Pit lake water quality closure tool for Hazelwood brown coal mine, Victoria, Australia

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Abstract

The ENGIE Hazelwood Coal Mine (HCM) was one of the world's most significant brown coal deposits, located near Morwell in the Latrobe Valley, Victoria, Australia. The mining and power generation operations ceased in March 2017 and the site is currently in a closure and rehabilitation work phase, after over 50 years of mining. ENGIE considers closure of the open pit as a pit lake the most feasible option for rehabilitation. It is envisaged that the pit lake and nearby surrounds would have the potential for recreational, agricultural, commercial and industrial uses following relinquishment.

The pit lake water balance and water quality (WB/WQ) was identified as a critical area requiring further study. To address this a WB/WQ model (tool) for the final void at HCM was developed using the mass balance approach with GoldSim software and the Contaminant Transport (CT) module. To provide input to the model, several supplementary hydrogeochemical assessments were undertaken, including wall washing experiments and kinetic leach testing. The key objectives of the model for the HCM pit lake includes: i) prediction of the pit lake water quality for a through-flow and terminal sink at closure and modelling of how the water quality will evolve into the future; ii) modelling the demand for water to fill and maintain the pit lake during and beyond closure; and, iii) assessment of how climate change and climate variability are likely to affect the water balance and water quality of the pit lake using deterministic and stochastic (probabilistic) climate sequences. This paper describes the detailed preliminary WB/WQ modelling undertaken to support initial closure planning for HCM.

Keywords: *mine closure, mine rehabilitation, pit lake, numerical modelling, GoldSim, Hazelwood Coal Mine*

1 Introduction

ENGIE considers closure of the Hazelwood Coal Mine (HCM) open pit as a pit lake the most feasible option for rehabilitation to address (amongst other reasons): i) the geotechnical stability of the pit that has been identified as the key closure risk due to its close proximity to the Princes Highway and the town of Morwell, and, ii) the risk of fire which would be mitigated by saturating a large portion of remaining coalface. It is envisaged that the pit lake and nearby surrounds would have the potential for recreational, agricultural, commercial and industrial uses following relinquishment.

The pit consists of a number of in-pit overburden dumps which are strategically placed and shaped to improve long-term geotechnical stability of the mine floor and pit walls, six sediment ponds and the Hazelwood Ash Retention Area (HARA) (i.e. coal ash storage facility) which would all become submerged as the pit lake forms providing an additional chemical load to the pit lake together with the exposed coal on the pit walls and floor and surface water/groundwater quality inputs.

The objective of the Rehabilitation and Closure Plan (RCP) is to achieve a safe, stable, sustainable and non-polluting landform. ENGIE sought to manage the risks of achieving these closure objectives for the pit lake through the implementation of three defined stages: Stage 1 – Fill commencement; Stage 2 – Fill completion; and, Stage 3 – Aftercare and relinquishment.

Ultimately ENGIE proposed to deliver:

- A landform that can sustain/support post-relinquishment end land uses.

- The final landform of a full water body (Reduced Level [RL] +45 m Australian Height Datum [AHD]) to maximise long-term ground stability, minimise fire risk and provide for optimal beneficial future uses for the site.

- The final landform that will require minimal long-term maintenance of water levels in the water body to ensure ongoing ground stability and management of fire risk.

The closure strategy for the HCM pit lake (at the time of modelling) is to operate as a terminal sink (i.e. outflows only occur as evaporation). In reality, the HCM pit lake systems could operate as a flow-through system, terminal sink or oscillate between the two.

This paper describes how a water balance and water quality (WB/WQ) model for the final void at HCM was developed to consider several different closure scenarios, including (amongst others): different external fill sources and fill rates, capping versus non-capping of the HARA and flow-through versus terminal sink system.

2   Methodology

2.1   Key mine domains

There are seven closure domains within the HCM RCP. A list of the domains is provided in Table 1.

Domain 1 (pit lake), Domain 2 (pit batters and mine floor), Domain 3 (external overburden dumps), Domain 4 (ash & asbestos landfills), Domain 5 (watercourse diversion structures) and Domain 7 (remaining land and conservation areas) have the potential to influence the water quality of the pit lake. Within the RCP domains there are subdomains which may be a potential source of contamination and contribute seepage and/or runoff to the final void and pit lake and are referred to as the geochemistry domains (Table 1). Each of these domains are built into the WB/WQ model.

Table 1   Rehabilitation and Closure Plan (RCP) domains and geochemistry subdomains

RCP domain	RCP domain description	Geochemistry subdomains
1	Pit lake	Inclusive of the open pit (mined void), two in-pit overburden dumps and HARA
2	Pit batters and mine floor	Including the pit wall (coal and overburden) and floor materials
3	External overburden dumps	Includes the external overburden dumps including overburden, spoil mounds and screening dumps
4	Ash and asbestos landfills	Includes the out-of-pit coal ash landfill sites (HAP1, HAP2, HAP3 and HAP4) and asbestos dumps (Nos. 1–3)
5	Watercourse diversion structures	Eel Hole Creek Diversion, Morwell River Diversion and Morwell Main Drain
6	Infrastructure	NA
7	Remaining land/conservation areas	Natural and rehabilitated land

2.2 Supportive field and laboratory investigations

A high-level review of relevant available reports and data pertaining to the geochemistry of HCM site and the pit WB/WQ was undertaken. Several key geochemical data gaps were identified that were needed to develop a WB/WQ model. Subsequently several field sampling and analysis investigation were undertaken to fill these data gaps.

