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Scale effects in engineered cover design: lessons from Queensland mine sites

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Abstract

Designing engineered covers for waste rock and tailings (mineralised waste) is essential for sustainable rehabilitation in Queensland's North West Mineral Province. A significant challenge is reliably predicting how materials will perform at field scale over several decades, as laboratory-derived data often fails to reflect real-world conditions. This paper examines the critical role of scale effects in cover design, drawing on research and long-term monitoring data from two sites in North West Queensland.

At the laboratory scale, determining hydraulic properties like soil–water characteristic curves (SWCCs) is fundamental to design. However, reconstituted laboratory samples often overestimate water-holding capacity because they lack the in situ structure, stress history and cementation found in the field. Furthermore, the common omission of hysteresis in laboratory testing can lead to non-conservative predictions of cover efficiency.

Intermediate-scale column trials provide valuable comparative water balance data for assessing options like non-acid forming waste rock covers. While effective for side-by-side design comparisons and model calibration, these trials cannot fully replicate natural atmospheric variability.

The most robust validation comes from large-scale field trials, such as the decade-long program at a semi-arid mine in North West Queensland. The field trials demonstrate that thick infiltration and storage layers, combined with reduced permeability layers, maintain low percolation rates even through extreme cycles of intense wet seasons and prolonged droughts. Integrating findings across these multiple scales, while acknowledging the limitations of each, enables the development of resilient covers capable of meeting long-term rehabilitation goals in challenging environments.

Keywords: *cover systems, scale effects, store-and-release, field trials, mine closure*

1 Introduction

Contemporary mine closure aims to establish landforms that are safe, stable and do not cause environmental harm (Environmental Services and Regulation, Department of Environment, Science and Innovation [DETSI] 2024b). Central to this objective is the application of engineered cover systems (the covers), which provide a stable interface between contaminating waste rock or tailings (mineralised waste) and the surrounding environment. Covers are critical for the management of acid and metalliferous drainage (AMD), the result of reactive mineralised waste sulphide oxidation. By limiting the transport mechanism (water infiltration) and resulting percolation, covers limit the potential for contaminated seepage to move to the receiving environment.

In North West Queensland and, more broadly, Australia, particularly where evaporation exceeds rainfall, cover design focuses on water infiltration control. For semi-arid and seasonally dry environments, the store-and-release cover has emerged as industry standard (Greaser & Weinig 2022; Jamson & Rohde 2019; Defferrard et al. 2016; Defferrard et al. 2024). Store-and-release covers use a thick, loose layer of (waste) rock and soil growth medium to store rainfall within the root zone, limiting or reducing percolation into

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underlying reactive mineralised waste. The stored rainfall is subsequently removed through the combined processes of evaporation and plant transpiration (evapotranspiration) during the dry season. An enhanced cover may include a reduced permeability layer (RPL), typically achieving a saturated hydraulic conductivity of less than 315 millimetres per year (mm/year) (10^{-8} metres per second (m/s)) to provide protection against extreme climatic cycles and high-intensity rainfall events, or a capillary break (CB) that mitigates the uptake of salts and other contaminants (capillary rise) from underlying reactive mineralised waste into the growth medium via evapotranspiration.

A primary challenge in mine closure is the reliable prediction of cover performance over long time frames. Monitoring from Queensland mine sites suggests that laboratory-scale soil–water characteristic curves (SWCCs) overestimate the water-holding capacity of cover materials because reconstituted laboratory samples lack the complex in situ structure, stress history and natural cementation observed in field conditions (Williams & Rohde 2009). Further, the common omission of hysteresis in standard laboratory testing can result in non-conservative predictions of cover performance. To bridge this gap, intermediate-scale column trials provide a transitional design phase that allows for the validation of numerical models and the assessment of cover layer properties in a controlled environment prior to field trials (Rohde et al. 2022). Column trials are advantageous due to their cost-effectiveness and small spatial footprint, which avoid many of the logistical constraints associated with field trials. However, a limitation is their inability to fully replicate natural atmospheric variability and complex climatic cycles (Office of the Queensland Mine Rehabilitation Commissioner 2025). Field trials represent the most robust form of cover performance validation by integrating actual construction techniques with atmospheric complexity. Field trials are essential for evaluating constructability as they are built at a scale that uses commercial-scale machinery and materials. The full-scale construction method allows for imperfection, such as preferential infiltration pathways, which are a major contributing factor to cover performance. Despite these technical advantages, the duration and monitoring of field trials present challenges. While a minimum trial period of 5 to 10 years is typically required to capture representative climatic cycles and allow for the initial evolution of cover material hydraulic properties (Environmental Services and Regulation, DETSI 2024a; Defferrard et al. 2024), this time frame is often insufficient to detect failure modes. Critical processes such as vegetation failure (International Network for Acid Prevention [INAP] 2003), root penetration, biological intrusions by termites (Lamoureux & O'Kane 2012) and geochemical lag times in AMD generation can take several decades to manifest. Further, there is an inherent risk that the trial period may not coincide with extreme weather events required to stress the covers store-and-release capacity (Environmental Services and Regulation, DETSI 2024a).

