Office of the Queensland Mine Rehabilitation Commissioner

Review of current approaches to model residual mine voids for rehabilitation planning

Technical paper 1

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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Citation

Tomlin, J., Phillipson, K., Lenahan, M., Durick, A., Manewell, N., Newton, D., Briody, M., and Dunlop, J. 2023. Review of current approaches to model residual mine voids for rehabilitation planning: Technical paper 1. Brisbane. Office of the Queensland Mine Rehabilitation Commissioner.

Acknowledgements

The authors would like to acknowledge Professor Peter Cook from the National Centre for Groundwater Research and Training (NCGRT), Flinders University for valuable contribution as a reviewer.

March 2023

Contents

Figures

Tables

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 involves the deployment of a range of models to represent the environmental processes occurring. The models are 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 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 typical 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 plans (PRCPs) 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*).

In instances where the final landform includes a water filled residual void, it is necessary to assess how this water body will interact with the surrounding environment to inform the development of appropriate rehabilitation and management strategies. A variety of modelling approaches are currently used, 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 practices includes the following three components:

- Stage 1 – a review of current mine void modelling practices in Queensland including comment on the advantages and disadvantages of available modelling approaches,
- Stage 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
- Stage 3 – step-by-step guidance describing how to implement leading practices.

This document summarises the outcomes of Stage 1 of this project. This review considers current approaches used by industry to predict long term water levels, water quality in water bodies which form within residual voids and potential for migration of pit water into surrounding groundwater systems. The focus for this review is on mining activities that utilise open cut methods that commonly result in residual voids in Queensland. The scope of work excludes quarries and abandoned mines. The target audience is proponents or operators and their consultants undertaking modelling, and government officers charged with assessing PRCPs. Examples of industry practices used to assess residual void water bodies presented in this document are therefore focussed on Queensland-based resource activities where possible.

This Stage 1 report does not outline recommended approaches for modelling how water bodies in residual voids form. Rather it explains the approaches currently used by industry to predict water quality and water balance of residual voids to support rehabilitation planning. This review will provide a platform for future Stages of this project that will identify leading practice in this area.

2. Residual void hydrogeology and water quality

The quantity and quality of water within residual voids is the result of interactions between complex physical and chemical processes. One of the key differences between residual voids and other surface water storages is the degree of interaction between residual voids and groundwater. This is because residual voids are often excavated tens or hundreds of metres below the natural land surface and can directly cut through aquifers. The rate residual voids fill with water, and the quality of the water in residual voids is influenced by the sources of inflow, how this water interacts with the landscape, and the mechanisms that remove or add solutes to the water body.

Sources of water that accumulate within residual voids include, catchment runoff[1], direct rainfall[2], groundwater seepage[3] and water pumped or diverted into the void[4] as part of resource activities. As these different water sources accumulate within residual voids they can mix, stratify, and solutes can become concentrated over time due to ongoing evapo-concentration. Mechanisms that remove water from residual voids include evaporation from the water body surface, seepage to groundwater systems, losses to water courses through controlled releases or uncontrolled overflows, and intentional extraction for beneficial uses like resource activities, stock watering, irrigation and pumped hydro projects.

The sources and volumes of water inputs to and outputs from a residual void are described by a water balance[5] which forms a focus of studies seeking to understand how water bodies in residual voids will form and behave after resource activities are completed. The key elements of a water balance for a residual void are shown graphically in Figure 1 below. An example water budget for a residual void is provided in Table 1.

[1] **catchment runoff** is incident rainfall in the area that moves by overland flow and flood flows into the residual void.

[2] **direct rainfall** is water from rainfall events that fall directly onto the pit lake water body in a residual void

[3] **groundwater seepage** is subsurface water that enters the residual void either through the walls or floor of the void, or via mine waste used to partially backfill the void. Groundwater seepage is commonly evident as patchy wet areas on mine walls or floors. The term “groundwater inflow” is also used in this document when referring to volumes of groundwater seepage that enter or leave mining areas.

[4] resource activities often manage excess water collected from disturbed mining areas by storing it within residual voids. Mine affected water can be pumped directly and/or diverted (deliberately or otherwise) into pits.

[5] a **water balance** describes the inflows to a residual void, as well as its outflows, and the subsequent change when these volumes are not equal.

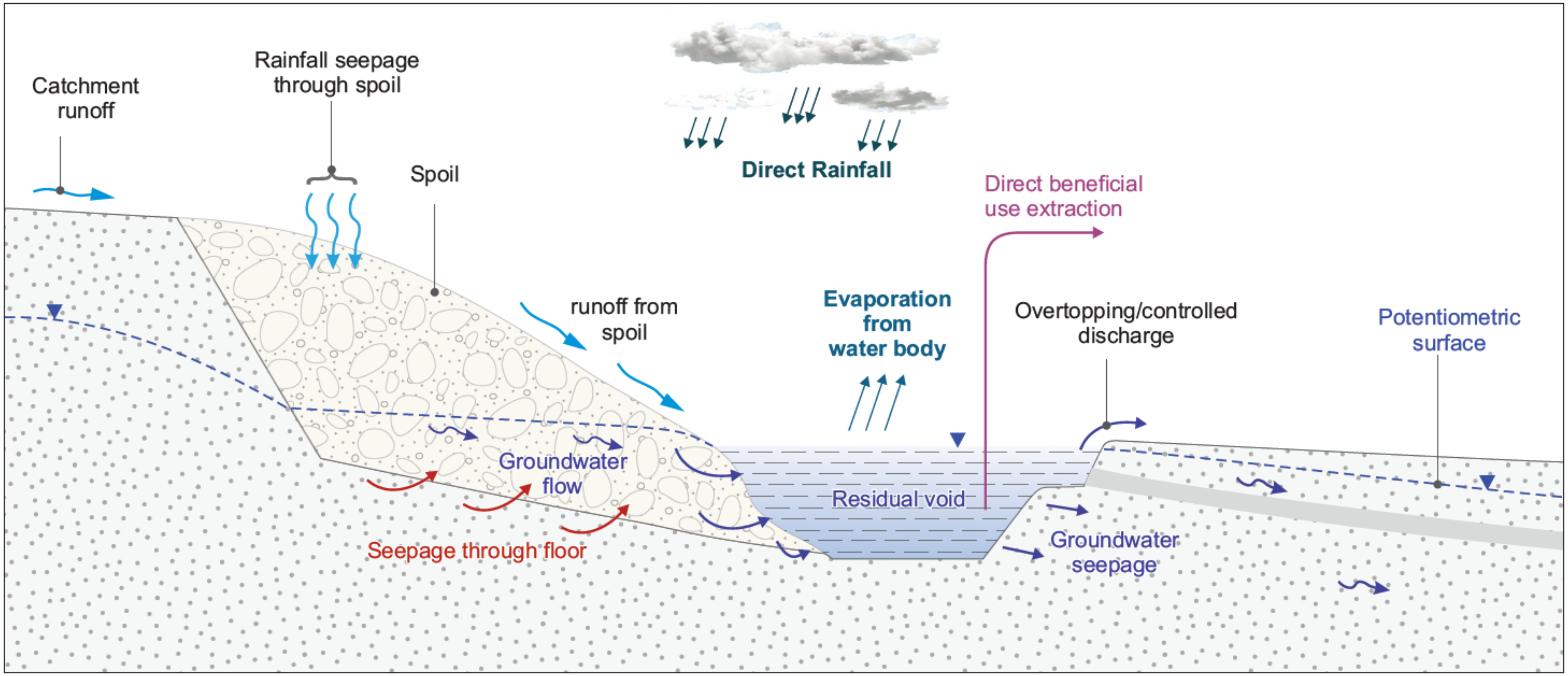

Figure 1. Simplified conceptual model of a residual mine void showing key water balance components

