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# Closure concepts for sustainable groundwater management: A case study

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## Abstract

*To meet the growing technical demand of regulators and independent panels, enhanced engineering and scientific assessment are required to demonstrate the feasibility and environmental sustainability of mine closure concepts. This case study supports the development of viable mine closure concepts for groundwater management for an operational underground resource project in New South Wales, Australia.*

*In this study, the establishment of differential groundwater repressurisation is designed to address the concerns of regulator and independent technical panels, that post-closure mine water outflow may discharge at uncontrolled locations, triggering land instability along an extensive ~300 m high escarpment. An innovative rationale was adopted to enable sustainable post-closure inflow and outflow management, with enhanced environmental outcomes, namely achieving groundwater repressurisation in sought-after locations limiting impacts on slope stability and providing long-term passive outflow management. The concept design considered the existing and future mine layout, groundwater behaviour, geomechanics and downstream water management infrastructure as an integrated system. A three-dimensional numerical groundwater model was used to validate technical feasibility, supported by engineering first principles, industry standards and relevant case studies from other operations.*

*The configuration of groundwater recharge and outflow management were assessed under the following categories 1) the viability, location and impacts of bulkheads (mine seals) and their effects to the groundwater system; 2) post-closure groundwater system recovery and quantification of mine water outflow; and 3) long-term water quality and management.*

*Contrary to typical rationales, the objective of the design was not to completely seal or prohibit outflow of water from the mine, but to control groundwater recovery and subsequent outflow through the natural permeability of the surrounding strata, directing it to a controlled location. Similarly, rather than adopting bulkheads (seals) near or at mine portals, modulation bulkheads were devised deep within the workings to achieve target groundwater recovery in desired locations, but also limit recovery in areas of historical adjacent mining. The methodical placement of bulkheads in the groundwater model determined a means to reduce the risk of groundwater repressurisation interacting with anthropogenic and environmental flow pathways.*

*The integrated system was modelled to predict future outflow rates and volumes, calibrated by contemporary in-situ testing and monitoring. Predicted outflow metrics were incorporated with long-term water quality observations to develop a series of viable post-closure passive and active treatment options, to be further evaluated closer to closure. This case study demonstrates the benefits of effective collaboration between hydrogeologists, geotechnical engineers, hydrologists and water quality specialists in the identification of post-closure risks and the development of sustainable groundwater management solutions.*

**Keywords:** *mine seals, bulkheads, inflow, outflow, post-closure, groundwater recovery, differential repressurisation, water quality, risk management*

# 1 Introduction

This objective of this study was to address concerns raised by regulators, an independent technical advisory and independent planning commission regarding the closure considerations for current and future mining operations. The key groundwater related mine closure considerations raised included the viability, location and impacts of mine closure bulkheads and their effects to the groundwater system; groundwater system recovery; management of mine water outflow; and long-term water quality and management.

The study addressed key considerations under the following framework: determine post-closure water management objectives; characterise groundwater behaviour; develop a Basis of Design, develop design concepts; assess and validate through numerical modelling.

# 2 Study area

The operational underground resource project is located within the New South Wales (NSW) Southern Coalfield (Figure 1), operating a number of underground mining domains, with a capacity of around 5 million tonnes per annum.

