

Optimising revegetation for mine closure: initial learnings from a multi-faceted approach to minimise net percolation using native vegetation

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Abstract

Acid mobilisation due to net percolation (NP) through overburden storage areas poses a significant water quality risk at closed mine sites. Our research program aims to optimise cover system performance to minimise NP and associated acid mine drainage (AMD) risk at BHP's Mt Whaleback operation in Western Australia. Recognising vegetation as crucial for reducing NP, the Revegetated Cover System Program (RCSP) investigates vegetation–substrate interactions to inform and guide closure commitments.

The RCSP encompasses five tasks:

- 1. controlled NP experiment (small-scale)*
- 2. controlled species assemblage, transpiration, and NP experiment (small-scale)*
- 3. large-scale revegetated cover system trial*
- 4. mature rehabilitation physiological monitoring*
- 5. natural analogue physiological monitoring.*

This paper presents initial findings from a multi-year research program investigating the role of revegetation in minimising NP and mitigating ARD risk at BHP's Whaleback operation. The program aims to optimise cover system performance by quantifying plant water use and its influence on NP under various scenarios. Initial results from controlled experiments demonstrate the importance of substrate properties and irrigation regimes on soil moisture dynamics and NP. Analyses from the first year of the large-scale revegetated cover system trial, including lysimeter and plot-based measurements, will be presented. These data will provide insights into vegetation establishment, growth rates, and early indications of plant water use. Preliminary findings from physiological monitoring of mature rehabilitation and natural analogue sites will also be discussed.

This research program is crucial for developing science-based solutions to achieve vegetation communities that are comparable to natural analogues and that provide fit-for-purpose function. By integrating these findings into cover system design and management practices, BHP aims to significantly reduce AMD risk and contribute to long-term environmental sustainability.

Keywords: *ecosystem restoration, acceptable risk and failure modes, closure objectives*

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1 Introduction

Globally, the mining industry confronts the enduring environmental challenge of acid and metalliferous drainage (AMD), arising from the oxidation of sulphide minerals exposed during mining activities. The percolation of water through mine waste materials and cover systems facilitates this process, leading to the mobilisation of acidity and heavy metals, which can detrimentally impact surrounding ecosystems. Consequently, the development of effective and sustainable mine closure strategies focused on minimising AMD generation is crucial for responsible resource management and environmental stewardship.

Cover systems are engineered barriers critical for minimising water infiltration into mine waste materials and overburden storage areas, thereby reducing the generation of AMD. A key design concept, particularly relevant in arid and semi-arid climates, is the “store-and-release” approach. This strategy relies on the cover’s capacity to temporarily store infiltrated water and subsequently release it back into the atmosphere through evaporation and transpiration. However, the effectiveness of these systems can be significantly enhanced by the integration of vegetation.

The functional traits and diversity of vegetation are key determinants of its effectiveness in controlling net percolation (NP). Root systems, with their penetration depth and density, directly influence the capacity for evapotranspiration. While the majority of roots typically reside in the upper 50 cm of soil, certain species, including arid grasses like *Triodia* species (Reid et al. 2008), exhibit significantly deeper root penetration (Schenk & Jackson 2002, 2005). Cover systems incorporating such deep-rooted plants are hypothesised to possess an enhanced capacity for water storage and release, consequently leading to a greater reduction in NP and associated AMD risks. Furthermore, plant functional diversity, encompassing variations in water uptake strategies and phenology, can optimise water utilisation across different seasons and hydrological events (Ogle & Reynolds 2004). Understanding the physiological adaptations of locally native Pilbara plant species, and how diverse communities exploit water resources, is therefore crucial for developing revegetation strategies that maximise water removal from cover systems, thereby minimising NP and the potential for contaminant mobilisation. This functional perspective underscores the need to move beyond simple vegetation establishment towards a nuanced understanding of plant traits and plant community dynamics in the design of effective AMD mitigation strategies.

Studies conducted at sites such as BHP’s Mt Whaleback (Whaleback) since 1995 have consistently highlighted the ongoing need to understand and effectively manage these processes. The recognition of vegetation’s potential to minimise NP was a key outcome of the failure modes and effects analysis (FMEA) at Whaleback in 2017, leading BHP to prioritise a deeper understanding of vegetation water use on their cover systems prior to mine closure. This necessitates the refinement of vegetation input parameters used in cover system models to accurately reflect site-specific plant water use characteristics.

