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To spill or not to spill? Closure water management for tailings storage facilities

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Abstract

Water is the key driver of tailings storage facility (TSF) failures, both in operations and closure. In closure, water management changes fundamentally: active decant systems are decommissioned, routine inspections are reduced and operational or emergency interventions can no longer be relied upon to the same degree. This does not imply an absence of controls in closure. Rather, reliance shifts from active to passive controls. Closed TSFs become permanent landforms that must safely and passively manage water in the face of deep climatic and geomorphic uncertainty. This paper explores closure water management strategies for TSFs and asks: to spill or not to spill?

Closure configurations are framed in terms of 3 idealised types: (1) non-discharge systems that retain all inflows within the basin; (2) direct-shed systems that minimise storage and routinely discharge run-off via spillways; and (3) store-then-spill hybrids that provide substantial storage but incorporate a controlled overflow pathway. The paper discusses the strengths, limitations and key design considerations of each type, emphasising the importance of critical storm duration, long-term evolution of storage capacity and the sensitivity of non-discharge concepts to long-duration, multiday events.

Anchored in the 'hierarchy of closure needs', physical stability is treated as a non-negotiable constraint that must be satisfied before prioritising chemical, ecological or socio-economic outcomes. The paper outlines guiding principles for risk-based option assessment, advocating for robust and redundant designs for a range of futures.

Two hypothetical case studies illustrate how these principles can be applied: a paddock TSF where a predominantly non-discharge concept is strengthened by adding an emergency overflow; and a lined TSF with reactive tailings where long-term ponding is unacceptable, necessitating a direct-shed landform and engineered cover. Drawing on these examples, the paper argues that, for most closed TSFs, an emergency spillway or controlled overflow pathway should be regarded as a minimum closure feature to strengthen long-term safety and resilience.

Keywords: *tailings storage facility, mine closure, water management, freeboard, critical storm duration, overtopping risk, spillway design, climate change, risk assessment*

1 Introduction

Water is arguably the dominant driver of tailings storage facility (TSF) failures, both during operations and in closure. Weather-triggered tailings flow incidents are increasing, with extreme rainfall and flood events frequently implicated as initiating or contributing causes of TSF failures (Rana et al. 2021). Overtopping alone is recently noted as the most common TSF failure mode (in failures that have occurred since the year 2000) (Stark et al. 2022) and the (equal) most common failure mode in closure landforms (Barsi & Slingerland 2025). In closure, the nature of TSF water management changes fundamentally – operational controls such as active

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decant pumping, monitoring, inspections and emergency intervention are progressively reduced or ceased. Closed TSFs must rely on passive systems to safely manage water for very long time frames, often considered as 'in perpetuity'; noting that 'in perpetuity' is best understood as a design philosophy of passive resilience rather than an assumption that no further management or review will ever occur.

Closure water management strategies for TSFs can be conceptualised along a spectrum ranging from fully non-discharge facilities through hybrid store-then-spill configurations to facilities that routinely shed water via spillways or outlet structures. Each approach presents different advantages, limitations and risk profiles in closure. Non-discharge strategies aim to avoid releases but rely on adequate basin storage and freeboard; direct-shed facilities minimise stored water but rely on passive outflow structures, and store-then-spill concepts lie between. Selecting a preferred strategy is site-specific and requires balancing the respective risks.

Closure designs must recognise that physical stability is the foundational prerequisite for all other closure objectives. The 'hierarchy of closure needs' [Asia-Pacific Economic Cooperation (APEC) Mining Task Force 2018] places physical stability at the base, supporting chemical stability, environmental performance, beneficial land use, socio-economic outcomes and biodiversity. If a TSF fails physically (e.g. through overtopping, slope instability or internal erosion), none of these higher-order goals can be sustained. Decision-making tools, such as the commonly used multiple accounts analysis (MAA), must be applied carefully to avoid treating physical stability as one criterion among many, to be weighed against environmental, social and economic factors; that is, to not underplay the non-negotiable nature of physical stability and favour options that deliver attractive secondary benefits (for example improved revegetation or reduced downstream discharge) at the cost of elevated physical-failure risk.

