Office of the **Queensland Mine Rehabilitation Commissioner**

Applying leading practice modelling of residual mine voids for mine rehabilitation planning

Technical paper 3

Queensland Government

Prepared by: Australasian Groundwater and Environmental Consultants Pty Ltd (AGE) and WRM Water & Environment (WRM) on behalf of the Office of the Queensland Mine Rehabilitation Commissioner.

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Where the final rehabilitated landform for a mine includes a water-filled residual void, it is necessary to assess how the water body will behave and interact with the surrounding environment to inform the development of appropriate rehabilitation and management strategies that minimise long-term environmental risks. A variety of approaches are currently used to predict the water quality and hydrology of residual voids, each with its own set of assumptions and limitations. It is often difficult, therefore, for decision makers to compare and assess the suitability of modelling approaches and to determine whether the predictions made are useful for decision making.

The Office of the Queensland Mine Rehabilitation Commissioner engaged Australasian Groundwater and Environmental Consultants Pty Ltd (AGE) and WRM Water & Environment (WRM) to provide advice on leading practices for mine void modelling used to support rehabilitation planning. This project was undertaken in three stages and produced three Technical papers. The first Technical paper is a review of current void modelling practices, the second describes leading practice modelling approaches (including issues such as conceptual model development, calibration, predictions, presenting uncertainty and considering risk), and the third provides guidance on how to implement recommendations for leading practices.

Technical paper 1 describes current practice for modelling the behaviour of water bodies forming within residual voids. This commonly involves the deployment of a range of models to represent the environmental processes occurring. The models are commonly used to develop synthesised datasets where measurements of groundwater or runoff inputs to residual voids cannot be obtained, as well as for making predictions of water level and water quality changes over time. In most cases actual and synthesised datasets are used as inputs to a residual void water balance and drawdown model. Impacts on the groundwater regime surrounding a residual void are commonly determined by using separate groundwater flow models, with water levels predicted by the water balance model used as inputs. Void water quality is typically predicted using simple mixing models informed by site environmental compliance monitoring results, and short-term laboratory scale geochemical studies.

These methods provide predictions of residual void water level, contaminant loads and impact on surrounding groundwater levels. However, the modelling work is typically undertaken at an early stage in a project life (i.e. prior to construction), and there is potentially limited consideration of uncertainty associated with model inputs and predictions. Validation of predictions from surface water balance models and groundwater flow models during the operational stage is also not commonly undertaken as either time series water level and solute concentration data are not available for water bodies in residual voids, or the resource activities have yet to be completed. Modelling of complex processes which can occur in residual voids like stratification, and geochemical behaviour of elements/ions are rarely modelled, especially at an early stage of a project life. However, such approaches may be necessary in some instances. It is common to use separate models for surface, groundwater models and water quality. This ‘quasi coupling’ approach to modelling occurs for example where surface water balance predictions are used as inputs of groundwater flow models. While this can provide a practical way to model the system, there are some disadvantages such as the use of varying timescales and simplifying assumptions. Dynamic coupling of surface, groundwater and water quality models provide the most advanced way to model residual voids. Attempts to dynamically couple groundwater and water balance models exist in academia but are yet to be adopted in current practice in Queensland.

Technical paper 2 and 3 present step by step guidance intended to assist mining proponents, mine operators and their consultants with achieving best practice modelling outcomes. The guidance is also intended to assist government officers charged with assessing PRC plans. The following stages are identified:

- Stage 1 – Planning
    - Build a multi-disciplinary team
    - Define aims/objectives and prepare a project plan
    - Initial engagement with stakeholders
- Stage 2 – Data collection and conceptualisation
- Stage 3 – Model design and construction
- Stage 4 – History matching
- Stage 5 – Prediction
- Stage 6 – Uncertainty analysis and risk assessment
- Stage 7 – Reporting
- Stage 8 – Monitoring and validation.

The initial planning stage is seen as being particularly important to achieving leading practice outcomes. The intent of the planning stage is to ensure (as far as possible) that modelling of residual voids meets the needs of all stakeholders the first time it is delivered; minimising the need for further work and reducing the timeframe for assessments to be completed. During the planning stage, the scope and timing of the modelling effort, as well as the multi-disciplinary project team members is determined. At the conclusion of the planning stage the project plan should be presented to regulatory stakeholders as well as local community stakeholders.

In most cases achieving best practice outcomes will require the collection of site-specific data for site conceptualisation (Stage 2), model design and construction (Stage 3) and history matching purposes (Stage 4). A key initial task for the project team is therefore to review the existing data sources and determine data necessary to achieve the project objectives. Since no models can predict the future with 100% accuracy, data collection, model design and subsequent modelling activities must aim to minimise and quantify predictive uncertainty (Stages 5 and 6). In practice this means presenting model results as a range of possible outcomes, rather than single predictions, which allows the likelihood and risk of unwanted outcomes to be quantified (see Table 3). This in turn will allow for risk-based decision making when preparing PRC plans. Best practice in residual void modelling also requires that the study outcomes are clearly documented in plain English (Stage 7) and regularly reviewed against actual site monitoring data, in order to validate model-based predictions of future void water levels and water quality (Stage 8).

1. Introduction

Progressive rehabilitation and closure (PRC) plans are required for all holders of site-specific Environmental Authorities (EA) for a mining activity relating to a mining lease. These plans describe how and where activities will be carried out on land in a way that maximises the progressive rehabilitation of the land to a stable condition (section 126B of the *Environmental Protection Act 1994*). Under this definition, returning land to a stable condition means that a post-mining land use is achieved.

In instances where the final rehabilitated landform includes a water-filled residual void, it is necessary to assess how this water body will behave and interact with the surrounding environment to inform the development of appropriate rehabilitation and management strategies that minimise long-term environmental risks. A variety of approaches are currently used to predict water quality and hydrology of residual voids, each with its own set of assumptions and limitations. It is often difficult, therefore, for decision makers to compare and assess the suitability of modelling approaches and to determine whether the predictions made are useful for decision making.

The Office of the Queensland Mine Rehabilitation Commissioner engaged Australasian Groundwater and Environmental Consultants Pty Ltd (AGE) and WRM Water & Environment (WRM) to provide advice on leading practices for mine void modelling used to support rehabilitation planning.

The process to develop best practice guidance included the following three components:

- Technical paper 1 – a review of the current practice in Queensland including comment on advantages and disadvantages of available modelling approaches
- Technical paper 2 – a description of leading practice modelling approaches including issues such as conceptual model development, calibration, predictions, uncertainty and risk, and
- Technical paper 3 – step-by-step guidance describing how to implement leading practices.

Each of these components is described in separate documents. This document summarises the outcomes of Technical paper 3 and describes how to implement leading practice approaches. Accordingly, it is intended that the three documents are considered together to provide a complete set of guidance.

