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Yallourn coal mine water quality closure tool

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Abstract

This technical paper presents development and application of a water balance and water quality (WB/WQ) model for the Yallourn coal mine in Victoria's Latrobe Valley. The project proposes conversion of the Yallourn coal mine voids into high-level pit lakes within the Yallourn Township Field (YTF) and Yallourn East Field (YEF). The modelling objectives were to estimate final lakes water quality and their long-term evolution, quantify water demand for initial filling and ongoing top-up, assess the influence of climate variability and climate change and compare alternative filling scenarios.

The WB/WQ model integrates hydrological, hydrogeological and geochemical components. Catchment run-off was simulated using the Australian Water Balance Model (AWBM), incorporating stochastic climate sequences and projected rainfall and evaporation factors. Groundwater flux inputs were derived from external groundwater modelling. Pit geometry, seepage, direct rainfall, evaporation, river inflows and managed transfers were represented within a probabilistic framework (GoldSim). Extensive geochemical investigations, including pit wall washing, static testing and kinetic leach column tests on coal and overburden materials, were undertaken to derive source terms. Geochemical reactions, mineral precipitation and atmospheric equilibration were evaluated using thermodynamic modelling (PHREEQC).

Model results indicate that lake filling timeframes, top-up requirements and long-term water levels vary by scenario and climate condition. Salinity (total dissolved solids, TDS) generally increases during filling before stabilising, with differences between YTF and YEF reflecting source material geochemistry and hydrological connectivity. Predicted pH and metal concentrations are sensitive to iron inputs and solubility controls. Thermodynamic modelling suggests precipitation of iron (oxy)hydroxides can substantially reduce dissolved aluminium and copper concentrations, with variable effects on zinc. Climate change influences are moderated by dominance of fill-water inputs and availability of supplementary sources.

Overall, the model provides a defensible basis for environmental assessment and closure planning.

Keywords: *mine closure, pit lake, numerical modelling, GoldSim, Yallourn*

1 Introduction

The Yallourn coal mine and associated Yallourn power station are located in Victoria's Latrobe Valley and operated by EnergyAustralia Ltd. The site is located approximately 150 km southeast of Melbourne on the traditional lands of the Gunaikurnai people.

Coal mining operations have been part of the Latrobe Valley landscape for over 100 years. The Yallourn power station is scheduled to cease operation in mid-2028, at which point the Yallourn coal mine will also cease production. Following the end of the productive life of the mine, the site will transition to rehabilitation phase and eventually to an anticipated future use beyond mining. The current mining licence has been extended to 2051 to incorporate the rehabilitation of the mine site.

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1.1 Project description

EnergyAustralia Ltd aims to rehabilitate the Yallourn coal mine and Yallourn power station to a safe, stable and sustainable landform, with the final void configured as one or more pit lakes.

Key project components for the WB/WQ assessment include progressive filling of mine voids to RL +37 m Australian height datum (AHD) various potential sources, alongside earthworks to stabilise and reshape landforms. Earthworks focus on regrading upper batters above the final lake level to achieve geotechnically stable slopes, with appropriate vegetation and surface drainage controls.

Void filling is the dominant process controlling hydrological and geochemical evolution. Two main end-member lake configurations are assessed: a base case unconnected (terminal) system, where water losses are dominated by evaporation and minor seepage, and a preferred connected (flow-through) system with hydraulic linkage to the Morwell River, enabling controlled diversion of flood flows into the pit lake and managed discharge to the Latrobe River via spillway infrastructure.

Primary water sources include Latrobe River bulk entitlements (~24 GL/year), groundwater abstraction (declining from ~1.5 GL/year at lower elevations to zero at RL +37 m AHD) and potential supplementary supplies. Under connected scenarios, additional variable inputs may include Morwell River flood flows.

The baseline scenario assumes continuation of existing approved operations, including groundwater pumping, ongoing earthworks and retention of operational and catchment water within the void, providing a reference case for comparison.

The preferred scenario involves continuous filling to RL +37 m AHD using all available water sources, maintaining hydraulic connectivity between voids to optimise filling efficiency. This approach is expected to increase filling rates and significantly influence long-term water balance and water quality outcomes.

1.2 Site layout

The Yallourn coal mine consists of 2 adjacent open pits, YTF and YEF (including Maryvale Field), separated by a coal dyke that hosts the Morwell River Diversion (MRD) (Figure 1). To the north, the Latrobe River separates Yallourn coal mine from the Yallourn North open cut, which is used for ash disposal and has no hydraulic connection to the mine voids.

There are 3 internal overburden dumps: the YTF overburden dump and Midfield dump (YTF) and the YEF overburden dump (YEF).

Geochemical characterisation indicates that the YTF northern overburden and YEF dumps contain potentially acid forming (PAF) materials, while the YTF southern overburden and Midfield dumps are generally non-acid forming (NAF). Across all dumps, there is potential for generation of saline drainage.

