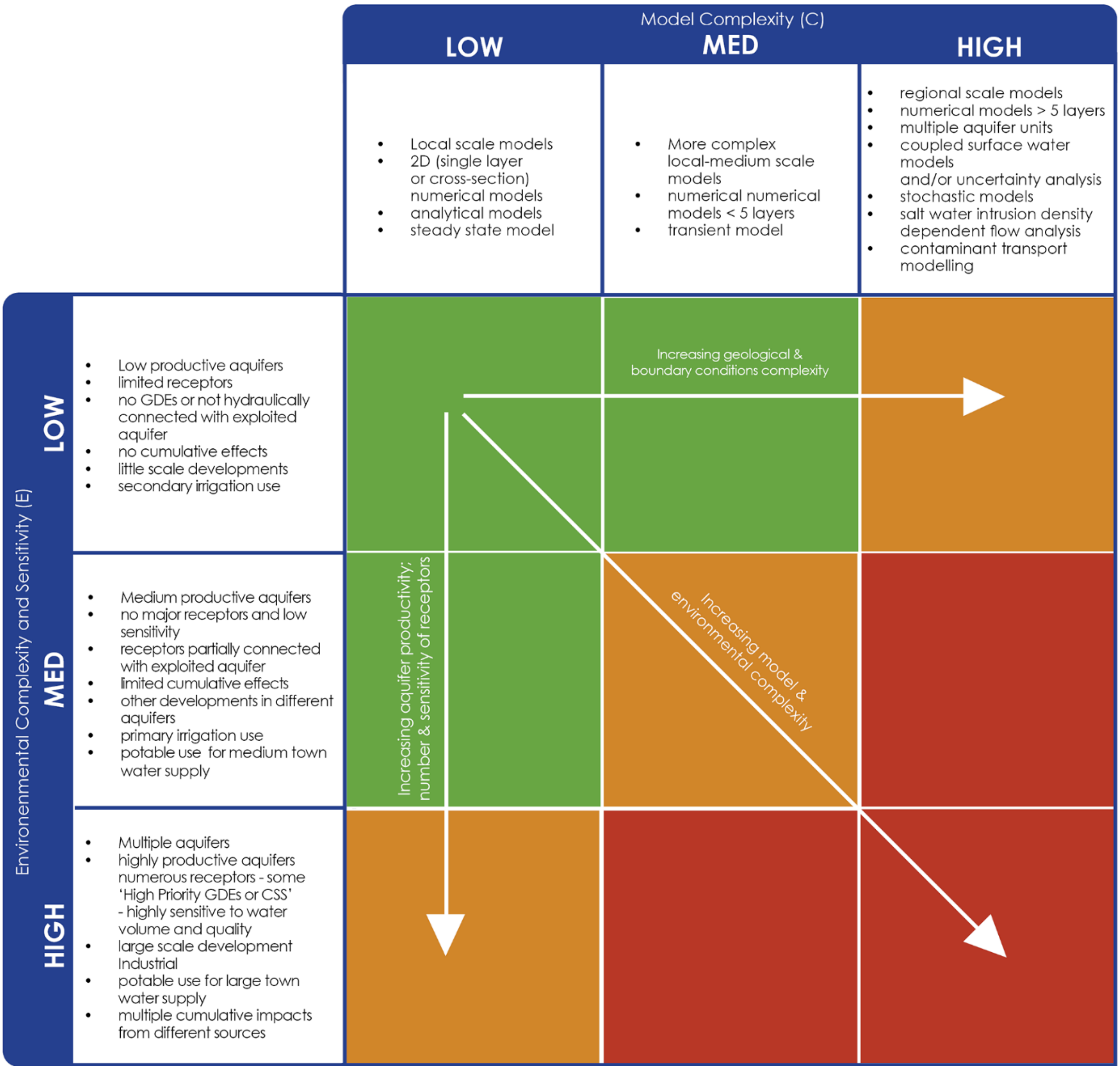

Figure 3: Environmental sensitivity and model complexity.

4.3 Code selection

Once an acceptable conceptual model is in place and the modelling objectives have been agreed upon, a suitable computer code must be selected. There is no 'best' computer code for groundwater modelling, so the decision requires balancing multiple criteria. Key issues to consider and document when selecting the modelling code include:

- Ability to fulfill essential capabilities identified in the GMP and represent key aspects of the conceptual model.
- Balance between nonessential but useful capabilities identified in the GMP and conceptual model.
- Efficiency of numerical approach – an efficient numerical method should result in shorter run times, which will be a benefit to the overall project.
- Documentation and validation of the code – the selected code must be well documented and widely accepted in the scientific and regulatory communities.
- Availability – the selected code must be commercially available, and ideally would be in the public domain.

Each code has different capabilities and applications that must be reviewed to ensure the most appropriate code is selected. Successful implementation of the code in projects with similar modelling objectives must be documented if possible.

The MODFLOW family of finite difference numerical codes, developed by the United States Geological Survey (USGS) is well documented, available in the public domain, and has gained acceptance for groundwater modelling in jurisdictions around the globe. As its name implies, the code is implemented with modules that each simulate specific aspects of a groundwater flow system such as wells, drains, rivers, lakes, flow barriers etc. on the model solution.

If MODFLOW is the selected code, the specific package (e.g. MODFLOW-6, MODFLOW-2005, MODFLOW-USG etc.) must be capable of implementing the essential and desired nonessential capabilities.

Several commercial graphical user interfaces (GUIs) exist that can be used in conjunction with the MODFLOW model code to assist with model construction. The USGS also maintains in the public domain a GUI, ModelMUSE, for MODFLOW. While not required, a GUI can greatly simplify and speed model development.

Another widely implemented and accepted commercial code is FEFLOW. This code implements a finite element numerical method. It also includes an integrated GUI to aid in model development. FEFLOW is part of a larger family of commercially available hydrological modelling tools.

Some jurisdictions list acceptable codes, e.g. the Nevada Division of Environmental Protection (NDEP, 2018). The department's Water division does not require that a code be selected from a pre-screened list of alternatives. While MODFLOW and FEFLOW are commonly used on groundwater modelling project in NSW, mention of these codes does not imply endorsement by the department's Water division. Other computer codes are available as well. Depending on the modelling objectives, neither MODFLOW nor FEFLOW may by themselves be suitable for a particular project.

4.4 Horizontal and vertical extent

The horizontal, or spatial, extent of the model must be large enough to capture the geographic distribution of significant hydrological features on the surface and at depth. The vertical extent of the model must be deep enough to accurately model potential flow paths and relevant hydrostratigraphic units. Both must also reflect the modelling objectives and conceptual model.

A prohibitively large horizontal or vertical domain may result in increased run times and unnecessary complexity. Conversely, a small extent may not capture all important hydrological features in the system and result in large uncertainty in predictions.

The model extent must be large enough so that external boundary affects do not affect the model predictions in the areas of interest. The influence of external boundaries propagates inward, and proximity to areas of interest may yield invalid model solutions. Overall, the spatial extent of the model must follow the conceptual model, which may need to be revised during the implementation of the mathematical model.

4.5 Model layering

Most groundwater systems consist of multiple hydrostratigraphic units or stacked aquifers (Broadstock, 2011). In general, model layering must reflect the hydrostratigraphic units defined in the conceptual model and be consistent with the objectives of the model.

Constructing model layers that accurately simulate the extent and dimensions of actual hydrostratigraphic units can be complicated. For models where vertical flow components are unimportant, a single layer may be used to simulate horizontal flow. Conversely, if vertical flow is important within a single hydrostratigraphic unit, it may need to be divided into multiple layers in the mathematical model. An additional model layer or layers simulating an aquitard may also be required.

