Office of the **Queensland Mine Rehabilitation Commissioner**

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

Technical paper 2

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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Executive summary

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 develop separate models for different processes which are then coupled together to some degree, for example where surface water balance predictions are used as inputs of groundwater flow models. While this quasi-coupling approach 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 leading 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 leading 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. This in turn will allow for risk-based decision making when preparing PRC plans. Leading 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 (EAs) 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*). Returning land to a stable condition means that a post mine land use is achieved where possible.

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 leading 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 mine void modelling approaches including issues such as conceptual model development, model selection, scenario testing, deciding appropriate timeframes for prediction, defining suitable modelling outputs, and
- Technical paper 3 – step-by-step guidance describing how to implement leading practices.

Each of these components are described in separate documents. This document summarises the outcomes of Technical paper 2 and outlines a series of stages to follow when conducting modelling for residual voids and the associated principles that underpin leading practice. Practical guidance on applying these stages and principles is provided in Technical paper 3. 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, silica, silver and vanadium 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. 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 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 report 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 subsurface water flows into the void and does not leave the void (except via evaporation). In a groundwater source scenario, the void water level is above the level of the surrounding water table and subsurface water flows 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 water 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

It is recommended that projects modelling the behaviour of residual voids and water in the interconnected landscape should be undertaken 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 the recommended approach for modelling mine voids and describes key principles within each stage of the modelling process.

4. Leading practice

The intent of this document is therefore to outline a modelling workflow which represents current leading practice for residual void modelling in Queensland as part of the PRC planning process. Within this document, guiding principles underpinning leading practice outcomes are identified. These principles are based on the authors' experience investigating and modelling water bodies within residual voids, as well as existing groundwater modelling guidance documents (Doherty and Moore 2021, Barnett et al 2012, Middlemis and Peeters 2018). It is important to note that leading practice approaches do not necessarily involve complex modelling approaches for all scenarios. Rather leading practice as described here provides a structured approach to explore the research questions, identify the potential hazards associated with a final void, and ultimately in Stage 6 quantify potential risks. This guidance recognises that the level and extent of modelling needed can vary and that the approaches should be proportionate to the social, environmental, and economic risks associated with the scenario being explored.

Further guidance including examples demonstrating the practical implementation of the workflow is provided in the leading practice implementation guide (Technical paper 3).

5. Stages and tasks

Stage 1 – Planning

Task 1a – Build a multidisciplinary team

The first task of Stage 1 is to identify a multidisciplinary team to undertake the void modelling study and familiarise the team with the subject site. 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.

Successful modelling efforts gather specialists with appropriate experience in these disciplines to contribute to a residual void water body study under the control of a project manager. Omitting some of these key disciplines from a study team increases the risk that the modelling and assessment outcomes will not meet the needs of all stakeholders.

Once an appropriate team has been identified a site visit to inspect the residual void or its future location and gather local knowledge important for the study should be undertaken. This step may not always be practical as residual voids in Queensland can be remote and difficult to access, but where possible it is an important first task the team should attempt to implement. Becoming familiar with the characteristics of the site ensures the multidisciplinary team will not overlook any critical features, opportunities or constraints, and can contribute their skills with a practical and achievable approach.

Further guidance on the objectives of the multidisciplinary team site visit is provided in the leading practice implementation guide (Technical paper 3).

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

The second task of Stage 1 is to describe the hypotheses to be tested during the study and prepare a project plan to achieve this. 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.

During this task an important principle is that **the multidisciplinary team determine how to apply the scientific method** to the problem being assessed. The workflow determined for the modelling should follow the rules of the scientific method with an acknowledgement that models cannot predict exactly what will occur in residual void water bodies over time. Rather their purpose is to assist with testing of hypotheses regarding a range of potential hazards. This is an important principle that when acknowledged early will assist all parties interpreting and utilising the predictions of modelling.