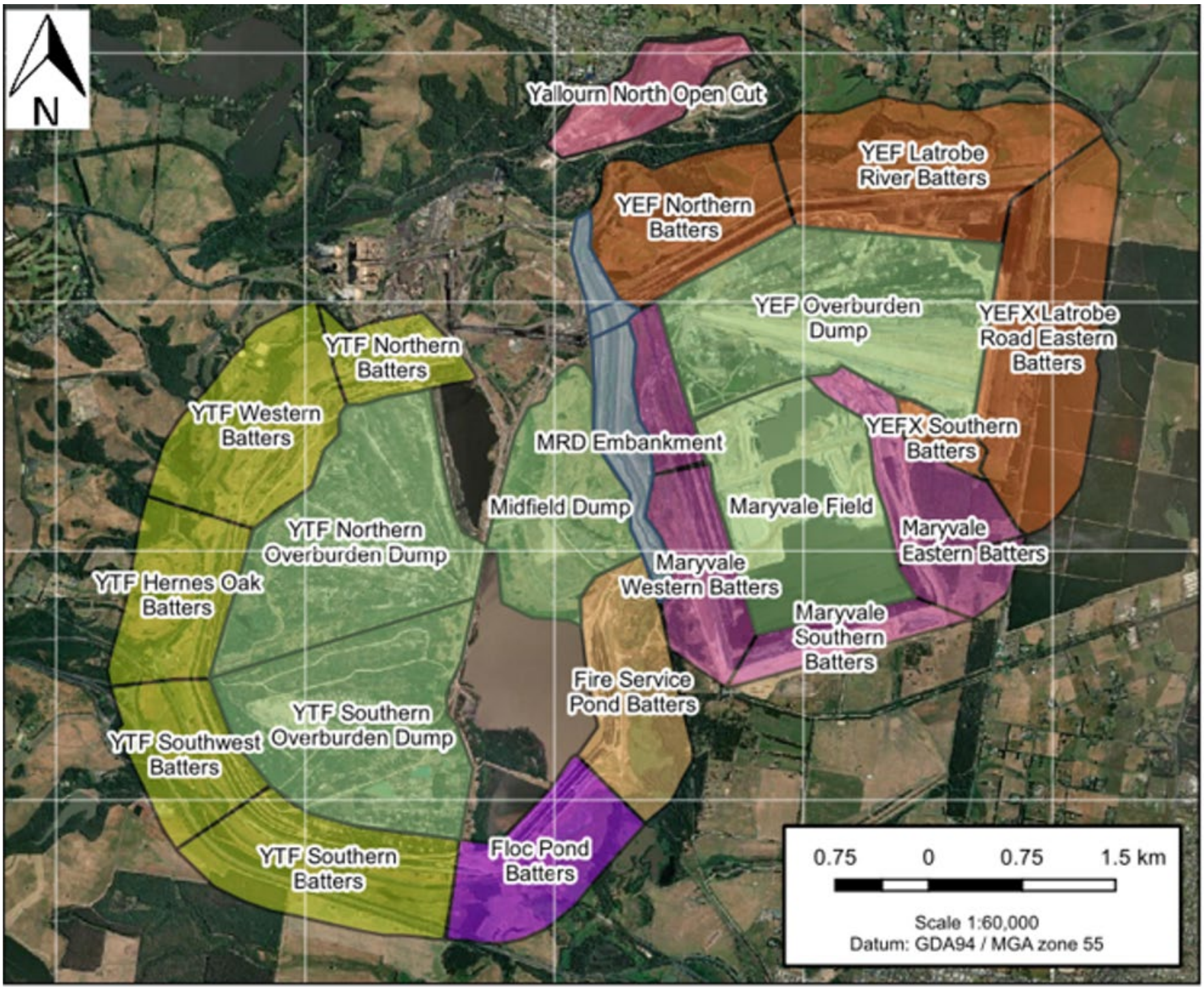

Figure 1 Site layout

2 Methodology

2.1 Geochemical testing

Geochemical testing was undertaken to understand the levels of potential contaminants that may be transferred into the water column when various materials (weathered and fresh coal and overburden) come into contact with water.

RGS conducted a staged geochemical assessment to support development of the pit lakes WB/WQ model. An initial desktop review of existing geochemical and hydrochemical datasets identified key data gaps relating to materials likely to influence pit lake water quality (e.g. in-pit backfill, overburden, pit floor and wall materials).

To address these gaps, field investigations were undertaken, focusing on characterising potential source terms for acid, neutral to alkaline, saline, and metalliferous drainage. Drilling and sampling programs were completed across in-pit overburden dumps and limited ex-pit overburden areas, comprising 43 drill holes (41 in-pit, 2 ex-pit). Twelve drill holes were completed as groundwater monitoring bores to support ongoing hydrochemical monitoring.

A total of 1,522 solid samples (grab and core) were collected and subjected to geochemical screening. Selected samples underwent static geochemical testing, with further compositing of representative materials for kinetic leach column testing to characterise long-term solute release behaviour and inform source term inputs for the WB/WQ model.