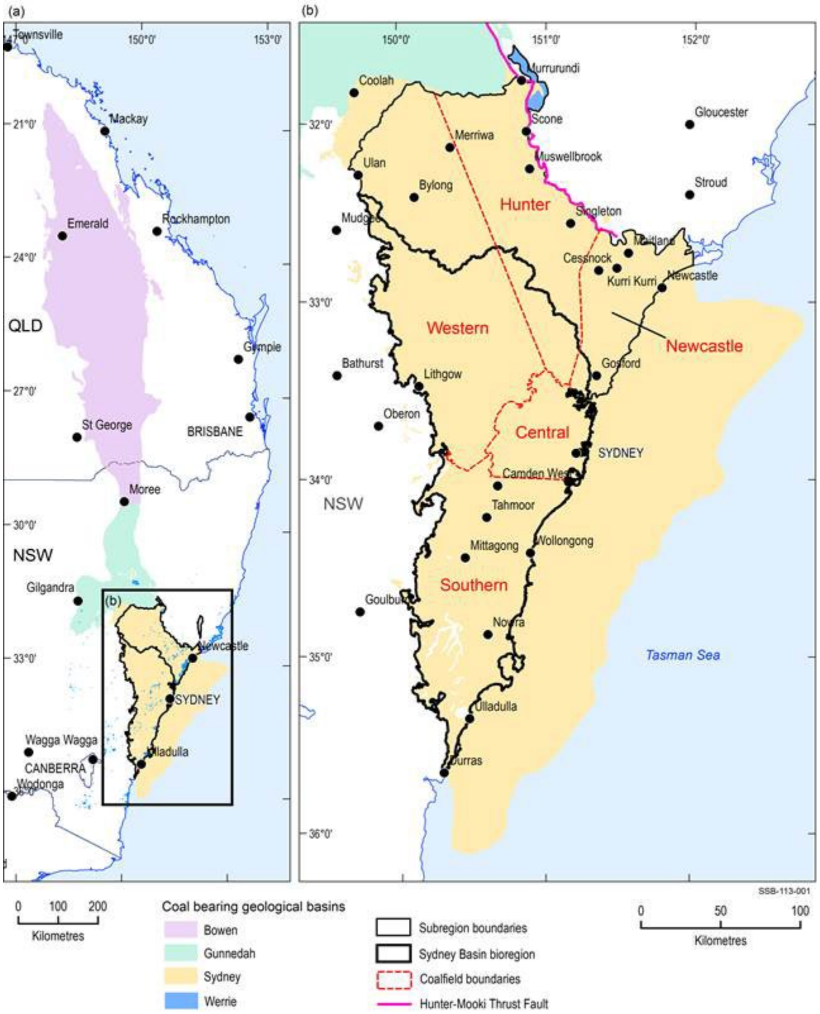


**Figure 1** **Study area location in the Southern Coalfield (after DoE et al. 2022)**

For the purpose of this paper, the site can be characterised by two principal mine areas: 1) the Outer Mine Area, representing completed resource extraction in close proximity to the mine portals at the Illawarra Escarpment and 2) the Inner Mine Area, which is represented by both completed domains and current extraction areas inland of the escarpment (Figure 2). The outer and inner mining areas are approximately 2 km apart, connected by the main gate (i.e. principal central heading comprising roadways and conveyor).