The challenges of TSF closure design are amplified by deep uncertainty in long-term climate and landform evolution. Typical closure design lives of 300–1,000 years (and beyond) extend well past the horizon of most climate projections. Non-stationary rainfall statistics, evolving catchment conditions and gradual changes in TSF geometry (e.g. settlement, erosion, sedimentation and tailings consolidation) can materially affect storage and freeboard performance over time.

As such, there is a need for practical guidance on how to evaluate closure water management options for TSFs using a risk-based framework that recognises the criticality of physical stability. This paper focuses on the question 'To spill or not to spill?' in closure: whether TSFs should incorporate spillways or controlled overflow pathways as standard closure features, and how that decision can be justified. While every TSF is unique and there is no one-size-fits-all closure strategy, this paper highlights the challenges and presents some general principles to consider when selecting TSF closure water management strategies.

2 Closure water management

The transition from operations to closure fundamentally changes the way water is managed on a TSF. During operations, water levels and pond locations are actively controlled through passive or pumped discharge systems, supported by routine monitoring, inspection and maintenance. Critical conditions can be detected and addressed.

At closure, discharge systems and pumps are decommissioned or left in a reduced-capacity state that cannot be relied upon indefinitely. Emergency interventions that depend on immediate mobilisation of equipment and onsite staff become less realistic as the site transitions from operations. A closure water management strategy must thus be defined to ensure that the closed TSF is capable of passively managing water in perpetuity without regular intervention. In practice, this means that closure designs must be robust to climatic and hydrological variability without relying on delicate engineered elements or ongoing operational controls.

Closure water management for TSFs can be conceptualised in terms of 3 idealised strategies:

1. Type 1 – non-discharge. The landform is designed to retain all flood water within the basin. No spillway is present

2. Type 2 – direct-shed. The landform is designed to shed all flood water via a spillway. No water is retained within the basin
3. Type 3 – store-then-spill (hybrid). The landform is designed to retain some flood water within the basin. Once the available storage capacity is exceeded, excess flow is discharged via a spillway (i.e. falling between Types 1 and 2).

Most industry guidance and standards such as ICOLD (2025) and ANCOLD (2019) support that good practice is to always include a spillway – even in non-discharge facilities – to passively pass significant design floods in emergency scenarios. However, spillways can be complex and costly to construct, and inherently introduce additional risks, particularly for facilities lacking a suitable spillway location. The closure design must therefore be based on well-justified, risk-based decisions that balance the risks associated with discharging versus storing water.

2.1 Type 1: non-discharge

In arid and semi-arid climates it is common to design and operate TSFs as non-discharge systems in which all inflows are retained within the TSF basin under both normal operating and flood conditions. This approach can be attractive where a site-wide water deficit is present, evaporation significantly exceeds rainfall, catchment areas are limited (e.g. paddock-style facilities), large tailings beach areas provide substantial storage, suitable spillway alignments are unavailable or complex, and/or downstream discharge water-quality risks are high.

In many situations it is considered more cost- and/or risk-effective to rely on a combination of basin storage and freeboard to contain floodwater, functioning as the primary defence against water-driven failure modes. This is particularly common in Western Australia (WA), supported by WA regulatory guidance (DMP 2015) which states that '…the use of spillways is not encouraged, particularly for paddock or ring-dyke type facilities with perimeter retaining structures constructed using tailings.'

Maintaining larger ponds or higher degrees of saturation within the tailings basin at closure can appear more cost effective and present additional benefits, such as sustaining vegetation and reducing downstream discharge volumes. The non-discharge label can also simplify stakeholder communication and project approvals.

However, added stored water can raise the risk of overtopping, result in elevated phreatic surfaces and associated slope instability, exacerbate the risk of internal erosion or piping, and increase infiltration, seepage and chemical risks.

Further, when active discharge systems are removed in closure, the only outflows in a non-discharge TSF are passive (e.g. evapotranspiration and infiltration) and can be considerably slower than inflows. Thus, the critical storm duration is driven by the balance between increasing inflows, limited passive losses and decreasing storage capacity over time, and may be significantly longer than the default 24- to 72-hour duration events commonly adopted (Thomson et al. 2026, in press). The critical storm duration associated with a given design annual exceedance probability is inherently site-specific and tends to increase for rarer events, meaning that adopting a 24- or 72-hour design storm may substantially underestimate the overtopping risk for extreme events.