The criteria used to classify the potential of the samples to generate acidic drainage are shown in Table 1. The classification criteria reflect, among others, the Commonwealth of Australia (COA 2016) and international Network for Acid Prevention (INAP 2009) guidelines for the classification of mining waste materials. The net acid production potential (NAPP) is used as an indicator of materials that may be of concern with respect to acid generation. The NAPP calculation represents the balance between the maximum potential acidity (MPA) of a sample, which is derived from the sulphide sulphur (chromium reducible sulphur; S_{CR}) content, and the acid neutralising capacity (ANC) of the material, which is determined experimentally. By convention, the NAPP result is expressed in units of kg H_2SO_4/t sample. If the capacity of the solids to neutralise acid (ANC) exceeds their capacity to generate acid (MPA), then the NAPP of the material is negative. Conversely, if the MPA exceeds the ANC, the NAPP of the material is positive. The results of the geochemical classification criteria are provided in Figure 2.

Table 1 Classification criteria and sample classifications for samples from the Yallourn coal mine

Classification	S_{CR} (%)	NAPP (kg H_2SO_4/t)
Non-acid forming (barren) (NAF-B)	< = 0.1	–
Non-acid forming (NAF)	> 0.1	< = -10
Uncertain	> 0.1	< = 5
Potentially acid forming (low capacity) (PAF-LC)	> 0.1	< = 10
Potentially acid forming (PAF)	> 0.1	> 10

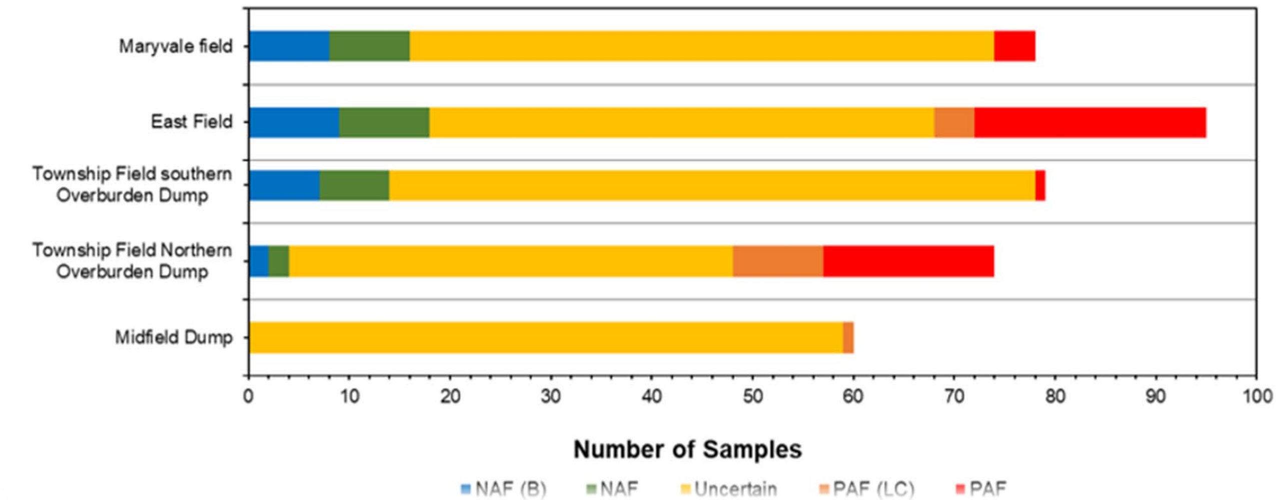

Figure 2 Geochemical classification according to sampling location at the Yallourn coal mine

2.2 Hydrogeochemical conceptual model

General statements regarding the impacts of hydrological processes on water quality can be made and these are applicable to Yallourn coal mine:

- Groundwater inflows carry dissolved constituents at background concentrations into the lakes. Natural, upgradient groundwater will have a certain water quality and will contribute to the lakes' quality. Inflowing groundwater can also pick up constituents from weathered coal immediately surrounding the mine void or from recharging meteoric water passing through the dewatered zone.

- Surface water run-off from pit walls and local catchment may transport constituents and sediments that will affect the chemistry of the lakes.
- Flood flows from the Morwell River in a connected lake scenario, will carry dissolved constituents via the 3 spillways.
- In-pit overburden dump seepage and run-off may carry dissolved constituents into the lakes.
- Direct precipitation generally is a diluting factor on lake water quality although zinc regularly exceeded the Australian and New Zealand (ANZG) guidelines for freshwater aquatic ecosystem (95% species protection) guideline (Australian and New Zealand Governments and Australian State and Territory Governments 2018).
- Water transferring from lake-to-lake via a conveyor tunnel (as a result of hydraulic head differences) may have a dilution or concentrating effect on the receiving lake.
- Since evaporation removes water and leaves behind any dissolved constituents, evaporation tends to have a concentrating effect on lake water quality (known as evapoconcentration).
- Groundwater and surface water outflows (via the outflow channel) from the lake(s) typically have the effect of removing constituents from the lake(s). However, if the lake(s) is stratified, these outflows may remove water of different quality, which may result in either improved or reduced water quality in the lakes (note: outflows would only reduce the lake water quality if there was a freshwater surface lens that is flowing out).
- Depending on the water quality of the external water sources used to fill and top-up the lake(s), these may result in either improved or reduced water quality in the lake(s).