In some cases, cross-sectional models may be adequate. Single layer and cross-sectional models are two-dimensional (2D). Simulation of 3D flow is best achieved using multiple model layers for both aquifer and aquitard units. Each layer may represent an individual hydrostratigraphic unit, a smaller division of the same unit, or multiple units. 2D models may also entail the representation of multiple hydrostratigraphic layers.

4.6 Discretisation in space and time

Discretisation is the process of dividing the model domain into discrete components. The resulting resolution in space and time must satisfy the modelling objectives without compromising project constraints. A higher-resolution discretisation can yield a more informative solution, but may also strain memory, run time, and budget limits of the project.

Steady-state solutions assess the condition of the system at equilibrium, while transient simulations model temporal variations in model inputs and the resulting predictions over time. Transient models require the discretisation of both space and time, while steady-state models only require discretisation of space.

In general, a transient model will be needed to predict potential future impacts over time. In some limited cases, multiple steady-state models with inputs representing different inputs and boundary conditions may be sufficient.

4.6.1 Spatial

Spatial discretisation takes the form of a grid or mesh, which must provide sufficient horizontal and vertical resolution to accurately simulate the geometry of important features within the model domain. Two major grid methods exist for spatial discretisation: finite difference grids and finite element meshes.

Finite difference grids consist of a horizontal, rectangular grid of parallel lines combined with vertical layers that define individual model cells. Horizontal cell dimensions can be reduced in areas of interest by reducing the horizontal spacing along either or both axes. These increase the resolution along each axis in all regions of the model which can increase run times.

Finite element meshes are made up of a system of nodes connected by lines. In two dimensions the nodes form the vertices of a system of triangular or quadrilateral elements. The horizontal elements can be combined with layering to form a 3D structures, or fully 3D elements can be defined as polyhedra.

In a finite element formulation the resolution around an area of interest can be increased with the addition of more nodes in only that area, leaving areas of lesser interest with a lower resolution (larger elements). Finite element meshes can more easily accommodate complex geometry than Finite difference grids.

In general, finite element numerical methods are more intense computationally than finite difference methods. The use of unstructured grids in the finite difference method as implemented in MODFLOW-USG attempts to blend the geometric advantages of the finite element approach with the computational efficiencies of the finite different methods. The decision between finite difference and finite element formulations is an important part of code selection (Section 0).

4.6.2 Temporal

Temporal discretisation consists of dividing the time for which a transient model runs into stress-periods and time steps. Stress-periods are set according to significant changes in model inputs (see Section 4.9). The length of each stress-period depends primarily on the data available regarding the individual inputs.

Stress-periods are divided into time steps for model calculations. Shorter time steps can better resolve the influence of sudden stress changes, while longer time steps may be appropriate for capturing the impact of more gradual changes.

The desired frequency of model outputs must be considered when defining stress-periods and time steps. Outputs can be calculated as frequently as every time step if desired. Frequent model outputs can result in large output files that are difficult to manage.

4.7 Boundary conditions

A boundary is a geometrical surface defining the 3D extent of the model domain. Boundary conditions are the flow properties at those boundaries defined by a mathematical expression of the state of the groundwater system that constrain the equations making up the mathematical model. The three main types of boundary conditions are characterised as follows:

- **Specified head** – also referred to as a Dirichlet (Type 1) boundary: The head value at the given cells/nodes is a function of position and time and a flow rate across the boundary is calculated accordingly. Constant-head boundaries are a type of specified head boundary.
- **Specified flux** – also referred to as a Neumann (Type 2) boundary: The flux across the boundary is defined as a function of position and time and is specified according to circumstances external to the system. No-flow boundaries are a type of specified flux boundary.
- **Head dependent flux** – also referred to as a general head or Cauchy (Type 3) boundary: The flux across the boundary or part of the boundary is a function of the change in head within the aquifer adjacent to the boundary. These values change throughout the problem solution in response to the calculated changes in head.

Any of these boundary conditions may be constant or variable through time. In some cases model boundaries can and must be used to represent hydrological features in the system. However, exercise caution when representing groundwater divides as no-flow boundaries in transient models. Stresses in the groundwater system may change the location of groundwater divides and cause the model to yield an invalid solution.

The effects of all boundaries on model results must be assessed, particularly when model boundaries are placed closer to areas of interest than they are found in the natural system. This may be done to reduce the model domain to a reasonable size, but the placement of each boundary must be evaluated to avoid invalid model solutions.

4.8 Initial conditions

The conditions of the groundwater system at the beginning of a steady-state model run are known as initial conditions. They do not influence the final solution, but initial conditions more proximal to the final solution shorten model run time. Initial conditions for transient models are not pre-defined constant values but are included in the mathematical problem statement. These conditions in transient model impact solutions at each time step. The model utilises an initial condition for each parameter analysed in the solution.

When possible, the solutions of a steady-state model with identical boundary conditions must be used in transient models. This can only be done for systems that are assumed to reach equilibrium at some point but provides initial conditions that are stable and proximal to final solutions of the transient model. Otherwise, results during the early stages of transient model runs can be misleading. In this case allow the transient model sufficient run time to equilibrate, which may involve ignoring solutions from early time steps. The impact of the initial conditions on transient solutions becomes more negligible with increased time.

4.9 Inputs

Groundwater stresses are defined as natural or anthropogenic (human-induced) processes that lead to the removal or addition of water from or into a groundwater domain. Natural stresses include recharge through precipitation and ET. Anthropogenic stresses include factors such as pumping water from an aquifer or injecting/infiltrating water into an aquifer.

Stresses to the groundwater system are implemented in mathematical models by defining appropriate inputs. Inputs commonly include recharge to the system from various sources (precipitation, losing streams, injection wells, etc.), and defined outflows such as ET and pumping rates. Field measurements must be used to define inputs if sufficient data is available.

5 Calibration and sensitivity analysis

In this section: Calibration process and sensitivity analysis.

Key references consulted:

- *AGMG* (Barnett et al., 2012);
- *Applied groundwater modelling - simulation of flow and advective transport* (1st ed Anderson and Woessner, 1991; 2nd ed Anderson et al., 2015);
- *D5981/D5981M Standard guide for calibrating a groundwater flow model application* (ASTM, 2018);
- *China – UK, WRDMAP. Integrated Water Resources Management Document Series. Thematic Paper 1.1: Groundwater flow modelling* (WRDMAP, 2010); and,
- *Guidelines for groundwater modelling to assess impacts of proposed natural resource development activities* (Wels et al., 2012).

Model calibration is the process of adjusting model parameters (for example, hydraulic conductivity, specific storage, recharge flux in, ET flux out and extinction depth) and boundary conditions in order to match simulated model results to field hydrological measurements and processes such as water level elevations and drawdowns, dewatering rates, stream baseflows and spring flows (calibration targets).

5.1 Purpose of calibration

The purpose of model calibration is to demonstrate that the model can adequately simulate field measured water levels and flows, and therefore, predict future groundwater conditions to a desired level of confidence. Depending on the objectives on the modelling study, models may be calibrated to steady-state, transient groundwater conditions, or both.

5.2 Calibration targets

A calibration target is a measure of the state of a hydrological system that can be used to test whether a groundwater model is adequately reproducing historical conditions. Calibration targets may be quantitative or qualitative. Targets must be chosen to represent areas of concern within the model and must be spatially distributed both horizontally and vertically. However, available field data may limit the distribution of target locations. Types and locations of calibration targets must also be chosen based on the objectives of the groundwater model.

Primary quantitative calibration targets are typically groundwater levels measured in monitoring wells within the model domain. Calibration targets may also include artesian well and spring discharges, void inflows (inflows into tunnels, mine pits or underground workings, etc.), lake levels, and stream baseflow (or infiltration in the case of a losing stream section) where such measurements are available.