Table 1. Example hypothetical water budget for water body within residual void (ML)

Water budget element	Summer	Autumn	Winter	Spring
Catchment runoff	120	4	0	8
Direct rainfall	750	100	0	200
Groundwater seepage	50	75	50	25
Total inputs	**920**	**179**	**50**	**233**
Beneficial use extraction	0	0	0	200
Evaporation from water body	750	500	250	350
Groundwater seepage	40	60	40	20
Total outputs	**790**	**560**	**290**	**570**
Net (input minus output)	**130**	**-381**	**-240**	**-337**
Storage	1000	619	379	42
Δ Storage	-	381	240	337

Direct rainfall is the most obvious input to a water body within a residual void. Rainfall on the surface of the water body adds low salinity slightly acidic water to residual void water bodies over time. Evaporation also occurs directly from the water surface of the water body. The amount of rainfall and evaporation depend on the climate in the locality, and evaporative losses in particular are also influenced by a range of site-specific factors unique to each residual void including the shape, orientation and depth of the water body.

The significance of catchment runoff in the water balance commonly depends on the environmental setting, and the type of resource activity being conducted. Excavations for coal mining activities are commonly long and linear in shape (strip mining) and tend to be partially backfilled with waste rock materials, creating an 'in-pit catchment' dominated by waste rock. These pits can also include external natural catchments in some cases, that promote overland flow into the residual void. In contrast, metalliferous mines commonly remove waste rock material from excavations to out-of-pit emplacements, and construct bunds around mining areas, resulting in significantly less catchment inflow to the excavation. There are also examples where residual voids and/or active open cut mining operations located within floodplains have been intentionally or accidentally connected to larger surrounding catchments, resulting in large volumes of fresh water rapidly entering the mine or residual void during periods of high flows. A recent example of which was the suspension of operations at the Baralaba North Mine when the Dawson River broke through a mine levee.

The quality of runoff that enters residual voids is influenced by the geochemical nature of the materials in the residual void catchment area. For example, runoff from native sediment/regolith materials may closely resemble the chemical composition of rainwater. In contrast, runoff from mine waste storages such as tailings storage facilities, waste rock dumps or heap leach piles can be acidic, more saline and have elevated concentrations of solutes relative to rainwater. The chemical quality of pit inflows to residual voids may be further influenced by reactions with minerals on the void walls, coal seams and in-pit spoil that can comprise waste rock, coarse rejects, and/or tailings. Tailings and waste-rock materials can also form significant stores of salts, other precipitates and/or saline pore waters, that can be readily mobilised when the materials become saturated or partially saturated by pit inflows or groundwater seepage.

Changes in void water quality are often reflected by changes in major, minor and trace element solute concentrations. These changes can occur relatively quickly if the rates of water movement through in-pit spoil are high and highly reactive minerals (e.g. sulfide minerals) or large solute stores are present. They can also occur relatively slowly where flow through in-pit waste materials are low or mineral reaction rates are slow. Similarly, the degree and timeframes of pit wall mineral influences on void water quality are dependent on a number of factors, most notably, the abundance of reactive minerals and circulation rates of oxygenated water.

Groundwater seepage occurs into most residual voids excavated below the water table. The volumes and quality of groundwater seepage depend on the hydrogeological setting, and on the hydraulic gradients around the void. The quality of groundwater seepage can be influenced by the quality of water in the aquifers and the chemistry of the host geology. For example, brackish or saline water is often associated with seepage from coal seams. Water bodies in residual voids can be classified by how they interact with the surrounding groundwater regime. Whilst resource operations are actively dewatering mining areas, and for a period of time after closure, inward hydraulic gradients promote continual flow of groundwater into the residual void. In this circumstance the water body in the residual void is referred to as forming a 'sink' for groundwater flow. As the water level in the water body increases over time, it can reach a similar level to that in the surrounding rock mass.

In this circumstance the water body in the residual void can form a 'groundwater flow through system' whereby groundwater flows into the void from one direction, mixes within the residual void water body, and then flows back into the groundwater regime in another direction. This is more likely to occur in large residual voids created by open cut coal mining activities since the water table in the surrounding strata can vary significantly within the footprint of the residual void. The final, and less common outcome is that water bodies in residual voids fill to a level higher than the surrounding water table, resulting in a flow of water from the void into the surrounding groundwater regime. In this circumstance the water body in the residual void is referred to as a 'source', although this generally only occurs intermittently following high rainfall or flood events (e.g. the Baralaba North example mentioned above). Other voids can form a 'surface water flow through system' whereby surface water enters one end of the void and discharges at the other. Depending on the relative elevations of the inflow and outflow points and in receiving water courses then such voids can provide some attenuation of flood peaks during high rainfall periods.

Groundwater seepage into residual voids can commonly be enriched in solutes relative to meteoric water and rainwater runoff, and this can increase the salinity of water bodies within residual voids. This is particularly the case when the residual voids act as 'sinks' drawing in groundwater to the water body, but with no mechanism for removal of solutes, which are concentrated over time due to evaporation. In contrast residual voids that act as 'groundwater flow through systems', or 'sources', can gradually release solutes to the surrounding groundwater regime, and may not be subject to a continually increasing evapo-concentration of salts.

Water within residual voids can also be extracted for beneficial use. Examples of beneficial use of residual void water include dust suppression, product washing, irrigation, stock watering and pumped hydro projects.

As shown in Figure 2 below a typical outcome in Queensland is that water bodies within residual voids are expected to fill with large volumes of brackish water over time due to the input of salts from the catchment, from groundwater, and from evapo-concentration at the water body surface. An increase in salinity can limit beneficial use unless efforts are made to control components of the water balance and the morphology of the residual void. Conversely, as shown in Figure 2, water level recovery within rehabilitated residual voids is commonly predicted to follow the shape of a logarithmic curve that initially rises rapidly then slows, approaching an asymptotic condition over time (with seasonal variation in water level).