2.3 Model development

The numerical model, incorporating both water balance and water quality components, was developed using GoldSim software. It is designed as a decision-support tool to evaluate closure scenarios, with flexible structure enabling ‘what if’ simulations and sensitivity analyses through adjustment of input parameters and model controls. The model operates on a daily timestep and supports probabilistic simulations over a period of up to 100 years.

Model architecture is presented in Figure 3 and includes integrated water balance and water quality components. The water balance accounts for direct rainfall, groundwater inflows and surface water inputs, and is governed by climatic drivers (rainfall and evaporation) and external water supply sources. Each inflow pathway is assigned an associated water quality source term derived from a combination of site-specific measurements and inferred geochemical data.

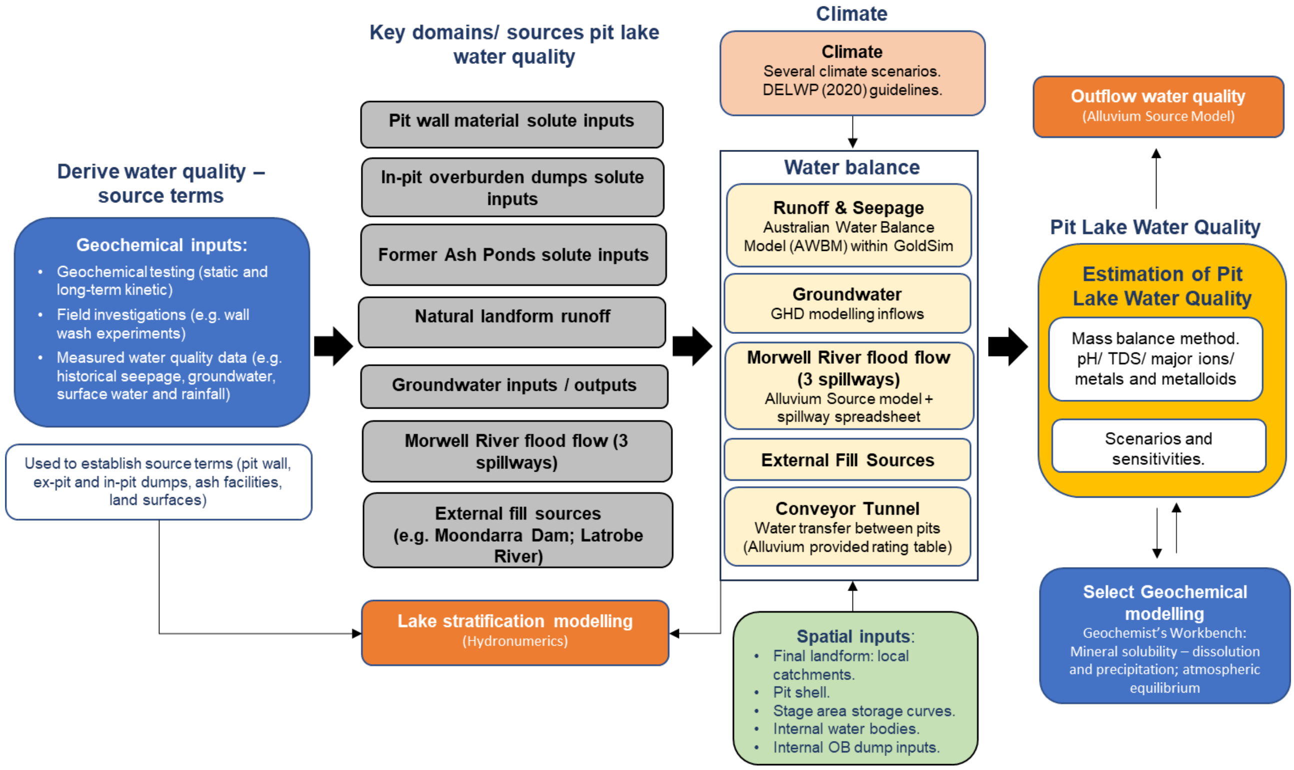

Figure 3 Yallourn coal mine pit lakes water balance and water quality model development

2.3.1 Model scenarios

The modelling framework comprises one base case (Scenario 1) and multiple project scenarios (Scenarios 2–6), with key sensitivities summarised in Table 2.