2 Case studies

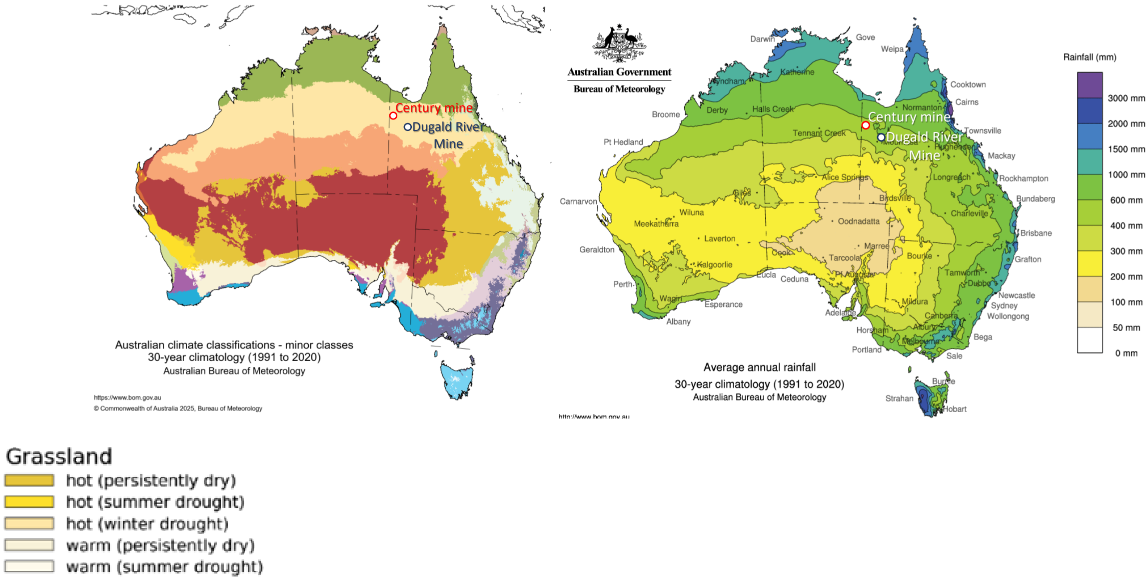
This paper examines results from 2 cover trial programs to evaluate the influence of scale effects on performance and long-term predictive reliability. The first case study involves an intermediate-scale column trial at the Dugald River mine (Rohde et al. 2022), which used a 2.4-metre-tall column to assess a DETSI high-risk cover (Environmental Services and Regulation, DETSI 2024a) under controlled, artificial climatic conditions. This laboratory-based assessment is contrasted with a second case study: a large-scale field trial of a 2.7-metre-tall DETSI high-risk cover at the Century mine (Defferrard et al. 2024). Comparison of cover performance at different scales allows an assessment of the advantages and disadvantages of both approaches and lays the foundation for an integrated approach to cover design.

2.1 Location

Both mines are in the northern Mineral Province of North West Queensland. Dugald River mine is located approximately 85 kilometres (km) northeast of Mount Isa and 65 km northwest of Cloncurry. Century mine is located at Lawn Hill, 250 km northwest of Mount Isa and about 185 km from Dugald River mine.

2.2 Climate and rainfall

Both mines have Köppen-Geiger classification as grassland hot (winter drought) zones (Figure 1a) of North West Queensland. The zone is characterised by a semi-arid climate where evapotranspiration exceeds rainfall. In regions such as Cloncurry and the surrounding Mount Isa Mineral Province, evaporation rates typically exceed rainfall every month of the year, often by a factor of 3.



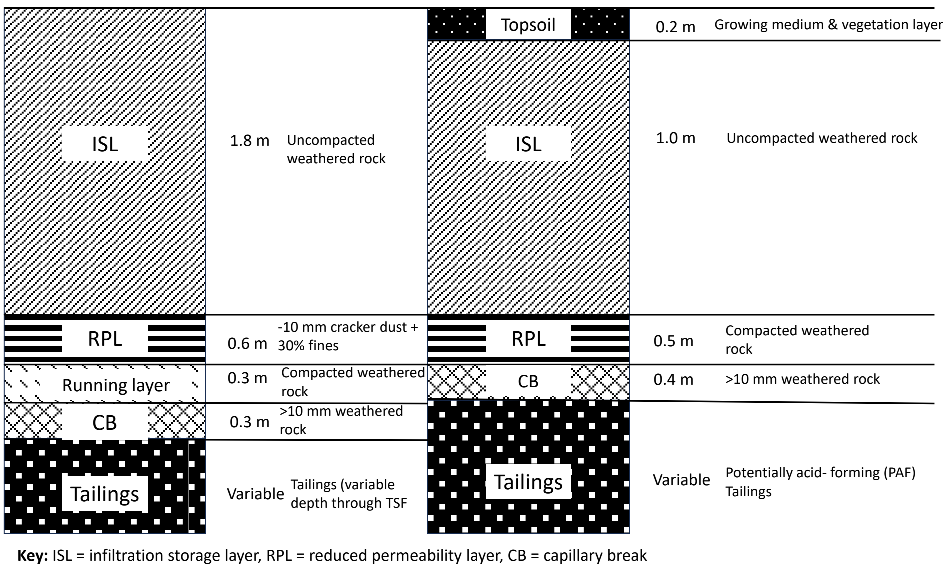
(a) (b)

Figure 1 Climate characteristics. (a) Köppen-Geiger minor climatic zones; (b) Total rainfall

The winter drought aspect of this zone refers to highly seasonal rainfall patterns (Figure 1b) where on average, 600–1,000 millimetres (mm) of rainfall is concentrated between November and April annually (the wet season). During the wet season, monthly averages can exceed 100 mm, while the winter months of July to October frequently record rainfall of less than 5 mm and average less than one rain day per month.

2.3 Cover types

Store-and-release covers are recommended for long-term management of mineralised waste (INAP 2009) where evapotranspiration dominates. Figure 2 presents the covers that have been trialled at Century mine (Figure 2a) and Dugald River mine (Figure 2b).



(a) (b)

Figure 2 Cover types. (a) Century mine; (b) Dugald River mine

The covers share high-risk architecture combined with a CB and make use of equivalent layers arranged in identical stratigraphic order. Both covers employ a thick, uncompacted weathered rock infiltration storage layer (ISL) designed to store rainfall infiltration. This layer overlies a compacted RPL, which limits percolation. Both covers utilise a coarse-grained gravel layer (> 10 mm weathered rock) as a CB directly above the tailings, breaking capillary tension, and limiting upward movement of potentially contaminating solutes to the ISL.

Site-specific optimisation and structural requirements create functional differences between the 2 covers. The primary differences are the inclusion of a 0.2-metre topsoil layer in the Dugald River mine cover, and a thicker ISL and running layer in the Century mine cover which functionally increases the RPL thickness to 0.6 m.

3 Method

3.1 Laboratory soil–water characteristic curves

Drying SWCCs for the Dugald River mine cover was characterised using multistep pressure extraction with high-air-entry ceramic plates within pressurised vessels (Figure 3).