The objective of the field investigations was to characterise the geochemical properties of materials that may affect water quality in the proposed pit lake; therefore, the focus was on in-pit backfilled overburden, ash (HARA) and pit wall and floor materials, as these materials may contribute to the potential for acid to alkaline pH water that may also have the potential to be accompanied by saline and metalliferous drainage.

More than 1,000 grab and drillholes samples were collected over several programs and represented fresh and oxidised coal (of varying ages), overburden and coal ash. These samples were subjected to a series of geochemical screening tests and based on the results, select samples (233) underwent more comprehensive static geochemical testing. A total of 20 composite samples were utilised for large 6–15 kg kinetic leach column (KLC) tests, that were operated under free leaching unsaturated ('wet-dry') and saturated conditions. The primary objectives of the KLC test program were to quantify the concentration and rate at which weathering products (acid, soluble salts and metal(loids)) are leached from the solid phase materials (coal ash, coal and overburden) over time. The KLC teste were operated for up to 133 weeks.

Other supporting filed investigations included permeability testing (double ring infiltrometer) and wall wash experiments. Wall washing allows for evaluation of runoff quality from an isolated section of in situ overburden/coal after application of a controlled amount of irrigation (Figure 1). The wall washing test is considered to represent a very useful order-of-magnitude estimate of contributions from exposed open pit walls (International Network on Acid Prevention 2009). The results from wall washing were used together with other information to develop source terms for pit wall contaminant release.

Figure 1   Wall washing experiments within the HCM pit, by RGS Environmental Consultants Pty Ltd

2.3 Conceptual model

The water quality of a pit lake is a result of many factors including but not limited to geology and minerology of the host formations, surface water and groundwater quality entering the pit void, concentrating effects of

evaporation, geochemical, biological, and limnological processes with the water body and anthropogenic impacts. The key water quality inputs to the pit lake water quality at HCM are summarised in Figure 2.

The hydrology of a pit lake affects the water quality of the pit lake by changing the chemical mass balance associated with the pit lake. General statements regarding the impacts of hydrological processes on water quality can be made:

- Groundwater inflows carry dissolved constituents at background concentrations into the pit lake. Natural, upgradient groundwater will have a certain water quality and will contribute to the pit lake. Inflowing groundwater can also pick-up constituents from weathered coal immediately surrounding the pit water body or from recharging meteoric water passing through the dewatered zone. However, the coal itself is considered an aquitard and therefore porewater within the coal is not expected to be very mobile.

- Surface water runoff from pit walls (coal and overburden) may transport constituents and sediments that will affect the chemistry of the pit lake.

- Out-of-pit overburden dump seepage and runoff may carry dissolved constituents into the pit lake.

- Direct precipitation generally is a diluting factor on pit lake water quality.

- Since evaporation removes water and leaves behind any dissolved constituents evaporation tends to have a concentrating effect on pit lake water quality (i.e. evapo-concentration).

- Groundwater and surface water outflows from pit lakes typically have the effect of removing constituents from the pit lake. However, if the pit lake is stratified, these outflows may remove water of different quality, which may result in either improved or reduced water quality in the pit lake.

- Depending on the water quality of the external water sources used to fill and top-up the pit lake, these may result in either improved or reduced water quality in the pit lake.
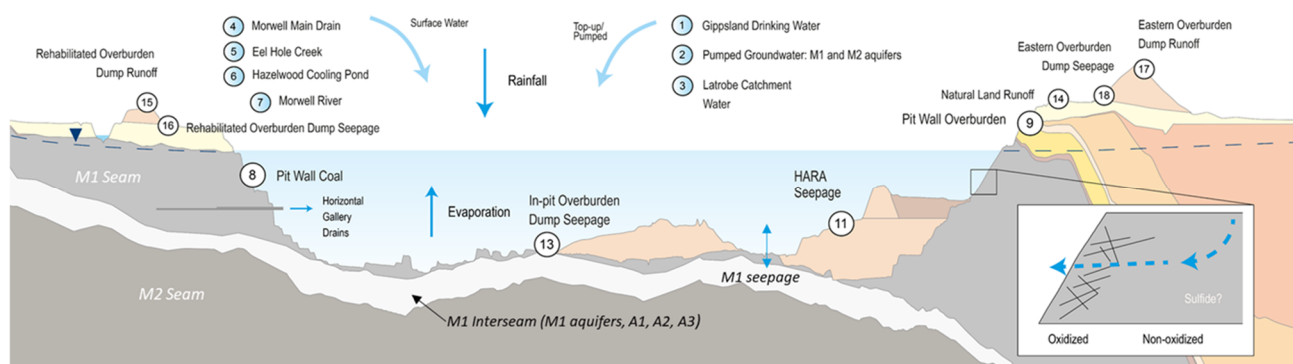

Figure 2   Conceptual hydrogeochemical model of Hazelwood Coal Mine pit lake (full lake)