Given the reliance on available storage volume and remaining freeboard, the success of Type 1 configurations relies on accurate predictions of inflow ranges and the long-term evolution of basin and containment profiles. This is challenging for very long closure design lives.

Despite these limitations, Type 1 configurations are widely used in arid and semi-arid climates in Australia for both operations and closure.

2.2 Type 2: direct-shed

At the opposite end of the spectrum are closure configurations in which the TSF is designed to shed most incident water directly, with minimal storage within the basin. Conceptually, the closed facility has little or no permanent pond; precipitation and run-off are routed via a spillway or engineered outlet and discharged downstream for all events.

The key advantage of this approach is the reduced long-term hydraulic load on the embankment and tailings. By minimising potential ponding and maintaining low phreatic surfaces, direct-shed facilities can reduce the risk of geotechnical instability. Long-term performance becomes less sensitive to antecedent storage and settlement as the system does not rely on the maintenance of large internal storage volumes to remain below freeboard limits.

However, direct-shed designs rely on the performance of the spillway and the resilience of the receiving downstream environment. Spillways and outlet structures can be subject to gradual degradation and blockage through erosion, deposition, abrasion and weathering. Uncertainty in future land use, catchment conditions and climate can alter inflows and hydrograph characteristics, potentially exceeding the original design expectations and stressing spillway capacity.

Where receiving environments are relatively resilient, tailings are benign or can be effectively isolated from surface run-off, and stable spillway alignments and armouring material are available, direct-shed closure configurations can be highly effective. They can be more readily designed to be robust to long-term climatic variability. Nevertheless, because spillways become the critical safety element, they must be designed for very high durability and passive reliability.

2.3 Type 3: store-then-spill

Store-then-spill hybrid configurations are designed to provide significant pond storage and attenuation up to a defined level, above which a spillway or engineered outlet activates. Under frequent and moderate events, the facility behaves similarly to a non-discharge system with no or minimal routine release. Under rarer, more extreme conditions, water is intentionally discharged along an engineered, armoured pathway.

The hybrid approach offsets some inherent disadvantages of fully non-discharge facilities by providing a fail-safe overflow mechanism while maintaining the advantages of water retention. Internal storage can buffer inflows, reduce the frequency of discharge and provide water to support revegetation or dust control, while the spillway or outlet releases water in a controlled manner rather than through uncontrolled overtopping of the containment structure.

Designing such systems requires careful definition of the activation or trigger level for overflow. This level must preserve adequate freeboard to the embankment crest for the design event while accounting for long-term changes in climate and TSF geometry, including embankment settlement and deformation, erosion of beaches and internal slopes, progressive sedimentation and infilling of ponded areas, and tailings consolidation.

2.4 Summary

A comparative summary of the 3 strategy types discussed above is provided in Table 1.

Table 1 Water management strategy comparative summary

Type	1. Non-discharge	2. Direct-shed	3. Store-then-spill
Concept	All inflows are retained within the tailings storage facility; no spillway or controlled outlets	Minimal or no permanent pond; inflows are routed to a spillway and discharged downstream	Some internal storage and attenuation up to a defined level; above this, a spillway or controlled overflow path activates
Typical settings	Arid and semi-arid climates; high evaporation; large basin storage volumes; high downstream water quality sensitivity; limited spillway options	Settings with resilient receiving environments; non-reactive tailings or effective segregation of contact water; favourable spillway alignments	Sensitive downstream environments where routine discharge is discouraged but emergency overflow is acceptable; sites where overflow can be routed along a low-consequence path
Main advantages	Simple ‘no-release’ message; potentially fewer regulatory obligations for discharge; avoids spillway construction and long-term reliance on spillways/outlets	Reduced long-term water load on facilities; lower phreatic surfaces and seepage pressures; no reliance on storm storage	Combines ‘non-discharge’ with a fail-safe overflow mechanism; reduces catastrophic failure risk from underestimated storage
Key risks and limitations	Increases risk of physical and chemical instability; high reliance on storage and freeboard (overtopping remains a leading failure risk)	Long-term risks of spillway blockage or degradation; more challenging to sustain vegetation	Relies on storage and freeboard estimates; needs careful selection of spill level; must manage occasional discharges and downstream impacts; spillway must remain functional over very long time frames
Critical design considerations	Robust water balance and critical-duration analysis; conservative freeboard allowing for long-term geometric (i.e. settlement, consolidation, sedimentation) changes; consideration of climate and hydrological uncertainty; monitoring of post-closure pond levels and settlement	Durable, low-maintenance spillway/outlet design; peak flow analysis to size spillway; erosion protection; robust water quality management	Peak flow analysis to size spillway; allowance for settlement, erosion, sedimentation and consolidation; robust design of controlled overflow pathway; defined closure criteria and regulatory approvals regarding rare-event discharges