Figure 3 Pressure plate extractor

Initially the ceramic plates were saturated under vacuum, and cover samples contained within ceramic rings were saturated from the base upward to remove trapped air. Hydraulic contact was maintained between the pressure plate and cover sample using saturated filter paper which does not interfere with internal drainage. Matric suction was applied in increments of air pressure ranging from 1 to 1,500 kilopascals (kPa). Hydraulic equilibrium was reached when drainage into an external collection flask had stopped; a process typically requiring 48 to 120 hours per matric suction step. After reaching equilibrium at the final pressure increment, samples were removed and oven-dried at 105°C for 24 hours to determine the final gravimetric water content. Volumetric water content (VWC) corresponding to each matric suction step was calculated using dry density, with the resulting data points fitted to the van Genuchten (1980) or Fredlund & Xing (1994) model to define the SWCC.

3.2 Column trial

To address scaling and boundary condition limitations inherent in laboratory-scale characterisation, an intermediate-scale column trial was established for the Dugald River mine cover to provide a high-resolution, short-duration dataset for numerical seepage model calibration (Figure 4). The column was instrumented throughout its thickness with VWC and matric suction sensors (Figure 4), allowing continuous monitoring of water infiltration, storage and seepage under dynamic, cyclic climatic forcing. This methodology yields a more representative in situ SWCC that incorporates complex hydraulic phenomena such as hysteresis. A significant advantage of the experimental design is its flexibility to precisely manipulate the frequency and intensity of simulated rainfall, which enables the rapid development of a maximum water balance. While this method does not allow measurement of actual evaporation, it can be interrogated during numerical modelling.

The resulting spatial and temporal profiles of VWC and matric suction provide validation targets to ensure the predictive accuracy of the calibrated seepage model.

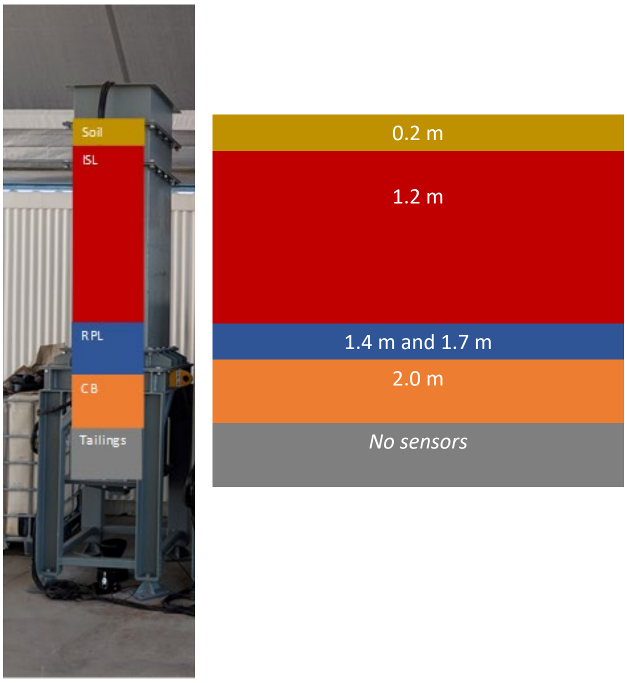


Figure 4 Column trial and sensor burial depth. ISL = infiltration storage layer, RPL = reduced permeability layer, CB = capillary break

3.3 Field trial

The Century mine cover field trial was established in 2014 on the upper beach of the tailings storage facility. Site preparation included grading the tailings surface to a uniform 1% grade (Figure 5a), followed by a running layer (Figure 5b), RPL (Figure 5c), CB (Figure 5d) and ISL.

(a) (b) (c) (d)

Figure 5 Century mine cover. (a) Tailings beach preparation; (b) Running layer; (c) Reduced permeability layer; (d) Capillary break

Performance monitoring used an acid-resistant high-density polyethylene lysimeter (2 metre diameter, 2.3 metre depth). Two lysimeters were installed in an excavated pit and monitored by an individual groundwater pump and sump operation (Figure 6a). Two lysimeters were installed to examine the potential impact and preferential flow paths. A 0.5 metre-thick filter of washed river gravel, sand and geofabric was installed in the base of each lysimeter to prevent the migration of silt and clay-sized particles from clogging the sump (Figure 6b). The internal area of the lysimeters and the surrounding excavations were backfilled with tailings in unison and periodically compacted to prevent deformation of the lysimeter wall (Figures 6c and 6d).

(a) (b) (c) (d)

Figure 6 Lysimeter installation. (a) Sump; (b) Backfilling filter; (c) Internal compaction; (d) External compaction

Climate was measured using an automated weather station and nested instrumentation capable of calculating potential evapotranspiration rates using the Penman-Monteith method (Allen et al. 1989). Infiltration dynamics were monitored using VWC and matric suction sensors (Figures 7a and 7b). Percolation captured by the lysimeter was manually purged using a 12-volt battery-driven pump.

(a) (b)

Figure 7 Cover instruments. (a) Instrument tree; (b) Installed instrument tree

4 Result and discussion

4.1 Laboratory scale

Laboratory-measured SWCCs for the Dugald River mine cover are presented in Figure 8 (Fredlund & Xing 1994). Laboratory analysis provides early indications of cover material hydraulic behaviour. The laboratory-measured SWCCs exhibit pronounced anomalies that directly highlight the systemic errors associated with sample scalping. By screening the material at a -2.36 mm to accommodate a standard laboratory testing apparatus, the coarse gravels and weathered rock fragments that naturally dictate macropore hydrology are removed. This structural alteration isolates a fine sand, silt and clay matrix that packs densely, leading to an inflation of the air-entry value (AEV) towards 100-200 kPa. This range is characteristic of cohesive clays rather than uncompacted weathered rock, because AEV is inversely proportional to pore radius. This narrow pore size distribution similarly skews the results of the CB, which is defined as a coarse-grained weathered rock gravel greater than 10 mm. While an in situ gravel layer exhibits an AEV near zero and negligible capillary rise due to its large inter-particle voids, the scalped laboratory sample instead reflects the properties of the fine coatings or matrix filling those rocks, generating an artificially high AEV and capillary rise that paradoxically suggest the layer would pull water and salts upward rather than arresting them. Furthermore, a mismatch exists regarding the porosity and field water content of the CB layer; the laboratory curve caps porosity at 8%, a value comparable to dense basalt or limestone. This constraint contradicts multitemporal field-monitoring datasets that record porosity generally greater than 30%. This underestimation indicates over-compaction within the laboratory test cell, resulting in laboratory SWCCs that are unrepresentative of actual field-scale hydrology.