For models where available field measurements are limited calibration targets may be supplemented with qualitative data. For example, simulation of springs, seeps, ephemeral and perennial streams mapped in the field or referenced on a topographic map may lend confidence to model results in the absence of actual field measurements. In addition, a qualitative assessment of the modelled potentiometric surface(s) compared with measured potentiometric surface(s) based on field measurements and hydrogeological interpretation must also be conducted. Calibration targets may be given weights for use in focusing automated calibration methods to particular zones of interest in the model or in determining calibration statistics.

5.3 Calibration methods

The goal of the calibration process is to minimise the difference between the simulated and measured values, or residuals, at the calibration target locations. Model calibration can be accomplished by an iterative process of manually changing model inputs (hydrogeological parameters and boundary conditions) within reasonably expected ranges and gauging model output (heads, fluxes, saturation) against target measurements or by automated methods using inverse modelling codes such as PEST (Watermark Numerical Computing, 2018) or UCODE (Poeter et al., 2014). Typically, a combination of manual and automated calibration methods is required.

Reasonably expected ranges of key model input parameters must be identified prior to beginning model calibration. Limiting the range of changes in input parameters is particularly important when using automated inverse modelling codes which, if unconstrained, can result in a good fit between measured and simulated results with unrealistic hydrological parameters. An initial unconstrained automated calibration run can provide useful insight into input parameter sensitivity to help guide the calibration process.

5.4 Minimum calibration criteria

The goal of model calibration is to minimise the difference (residuals) between the simulated and measured values at the calibration target locations. Calibration results must be evaluated both qualitatively and quantitively by graphical and statistical means. At a minimum the calibration criteria described in Table 5.1 must be calculated and documented.

Table 5: Minimum calibration criteria.

Objective	Rationale
Simulated vs. interpreted potentiometric surfaces	Comparison of simulated potentiometric surface(s) against potentiometric surface(s) for each aquifer unit based on field measurements and hydrogeologic interpretation
Tabulation of simulation results vs. measured data at target locations	The table should contain: • Target name; • Rationale/significance; • Coordinates; • Measured head or flux; • Simulated head or flux; and, • Target residual (measured minus simulated head or flux).
Graphics of simulation results vs. measured data at target locations	The graphs should include: • Scatter plot of measured vs. Simulated heads (steady state and transient as applicable: additional plots for individual layers/units may be useful); • Reference line of equal measured and simulated values on the scatter plot; • Histogram of residuals; • A map with residuals posted at the target locations; and, • For transient calibrations, hydrographs of measured and simulated heads.

Objective	Rationale
Model mass balance	Table of individual mass balance components compared to conceptual model. Additional tables for individual layers/units/zones may be useful.
Calibration statistics	Calibration statistics should include: • Root mean squared (RMS) error of the residuals; • Scaled RMS error (RMS/range of measured values); • Minimum and maximum residuals; and, • Other metrics may be appropriate depending on the nature of the project.

Calibration statistics provide a useful numerical method for evaluating model calibration. However, calibration results must be evaluated both qualitatively and quantitively. Calibration scatter plots, model mass balance, and modelled potentiometric surfaces must all be evaluated with calibration statistics when assessing the overall model calibration.

5.5 Sensitivity analysis

A sensitivity analysis must be conducted to evaluate the relative effect of different model input parameters and boundary conditions on model calibration. A sensitivity analysis is done by varying individual model parameters and/or boundary condition parameters over a range of values and comparing the simulated results to the calibrated model results. Automated inverse modelling codes may provide parameter sensitivity statistics in output files along with calibration results.

Table 5.2 provides a summary of typical parameters and ranges for sensitivity analyses.

Table 6: Typical sensitivity testing ranges for individual model parameters.

Parameter/Process	Sensitivity Multiplier			
Horizontal hydraulic conductivity	0.1	0.2	5	10
Vertical hydraulic conductivity	0.1	0.2	5	10
Specific yield (Sy)	0.67	0.8	1.25	1.5
Storativity	0.1	0.2	5	10
Net annual recharge	0.5	0.67	1.5	2
ET rate	n/a	0.5	1.5	n/a
ET depth	n/a	Up 0.5 m	Down 0.5 m	n/a
Boundary conductance	0.1			10

Results of model sensitivity analysis must be tabulated and presented graphically including:

- tabulated differences in key calibration statistics for each sensitivity run;
- simulated versus measured scatter plots for steady-state models; and,
- simulated versus measured hydrographs for transient model runs.

6 Model predictions

In this section: Predictions to be included in model runs.

Key references consulted:

- *AIP* (NSW Office of Water, 2012); and,
- *AGMG* (Barnett et al., 2012).

The AIP requires proponents to provide estimates of all water likely to be taken from any water source during or following the activity and all predicted impacts associated with the activity based on certain minimum standards. After a model is calibrated to acceptable levels it can be used as a tool to assess potential impacts of current or future projects. The steady-state condition from the calibrated model, or a specified time from a transient calibration, is used as the initial condition for predictive scenario runs (termed the 'null scenario' in the AGMG).

The GMP and the conceptual model must include descriptions of the predictions required from the mathematical model. Predictive scenarios are typically set up as transient simulations over a predetermined time period. Hydraulic (or mass transport) stresses represented by model boundary conditions or changes in hydrogeological parameters are either added to or removed from the calibrated model to represent the industrial process or climatic event being simulated.

Typical processes modelled in predictive impact assessments include:

- Depletion of groundwater resources.
- Potential changes in water quality for downgradient water users or connected surface water resources.
- Depletion of surface water resources that could impact GDEs or baseflow in perennial streams.

Model predictive scenarios can also be used to assess impact mitigation strategies such as mine reclamation, contaminant source removal or capping, pump and treat remediation systems, etc.

6.1 Predictions required by the AIP

The AIP requires that predictions related to water sources include, at a minimum, the elements listed in Table 6.1.

Table 7: Model predictions required by the AIP.

Prediction	Comment/rationale
Details of potential water level/pressure drawdown or quality impacts on nearby water users who are exercising their right to take water under a basic landholder right.	Consider relevant distance restriction requirements from water sharing plans, or remediation measures to address impacts.
Details of potential water level, quality or pressure drawdown impacts on nearby licensed water users in connected groundwater and surface water sources.	Evaluate potential impacts of the proposed project on existing users.
Details of potential water level, quality or pressure drawdown impacts of GDEs.	Evaluate potential impacts of the proposed project on GDEs specifically.

Prediction	Comment/rationale
Details of potential for increased saline or contaminated water inflows to aquifers and highly connected river systems.	Assess potential salt water intrusion or water quality impacts on water sources.
Details of the potential to cause or enhance hydraulic connection between aquifers.	Assess potential increases intake of water from a source that is otherwise not accounted for

6.2 Cumulative impacts

A cumulative impact can be defined as the incremental impact due to an action when added to other past, present, and reasonably foreseeable future actions (Stantec, 2021a). In some cases, there may be hydrological processes or events occurring outside the project boundary that have the potential to affect hydrological conditions within the project area. A proposed action may also have a cumulative impact, combined with incremental impacts from other nearby operations, on a third party that must be assessed. For instance, a model domain set up to assess the impacts of a new open pit mining operation may have drawdown impacts from nearby mines, in which case drawdown in some areas of the model domain will be cumulative from both operations.

Groundwater models are commonly employed to predict cumulative impacts due to factors such as the large area to be simulated; long temporal scale to assess impacts; the presence of multiple aquifers, multiple groundwater users, and GDEs; surface and groundwater interactions; and coalescing data, impacts, and models from multiple projects. If cumulative impacts are identified as a factor in the conceptual model and GMP, they must be included in the groundwater model predictions.

In some cases, nearby operations may have their own predictive model. If predictive model results are available from nearby operations, these results can be added to the predictive scenario results from the model under consideration to assess the cumulative impacts due to both operations.