To address this need, the Revegetated Cover System Program (RCSP), a collaborative research initiative involving BHP, Okane, and The University of Western Australia (UWA), was established. Based at Whaleback, and building upon existing knowledge of plant establishment barriers (Erickson et al. 2016; Lewandrowski et al. 2017; Masarei et al. 2020; Erickson et al. 2023), this program investigates longer-term vegetation–substrate interactions with the primary objective of reducing NP, particularly during periods of high rainfall, while ensuring vegetation survival during drier periods to promote resilient ecosystems. The overarching goal of this research is to deliver practical and scalable science-based solutions that will inform and guide BHP’s approach to achieving revegetation closure commitments and reducing the residual risks and costs associated with AMD.

This paper outlines the experimental design of the large-scale revegetated cover system trial – a crucial component of the broader RCSP – and provides a summary of the methodologies employed across the program’s five interconnected tasks. Furthermore, it draws upon the findings from smaller-scale controlled experiments and the monitoring of mature rehabilitation and natural analogue sites to contextualise the overarching research goals. The insights gained from this comprehensive program are intended to deliver practical and scalable science-based solutions that will inform and guide BHP’s approach to achieving its

revegetation closure commitments and decrease the level of residual risk and cost associated with AMD at closure.

The RCSP focuses on four areas:

- Vegetation systems: quantifying the transpiration rates of different plant communities and their impact on NP.
- Substrate systems: understanding how soil properties and moisture dynamics influence water movement and NP partitioning within the cover system.
- Model systems: evaluating existing models used to predict NP rates by incorporating site-specific vegetation characteristics.
- Technology transfer and feedback loops: ensuring research outcomes translate into practical and scalable solutions for BHP.

2 Methodology

The RCSP utilises a multi-faceted experimental design across five distinct tasks, each contributing to a comprehensive understanding of vegetation–substrate interactions and their influence on net percolation (NP) and AMD mitigation. Tasks 1 and 2 involve controlled small-scale experiments within the Whaleback Controlled Environmental Facility (CEF) (Bateman et al. 2021; Erickson et al. 2023), allowing for manipulation of environmental variables and detailed monitoring of hydrological processes under different vegetation scenarios. Task 3 comprises a large-scale field trial on the Whaleback W40 waste rock dump plateau, bridging the gap between controlled experiments and real-world conditions. Tasks 4 and 5 focus on field monitoring of mature rehabilitation sites and a natural analogue site, respectively, providing insights into long-term vegetation performance and water use in relevant ecosystems. The methodologies employed within each of these tasks are detailed in the subsequent sections. Figure 1 shows the locations of the trials at Whaleback.