The focus of the guidance is on mining activities that utilise open cut methods that result in residual voids in Queensland. This guidance is primarily applicable to metallurgical and thermal coal sectors and base and precious metals. Although not the focus, the approaches presented here may also be applicable to other mining activities such as bauxite, phosphate and mineral sand mining. The scope of work excludes quarries and abandoned mines.

The approaches described here provide a generalised description of leading practices, however, it is recognised that there is wide variation in mine void behaviour and there may be a need to modify or adapt the approaches presented to accommodate site specific requirements. Where deviation from the approaches presented here are proposed, and particularly where a more simplified approach is adopted, the rationale for doing so is to be explained. The target audience for the Technical paper is mining proponents and mine operators and their consultants undertaking modelling, and government officers charged with assessing PRC plans. This document outlines practices to describe the water quality and water balance of residual voids, and their long-term impact on surrounding groundwater and surface water resources. The approaches described here are intended to provide a basis to standardise approaches to residual void modelling and reporting as they relate to mine rehabilitation planning in Queensland.

2. Purpose of modelling residual voids

This document aims to describe leading practice approaches to predict water quality and hydrology of residual voids to support rehabilitation planning. Understanding of void hydrology and the likely long-term interaction of the water body with the surrounding environment forms the basis for the assessment of environmental impacts. In particular, it is important to know if the water body will:

- fill and overflow
- be a groundwater sink
- be a groundwater source, and/or
- result in water quality impacts.

In the fill and overflow scenario, water from the void will discharge to the receiving surface water environment and a strategy to reduce water levels may be required, such as through controlled releases, enhancing evaporation, or seeking other beneficial uses of water stored in the void. In a groundwater sink scenario, the void water level at equilibrium is below the level of the surrounding water table and groundwater flows into the void. In a groundwater source scenario, the void water level at equilibrium is above the level of the surrounding water table and water discharges from the void to the surrounding groundwater regime. Void water quality must be suitable for any proposed reuse and is an important consideration to assess the need for and potential impacts associated with releases or seepage from the void into the surrounding surface or groundwater environment.

The primary objective of residual void water modelling is to gain an understanding of the behaviour of the residual void water body with reference to these four fundamental states and the water-related social and economic risks associated with voids.

3. Project stages

As described in Technical paper 2 it is recommended that projects modelling the behaviour of residual void water bodies and in the interconnected landscape should be progressed in the sequential stages as follows:

- Stage 1 – Planning
- Stage 2 – Data collection and conceptualisation
- Stage 3 – Model design and construction
- Stage 4 – History matching
- Stage 5 – Prediction
- Stage 6 – Uncertainty analysis and risk assessment
- Stage 7 – Reporting
- Stage 8 – Monitoring and validation

These stages are based on the stages recommended for groundwater modelling provided by Barnett et al (2012) but apply equally to other types of modelling required for final voids which may include rainfall runoff, water balance and/or geochemical modelling. This document outlines how to apply leading practice within each stage of the modelling process.

4. Stages and tasks

Stage 1 – Planning

The intent of the planning stage is to ensure (as far as possible) that modelling of residual voids meets the needs of all stakeholders the first time it is delivered; minimising the need for further work and reducing the timeframe for assessments to be completed. During the planning stage, the scope and timing of the modelling effort, as well as the project team members, should be determined. The planning stage is comprised of the following three sub-tasks:

- Task 1a – Building a multidisciplinary team
- Task 1b – Defining aims and objectives and preparing a project plan
- Task 1c – Engaging with stakeholders

Practical implementation of these tasks is outlined in the sections below.

Task 1a – Build a multidisciplinary team

As described in Technical paper 2, successfully assessing the future behaviour of a water body forming within a residual void is likely to require input from the following ‘core’ disciplines:

- geochemistry and hydrogeochemistry
- geology and hydrogeology
- hydrology and
- ecology.

However, the skills of the multidisciplinary team members should be identified based on the type of project and any previously identified site risks. For example, the team required to assess a residual void at a metalliferous mine where acid forming materials have been identified in the material in which the residual void water body forms would need input from a team member with sufficient geochemistry expertise to quantify the significance of this issue. At sites where exposed natural strata and/or in-pit spoils/tailings are known to be non-acid forming, then the required input from a geochemistry specialist may be reduced. Residual voids which are in close proximity to sensitive receptors such as aquatic ecosystems or groundwater dependent ecosystems would require input from an appropriately experienced aquatic/terrestrial ecologist or botanist. Residual voids which are potentially connected to productive aquifers, surface water bodies or sensitive receptors would require input from a hydrogeologist. Where surface water is the main element of a residual void water balance a hydrologist or environmental engineer would be appropriate to take the lead role in the water balance modelling activities. These disciplines are not always available in one company or location, and therefore input from an experienced project manager, to select and coordinate the multidisciplinary team undertaking modelling activities, may also be required.

The make-up of the multi-disciplinary team may not remain static throughout the course of the study. Input from other specialists, in addition to the four main disciplines identified above, may be required as the modelling study progresses. For instance, where water balance modelling results suggest that a large water body may develop then the project hydrologist may advise that additional specialist input is required from a limnologist. Identifying the need for additional specialist input therefore represents a key responsibility of each team member.

Technical paper 2 also recommends the project team visit the mine site to inspect the residual void and gather local knowledge important for the study. The purpose of the site visit is to ensure the project team is familiar with the residual void, and is less likely therefore to overlook any critical features, opportunities or constraints. The scale of residual voids is often significant and best appreciated in-person. The site visit may be less important where the project team has prior experience at the subject mine site, or similar sites, and where the void is well documented by photographs, videos and scaled drawings.

During the site visit the project team should aim to inspect and photograph:

- the residual void including exposed geology if it is dewatered at the time of the visit including seepage and chemical precipitation
- the mine landscape including waste rock dumps that are potentially within the pit catchment and any monitoring locations and equipment
- any surface water systems (including bunding, levees and water release infrastructure)
- any potential sensitive receptors associated with water sources (including potentially groundwater dependent vegetation, surface water bodies) and
- any private water supply bores in close proximity to the void and gain an understanding of groundwater use and dependence (this may reveal a separate water supply bore audit is required).

Sufficient photographs should be taken of the main features of the residual void to assist in communicating the key features of the system to stakeholders. Drone videos may also be an effective tool for this purpose especially if a site visit is not possible.

The multidisciplinary team should also meet with the mine operators who are knowledgeable about the site and have valuable knowledge of site characteristics as well as key data to assist the residual void modelling process. This could include information on historic groundwater inflow rates, results from previous water balance models, water level, and/or water quality monitoring datasets. Obtaining an understanding of site monitoring data, such as where key monitoring sites are located and the quality and quantity of available data, is another important objective of the site visit.