Project proponents must be aware, in the event two or more models represent fundamental differences in model development (e.g. definition of boundary conditions) or the predicted impacts for an area, resolution of differences most commonly invokes the ‘Precautionary Principle’. In these cases, the worst-case impact would be considered the most likely and all parties would need to accommodate the associated impact mitigation. There are ways to avoid the application of this worst-case scenario including:

- Collaborate with the department’s Water division from the initial scoping process through final submittals. Given the progression of conceptual models and numerical models is an iterative process, the department’s Water division can provide input throughout the project and ultimately if models are different, the department can provide recommendations on how to resolve the differences or provide a technical opinion as to which model is more representative. In addition, as stated previously, collaboration with the department’s Water division will help avoid fundamental flaws in the model process.
- Submit data collected for the project to the department’s Water division to facilitate releasing the data to be publicly available. The more data are widely shared, the better they may be used to assess differences amongst models.

6.3 Timeframe for predictions

The time periods over which model predictive scenarios are run are determined by regulatory guidelines, operational plan timelines, or estimated durations of the hydrological or transport processes being modelled. Predictive model results must be assessed to determine whether the time duration of the model run is sufficient to assess the process being modelled.

6.4 Incorporating climate change

In modelling studies where recharge or ET are large components of the conceptual model water balance, predictive scenarios run over extended time periods may need to assess potential impacts due to climate stresses such as extended drought periods, increased recharge, or periods of higher-than-normal cyclonic activity that may be related to climate change. Potential effects of climate change on model stresses may be qualitatively or quantitatively described and are understood to be uncertain.

The need to consider the potential effects of climate change in a particular model must be determined by the project proponent in consultation with the department’s Water division. In general, climate change must be taken into account for:

- Projects that have a lifespan of 50 years or greater.
- Projects that are located in areas where considerable changes to the hydrological cycle due to climate change are predicted.

When required, climate change prediction datasets must be used for scenario modelling to determine the impact of climate change on predicted impacts, including cumulative impacts.

6.5 Particle tracking

Particle tracking routines can be used to assess the flow path direction and travel times of potential contamination associated with processes being modelled in the predictive scenarios. The zone of influence of activities can be delineated in 2D or 3D using particle tracking. The zone of influence of an activity such as extraction of water from a pumped well or dewatering of a void is defined as the area within which the water table or piezometric surface is under the influence of pumping (Moreau et al., 2014).

Forward particle tracking can be used to model predicted future migration from potential contaminant sources. In this case particles are released at the potential contaminant source at the beginning of the predictive scenario.

Reverse particle tracking can be used to assess potential impacts on sensitive receptors such as nearby drinking water sources or wetlands. In this case, particles are released at the sensitive receptor location, and the reverse particle tracks model flow paths which flow to the release locations.

7 Uncertainty analysis

In this section: Requirements for uncertainty analysis.

Key references consulted:

- AGMG (Barnett et al., 2012).
- Calibration and uncertainty analysis for complex environmental models (Doherty, 2015).
- Information guidelines explanatory note: Uncertainty analysis - guidance for groundwater modelling within a risk management framework (Middlemis and Peeters, 2018).
- Applied groundwater modeling - simulation of flow and advective transport (1st ed Anderson and Woessner, 1991; 2nd ed Anderson et al., 2015).
- Effective groundwater model calibration (Hill and Tiedeman, 2007).

The AIP requires that an analysis of prediction uncertainties be included in a groundwater modelling project whenever such uncertainty may have a significant impact on the environment or other authorised water users. Under these conditions the AIP requires the following elements to be assessed:

- Any potential for causing or enhancing hydraulic connection between aquifers or between groundwater and surface water sources, including quantification of the risk in the volumetric inflow estimates.
- Quantification of any other uncertainties in the groundwater or surface water impact modelling conducted for the activity.
- Strategies in place for monitoring actual and reassessing any predicted take of water and how any changes in these requirements will be accounted for, including analysis of water market depth and/or in-situ mitigation and remediation options.

In addition, the AGMG recommends that modelling results presented to decision-makers include estimates of uncertainty in the predictions.

Uncertainty analysis is distinct from sensitivity analysis conducted during model calibration (Section 5). Sensitivity analysis evaluates model parameterisation in the context of how well historical conditions can be represented by an individual mathematical model. Uncertainty analysis refers to evaluation of uncertainty in model predictions, typically forward looking in time for the purposes of impact assessment related to proposed project development. Predictive uncertainty is more often related to uncertainty in choice of model conceptualisation than it is uncertainty in parameter values (Anderson et al., 2015; Bredehoeft, 2005; Ye et al., 2010).

7.1 Goal of uncertainty analysis

The mathematical model must be constructed with specific objectives in mind. These objectives are usually described as required or desired predictions and must be included in the GMP (Section 2).

The goal of the uncertainty analysis is to quantitatively or, if necessary, qualitatively describe the uncertainty surrounding the model predictions. Uncertainty in model predictions does not render the predictions invalid; rather, the uncertainty needs to be understood by project proponents, stakeholders, and the department’s Water division so that informed decisions can be made.

7.2 Causes of model uncertainty

Middlemis and (2018) identify four sources of scientific uncertainty that can affect groundwater model predictions (Table 8). Together, these four sources of scientific uncertainty result in predictive uncertainty for a given groundwater model.

Table 8: Sources of model uncertainty (after Middlemis and Peeters, 2018).

Source of uncertainty	Description
Structural/conceptual	Geological structure and hydrogeological conceptualisation assumptions applied to derive a simplified view of a complex hydrogeological reality (any system aspect that cannot be changed in an automated way in a model.
Parameterisation	Hydrogeological property values and assumptions applied to represent complex reality in space and time (any system aspect that can be changed in an automated way in a model via parameterisation).
Measurement error	Combination of uncertainties associated with the measurement of complex system states (heads, discharges), parameters and variability (3D spatial & temporal) with those induced by upscaling or downscaling (site-specific data, climate data).
Scenario uncertainties	Guessing future stresses, dynamics and boundary condition changes (e.g. mining, climate variability, land and water use change).

7.3 Type of uncertainty analysis

Three basic types of uncertainty analysis are generally recognised:

- **Scenario analysis with deterministic modelling:** The mathematical model is run with modified sets of parameters representing alternative scenarios for predictions of future conditions.
- **Linear uncertainty analysis with deterministic modelling:** The calibrated model is assumed to behave in a linear fashion for parameter values within a reasonable range of the calibrated values. Uncertainties in parameters and observed data are assumed to follow a multi-variate normal distribution. Linear error propagation methods are used to estimate confidence intervals around the predicted values.
- **Bayesian analysis with stochastic modelling:** A large set of model predictions is generated with different parameter values that are reasonable with respect to historical conditions. Probability distributions for each model output of interest estimated from the set of model predictions.

While most individual methods of uncertainty analysis fall into these three categories, others may also be available for use. The type of uncertainty analysis used for a particular project must be based on the data available, sensitivity of decision alternatives to model predictions, and overall model complexity.

The AGMG recommends that linear uncertainty analysis be employed due to its computational efficiency. However, others (e.g. Middlemis and Peeters, 2018) suggest that linear methods only be used if their underlying assumptions can be justified.

The type of uncertainty analysis used for a particular project must be clearly identified and described in the model report. The assumptions underlying the method chosen must be clearly discussed and the approach justified.

8 Groundwater model report

In this section: Elements of a groundwater model report.

Key references consulted:

- *AGMG* (Barnett et al., 2012);
- *D5718-13 Standard guide for documenting a ground-water flow model application* (ASTM, 2013);
- *Guidance for hydrogeologic groundwater flow modelling at mine sites* (Newman, 2018);
- *Groundwater modelling guidance for mining activities* (BLM, 2008); and,
- *Applied groundwater modelling - simulation of flow and advective transport* (1st ed Anderson and Woessner, 1991; 2nd ed Anderson et al., 2015)

The final step in groundwater flow modelling is reporting. The model reporting needs to be transparent, accurate, and include all necessary components at an appropriate level of detail.