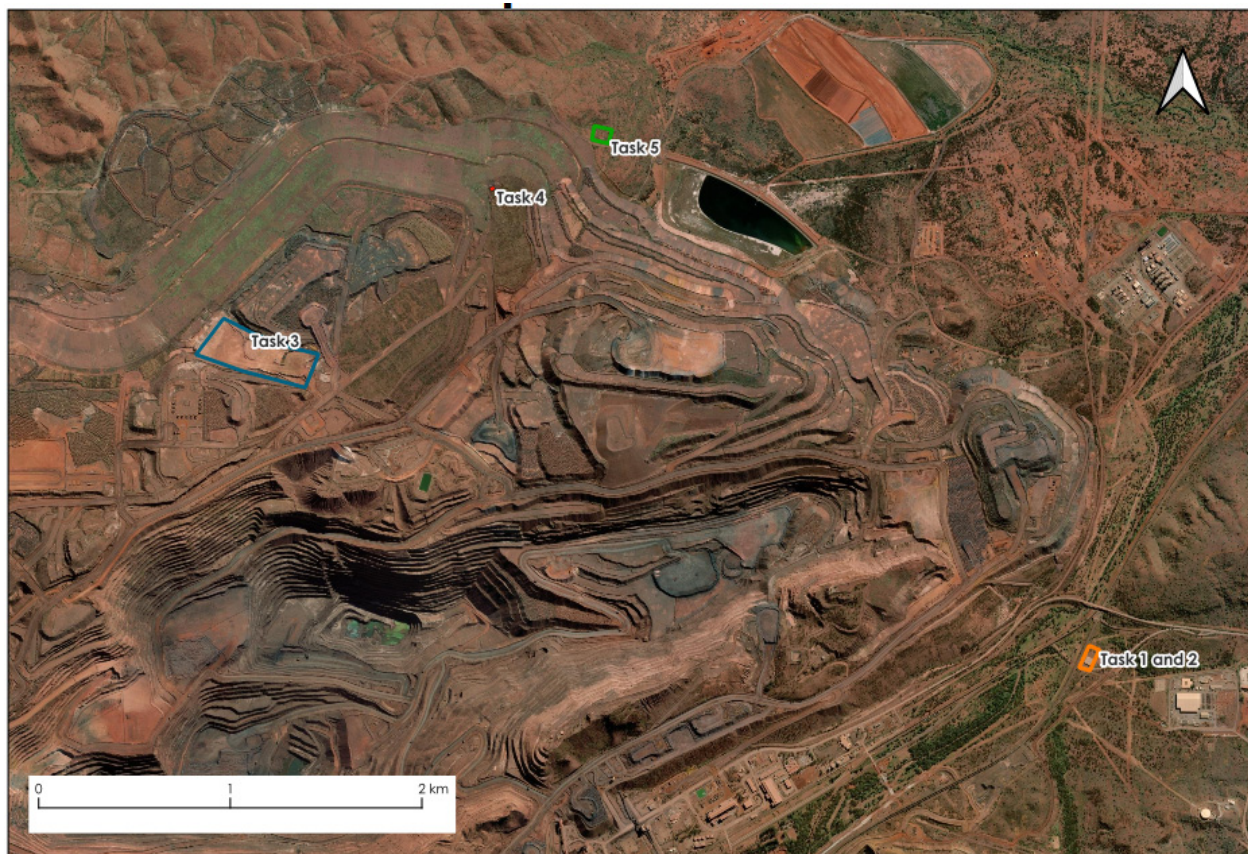


Figure 1 Mt Whaleback Revegetation Cover Systems Program trial sites

The Whaleback site is located in a region classified under the Köppen–Geiger climate system as BSh, characterised by hot summers and cold winters (Kottek et al. 2006). Most rainfall occurs during the summer months (December to March), with an average annual precipitation of 321.8 mm (Bureau of Meteorology [BOM] 2023). The annual average maximum temperature is 34.3°C, with summer temperatures often exceeding 40°C. The minimum annual average temperature is 19.1°C (BOM 2023).

2.1 Task 1: controlled NP experiment (small-scale)

The controlled NP experiment (Task 1) was conducted within the Whaleback CEF using small-scale bare planters first designed and used in Bateman et al. (2021). The primary objective of this task was to investigate the fundamental processes of NP through a controlled substrate in the absence of vegetation. This involved the construction of sealed planters filled with representative overburden material. Each planter was equipped with instrumentation to monitor key hydrological variables, including volumetric water content at two depths using soil moisture sensors, soil temperature, and the collection of any percolated water at the base of the planter using a lysimeter system.

A series of controlled irrigation events were applied to the bare planters, mimicking different rainfall intensities and durations following key rainfall patterns identified in Lewandrowski et al. (2017) and Erickson et al. (2023). The volume of water applied and the timing of each irrigation event were carefully recorded. Continuous monitoring of soil moisture content and temperature provided data on the wetting and drying cycles within the substrate. The volume of NP collected in the lysimeters was measured and recorded over time, allowing for the calculation of percolation rates and the determination of the time lag between irrigation and percolation. Additionally, surface evaporation rates were estimated using evaporation chambers deployed on selected planters. The data collected from this experiment was analysed to understand the hydraulic properties of the overburden material and to provide baseline NP data in the absence of vegetation, informing the design and interpretation of subsequent vegetated experiments and the large-scale field trial.