Task 1b – Define modelling aims/objectives and prepare a project plan

As described in Technical paper 2 the ultimate purpose of modelling of residual voids is to assist with testing of hypotheses regarding a range of potential hazards associated with residual voids. Successful residual void modelling studies will identify the likelihood of key hazards occurring and hence assist with quantifying risk. The potential hazards that need to be evaluated will depend on the nature of the residual void and the environmental setting.

A key initial task the project team should complete is a detailed risk assessment where the potential hazards associated with the residual void are identified and the consequences considered qualitatively. This could potentially be undertaken during the site visit with input from the entire multidisciplinary team.

Where the identified hazard and associated consequence could result in a significant risk then the likelihood of the hazard occurring should be assessed with modelling. The project plan should document all the identified hazards and those considered significant enough to warrant modelling to estimate their likelihood. This is one of a number of occasions during the study when the need for additional specialist input may also be identified.

The purpose of the project plan is to outline the aims and objectives of the modelling and the scope of work that will be undertaken to achieve these aims and objectives. It is not intended to be an extra step in the modelling process, rather a bringing forward of some tasks that would otherwise be undertaken at a later stage. This is intended to ensure that modelling of residual voids meets the needs of all stakeholders at the first attempt thereby minimising the need for re-work and reducing the timeframe for assessments to be completed. Recommended content for the project plan is described in Table 1.

Table 1. Example content of project plan.

Section	Content
Introduction	site location, company(s) engaged and for what purpose
Project team	table with team member names, roles, contact details and responsibilities
Residual void(s) details	residual void name(s), location(s), existing water volume and maximum water volume at spill point level and data source
Site setting	brief summary of location, climate, water resources, groundwater systems and vegetation including site visit photos (note this text should be prepared so it can be reused in subsequent modelling reports)
Residual void water balance components	brief summary of the existing state of knowledge of each water balance component contributing to the residual void including groundwater, rainfall, runoff, evaporation and extraction for beneficial use
Preliminary risk identification	standard risk assessment matrix with potential hazards, likelihoods and consequences as identified by project team
Aims/objectives of modelling	statement of hazards that could be significant and require modelling, and hypotheses to be tested
Data requirements	summary of data available for modelling, and if this data has potential to reduce uncertainty in model predictions
Modelling methodology	types of models to be developed, model scenarios and definition of interaction between models
Modelling predictions and outputs	model scenarios and processing of model outputs that will be undertaken
Schedule	schedule for modelling and reporting, timing of key milestones

Models are sometimes called upon to answer a wide range of questions they have not been designed to address. When determining the aims/objectives of the modelling it is important to ensure the model(s) purpose is clearly identified so it can be designed accordingly. If a number of different predictions are required, a number of different models may also be required, the construction and deployment of which should be ‘tuned’ to the questions it must answer.

For example, a basic water balance for a metalliferous mine void in a semi-arid setting may clearly show overtopping is not a plausible outcome. In this case the main hazard to be assessed may be the potential for acid forming processes to result in the void water having no potential beneficial use or environmental value. In this case the hypothesis to be tested could be framed as *“the salinity, pH and metals concentrations in the residual void will not exceed the water quality guideline values for the intended use or environmental values”* and the modelling work would then focus around accepting or rejecting this hypothesis. Where this hypothesis cannot be rejected, the modelling must also be able to provide insight into the likelihood of salinity, pH and metals exceeding relevant water quality guideline values so that risk can be understood.

At a large coal mine where strip mining has resulted in multiple residual voids creating long linear features, the key hazard identified may be the potential for outflow of void water into the surrounding groundwater. In this case the hypothesis to be tested could be framed as *"the water level within the residual voids will exceed the lowest water level in the adjacent groundwater regime and therefore the void will form a source".* Again, the adopted modelling approach would then focus around accepting or rejecting this hypothesis, and if/when it cannot be rejected assessing the likelihood of the void forming a source.

A residual void in close proximity to a sensitive creek or drainage line may have the hypothesis to be tested framed as *"the water level in residual voids will not exceed the crest of the void and spill to the adjacent water course*". Again, the modelling approach would focus around accepting or rejecting this hypothesis, and if/when it cannot be accepted assessing the likelihood of this event occurring through modelling.

Once the hypothesis to be tested has been determined then the need for additional data collection to inform the modelling must be considered. The required data will be site and context specific, and the multidisciplinary team can refer back to the stated aims, objectives and hypotheses to assist in determining if further data collection is required.

Some general guidance on the datasets for modelling is provided below in Table 2 below. It should be noted that this table is intended to provide a starting point for review by the project team. Depending on the results of the project risk assessment (discussed above) then some data items listed below may not be required and more data may be required in other areas.

Table 2. Datasets for model conceptualisation and construction.

Data	Comments
Hydrogeology	
Groundwater levels	The monitoring bore network should be sufficient to establish: • hydraulic gradients and flow directions in each of the key hydrostratigraphic units potentially affected by the residual void(s). • if the mine and/or residual void currently behaves as a source, sink or flow through system – note long linear voids may be a source at one end and a sink at the other end, and sufficient monitoring bores should be available to establish this behaviour.
Hydraulic properties	Identify and describe the hydraulic properties of key hydrostratigraphic units potentially affected by or influencing groundwater flow from/to the void. The hydraulic properties of each unit (including mine wastes and spoils) should be measured locally close to the site of each residual void unless 1) hydraulic properties have previously been well established for the site or locality and are applicable, or 2) uncertainty in hydraulic properties will not influence the ability of the modelling to answer the questions it is required to address.
Groundwater quality	The monitoring bore network should be sufficient to develop models to establish: • the pH, salinity, major ions (including alkalinity), metal/metalloid concentrations any other contaminants of potential concern adjacent to the residual void(s). • beneficial use in each of the key hydrostratigraphic units locally around the residual voids prior to formation of the residual void water body.
Groundwater dependent receptors	The desktop and associated field investigations (where necessary) should be sufficient to establish the location and details of the following potential receptors within the potential zone of influence of the residual void(s): • water supply bores (stock/domestic/irrigation/industry/town) • wetlands, springs, lakes, creeks and rivers directly or indirectly connected to the hydrostratigraphic units that are potentially affected by the residual void(s). • groundwater dependent vegetation and ecosystems.
Groundwater	Where the rate of local groundwater recharge to key hydrostratigraphic units (including