The written technical report must describe the basis for the model, key assumptions, modelling approach, limitations, and the study findings, conclusions, and recommendations. The modelling archives must include documented data analysis, modelling data and software program files if they can be provided in accordance with copyright or distribution agreements. It is important that model archiving is undertaken such that the model could be regenerated if necessary for review and/or further refinement.

8.1 Timing of reports

Project proponents must work with the department's Water division to determine the need for interim reports or whether study status, issues and preliminary results, and feedback from the department's Water division and project stakeholders must be obtained by other means. Consultation or interim reporting must be considered at the following model stages, or more frequently:

1. After conceptualisation and model design;
2. After calibration and sensitivity analysis; and,
3. After predictive modelling and uncertainty.

Staged reporting or consultation makes it possible to change or remediate the direction of a modelling project and allows the overall report to be prepared progressively throughout the study. A staged reporting or consultation approach increases the opportunities for progressive reviews, which should benefit the quality of the final report.

8.2 Target audience

The report must effectively communicate the modelling process to the target audience. Most reports will need to achieve the correct balance between the technical details and the degree of readability for the client.

The AGMG recommends that model reports should consist of two sections:

- Executive summary-style section targeted for non-technical stakeholders including traditional owners and the public; and,
- Detailed model report section for technical reviewers, e.g. the department experts.

The executive summary needs to characterise the essentials of the objectives, model conceptualisation, and conclusions for nontechnical stakeholders, while the final report should provide them with more detailed information about the modelling outcomes and predictions. The detailed model report for a technical audience needs to provide a detailed description and justification of all aspects of the modelling so that a thorough peer review could be undertaken using the document.

8.3 Structure and minimum contents

The groundwater modelling report(s) may be standalone, included in GIAs, or incorporated in environmental impact statements (EIS). The department’s Water division prefers standalone modelling reports. The appropriate level of documentation will vary depending on the scope of the study objectives, the phase of the project and the complexity of the model simulations. At a minimum a report must present:

- The objectives of the study.
- A description of the work that was done.
- Logical arguments to convince the reader that the methods and analyses used in the study are valid.
- Results and conclusions.

An example of an appropriate model reporting structure, adapted from the AGMG (2012) and ASTM (2013) is shown in Table 9. The narrative modelling report must be accompanied by tables and graphics that support the text. Anticipated tables and graphics include:

- Topographic map of the study area and model domain.
- Hydrogeological cross-sections and structural contour and potentiometric surface maps to illustrate the conceptual model.
- Tabulated summary of conceptual model characteristics such as measured or estimated hydraulic conductivity, storage parameters, well pumping rates, spring and stream flow, lake levels etc..
- Model domain and discretisation overlaid on appropriate basemap (aerial or satellite image, topographical or geological map, or hybrid map).
- Section illustrating model layering in relation to hydrostratigraphic units.
- Maps of parameter values and areal-distributed inputs (hydraulic conductivity, storage, effective porosity, recharge, ET, river or stream locations and parameters, etc.) for each model layer.
- Boundary conditions for each model layer.
- Locations of point inputs (extraction wells, injection wells etc.).
- Initial conditions.
- Tables of parameter values.
- Graphs of simulated vs observed heads.
- Maps of residual values.
- Graphs such as histograms or time-series comparing simulated and measured heads, flows, or lake levels as appropriate.
- Maps comparing simulated head contours with contours interpreted from measured data to compare groundwater flow directions and gradients.
- Graphs, maps or tables showing simulated vertical gradients and vertical gradients interpreted from measured data.
- Water budgets for final predictive model runs.
- Maps and tables summarising model predictions (incl cumulative impact).
- Maps, graphs, or tables summarising uncertainty in predictions, range of predicted outcomes and likelihood across the model domain and within areas of specific interest.

Table 9: Example model report structure (compiled from ASTM, 2013; Barnett et al., 2012).

	Title	Description
1	Report title	The title should reflect the model and project objectives rather than just the study location.
2	Executive summary	The detailed model report includes a brief executive style report to summarise the major findings of the study for non-technical audiences.
3	Introduction and model objectives	Clearly state the modelling objectives, the purpose and goals of the study, and the applicability of the model as part of the study. Discuss what types of predictions are to be made with the model. Include the target confidence level.
4	Conceptualisation	This section describes the current level of understanding of the aquifer system and how this is translated into a conceptual model to address the model objectives. Include a general setting of relevant information on the regional characteristics of topography, geology, hydrology, and land use. Present a regional map with the study area defined. Present and discuss data set origins, strength, deficiencies and their effects on the conceptual model. Include reference to a data inventory.
5	Model design	The model design section specifies the model confidence level and the technical details of the groundwater model such as domain, spatial and temporal discretisation, parameter distributions, implementation of stresses and boundary conditions, and model code and software. Discuss the selection criteria for the model code. Identify the code and whether any custom or altered code is used. Present the simplifying assumptions inherent to the code, the limitations to the code, and the governing equations that the code solves.
6	Model calibration	Summary of how model parameters are changed within predefined constraints to match observations. This requires a clear description of the parameterisation, objective function and constraints as well as the calibration methodology and sensitive analysis. Discuss comparison of calibration simulations to site-specific information using qualitative and quantitative techniques. Discuss and present the simulation’s overall water budget and mass balance. Discuss additional insight gained from the calibration regarding the conceptual model and resulting changes, if any to the conceptual model.
7	Predictive modelling	Description of the use of the model to address the model objectives by exploring aquifer behaviour under different stresses. Detail and justify the changes made to permit the calibrated model to simulate these predictions. Present results of any predictive simulations in graphical form.
8	Uncertainty analysis	Presentation of the uncertainty associated with the predictions, based on, at least, heuristic descriptions of measurement uncertainty associated with parameters, results of sensitivity analysis, stresses and calibration targets and structural model uncertainty, associated with the conceptual and mathematical model. Presentation of the range of probabilistic results of drawdown and take.
9	Model limitations	States the limitations of data and code, the reliability of different outcomes of the model and how further data collection or research may improve reliability.
10	Conclusions and recommendations	Summary of model findings and recommendations for further analysis. Draw conclusions related to the study objectives. Discuss how uncertainties inherent to the model affect conclusions derives from the model.
11	References	Full references of cited literature and data sources.

12	Appendices	Maps, graphs and tables containing detailed information on the model that is important to fully document the model.

8.4 SEARs and COA

The model report must identify the SEARs and COA that relate to the water related aspects of the project. The report must clearly indicate how each of the SEARs and COA is addressed by the model results or the model update and recalibration, preferably in table format.

8.5 Model file archive

Once the study is finished, the model files, data, information, and knowledge accumulated through the modelling process must be organised and archived. The purpose of the archive is to ensure that the results presented in the model report are reproducible in the future either by the model developer or other interested parties.

The model archive serves as a repository to facilitate future analysis and refinement of the groundwater model. The model archive must be made available to the department's Water division upon request.

9 Model review

The AIP requires that models submitted in support of Major Project developments undergo independent review, be consistent with the AGMG, and that they be determined to be fit for purpose to the satisfaction of the Minister. The department's Water division staff will review the modelling report to evaluate whether it is consistent with requirements of the AIP.

The AGMG suggests three levels of review:

- Appraisal by a nontechnical reviewer to evaluate model results.
- Peer review by one or more experienced hydrogeologists and modellers.
- Post audit after new data are available or model objectives change.

Appraisal and peer reviews generally occur periodically during the modelling project. Post audits may occur well after the modelling project is complete.

9.1 Independent review

The independent review required by the AIP must take the form of a peer review as described in the AGMG. The reviewer(s) and review process must be identified in the GMP (Section 2). Reviewers must be engaged early in the project and be available to evaluate key modelling decisions.