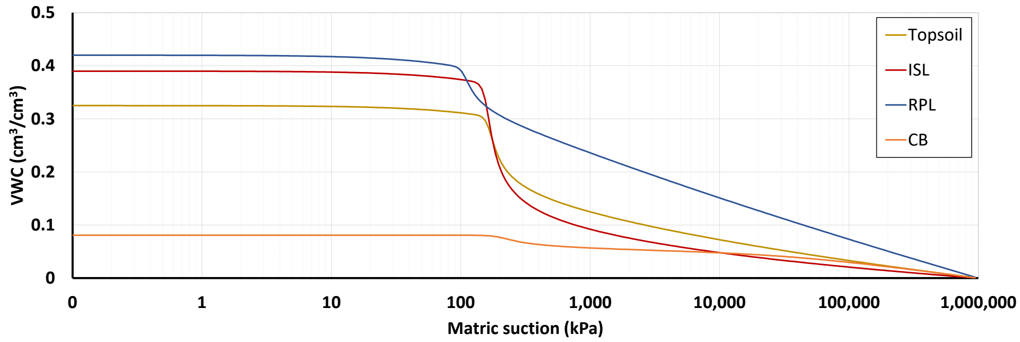


Figure 8 Dugald River mine cover laboratory soil–water characteristic curves. ISL = infiltration storage layer, RPL = reduced permeability layer, CB = capillary break

Porosity (n) is represented by the vertical axis intercept; typically a higher density results in a lower initial water content. The AEV, measured in kilopascals (kPa), identifies the matric suction at which air begins to penetrate the cover material pores. Until this value is exceeded, the material remains saturated with a degree of saturation (S) greater than 85%. The capillary rise potential is functionally equivalent to the AEV divided by the unit weight of water (AEV/9.81). Finally, the water-entry value (WEV) represents the matric suction beyond which osmotic suction and water vapour flow become the dominant transport mechanisms, characterised by a significant flattening of the curve where further dewatering becomes progressively difficult (Table 1 – interpreted from Figure 8).

Table 1 Soil–water characteristic curves interpretation

Cover material	Porosity	AEV (kPa)	WEV (kPa)	Capillary rise potential (m)
Topsoil	0.33	150	2,500	15.3
ISL	0.39	140	1,500	14.3
RPL	0.42	150	3,000	15.3
CB	0.08	180	3,000	18.4
Tailings	0.31	10	3,000	1.0

AEV =air-entry value, WEV = water-entry value, ISL = infiltration storage layer, RPL = reduced permeability layer, CB = capillary break

The RPL, ISL and topsoil have the highest saturated porosities (0.33-0.42), reflecting their roles in infiltration storage. These materials share high AEVs ranging from 140–150 kPa, indicating they remain near-saturated until significant matric suction is applied. This translates to a high capillary rise potential (> 14 m), which is necessary for maintaining hydraulic separation and preventing drying. In contrast, the CB represents extremes in hydraulic performance. The tailings exhibit a very low AEV (10 kPa) resulting in a minimal capillary rise potential of 1.0 m. This ensures that once the tailings desaturate, they lose water rapidly through their pores. The CB is a hydraulic barrier maintaining a near-zero VWC even at low suctions, relative to the overlying cover layers, and its low porosity stops the capillary rise of potentially contaminating solutes.

4.2 Column trial scale

Transition from laboratory-scale characterisation to intermediate-scale column trials highlights the influence of scale effects on cover material hydraulic properties. While laboratory-measured SWCCs provide a baseline they are limited by particle size, which requires scalping of the coarse fraction, typically restricting analysis to a sub-2 mm fraction. Particle size scalping leads to overestimation of water-holding capacity and an elevated AEV (Figure 9). This discrepancy arises because reconstituted laboratory samples lack the non-porous larger aggregates, complex in situ structure and natural cementation that define field performance. In contrast, the intermediate-scale column trials allow testing of a representative volume element incorporating the full particle size distribution, including the greater than 10 mm CB fraction. By reconstituting macrostructure and hydraulic connectivity, the column trial method provides a more realistic approximation of field conditions compared to idealised laboratory samples.

Column trials also allow for the measurement of complex hydraulic phenomena, such as hysteresis, which are frequently omitted in standard laboratory testing despite their critical role in conservative performance predictions. Hysteresis is observable in the column trial SWCCs (Figures 9a to 9d) through the distinct vertical scatter of VWC for a single matric suction. While the laboratory-derived SWCC represents a single drying path measured by controlled multistep extraction, the column trials respond to dynamic, cyclic climatic forcing. The scatter is indicative of path-dependency, where the VWC for a given matric suction differs depending on whether the material is undergoing a wetting or drying phase.