Data	Comments
Recharge	mine wastes and spoils) may influence the behaviour of the residual void water body then both initial best estimate and possible ranges should be estimated using more than one recognised approach (e.g. chloride mass balance and observed water level fluctuations).
Surface Water	
Rainfall	Rainfall is a key input to surface and groundwater modelling. Available data is likely to include on-site records, as well as longer-duration records from nearby Bureau of Meteorology rainfall gauges. Daily data is widely available and is typically a suitable resolution for simulation of residual void behaviour. In addition to individual rainfall gauges, the Queensland Government publishes gridded daily rainfall data across all of Australia (www.longpaddock.qld.gov.au/silo/). This data set is well suited to hydrologic modelling because it has been filtered to remove accumulated totals (where manual gauges are not read every day) and periods of missing data, which are filled by interpolation between surrounding gauges.
Evaporation	The configuration of a residual void can influence the rate of surface evaporation from water within the void. Deep voids with high walls may be affected by shading of the water surface that reduces evaporation. The orientation of the void to prevailing winds can also have an effect on whether evaporation is higher or lower than at the ground surface. Available methods for estimating evaporation include direct measurements from an evaporation pan, and empirical equations based on an energy balance. Whichever method is chosen to estimate evaporation, the influence of void configuration will need to be considered. This may require base estimates to be factored up or down to reflect site conditions. Ideally, site data should be used to confirm the accuracy of evaporation estimates. Where significant uncertainty remains, sensitivity analysis should be undertaken to assess the influence of evaporation on void behaviour.
Runoff	Mine pits and residual voids usually have relatively small contributing catchment areas and rarely have concentrated inflows from creeks or rivers that can be measured. However, estimates of runoff volumes from stream gauges on nearby watercourses can provide useful information on typical volumes of catchment runoff per unit area. A key consideration in using any such data is to understand the potential influence of land use on surface runoff. Data from a nearby stream gauge may not be representative of runoff rates from a void catchment that is highly disturbed by mining activities.
Void water level	A time history of water level elevation within existing mining pits or voids can provide valuable information to verify that a water balance model is providing a realistic representation of water level behaviour. Water levels may be directly recorded, or can sometimes be inferred from aerial photographs or other anecdotal information. Water levels during an extended dry period can be used to infer net groundwater inflows or outflows and evaporative losses, since other inputs from direct rainfall and catchment runoff will be negligible. Similarly, observed rises in water level after significant rainfall events can be used to estimate catchment runoff inflow volumes. Any assessment of pit or void inflows or outflows will need to consider all key components of the water balance, including direct rainfall, catchment runoff, evaporation, seepage inflow or outflow, and potential pumped inflows or outflows.
Site pumping data	Pumping is often used on active mine sites to prevent excess accumulation of water in mine voids. Estimates of water volumes pumped into or out of a void may be obtained from pipeline flow meters, or estimated from information on pump operating hours. Pumped volumes can be helpful in inferring other components of a pit or void water balance.
Geochemistry	The field investigations should be sufficient to establish the hydrochemical/geochemical conditions of groundwater and void water bodies and inform predictive modelling to assess how these may change over time by undertaking the following: • Routine monitoring of field determined pH, oxidation reduction potential (ORP), dissolved oxygen (DO), electrical conductivity (EC) and temperature. • Water sampling for laboratory analyses of the field water quality parameters (above) and key redox indicators such as manganese, ferrous iron, reduced forms of sulfur (S^{2-} and HS^{-}), organic carbon and methane.

Data	Comments
	• Vertical profiling of hydrochemical/geochemical conditions in any existing void water bodies. • Collection of samples for water quality analyses at various depths in existing void water bodies. • Sampling of mine waste materials that may influence the final void water quality (spoil, tailings, pit wall rock). Samples should be subjected to standard acid base accounting methods, static and/or kinetic leach testing, bulk element concentrations, and quantitative mineralogical analysis.

Often it is not possible to obtain data for all elements of a residual void water balance and geochemistry. In this case models are also used to provide simulated data. However, in most cases a number of models will also be developed to predict long term behaviour and test key hypotheses developed by the Project team. Figure 1 below contains a flow chart which is designed to assist in determining:

- when subsidiary models are required to provide simulated data inputs for an over-arching residual void water balance model
- the type of models required to meet the project objectives and
- predictions required from each model.

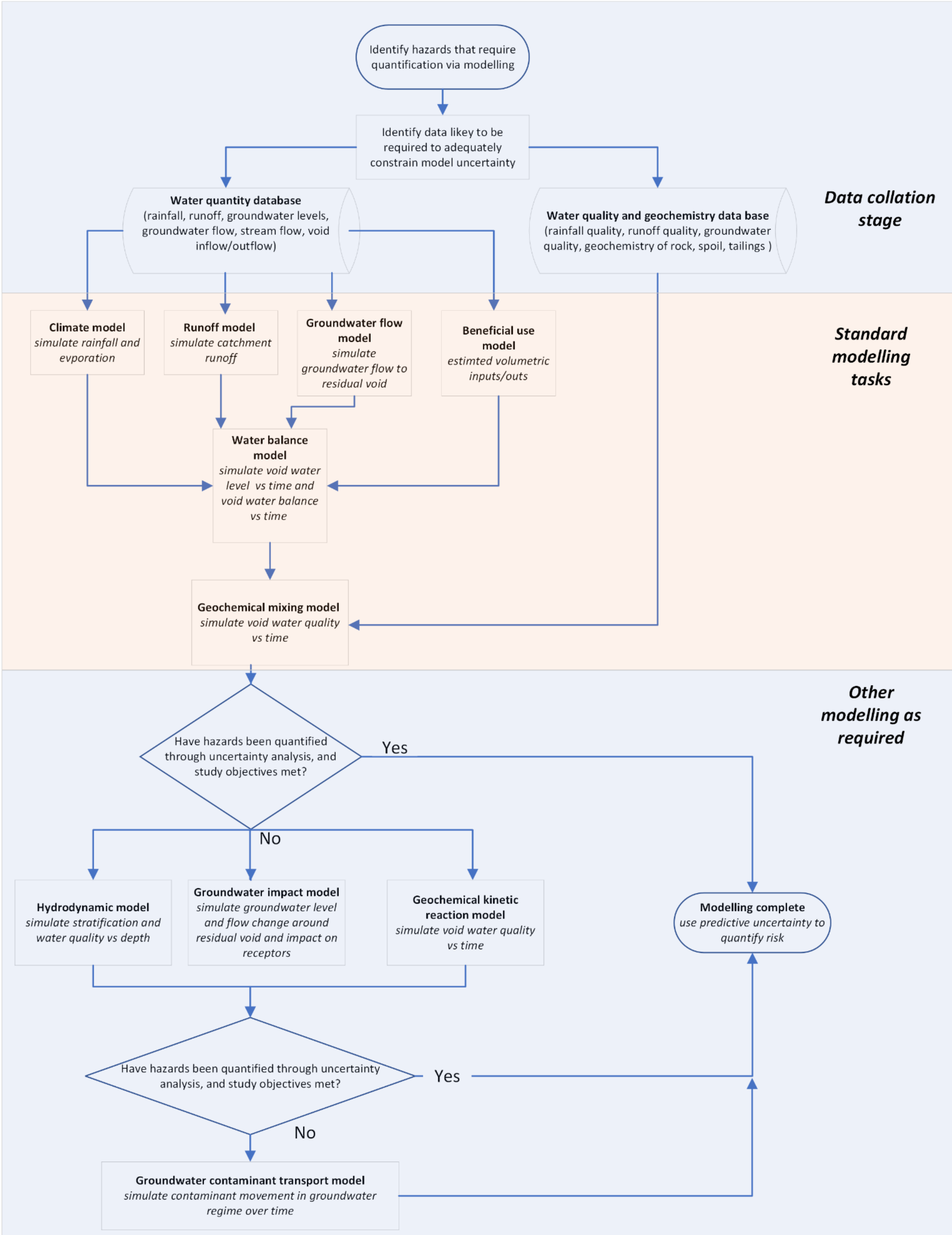

Figure 1. Flow chart for model selection and modelling process.