2.4   Model development

The numerical model, including the water balance and water quality components, has been developed using GoldSim software (GoldSim Technology Group). The model has been developed as a decision support tool for assessing closure options. For this reason, it has been developed with flexibility to allow the user to run a series of different 'what-if' scenarios and sensitivity analyses, by varying different inputs and model switches. The model has been developed on a daily time-step, to run for periods of up to 200 years. The general model development is expressed visually in Figure 3.
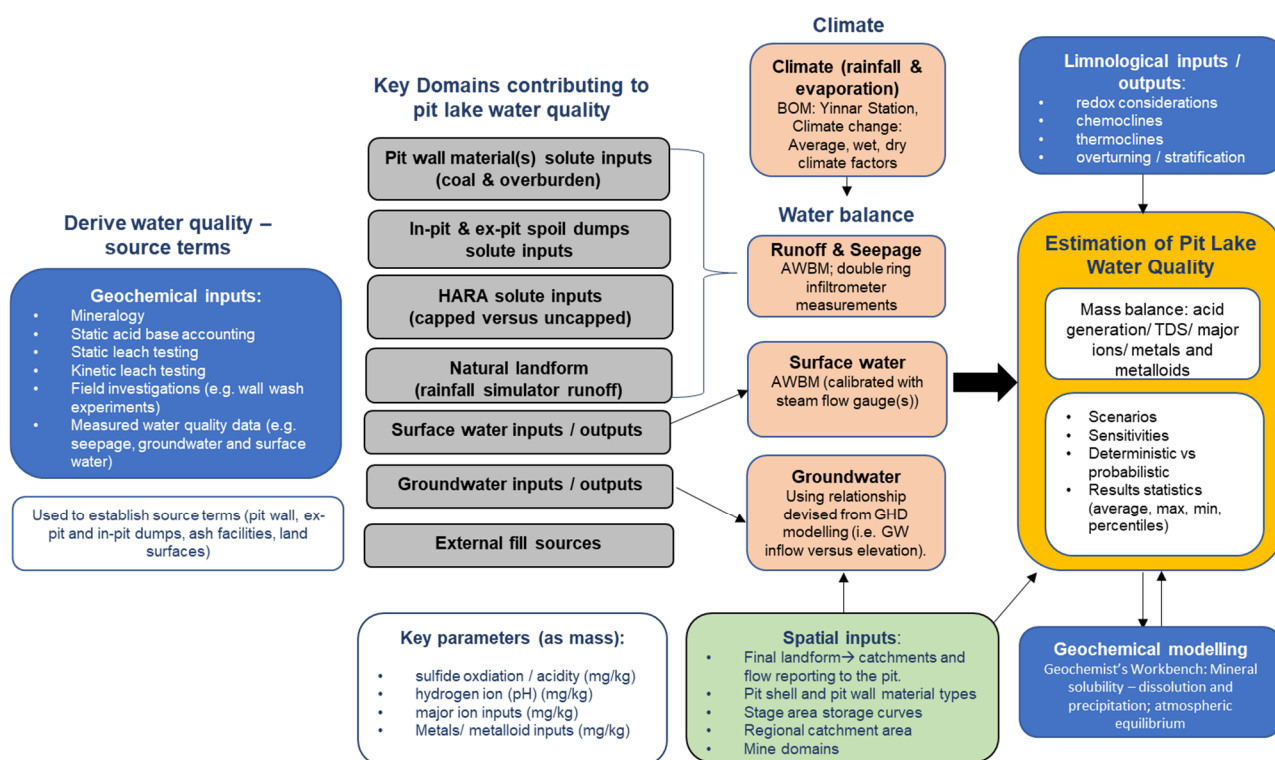
Figure 3   Hazelwood Coal Mine pit lake water balance/water quality model development

2.4.1   Modelling scenarios

ENGIE proposes to rehabilitate the decommissioned HCM final void into a full pit lake (RL +45 m AHD), although a partial pit lake scenario (RL -7 m AHD) was also modelled. After the fill phase is completed, the pit lake level will be maintained at +45 m RL, in perpetuity, by topping-up with external water sources (refer to Table 2).

Several iterations of modelling have been undertaken from 2019 to 2021, with a total of 33 model simulations. Only the simulations from 'Stage 4' are discussed in this paper (Table 2). The modelling includes three key pit fill scenarios (i.e. medium, high and low fill rate) assuming the mined pit void is a terminal sink and using average geochemistry source term inputs (i.e. the model has the ability to also model P95 source terms). A key assumption for the three fill scenarios is that the HARA will be uncovered; however, for the median fill rate (median climate), an additional sensitivity simulation was created to simulate the HARA covered with a cap (i.e. Run 3). Climate sensitivities were modelled for median, dry and wet scenarios using probabilistic (stochastic) simulations. The fill approach is undertaken as a seamless fill whereby the pit lake is filled to an RL of +45 m AHD without pause; therefore, requiring no top-up during the fill phase. After the pit is filled, the top-up water quality is pumped M2 aquifer groundwater for each of the scenarios and simulations (when required).