Results of the independent review must be documented and included in the groundwater modelling report. Appendix A provides a framework, adapted from the AGMG, that would be appropriate for an independent review of a groundwater model submitted to the department's Water division. The AGMG checklists have been adapted so that a 'yes' answer always indicates a pro and a 'no' answer always indicates a con. In addition, allowance has been made to accommodate questions that cannot be answered by yes or no. The format of the second checklist (Appendix A: Model review checklists) reflects the hierarchical nature of the questions to be answered as part of a systematic model review process.

9.2 Agency review

The department's Water division will review the groundwater modelling reports for suitability after submittal by the project proponent. Key considerations in this assessment include:

- Suitability of conceptualisation.
- Duration of calibration period (two year minimum, in some instances).
- Calibration performance.
- Model sensitivity and uncertainty analysis.
- Accounting for cumulative impacts where more than one aquifer interference activity may affect the natural conditions.
- Outcome of the independent peer review.

In addition, it must be demonstrated that the model is deemed fit for purpose to the satisfaction of the Minister. The fitness for purpose must be evaluated in relation to the scope and objectives of the model defined in the GMP.

Appendix B summarises the department's Water division's criteria for assessing low to medium complexity groundwater models (LMCM) for low to medium environmental sensitivity (LMES) projects. The department's Water division will review high complexity models (HCM) and models for high environmental sensitivity (HES) projects more freely, using national and international best practice guidelines.

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Appendix A: Model review checklists

Table A-1: Generic model compliance checklist (adapted after AGMG, Barnett et al., 2012).

Question	Yes/ No	Comment
Are the modelling objectives and model target confidence level class clearly stated?		
Are the modelling objectives satisfied?		
Is the conceptual model consistent with the modelling objectives and target confidence level class?		
Is the conceptual model based on all available data, presented clearly, and reviewed by an appropriate reviewer?		
Does the mathematical model design conform to best practice?		
Is the model calibration satisfactorily addressed, including appropriate sensitivity analysis?		
Are the calibrated parameter values and estimated fluxes plausible?		
Do the model predictions conform to best practice?		
Is the uncertainty associated with the predictions reported?		
Is the model fit for purpose?		

Table A-2: Model review checklist (adapted after AGMG, Barnett et al., 2012).

Review questions	Yes/ No	Comment
1. Planning		
1.1 Are the Project objectives stated?		
1.2 Are the model objectives stated?		
1.3 Is it clear how the model will contribute to meeting the Project objectives?		

Review questions	Yes/ No	Comment
1.4 Is a groundwater model the best option to address the Project and model objectives?		
1.5 Is the target model confidence level class stated and justified?		
1.6 Are the planned limitations and exclusions of the model stated?		
2. Conceptualisation		
2.1 Has a literature review been completed, including examination of prior investigations?		
2.2 Is the aquifer system adequately described?		
2.2.1 hydrostratigraphy including aquifer type (alluvium, porous rock, fractured rock)		
2.2.2 lateral extent, boundaries, and significant internal features such as faults and regional folds		
2.2.3 aquifer geometry including layer elevations and thicknesses		
2.2.4 confined or unconfined flow and the variation of these conditions in space and time		
2.3 Have data on groundwater stresses been collected and analysed?		
2.3.1 recharge from rainfall, irrigation, floods, lakes		
2.3.2 river or lake stage heights		
2.3.3 groundwater usage (pumping, returns, etc.)		
2.3.4 evapotranspiration		
2.3.5 other (specify in comments)		
2.4 Have groundwater level observations been collected and analysed?		
2.4.1 selection of representative bore hydrographs		

Review questions	Yes/ No	Comment
2.4.2 comparison of hydrographs		
2.4.3 effect of stresses on hydrographs		
2.4.4 water table maps/piezometric surfaces		
2.4.5 If relevant, are density and barometric effects taken into account in the interpretation of groundwater head and flow data?		
2.5 Have flow observations been collected and analysed?		
2.5.1 baseflow in rivers		
2.5.2 discharge in springs		
2.5.3 location of diffuse discharge areas		
2.6 Is the measurement error or data uncertainty reported?		
2.6.1 measurement error for directly measured quantities (e.g. piezometric level, concentration, flows)		
2.6.2 spatial variability/heterogeneity of parameters		
2.6.3 interpolation algorithm(s) and uncertainty of gridded data		
2.7 Have consistent data units and geometric datum been used?		
2.8 Is there a clear description of the conceptual model?		
2.8.1 Is there a graphical representation of the conceptual model?		
2.8.2 Is the conceptual model based on all available, relevant data?		
2.9 Is the conceptual model consistent with the model objectives and target model confidence level class?		
2.9.1 Are the relevant processes identified?		

Review questions	Yes/ No	Comment
2.9.2 Is justification provided for omission or simplification of processes?		
2.10 Have alternative conceptual models been investigated?		
3. Design and construction		
3.1 Is the design consistent with the conceptual model?		
3.2 Is the choice of numerical method and software appropriate?		
3.2.1 Are the numerical and discretisation methods appropriate?		
3.2.2 Is the software reputable?		
3.2.3 Is the software included in the archive or are references to the software provided?		
3.3 Are the spatial domain and discretisation appropriate?		
3.3.1 dimensionality (specify in comments; 1D, 2D, or 3D)		
3.3.2 lateral extent		
3.3.3 layer geometry		
3.3.4 Is the horizontal discretisation appropriate for the objectives, problem setting, conceptual model and target confidence level class?		
3.3.5 Is the vertical discretisation appropriate? Are aquitards divided in multiple layers to model time lags of propagation of responses in the vertical direction?		
3.4 Are the temporal domain and discretisation appropriate?		
3.4.1 time dependency (specify in comments; steady-state and/or transient)		
3.4.2 stress-periods		
3.4.3 time steps		

Review questions	Yes/ No	Comment
3.5 Are the boundary conditions plausible and sufficiently unrestrictive?		
3.5.1 Is the implementation of boundary conditions consistent with the conceptual model?		
3.5.2 Are the boundary conditions chosen to have a minimal impact on key model outcomes? How is this ascertained?		
3.5.3 Is the calculation of diffuse recharge consistent with model objectives and target confidence level class?		
3.5.4 Are lateral boundaries time-dependency appropriate (constant vs time-invariant)?		
3.6 Are the initial conditions appropriate?		
3.6.1 Are the initial heads appropriately based on interpolation or on groundwater modelling? Specify in comments.		
3.6.2 Is the effect of initial conditions on key model outcomes assessed?		
3.6.3 If relevant, is the initial concentration of solutes obtained appropriately? Specify how in comments.		
3.7 Is the numerical solution of the model adequately addressed in the following terms?		
3.7.1 solution method/solver		
3.7.2 convergence criteria		
3.7.3 numerical precision		
4. Calibration and sensitivity		
4.1 Are all available types of observations used for calibration?		
4.1.1 groundwater head data		
4.1.2 flux observations		

Review questions	Yes/ No	Comment
4.1.3 other: environmental tracers, gradients, age, temperature, concentrations etc.		
4.2 Does the calibration methodology conform to best practice in terms of the following?		
4.2.1 parameterisation		
4.2.2 objective function		
4.2.3 identifiability of parameters		
4.2.4 methodology used for model calibration (manual and/or automatic)		
4.3 Is a sensitivity of history matching outcomes assessed against the following?		
4.3.1 parameters		
4.3.2 boundary conditions		
4.3.3 initial conditions		
4.3.4 stresses		
4.4 Have the calibration results been adequately reported as follows?		
4.4.1 Are there graphs showing modelled and observed hydrographs at an appropriate scale?		
4.4.2 Is it clear whether observed or assumed vertical head gradients have been replicated by the model?		
4.4.3 Are calibration statistics reported and illustrated in a reasonable manner?		
4.5 Are multiple methods of plotting calibration results used to highlight goodness of fit robustly? Is the model sufficiently calibrated?		
4.5.1 spatially		
4.5.2 temporally		
4.6 Are the calibrated parameters plausible?		