Task 1c– Initial engagement with stakeholders

Engagement on the project plan once completed should occur at a technical level, with the Department of Environment and Science (DES) and stakeholders within the local community. Community consultation represents a key component of the PRC planning process and is intended to ensure that anyone impacted by rehabilitation activities has an opportunity to provide input to the planning process (DES, 2022). Residual void modelling represents a key part of this planning process and hence regular community consultation should be undertaken. At least two meetings or workshops or other consultation pathways are therefore envisaged at the conclusion of the project planning phase, one with technical representatives of DES and other statutory consultees and another with community consultation groups (or similar) set up as part of the wider PRC planning process.

These meetings will provide an opportunity to engage with a range of stakeholders to discuss potential impacts of concern and agree how the modelling will address these issues. These potential impacts will provide a basis for design of the model(s), and for definition of the tasks that modelling must accomplish. The meeting will also allow the stakeholders to explain their interests, raise questions and outline the information that is needed to support understanding of the systems, rehabilitation planning requirements and implications for the decisions to be made. The meetings will also ensure that traditional owners are consulted and that indigenous knowledge and cultural and spiritual values for managing water in the landscape can be incorporated. The project plan should be provided to all attendees prior to each meeting. In addition to receiving feedback during the meeting there should also be an opportunity for attendees to provide comment afterwards and for the multidisciplinary team to update the project plan to incorporate these comments.

A program for ongoing engagement with stakeholder groups, at key stages of the project, should also be outlined in the project plan for discussion and agreement with attendees at the initial engagement meetings.

Stage 2 – Data collection and conceptualisation

Data collection should focus on achieving two key things. Firstly, it should be sufficient to develop a source-pathway-receptor model for the residual void setting, and secondly it should provide sufficient data to calibrate models through history matching thereby reducing uncertainty in model predictions.

Collecting data for the source, pathway, receptor model

In a residual void setting the ‘source’ of potentially degraded water quality may be waste rock, tailings, exposed wall rocks or the residual void water body itself. The evaporative pumping effect from the surface of a residual void water body can also concentrate solutes and create a potential ‘source’ of impact on the adjacent groundwater regime including a source of contaminants.

At a coal mine there should be sufficient data available to describe the properties of tailings and spoils backfilled within former mining areas, and how these materials influence water infiltration, storage, movement, and chemistry. At metalliferous mines there is commonly no backfilling of waste material within the open cut mining area where out of pit dumps are used. This means the only contributing catchment to the residual void is the sloping pit wall rocks, which may need geochemical characterisation to understand their significance as a ‘source’. Often mining operations collect water samples from operating pits which have potentially been influenced by the various ‘sources’ in the pit. These water analyses can provide a useful initial indication of the potential ‘source’ water quality prior to conducting any modelling.

There are two types of potential ‘pathways’ from residual voids; surface and subsurface. Surface pathways can occur where there is potential for water from the residual void to overtop and spill into adjacent drainage lines, creeks and rivers. Groundwater or subsurface pathways potentially occur where water within the residual void can leak through strata exposed in the pit walls.

To understand the significance of subsurface ‘pathways’ an understanding of the hydraulic properties of the subsurface strata is required. This should include information on the ability of key hydrostratigraphic layers exposed within the residual void walls to store (porosity), release (specific yield/specific storage) and transmit (hydraulic conductivity) water. Information on hydraulic conductivity should be collected from the site with the most suitable method depending on the strata to be characterised. Packer testing is useful for characterising the hydraulic conductivity of lower permeability strata in fractured and porous rock settings. A rising/falling head test is a useful method for collecting data from pre-existing monitoring bores, while pumping tests are the most appropriate methodology for characterising the properties of relatively permeable strata.

Samples of geological materials can also be collected to measure hydraulic properties in a laboratory. Rock cores can be tested for hydraulic conductivity and porosity and provide a useful lower bound value estimate of permeability as fracture flow is excluded from the test. Unconsolidated samples of spoil materials or tailings can also be collected and remoulded in the laboratory to measure hydraulic conductivity.

It is important to characterise the hydraulic properties of the main hydrostratigraphic units exposed within the residual void and their connectivity with adjacent aquifers. In a coal mining setting examples of connectivity pathways that may need to be characterised include:

- coal seams within the mining area that may also outcrop or subcrop under adjacent creeks and alluvial systems and therefore form a potential ‘pathway’
- surficial regolith layers that may become saturated if the residual void water body rises above the interface between the regolith and the underlying bedrock
- alluvial sediments exposed in pit walls by former creeks and drainage lines have been mined through and diverted
- basalt aquifers and the contact zone at the base of the basalt flow(s) exposed in pit walls.

Geological structures may also form a potential ‘pathway’ and may need to be characterised as part of the conceptual model development. This can be a very challenging activity and is worthy of careful consideration by appropriately skilled geologists and hydrogeologists. Murray and Power (2021) provide guidance on characterisation and modelling of geological fault zones in a sedimentary setting.

There are a range of potential ‘receptors’ that could be affected by residual voids including:

- downstream surface water users
- water supply bores
- groundwater dependent vegetation
- stygofauna
- aquatic ecosystems occurring within creeks and water bodies fed by discharge of groundwater.

It is important the ‘receptors’ are identified and their connection to surface water and groundwater resources characterised. For water supply bores this usually entails conducting a bore census of surrounding properties to locate water bores and understand their construction and usage details. The Department of Environment and Science (2022) provides guidance on identifying and assessing Groundwater Dependent Ecosystems when preparing Environmental Impact Statements. Identifying downstream surface water users may require engagement with downstream landholders and seeking water licensing information available in the public domain.

Collecting data for history matching

Data collection is commonly a time consuming and expensive exercise, and therefore it is important that the data collected is optimised to provide key input data for model calibration through history matching and to reduce uncertainty in model predictions (as far as possible). It is possible that data, depending on its nature and location, will not assist in reducing the uncertainty of model predictions. Such data has a lesser value in the residual void modelling process. The most valuable data to be collected for history matching is similar in nature and location to where predictions of impact will occur due to the residual void.