The hypotheses applicable to residual void water bodies to be tested should relate to the key hazards that must be quantified to determine the level of risk. Examples of hypotheses which are likely to be appropriate for void modelling projects include*:*

- *the water body will fill and spill into a neighbouring water course*
- *water balance results suggest excess water that may need to be managed*
- *contaminants such as salinity in the water body exceed thresholds for beneficial use*
- *contaminants will reach an equilibrium concentration in a residual void*
- *water and contaminants will migrate into the surrounding groundwater systems*
- *the residual void water body will remain a sink within the groundwater regime, or*
- *that evaporation from the water body will generate drawdown exceeding a maximum threshold at the location of nearby groundwater dependent ecosystems or water bore.*

Once the hypotheses that require testing have been identified, the modelling approach required to test these hypotheses can be developed. Stochastic modelling approaches are to be used to enable the likelihood of future hazards to be estimated statistically, and applied to the hypotheses to be tested. A modelling study has not achieved its intended purpose if it cannot be used for decision making as part of the PRC planning process because the methodology does not allow the likelihood of the key hazards to be quantified (in the context of groundwater modelling see Doherty and Moore

2021). It is essential the modelling provides an understanding of the likelihood of the key hazards occurring, as this is required before the level of risk can be quantified.

If the residual void modelling is designed to evaluate the likelihood of key hazards, and the consequence of these outcomes can be evaluated then the level of risk can be estimated. This is a key principle that ensures that the outcomes of modelling studies can be used to understand risk and assist with progressing the PRC planning process and ultimately relinquishment of the mine site.

Further guidance on the content of the project plan and the need for further data collection activities is provided in the leading practice implementation guide (Technical paper 3).

Task 1c– Initial engagement with stakeholders

The third task of Stage 1 is to engage with stakeholders to describe and seek feedback on the objectives, scope, opportunities and constraints of the proposed modelling process. Engagement should be undertaken at the technical level with relevant Queensland government officers through the Department of Environment and Science (DES), and with stakeholders within the local community. Community consultation represents a key component of the PRC planning process (DES, 2021) and hence void modelling projects should seek to tie into consultation protocols which are likely to have been established as part of this process.

Successful residual void modelling studies should aim to meet the needs of stakeholders by providing information to enable decision making in a cost effective and timely manner. When these groups engage with each other early in the modelling and assessment process there is an opportunity to gain a shared understanding of the role of modelling in the process, its strengths and inherent limitations.

Early engagement provides an opportunity to discuss the outcomes sought by all stakeholders and is likely to increase acceptance of the process and lead to more successful outcomes being achieved. In particular, engagement between stakeholders on the modelling process is needed to allow:

- The mine owner/operator to explain the project plan to stakeholders including the objectives, scope, opportunities and constraints of the proposed modelling process
- Queensland government officers to explain the PRC plan process and outcomes
- Local landholders to explain their desired uses for water bodies in residual voids and surrounding environments
- A shared understanding and consideration of indigenous knowledge and cultural and spiritual values for managing water in the landscape.

Further guidance on initial and ongoing stakeholder engagement is provided in the leading practice implementation guide (Technical paper 3).

Stage 2 – Data collection and conceptualisation

The first task of Stage two is to develop a conceptual model of void hydrology and water quality and its potential interaction with the surrounding environment. Conceptualisation is a process that communicates to a wide range of audiences how environmental systems work and provides the basis for numerical model design. Conceptualisation is a well-established aspect of hydrogeological and hydrogeochemical investigations as the groundwater regime, including chemical reactions, cannot be seen and therefore must be explained through data, text and graphical models.

As outlined by Barnett et al (2012) and other authors a conceptual model infers the likely contribution of key processes in a system based on interpretation of available datasets. Development of a conceptual model is a key stage in the modelling process where a decision to proceed past the conceptual stage to conduct modelling is required. A conceptual model also provides a basis for the hypotheses to be tested as part of the scientific method and may be reviewed and updated based on history matching or validation results.

At this point it is important to determine if there is sufficient knowledge of the key processes occurring at the site of the residual void to inform conceptual models, or alternatively if further data collection is required. In particular the available data should be reviewed to confirm whether or not it is sufficient to develop and source-pathway-receptor conceptual model and enable model calibration through history matching.

The conceptual model is to consider the following:

- The geological formations and aquifers that are likely to dominate the behaviour of the residual void water body

- The expected or known direction of groundwater flow
- The relative level of the void floor compared to regional groundwater levels and geologic units
- The key contaminants and sources of these contaminants in the residual void
- Whether key contaminants are likely to persist or attenuate under the hydrogeochemical conditions
- The influence of surface runoff on void hydrology and water quality
- The volume of in-pit spoil and its physical and chemical characteristics
- How key elements of the system behaviour are likely to change over extended timeframes.
- Any potential surface and groundwater linkages
- Location and nature of environmentally and culturally sensitive receptors.