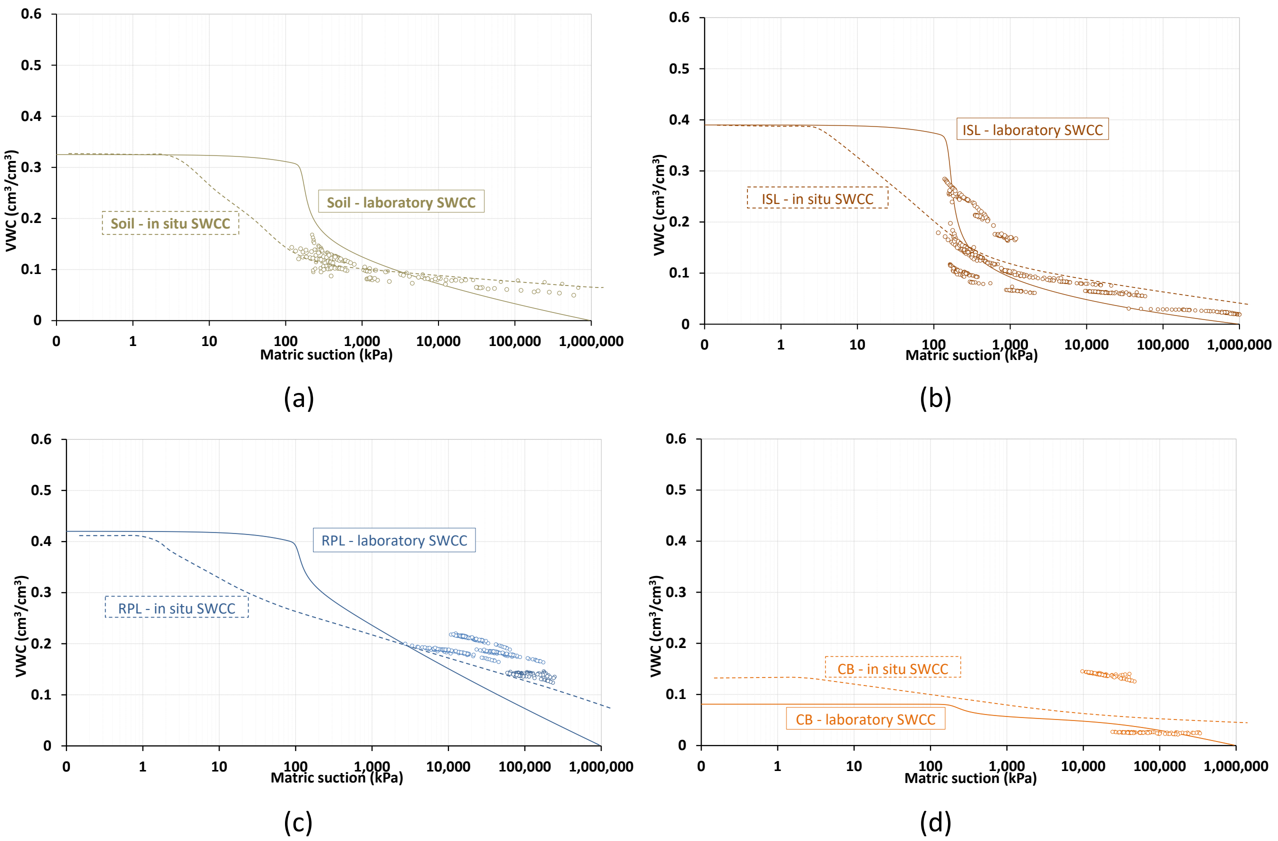


Figure 9 Dugald River mine cover in situ versus laboratory soil–water characteristic curves (SWCCs). (a) Topsoil; (b) Infiltration storage layer; (c) Reduced permeability layer; (d) Capillary break. SWCC = soil water characteristic curve, ISL = infiltration storage layer, RPL = reduced permeability layer, CB = capillary break

Comparison of the results in Figure 9 shows distinct hydraulic contrasts between laboratory-derived and column trial-measured SWCCs in the cover materials.

The laboratory SWCCs for topsoil and the ISL (Figures 9a and 9b) are notably shifted towards higher VWCs and AEVs (140–150 kPa) compared to the column trials. The column trial data shows a more gradual desaturation profile, reflecting the presence of coarse, non-porous aggregates which reduce the water-holding capacity of cover materials.

The RPL laboratory SWCC maintains the highest saturated porosity (0.42) and AEV (150 kPa); however, the column trial demonstrates that its storage capacity is lower than predicted by idealised laboratory samples (Figure 9c). Notably, the RPL retains a flatter post-AEV slope compared to the ISL, confirming its functional role in providing infiltration storage and hydraulic separation.

The most pronounced contrast occurs within the CB (Figure 9d). Laboratory testing of the fine-grained matrix suggests a water-holding capacity that is physically absent in the field scale trials (>10 mm weathered rock). The column trials correctly identify the CB as a hydraulic barrier that maintains a near-zero VWC even at low suctions, thereby preventing the upward capillary rise of potentially contaminating solutes.

Transition to the WEV and subsequent vapour flow is characterised by flattening of the SWCC, which occurs more rapidly in the column trial than in the laboratory model. In the RPL, this transition persists to approximately 3,000 kPa, while the ISL transitions to vapour flow earlier at 1,500 kPa, illustrating the relative ease with which the ISL releases stored water under climatic forcing.

The hydrological performance of the Dugald River mine cover under forced climatic conditions (artificial rainfall) is exemplified by the maximum water balance, which demonstrates a high efficiency at managing extreme infiltration (Figure 10). During the experimental period, a cumulative rainfall of 710 mm resulted in a cumulative percolation of 1 mm, representing approximately 0.14% of cumulative rainfall. The cover system performance is well within natural groundwater recharge rates often cited for semi-arid Australian environments (Lee et al. 2024); that is, 0.6–522 mm/yr and a mean recharge rate of 6.3 mm/yr. Cumulative evaporation was 690 mm, closely tracking rainfall and maintained infiltration storage at 68 mm. Advantages of the intermediate-scale column trial method include flexibility to manipulate rainfall frequency and intensity to develop a maximum water balance scenario quickly. This approach allows the testing of a representative volume element that preserves hydraulic connectivity and cover material macrostructure, effectively bridging the gap between laboratory idealisation and field-scale complexity. However, the Office of the Queensland Mine Rehabilitation Commissioner (2025) identifies critical limitations, noting that column trials cannot fully replicate natural atmospheric variability or complex, long-term climatic cycles. Furthermore, the method lacks the capability to measure actual evaporation, requiring this variable to be interrogated through numerical modelling. This method fails to account for long-term failure modes, such as biological intrusions, vegetation, and preferential flow associated with full-scale machinery and construction.