2.2 Task 2: controlled biodiversity, transpiration, and NP experiment (small-scale)

Building upon the findings of Task 1, the controlled biodiversity, transpiration, and NP experiment (Task 2) was also conducted within the Whaleback CEF using small-scale vegetated planters. The aim of this task was to investigate the influence of different vegetation communities on NP, transpiration rates, and overall water balance within a controlled environment. Planters were established with various species assemblages, including a grass species, and mixtures of grasses and shrubs (Table 1), representative of those selected for the large-scale field trial (Task 3). To maximise target plant establishment, seeds were treated with species-specific dormancy treatments following methods outlined in Erickson et al. (2016). Control planters without vegetation were also maintained for comparison.

Each vegetated planter was instrumented to monitor volumetric water content at two depths using soil moisture sensors (e.g. CS655), and NP was collected using a lysimeter system at the base. Environmental conditions, such as temperature, humidity, and light intensity, were also monitored. Controlled irrigation events were applied to the planters, and the resulting changes in soil moisture and NP were recorded. Plant growth parameters, such as biomass accumulation and leaf area index, were periodically assessed to correlate vegetation development with hydrological processes. The data from this task was analysed to quantify the impact of different vegetation types on NP reduction through evapotranspiration and to inform species selection and experimental design for the larger field trial.

Table 1 Vegetation functional groups and species composition of Revegetated Cover System Program field trial treatments

Grassland	Grassland with woody trees and shrubs
<i>Triodia pungens</i>	<i>Triodia pungens</i>
	<i>Acacia bivenosa</i>
	<i>Acacia inaequilatera</i>
	<i>Acacia ancistrocarpa</i>
	<i>Eucalyptus gamophylla</i>

2.3 Task 3: large-field revegetated cover system trial

Task 3 involves a large-scale field trial established on a waste rock dump plateau at the Whaleback mine site. The study area comprises 18 plots (15 vegetation plots of 24 × 24 m and three 24 × 24 m plots each containing a 20 × 20 m lysimeter) (Figure 2), constructed with two 2.5 m lifts of overburden material to simulate full-scale cover system construction. The study area footprint and has been built up to a uniform elevation by Whaleback Mine Operations using typical inert Whaleback cover material which has been designated to have no AMD potential. As part of BHP’s material management program, overburden is classified in accordance with physical and geochemical properties. This overburden has been classified to be suitable for cover system material based on AMD classification and physical property classification (primarily an erosion resistance classification).

The experiment employs a randomised factorial design with two main treatments: three vegetation community types (grasslands, grasslands with shrubs, and bare soil) and two simulated rainfall regimes (presence or absence of a rainfall pulse). The trial was installed in mid-2024, with seeding anticipated by late 2025 using precision seeding machinery suited for native seeds in rocky soils. To promote initial vegetation establishment, all 18 plots will be irrigated shortly after seeding with a repeated watering schedule over seven days (Lewandrowski et al. 2017; Erickson et al. 2023). Following establishment, rainfall simulation experiments will be conducted annually, applying either 50 mm over two days or 100 mm over three days to selected plots, with non-irrigated plots serving as controls.

Comprehensive monitoring infrastructure has been installed. A fully automated weather station records local climate data. NP will be directly quantified in the three lysimeter plots using automated tipping bucket systems with redundancy. Soil moisture dynamics will be monitored in all lysimeter plots and six vegetation plots using sensor nests at five depths (0.1, 0.25, 0.5, 1 and 3 m) measuring matric suction, temperature, and volumetric water content, connected to automated data acquisition systems. Additionally, electrical resistivity tomography (ERT) lines across all plots will monitor spatial and temporal variability in subsurface water distribution. Stable isotopic analysis of rainfall, irrigation, and soil water will be conducted to track water movement and estimate evaporation. Vegetation establishment and development will be monitored quarterly through species counts, richness assessments, survival rates, and growth measurements. As vegetation matures, plant morphology and physiology, including leaf traits, sap flow, plant water status, transpiration rates, and root distribution, will be assessed. Full details of the Task 3 trial, including methods, irrigation, seeding, material characterisation, and monitoring can be read in Johnson et al. (2024).