Answers to each of these questions are informed by an assessment of relevant site data, knowledge of stakeholders and previous modelling reports.

Barnett et al (2012) provide further advice on developing conceptual models and data collection that the reader is referred to. In addition, Bethke (2007) outlines the importance of data collection, data interpretation and conceptualisation of hydrogeochemical models. A study by Collings (2012) describes approaches for water quality management taking into account indigenous cultural and spiritual values. It includes case studies incorporating indigenous cultural and spiritual values into water planning including a conceptual model of the Police Lagoons in central Queensland that document the cultural, spiritual and historical significance of Police Lagoons for indigenous people.

The second task of Stage 2 is to summarise and review the suitability of available site and regional data to support the modelling methods proposed. All data used to inform modelling are to be collected using a sound monitoring design, and meet quality assurance and quality control standards for sampling and analysis. Although it is not the purpose of this document to describe such requirements, these aspects are discussed in detail elsewhere, such as in the Queensland Monitoring and Sampling Manual (DES, 2018), the Queensland (EHP, 2013) and national Water Quality Guidelines (ANZG, 2018). Guidance provided in (ANZG, 2018) recommends a minimum of two years of monthly baseline data to provide a reasonable basis to assess natural variability in surface water. However, it is recognised that groundwater samples may be collected less frequently and require a longer duration to assess long term trends.

Models use field data to calibrate parameters and ensure model predictions of future system behaviour remain within plausible ranges. It is possible to construct models of a residual void system with very little site-specific data, however, models based on limited data will have more uncertain predictions of residual void behaviour. This situation may be acceptable where risks are low, but it is important model uncertainty does not mean hypotheses that require testing cannot be quantitively assessed. A lack of good quality data is not an acceptable reason to apply an overly simplistic modelling approach. Where a lack of data will limit proper application of the modelling methods identified as being required in the project plan, further data is required before modelling can be undertaken. If the hypotheses cannot be tested reliably, then the key questions about the behaviour or the residual void water body and associated hazards may not be able to be answered, and risks cannot be quantified. Where modelling fails to provide useful outputs the modelling process will not provide the intended outcomes. This may be avoided by targeted collection of key field datasets.

Models of residual void processes are to be based on site specific measurements of the key components affecting the residual void water balance, void water quality and surrounding groundwater regime where site specific information is required to reduce uncertainty in predictions. This is a key principle that should be considered when determining if it is necessary to collect data from the site as data collection is often expensive and time consuming. Since the water balance, water quality and groundwater regime may be unique to each void, a site-specific conceptual model is required to describe the key water quantity and quality components at each site. At many sites, data is collected on a regular basis throughout the project life cycle and can be used to develop conceptual models. Where water bodies have formed within residual voids and monitoring data is available, this information can also sometimes be used to validate the predictions of models (see also Stage 8).

Historically, void modelling studies have often been undertaken without referencing site specific information on key water balance components, however, this does not represent leading practice. Where broad estimates are proposed to be used as input variables to models, there would need to be a clear demonstration that the data are of local relevance and will produce reliable predictions. For instance, pan factors used to derive evaporation rates from pit lakes are often assumed, rather than being derived from site specific measurements. Volumetrically evaporation losses often represent the most significant loss term and are known to be affected by complex microclimatic effects which vary depending on the shape and orientation of the void (McJannet et al, 2019). As a result, the relationship between evaporation rates measured using an evaporation pan to those occurring from a pit lake is likely to vary from site to site. Given the use of such estimates have been shown to introduce substantial error, the use of site-specific evaporation data is preferred unless it can be demonstrated that the use of estimates of evaporation loss do not introduce an unacceptable level of uncertainty to the modelling predictions. 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

The first task of Stage 3 is to describe how the model (or likely models) represents the key processes identified in the conceptual model in a quantitative framework. This is achieved by constructing each model using appropriate modelling software.

Simulating the behaviour of water bodies within residual voids and the surrounding environment cannot generally be achieved using a single numerical model (at the time of writing). In most cases multiple models are developed by multidisciplinary teams to represent processes influencing residual void water bodies. These can include a:

- rainfall runoff model
- groundwater flow model
- geochemical model or models
- a water balance simulation (which draws on outputs from other numerical models)
- flooding models
- evaporation models
- limnological models and
- contaminant transport models.