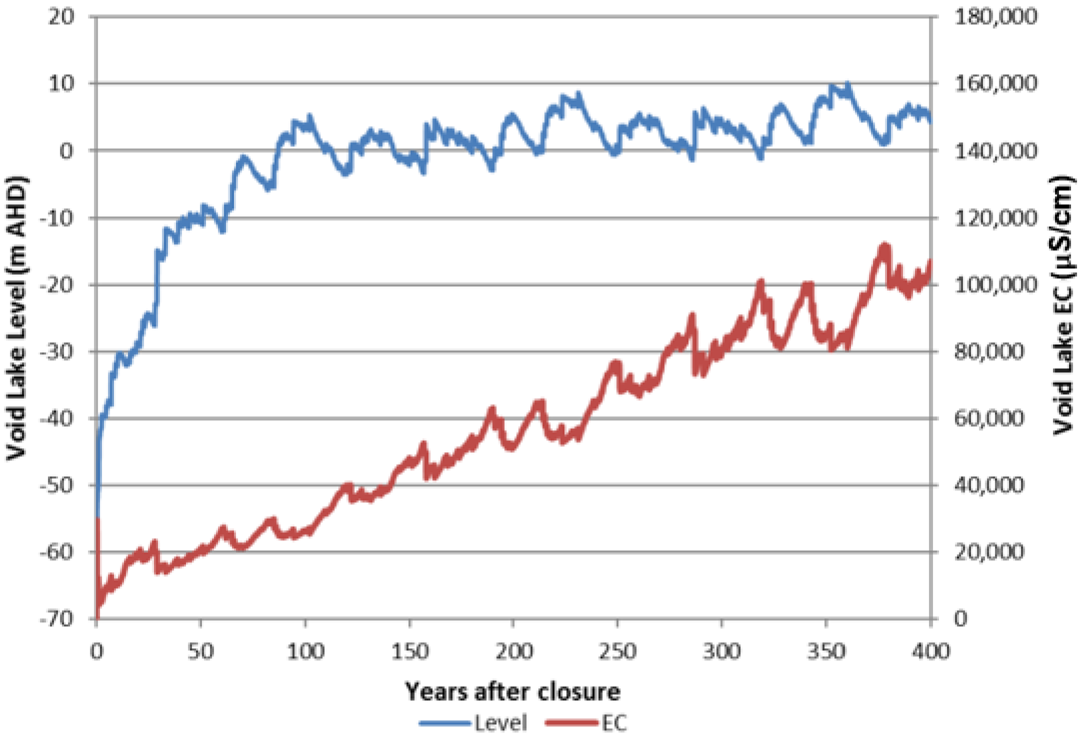

Figure 2. Example of predicted water level recovery and salinity within a residual void from the Jellinbah Central North Extension Project (AARC, 2019)

A combination of factors can contribute to this predicted outcome. Firstly, as residual void water levels rise, the surface area increases relative to the volume stored due to the angled slopes of the mining pit walls. This means a smaller volume of water is required to fill the deeper parts of the residual void, more rapidly filling the lower sections. Secondly, when water levels are higher (creating a deeper water body) in residual voids, the surface area available for evaporation is also lower, reducing evaporative losses during the initial recovery period relative to depth. As the water level within the residual void rises during filling, the sloping pit walls increase the surface area of the water body leading to increased evaporative losses from the larger pit lake. Finally, as water levels rise within the residual void, groundwater inputs also tend to reduce as the level in the pit approaches full recovery. These factors combine to slow the rate of water level rise over time, until eventually inputs and outputs reach an equilibrium condition, with water levels fluctuating about a long-term equilibrium water level as shown in Figure 2 above.

3. Legislation and guidance

Under the *Environmental Protection Act 1994* (EP Act), organisations carrying out mining in Queensland must rehabilitate the land (DES, 2020). Proponents of new and existing large scale mining activities (that meet requirements for a site-specific Environmental Authority) need to submit a Progressive Rehabilitation and Closure Plan (PRCP) describing a) how and where activities will be carried out progressively over the life of a mine and b) the condition to which the land must be rehabilitated before the Environmental Authority for the activity may be surrendered (EP Act section 126B). The EP Act stipulates that land disturbed by mining must be progressively rehabilitated to a ‘stable condition’ after mining (EP Act section 111A). Land is in a stable condition if — (a) the land is safe and structurally stable; and (b) there is no environmental harm being caused by anything on or in the land; and (c) the land can sustain a post-mining land use (PMLU). Although a ‘stable condition’ does not necessarily require that the water level or water quality in any residual voids remain at the same concentration over time, a decline in water quality may affect the viability of a PMLU. For instance, the gradually increasing salinity shown in Figure 2 might at some time make the residual void unsuitable for the intended PMLU.

A mine void that cannot be rehabilitated to a ‘stable condition’, may be proposed as a non-use management area (NUMA), subject to being managed to achieve leading practice management of the area and minimise risks to the environment. Under section 126D(2)(b) of the EP Act a NUMA can be proposed as part of a PRCP where a) rehabilitation would create a greater risk of harm than not doing so, or b) the risk of environmental harm is confined to the area of the relevant resource tenure and c) where it is in the public interest as determined through a Public Interest Evaluation (PIE) apply. A NUMA may be proposed for new and existing mines through the PIE process, however, existing mines that have an approved NUMA (i.e. one that is identified in a land outcome document) do not need to demonstrate that the above requirements have been met when considered under the PRCP framework. Although existing approvals for a NUMA may be recognised, new proposals for a residual void located in a floodplain must achieve a ‘stable condition’ (see section 126D (3) of the EP Act 1994).

The distinction between a void considered as a NUMA and those required to have a PMLU influences how a void is considered in the PRC planning process. According to the Department of Environment and Science ‘non-use management areas information sheet’, “*the Department’s expectations for leading practice management of a NUMA would result in the area being made safe and structurally stable so that it causes no environmental harm, despite a PMLU not being achievable*” (DES, 2020). The PRCP Performance Outcomes for a NUMA require that management milestones and milestone criteria “*prevent contaminants from being produced or, if prevention is not possible, minimise the impact of the release of contaminants*” (Schedule 8A, Table 3 of the Environmental Protection Regulation 2019). The EP Regulation also provides examples of what minimising the impact of the release of a contaminant means. Examples include appropriately containing the contaminant and appropriately treating the contaminant before it is released.

Modelling is an important tool that provides information to support planning and development of strategies for rehabilitation and management of mine voids during operation and post mine closure. Where a mine site includes a residual void, the rehabilitation plan for the mine is to include a void closure plan (DES, 2021). Modelling underpins the information needed to develop a void closure plan. Key information needed to support rehabilitation planning includes:

- a long-term water balance and assessment of the potential for surface water releases and overtopping,
- interaction with groundwater systems including whether the void is or will act as a sink or a source
- the long-term water quality, suitability to support a post mine use or beneficial use and potential for stratification,
- assessment of the potential risk of harm to the surrounding environment from groundwater seepage and/or groundwater drawdown.

Outputs from modelling can also be used to define ‘management milestones’ and ‘milestone criteria’ in the case of a NUMA or ‘rehabilitation milestones’ in the case of an area with a PMLU.

4. Existing guidelines

There is very limited specific guidance on modelling of residual voids in the public domain either within Australia or other jurisdictions. Guidance on numerical modelling activities is provided in the Australian Groundwater Modelling Guidelines (Barnett et al, 2012) and other documents developed on behalf of the Independent Expert Scientific Committee (IESC) including a report by Middlemis and Peeters (2018). The Good Modelling Practice Principles published by the Queensland Water Modelling Network (Jakeman et al, 2018) also provides advice on the modelling principles relevant to water modelling and include a list of further references describing water modelling practices. However, none of these documents provide specific guidance on modelling of residual voids.