Table 2   Modelling scenarios and sensitivities

Pit fill sources (external)	Scenario	Climate change	Pit isolated/connected to Morwell River	HARA covered/uncovered
25 GL/year of Moondarra Reservoir water (Gippsland Water), 17 GL/year of M2 groundwater and 1 GL/year of M1 groundwater	Run 1	Dry	Isolated	Uncovered
	Run 2	Median	Isolated	Uncovered
	Run 3	Median	Isolated	Covered
	Run 4	Wet	Isolated	Uncovered
42 GL/year of Moondarra Reservoir water (Gippsland Water), 17 GL/year of M2 groundwater and 1 GL/year of M1 groundwater	Run 5	Median	Isolated	Uncovered
	Run 6	Wet	Isolated	Uncovered
14 GL/year of Moondarra Reservoir water (Gippsland Water), 17 GL/year of M2 groundwater and 1 GL/year of M1 groundwater	Run 7	Dry	Isolated	Uncovered
	Run 8	Median	Isolated	Uncovered

2.4.2   Climate inputs

The climate simulated in the numerical model includes rainfall, evaporation and evapo-transpiration. The base climate for the model is derived from the Bureau of Meteorology (BoM) Yinnar station 85100. Scientific Information for Land Owners (SILO) Patched Point Data (PPD) was obtained for the Yinnar station, which has infilled any gaps in the data. The SILO data available for the Yinnar station included daily historic rainfall, evaporation and evapo-transpiration data.

The approach to generating climate datasets for the modelling is to use the complete available SILO climate record (for Yinnar station 85100). This is approximately 131 years of record. From this historical climate sequence, the 'base climate sequence' was developed by stacking 131 years of record. In the next step, three deterministic climate change scenarios (dry, median and wet) were generated by applying climate factors from the Victorian Guidelines (Victorian State Government and the Department of Environment, Land, Water and Planning 2016), to the base sequence. From these three deterministic sequences, three different stochastic (probabilistic) sequences, of 200 years in length were generated using the eWater Stochastic Climate Library Software (SCL) for use in the GoldSim model. For each probabilistic climate sequence, 200 stochastic climate sequences or replicates were generated. The approach is summarised in Table 3. Sensitivity analysis of the climate approach was undertaken in GoldSim.

Table 3   Approach to generating climate datasets for modelling

Base climate	Climate change scenarios (Deterministic)	Climate change scenarios (Probabilistic)
Base climate. Yinnar station 85100 (SILO data); use all available years of SILO climate data (i.e. 1889–2019 (inclusive))	**Dry** 200-year sequence developed through 'stacking' 131 years of record. Dry climate factors applied to base climate sequence. **Median** 200-year sequence developed through 'stacking' 131 years of record. Median climate factors applied to base climate sequence. **Wet** 200-year sequence developed through 'stacking' 131 years of record. Wet climate factors applied to base climate sequence.	**Dry** 200 realisations (sequences) generated based on the statistics of base sequence with dry climate factors applied after probabilistic sequences generation. **Median** 200 realisations (sequences) generated based on the statistics of base sequence with median climate factors applied after probabilistic sequences generation. **Wet** 200 realisations (sequences) generated based on the statistics of base sequence with wet climate factors applied after probabilistic sequences generation.

2.4.3   Final landform

The final landform surfaces for the site and surrounding catchment were used in Deswik to produce a range of input data to the GoldSim numerical model, including: pit physical characteristics, stage area storage curves and catchment areas.

2.4.3.1   Pit physical characteristics

Details of each pit void geometry input which is incorporated in the model, and their application in the water balance is provided in Table 4. Each of these geometries was extracted from the final landform surface in Deswik, at 1 m intervals.

Table 4   Geometry data and application to water balance

No.	Geometry dataset	Application in water balance
1	Storage volume versus water surface area curve	Relates the pit water volume to the pit water surface area at each time-step. Used to calculate evaporation volume loss from and direct rainfall volume into the pit lake.
2	Elevation versus volume curve	Relates the pit water volume to the pit water surface elevation at each time-step. Essentially a lookup table which returns the volume for a given elevation. Used to calculate the pit water elevation at each time-step as the pit fills.
3	Volume versus elevation curve	Same as the Elevation volume curve but simply in the opposite order. As such, it provides a lookup table to return pit water surface elevation for a given water volume.
4	Elevation versus pit wall area (overburden) curve	Relates the pit elevation to the pit wall surface area at each time-step. This dataset considers the pit wall surface area which is overburden material only. Used to calculate the loading rates coming from the exposed pit wall (overburden) surface area during rain events.
5	Elevation versus pit wall area (coal) curve	Relates the pit elevation to the pit wall surface area at each time-step. This dataset is similar to no. 4 but considers the coal pit wall surface area only.
6	In-pit water elevation versus exposed overburden volume curve	Relates the pit water elevation to the exposed overburden volume at each time-step. Used to calculate the submerged overburden volume at each time-step.
7	In-pit water elevation versus exposed overburden area curve	Relates the pit water elevation to the exposed overburden area at each time-step. Also used to calculate the submerged overburden area at each time-step and then used to calculate the contributing surface water runoff from the exposed overburden and subsequently attribute exposed geochemistry source terms to this contributing inflow.
8	HARA elevation versus exposed area curve	Relates the pit water elevation to the exposed HARA area at each time-step. This is also used to calculate the submerged HARA overburden area at each time-step and then used to calculate the contributing surface water runoff from the exposed HARA and subsequently attribute exposed geochemistry source terms to this contributing inflow.
9	HARA elevation versus exposed volume curve	Relates the pit water elevation to the exposed HARA volume at each time-step. Also used to calculate the submerged HARA overburden area at each time-step.