As a minimum, a stochastic water balance model is typically required to simulate the formation of the water body within the residual void and the accumulation of solutes. Depending on the site specific setting of each project a number of other numerical models listed above may also be identified by the project team as being required. The number and type of models chosen for a particular residual void setting should be based on the conceptual understanding developed in Stage 2, the main purpose of which is to identify the key processes affecting residual void water bodies. A numerical model should then be developed to simulate the key processes identified in the conceptualisation. Where stochastic modelling is not warranted or not possible, a justification of the rational is to be described.

It is beyond the scope of this document to outline how to implement the variety of models that may be necessary to simulate the range of processes occurring at residual voids. Instead, this guidance describes a series of steps and principles to be followed to apply leading practice approaches to modelling a wide range of processes.

The environmental risks posed by each residual void are to be identified and used to scope the level of effort required consistent with other guidelines in the environmental approval and compliance space. The process of risk assessment and conceptualisation and model development is to be undertaken in an iterative manner. Risk assessments should consider utilising the AS ISO 31000:2018 approach, using an appropriate risk ranking matrix and adopting a conceptual source – pathway – receptor approach commonly applied to groundwater contamination studies (Standards Australia, 2018). Prior to completing the risk assessment, consideration should be given to whether or not there is sufficient site-specific data to develop a conceptual model and complete the assessment. Assuming that the conceptual model is sufficiently well developed then proponents would assess the environmental risks associated with each residual void in terms of whether or not:

- the void represents a potential **source** of groundwater/surface water impact on the surrounding environment
- there are potential **receptors** in the receiving environment within the area of influence of the void and
- there are potential **pathways** which could allow groundwater/surface water impacts at the

source to reach potential receptors.

In cases where the residual void does not represent a potential source of impact, where there are no potential receptors and/or where there are no pathways which would allow impacts to reach receptors then the assessed risk would be low. In these instances, subsequent groundwater modelling could be limited to a methodology with higher associated uncertainty in the predictions if an undesirable outcome is highly unlikely. On the other hand a more thorough assessment of impacts and uncertainty is required for residual voids where the assessment suggests high source, pathway and/or receptor risks.

Doherty and Moore (2021) provide strategic guidance on how to approach groundwater modelling depending on the availability of structural data and parameter datasets. Where there are limited data but expert knowledge or opinion available they recommend either geostatistical datasets are developed, or worst case scenario analysis. Where available datasets are significant then history matching and uncertainty analysis is recommended.

Of course, the ultimate purpose of this initial assessment in Stage 3 is to assess the level of risk prior to further, quantitative assessment. This is because during Stage 3, model predictions are not yet available, and the level of risk can only be considered subjectively when designing the modelling approach. When interpreting the risk based approach it is important to understand that it is not necessarily intended that more complex models be constructed for residual voids which pose a greater risk to the local environment, or that simple models are suitable for low risk settings. The aim in higher risk settings is therefore to achieve greater certainty in predictions in order that impacts on nearby sensitive receptors can be ruled out. Achieving this outcome is likely to require additional effort at all assessment stages including site data collection and conceptualisation, but it does not necessarily require a complex suite of models. The complexity of the model required should instead depend on the complexity of the key processes identified in the conceptual model.

Further guidance on model design and construction, including on appropriate levels of complexity, is provided in the leading practice implementation guide (Technical paper 3).

Stage 4 – History matching

Calibration or history matching to site specific historic data represents a key component of leading practice void modelling. During history matching model parameters are adjusted until model outputs are considered to appropriately fit historical measurements or observations (Barnett et al., 2021). This process provides confidence in the capability of each model to reproduce or simulate the observed behaviour of the physical system and applies to all component models that feature in the assessment, including groundwater models, surface runoff models and water quality models. The degree of calibration able to be achieved will vary depending on the process being modelled and the available data.

Ideally history matching should be carried out on all component models and where this is not the case then it would need to be justified by the multi-disciplinary team in the Stage 1 project plan. Furthermore, history matching should be undertaken using site specific data including time series observations of groundwater levels, drawdown, inflows to workings, surface water flows and groundwater and surface water quality. Broad, spatial and temporal trends such as seasonal and long term climatic variation need to be taken into account when establishing an appropriate period for history matching. In most cases parameter values should be optimised using an automated, rather than a trial and error, calibration approach and parameters should also be allowed to vary spatially as necessary to fit the available data. The use of a trial and error approach or groundwater flow parameters is likely to introduce a higher level of residual uncertainty that may mean the model does not meet the intended objectives.