Project scenarios evaluate pit lake filling with and without hydraulic connection to the Morwell River. Scenarios 2–5 include varying levels of river connectivity via spillways, while Scenario 6 remains unconnected. Additional water inputs include Latrobe River allocations (24–34 GL/year depending on scenario) and, in Scenario 3 only, hypothetical water supply (14 GL/year of hypothetical freshwater supply). Latrobe water is supplied to the YTF, while hypothetical water is directed to the YEF.

River flood inflows are incorporated in connected scenarios (2, 3 and 5) via spillways, while Scenario 4 assumes full river diversion removal at completion of filling, creating a single lake discharging to the Latrobe River via Spillway 4.

After fill, a top-up trigger activates at RL +36 m AHD, supplying Latrobe water.

Table 2 Yallourn coal mine modelling scenarios

Scenario ID	Fill sources (annual until reach RL + 37 m AHD)	Morwell River connected?	Top-up water	Climate
Scenario 1	Local catchment flows, natural groundwater & pumped groundwater (1.5 GL to RL 0; 1 GL to RL 37; 0 GL ongoing)	No	No	Median
Scenario 2	Local catchment flows, natural groundwater, pumped groundwater (1.5 GL to RL 0; 1 GL to RL 37; 0 GL ongoing) & 24 GL Latrobe water	Yes (flood flows only)	Yes	Median
Scenario 3	Local catchment flows, natural groundwater, pumped groundwater (1.5 GL to RL 0; 1 GL to RL 37;	Yes (flood flows only)	Yes	Median

Scenario ID	Fill sources (annual until reach RL + 37 m AHD)	Morwell River connected?	Top-up water	Climate
	0 GL ongoing), 34 GL Latrobe water & 14 GL hypothetical water			
Scenario 4	Local catchment flows, natural groundwater, pumped groundwater (1.5 GL to RL 0; 1 GL to RL 37; 0 GL ongoing) & 24 GL Latrobe water	Yes (all)	Yes	Median
Scenario 5	Local catchment flows, natural groundwater, pumped groundwater (1.5 GL to RL 0; 1 GL to RL 37; 0 GL ongoing) & 24 GL Latrobe water	Yes (flood flows only)	Yes	Dry
Scenario 6	Local catchment flows, natural groundwater, pumped groundwater (1.5 GL to RL 0; 1 GL to RL 37; 0 GL ongoing) & 24 GL Latrobe water	No	Yes	Median

2.3.2 Final landform

The final landform surfaces were used in Deswik (geospatial and computer-aided design (CAD) software) to produce a range of input data to the GoldSim numerical model, including pit physical characteristics and stage curves and catchment areas. The local catchment area draining to the pit is presented in Figure 4. The catchments were then subdivided based on land use type by identifying different landform features to represent different land use types.