3 Options assessment

3.1 Guiding principles

A closed TSF that is not physically stable cannot reliably support long-term land use, environmental or socio-economic outcomes. A breach or major instability event compromises chemical containment; damaging ecosystems and infrastructure, and undermining stakeholder confidence. Conversely, a physically stable landform can support higher-level objectives.

These relationships are conceptualised in the APEC Mining Task Force (2018) hierarchy of closure needs (Figure 1). If the base layer of physical stability is compromised, the higher-order layers above cannot be sustained. This implies that the choice of TSF closure water management strategy must first and foremost be tested against the implications for long-term physical stability. Only those options that demonstrably meet robust stability criteria under a range of future (and largely uncertain) conditions should be carried forward for optimisation against higher-order closure objectives.

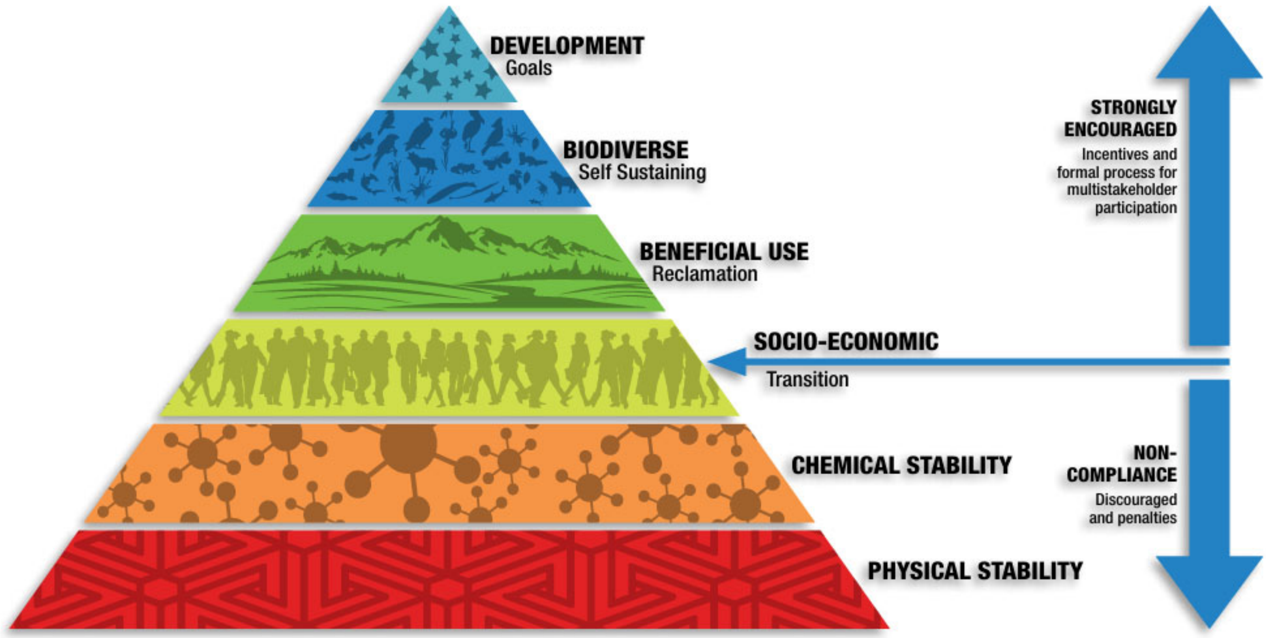

Figure 1 Hierarchy of closure needs (Asia-Pacific Economic Cooperation Mining Task Force 2018)

Closure planning frameworks frequently apply various decision-making tools such as MAA or similar to weigh environmental, social, technical and economic factors. While these tools are useful for structuring discussions and documenting value judgements, they must be applied with consistent alignment to the objectives. Stability must be treated as a non-negotiable basis for the overlying comparison of alternatives (i.e. there is no alternative that does not meet the stability requirements). Options that offer attractive secondary benefits such as enhanced revegetation, reduced surface water discharge or lower short-term cost should not be favoured if they increase the likelihood or consequences of physical failure.