2.4.3.2   Catchments

The final landform surface was used to delineate the total external and local catchment area draining to the pit. These catchment delineations were undertaken using Deswik.CAD.

Figure 4a shows the catchment boundaries for the isolated scenario. Figure 4b shows the catchment boundaries for a connected scenario (i.e. connected to Morwell River) which is not included as part of this assessment but demonstrates the small catchment size of the pit relative to external catchments.
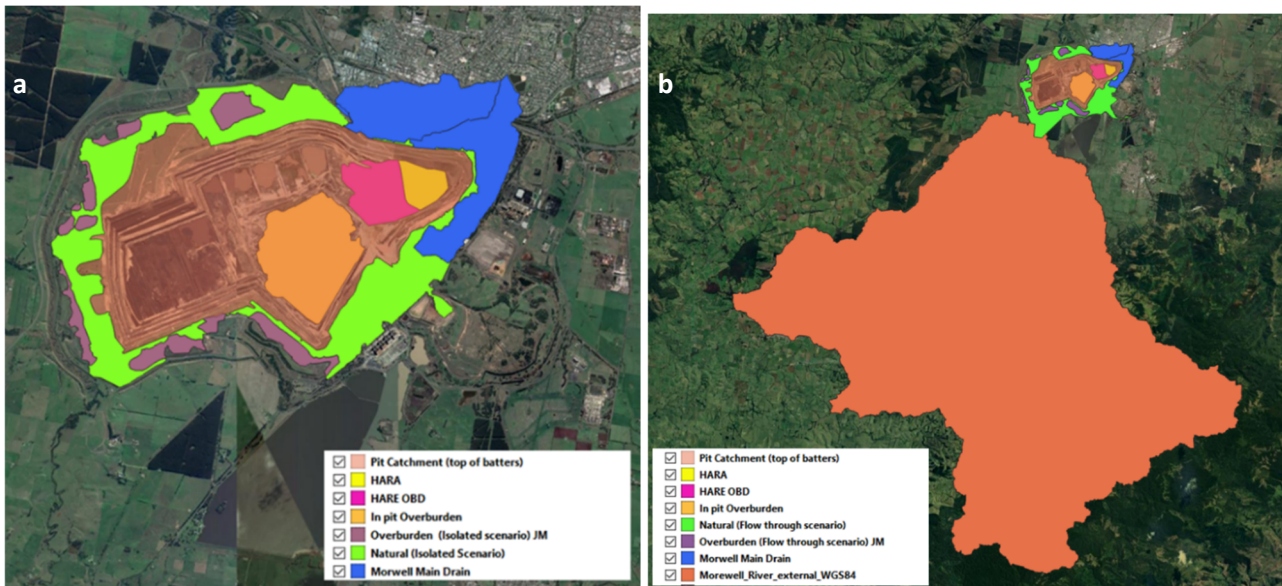
Figure 4   Hazelwood Coal Mine sub catchment boundaries draining to the pit: (a) Morwell River isolated; (b) Morwell River connected

2.4.4   Water balance

2.4.4.1   Surface water

After closure, there will be various potential surface water inflows to the pit void 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), as well as external catchments which may contribute flow into the pit lake for potential future scenarios. The key surface water flows incorporated in the model are:

- Local rainfall and runoff:
  - Runoff from pit walls.
  - Runoff and seepage from the in-pit overburden dumps.
  - Runoff and seepage from the out-of-pit overburden dumps.
  - Runoff from the HARE OBD and Groyne areas.
  - Runoff and seepage from the HARA.
  - Direct rainfall onto the pit water body surface.
  - Local runoff from the catchment within the mining lease (various land use types).
- External runoff:
  - External Morwell River upstream catchment. This may potentially contribute flow to the pit in a flow-through scenario.
  - Morwell main drain. This may potentially contribute flow to the pit in a flow-through scenario.

All surface water inflows to the pit and their hydrological response were simulated within the GoldSim model itself, using the Australian Water Balance Model (AWBM) as a module.

The AWBM module was calibrated to observed streamflow data for the Morwell River at Yinnar gauge – BoM ID 226210. In the calibration, SILO rainfall and potential evapo-transpiration data from the nearby Yinnar

rainfall gauge (BoM ID 85100) was used. The model was calibrated within GoldSim using the available data from 1951 to 1960. An optimisation algorithm was used to maximise the Nash Sutcliffe efficiency index (as the objective function). The Nash Sutcliffe efficiency (NSE) index is used to measure fit of hydrology models, with an NSE of 0.65 or greater considered to be good fit. The calibration achieved a Nash Sutcliffe efficiency of 0.71.