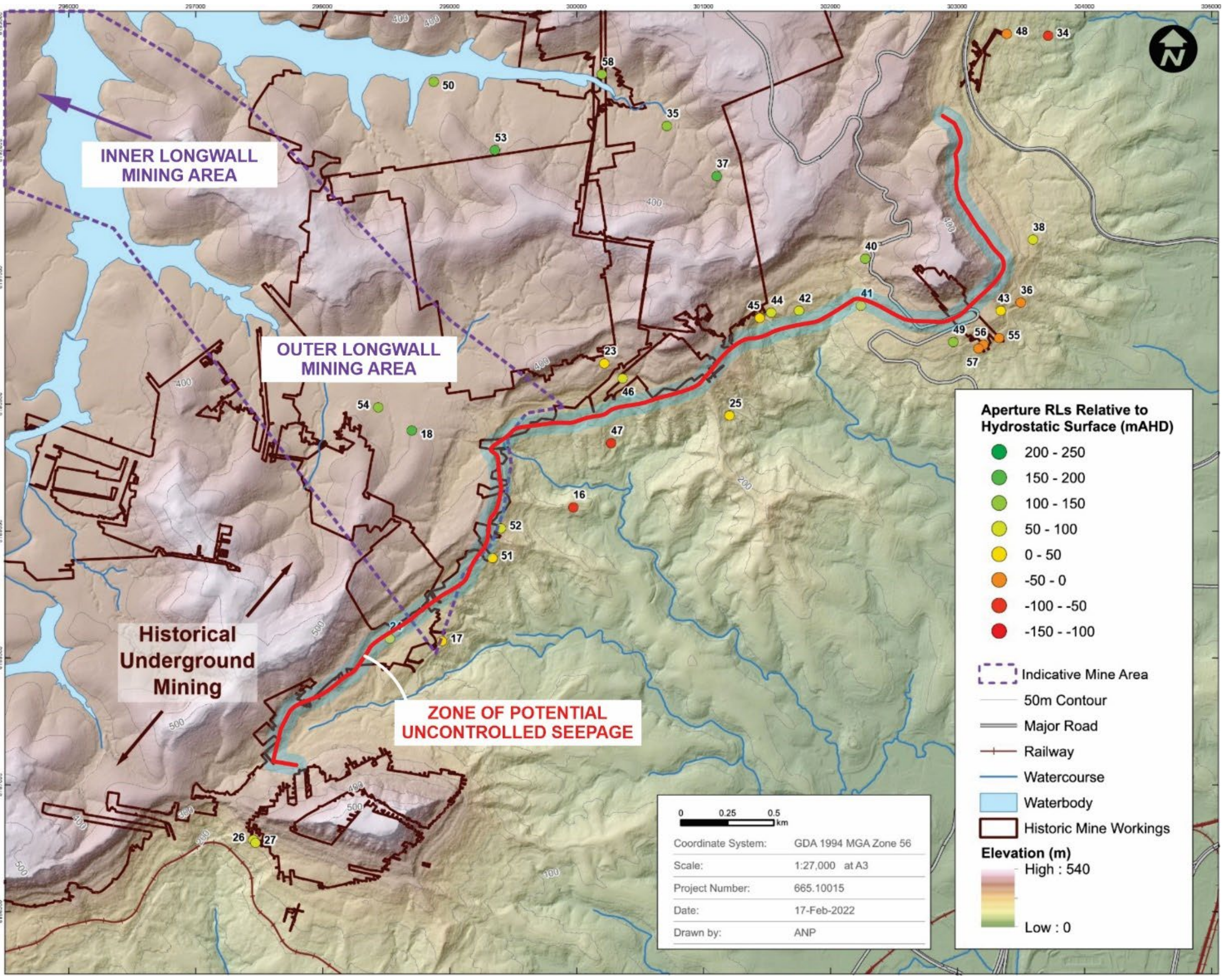


**Figure 2 Site overview**

There are a number of potential hydraulic connections to the mining domains and target seam via the main gate, in the form of primary active access, including the Personnel and Materials Drift, Conveyor Drift and Vent Shafts. The primary access Personnel and Materials Drift Portal is located near the crest of the Illawarra Escarpment (Young, 1979) at RL 203 metres. Product is output via a Conveyor Drift, which intersects the Personnel and Materials drift ~900 metres inbye (i.e. from the portal toward the resource) of the Personnel and Materials Drift Portal; and daylights 1.7 km to the northeast at RL 120 metres. There are also extensive historic mine workings in other seams (some over 100 years old) laterally and vertically adjacent to the operational mine workings, including first workings and board and pillar (Figure 2). The RLs of potential hydraulic connections (e.g. including historic portals, drifts and shafts) relative to the modelled hydrostatic surface are also shown in Figure 2.

## 2.1 Existing mine water management

The current operation manages groundwater inflows in the order of 8-10 Megalitres per day (ML/day), with an array of real-time flow meters utilised to determine the volume of water being pumped around the underground operations. Measured groundwater inflow is highly variable and correlates to heavy rainfall events. This climate-inflow relationship has been considered in managing groundwater post-closure.

Existing water management infrastructure is located at the Conveyor Drift Portal, with water excess to operational requirements discharged via pipeline to a Licenced Discharge Point upstream of the local harbour, with an average discharge at of around 6.5 ML/day with a peak of around 9.2 ML/day.

# 3 Mine closure – Water management objectives

As an input to the framework for the development of detailed closure and rehabilitation plans for specific areas, the key water management objectives of the study were:

- Develop a rationale for the application of underground water management structures, to:
  - Re-pressurise groundwater inbye of the Outer Mine Area.
  - Limit groundwater repressurisation outbye of the Inner Mine Area, to limit connectivity and seepage from current mine working into the overlying historic mine workings, including legacy shafts and portals, that may cause uncontrolled seepage at the Illawarra Escarpment, which is a potential trigger for landslides in the steep colluvial terrain.
  - Direct mine water outflows to controlled locations where practical.
- Safely prohibit public access to the mine workings consistent with relevant Standards and Policies.
- Consider appropriate options to manage mine water outflow, including potential surface water quality impacts such as those associated with the potential re-emergence of baseflow through shallow fracture networks, or the upward flux of coal measure affected water to surface water features.
- Assess the ability to measure, manage and mitigate water quality impacts long-term; and facilitate ongoing monitoring, review, and management of deep groundwater levels.

# 4 Groundwater management – Basis of design

To achieve the mine closure water management objectives in Section 3¸ the application of groundwater management structures was considered. Whilst often referred to as seals, the term bulkhead is adopted herein to capture a wider range of applications and functions that are dependent on a number of intrinsic and extrinsic considerations (presented in Section 4.1). This section describes the key design rationale and assumptions considered for the different types, function, application, and location of bulkheads in the conceptual closure configuration specific to the project site. These key assumptions were numerically modelled to assess their impact on groundwater behaviour at closure (Minchin, 2022).

## 4.1 Bulkhead applications

Underground mine bulkheads are routinely required and applied for many operational and closure purposes, including (but not limited to):

- Prohibiting mine portal access at closure (i.e. safety) – typically low hydrostatic pressure
- Drift backfill at closure (i.e. supporting overlaying strata) – low to medium hydrostatic pressure
- Management of seepage, the need to impound water – med-high hydrostatic pressure
- Management of groundwater in-rush (e.g. mining below water bodies) – high hydrostatic pressure
- Groundwater recharge and attenuation of outflow (BLM, 2006; Younger et al., 2002; Walton-Day et al. 2021) – high hydrostatic pressure
- General underground fluid management (e.g. groundwater make and ventilation stoppings) – variable high hydrostatic pressures
- Management of explosion potential – high pressure

- Emplacement of mine waste (tailings) pumped underground to backfill old workings and roadways - typically low to medium hydrostatic pressure

Examples of bulkhead construction for groundwater outflow control include: Dinero Mine (Walton-Day et al. 2021) United States of America (USA), final mine sealing at Tasman Colliery NSW, Baal Bone NSW, Wambo Underground NSW, Ulan Mine NSW and Kandos NSW.

## 4.2 Bulkhead design

Typically, the design of bulkheads in underground coal mining operations in Australia is derived from the principles of water retention bulkheads that are intended to provide an active barrier between impounded water and active mine workings (Mutton & Remennikov, 2011). A structural bulkhead is an engineered concrete structure extending from floor to ceiling in a mine void (e.g. roadway) with enough thickness to withstand the lithostatic overburden pressure of overlying rocks, hydrostatic groundwater pressure and additional pressure that could occur (e.g. an explosion or during an in-rush, when impounded water in an upgradient part of the mine is abruptly released).

Whilst underground bulkheads in Australia do not have their own design standard, the structural design of underground bulkheads is typically undertaken with reference to Australian Standards (AS) 1170 Structural Design Actions (2007) and AS3600 Concrete Structures (2018), structural design actions and empirical relationships with lab and field testing and/or engineering first principles.