A number of guidance documents have also been developed relating to mine closure (including DES, 2021; Australian Government, 2016a and 2016b). Whilst these and other similar guidance documents discuss the need for numerical modelling of groundwater and other inflows to residual voids there is no specific guidance on how this should be undertaken. The Australian Government guidance on Preventing Acid and Metalliferous Drainage (2016b) outlines a risk and outcomes based approach to predicting long term water quality, whereby a relatively simple initial assessment is undertaken and further more detailed predictions are only developed where results suggest sufficiently good water quality to support ‘higher level uses’ of the pit lake. Where further modelling is undertaken the Australian Government guidance stresses the importance of:

- a well-defined conceptual model requiring input from mine staff and technical specialists from a range of relevant disciplines (including hydrogeology, climate, hydrology and limnology);
- gradual refinement of the conceptual model drawing on subsequent numerical modelling, monitoring and validation exercises; and
- consideration of the importance and sensitivity of predictions to uncertainty in input data as well as model assumptions and parameters.

The guideline outlines the following three criteria for model selection:

- the approach and package meets the requirement of the modelling question;
- the data are available; and
- the level of technical expertise and experience available either in-house or from external consultants to run the model and to interpret its outputs.

While practical requirements such as the availability of staff with appropriate skills may mean a modelling approach cannot be implemented, such a limitation should not preclude identifying a model that may suit. The report also recognises that previous experience and confidence of regulators with certain modelling packages may also be important factors. In particular “*open source models or models that are broadly accepted and used should be preferred, as they are more able to be independently tested and peer-reviewed*” (Australian Government, 2016b).

5. Review of existing practices

The following sections provide a review of the main components of a residual void water balance, and how these components are quantified, followed by a review of current methodologies adopted for modelling the behaviour of water bodies within residual voids. The review is based on a review of the scientific literature, the combined industry experience of the consulting team, as well as PRCP and other documents associated with approval processes. The following sections comment on the challenges inherent in developing a water balance for a residual void and modelling its behaviour, but do not provide recommendations for future practice. This will be covered in future stages of the project.

5.1 Void inflow/outflow volumes and water quality

5.1.1 Evaporation

Evaporation is the process by which water changes from a liquid to a gas, and is the primary pathway that water moves from the liquid state back into the water cycle as atmospheric water vapor. Evaporation represents an important component of the water balance for residual void waterbodies because it often explains a large proportion of water loss and in some cases may be the only mechanism by which water can leave the residual void. Evaporation of water from pit water bodies can also result in evapo-concentration of the remaining solutes.

Evaporation rates from residual void water bodies may be estimated based on recorded data such as pan evaporation or calculated using various formulae (for example, Morton, 1983). It is common to apply a correction factor that adjusts the evaporation rate to be more representative of the actual evaporation that is likely to occur in the residual void. Where pan evaporation is adopted as the basis of estimating evaporation, this correction factor is referred to as a “pan factor”. Ideally, the correction factor is obtained by comparing evaporation rates to recorded water level data for waterbodies on site. However, the factors affecting actual evaporation rates from water bodies within voids are complex due to the microclimatic effects of shading of the water body by the pit walls and the circulation of wind currents (see Section 4.4, Cook, 2021). A correction factor of 0.7 is commonly applied to the chosen estimate of evaporation (Cook, 2021), based on the principle that evaporation in a deep void, which is shaded by the pit walls and protected from surface wind currents, is likely to be lower than what would occur from a lake on the land surface. A recent CSIRO study at a Central Queensland coal mine concluded that the shape and orientation of the void can have a significant impact on the evaporation from the pit lake surface due to acceleration of wind within long, narrow voids (McJannet et al, 2019). This suggested that surface wind currents and therefore evaporation in these types of voids was higher than initially predicted.

The Queensland Government's SILO database (https://www.longpaddock.qld.gov.au/silo/) provides spatially distributed values of both pan evaporation and Morton's Lake evaporation on a daily basis across all of Australia. These data are widely used as inputs for modelling of residual void water bodies. In some cases, general relationships between the various types of evaporation estimates (for example, Nash, 1989) and local conditions are also used to ensure estimates of evaporative losses are representative. Although such modifications may be advantageous, site or locally specific assessments which are not always undertaken are needed to support this.

From a water quality perspective the process of evaporation removes water and leaves behind any solutes leading to potential evapo-concentration, depending on the rate of inflow from other sources. Reference to technical reports for coal mining projects available via the IESC website (https://www.iesc.gov.au/advice/scientific-advice) suggests that most residual void studies assume that solutes will concentrate proportionally during evaporation. This assumption is mostly valid for predicting changes in salinity and concentrations of major elements/ions for residual voids that have relatively low initial salinities (e.g. < 10,000 mg/L TDS). For higher salinity systems, or systems with high concentrations of a given element/ion such as sulfate, calcium, bicarbonate, barium and strontium, progressive evaporation may lead to mineral precipitation. Although these processes may not have a significant influence on the predicted trends in salinity or major element/ion concentrations, mineral precipitation can play an important role in controlling the accumulation of trace elements in residual voids.

5.1.2 Rainfall

Precipitation is any liquid or frozen water that forms in the atmosphere and falls back to the Earth. It comes in many forms, like rain, sleet, and snow. In Queensland it is almost always in the form of rainfall. Rainfall is an obvious source of direct inflow to residual void water bodies. Estimates of rainfall are also required for assessing short-term runoff from catchments of the void, and longer-term seepage through any in-pit spoil material.

Rainfall is easily measured by rain gauges, and data is widely available. The Queensland Government's SILO database (https://www.longpaddock.qld.gov.au/silo/) provides spatially distributed values of daily rainfall across Australia from 1889 to date (continuously updated). Rainfall can be obtained as either gridded data (obtained by interpolating between available rainfall stations) or "patched point" data, which is a single rainfall gauge where interpolated data is used to infill missing data in the period of record.

Historical data are necessary to calibrate runoff and mining void water balance models. There are no standards describing what period of rainfall data is necessary, however, to minimise potential bias in short term data sets most water balance calculations are undertaken over a relatively long period (200 years or more is typical). As the available period of historical rainfall data (about 130 years) is less than the adopted 200-year simulation period, an extended rainfall data set is typically obtained by either:

- looping the historical data set; or
- generating synthetic rainfall data with the same statistical characteristics as the historical rainfall data.

Each of these approaches has advantages and disadvantages. In practice, looping of the historical data set is the most commonly adopted approach because the data is "real" and therefore represents the true historical variability of rainfall which is difficult to accurately build into synthetic data sets (Srikanthan and McMahon, 2000).

Rainwater is the main atmospheric input to the continental freshwater cycle. On average, it is estimated that 30% of continental precipitation is sourced from the oceans (Garrels et al, 1975). Rainwater in coastal areas therefore often exhibits similar proportions but significantly lower concentrations of major elements/ions (solutes) as observed in average global seawater. Atmospheric precipitation over inland areas can exhibit major elements/ions proportions that vary considerably from seawater due to progressive solute deposition as weather systems track inland and the incorporation of continental dust. Biomass burning, use of fertilizers and industrial activities can further alter the chemical composition of rainwater.