Figure 5 presents the observed flow timeseries plotted against the calibrated simulated flow timeseries. The figure shows that the calibration achieved a very good fit between the observed and modelled streamflow data. Generally, the AWBM model captured both the baseflow and the peaks quite well.
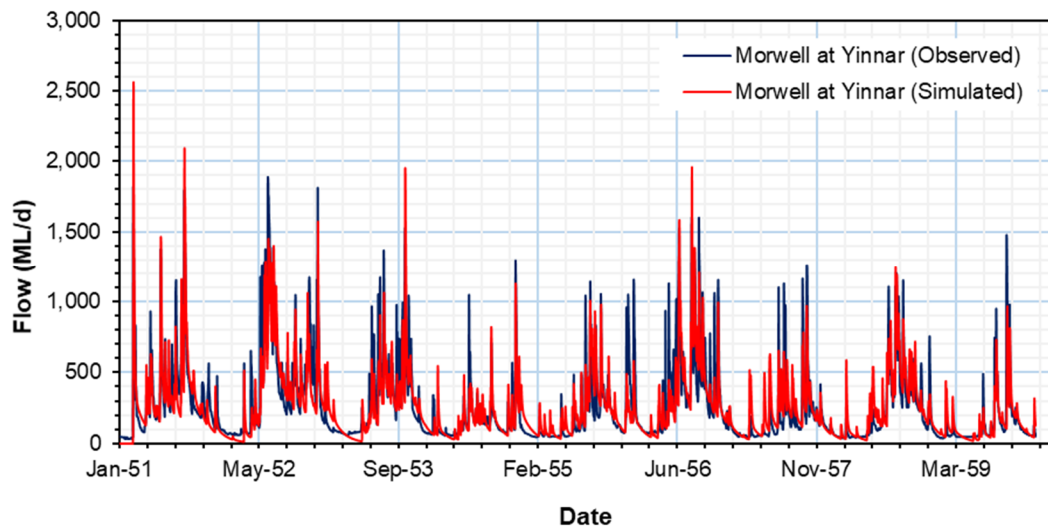

Figure 5   Observed versus simulated streamflow data for Morwell and Yinnar

2.4.4.2   Groundwater

Groundwater inflow rates into the pit were provided as time series groundwater fluxes (these were generated in a groundwater model constructed by others) under a certain set of hydrodynamic boundary conditions, including complete refill of the pit water body level to +45 m RL.

Analysis of the original groundwater fluxes suggested the following:

1. Groundwater fluxes have only a minor contribution to the total pit inflow rates. The groundwater fluxes contribute only approximately 1.5% of all combined inflows into the pit (i.e. 27 GL out of 1841 GL).

2. The majority of the groundwater inflow comes from a single aquifer, the Haunted Hills Formation (HHF) aquifer, contributing 93% of the total groundwater inflow.

3. The dynamics of the groundwater inflow suggest that it mostly depends on the relationship between pit lake level and the surrounding groundwater level.

In the absence of the updated groundwater fluxes at the time of GoldSim simulation work, the decision was made to simulate groundwater inflows were simulated based on the linear relationship between pit water level and groundwater inflow rates. Figure 6 presents the relationship between groundwater inflow rates and pit lake level.
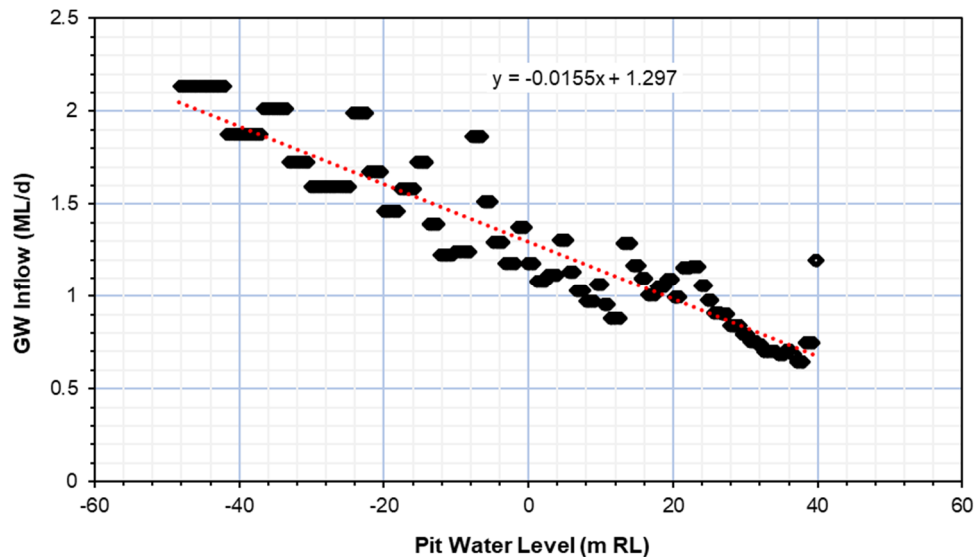
The chart shows the equation: $y = -0.0155x + 1.297$

Figure 6 Hazelwood Coal Mine pit lake groundwater flux (ML/day) versus pit lake water level

2.4.5 Water quality inputs

The model has the capacity to simulate 32 chemical species. The general approach to simulating water quality within the model for each scenario includes:

- Determination of the exposed/saturated pit wall (coal and overburden), HARA, in-pit overburden dump and water volumes in each (daily) time-step of the simulation.

- Addition of dissolved loads added to the system through groundwater inflows, surface water runoff, pit wall reactions (runoff) and HARA/in-pit overburden dump reactions.

- Mixing of loads and volumes to determine mass balance concentrations.

- Calculation of water losses via evaporation, groundwater and other losses with distributed dissolved mass loss; subsequent mass additions and water balance considerations.