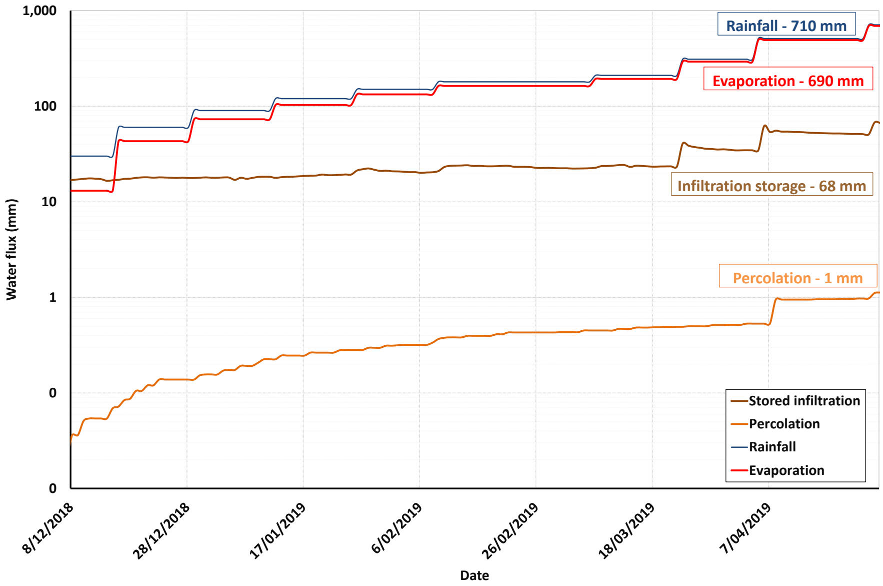
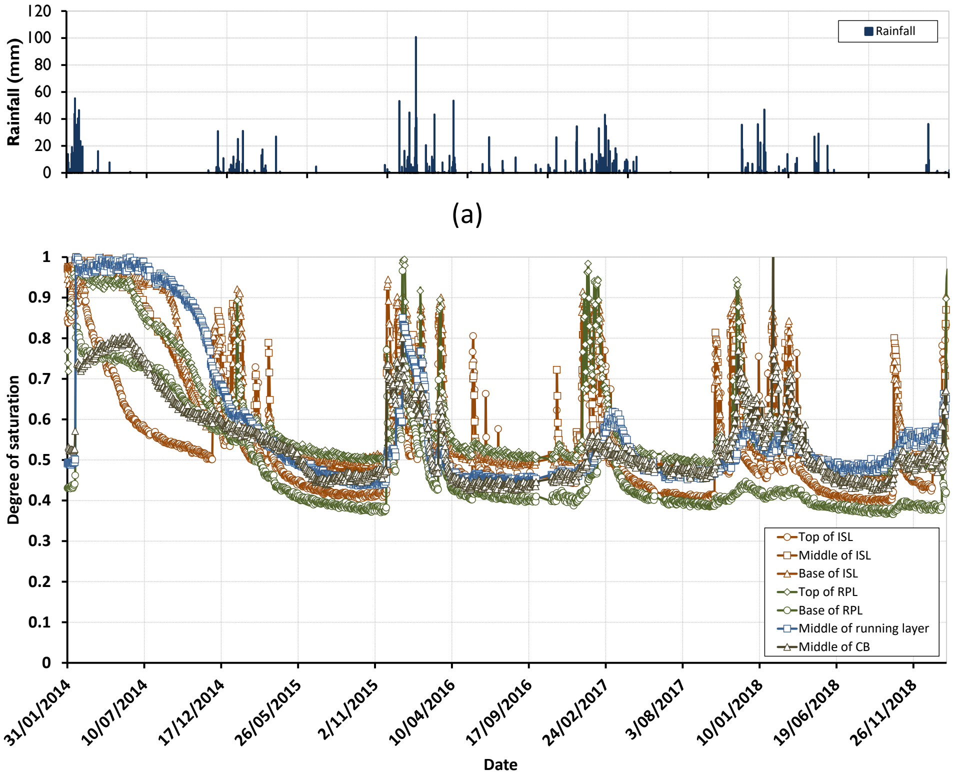


Figure 10 Dugald River mine cover maximum water balance

4.3 Field trial scale

Field trial cover evaluation at Century mine (Figure 11) is the most robust validation of cover performance because it integrates actual construction techniques with natural atmospheric complexity. In contrast to the controlled, accelerated climatic forcing applied to column trials, the hydrological response in field trials is driven by stochastic meteorological variability (Figure 11a). This exposure to natural rainfall subjects the cover to a significantly wider range of wetting and drying states than observed in column trials (Figure 11b).



(a)

(b)

Figure 11 Century mine cover field trial results. (a) Rainfall; (b) Degree of saturation. ISL = infiltration storage layer, RPL = reduced permeability layer, CB = capillary break

The dynamic behaviour (illustrated by degree of saturation) in Figure 11b shows how wetting and drying within the cover fluctuates in response to highly seasonal North West Queensland rainfall patterns, where most of the 550 mm annual average is concentrated in the summer months.

A comparison of SWCCs from column (Figure 9) to field trials (Figure 12) shows that while both methods capture hysteresis, field trials provide a better definition of porosity and AEV. The increased certainty of estimation comes from observing the cover under the cumulative influence of commercial-scale construction coupled with dynamic atmospheric forcing (for example, fluctuating wind speeds and solar radiation) that define actual evaporation.