An example of this is monitoring bores that are located in close proximity to a mine pit and provide a record of actual groundwater level response to mining dewatering activities. Such datasets represent particularly valuable data for history matching purposes as their inclusion tends to reduce the predictive uncertainty especially in situations where evaporative losses from the residual void water body lead to long term drawdown. In contrast datasets that are remote from the residual void may contribute little to reducing the uncertainty in model predictions. When prioritising data collection it is therefore important to focus on data that is likely to be most effective in reducing uncertainty in the key questions the model has been designed to answer. Since the effectiveness of different types of data in reducing predictive uncertainty is unlikely to be known at this stage the project team should focus on presenting a sound scientifically based justification for the adopted data collection approach. In some cases an iterative data collation approach might be most appropriate whereby some initial modelling activities are undertaken during the planning and/or conceptualisation stages in order to scope in or out further data collection activities.

Stage 3 – Model design and construction

Once the field data collection stage has been completed and a conceptual model including the source-pathway-receptor model developed, the project team should return to the project plan and the preliminary risk assessment to see if the modelling methodology remains appropriate for the identified hazards. For example, where the source-pathway-receptor model does not identify any sensitive receptors within the zone of influence of the residual void, then a higher degree of predictive uncertainty and/or a simpler modelling approach may be acceptable as the risk is relatively low. In contrast in a setting where sensitive receptors are identified and there is a potential ‘pathway’ from the residual void water body, then the numerical modelling methodology should be designed to determine the likelihood of the receptor being impacted so that the magnitude of risk can be better understood.

As noted in Technical paper 2, simulating the behaviour of water bodies within residual voids and the surrounding environment cannot generally be achieved using a single numerical model. In most cases multiple models are developed by multidisciplinary teams to represent the different processes influencing residual void water bodies. The design of models should be focussed around the prediction that the models are required to make.

As a minimum, a water balance model is typically required to simulate the formation of the water body within the residual void and the accumulation of solutes. The first consideration in developing such a model is how it will quantify and integrate the various components of the water balance such as rainfall, runoff, evaporation and groundwater inflow/outflow. As a starting point, water balance models should normally be run on a daily timestep for a sufficient duration to capture long-term variations in rainfall and groundwater. This means that typical water balance models of residual voids would run for hundreds of years.

The second key consideration is how the model will link with other models, such as groundwater or geochemical models. The design of the water balance model needs to be considered by the project team so there is a common understanding of which processes will be represented in the water balance model and how fluxes of water or solutes are exchanged between the different models. This may be complicated by the use of different timesteps in the different models. If these issues are not clearly understood from the outset, there is the potential for ‘double-counting’ of physical processes or mismatches or gaps occurring between the inputs and outputs of the different models. An iterative modelling approach, where outputs from the water balance model are input to other process models, and the outputs of those models fed back into the water balance until all models converge to a common result, may also be required.

As noted above, appropriate water quality datasets and detailed interpretation are required to conceptualise the mechanisms likely to be controlling the composition of different end-member waters relevant to final void assessments. The datasets listed in Table 2 are critical to informing model conceptualisation, especially the field determined parameters and laboratory determined concentrations of redox indicators.

Numerous modelling techniques can be applied to assess the potential changes in void water quality as a result of mixing, evaporation, atmospheric equilibration and reactions with pit-wall minerals, spoil materials or tailings. These mechanisms need to be ranked in terms of significance based on the hydrologic predictions and hydrochemical observations. Appropriate thermodynamic databases should be selected that can consider the solutes of interest and associated reactions that may occur based on the conceptualisation process. Geochemical modelling techniques should be staged based on the order of reactions that are likely to occur and fundamental geochemical concepts. For example, following groundwater discharge into a void, mixing with other water sources (incident rainfall and catchment runoff) and atmospheric equilibration may be the primary drivers of initial water quality changes. Later on these processes may be superseded by slower mineral weathering mechanisms which occur between the void water and spoil deposits, tailings deposits or pit wall rocks. Detailed examples of contemporary modelling techniques for sequential reactions and associated kinetics are presented by Bethke (2012) and others.

When designing groundwater flow and/or solute transport models Doherty and Moore (2021) provide excellent guidance on appropriate levels of model complexity. They recommend the design process for groundwater models should:

- lean towards structural simplicity and parametric complexity
- represent, in an abstract or explicit way, those aspects of the subsurface to which predictions are sensitive
- represent the effects of hydrogeological complexity, rather than its details, and therefore accept that parameter-based abstraction in representation of the many nuances of geology that are important to flow of water and transport of contaminants
- ensure the groundwater simulation is numerically stable and relatively fast – the faster that a model runs, the more thoroughly uncertainty can be explored
- endeavour to ensure that the numerical model can accommodate conceptual surprises once information starts to flow
- result in a model that can incorporate key datasets and reduce the uncertainty of the predictions required.

A key message of Doherty and Moore (2021) is to design for a relatively simple (but appropriate) model structure that is able to host a sophisticated, flexible parameterisation scheme that will allow exploration of impacts, rather than a complex (and possibly expensive) model structure that embodies a single realisation of hydrogeological parameters.

In a coal mining setting there is often a large number of sedimentary layers that have been identified and modelled in a geological model. When designing a groundwater flow model the modeller should consider how multiple geological layers can be grouped into simplified hydrostratigraphic layers with similar properties and focus on those layers that may form a pathway to a receptor. Generally, as residual voids fill with water over time, the potential for drawdown in adjacent groundwater systems reduces compared to the period of operations. Groundwater flow models developed for the purpose of assessing the impacts of drawdown on aquifers surrounding residual voids may not need to be as spatially extensive as those developed, typically at the approval stage, to predict operational impacts. To do this the project team should draw upon data showing the extent of drawdown measured during mining operations as well as predictions from previous models to reduce the extent of the models where possible.

Another aspect to consider is how to represent the residual void behaviour within the groundwater flow model. Technical paper 1 outlined the methods currently utilised to represent residual voids within groundwater models including the ‘high K lake approach’, ‘quasi-coupling’ with a water balance model, and a ‘live coupled’ option. Regardless of the adopted methodology, a leading practice approach will represent the uncertainty in the residual void water level within the groundwater flow model typically by developing a range of void water level and other predictions based a range of possible model parameters. Ideally these predictions should be calibration constrained to exclude those parameter sets which are inconsistent with the available observations.

Stage 4 – History matching

History matching or calibration is a process by which model parameters are adjusted until modelled outputs (typically water levels, flows or concentrations) are considered to appropriately fit historical measurements or observations (Barnett et al, 2012). This process seeks to extract key information about the system from the available observations and provides more confidence in the capability of the model to reproduce or simulate the observed behaviour of the physical system.