Review questions	Yes/ No	Comment
4.7 Are the water volumes and fluxes in the water balance realistic?		
4.8 Has the model been verified?		
5. Prediction		
5.1 Are the model predictions designed in a manner that meets the model objectives?		
5.2 Is predictive uncertainty acknowledged and addressed?		
5.3 Are the assumed climatic stresses appropriate?		
5.4 Is a null scenario defined?		
5.5 Are the scenarios defined in accordance with the model objectives and target confidence level class?		
5.5.1 Are the pumping stresses similar in magnitude to those of the calibrated model? If not, is there reference to the associated reduction in model confidence?		
5.5.2 Are well losses accounted for when estimating maximum pumping rates per well?		
5.5.3 Is the temporal scale of the predictions commensurate with the calibrated model? If not, is there reference to the associated reduction in model confidence?		
5.5.4 Are the assumed stresses and timescale appropriate for the stated objectives?		
5.6 Do the prediction results meet the stated objectives?		
5.7 Are the components of the predicted mass balance realistic?		
5.7.1 Are the pumping rates assigned in the input files equal to the modelled pumping rates?		
5.7.2 Are predicted seepage into or from rivers within measured or expected river flow?		

Review questions	Yes/ No	Comment
5.7.3 Are there no anomalous boundary fluxes due to superposition of head dependent sinks (e.g. evapotranspiration) on head-dependent boundary cells (Type 1 or Type 3 boundary conditions)?		
5.7.4 Is diffuse recharge from rainfall smaller than rainfall?		
5.7.5 Are model storage changes not dominated by anomalous head increases in isolated cells that receive recharge?		
6. Uncertainty		
6.1 Is some qualitative or quantitative measure of uncertainty associated with the prediction reported together with the prediction?		
6.2 Is the model with minimum prediction-error variance chosen for each prediction?		
6.3 Are the sources of uncertainty discussed, including		
6.3.1 measurement of uncertainty of observations and parameters		
6.3.2 structural or model uncertainty		
6.4 Is the approach to estimation of uncertainty described and appropriate?		
6.5 Are there useful depictions of uncertainty?		
7. Solute transport		
7.1 Has particle tracking been considered as an alternative to solute transport modelling and is this appropriate?		
7.2 Has all available data on the solute distributions, sources and transport processes been collected and analysed?		
7.3 Has the appropriate extent of the model domain been delineated and are the adopted solute concentration boundaries defensible?		

Review questions	Yes/ No	Comment
7.4 Is the choice of numerical method and software appropriate?		
7.5 Is the grid design and resolution adequately addressed, and has the effect of the discretisation on the model outcomes been systematically evaluated?		
7.6 Is there sufficient basis for the description and parameterisation of the solute transport processes?		
7.7 Are the solver and its parameters appropriate for the problem under consideration?		
7.8 Has the relative importance of advection, dispersion and diffusion been assessed?		
7.9 Has an assessment been made of the need to consider variable density conditions?		
7.10 Is the initial solute concentration distribution sufficiently well-known for transient problems and consistent with the initial conditions for head/pressure?		
7.11 Is the initial solute concentration distribution stable and in equilibrium with the solute boundary conditions and stresses?		
7.12 Is the calibration based on meaningful metrics?		
7.13 Have the effect of spatial and temporal discretisation and solution method been taken into account in the sensitivity analysis?		
7.14 Has the effect of flow parameters on solute concentration predictions been evaluated, or have solute concentrations been used to constrain flow parameters?		
7.15 Does the uncertainty analysis consider the effect of solute transport parameter uncertainty, grid design and solver selection/settings?		
7.16 Does the report address the role of geological heterogeneity on solute concentration distributions?		

Review questions	Yes/ No	Comment
8. Surface water–groundwater interaction		
8.1 Is the conceptualisation of surface water–groundwater interaction in accordance with the model objectives?		
8.2 Is the implementation of surface water–groundwater interaction appropriate?		
8.3 If the groundwater model coupled with a surface water model,		
8.3.1 is the adopted approach appropriate?		
8.3.2 have appropriate time steps and stress-periods been adopted?		
8.3.3 are the interface fluxes consistent between the groundwater and surface water models?		

Appendix B: Assessment criteria for low to medium complexity groundwater models for low to medium environmental sensitivity projects

Assessment criteria for low to medium complexity groundwater models for low to medium environmental sensitivity projects

The questions below represent DPE's assessment criteria of low to medium complexity groundwater models for low to medium environmental sensitivity Major Projects in NSW (Stantec, 2021b).

1 Planning

1.1 Development project background

1.1.1 Are the objectives of the development project stated?

1.1.2 Are the development project background, history and relevant neighbouring activities adequately described?

1.2 The mathematical model

1.2.1 Is a mathematical groundwater model the best option to address the objectives of the project's environmental impacts assessment?

1.2.2 Are the model objectives stated and appropriate?

1.2.3 Is it clear how the model will contribute to meeting the impacts assessment objectives?

1.2.4 Are the target model complexity and confidence level classification stated and justified?

1.2.5 Are the planned limitations and exclusions of the mathematical model stated?

1.2.6 Have previous models been critically reviewed and the knowledge gained incorporated in planning the conceptual and mathematical model development?

1.2.7 If the model is an update, upgrade and/or extension of previous model/s, is it clear how the new modelling was planned to meet the new and/or revised environmental impacts assessment objectives?

2 Conceptualisation

2.1 Transfer of project objectives to conceptual model

2.1.1 Is the description used for the conceptual model consistent with the project, assessment, and modelling objectives?

2.1.2 Is an acceptable level of model complexity and confidence level target discussed in the conceptual model report?

2.1.3 Have the key hydrogeological processes been identified?

2.1.4 Are appropriate boundary conditions identified and constrained?

2.2 Literature review and existing data

2.2.1 Has a thorough and unbiased literature review been undertaken?

2.2.2 Is the conceptual model based on key available information? Has the information been reviewed and is it presented clearly?

2.3 Collation of observed heads and flow data (old and new)

2.3.1 Have groundwater level data been collected and analysed appropriately?

2.3.2 Have flow observations been collected and analysed appropriately?

2.3.3 Has recharge/groundwater flux been assessed appropriately?

- 2.3.4 Have natural discharge locations been considered?
- 2.3.5 Are the data presented graphically (e.g. selected hydrographs, water table contour maps)?

2.4 Geology: Has the geological framework been understood?

- 2.4.1 General geological setting
- 2.4.2 Geomorphology/landforms
- 2.4.3 Stratigraphy
- 2.4.4 Structure
- 2.4.5 Special features/characteristics (specify in comments)

2.5 Hydrogeology: Has the aquifer system been described adequately?

- 2.5.1 Is the hydrostratigraphy including aquifer types (alluvial, porous rock, fractured rock) described adequately?
- 2.5.2 If applicable, are preferential flow horizons described adequately?
- 2.5.3 Is the aquifer geometry including layer elevations and thicknesses described adequately?
- 2.5.4 Have confined or unconfined flow and the variation of these conditions in space and time been described adequately?
- 2.5.5 Have the main processes controlling groundwater occurrence, quantity, and flow been reliably identified?

2.6 Have data on groundwater stresses been collected and analysed?

- 2.6.1 Inflows (e.g. discharges, infiltration recharge, river leakage)
- 2.6.2 Outflows (e.g. abstractions, evapotranspiration, baseflow)

2.7 Have the responses to stresses been understood?

- 2.7.1 Have the [dominant] horizontal flow directions and gradients been reliably established?
- 2.7.2 Have vertical flow directions and gradients been reliably established?

2.8 Data uncertainty

- 2.8.1 Are the measurement error and other sources of data uncertainty reported?

2.9 Conceptual model certainty

- 2.9.1 Has the conceptual model been tested (e.g. simple water balance, exploratory modelling)?
- 2.9.2 Have alternative conceptual models been investigated?
- 2.9.3 Is there sufficient discussion of uncertainty in the conceptual model?