Design guidelines for the construction of bulkheads in coal mines were introduced in the United States in IC 9506 (Harteis, 2008). Previously the United States Bureau of Mines (USBM) had published IC9020 'Design of Bulkheads for Controlling Water in Underground Mines' (Chekan, 1985) that presented three methods for designing bulkheads to impound water underground.

Under the IC9506 guidelines (Harteis, 2008) the amount of fluid pressure that a bulkhead must resist is equal to the static pressure applied by the column of fluid being restrained by the structure. The bulkhead design must consider all sources of fluid that could increase the pressure on the structure and design for the maximum anticipated fluid level. The selected bulkhead construction material must also be compatible with the fluid impounded.

### *4.2.1 Bulkhead type*

Mutton & Remennikov (2011) provide a review of types of bulkheads and plugs typically used in underground coal mine applications. Most bulkheads constructed in mines fall into two categories which can collectively be described as barriers (Figure 3):

- Slabs or plate bulkheads, have a length or thickness (along the drive axis) less than their height and strength is limited by flexure for thinner structure and shear resistance along the drive wall. Most Australian bulkhead designs in coal mines are in this category; or

- Plugs, whose lengths are greater than the roadway dimensions and are limited by shear resistance at the strata contact. Globally the primary bulkhead designs for underground coal mines are tapered plugs, parallel plugs and notched slabs, that can withstand high hydrostatic pressures (Garrett & Campbell, 1958).

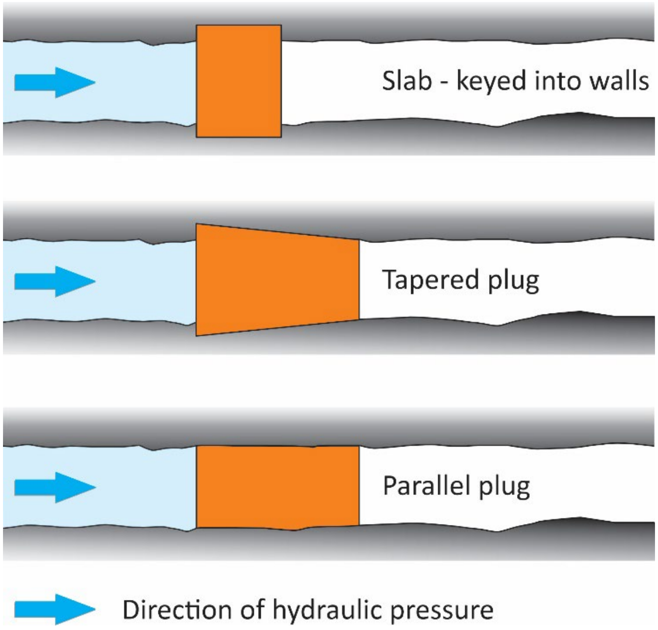


**Figure 3 Basic design of bulkheads in underground coal mines (after Harteis & Dolinar 2006)**

## 4.3 Portal and shaft closure bulkheads

The NSW Trade and Investment Mine Safety Operations Regulator provides guidelines for final drift sealing in Mine Design Guideline (MDG) 6001 – Guidelines for Permanent Capping and sealing of Entries to Coal Seams (2012); which forms the basis of the bulkhead configurations considered.

The key design requirements within the guidelines are summarised below:

- A bulkhead should be constructed at a point in the drift which has at least 15 m of solid rock strata cover over the roof of the drift;
- The design of the bulkhead should take into account any possible fretting of the drift perimeter, and where there is a possibility of fretting of the strata surrounding the bulkhead, the bulkhead design should include provision for strata reinforcement to prevent any reduction of the strength of the bulkhead;
- The inbye bulkhead may be designed to permit the passage of water but must prevent the flow of any gas from the workings;
- Where the bulkhead is designed for water passage, the fill material outbye of the bulkhead should be unaffected by water, to prevent it from becoming fluid or capable of flowing when wet;
- Any man-made structures or fittings in the drift which can be safely removed, should be removed;
- The void from the inbye bulkhead to the drift entrance should be carefully and uniformly filled (to achieve 15 m of cover). Particular attention should be paid to completely filling the drift profile; and
- The fill material should be such that it will maintain its integrity over time.

## 4.4 Construction materials

Due to the requirement for high strength materials in bulkhead construction, steel reinforced concrete is typically utilised, with strengths of 20 to 40 Megapascals (MPa) adopted. Where larger void spaces such as drifts and shafts are required to be filled as part of mine closure objectives, expansive materials (i.e. using less input volume) can be sought, where lower strengths are acceptable. Alternative materials in these applications include:

- Foamed Cement - a stable mixed mass of bulk emplaced Cellcrete Foamed Cement Slurry, which primarily utilises Portland cement and a “foam” (or surfactant) to expand the raw volume. It can also contain coarse and fine fly-ash, fine aggregate, superplasticiser, polypropylene fibres, and accelerator.
- Combination Grouting - the injection of a hydro active Polyurethane Resin (PUR) mixed with a micro fine cement. The benefit of this technique is the very high expansion factor (V), when compared to cement (0V) and foamed cement (3V), a typical expansion factor for a specialist void fill PUR is 20V (i.e. 1 cubic metre ($m^3$) will expand to 20 $m^3$). The combination of the cement/water and PUR keeps the thermal reaction low whilst creating a medium compressive strength flexural material.