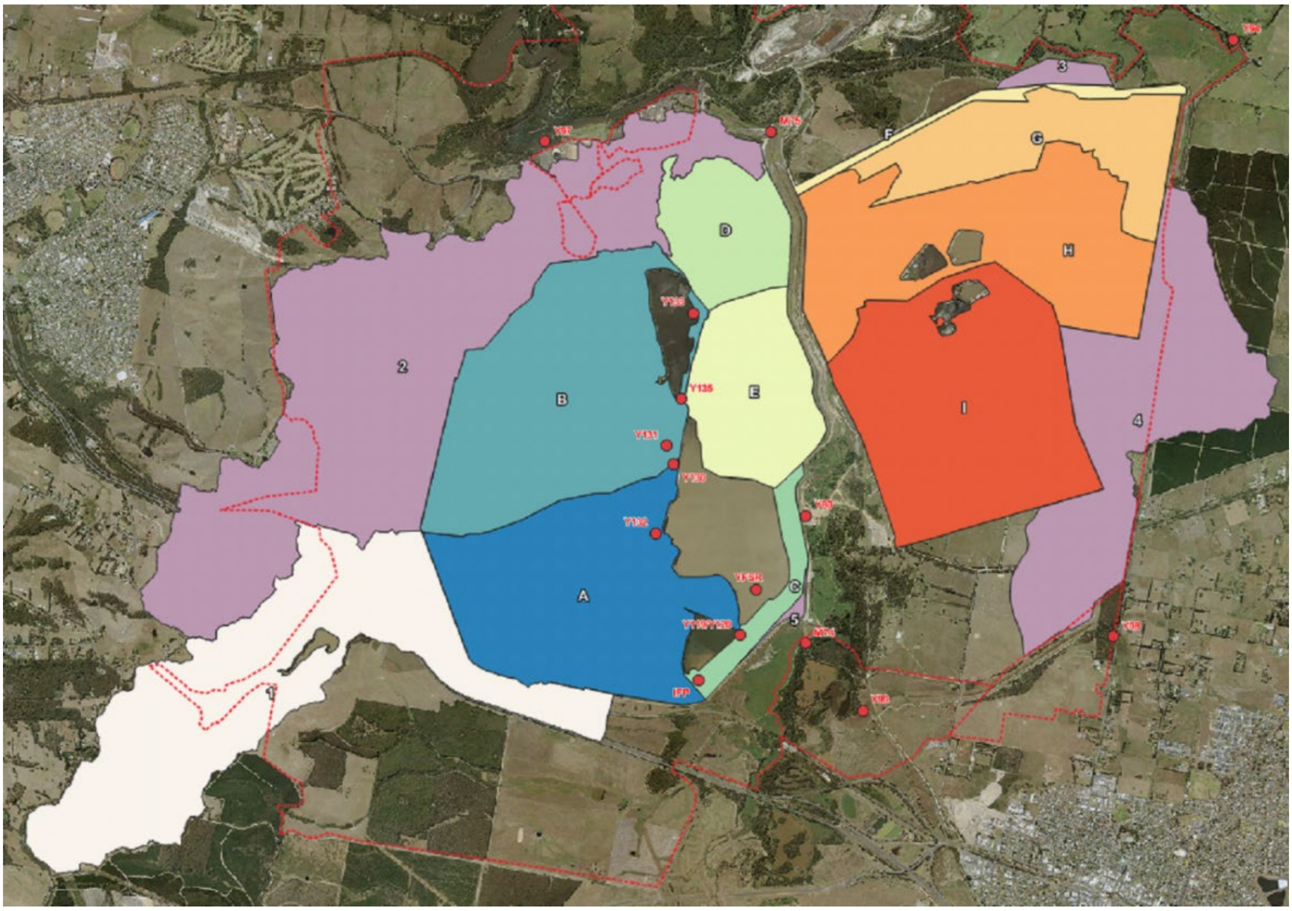

Figure 4 Sub-catchment boundaries draining to the pit (including in-pit catchments)

2.3.3 Surface water

After closure, there will be various potential surface water inflows to the pit voids from the catchments and each of these has been accounted for within the model to allow simulation and comparison of different closure scenarios.

The catchments included in the model are both local catchments (within the mine lease itself; Section 2.3.2), as well as external catchments which may contribute flow into the lakes (i.e. Morwell River interconnection). The key surface water flows incorporated in the model are:

- Local rainfall and run-off:
  - run-off from pit walls (e.g. catchments F and C)
  - run-off and seepage from the in-pit overburden dumps (e.g. catchments A, B, E, G, H and I)
  - run-off and seepage from the Former Ash Ponds (catchment D)
  - direct rainfall onto the lake surface
  - local run-off from the catchments within the mining lease.
- External run-off:
  - external Morwell River upstream catchment. This contributes flow to the pit for a connected scenario (via 3 spillways or fully integrated). Flow is allowed to overflow via Spillway 4.

Local rainfall and run-off are modelled within GoldSim while external run-off, specifically flows from the upper Morwell River catchment, were modelled by others and the outputs used as inputs into the WB/WQ model.

All local surface water inflows to the pit (and within the pit) and their hydrological response are simulated within the GoldSim model itself, using the AWBM as an inbuilt module.

The AWBM is a daily timestep hydrological model that simulates run-off using rainfall and evapotranspiration inputs. It represents infiltration, soil moisture storage (including antecedent conditions) and catchment lag effects to generate daily run-off outputs. Separate land use modules are used to account for differences in hydrological response, each producing surface run-off and shallow baseflow components.

The external run-off was generated as part of a regional hydraulic modelling assessment undertaken by others. A preliminary spillway design arrangement (Figure 5) was assessed for the site for a connected scenario.

Daily estimation of flows through each of the spillways was determined using calibrated flow data from the regional hydraulic modelling assessment. Using the calibrated flow data, rating curves for each spillway were determined and used to estimate daily flows over the spillways (for equivalent flow levels in the Morwell and Latrobe rivers).

Stochastic flows scenarios (101 realisations) for both the dry and medium climate scenarios were run through the spillway rating curves to produce a daily time series of flows over the spillways for each model scenario.

These flow series were used as inputs to the GoldSim model.

