# Opportunities to Improve Groundwater Models for Mining Assessments in South Australia: Learnings from Common Shortcomings

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**Abstract**

The environmental assessment and management of mines in South Australia frequently relies on groundwater modelling. Government hydrogeologists often see repeated and avoidable shortcomings in proponent modelling. These shortcomings must be identified and addressed to provide confidence that a project can be responsibly developed, particularly in South Australia, where groundwater resources are limited, and mining is economically important. Five hydrogeologists compiled a list of common errors from more than forty models. These relate to: representation of the conceptual hydrogeology, potentiometric head maps, groundwater-dependent ecosystems, potential for watertable rise, uncertainty analysis, and environmental compliance criteria.

**Keywords:** Hydrogeology, numerical groundwater modelling, environmental impact assessment

## Introduction

The mining and energy sector is an important part of the South Australian economy: it contributed \$7 billion to the state's total \$18 billion of exports in 2023. Important minerals mined include copper, uranium, iron and gold. Groundwater is a critical concern of South Australia's mining sector due to the state's climate and scarce water resources. Most major mines are located in remote semi-arid and arid regions, where there is low rainfall and little data (Fig.1).

Groundwater is by far the most disputed environmental element in South Australian mining, ahead of air quality, noise, conflict with land use and traffic. This is because in the South and Coastal areas (Fig.1) the generally good quality groundwater resources are highly utilised and concerns about ongoing access to and protection of groundwater are widely held in the community. In the lower rainfall Mid-North and western Far North areas groundwater is generally brackish to saline. In recent years, competition has been developing even for saline groundwater in these parts of the state.

The environmental assessment and management of mines in South Australia frequently relies on groundwater modelling. Numerical groundwater flow models support the environmental impact assessment for both new mining applications and mining program changes for almost all major mines. These models are reviewed by government hydrogeologists to ensure that the environmental impacts of mining are assessed as reliably as possible. The reviews follow the requirements of the Mining Act 1971 and water allocation plans (if applicable), using a source, pathway and receptor approach.