Rainwater typically contains very low solute concentrations relative to other sources of inflow to mine voids (e.g. runoff and groundwater inflows). As such, direct rainfall into mine voids tends to decrease/dilute the concentrations of solutes in pit lake waters. Nevertheless, an understanding of the chemical composition of rainwater is important for estimating the overall solute balance especially for mine voids which have limited external catchments.

Accurate determination of the chemical composition of rainwater in a given locality (i.e. “local meteoric water”) requires long-term monitoring over a number of water years to acquire datasets that capture that natural variability and allow for rigorous statistical analysis. Unfortunately, long-term rainwater chemistry datasets from Australia are limited. The most recent national survey included rainwater monitoring at six locations in Queensland that were sampled on a monthly basis over a two to four year period (Crosbie et al., 2012). Depending on the mine site location, the Crosbie et al, (2012) dataset may be a useful reference for estimating rainwater solute inputs. The Crosbie et al, (2012) study details methods of rainwater collection (site selection, equipment, sampling frequency, analytical suites) and data analysis that would be suitable for mine site applications.

5.1.3 Runoff

Runoff is simply water ‘running off’ the land surface. Runoff can be measured using current meters and calibrated or rated channel cross sections, flumes or standardised weirs, together with water level readings, which can be correlated to flow. Whilst runoff can be measured there are practical difficulties with flumes and weirs, that mean runoff is often estimated at the site of residual voids.

The simplest method of estimating runoff is via a fixed volumetric runoff coefficient which assumes that runoff represents a fixed proportion of incident rainfall regardless of antecedent conditions. This simple approach can be justified where a simple straight line correlation can be identified between observed rainfall and runoff. However, as identified by Shaw et al (2010) more complex relationships typically exist between rainfall at runoff at the daily time steps used in most residual void water balance studies.

The influence of antecedent conditions is therefore typically accounted for using a more sophisticated rainfall-runoff model. The Australian Water Balance Model (AWBM, Boughton 1993) has a number of advantages and is widely used for this purpose because it has enough parameters to represent key aspects of runoff behaviour without being overly complex. Another advantage is that AWBM is widely available and can be easily incorporated into various modelling platforms that simulate the void water balance. Ideally, model parameters are obtained through calibration of the model to site-specific data.

Estimation of surface runoff from spoil catchments presents a particular challenge for water balance modelling due to the wide range of hydrologic properties that can occur in the spoil. Spoil can consist of widely-variable proportions of fine material, which may result in sealing of the spoil surface, generating higher rates of runoff. Alternatively, coarse spoil with few fines can result in large volumes of deep percolation, reducing the rates of runoff (but increasing the volume of seepage through the spoil). Where possible, site-specific calibration is the best method of obtaining a realistic estimate of runoff volumes from spoil areas.

An important aspect of simulating runoff to residual voids is the adoption of an appropriate timescale. Runoff volume can be sensitive to the daily distribution of rainfall. This means that two different years with similar total rainfall can generate very different volumes of runoff depending on whether the rain falls in a smaller number of large events or is more evenly distributed over the year. For this reason, runoff calculations are typically undertaken on a daily basis to better simulate short term variability.

Estimating the quality of runoff into residual voids requires consideration of runoff quantities from various portions of the mine catchment. Incident rainfall represents the primary source of runoff; however, the chemistry of the resulting runoff can be altered significantly due to evaporation and mobilisation of readily soluble solutes at the ground surface. Runoff chemistry can therefore vary significantly depending on the type of ground cover which on mine sites can include native sediment/regolith, mine waste materials (e.g. spoil, waste rock dumps, ROM pads), and haul roads that may have elevated, near-surface solute accumulations sourced from evaporation of dust suppression waters.

Collection and laboratory analysis of composite samples of runoff during and following rainfall events is the most accurate method of quantifying the chemical composition of runoff. The practicality of collecting runoff samples will vary between sites; however, most mine sites have runoff collection and diversion networks which can be readily sampled. Similar to sampling of ephemeral creeks, runoff samples should be collected throughout a rainfall event to capture the variability in chemistry during periods of increasing and decreasing runoff. Sampling during the initial stages of a runoff event is particularly critical for capturing the “first flush” or peak solute flux from the catchment. Whilst such sampling is undertaken on site for environmental compliance purposes it is rarely used for water balance modelling purposes.

Leach testing of waste materials conducted as part of geochemical studies is often utilised to estimate the quality of runoff from mining areas into residual voids. Static and kinetic leach tests are commonly undertaken using mine spoils in Queensland. A significant challenge associated with this approach is the need to adjust the results from the laboratory scale test work to the real-world scale at the residual void. This can require ‘scaling up’ or ‘scaling down’ the data sets to apply to the residual void.

5.1.4 Groundwater inflow and outflow

Groundwater is water occurring underground in the fractures and pore spaces of sediments and rock. It is stored in and moves slowly through geologic formations known as aquifers.

Quantifying the volume of groundwater entering residual voids for the purposes of a water balance can be challenging. Direct measurement of the groundwater seepage component of a water balance is often not possible. The ability to measure groundwater inputs commonly depends on the volume of groundwater entering excavations and the size of the excavation. Where volumes of groundwater inflow are relatively small, relative to the size of the excavation, and resource extraction activities are ongoing, groundwater that enters excavations can evaporate, become bound to waste material, or mix with catchment runoff, preventing direct measurement. Occasional opportunities exist to estimate groundwater inflow where records of water pumped from excavations during dry periods of no rainfall are available and can be assumed to represent groundwater.

After resource extraction activities cease and water bodies begin to form within residual voids, small flows of groundwater can enter from a diffuse area around the pit walls and floor, either below or above the level of the water body, again preventing direct measurement. In some scenarios, groundwater seepage can occur from the residual void into the surrounding strata post closure. Many coal and metalliferous mines in Queensland fall into this category where direct measurement of groundwater cannot be practically achieved, and hence the groundwater seepage volumes for the purpose of a water balance always have inherent uncertainty.

In contrast, where groundwater inflows to excavations are large relative to the losses, direct measurement of volumes can be achieved as continuous active pumping is required to maintain a dry state within excavations to allow safe operations. This circumstance is not common in Queensland mines. Exceptions include excavations which intersect highly permeable alluvial sediments or productive fractured rock aquifers (e.g. Tertiary basalts). Even in these cases, however, since these strata tend to be relatively thin then elevated groundwater inflows do not typically persist for long periods and few records of inflow rates are taken or used for water balance modelling purposes. Advance dewatering from bores external to the excavations is also not common practice at resource activities in Queensland for the same reasons described above.

Because the groundwater component of a water balance often cannot be directly measured, then it must be estimated using analytical or numerical methods. Analytical equations are relatively simple and rapidly provide broad estimates of groundwater seepage to residual voids. The most well-known analytical equation used to provide estimates of groundwater seepage to excavations is Darcy's Law (an indirect approach). Whilst Darcy's Law is relatively easy to apply to estimate groundwater inflow to residual voids current practice rarely utilises this approach due to the draw backs of simplifying assumptions.