This process is a particularly critical component of groundwater modelling studies since the hydraulic parameters which govern groundwater inflow can vary across several orders of magnitude and hence history matching to actual observations represents a key means of reducing predictive uncertainty. In cases where history matching cannot be undertaken then the use of expert knowledge and/or geostatistical estimations of hydraulic parameters may be appropriate, although would need to be justified by the project team.

Geochemical models can and should also be developed and refined using observed historical trends in water quality. Spatial and temporal trends in water quality and associated data interpretation are critical to conceptualising contaminant source areas, materials and mechanisms. Many hydrogeochemical mechanisms are controlled by kinetic constraints (rates of reactions) and are simulated in geochemical models using data from published studies on reaction rates and refined until predictions fit historical measurements or observations at the site in question. History matching is therefore often critical to developing reliable forward in time predictions in water quality (groundwater or void water).

Stage 5 – Prediction

The first step of Stage 5 is to run the models to make predictions. Once history matching and model calibration are completed then the suite of models being utilised for the residual void assessment can be used to make predictions of changes in water level, flux or quality. For modelling risks associated with void-groundwater interactions, predictions in most cases should be run transiently and over a long enough period that an equilibrium condition for water levels and/or water quality is reached. In the case of water quality modelling this may require mineral saturation limits to be represented in the modelling process. Typical model prediction timeframes will be hundreds of years.

The effect of short-term climatic variability, and longer term climate change are to be assessed. Long-term climate sequences can be developed by looping the available historical data, such as patched point rainfall data, or by stochastic generation. Using historical data has the advantage of providing a realistic representation of climatic variability at the site, although there is likely to be some discontinuity at the end and beginning of the data set. Stochastic data allows a long period of representative climatic data to be generated with known statistical properties. Predictions of potential climate change impacts are typically assessed as a proportional change in historical conditions, based on various alternative climate change scenarios. Leading practice for climate change analysis is to carefully consider the alternatives for downscaling of climate model projections and select one that addresses the risk being investigated. Detailed climate projection predictions for different parts of Queensland in 2030, 2050 and 2070 are available via the Queensland Future Climate Dashboard[1] and should be used by default.

Where modelling predictions from one model are used in another model, for example using rainfall runoff model and groundwater model predictions in a water balance model, **it is important that that a coherent approach is adopted that uses (as far as possible) common input data and identifies possible ranges in model outputs** to allow uncertainty to be assessed as discussed in Stage 6 below.

Stage 6 – Uncertainty analysis and risk assessment

The first step of Stage 6 is to evaluate the level of risk. Significant effort will have been expended by the time any assessment reaches Stage 6. Whilst this is the case the project team must remain cognisant that models cannot predict the future and exactly what will occur in residual void water bodies over time. The purpose of the models is to assess the likelihood of hazards occurring. These hazards should have been identified in Stage 1 and Stage 2, as should the hypotheses that require testing framed around these issues. For example, the modelling should have been setup to assess the likelihood of the residual void spilling over into a local water course, groundwater levels falling below an acceptable threshold at a sensitive receptor, and/or water quality deteriorating over time and posing a risk to off-site environmental receptors. Therefore, the ultimate purpose of modelling conducted for residual voids is not to predict exactly what will happen, but to quantify the likelihood of a hazard occurring. When the likelihood of a hazard occurring has been assessed then these results can then be used to assess the level of risk.

It should be noted that since deficiencies in the input data (Stage 1) and/or conceptual model (Stage 2) may only become evident during the later modelling stages then a number of iterations of the data collation, conceptualisation and modelling workflow may be required to allow the project risks to be evaluated.

The level of risk is the function of the likelihood of a hazard occurring and the consequences if the hazard was to occur. The likelihood of the hazard occurring should be determined by assessing

[1] https://www.qld.gov.au/environment/climate/climate-change/resources/science#dashboard

uncertainty using a probabilistic approach to the modelling. Hazard predictions made using groundwater models are particularly prone to uncertainty since the hydraulic parameters governing groundwater flow can vary across several orders of magnitude. Predictive uncertainty analysis are therefore already a common feature of many groundwater modelling studies, in most cases adopting one of the three different uncertainty quantification techniques identified in Middlemis and Peeters (2018).