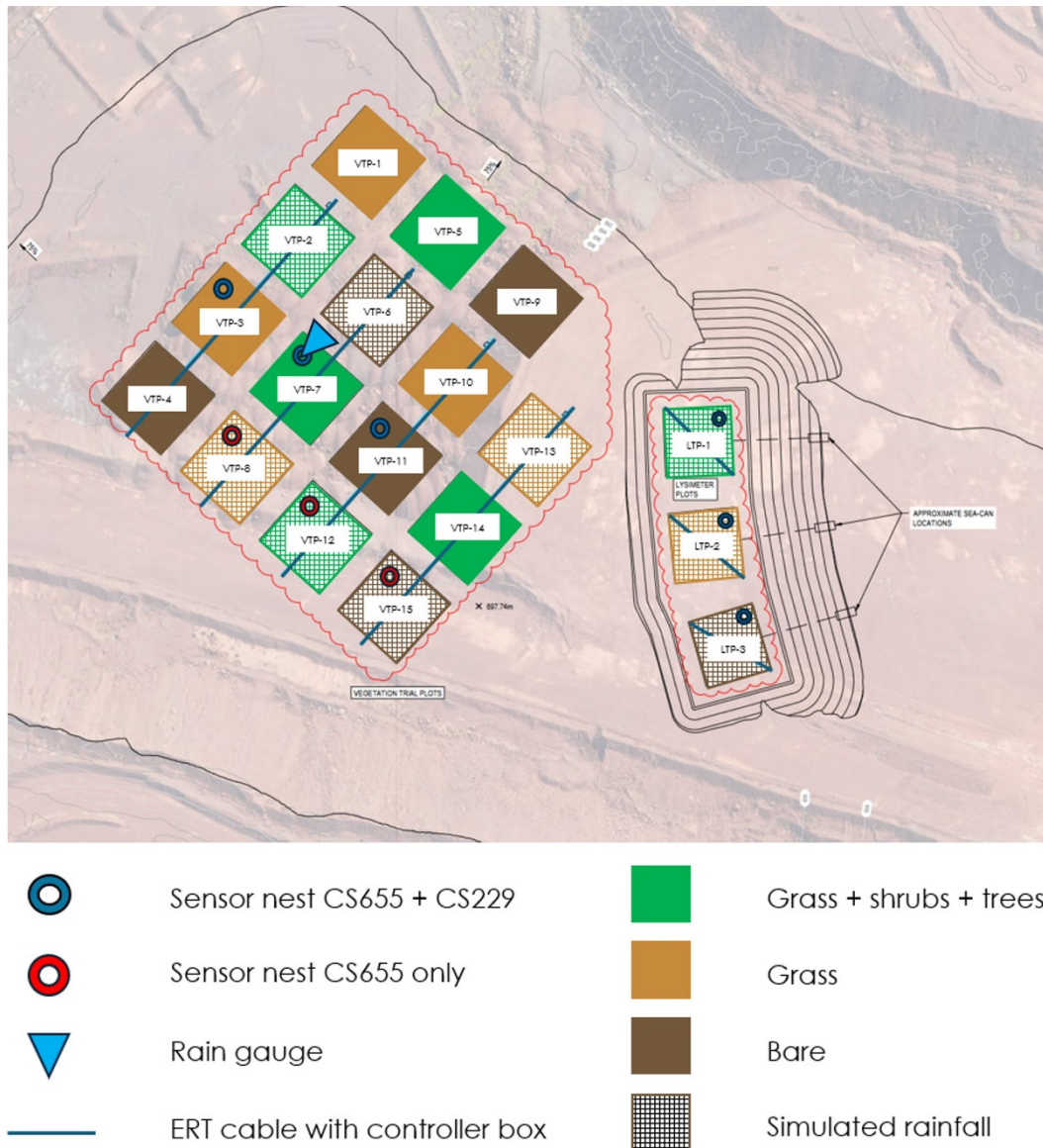


Figure 2 Layout of the 15 vegetation plots and three lysimeter plots with their assigned treatments (vegetation community and simulated rainfall) and positioning of the four 96 m electrical resistivity tomography (ERT) cables

2.4 Task 4: mature rehabilitation physiological monitoring

Task 4 focuses on the physiological monitoring of a mature rehabilitation site at Whaleback. This task aims to provide insights into the long-term water use characteristics of established vegetation on rehabilitated mine waste materials. The selected rehabilitation site represents an older revegetation effort, allowing for the study of mature plant communities and their interactions with the underlying substrate.