On this basis, several guiding principles for closure water management of TSFs are proposed:

- Physical stability should be treated as a hard constraint. Options that cannot maintain acceptable levels of physical stability under credible extremes of hydrological and climatic loading should be eliminated outright, regardless of their performance on other metrics.
- Chemical and environmental performance are critical but secondary to physical stability. Where trade-offs are required it is preferable to accept additional water-quality impacts or monitoring than an elevated risk of catastrophic failure.

- Key stability-related design elements should be treated as minimum requirements. Examples include maintaining defensible freeboard margins under closure conditions and, in most settings, providing a controlled overflow path or emergency spillway to manage extreme or unforeseen events.
- Risk assessment should emphasise robustness and redundancy. Designs should perform acceptably across a wide range of plausible futures, not just under a single 'best estimate' scenario. Redundant safety features that are rarely or never activated in practice can still be justified where they can reduce the consequences of model error or unforeseen extremes.
- Tools used to trade physical-failure risk against cost or other benefits can give insufficient weight to low-probability, high-consequence events and should not be the primary basis for decisions about fundamental landform configuration. Pure cost-benefit approaches are inappropriate for decisions that materially affect structural stability.

3.2 Designing for the unknown

Mine closure design is conducted under deep uncertainty. Typical closure design lives of 300–1,000 years (and beyond) extend well beyond the range of reliable climate projections, and the long-term evolution of landforms and human land use is difficult to predict. In this context, design concepts that aim for finely optimised performance under a single 'most likely' future are inherently fragile.

Australian Rainfall and Runoff (Ball et al. 2019) states:

> *'…the defensibility of designing for specific climate change projections beyond 2100 is…questionable, and a more flexible and adaptive approach may be advisable. No formal guidance on adaptive approaches has yet been developed for flood design in Australia, but adaptive design generally involves building in flexibility to adapt to changing conditions.'*

An appropriate approach is to provide robust designs that are tested across a wide range of plausible futures, supported by redundancy in critical safety functions. Examples include:

- providing emergency spillways or controlled overtopping sections that may never activate under design-basis scenarios, but which ensure that any overflow occurs at a known, armoured location rather than through uncontrolled erosion of embankment crests
- allowing for conservative freeboard margins that can accommodate greater-than-anticipated settlement, erosion or climate shifts rather than minimising crest heights based on a single set of assumptions
- designing spillways and drainage structures with simple, durable geometries and materials that can tolerate gradual degradation without immediate loss of function.

The 'Rumsfeld matrix' provides a useful conceptual tool for framing these uncertainties as:

- known knowns – current climate statistics, present TSF geometry and storage, and observed performance during operations
- known unknowns – ranges of future climate change, long-term settlement and erosion patterns, spillway degradation and tailings consolidation
- unknown knowns – organisational knowledge that may be lost post closure, undocumented design assumptions and intent not carried forward into future management
- unknown unknowns – novel climate regimes, unprecedented combinations of events, and unforeseen failure mechanisms or human activities over centuries.

A robust closure design explicitly addresses the known unknowns through sensitivity analysis and conservative allowances, seeks to preserve or document critical organisational knowledge, and incorporates redundancy and controlled failure modes to mitigate the impact of unknown unknowns. A combination of engineering judgement, conservative assumptions and explicit recognition of non-negotiable safety constraints is required to design closed TSFs that are resilient over the very long term.

4 Examples

Two examples are presented to demonstrate how the recommended approach might be applied in practice. The examples are drawn from real closure projects, anonymised and simplified to protect client confidentiality and focus on the water management principles. These examples demonstrate the level of subjectivity and engineering judgement involved in the process.