Rainfall variability, rather than parametric uncertainty, often represents the key source of uncertainty in surface water modelling. However, in instances where the pit water balance is dominated by surface water runoff then uncertainty in runoff coefficients and other model parameters are likely to become more significant. Fortunately, rainfall can be easily and accurately measured, and the historical record will typically contain periods of extremely wet and extremely dry conditions that will represent a very wide range of catchment hydrologic response.

Uncertainty in geochemical models primarily relates to reliance on tabulated thermodynamic data and experimentally determined kinetic data published in the scientific literature for reactions between water and pure mineral phases. The modelling cannot typically account for impurities and surface armouring that are known to affect thermodynamic properties and often limit the rate at which minerals react in natural systems. Furthermore, kinetic reaction modelling requires assumptions of reaction mechanisms, surface areas of minerals undergoing dissolution/precipitation reactions, and density of nucleation sites for crystallisation/mineral precipitation. Unlike groundwater modelling, variations in input parameters for geochemical models are typically undertaken manually until model predictions match historical observations. Like groundwater modelling, variations in input parameters for geochemical models can be automated; however, this is challenging and there is limited technical guidance for void modelling. As such leading practice remains to manually vary parameters until model predictions match historical observations. Adjustments of input parameters should be justified based on historic water quality observations (discussed above) and consistent with principles of geochemistry. Methods of uncertainty analysis in geochemical modelling are discussed by Srinivasan et al. (2007) and others.

Outputs from modelling of residual voids that utilise a stochastic approach commonly comprise several hundred model realisations. The predictions from this body of realisations are statistically analysed, with the output most commonly presented as percentiles and also using a uniform or calibrated ‘probabilistic language’, examples of which are provided below in Figure 1, Figure 2 and Table 1.

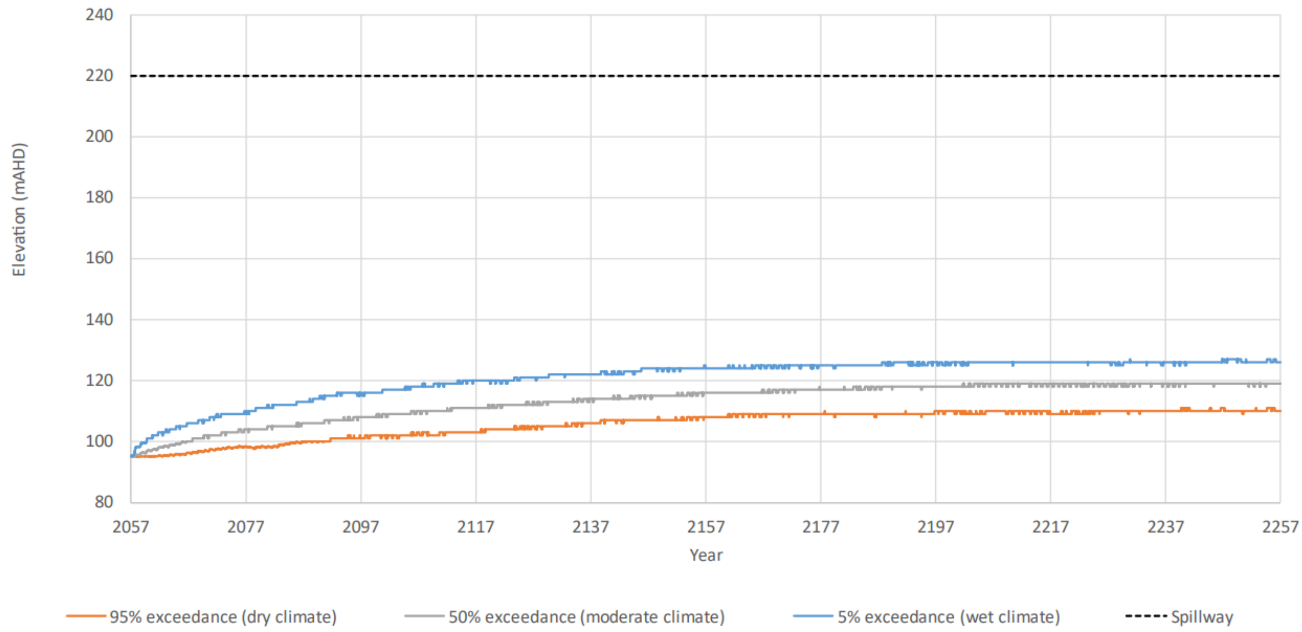

Figure 1. Model output of predicted residual void water levels over time Caval Ridge Mine (SLR, 2021)

The use of ‘probabilistic language’ summarised in Table 1 is recommended by Middlemis and Peeters

(2018) as a means of removing as much subjectivity and personal bias as possible from the assessment of modelling results. As shown Table 1 Middlemis and Peeters (2018) also provide a suggested colour coding system to assist with visual presentation of predictive uncertainty analysis results in figures and maps.