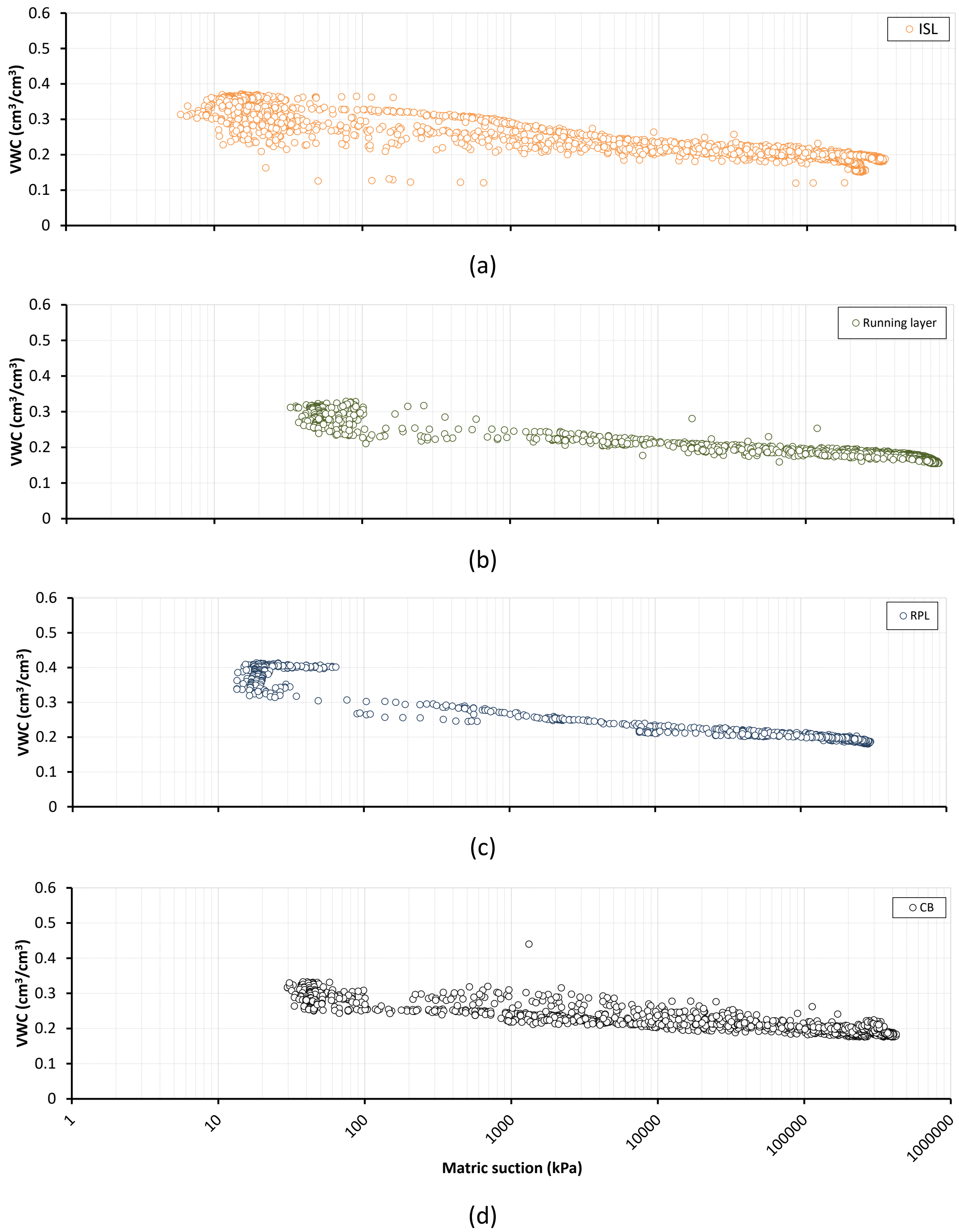
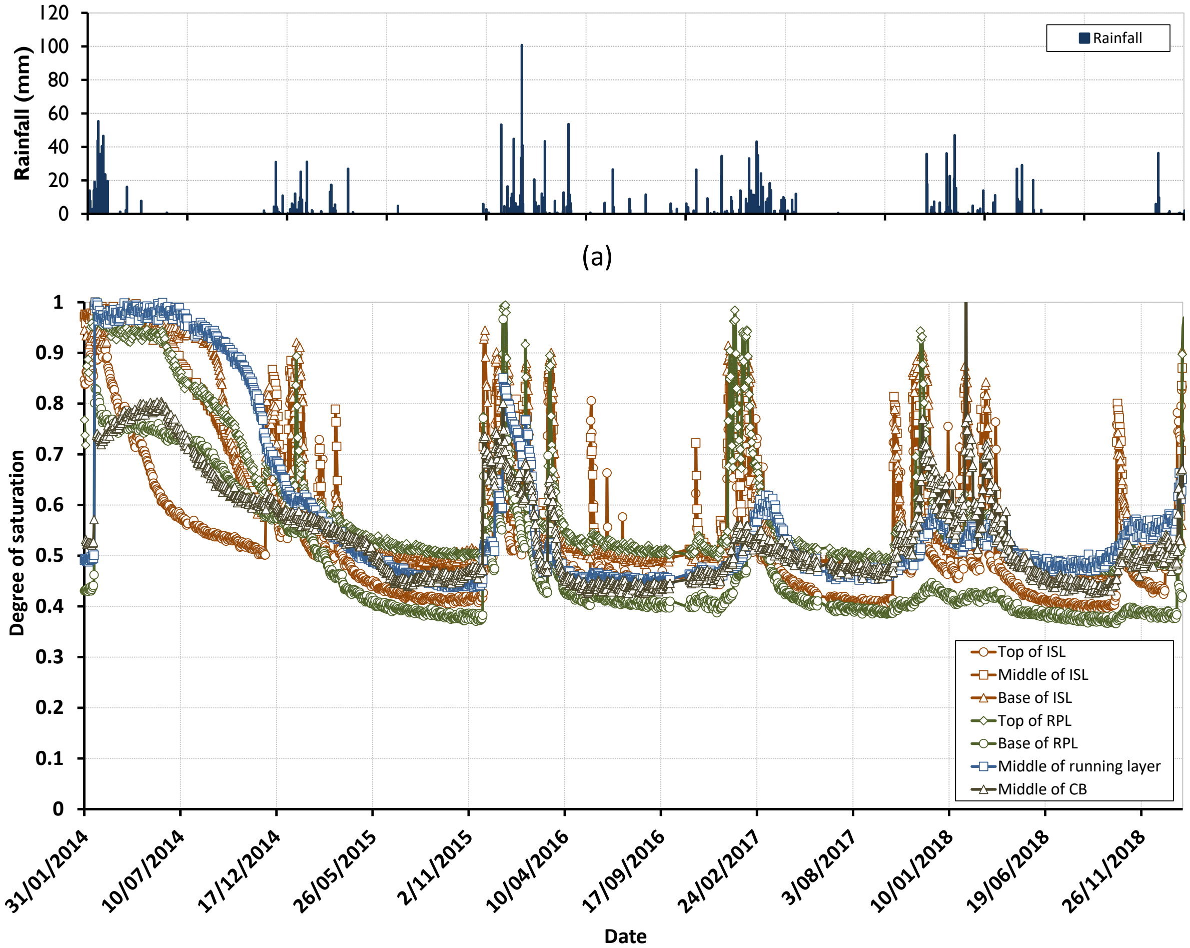


Figure 12 Century mine cover field trial soil–water characteristic curves. (a) Infiltration storage layer; (b) Running layer; (c) Reduced permeability layer; (d) Capillary break. ISL = infiltration storage layer, RPL = reduced permeability layer, CB = capillary break