- Recalculation of mine pit lake quality progressively (daily) over the duration of model simulation.

- Selectively apply geochemical controls (e.g. mineral solubility, atmospheric equilibrium) in PHREEQC (Parkhurst & Appello 1995) and/or Geochemist's Workbench (GWB) 'React' module (Bethke & Yeakel 2009).

The geochemical inputs (source terms) have been generated from a combination of inferred, assumed and measured data. Surface water and groundwater quality source terms were developed from historical site monitoring data; average and 95th percentile values of water quality data were applied to the model. The source terms for the pit walls, HARA and in-pit overburden dump were inferred using results of laboratory KLC testing.

The geochemical solute release rates (loading rates) have been calculated by interpretation of leachate water quality from the KLC tests and the volume of representative materials within the columns and converting the time lapse data into release rates (mg/kg/time). Additional factors are considered in these calculations, such as 'flushing'.

For the pit wall materials, scaling factors are applied to the calculated loading rates to scale the laboratory derived release rates to field conditions at HCM (Table 5). The scaling factors account for (amongst other things): particle size effects, water-rock contact and oxygen availability (e.g. saturated versus unsaturated) and are consistent with reported values elsewhere (Kempton 2012; Linklater et al. 2017).

Table 5   Scaling factors applied to laboratory derived loading rates

Pit wall type	Density (kg/m³)	Infiltration depth (m)	Surface area correction	Oxygen availability	Fraction flushed
Pit wall coal exposed	1100	0.015	0.2	1	0.6
Pit wall coal saturated	1100	0.005	0.2	0.1	1
Pit wall overburden exposed	1500	0.01	0.2	1	0.3
Pit wall overburden saturated	1500	0.005	0.2	0.1	1

2.4.5.1   *Pit wall solute reservoir*

Distribution of pit wall materials (coal and overburden) were derived from the mining pit shell and geological information. To reflect the interaction of the pit wall materials with rainfall and runoff, the model implements specific logic around the release of solutes from the pit wall to the pit lake. The general logic is as follows:

- The daily loading rate is accumulated in a 'reservoir' for each time-step where no rain occurs.

- The daily loading rate is linked to the pit wall surface area for a material type that is either exposed or inundated by the pit lake.

- When there is a rainy day of greater than 10 mm/day, the cumulated solute mass within the reservoir is released to the pit lake on that day.

- If there is a dry day (i.e. rainfall less than 10 mm/day) following the rain day, then the accumulation starts again.

If there are subsequent rain days (i.e. greater than 10 mm/day) after an accumulated mass is released from the reservoir, then the loading rate keeps releasing a daily load.

3   Results and conclusions

The key results and conclusions from the water balance are summarised in Table 6 and in the following points:

- The modelling showed that the pit filled to +45 m AHD within 10.1 to 20.6 years with the mean values being 10.5 to 19.9 years, depending on which fill rate scenario was modelled and climate variability/uncertainty. The range of uncertainty in the fill times for each of the scenarios was between 0.7 to 1.1 year(s).

- The climate change sensitivity analysis showed that the pit fill time frames were not overly sensitive to climate (dry, median and wet), and this is due to the fact that during the pit fill period, the local rainfall and runoff (which are climate dependent) are relatively small inflows in comparison to the external fill sources (which are not climate dependent) (Table 6).

- The modelling showed that the probability of top-up for each of the different fill rates should essentially be the same.

- The requirement for the top-up occurs when the evaporation from the pit lake surface exceeds the pit inflow volumes. When that occurs, the annual top-up (for such year) varies between a maximum of approximately 9.4 and 16.5 GL. In some cases, mostly during the dry climate scenarios, the requirement for top-up may occur up to >185 times over the 200-year simulation period.

Table 6   Summary of water balance results

Run	Climate	Years to fill pit to +45 m Australian Height Datum (AHD) (Mean)	Date pit fill to +45 m AHD (Mean)	Probability top-up required	Max. top-up required (per year) (GL)	No of years when top-up required (in 200 years)
Run 1	Dry	14.8	Oct-35	Most years	16.5	>185
Run 2	Median	14.7	Sep-35	> 90% of time	10.3	>180
Run 4	Wet	14.6	Jul-35	>80% of time	9.4	>160
Run 5	Median	10.5	Jul-31	> 90% of time	10.5	>180
Run 6	Wet	10.5	Jun-31	>80% of time	9.6	>160
Run 7	Dry	19.9	Nov-40	Most years	16.5	>185
Run 8	Median	19.5	Jun-40	> 90% of time	10.2	>180

The key results and conclusions from the water quality modelling are summarised in the following points.

- The results for each of the modelling scenarios and sensitivities indicate that pH is slightly alkaline to neutral over the simulation period with a mass balance pH range of ~8 to 9 (mean probability climate). Atmospheric equilibration resulted in minor adjustments of the pH to ~8.2 to 8.5 for a particular scenario.

- The total dissolved solids (TDS) ranged from around 740 to 1,380 mg/L (mean probability) at the end of the 200-year assessment period. There is a gradual increase in TDS with time due to evapo-concentration.