Physiological monitoring at this site primarily involves the measurement of plant transpiration rates using sap flow sensors installed on representative woody species. These sensors continuously record the movement of sap within the plant stems, providing a direct measure of water uptake and transpiration. Measurements are taken over extended periods to capture seasonal variations in water use in response to rainfall events and evaporative demand. Meteorological data, including rainfall, temperature, humidity, and solar radiation, are also collected at or near the site to contextualise the physiological measurements. The data collected from this task will be analysed to quantify transpiration rates of mature rehabilitated vegetation, identify key water use traits of different species, and compare these findings with data from the natural analogue site (Task 5) to understand the potential endpoint of vegetation water use on mine sites.

2.5 Task 5: natural analogue physiological monitoring

Task 5 involves the physiological monitoring of a natural analogue site, an adjacent natural open woodland ecosystem near the Whaleback mine. The objective of this task is to provide a benchmark for understanding the water use characteristics of a mature, undisturbed native vegetation community in a similar climate and hydrogeological setting to the mine site. This allows for a comparison with the mature rehabilitation site (Task 4) to assess the degree to which rehabilitated ecosystems can achieve similar hydrological functions.

Similar to Task 4, the primary method employed in Task 5 is the measurement of plant transpiration rates using sap flow sensors installed on dominant woody species within the natural woodland. The data from this task will be analysed to determine the transpiration rates and water use traits of the native vegetation community. By comparing these data with those from the mature rehabilitation site, this task aims to provide insights into the potential long-term hydrological functioning of rehabilitated mine sites and to identify target endpoints for vegetation water use in closure planning.

3 Results

3.1 Task 1: controlled NP experiment (small-scale)

During the experimental period, daily air temperatures fluctuated between 35 and 39°C. Soil surface temperatures in the un-irrigated planters consistently exceeded air temperatures by 4 to 22°C. Conversely, on days following irrigation, soil surface temperatures were lower than the ambient air. Prior to irrigation, soil evaporation rates were below 1.5 mm/day⁻¹. Following the first 60 mm irrigation event, evaporation rates peaked at approximately 24 mm/day⁻¹, decreasing to below 6 mm/day⁻¹ on the subsequent non-irrigation day. A smaller increase in evaporation (13–15 mm/day⁻¹) was observed after the second irrigation. Soil moisture content at both 5 and 50 cm depths increased rapidly within hours of each irrigation event, with a slightly faster response observed during the second and third watering cycles. The 110 mm irrigation treatment resulted in consistently higher soil moisture levels compared to the 60 mm treatment after the initial watering. Cumulative NP for the 60 mm irrigation treatment was measured at 14 mm, representing 23% of the total applied water, with a lag of approximately 12 days between the first irrigation and the onset of percolation at the 0.8 m depth.

3.2 Task 2: controlled biodiversity, transpiration, and NP experiment

The planter experiment demonstrated successful establishment and substantial growth of all selected plant species (*Triodia pungens*, *Acacia bivenosa*, *A. inaequilatera*, *A. ancistrocarpa*, and *Eucalyptus gamophylla*) under the initial irrigation regime. Visual observations indicated rapid biomass accumulation and canopy development, leading to significant inter-plant competition in most planters, potentially exceeding field densities. While quantitative measurements of NP and transpiration were not obtained due to logistical constraints and equipment reliability issues, the vigorous growth observed across all species suggests a high capacity for water uptake and potential for significant evapotranspiration under favourable moisture conditions. The rapid establishment also indicates that the selected species are well-suited for the Whaleback cover substrate when sufficient water is available for germination.