Long-term percolation for the Century mine cover (Figures 13 and 14) indicates a cumulative net percolation of between 5 and 9 mm over the 10-year monitoring period. While this remains well below the nominal groundwater recharge rates often cited for semi-arid Australian environments (0.6–522 mm/yr and a mean recharge rate of 6.3 mm/yr for arid environments) (Lee et al. 2024), it represents a notable increase compared to the 1 mm (0.14% of cumulative rainfall) recorded in the short-duration Dugald River column trial. This discrepancy highlights the scale effects and construction-related factors identified in the Office of the Queensland Mine Rehabilitation Commissioner (2025) review. Specifically, the field trial incorporates commercial-scale machinery and full-scale placement methods which allow for the development of preferential infiltration pathways and imperfections in the RPL that are largely absent in hand-packed column trials. Observation of the percolation trend after a decade suggests that the cover may be transitioning from a linear increase toward a plateau, aligning with the Queensland Mine Rehabilitation Commissioner (2025) findings regarding the advantages of field trials in capturing the initial evolution of hydraulic properties and representative climatic cycles. However, the results also underscore the primary disadvantage of field trials: the significant time lag required to detect complex failure modes such as biological intrusions by termites, root penetration and vegetation failure, which can take years to decades to manifest.



(a)

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Figure 13 Century mine cover field trial results. (a) Rainfall; (b) Degree of saturation. ISL = infiltration storage layer, RPL = reduced permeability layer, CB = capillary break

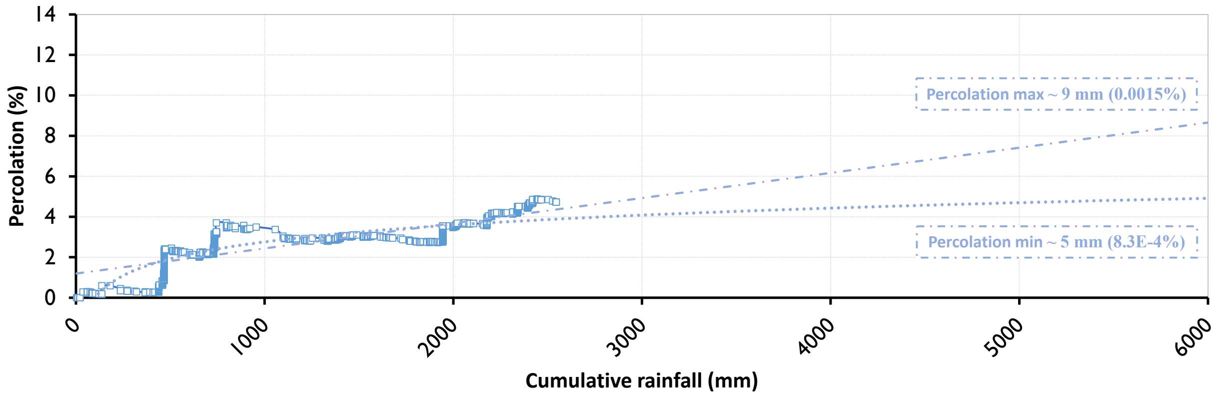

Figure 14 Century mine cover percolation results

4.4 Integrated multiscaled cover design

An understanding of cover performance requires a multiscaled experimental framework that integrates laboratory characterisation, intermediate column trials and large-scale field trials. Relying on a single scale alone introduces non-conservative risk because the limitations of one method are addressed by the strengths of another. By adopting an integrated approach, practitioners can progressively refine predictive reliability from an initial scoping phase to definitive pre-feasibility and final execution.

Laboratory-scale analysis is the essential starting point during scoping, providing a baseline for fundamental hydraulic behaviour and material properties. While benchtop testing is effective for early identification of hydraulic properties, reconstituted laboratory samples fail to reflect the in situ structure, stress history, and natural cementation observed in field conditions. Furthermore, the common practice of scalping coarser fractions to satisfy specimen-to-particle-size ratios leads to overestimation of water-holding capacity and AEVs. To bridge the gap between laboratory idealisation and real-world complexity, intermediate-scale column trials should be used during the pre-feasibility stage to test a representative volume element that preserves the full particle size distribution and hydraulic properties. This scale of study is advantageous for its flexibility in manipulating climatic forcing to develop a maximum water balance quickly, providing high-resolution datasets for numerical model calibration. Column trials allow for the observation of complex phenomena such as hysteresis, which is missed in laboratory drying SWCCs. Intermediate-scale column trials operate within controlled environments and remain unable to fully replicate natural atmospheric variability or account for long-term construction-related imperfections.

Definitive validation can only be achieved through large-scale field trials, which integrate commercial-scale machinery and actual placement methods with stochastic climatic forcing. This is critical for evaluating real-world constructability and identifying preferential infiltration pathways that are functionally absent in hand-packed column trials or laboratory testing. Field trials provide the most robust definition of hydraulic properties and performance because they account for actual evaporation drivers such as solar radiation and fluctuating wind speeds. While field trials offer the best assessment of cover performance, they are constrained by the time lag required to reliably predict long-term performance. Consequently, a resilient cover design strategy should use all 3 scales to provide a conservative predictive envelope that meets long-term rehabilitation and closure goals.

5 Conclusion

The reliable prediction of long-term engineered cover performance remains a primary challenge in achieving sustainable mine closure. This paper demonstrates that while laboratory characterisation provides an essential hydraulic baseline, the inherent limitations of small-scale testing, specifically particle scalping and the omission of hysteresis, necessitate a transition to more representative methods to avoid non-conservative predictions. Intermediate-scale column trials effectively bridge this gap by facilitating numerical model calibration and the assessment of full particle size distributions under dynamic conditions.

Furthermore, although the Office of the Queensland Mine Rehabilitation Commissioner (2025) advocates for large-scale field trials as the most robust means of validating constructability and atmospheric coupling, these programs are constrained by significant time lags required to detect long-term failure modes such as biological intrusions or vegetation failure. Consequently, successful rehabilitation requires a call to action for the mining industry to adopt a more holistic investigative framework. A truly well-considered design must integrate findings across all 3 scales to establish a resilient and conservative predictive envelope that ensures long-term rehabilitation goals are met.

Use of artificial intelligence disclosure statement

In the preparation of this work the authors used Gemini Pro to improve clarity. The authors have reviewed the content and edited it where required, and take full responsibility for said content.

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