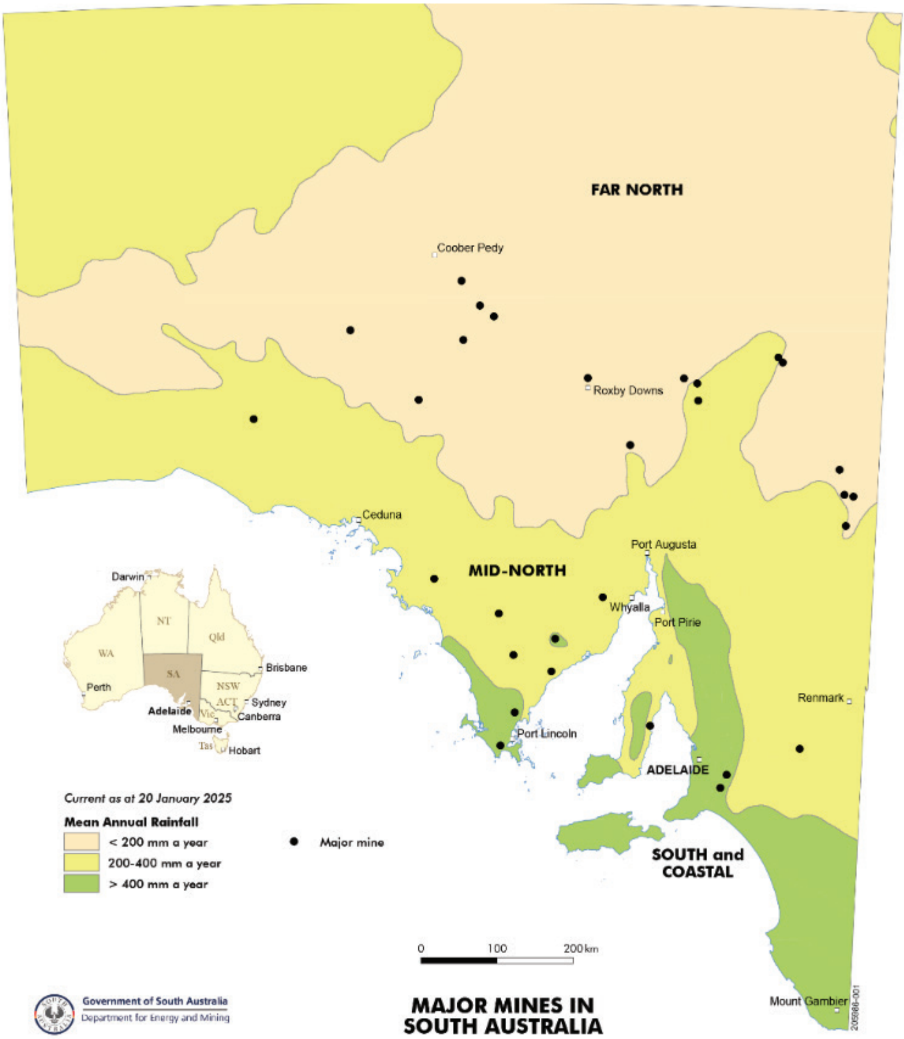


***Figure 1** Major mines in South Australia and climate zones.*

Often government reviewers repeatedly see the same avoidable shortcomings in these models. The identification and resolution of common shortcomings is important to improve modelling and provide confidence to decision makers that a project can be responsibly developed.

## Methods

To improve model assessments, five hydrogeologists from two government departments, with a combined experience of approximately 150 years, compiled a list of common errors and omissions in numerical models developed for new mining applications and operational programs for existing mines. The list of errors and omissions is based on the review of more than 40 numerical groundwater flow models associated with mining applications and programs. These errors were classified into the following categories:

1. Regulatory (information required by mining regulations was not provided).
2. Data deficiency (inadequate data coverage, or the use of incorrect data).
3. Conceptual (errors and omissions in conceptual hydrogeology).
4. Errors and omissions in the conceptual hydrogeology to numerical model translation.

5. Model (errors and omissions related to the building of the model or its documentation).

Next, each of the five hydrogeologists identified the most common and important issues in their experience. Those that were identified by at least two of the hydrogeologists are presented here.

## Results

The following common errors and omissions were identified in many of the reviews:
1. inconsistent representation of the conceptual hydrogeology in the numerical model;
2. insufficient model-independent groundwater potentiometric head maps for each aquifer to describe existing groundwater conditions and inform model boundary conditions;
3. lack of consideration of groundwater dependent ecosystems;
4. little focus on the damage that rising groundwater can cause to ecosystems in arid areas;
5. calibration or uncertainty analysis used in place of field data or good conceptual hydrogeology; and,
6. unnecessarily complex and difficult to enforce environmental compliance criteria that are linked to model predictions.

Each of the items above is briefly discussed in the following section.

### *Inconsistent representation of the conceptual hydrogeology in the numerical model*

A groundwater model must start with a well-defined aim for the required model outputs. The conceptual hydrogeology is then developed, summarising and simplifying data and expert knowledge, to describe the critical hydrogeological features which will influence the required outputs. The numerical model should then embody the conceptual hydrogeology. Often the conceptual hydrogeology is informed and amended during the modelling process, as its assumptions are tested against observations. Occasionally the development of alternative concepts may be required, which in turn may help to understand conceptual uncertainties. The conceptual hydrogeology and numerical model should not be expected to match every detail of a groundwater system but should capture the salient behaviour.

The conceptual hydrogeology and the groundwater model should be consistent in the nature of hydrostratigraphic units, their hydraulic parameters, and how the groundwater system exchanges water with the surrounding environment. A simple and real mining example is a conceptual hydrogeology suggesting an aquifer – aquitard - aquifer sequence. The calibrated model, however, indicated very little contrast in hydraulic conductivity between the three hydrostratigraphic units and the numerical values suggested that all the three units were aquitards. In addition, the range for model calibrated hydraulic conductivity appears to be up to two orders of magnitude less than those interpreted from actual hydraulic aquifer tests. Such inconsistencies between the conceptual hydrogeology and the numerical model must be discussed and justified. Either the conceptual hydrogeology should be revised, with explanation, or the model calibration should be reconsidered. Where possible, conceptual and parameter uncertainties should be resolved by additional data collection.

Other examples encountered include different groundwater flow directions (horizontal or vertical) in the conceptual hydrogeology and in the model; and the model having to include processes that are not explained in the conceptualisation, such as artificially draining groundwater out of the model without explaining the physical/hydrological process that is simulated.