Additional high strength and low permeability products (coatings) can be applied to reduce the permeability of bulkhead fascias; however, the function of such products is inadvertently questioned in this case study.

#### *4.4.1 Bulkhead permeability*

Although bulkheads can be designed and constructed to physically limit gross-flow, this study considers that they should not be considered impermeable (Gusek & Figueroa, 2009). Whilst the seal materials themselves can be almost impermeable (e.g. specialist coatings), their confining strata are not. When impounding water, the hydrostatic head is able to pass through the surrounding strata or along the strata/bulkhead interface, i.e. through the floor, rib and roof structures (e.g. bedding and cleats in coal), which the author has observed first hand. As such, for the purpose of this study, the numerical groundwater modelling (Minchin, 2022) assumed that the permeability of the bulkheads is the same as their surrounding strata (i.e. the pillars of target seam, roof and floor). In this case the highest permeability unit was 1E-7 to 5E-6 metres per second (m/s) or 1E-2 to 4E-1 metres per day [m/d], (based on 12 packer tests).

### 4.5 Bulkhead configuration

Based on assessment of hydrogeological cross-sections derived from the geological model and the groundwater model, it was determined that the Mine Closure Water Management Objectives could be achieved through the considered location and function of bulkheads, relevant to key geometrical features of the target seam and historical mine workings. A basis of design summary is presented in Table 1.

Table 1 Bulkhead - basis of design summary

| Water Management Objectives | Bulkhead – Type | Basis of Design | Groundwater Model Assumption |
|---|---|---|---|
| Re-pressurise groundwater inbye of the Outer Mine Area.<br>Limit groundwater re-pressurisation outbye of the Inner Mine Area, to limit connectivity and seepage into overlying historic mine workings, including legacy shafts and portals, that may cause uncontrolled seepage at the Illawarra Escarpment. | ***Primary Modulation Bulkheads***<br>To be installed in mains between Outer Mine Area and Inner Mine Area, enabling impounding of mine water west of the Outer Mine Area.<br>Modulated seepage outbye of Primary Modulation Bulkhead(s) to gravity outflow at the Conveyor Drift Portal | Requires a structural bulkhead in each main gate roadway (x 3), that can withstand =/> 100 m hydrostatic head pressure (e.g. tapered plug design) | Model assumes permeability of bulkhead is the same as surrounding seam, i.e. 1E-7 to 5E-6 m/s (1E-2 to 4E-1 m/d) in nearby Inner Mine Area.<br>Gross seepage of Inner Mine Area restricted to permeability of seam and surrounding lithology. |
| Direct mine water outflows to controlled locations. | ***Secondary Bulkheads***<br>To be installed in Personnel and Materials Drift, inbye ~900 m of Portal, enabling modulated seepage from Primary Modulation Bulkheads to be directed to the Conveyor Drift, outflowing at the Conveyor Drift Portal. | Requires a structural bulkhead that can withstand =/> 30 m hydrostatic head pressure.<br>Option to install additional partial bulkheads inbye of Personnel and Materials Drift/Outer Mine Area mains intersection to provide further outflow attenuation if required. | Assumes modulated seepage of groundwater into Outer Mine Area mains.<br>Outer Mine Area unable to repressurise, avoiding 'spill over' into overlying workings due to gravity outflow at Conveyor Drift Portal |
| Safely prohibit public access to the mine workings consistent with relevant Standards and Policies | ***Portal & Drift Closure Bulkheads***<br>To be installed at Personnel and Materials Drift portal and Conveyor Drift Portal. | Required structural bulkheads in accordance with MDG6001.<br>Bulkhead to incorporate drainage culverts to permit outflow | Not in groundwater model, but groundwater and hydrological model output to be used to determine culvert sizing. |

### *4.5.1 Primary modulation bulkheads*

To address the required repressurisation of groundwater within the Inner Mine Area, high-strength plug style Primary Modulation Bulkheads were modelled in the main gate, enabling impounding of mine water inbye of the Outer Mine Area. The connecting main gate area serves as a pinch-point within the mine workings to enable control of the gross-outflow of water from the Inner Mine Area to the Outer Mine Area.

Figure 4 presents the potentiometric surface in the target seam immediately post mining in 2039, and in 2200, 140 years post-closure. Depressurisation in the target seam is consistent with operational mine dewatering, while repressurisation in the Inner Mine Area is attenuated by the Primary Modulation Bulkheads with continued drawdown into the Outer Mine Area and toward the escarpment post mine closure.

As the groundwater model assumes the permeability of the Primary Modulation Bulkheads are equivalent to the surrounding strata and target seam, the groundwater seepage around the bulkhead into the Outer Mine Area is considered ‘modulated’ – depending on hydrostatic head. The resultant modulated groundwater seepage then flows through Outer Mine Area mains and is directed by Secondary Bulkheads to gravity outflow at the lower Conveyor Drift Portal.