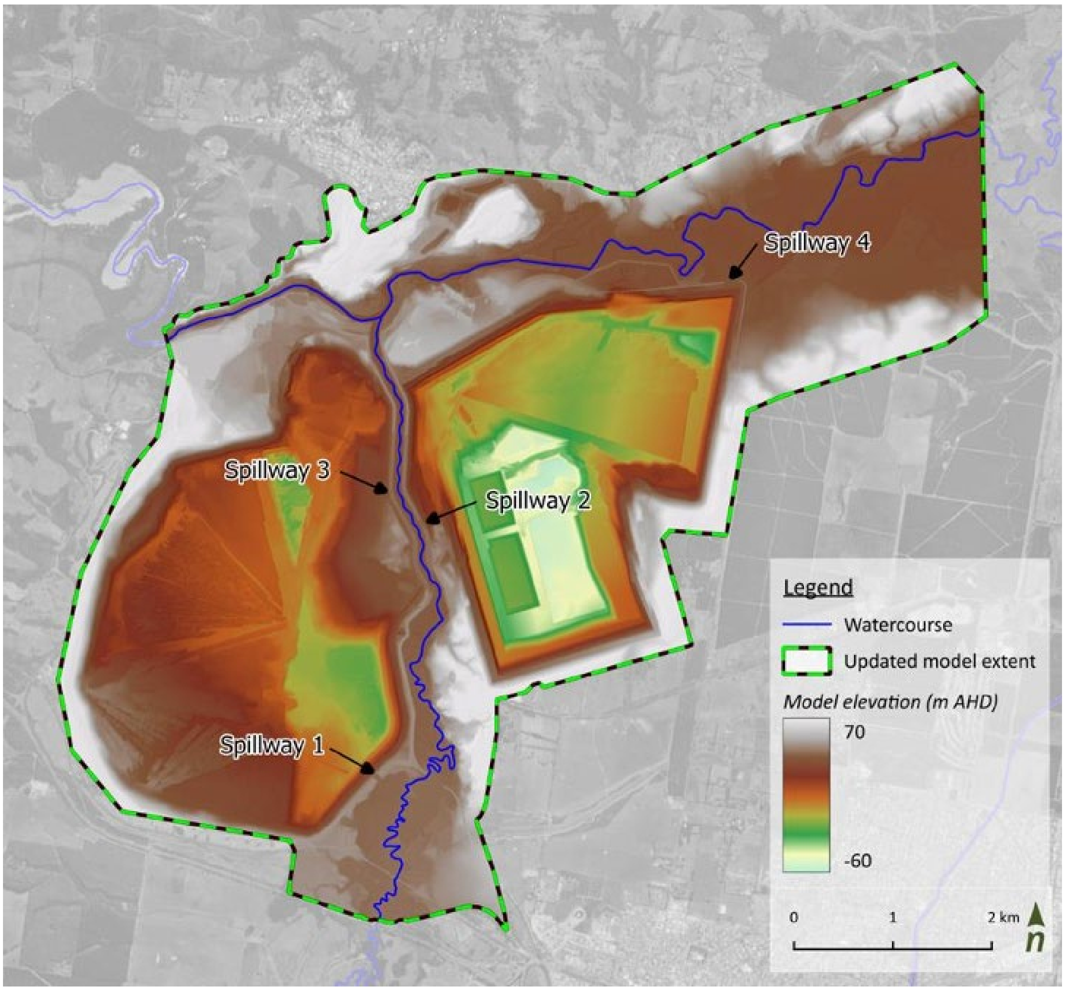

Figure 5 Spillway locations

2.3.4 *Groundwater*

The conceptual groundwater model extends beyond the extent of the pit shells, and the groundwater model outputs were generated by others.

Groundwater inflow rates into each of the pits were generated as time series groundwater fluxes generated in the groundwater model under a certain set of hydrodynamic boundary conditions, including complete fill of the lake to +37 m RL. The provided groundwater fluxes into and out of the pits/lakes were a time series with quarterly timesteps. Fluxes in and out were provided for 6 different aquifers/geological formations: Haunted Hills Formation (L1), Yallourn Coal (L2), Yallourn Coal (L3), Yallourn Coal (L4), Yallourn Coal (L5) and Yallourn Interseam (L6).

The GoldSim model operates on a daily time step; therefore, groundwater inputs were disaggregated from quarterly fluxes to equivalent daily flux rates. The implementation in GoldSim assumed a linear interpolation of the fluxes between the provided 90-day periods.

2.3.5 *Water quality components of the model*

The general approach to simulating water quality within the model for each scenario includes:

- determination of the exposed/saturated pit wall, overburden dump and water volumes in each (daily) timestep of the simulation
- addition of dissolved loads added to the system through direct rainfall, groundwater inflows, surface water run-off (including pit wall run-off) and overburden dump reactions

- addition of mass load from the MRD spillways (for select scenarios)
- mixing of loads and volumes to determine mass balance concentrations
- calculation of water losses via evaporation, groundwater, outflow and other losses with distributed dissolved mass loss; subsequent mass additions and water balance considerations
- recalculation of lake(s) quality progressively (daily) over the duration of model simulation (100 years)
- selective application (annual) of geochemical controls (e.g. mineral solubility, atmospheric equilibrium) using PHREEQC (Parkhurst & Appelo 1999).

The source terms (geochemical inputs) have been generated from a combination of inferred, assumed and measured data. Surface water and groundwater quality source terms were generally developed from historical site monitoring data. Seepage water quality for each of the overburden dumps was inferred from measured groundwater data collected from bores installed in each of the dumps. Pit wall and overburden dump run-off water quality was inferred from wall washing experiments conducted on site.

3 Results discussion

The key results of the water balance for each of the scenarios are summarised in the following points.