Probabilistic (stochastic) numerical models should also be consistent with the conceptual hydrogeology. If hundreds or thousands of realisations, each with a different parameter set, are presented as acceptable, then each realisation should be consistent with the conceptual hydrogeology. This can be difficult and time-consuming to assess.

Often inconsistency between the conceptual hydrogeology and its numerical model representation emerges at the regulatory review of the completed model.

Modellers are often reluctant to go back and change the conceptual hydrogeology as this would also trigger a model review, increase the costs and prolong the approval process. On the other hand, regulators are reluctant to approve models with unresolved inconsistencies.

Modellers often use "good" calibration of the model as a proof that there is nothing wrong with the conceptual hydrogeology. Bredehoeft (2003) concluded that good calibration of a model does not ensure a correct conceptual hydrogeology and we concur unreservedly. Both modellers and regulators should also be conscious that conceptual hydrogeology is not always immutable (Bredehoeft 2003) and sometimes even the most comprehensive uncertainty analysis cannot compensate for conceptual uncertainties.

This type of error occurs mainly because of an insufficient review process. Ideally, frequent reviews and consultation between mining proponents and regulators are required. Barnett *et al*. (2012) suggest model reviews at the completion of the conceptualisation and design stage, the calibration and sensitivity analysis, and at the completion of the project. In our experience, such frequent consultations are rare for mining proposals.

Regrettably, even when the conceptual hydrogeology and numerical model are initially consistent, later observations may invalidate both. Bredehoeft (2005) defined the *conceptualization model problem – surprise* as new data that render the prevailing conceptual hydrogeology invalid and considered that *surprise* occurs in 20 to 30% of model analyses. Hence numerical models should be revisited and revised periodically. Post-audits are recommended.

### *Insufficient model-independent groundwater potentiometric head maps for each aquifer to describe existing groundwater conditions and inform model boundary conditions*

Boundary conditions are important and integral aspects of both the conceptual hydrogeology and the building of the numerical model. The levels, direction and gradients of flows within and between the aquifers will influence the environmental impacts of a mine.

If a model-independent and reliable groundwater head contour map cannot be constructed, the model will inadvertently be based on questionable boundary conditions, leading to unsupportable model predictions. This type of error occurs in areas with an absence of sufficient groundwater head data. South Australia, with an area of 983,000 km$^2$ and a population of 1.8 million (of which the capital Adelaide has 1.4 million inhabitants) has many remote areas where groundwater data are sparse.

Notwithstanding the above, if realistic boundary conditions cannot be determined in the absence of data, perhaps an interim and simple analytical solution should be developed, and efforts should be focussed on obtaining new data to aid the development of a future numerical model. New data do not necessarily require drilling if re-measuring existing wells would suffice. Hydraulic head measurements can often be obtained in the field relatively easily (Cohen and Cherry 2020) and such data can also improve the conceptual understanding.

### *Lack of consideration of groundwater dependent ecosystems*

Addressing groundwater dependent ecosystems (GDEs) as environmental receptors is a requirement of the Mining Act (1971) of South Australia, yet GDEs are often inadequately addressed in modelling assessments.

Frequently, there is an absence of potentiometric head observations near potential terrestrial GDEs to determine depth to groundwater over time, or no consideration of streamflow data if there are potential aquatic GDEs.

Further, groundwater models for mining typically use time steps in the order of years and therefore cannot consider the seasonality and variability of the watertable, potentiometric surface, or surface water-groundwater interactions that are all important for the proper consideration of GDEs.

These inadequacies may be due to limited consideration of the model's aims at the beginning of the project. For example, mining groundwater models often focus on dewatering rates and regional drawdown, and their conceptualisation and construction reflect that. For those purposes, they concentrate appropriately on the mine site, mining actions and regional flows, with large spatial scales outside the mine, and annual or greater stress periods/timesteps. However, these may not be the most important hydrogeological features for assessing GDEs. GDE health is influenced by depth to water, spring flow and surface water/groundwater interaction near or upstream of the GDEs. Seasonal or episodic variations may be critical. Hence a model designed to estimate dewatering and regional drawdown may be a poor tool for estimating impacts to GDEs. It may be better to have a second groundwater model that captures processes important to the GDEs, which is informed by drawdown estimates from the larger-scale model.