In addition to providing a consistent approach to describing uncertainty, across a range of disciplines and modelling approaches, the probabilistic language also provides a uniform approach to assessing risk when the consequences are determined as shown in

Table 2 below.

Using the risk assessment matrix allows the key project risks initially identified in Stage 1 and Stage 2 to be quantified and discussed in a consistent manner for all projects across Queensland. For example, if none of the predictive uncertainty analysis realisations suggest that the residual voids will fill and spill into local water courses then this risk can be confidently eliminated and it can be stated this will not occur. If this outcome was predicted in less than 10% of the model realisations, and the consequence for local water sources was determined to be negligible then the risk would be described as low. If the consequences were more significant, it would be classified as a medium risk. Risks are high where the hazard is predicted to occur in a large percentage of the model realisations, and the consequence is critical or catastrophic.

Further guidance on predictive uncertainty analysis and risk assessment, including examples of the application of the calibrated probability language to common residual void hypotheses, is provided in the leading practice implementation guide (Technical paper 3).

Table 1. Example of a combined numeric, narrative and visual approach to describing likelihood (Middlemis and Peeters, 2018)

Percentile (outcomes ranked from small to large)	Colour code	Description (in terms of likelihood of exceedance)	Alternative description or framing
<10%		It is **very likely** that the outcome is **larger** than this value	It is **very unlikely** that the outcome is **smaller** than this value
10-33%		It is **likely** that the outcome is **larger** than this value	It is **unlikely** that the outcome is **smaller** than this value
33-67%		It is **likely as not** that the outcome is **larger** than this value	It is as **likely as not** that the outcome is **smaller** than this value
67-90%		It is **unlikely** that the outcome is **larger** than this value	It is **likely** that the outcome is **smaller** than this value.
>90%		It is very unlikely that the outcome is larger than this value	It is very unlikely that the outcome is smaller than this value.