The Primary Modulation Bulkhead also acts to limit groundwater re-pressurisation within the Outer Mine Area and toward the escarpment. A key consideration is to limit seepage into the historical board and pillar mine workings above eastern parts of the Outer Mine Area, which includes legacy shafts and portals with potential connectivity to the escarpment.

### *4.5.2 Avoiding connectivity with historical workings*

The goafing impact (mine induced impact on overlying strata) at the Outer Mine Area has likely resulted in hydraulic connection between the target seam and the historic overlying workings (where they coincide). A GIS based three-dimensional geometrical assessment of seam morphology in relation to the RL(m) of historic connections (e.g. shafts and portal) indicated that if the Outer Mine Area were to re-pressurise, there is potential to cause ‘spill over’ into the historical workings above the target seam at around RL 200 m. As such, maintaining de-pressurisation within Outer Mine Area (to approximately RL 180 m, coinciding with the spill point elevation for the Conveyor Drift Portal) allows for greater control of groundwater seepage and outflow. It also reduces the risk of repressurisation into overlying historic workings and mitigates against potential uncontrolled outflows at the Illawarra Escarpment.

### *4.5.3 Secondary bulkheads*

Secondary slab style concrete bulkheads are considered to prohibit the Outer Mine Area seepage outflow into the altitudinally higher Personnel and Materials Drift, directing the flow to lower Conveyor Drift Portal (Figure 5). Lastly, basic mass poured concrete Portal and Drift Closure Bulkheads are considered to be free draining, with the installation of culverts, but safely prohibit public access to the mine workings consistent with relevant Safety Standards and Policies. The Portal and Drift Closure Bulkheads are not considered in the groundwater model.

A conceptual cross-section and plan of the conceptual bulkhead configuration are presented in Figure 4 and Figure 5.