This type of error originates from either inadequate understanding of GDEs or not including GDEs explicitly in models. The Bureau of Meteorology developed a national online dataset of Australian GDEs (http://www.bom.gov.au/water/groundwater/gde/map.shtml), providing mining proponents with an initial indication of GDEs to address in their assessment. Further, most widely available modelling software allow for the simulation of groundwater-surface water interaction and therefore aquatic GDEs (surface water, wetlands, springs) can be included in models using one of the modelling packages specifically designed for that purpose. Terrestrial GDEs can be accommodated by an evaporation package that allows evaporating the shallow water table within an extinction zone.

### *Little focus on the damage that rising groundwater can cause to ecosystems in arid areas*

Mining related infrastructure, such as tailing storage facilities and waste rock dumps, can increase groundwater recharge and can mound the water table locally. The water table may rise as a result, up to and within the root zone of vegetation, and can cause damage or dieback to vegetation unable to cope with such changed groundwater conditions.

It is important that numerical groundwater flow models address such potential environmental impacts on vegetation and assess the resultant cumulative mounding (from tailing storage facilities and waste rock dumps) and drawdown (from dewatering or depressurisation) together. The models should consider the decades after mining ceases, as the increased recharge may persist long after the dewatering ends.

### *Calibration or uncertainty analysis used in place of field data or good conceptual hydrogeology*

It is very challenging to robustly simulate a region where there are minimal field data to inform the conceptual hydrogeology and numerical modelling.

A simple numerical model with few parameters may calibrate well to the limited data and yet its assumptions may be incorrect. Only field work and monitoring can determine this.

More complex numerical models with many parameters may make the best use of available data during calibration, but they too may calibrate well while having incorrect assumptions. Parameters distant from observations are unlikely to be influenced by data and will revert to the modeller's initial estimates, so there is little to be gained there.

Sometimes uncertainty analysis is used to explore many possibilities in the absence of data. Unfortunately, in practice it is very difficult to demonstrate that a complex model has adequately searched all the possibilities, given that it depends on all prior assumptions and parameter distributions. Also, it is not always understood that most of these approaches are unlikely to simulate a worst or best case: if hundreds or thousands of possibilities (realisations) are simulated probabilistically to explore hundreds or thousands of parameters, it is very unlikely that the realisations will pick "worst-case" values for all parameters at the same time. If there is a clear-cut undesirable impact to be avoided, the modeller should instead consider simulating both past and future, calibrating the model to historical observations and a hypothetical future dataset in which the undesirable impact occurs. If realisations/

parameter sets are found which are consistent with conceptual hydrogeology, meet calibration criteria, and allow the undesirable impact to happen, then subsequent fieldwork should determine if those conditions are present in actuality or if they can be ruled out.

### *Unnecessarily complex and difficult to enforce environmental compliance criteria that are linked to model predictions*

In South Australia, an environmental impact assessment is required to use the source-pathway-receptor approach. An environmental outcome and associated outcome measurement criteria are also required with details of the proposed groundwater monitoring (what, where, at what frequency and what background or control data will be used).

Sometimes unnecessarily complex and difficult to enforce outcome measurement criteria are proposed and linked to model predictions. An example is *no significant adverse drawdown above model predictions* without specifying the parameters of the relevant statistical test. Using inappropriate tests, for example using statistical methods designed for normal distribution for non-parametric data, or using linear trend estimators for non-linear temporal trends, also occurs. Difficulties also arise if subsequent model versions (for example after updates or re-calibration) vary considerably. If the outcome criteria are not changed the linkage between those and the model predictions disappears. If the model-linked criteria are varied the new criteria may allow, for example, a larger drawdown than originally; and it may have a detrimental effect on existing third party well operations or GDEs.

Most of these errors can be avoided by having an understanding of the hydrogeology, good quality baseline data and by appreciating the uncertainty in both measurements and in the model predictions.

## Conclusions

Based on the compilation of errors and omissions and the contribution of five hydrogeologists, common patterns in errors from the review of more than 40 numerical groundwater flow models have emerged. Feasible solutions were provided at the end of each of the six relevant sections.

The findings from this review were already used in workshops with hydrogeologists working on behalf of mining companies and will be considered in mining guidelines and may contribute towards new Australian groundwater modelling guidelines.

To avoid common errors and omissions, more early investment in data collection, conceptual hydrogeology and modelling may be required. However, these would be recouped due to easier and faster approvals, plus it would reduce potentially expensive risks in mining construction and management. Ultimately, this will help to ensure that potential environmental impacts are reliably identified, and appropriate regulatory controls applied.

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