- The general water quality concentration trends vary slightly for different modelled species and reflect the water balance inputs; however, there are generally three specific phases where the pit water quality evolves from the sector pond water quality to the fill water quality and then post fill which generally shows a steady increase in concentration of solutes over the simulation period reflecting the combined effects of evaporation (i.e. evapo-concentration), rainfall water quality (precipitation) and local catchment runoff water quality. In reality, bio-geochemical processes (e.g.-nutrient cycle, carbon cycling, etc.) would be expected to supress increasing concentrations and some form of equilibrium would eventually be attained (e.g. Figure 7).

- The water qualities for each of the scenarios and sensitivities for all fill rates are dominated by the major ions (namely Cl and Na), with metals and metalloid concentrations relatively low in comparison.

- The modelled mass balance results for Al, Cd, Cr, Cu, Ni, Pb and Zn concentrations are slightly elevated when compared to Water Quality Australia (2018) (freshwater ecosystem; 90% species protection) (Table 7); however, the geochemical modelling indicated that Al and Fe are most likely to precipitate out of the water body as Al and Fe (oxy)hydroxides (e.g. goethite, hematite and gibbsite) and thus significantly reduce their concentrations in the pit lake. Similarly, some metal(loid)s would likely co-precipitate with the Al and Fe (oxy)hydroxides or adsorb to the surface of these minerals also reducing their concentrations in the pit lake.

- Atmospheric equilibration and consideration of thermodynamic constraints on the water quality through geochemical modelling typically had very little effect on the mass balance results (excluding Al and Fe) due to the generally low concentration of salts and metal(loid)s in the pit lake.

- Based on the modelling assumptions, the results indicate that the HARA cap has little effect on the overall pit water quality for all metals/metalloids; this reflects the fact that the HARA only contributes between ~0.002 to 0.6% to the overall pit water balance over the 200-year simulation period.
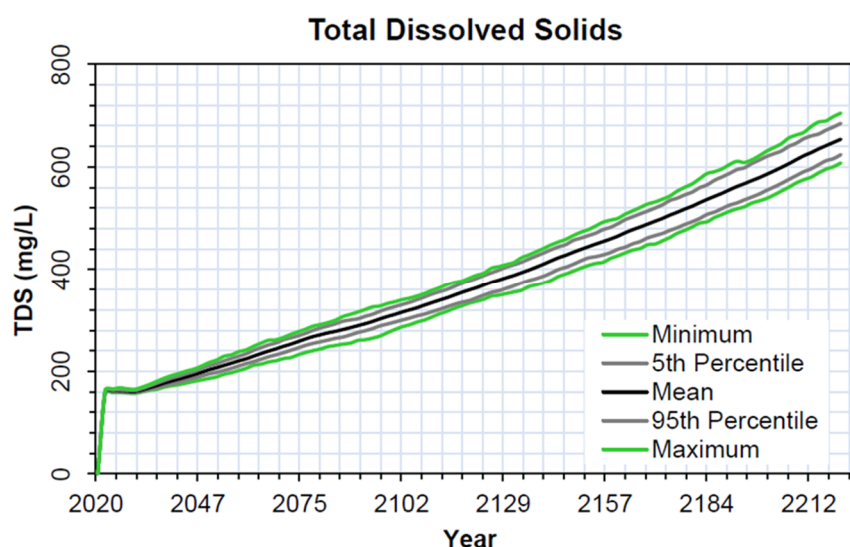
Figure 7   Modelling results for total dissolved solids for Run 6 (wet climate)

Table 7   Model predicted (indicated) water qualities for select parameters

Chemical parameter	Max/min	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
Aluminium (mg/L)	Min	2	4.25	4.3	4.77	4.21	4.74	2.96	6.47
	Max	2.49	5.02	5.08	5.56	4.97	5.51	3.72	7.58
Cadmium (mg/L)	Min	0.0004	0.0003	0.0003	0.0003	0.0003	0.0003	0.0004	0.0003
	Max	0.0004	0.0003	0.0003	0.0003	0.0003	0.0003	0.0004	0.0003
Chromium (mg/L)	Min	0.006	0.008	0.008	0.008	0.008	0.008	0.007	0.011
	Max	0.006	0.009	0.009	0.009	0.009	0.009	0.008	0.012
Copper (mg/L)	Min	0.1	0.13	0.13	0.13	0.13	0.13	0.1	0.13
	Max	0.1	0.14	0.14	0.14	0.14	0.14	0.1	0.14
Lead (mg/L)	Min	0.0153	0.0106	0.0107	0.0096	0.0102	0.0092	0.0162	0.0119
	Max	0.0159	0.0115	0.0115	0.0104	0.011	0.01	0.0167	0.0127
Nickel (mg/L)	Min	0.026	0.017	0.017	0.015	0.016	0.014	0.027	0.018
	Max	0.027	0.019	0.019	0.017	0.018	0.016	0.028	0.02
Zinc (mg/L)	Min	0.16	0.17	0.17	0.17	0.16	0.16	0.18	0.2
	Max	0.17	0.18	0.18	0.18	0.17	0.17	0.19	0.21

Note: highlighted cells reflect those modelled values that exceed the Australian and New Zealand Guidelines for fresh and marine water quality guidelines – freshwater ecosystem (90% species protection) (Water Quality Australia 2018). Modelled values below Water Quality Australia (2018) are not displayed in the table.

Acknowledgement

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