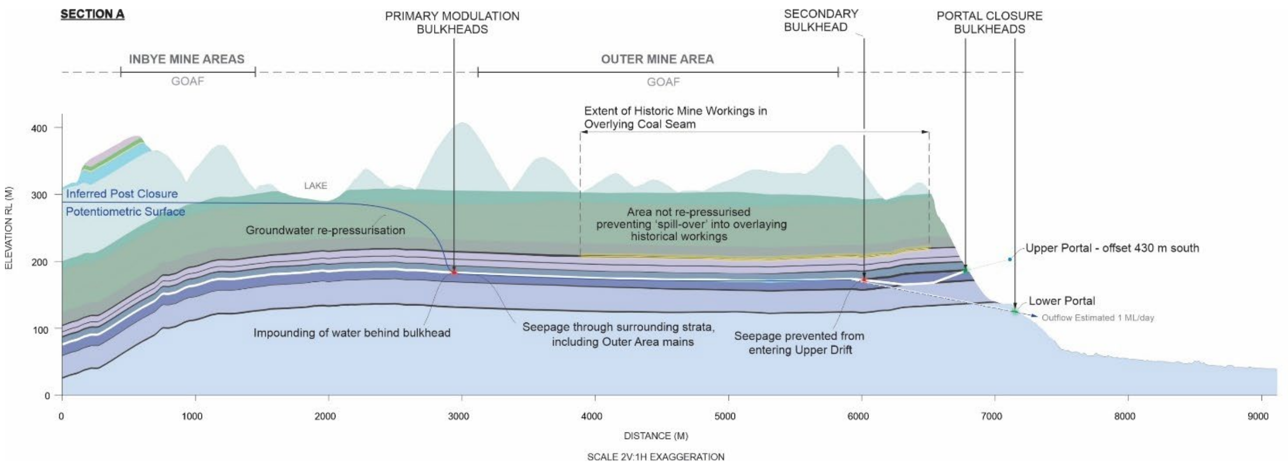


Figure 4 Conceptual bulkhead locations in critical cross-section

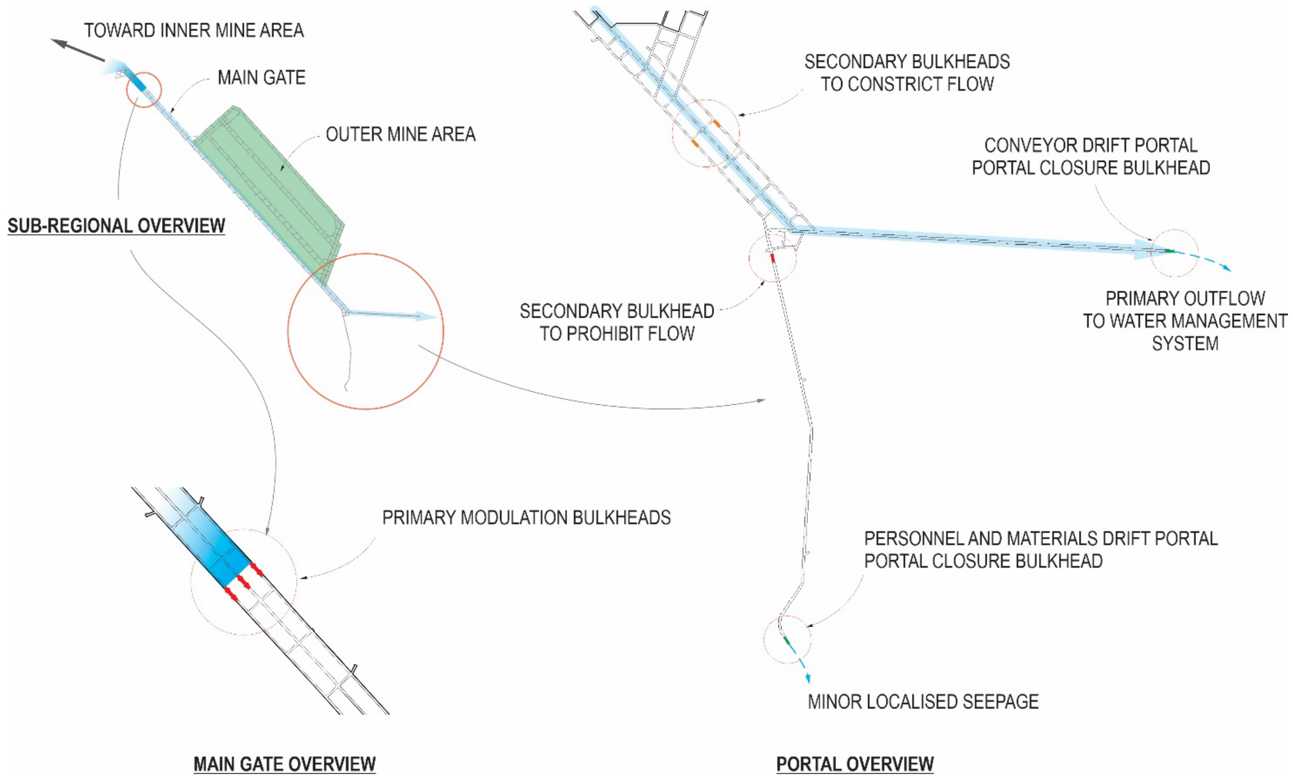


Figure 5 Conceptual bulkhead locations and function

# 5 Key groundwater metrics

Section 5 provides a description of how the proposed closure plan concepts and bulkhead configuration have been incorporated into the modelling, including:

- The level of groundwater recovery in within the target seam
- Predicted attenuated outflow rates at the Conveyor Drift Portal

## 5.1 Groundwater recovery

Results from numerical modelling (Minchin, 2022) indicate groundwater level recovery above the Outer Mine Area west of the flow modulation bulkheads can occur within approximately 60 years post-closure, while the Outer Mine Area remains depressurised as groundwater is allowed to discharge at the Conveyor Drift Portal.

Figure 6 shows the cross-sectional output from the numerical model, presenting a comparison of the target seam groundwater levels immediately post-closure (2039) and 140 years post-closure (2200) shows that the seam is depressurised during operations due to active dewatering, but recovers inbye of the flow modulation bulkhead.

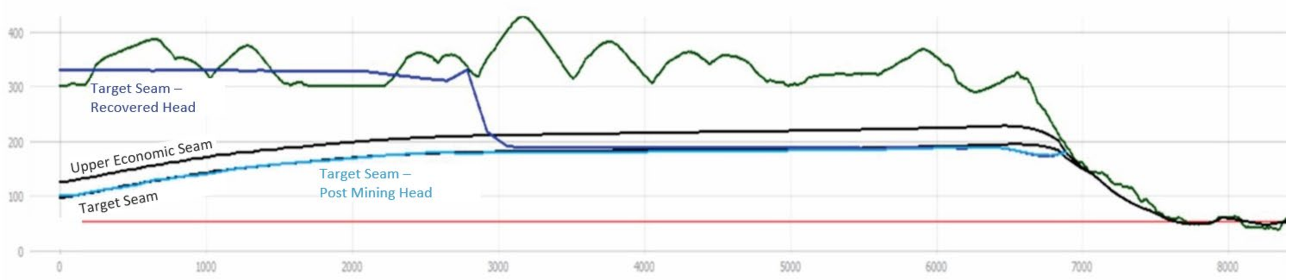


**Figure 6 Modelled post-closure (2039) and recovered (2200) groundwater level in the target seam**

## 5.2 Portal discharge

The numerical modelling indicates that once workings in Inner Mine Area flood and water levels recover to above the elevation of the bulkheads, then the volume of discharge would increase over time, reaching approximately 1.1 ML/day (range 0.9-1.3 ML/day) at the Conveyor Drift Portal (Figure 7).

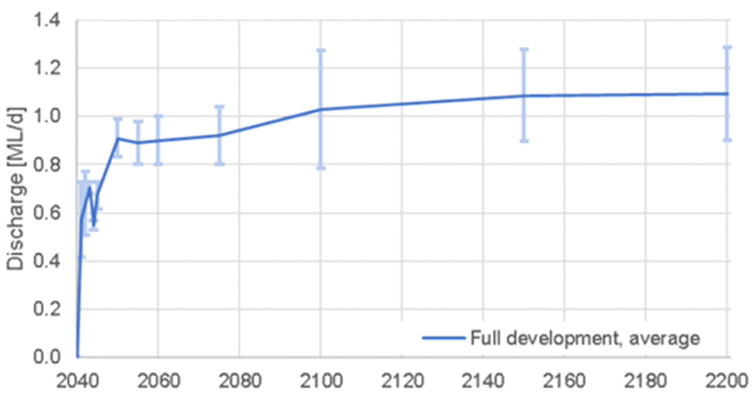


**Figure 7 Modelled discharge at the conveyor drift portal (from Minchin, 2022)**

# 6 Outflow management

Following recovery of the groundwater system and control of outflow to a dedicated location, the feasibility of long-term seepage management was considered for the Conveyor Drift Portal post-closure. Four concepts for seepage management were determined feasible, including passive and active treatment solutions, taking into account the steep terrain, existing infrastructure, hydraulic constraints, proximity to industry, labour availability and the hydraulic limitations of an existing mine water discharge pipeline.