For water balance models, it is easiest to match pit or void water levels over an historical period, where such data is available. However, this may not always be possible, such as in areas where mining has not yet commenced. In the absence of observations of pit or void behaviour, the focus should be on accurately simulating the component inflows and outflows of the water balance. Useful information on suitable model parameters may be obtained by considering parameters adopted at nearby sites, particularly where these have been derived through calibration to observations.

History matching of geochemical model outputs should also be undertaken, where possible. Appropriate water quality datasets are critical for this to be achievable. Geochemical modelling of systems having sufficient spatial and temporal datasets should aim to identify specific mechanisms or combination of mechanisms that can “replicate” the water quality observations. In this case model calibration would likely comprise adjusting the type or quantity of reactants identified by the data interpretation and conceptualisation process. For example, the evolution of groundwater composition along a flow path through a zone of mineralisation could be simulated by reacting the composition observed at upgradient, background monitoring locations with the minerals identified in core samples adjacent to a pit lake. The input composition of “background” groundwater or the quantities of reactant minerals would then be adjusted until the model predictions match the spatial trends observed in groundwater quality along the hydraulic gradient.

Similarly, the mechanisms controlling pit water evolution could be determined through rigorous data interpretation and conceptualisation followed by a similar iterative approach. The chemical composition of groundwater adjacent to a terminal evaporative sink and the composition of other water inputs (runoff and rainwater) would be used to simulate the effects of mixing based on the volumetric proportions and evaporation rates estimated by water balance modelling. These model inputs would be adjusted until the predictions match the water quality observations in the pit lake. It may also be necessary to reconceptualise the models to incorporate mineral weathering or other geochemical mechanisms, as justified by the data available. These hypothetical modelling scenarios are provided to highlight the importance of having suitable datasets to conceptualise and history match/calibrate geochemical models.

When conducting history matching for groundwater flow models it is important to provide the model parameters sufficient freedom to vary to achieve an optimal calibration to observation data. A model cannot attain a good fit with a measurement dataset if it has too few adjustable parameters. In this case the history-matching process therefore fails to extract as much information as possible from that dataset and this may bias predictions.

Leading practice therefore involves setting up the groundwater flow model so every model cell can adopt spatially variable hydraulic properties during the history matching process. Parameter ranges should be centred and guided by real-world information. Leading practice for history matching also means utilising a number of observed 'absolute' and 'difference' data sets such as:

- absolute groundwater elevations
- temporal changes in groundwater level observations (i.e. the difference between sequential readings)
- cumulative drawdown relative to an initial level
- vertical head differences measured between adjacent hydrostratigraphic units
- absolute leakage and/or estimated baseflow in local creeks
- leakage and/or baseflow gains/losses between creek gauging points and
- estimated inflows to mining operations including observations of negligible inflow, which after accounting for evaporation and other losses, suggest inflows are less than a certain threshold.

In particular it is generally not leading practice for groundwater models to be history matched solely against absolute groundwater elevations. Predictive uncertainty is typically significantly reduced by the inclusion at least one type of flow observation, even if these are estimates of actual flow derived from other means, rather than direct measurements (e.g. mine inflows derived from pumping run hours during dry periods). All observations used for history matching should be weighted so that the optimisation process has a chance to reduce residuals optimally and no single group of observations dominates the history matching process. In most cases this can be achieved most efficiently through the use of highly parameterised techniques and specialist software, rather than a manual trial and error approach.

Summary statistics such as root mean square misfit are often reported as a measure of history matching success. It is however the time series comparison charts which directly compare model outputs with each field measurement spatially and temporally that are a better measure of history matching success.

Stage 5 – Prediction

As noted previously a range of models are commonly utilised for residual void studies, some of which are designed to provide predictions that are utilised as inputs to other models. For example rainfall runoff and groundwater inflow model predictions being used as inputs to a water balance model. Other models provide predictions that are designed to address the aims and objectives of the modelling study, for example water level recovery or water quality changes within a residual void.

Predictions from water balance models need to be obtained over an extended timeframe (typically hundreds of years) to reflect the full range of historical and potential future hydrologic conditions and establish when an equilibrium condition for water levels and/or water quality is reached. As the key hydrologic driver of void water behaviour, predicted rainfall may be obtained by recycling historical rainfall or from stochastic rainfall generation models. Given the extended timeframe of water balance predictions, the impact of future climate change should also be considered in water balance model predictions. Results should be presented as time series plots showing predicted void water levels and water quality as well as snapshots showing predictions after 10, 20, 50, 100 and then say every 100 years after that until an equilibrium condition is attained.

Geochemical models are powerful predictive tools for a number of scenarios relating to final void water quality. As with groundwater modelling, the certainty of predictive geochemical models depends on the available dataset, model conceptualisation and an ability to iteratively match model predictions to current and past observations. Building on the mixing modelling scenario above (Stage 4), predictions of future water quality changes could be undertaken assuming the chemical composition of groundwater inflows and other water inputs (runoff and rainwater) remain constant, and the effects of mixing changes over time based on the temporal changes in volumetric proportions and evaporation rates as predicted by water balance modelling.

In cases where chemical reactions have the potential to significantly affect void water chemistry kinetic reaction models and/or more detailed data collection and conceptualisation may be required.

For example, in some circumstances the pH of an acidic pit lake can be buffered over time by reactions with acid neutralising pit wall minerals below the water level surface. Or conversely pH can decrease over time due to weathering of sulfide minerals on the pit wall surfaces during flooding of a void. Further conceptualisation may be required to confirm whether or not stratified conditions are likely to develop potentially requiring the collection of pit water quality profiling data.

Groundwater models generally have a superior ability to predict differences over absolutes. For this reason two predictive simulations are typically developed, one where the residual void is represented and one where the site was assumed to have not been developed. Results from these two simulations are then compared in order to predict:

- the zone of drawdown for key hydrostratigraphic layers
- groundwater levels and flow directions around the residual void in the key hydrostratigraphic units and how these change over time post closure
- groundwater inflow rates to the residual void and how these change over time
- outflow volumes from the residual void(s) and the model layers where this is predicted.

For drawdown, leading practice supports using the model predictions to calculate the maximum 'all time' drawdown which represents the highest value of drawdown encountered at any cell across all stress periods in the model simulation. When the date of maximum drawdown is plotted spatially along with the maximum drawdown value it provides a powerful insight into transient changes in groundwater levels over time due to the presence of the residual void.