3.3 Task 3: large-field revegetated cover system trial

It is anticipated that the lysimeter plots with vegetation (grasslands and grasslands with shrubs) will exhibit significantly lower NP volumes compared to the bare soil lysimeter plot following both natural rainfall events and simulated rainfall treatments. The magnitude of NP reduction is expected to vary between the different vegetation community types, with potentially greater reduction observed in plots with a higher diversity of plant functional traits (e.g. grasslands with shrubs potentially exhibiting more effective water extraction across different soil depths and seasons). The automated soil moisture sensors are expected to reveal distinct wetting and drying patterns in response to rainfall events and irrigation, with vegetated plots likely showing faster and more pronounced soil drying in the upper soil profile due to evapotranspiration. ERT data are

expected to illustrate the spatial and temporal patterns of soil moisture distribution across the plots, potentially showing a more heterogeneous moisture profile in vegetated plots due to localised root water uptake. Stable isotope analysis is expected to provide insights into the partitioning of water loss between evaporation and transpiration under different vegetation treatments. Quarterly vegetation monitoring will quantify establishment success, growth rates, and species-specific responses to the different rainfall regimes. As vegetation matures, physiological measurements are anticipated to reveal differences in water use strategies (transpiration rates, sap flow patterns, plant water potential) among the selected native plant species, potentially identifying species or community compositions that maximise water removal from the cover system and thus minimise NP. The long-term data collected over the 10-year lifespan of the trial is expected to provide robust datasets for validating and refining existing NP prediction models by incorporating site-specific vegetation characteristics.

3.4 Task 4 and 5: mature rehabilitation and natural analogue physiological monitoring

Sap flow velocity measurements indicated generally higher rates of water movement in the perennial woody vegetation at the mature rehabilitation site compared to the adjacent natural analogue site during the monitoring period, highlighting different water use strategies between the two locations and across species. At both sites, the water use of these woody species demonstrated a clear responsiveness to seasonal fluctuations in rainfall and associated changes in soil water availability, as well as variations in evaporative demand. This dynamic water uptake, observed to deplete soil water, suggests a mechanism for reducing NP and consequently the risk of AMD. However, the limited increase in water use during winter rains across both sites potentially points to an increased risk of AMD during out-of-season rainfall events when plant water demand is lower. The study also highlighted challenges in quantifying water use in herbaceous species, particularly the dominant *Triodia* grasses, as sap flow techniques are not suitable for such plants. Rainfall measurements from different local weather stations showed significant discrepancies, underscoring the highly localised nature of rainfall in the region. This information highlighted the need for site-specific hydrological data to accurately assess vegetation water use and its impact on cover system performance.

4 Conclusion

The initial findings from the RCSP offer valuable insights into the complex hydrological dynamics governing bare soil and vegetated systems, crucial for mitigating AMD at the Whaleback mine site. The controlled NP experiment (Task 1) established a fundamental understanding of water infiltration and evaporation within the Whaleback cover material in the absence of vegetation, revealing its low hydraulic conductance and the potential for significant NP following substantial rainfall events. Complementing this, the controlled biodiversity experiment (Task 2) demonstrated the successful establishment and vigorous growth of selected native plant species, suggesting a strong capacity for vegetation to influence the water balance through transpiration and likely reduce NP. Furthermore, the physiological monitoring of mature rehabilitation and natural analogue sites (Tasks 4 and 5) highlighted the dynamic water use patterns of established woody vegetation in response to seasonal changes, with variations in sap flow suggesting species-specific water uptake strategies and site-specific influences.

These initial results collectively underscore the intricate interplay between substrate properties, vegetation characteristics, and prevailing climatic conditions in determining the hydrological performance of mine rehabilitation systems. The ongoing large-scale field trial (Task 3) represents a unique and critical resource for further elucidating these interactions at a more representative scale and under controlled conditions of vegetation type and simulated rainfall. By directly quantifying NP through large lysimeters under different revegetation scenarios, Task 3 is strategically designed to address key questions related to vegetation systems, substrate systems, and model systems, ultimately providing critical data for validating and refining predictive models of AMD risk. The comprehensive, multi-scale approach of the RCSP is therefore crucial for developing evidence-based strategies to optimise vegetation cover design for mine closure, aiming to significantly reduce NP and the long-term environmental liabilities associated with AMD drainage at

Whaleback and similar mining operations, with a clear pathway for technology transfer to inform practical and scalable solutions for BHP.

Acknowledgement

The authors thank Whaleback Mine Operations for establishing the base of the field trial.

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