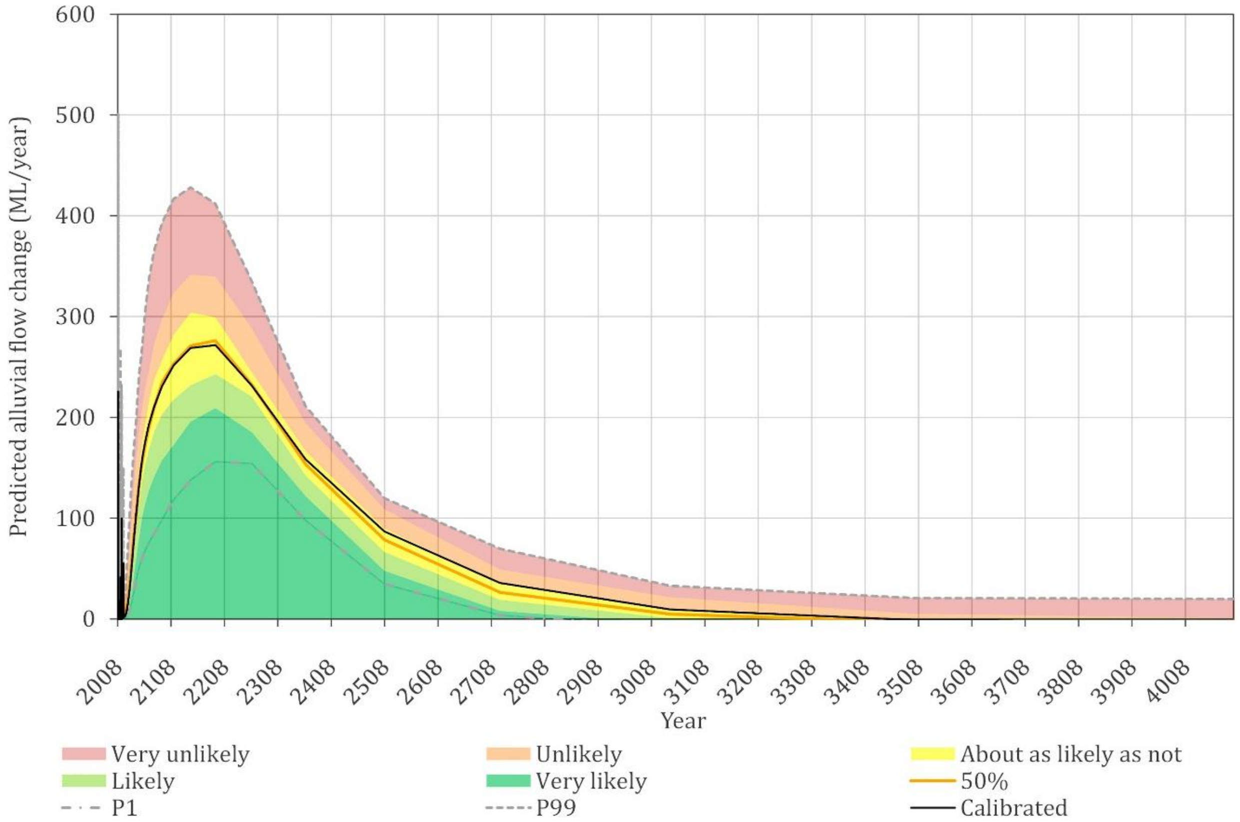

Figure 2. Example of application of language used to describe model calibration (AGE, 2020)

Table 2. Example of a risk assessment matrix using predictive uncertainty results

Consequence / Likelihood	**Catastrophic**	**Critical**	**Marginal**	**Negligible**
Very likely (very frequent)	High	High	Serious	Medium
Likely (frequent)	High	High	Serious	Medium
Likely as not (probable)	High	Serious	Medium	Low
Unlikely (occasional)	Serious	Medium	Medium	Low
Very unlikely (remote)	Medium	Medium	Medium	Low
Eliminated	None	None	None	None

Stage 7 – Reporting

All stages of the residual void modelling process including the modelling objectives, conceptualisation, model design, model calibration, predictive modelling, uncertainty analysis and risk assessment should be clearly presented in the final reporting. Stakeholder review may also be beneficial at key stages during the modelling process, including following completion of:

- conceptualisation and model design
- model calibration
- predictive modelling, uncertainty analysis and risk assessment.

Key model assumptions and limitations are to be clearly identified during this consultation process and in the final reporting. The reporting is to contain sufficient detail to allow peer review to be undertaken. This may require an overarching summary document and technical appendices outlining the different types of modelling undertaken to ensure that the reporting is accessible to a range of stakeholders.

Further guidance on reporting, including a recommended report structure and content for an over-arching report, is provided in the leading practice implementation guide (Technical paper 3).

Stage 8 – Monitoring and validation

The final component needed in a void modelling study is validation of model predictions. As per other stages in the void modelling process, the need for and scope of ongoing data collection and validation activities will depend on the degree of predictive uncertainty and the magnitude of the environmental risk. Hence for projects where the results of the Stage 6 predictive uncertainty analysis and risk assessment suggest relatively high risks and/or uncertainty then all model based predictions, including key parameters and assumptions underpinning the predictions, are to be validated using actual measurements from key stages of the project life cycle. Opportunities to collect validation data relating to key parameters affecting residual void water balances and/or water quality should be identified and included in routine monitoring programs or via ad hoc investigations. Model predictions should also be periodically reviewed at agreed time frames against new monitoring data to validate the predictions. Where the observations fall within the range of predictions resulting from the uncertainty analysis then the models can be considered validated. Alternatively, where the observations fall outside the range of predictions then revision of the conceptualisation, model design, calibration and/or potentially the uncertainty analysis stages of the modelling work may be necessary.

The PRC planning guidelines (DES, 2021) outline a process of annual returns and three yearly audits. Hence the default position should be for comparisons of on-site data to model inputs and predictions to be undertaken annually with model calibration and/or predictions to be revisited every three years. However, this may not be appropriate for some low risk projects. The project reporting should therefore include a recommended frequency for review and updates of and void modelling work.

Further guidance on ongoing monitoring and validation is provided in the leading practice implementation guide (Technical paper 3).

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