2.10 Reporting and presentation

- 2.10.1 Has the conceptual model been reported adequately (conceptual reasoning clearly communicated)?
- 2.10.2 Is there a useful and realistic graphical representation of the conceptual model (e.g. cross-sections, spatial maps, schematic geological diagrams)?

3 **Design and construction**

3.1 Initial modelling considerations

3.1.1 Is the design consistent with the conceptual model?

3.1.2 Has the choice of modelling method been discussed (analytical vs distributed numerical model, 2D vs 3D, steady-state vs transient, etc.)?

3.1.3 Is the choice of numerical method appropriate?

3.1.4 Is the chosen modelling software adequate?

3.2 Are the spatial and temporal domain and discretisation appropriate?

3.2.1 Is the model discretisation and model extent reasonable and clearly defined?

3.2.2 Are the effects of the model discretisation/extent on model runtimes understood?

3.3 Are the chosen boundary conditions appropriate?

3.3.1 Are the boundary conditions (type/location) consistent with the conceptual model?

3.3.2 Are the impacts of the boundary conditions on model objectives understood and assessed?

3.3.3 Are the boundary conditions hydrogeologically defensible (e.g. no-flow, flow line, groundwater divide)?

3.4 Initial conditions

3.4.1 Are the chosen initial conditions appropriate? In the comments, indicate whether they are based on interpolation of observed data or groundwater modelling.

4 **Calibration and sensitivity analysis**

4.1 Have all available types of observations been used in the calibration?

4.1.1 Groundwater and surface water levels

4.1.2 Groundwater and surface water flows and exchanges

4.1.3 Void inflows (specify measurement method in comments)

4.1.4 Other data (specify)

4.2 Does the calibration methodology conform to best practice with regards to the following?

4.2.1 Parameterisation (including method, e.g. zones, pilot points)

4.2.2 Objective function

4.2.3 Identifiability of parameters

4.2.4 Is the calibration method robust (describe in comments)?

4.3 Has the sensitivity of the calibration been assessed against variability in the following:

4.3.1 Boundary conditions?

4.3.2 Initial conditions?

4.3.3 Parameters, including homogeneity/heterogeneity and isotropy/anisotropy

4.3.4 Stresses?

4.4 Calibration outcome

4.4.1 Is the model sufficiently calibrated, i.e. acceptance criteria matched?

4.4.2 Has systematic bias (magnitude, spatial, temporal) been assessed and explained if necessary?

4.4.3 Are calibration statistics reported and illustrated?

4.4.4 Are calibration results adequately presented (e.g. spatial plots, time series graphs)

5 **Prediction**

5.1 Are the predictive scenarios designed adequately?

5.1.1 Are the predictive scenarios defined in accordance with the model objectives?

5.1.2 Are the assumed future climatic stresses appropriate (e.g. climate change considered)?

5.1.3 Are the assumed stresses and timescale appropriate for the stated objectives?

5.1.4 Has a baseline (null) scenario been defined?

5.2 Have the results been checked for anomalous results like:

5.2.1 Counter intuitive water balance estimates?

5.2.2 Great difference to baseline?

5.2.3 Other (specify in comments)?

5.3 Presentation

5.3.1 Have the prediction results been adequately presented (e.g. maps, cross-sections, timeseries graphs, water budgets)?

5.4 Scenarios and impacts assessment, including cumulative impacts

5.4.1 Do the modelled predictions meet the model objectives?

5.5 Predictive scenarios uncertainty

5.5.1 Has the uncertainty in predictive scenarios been acknowledged and addressed (e.g. potential change in mining methods)?

6 **Predictive uncertainty**

6.1 Are the sources of predictive uncertainty discussed?

6.1.1 Measurement of uncertainty of observations and parameters

6.1.2 Structural or model uncertainty

6.2 Assessment

6.2.1 Is some qualitative or quantitative measure of uncertainty associated with the prediction reported together with the prediction?

6.2.2 Is the reported predictive uncertainty assessment approach appropriate?

6.2.3 Is the model with minimum prediction-error variance chosen for each prediction?

6.3 Communicating uncertainty

6.3.1 Is the approach to estimation of uncertainty clearly described?

6.3.2 Are there useful depictions of the predictive uncertainty?

7 **Surface water-groundwater interaction**

7.1 Conceptualisation

7.1.1 Has groundwater-surface water interaction been appropriately characterised in space and time?

7.1.2 Is the conceptualisation of surface water-groundwater interaction in accordance with the model objectives?

7.1.3 Has groundwater-surface water interaction been appropriately quantified in space and time?

7.2 Is the implementation of surface water-groundwater interaction appropriate?

7.2.1 Is the groundwater model appropriately coupled with a surface water model (answer #N/A if coupling of models is not required)?

7.2.2 Is the adopted surface water modelling approach appropriate (clarify in comments)?

7.2.3 Have appropriate stress-periods and time steps been adopted for surface water (answer #N/A if there are no surface water features in the model domain)?

7.2.4 Are the interface fluxes consistent between the groundwater and surface water models (answer #N/A if there are no surface water features in the model domain)?

8 Cumulative impacts

8.1 Extent, nature, and magnitude of impacts

8.1.1 Are all the potentially impacted parties clearly described?

8.1.2 Is the predicted cumulative impact on other nearby developments, third party users, GDEs presented clearly?

8.1.3 Has the entity of the cumulative impact on each affected third-party user being clearly defined?

8.1.4 Are the predicted magnitude and duration in changes in groundwater levels and flow directions due to cumulative impacts evaluated and clearly presented?

8.1.5 Are predicted changes in the baseflow at individual surface water bodies documented?

8.2 Regulatory requirements and mitigation of impacts

8.2.1 Is the model used for apportionment of effects between various interfering development projects?

8.2.2 Have the Project’s licensing requirements (shares) been assessed (groundwater and connected surface water; direct and incidental)?

8.2.3 Have predicted impacts been assessed against the Aquifer Interference Policy (AIP) minimal impact considerations?

8.2.4 If applicable, does the model inform a Target Action Response Plan (TARP) that adequately addresses predicted cumulative impacts?

8.2.5 If applicable, does the model inform a make good provisions plan prepared to address cumulative impacts due to the proposed activities on affected third parties?

9 Report adequacy

9.1 Form and format

9.1.1 Is the modelling report standalone?

9.1.2 Is the report well structured, concise, and logical, including appendices, annexures, etc.?

9.1.3 Are figures and tables in the report of good quality, relevant to the data presented and easy to consult?

9.1.4 Is the report written and prepared to professional standards?

9.2 Content

9.2.1 Is the development project clearly described in the report, including clear statement of its objectives, elements, phases, etc.?

9.2.2 Is the approach and the construction of the conceptual model clearly presented and well documented?

- 9.2.3 Is the approach and the choice of numerical modelling package clearly explained and documented?
- 9.2.4 Are the sources of hydrogeological parameters, rainfall, and evapotranspiration information clearly provided and documented?
- 9.2.5 Are the sources, location, and details of the used field data clearly documented and shown with appropriate mapping?
- 9.2.6 Are numerical model calibration and sensitivity processes adequately described and data used clearly presented and documented?
- 9.2.7 Are model predictions clearly presented and in line with model classification principles (as per AGMG, 2012)?
- 9.2.8 Is uncertainty analysis process clearly explained and well documented?
- 9.2.9 Is the cumulative impact presented with clarity, adequate field data and completed with a clearly defined monitoring program?
- 9.2.10 Is the report, in its entirety, commensurate to the project complexity, providing an adequate tool for the assessment of the project/model?

9.3 Model fitness for purpose

- 9.3.1 Does the model as reported meet its stated objectives (see Question 1.2.2)?
- 9.3.2 Does the model as reported meet the target model confidence level classification (see Question 1.2.4)?