4.1 Emergency overflow

The first example is a circular, above-ground, paddock-style TSF located in the semi-arid region of WA. Key features include:

- Tailings are deposited from a series of spigots around the perimeter of the basin, forming a beach that gently slopes away from the embankment towards a central decant pond.
- Tailings containment is provided by a perimeter embankment, raised downstream in stages, constructed from compacted, well-graded, non-acid forming waste sourced from the nearby open pit.
- The tailings are benign; the quality of surface seepage and infiltration to groundwater is not of concern.
- Supernatant water is reclaimed and returned to the plant such that the facility maintains a small operating pond (< 10% of the cell area) under normal conditions. Pan evaporation exceeds rainfall by a factor of 10.
- The TSF has sufficient freeboard to store in excess of the operational design storm (a 72-hour probable maximum precipitation – PMP – event) volume above the maximum operating level (MOL).
- The facility is operated as non-discharge, with no operational or emergency spillway in place.

The proposed post-mining land use is to reinstate natural ecosystems that are broadly similar to the pre-mining condition.

At the end of mine life, the TSF landform is expected to resemble a large circular structure with a relatively flat upper surface elevated above natural ground. Several closure concepts were considered, with the general intent to mimic the most similar natural analogues in the surrounding landscape.

Three different strategies were evaluated, as illustrated in Figure 2:

1. Type 1: non-discharge. In semi-arid conditions, the gently inward-sloping surface resembles an elevated salt pan. The non-discharge option seeks to emulate natural salt pans of the region, which exhibit very limited and slow recharge.
2. Type 2: direct-shed. The direct-shed concept would reconfigure the current inward-draining surface into a water-shedding landform. The design would take inspiration from the original topographical features and aim to align surface water flows with the pre-mining hydrological regime.
3. Type 3: store-then-spill (hybrid). The store-then-spill option is essentially a non-discharge (Type 1) configuration with an added 'emergency overflow' structure. The TSF basin has the capacity to store run-off from an extremely large storm, and the overflow is not expected to operate under expected design basis conditions. Instead, it is intended as a last line of defence against overtopping of the perimeter embankment. The overflow discharge is directed to an identified low-consequence pathway, avoiding sensitive environmental receptors and localised areas of high cultural heritage value.

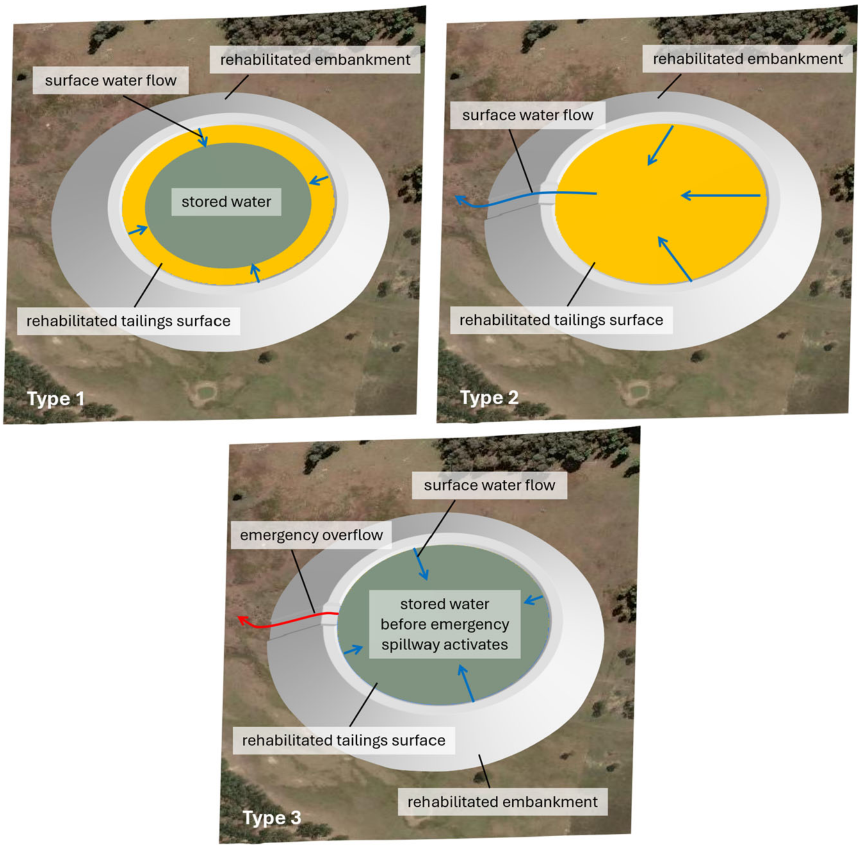

Figure 2 Emergency overflow example concepts

In the options assessment, Type 2 (direct-shed) was eliminated early because reprofiling the basin from inward draining to outward draining was assessed to be significantly more costly with negligible benefit in this context. The key decision therefore became whether the preferred concept should include an emergency overflow.