Equations that describe flow to a water supply well are also sometimes used to provide estimates of groundwater seepage to residual voids. These methods are more commonly applied in a metalliferous setting where the residual voids are more likely to be circular in shape and therefore can be used to approximate a very large bore or well. More sophisticated analytical solutions are available, which represent boundary conditions such as recharge, including one developed by Marinelli and Niccoli (2000) which is commonly applied for pre-feasibility level studies.

Commonly the simplifying assumptions associated with analytical equations such as steady state conditions, and uniform aquifer properties/boundary conditions means the groundwater regime at the site of residual voids cannot be well represented. For this reason, 3D numerical models of groundwater flow are developed at the Environmental Approval stage for virtually all resource extraction projects where an Environmental Impact Assessment is required. Such numerical models allow aquifer properties and boundary conditions to vary in time and space and provide a better approximation of processes that influence groundwater inflow to residual voids. Well known software packages MODFLOW and FEFLOW are commonly used to provide estimates of groundwater inflow for resource activities (KCB 2020, Hydrosimulations 2018).

The quality of groundwater seepage entering or leaving residual voids is also difficult to measure, for the same reasons described above in relation to groundwater inflow/outflow quantities. Consequently, the quality of groundwater entering residual voids is typically not measured and instead estimated using the results of analysis from water samples collected from bores and wells completed into strata which contribute groundwater flow into the void. Implicit within this approach is an assumption that groundwater quality at an adjacent bore is representative of groundwater that enters the residual void. Estimates of groundwater seepage quality yielded from this approach therefore also have an unavoidable uncertainty that should be considered when using this information as part of a water balance process, although this rarely if ever is assessed in practice.

5.1.5 Beneficial use and releases

Releases from residual void water bodies can be undertaken to manage the volume of water stored at the resource activity site. Whilst resource activities are active, it is common practice to extract excess water from residual voids for uses such as dust suppression on unsealed roads, firefighting as well as for use in mineral processing such as washing coal. Deliberate and planned releases from residual voids to water courses also occur from time to time where overtopping and uncontrolled outflow is considered a potential risk. Where water quality allows, void water can also be used for agricultural purposes including stock watering and irrigation, noting most irrigation uses require fresher water than for stock watering purposes. Whilst there is potential for beneficial use for agricultural purposes, there are no known examples occurring in Queensland.

Whilst beneficial reuse is not a common activity, quantifying the volume of water pumped from residual voids for beneficial use, or water management purposes is relatively simple and accurate where appropriate flow gauging equipment is installed on the pumping infrastructure. Where flow gauges are not available, volumes of water pumped from voids are commonly estimated using pump run hours and estimated maximum pump capacities. This method obviously contains a level of uncertainty and assumes a constant discharge rate from each pump.

An emerging use for water bodies within residual voids is for development of pumped hydroelectric projects where electricity is generated by transferring water between storages with differing levels. In most cases water is pumped into the upper reservoir, either at night using relatively low cost electricity or during the day using solar powered pumps, and then released during high electricity demand periods into the lower reservoir generating electricity in the process. An example of such a scheme is the Kidston Pumped hydropower project operated by Genex Power which utilises two residual voids (the Wises and Eldridge pits).

5.1.6 Geochemical process

In addition to mixing of various water inputs and evaporative concentration, the chemical composition of void water can be significantly altered by reactions with pit-wall rocks, mine waste materials deposited in the void, or mine waste materials that are within the catchment of the residual void. These reactions can affect the pH, salinity and concentrations of major elements/ions, minor and trace elements in void waters. The likelihood of these reactions occurring depends on a number of factors including the geochemistry of the pit wall rocks, geochemistry of mine waste materials deposited in the void, quantity of solutes stores in mine waste materials deposited in the void, and the chemical composition and temperature of the void water.

The geochemical properties of mine waste materials such as waste rock, tailings and spoil are commonly determined via standard methods of mine waste characterisation, as outlined by AMIRA (2002) and INAP (2009). These methods determine the potential for generating acid and metalliferous drainage (AMD) or leaching of readily mobilised solutes. The geochemistry of pit wall rocks can be inferred from the geochemical characterisation of waste rocks.

The traditional mine waste characterisation methods referenced above are useful for assessing both the short-term (“static”) and long-term (“kinetic”) geochemical behaviour of mine waste materials. However, these methods have numerous limitations, many of which are acknowledged within the guidelines themselves. These limitations need to be considered when extrapolating these laboratory results to mine-scale conditions.

In addition to the standard characterisation methods, quantitative mineralogical analysis can also be undertaken to further understand the geochemical behaviour of mine waste materials. Mineralogical results offer an advantage over standard characterisation methods by identifying the specific minerals that can generate or consume AMD. Once this is understood, predictive geochemical modelling can be applied to quantify the reactions that will occur over short-term and long-term periods in a residual void. The quantitative mineralogical and geochemical modelling approach can provide rapid identification of problematic materials and can be extended to evaluate/predict the effectiveness of various mitigation measures.

5.1.7 Application

It is difficult to directly measure the main components of a water balance in a residual void. Most residual voids are therefore not equipped with instrumentation to directly measure rainfall, runoff, evaporation and groundwater seepage volumes. Consequently the volume of most void water balance components including rainfall runoff, evaporation and groundwater seepage are typically estimated using analytical or numerical models, with water quality inferred from environmental compliance monitoring. Each of the water balance components inputs therefore have an inherent measurement and scale-based uncertainty when used in models to simulate the behaviour of water bodies in residual voids.

5.2 Modelling approaches

Models are routinely used to assess the future behaviour of water bodies forming within residual voids and the behaviour of voids after mine closure. The most common application of modelling is to assess long-term water levels and water quality within the residual void, the potential for water level change over time and the risk of overtopping to adjacent water courses and losses to groundwater from seepage.

As described above since the inflows and outflows include both surface water and groundwater components then long-term water levels in the residual void can be assessed using either:

- a water balance model, with estimated groundwater components potentially provided by a separate groundwater model;
- a groundwater model, with estimated surface water components potentially provided by a separate surface water model; or
- a coupled surface water-groundwater model.

Further details of the features, advantages and disadvantages of each of these approaches are summarised in the sections below.

5.3 Water level and quantity prediction methods

5.3.3 Water balance models

The application of a water balance model is the most common industry approach to simulating the long-term behaviour of residual void water bodies. The most commonly used software platform in Queensland is GoldSim (e.g. CDM Smith 2020), followed by OPSIM (2020). Spreadsheet models can also be used to prepare water balances for simple residual void systems, although this approach is relatively uncommon in Queensland due to the accessibility of more powerful programs like GoldSim.

Required inputs to a water balance model of this type are:

- sequence of forecast rainfall;
- sequence of forecast evaporation;
- elevation-storage relationship for the residual void;
- groundwater inflow/outflow, either as a time series or relationship between void water level and groundwater inflow/outflow.

The model then calculates runoff volumes (typically using AWBM) and other inflows (direct rainfall, runoff, groundwater seepage) and outflows (evaporation, groundwater seepage) on a daily basis. Typically, a representative solute concentration is assigned to each inflow stream and the model then also performs a simple mass balance at each timestep to track the mass of solutes entering or leaving the void water body.