An engineering review evaluated factors such as current and anticipated discharge rates, typical groundwater quality, discharge infrastructure, treatment methods, pipeline dimensions and construction type, grade changes to the discharge point, flow rate capacity and the receiving environment of the discharged water.

The groundwater model (Minchin 2022) estimated average daily seepage volume post-mining in the order of 1.1 ML/day (13 litres per second [L/s]), with peak rates of 1.3 ML/day (15 L/s) during wet weather conditions.

Groundwater quality characterisation was performed and the water quality of the current mine water discharge and groundwater in the Outer Mine Area goaf were utilised as proxies for estimating the seepage water quality at closure. It was anticipated that concentrations of various analytes might decrease over time, necessitating ongoing assessments leading up to mine closure.

The analysis indicated that the discharges can be classified as relatively benign groundwater with a slight salinity and slightly elevated concentrations of certain metals. By reconciling the water quality summary with the Australia and New Zealand Environment Conservation Council (ANZECC) default guideline values at 99% and 80% levels of species protection for both inland and tidal estuary waters, it was determined that based on the available data, post-closure groundwater discharge would likely be suitable for discharge to disturbed estuarine environments without treatment, or to inland waters with some treatment to remove or dilute salts to an acceptable level. Table 2 outlines the management options currently under consideration for post-closure groundwater discharge.

**Table 2 Water management options summary**

| No. | Option description | Treatment options | Type | Comments |
|---|---|---|---|---|
| 1 | Continued discharge at licence discharge point or other agreed estuarine location. | No treatment required if discharge under licensing regime and licence limits continues or if agreed by stakeholders. | Active/Passive | Requires Government stakeholder agreement. |
| 2 | Conveyance of untreated groundwater to local port for a beneficial reuse by a third Party (e.g. Hydrogen or Power Plant). | Utilise existing surface infrastructure, including mine water discharge pipeline.<br>Pipeline could be extended to the local port and continue to operate under gravity. | Active/Passive | Requires Government stakeholder and third-party agreement |
| 3 | Treatment at site and discharge to local waterway | Electrocoagulation<br>Lime precipitation + Manganese greensands filter<br>Membrane technology<br>Dilution shandying with recycled or harvested water to achieve acceptable water quality prior to discharge. | Active | Requires Government stakeholder agreement on water quality criteria and ongoing management and monitoring of treatment measures at site. |
| | | Constructed anaerobic wetlands | Passive | |
| 4 | Treatment and use at site and/or conveyance via existing pipeline to a third party for reuse. | Electrocoagulation<br>Lime precipitation + Manganese greensands filter<br>Membrane technology<br>Constructed anaerobic wetlands | Active | |

| No. | Option description | Treatment options | Type | Comments |
|---|---|---|---|---|
| | | Dilution shandying with recycled or harvested water to achieve acceptable water quality prior to discharge. | | Requires Government and third-party stakeholder agreement on water quality criteria and ongoing management and monitoring of treatment measures at site. |

Several feasible options for water management were identified, each offering varying degrees of benefit to the community, industry and the environment. Further discussions with government agencies and private stakeholders are planned to determine preferred options and guide future investigations.

Option 1 was considered the base case option for the project, as it represents a continuation of the currently approved excess mine water management system, involving licensed discharge to a tidal environment.

# 7 Conclusion

This paper presents a case study that focuses on developing viable groundwater management closure concepts for an operational underground resource project in New South Wales. The study employs an innovative rationale to achieve sustainable post-closure inflow/outflow management with enhanced environmental outcomes. By integrating considerations of mine layout, groundwater behaviour, geomechanics and downstream water management infrastructure, the concept design aims to control groundwater recovery and outflow rather than completely sealing or preventing water outflow from the mine. This is achieved by strategically placing bulkheads deep within the roadways connecting mined workings, allowing targeted groundwater recovery in desired locations while minimising recovery in areas of historical mining to reduce the risk of inadvertent groundwater repressurisation. The approach addresses concerns from regulators and stakeholders regarding uncontrolled outflows that could potentially cause land instability. The feasibility of the closure concept is assessed through a three-dimensional numerical model that predicts outflow rates and volumes, which are then combined with long-term water quality observations to develop a range of post-closure passive and active treatment water management options. The interdisciplinary collaboration between hydrogeologists, geotechnical engineers, hydrologists and water quality specialists is highlighted as a crucial aspect of this study, emphasising the importance of such approaches in addressing complex groundwater management challenges in mine closure planning and execution.

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