Stage 6 – Uncertainty analysis and risk assessment

Because all models have uncertainty no model prediction should be reported as a single model result unless that single result is also accompanied by an effort to quantify predictive uncertainty. Groundwater flow and transport models tend to suffer from significant uncertainty since the hydraulic parameters which govern groundwater flow can vary across several orders of magnitude and determining representative parameter values of each model cell can rarely be achieved as data density is never optimal. One of the key considerations for the project hydrogeologist throughout the study when developing parameters for use in the groundwater simulation is therefore what is the best estimate of each particular parameter and what are its likely upper and lower bounds (i.e. how wrong could this best estimate be?). These estimates of the best estimate and possible ranges should then be used to constrain both the history matching and uncertainty analysis stages of the study. In the event that the history matching process pushes parameters to either the upper or lower bounds then a wider range of parameters should be adopted for uncertainty analysis purposes to minimise the potential for bias in the predictions.

It should be stressed that parametric uncertainty is not unique to groundwater models. Accordingly, the influence of potential errors in parameters adopted in project rainfall runoff and other models should also be assessed. However, such models typically only include a relatively small number of parameters and these parameters tend to be less uncertain. For instance, runoff from any model cell cannot exceed the volume of incident rainfall.

Uncertainty analysis predictions should be extracted to enable the stated aims and objectives of the modelling to be addressed. These predictions should be statistically analysed and presented using the probabilistic language recommended by Middlemis and Peeters (2018). The predictions should be expressed as the likelihood of exceeding an acceptable threshold that was defined in the hypothesis that the model was required to test. Rejection of a hypothesis may or may not be possible. For example returning to our example hypothesis for modelling *"the water level in residual voids will not exceed the crest of the void and spill to the adjacent water course",* can be answered in a number of ways depending on the suite of model predictions from the uncertainty analysis. Where there are no model predictions that indicate the residual void will fill above the level of the void crest then it can be stated, based on the modelling, that this outcome will not occur and the hypothesis accepted. Where less than 10% of the model predictions result in levels above the crest of the void then, based on the thresholds and language presented in Middlemis and Peeters (2018), as shown in Table 3 it can be stated it is very unlikely a spill of the residual void water will occur. In contrast where more than 90% of uncertainty analysis realisations predict the water level will rise above the crest this can be described as a very likely outcome. Table 3 also presents likelihood descriptions for the other common hypotheses mentioned in the modelling aims and objectives discussion. Whilst these three hypotheses will apply to many void modelling studies the list is not intended to be exhaustive and is provided for illustrative purposes only. Information on the likelihood of the hazard illustrated in Table 3 can then be used to further quantify risk using standard risk assessment techniques based on the identified consequences of the unwanted impact event. For example what is the consequence of the water stored in the residual void discharging to surface water.

Table 3. Example hypothesis testing outcomes based on uncertainty analysis results and adopting the calibrated language and colour coding recommended by Middlemis and Peeters (2018)

Hypothesis	**Proportion of uncertainty analysis realisations which result in the unwanted outcome**	**Colour code**	**Likelihood description**
The water level in residual voids will not exceed the crest of the void and spill to the adjacent water course	<10%		It is **very unlikely** that the voids would discharge to surface water
	10-33%		It is **unlikely** that the voids would discharge to surface water
	33-67%		It is as **likely as not** that the voids would discharge to surface water
	67-90%		It is **likely** that water quality that the voids would discharge to surface water
	>90%		It is **very likely** that the voids would discharge to surface water thresholds
The salinity, pH and metals concentrations in the residual void will not exceed the ANZECC guideline values for the intended use or environmental values	<10%		It is **very unlikely** that water quality in the residual void would exceed relevant thresholds
	10-33%		It is **unlikely** that water quality in the residual void would exceed relevant thresholds
	33-67%		It is as **likely as not** that water quality in the residual void would exceed relevant thresholds
	67-90%		It is **likely** that water quality in the residual void would exceed relevant thresholds
	>90%		It is **very likely** that water quality in the residual void would exceed relevant thresholds
The water level within the residual voids will exceed the lowest water level in the adjacent groundwater system and therefore the void will form a source	<10%		It is **very unlikely** that the voids will represent a source
	10-33%		It is **unlikely** that the voids will represent a source
	33-67%		It is as **likely as not** that the voids will represent a source
	67-90%		It is **likely** the voids will represent a source
	>90%		It is **very likely** that the voids will represent a source

Stage 7 – Reporting

Typically, a range of reports will be prepared by each of the members of the multidisciplinary team documenting their modelling tasks. This might include a groundwater report, a surface water report, a geochemistry report and a groundwater dependent ecosystems report. A leading practice approach requires that the outcomes documented in these reports are integrated and summarised in an overarching report prepared by an appropriately qualified person such as the project manager. Recommended content for the overarching report should draw from the project plan and specialist consultant reports as much as possible (Table 4).

Table 4. Recommended content of an integrated modelling report

Section	Content
Introduction	site location, company(s) engaged and for what purpose
Residual void(s) details	residual void name(s), location(s), existing water volume and maximum water volume at spill point level
Site setting	brief summary of location, climate, water resources, groundwater systems and vegetation including site visit photos
Conceptual model	description of how groundwater, surface water, and ecological systems operate and interact with the residual voids
Aims/objectives of modelling	statement of hazards that could be significant and require modelling, and hypotheses to be tested
Modelling predictions and outputs	model scenarios and interaction between models
Uncertainty and risk	quantify risks posed by the residual voids by using the modelling predictions to discuss the likelihood of a hazard occurring and the potential consequences of each hazard based on the conceptual model
Monitoring and validation	discuss the residual uncertainties and the benefit/need for ongoing monitoring along with future validation of the model predictions.
Appendices	modelling reports for groundwater, surface water, geochemistry and ecology

Stage 8 – Monitoring and validation

Due to the time, cost and complexity of ongoing data collection, the modelled behaviour of residual voids is rarely validated using ongoing monitoring data. The need for ongoing monitoring will depend on the uncertainty associated with the model predictions and magnitude of the environmental risk. Where there is a wide range of uncertainty in the model predictions, additional monitoring data would allow a future modelling exercise an opportunity to reduce the uncertainty range. This would be beneficial where hazards from the residual void were identified to be present and significant. At sites where modelling uncertainty remains high, but risks remain low then ongoing monitoring and future model validation may be of limited benefit.

The need for and scope of ongoing monitoring should be decided with input from the multi-disciplinary team at the conclusion of the uncertainty analysis (i.e. once the predictive uncertainty range and the environmental risks have been defined). Where required ongoing monitoring may include regular measurement of:

- rainfall
- void water level and water quality
- water quality profiles with depth
- evaporation
- groundwater levels in adjacent monitoring bores
- flow and water quality in adjacent water courses.

Where collected, additional ongoing monitoring data should be used to validate both input data and assumptions used for void modelling purposes and also for validation of modelling predictions. In the event that any significant inconsistencies are identified then the relevant void modelling activities should be revised and re-run to generate a revised set of predictions.

5. References

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