Typically, the pit lake is modelled as a single water body which precludes any consideration of thermal or chemical stratification. Solutes are usually modelled as conservative. Chemical and biological transformation processes could theoretically be modelled. However, this vastly increases the complexity of the modelling exercise and may introduce further uncertainty in model outcomes, which are extremely difficult to verify. This therefore is not common in practice.

For large coal mines, which are common in Queensland, the presence of significant volumes of spoil within the residual void presents particular challenges for modelling. The hydraulic and geochemical properties of spoil can differ significantly to the native ground material due to the increased surface area of particles and increased hydraulic conductivity.

The interaction of groundwater with the water body in the residual void can also be an area of some complexity, particularly where the regional groundwater environment is changing over time due to cumulative impacts or climate change. This can mean that, for example, that the relationship between void water level, and flow to or from groundwater can also change over time.

5.3.4 Groundwater models

Groundwater flow models can also be used to estimate how long residual voids will take to fill with water, the equilibrium water level, as well as the long-term influence of the water body on the surrounding groundwater regime (e.g. Hydrosimulations 2018). This methodology requires that all elements of the residual void, and all elements of the water balance are represented, explicitly, or implicitly within the numerical groundwater flow model. However, this often exposes the limitations of groundwater modelling codes when it comes to simulating surface water components. Rainfall runoff, short term rainfall events, dynamically changing water body surfaces and complex void shapes are all processes associated with a residual void water balance that cannot be easily represented in commonly utilised groundwater flow models.

A number of approaches have emerged in common practice to represent a residual void and the associated water balance in numerical groundwater flow models. The most commonly utilised method for resource activities in Queensland is what can be referred to as the ‘high K lake approach’ (e.g. KCB 2020). This approach assigns high hydraulic conductivity and storage values to model cells which are used to represent the residual void. Where such an approach is adopted the accuracy with which the residual void volume and shape can be represented is an important limitation and highlights the importance of early planning during the model design phase such that the model mesh and layering are appropriate for representing void morphology.

Surface water inflow elements, including rainfall and runoff, are commonly represented in the ‘high K lake approach’ via use of groundwater recharge packages, and discretisation of time is commonly on a monthly, quarterly or yearly basis, rather than the daily time steps required for accurate simulation of rainfall and runoff events. Furthermore, most groundwater flow models used for residual void assessments are not coupled with rainfall runoff models, and therefore commonly runoff to residual voids is approximated as a multiplier on the direct rainfall recharge. Depending on their magnitude, representation of these surface water inflow components is necessarily simplistic.

Conversely estimation of groundwater seepage, into and out of a residual void is typically estimated in some detail since groundwater flow is calculated on a cell by cell basis using hydraulic heads, boundary conditions and calibrated hydraulic properties. Groundwater model based studies can also be used to assess uncertainty in predictions based on a range of plausible alternative model parameters. Whilst this is possible, it does not occur commonly in practice in Queensland at the time of writing for residual void water body applications.

Evaporation from residual void water bodies is commonly represented using groundwater modelling packages that are designed to represent transpiration via vegetation and evaporation through the soil profile when the water table approaches the land surface (e.g SKM 2013). These packages are therefore not particularly well suited to estimating evaporative losses from pit lakes which, as discussed previously, are affected by a range of additional factors including orientation, shading, water depth, prevailing winds and turbulence effects which are less significant for natural vegetated surfaces.

5.3.5 Coupled water balance and groundwater models

As noted in the preceding section, commonly utilised groundwater flow models are not designed to explicitly represent rainfall runoff processes, residual void morphology like sloping pit walls, short term intense rainfall events, and dynamically changing water body surface areas. These aspects of a residual void and the associated water balance can be more accurately represented by currently available water balance models such as GoldSim. When the predictions for water level recovery within a residual void from a groundwater flow model are compared to predictions for the same void from a surface water balance model there are inevitably some differences. In particular, the predicted time to reach an equilibrium water level, and the long-term water level with the residual void can differ between these models.

Given the inherent limitation in groundwater models to represent key aspects of residual void water balances, industry consultants commonly use a methodology where the surface water balance predictions are used as inputs of groundwater flow models. For the purposes of this document, we refer to this method as ‘quasi-coupling’ of groundwater flow and surface water balance models. Commonly the ‘quasi-coupling’ process proceeds as follows:

1. firstly, a steady state groundwater flow model simulation is developed, with constant heads assigned to the residual void at increasing stage heights and the predictions used to create a relationship between the rate of groundwater inflow to the residual void and water level in the void;
2. secondly the groundwater inflow versus water body elevation relationship determined from step 1 is represented within the surface water balance model to provide estimates of changing groundwater inflow rates as the water level rises within the residual void;
3. finally the resulting water level predicted by the water balance model is ‘fixed’ within the groundwater flow model via constant head cells (or general head boundary cells), with the predictions from this model used to assess long-term drawdown and other groundwater impacts.

An alternative to step 1 uses the predictions from a transient groundwater flow model setup with a ‘high K lake’ to produce a groundwater inflow versus water body elevation relationship. This alternative is potentially superior where cumulative impacts from surrounding resource activities influence the groundwater inflow rate, but is not commonly implemented.

‘Quasi-coupling’ is the most common methodology used for assessing the potential impact of residual voids at Queensland coal mining sites during the approvals stage (e.g. Hydrosimulations, 2018, SLR, 2021). Whilst the ‘quasi-coupling’ method is relatively simple, and overcomes some of the limitations of groundwater flow models when it comes to representing residual voids, it does have some limitations. If there are significant unsaturated strata surrounding and underneath the residual void, the emplacement of constant head cells can potentially introduce unrealistic volumes of water that replenish the unsaturated strata, potentially influencing predicted drawdown impacts. Furthermore, because the ‘quasi-coupling’ method fixes the water level within the residual void to match the predictions of the water balance model, it becomes difficult to explore the influence of both climatic and/or parametric variability on predicted long term drawdowns since all scenarios include a fixed head in the pit lake.

An alternative approach to ‘quasi-coupling’ is, rather than fixing water body levels within the groundwater flow model, to add the void water into the groundwater flow model. Using this approach, the net volume of rainfall, runoff and evaporation, as estimated using the water balance model, is ‘injected’ into the groundwater flow model at the location of the residual void base. This approach aims to overcome the assumption of unlimited water supply associated with constant head cells. Examples of this approach use a ‘reservoir’ node to inject water at the base of a ‘high K lake’ area in the model. When rainfall and runoff exceed evaporation, a positive rate of injection is applied to the residual water body. Conversely when evaporative and other losses exceed inflows then negative values of injection are applied to represent abstraction. This constrains the amount of water available to replenish the groundwater system, and also allows for a less constrained exploration of predictive uncertainty. For example, using this approach uncertainty analyses that vary hydraulic conductivity can be conducted and water levels within the residual void water body will vary. There are a small number of examples of the application of this methodology relating to resource development projects in Queensland and New South Wales in the public domain (including AGE 2020; AGE 2019; and AGE 2018).