- Scenario 1 (base case) did not reach fill elevation (+37 m AHD) over the simulation period (100 years); the maximum lake elevation reached is +15.5 m AHD for both the YTF and YEF lakes.
- For the other scenarios (Scenario 2 to Scenario 6), the modelling showed that the pit filled to RL +37 m AHD within 12.3 to 30 years with the mean values being 12.9 to 28.1 years (Table 3), depending on which fill scenario was modelled, climate variability/ uncertainty and if the Morwell River is connected.
- The climate change sensitivity analysis showed that the pit fill timeframes were sensitive to climate (medium versus dry showed a +2.8-year (mean probability) increase in fill time). The variation in the time to fill the pit for the probabilistic simulations is largely driven by the large contribution of Morwell River flood flows, direct rainfall and catchment run-off to the water balance which are all climate dependent.
- The requirement for the top-up occurs when the evaporation from the lake surface (and groundwater seepage) exceeds the lake inflow volumes. The annual top-up, for those scenarios that require top-up (scenarios 2, 3 and 6), varies between a mean of approximately 2.61 and 4.66 GL/year depending on the particular scenario (Table 3). There is an opportunity to reduce the top-up volumes by allowing a freeboard in the lake which would reduce the water loss via Spillway 4 (particularly if a flood event occurs shortly after top-up).

Table 3 Summary of water balance results

Scenario	Additional fill sources (annual)*	Morwell River connected?	Top-up?	Climate	Mean years (volume [GL]^) to fill	Mean annual top-up (GL/year)	Mean top-up volume (GL) over simulation
1	None	No	No	Median	NA	NA	NA
2	24 GL Latrobe water	Yes (flood flows only)	Yes	Median	25.3 (606)	2.61	194
3	38 GL Latrobe water & 14 GL hypothetical water	Yes (flood flows only)	Yes	Median	12.9 (620)	2.73	237
4	24 GL Latrobe water	Yes (all)	Yes	Median	25.3 (606)	0.00	0
5	24 GL Latrobe water	Yes (flood flows only)	Yes	Dry	28.1 (674)	4.66	334
6	24 GL Latrobe water	No	Yes	Median	25.9 (621)	2.80	207

*Additional fill sources include those sources of fill that are not common to all scenarios, i.e. local catchment flow, natural groundwater, direct rainfall, pumped groundwater (1.5 GL to RL 0; 1 GL to RL 37; 0 GL ongoing) are consistent for all modelled scenarios.

^Volume pumped water to achieve first fill (+37 m AHD).

The water quality modelling indicates that predicted pit lake chemistry is primarily controlled by inflow water quality and geochemical source term assumptions, with limited sensitivity to scenario variation.

PHREEQC modelling predicts near-neutral pH under atmospheric equilibrium conditions (~pH 7 for YTF and ~pH 7.6 for YEF).

Despite differing operational scenarios, predicted salinity and metal concentrations remain within a narrow range across cases, reflecting dominance of fill-water inputs (Latrobe River, groundwater, rainfall and top-up supplies) in controlling overall lake chemistry.

Guideline comparisons indicate all simulated parameters comply with livestock drinking water criteria (Australian and New Zealand Governments and Australian State and Territory Governments 2018), but exceedances occur for some metals against freshwater aquatic ecosystem protection levels (95% species protection). Aluminium exceedances are attributed to multiple inflows but may be overstated due to colloidal contributions; thermodynamic modelling suggests precipitation as gibbsite could reduce dissolved concentrations below guideline levels. Zinc exceedances are driven by rainfall and groundwater inputs, while copper exceedances occur primarily in YTF across all scenarios and in YEF only under high river connectivity (Scenario 4). Lead exceedances are observed in YEF, with redistribution occurring under fully connected scenarios.

Elevated copper, zinc and lead inputs are consistent with regional catchment influences, including atmospheric deposition potentially linked to historical coal combustion in the Latrobe Valley, as well as contributions from pit wall run-off and seepage. These inputs are expected to decline with reduced coal-fired generation over time, potentially improving long-term water quality outcomes.

Thermodynamic modelling indicates that precipitation and sorption onto iron (oxy)hydroxides significantly reduce dissolved metal concentrations, particularly aluminium and copper, with partial reduction of zinc.

Climate variability has limited influence on long-term lake water quality due to the dominance of controlled filling inputs and the buffering effect of top-up water supplies and, where applicable, Morwell River inflows.

4 Conclusion

The modelling indicates that the pit lakes will not reach the target fill elevation of +37 m AHD under natural inflows alone, but all scenarios incorporating supplementary water sources achieve filling within approximately 13–28 years. Fill rates are primarily influenced by climate conditions and Morwell River inflows, with some scenarios requiring ongoing top-up water to maintain lake levels.

Predicted water quality is largely controlled by inflow water chemistry and geochemical processes, with limited sensitivity to filling scenario or climate variability. While some metals may exceed aquatic ecosystem guideline values, overall water quality is expected to remain stable, with natural attenuation processes likely to reduce concentrations over time.

Acknowledgement

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