As previously discussed, robust representation of the relationship between inflow, rainfall, evaporation and residual void geometry is complex and relies on feedback loops. Dynamically coupled water balance and groundwater flow models that exchange predictions of water level and flow at every timestep address the limitations of the modelling frameworks. These coupled models exchange information at each time step; the surface water balance model simulates rainfall, runoff, and evaporation to calculate residual void water body level, then passes that information to the groundwater model. The groundwater model then passes groundwater flow information back into the water balance model, resulting in a revised water surface elevation for the next coupled time step.

There are no known industry examples of dynamically coupled models being used to assess the behaviour of residual void water bodies in Queensland, and only a few examples in published literature. Examples found in the literature are limited to theoretical applications described by Martin (2018) for GoldSim/Feflow, and Janzen et al, (2020) for GoldSim/Modflow-MT3D. The skills to implement this method are not considered to be currently present within industry and would need to be developed if it were determined to be beneficial, another limitation of the method.

5.4 Water quality prediction methods

5.4.1 Contaminant transport models

Understanding the movement of contaminants may be a critical requirement to quantify the risks associated with a residual void and an associated post mining land use. The risks can be assessed through simulating the movement of potential contaminants. After a flow model has been established to determine the likely flow of water to or from the residual void, then the potential risks of that water, should it contain a contaminant, can be assessed using a contaminant transport model.

Simulating contaminant movement provides an indication of both the direction and time of arrival of contaminants which is useful for quantifying the risks of contamination to receptors. The level of assessment can vary, and often a reasonably simple path line / particle tracking simulation can be employed to demonstrate the nature of the void (source vs sink vs flowthrough system). Such simulations assume that the contaminant of concern is transported through advective processes hence moves along the predicted the groundwater flow path.

Where necessary a 3D contaminant transport model can then also be developed to predict the concentration as well as the timing of contaminants reaching key receptors. Additional data including lateral and longitudinal dispersivity and adsorption are typically required as well as observations of actual contaminant concentrations for calibration purposes.

Contaminant transport models are rarely utilised as part of a specific study on residual voids in Queensland. Where contaminants are likely to be present in the residual voids then particle tracking simulations are more commonly used, typically to confirm the nature of the void as either a source or a sink and assess risks on nearby receptors.

5.4.2 Geochemical models

Chemical modelling was first applied in the field of geochemistry in the early 1960’s to calculate the distribution of chemical species in seawater and to simulate the reactions that occur during evaporation from springs and lakes (Garrels and Thompson, 1962; Garrels and Mackenzie, 1967). Since then, progressive conceptual and numerical advances have led to the development of contemporary geochemical modelling codes such as MINTEQ (Allison et al, 1992), EQ3/6 (Wolery and Jarek, 2003), Geochemist Workbench (Bethke, 2008) and PHREEQC (Parkhurst and Appelo, 2013).

Geochemical models can be used in the resources industry to identify mechanisms controlling water quality and to predict changes in water quality due to various changes or stresses in a system. Geochemical modelling codes are limited to aqueous systems and are often referred to as hydrogeochemical models. Geochemical models are particularly useful as they are significantly faster and cheaper to construct and run than field or laboratory experiments seeking to address the same questions. Geochemical models, like all models of natural systems, are limited by the competency of the modeller and availability and reliability of data to inform model conceptualisation and inputs. Additional, but less significant limitations to geochemical modelling are imposed by the thermodynamic datasets and laboratory kinetic data used to calculate reaction quantities and rates, respectively.

Geochemical models can be used to predict void water quality evolution due to mixing of different input waters of unique composition, evaporation and geochemical processes. Unlike mass balance models, geochemical models account for the chemical reactions that occur during mixing and evaporation. Furthermore, geochemical models can predict the chemical evolution of residual void waters in response to changes in pressure, pH and redox conditions following groundwater discharge and reactions between void waters and minerals on the pit walls or minerals within sub-aerial waste deposits. Carefully conceptualised and constructed geochemical models can simultaneously simulate the effects of multiple process, including all of the above. Whilst geochemical models are potentially powerful tools, they are not commonly used as part of residual void assessments in Queensland.

6. Summary

The QMRC is developing technical guidance for modelling water bodies within residual voids to assist industry and government stakeholders rehabilitate residual voids. The guidance is being developed through three sequential stages. This document describes the outcomes of Stage 1, which is a review of the current practice in Queensland. Stage 1 focussed on identifying the methods used to measure or estimate each component of the residual void water balance, followed by a review of methodologies currently used by industry to model the mixing and evolution of waters in residual voids. Stage 2 will identify the leading practice approaches to modelling, with Stage 3 providing guidance on how to implement the leading practice methods.

Modelling is a critical tool for rehabilitation planning and management. It is necessary to understand and predict the long-term water balance and water quality that will be held in voids to determine potential for surface water releases and overtopping, interaction with groundwater systems and whether the water in voids can be used to support a post mine use. The first step when assessing the future behaviour of a water body within a residual void is to understand the magnitude and behaviour of each component in the water and solute balances. These elements are unique to each void and environmental setting, but with commonalities across regions and geological settings throughout Queensland.

Rainfall, evaporation, and beneficial use extraction are elements of the water and solute balance that can be directly measured at the location of a residual void water body. Rainfall is measured at all operating Queensland mine sites. Measurement of evaporation from residual voids in Queensland is not common as it requires floating equipment only recently developed by researchers. Measurement data of volumes of water taken for beneficial use may not be available in some instances.

The other key components of a water and solute balance are rainfall runoff, and groundwater seepage. The volume of water and mass of solutes contributed by these elements is difficult to measure in the field and therefore is not commonly attempted in Queensland. Currently studies assessing the behaviour of residual voids typically commence with estimates of all water and solute balance components including rainfall runoff and groundwater. Rainfall and evaporation data is provided by interpolated datasets, whilst runoff and groundwater seepage are estimated using surface water and groundwater flow models respectively. Solute contributions for each water balance component are often inferred from site monitoring and short-term laboratory scale geochemical studies before being assumed to apply over much larger scales and timeframes.

A range of modelling methods are currently adopted for assessing the long-term water level and solute behaviours in residual voids. The most common methodology employed in Queensland involves the use of water balance models, informed by water balance inputs from groundwater flow and rainfall runoff models known as ‘quasi-coupling’ of groundwater flow models and surface water balance models. Impacts on the groundwater regime surrounding a residual void are determined by using groundwater flow models, with water levels predicted by the water balance model as inputs. These methods provide predictions of residual void water level, salt load and impact on surrounding groundwater levels. Much of this modelling occurs at the approvals stage, and there is typically little or 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.

Whilst the ‘quasi-coupling’ method overcomes some of the limitations of using a either a surface water balance model or groundwater flow model on their own it does have some limitations. The development of more dynamically coupled surface water balance and groundwater flow models that exchange predictions of water level and flow at every timestep has recently been achieved by researchers, but has not been adopted by industry to date.

More complex processes which can occur in residual voids like stratification, and geochemical behaviour of elements/ions are rarely modelled, especially at the approvals stage. Determining if residual voids will be safe, stable and non-polluting is not a direct objective of modelling undertaken during the approvals stage. For this reason no examples of this work with these objectives were obtained from the public domain.

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