Although the basin has apparent excess capacity to store run-off from the operational design event (72-hour PMP), the critical storm duration in closure may be much longer than during operations. Following the approach suggested by Thomson et al. (2026), the closure critical storm duration for this TSF was estimated to be in the order of 2 to 3 months. Under such extreme conditions it is plausible that the pond could approach the embankment crest.

Combined with uncertainty in long-term conditions (e.g. settlement, erosion, climate change, human interventions and other unknown unknowns), this points to the need for a robust and resilient closure strategy. Inclusion of an emergency overflow – to prevent the pond from reaching and overtopping the embankment during unprecedented events – was assessed as a valuable enhancement to the robustness and resilience of the design and contributed to it scoring highest in the assessment.

The emergency overflow is implemented as a local low point in the embankment crest, with the downstream slope heavily armoured with competent rock. This arrangement controls where any (extremely unlikely) overtopping occurs and adds redundancy at little or no additional cost, given the ready availability of suitable rock armour. The feature was deliberately termed an 'emergency overflow' rather than a 'spillway' to emphasise that it is not anticipated to operate in normal or design basis conditions. Rather, it provides a preferential, controlled route for any overflow in extreme, emergency or unforeseen circumstances (accounting for the unknown unknowns).

Traditional qualitative risk comparison is of limited value in this case as the probability of the overflow being triggered is extremely low and effectively impossible to estimate with confidence. Similarly, a conventional MAA process would provide little insight.

Conceptually, this example illustrates how robust design under deep uncertainty can justify additional safety features even when the associated reduction in risk is difficult to quantify.

4.2 Direct-shed

The second example is a rectangular, above-ground, paddock-style TSF, also located in the semi-arid region of WA. Key features include:

- Tailings are deposited from a series of spigots along 3 sides of the basin, forming a beach that gently slopes towards a decant pond situated against the southern embankment.
- Tailings containment is provided by a perimeter embankment raised downstream in stages, constructed from compacted fine material from nearby borrow pits, with an outer shell of coarse, competent, non-acid forming waste.
- The basin footprint and upstream embankment slopes are lined with a dual-layer compacted clay and synthetic geomembrane liner.
- The tailings are highly reactive and potentially acid forming (PAF). As tailings become unsaturated and exposed to oxygen, they oxidise and generate acid and metalliferous drainage (AMD). The tailings are expected to remain a long-term contaminant source; and the rate of AMD generation will depend on the net rate of infiltration into the facility.
- The facility is designed to store water to support operations, as well as tailings. It maintains a large operating pond (up to 100% of the cell area) under normal conditions, with supernatant water reclaimed and returned to the processing plant.
- The TSF has sufficient freeboard to store in excess of the operational design storm (72-hour PMP) above the MOL. Pan evaporation exceeds rainfall by a factor of 10.
- The facility is operated as non-discharge, with no operational or emergency spillway in place.

The overarching TSF closure objective is to establish a safe, stable and non-polluting landform with self-sustaining vegetative cover.

Synthetic liners can be subject to degradation over time and often are not relied upon in perpetuity. Although the facility was designed to store water during operations, if the liner was to degrade significantly, long-term ponding would present significant risks, including:

- rising phreatic surfaces and saturation of foundation materials
- elevated potential for embankment instability and piping
- increased recharge and AMD generation from PAF tailings. Because the tailings will remain a long-term contaminant source, post-closure recharge to the tailings deposit must be limited to keep seepage and environmental impacts within acceptable bounds.

To meet closure commitments and create a safe, stable and non-polluting landform, a direct-shedding landform (Type 2) is necessary. Further, re-profiling the basin to shed run-off towards a central pond (i.e. a non-discharge or hybrid configuration) would be extremely costly and technically challenging due to the soft, saturated tailings, and would not adequately mitigate the risks highlighted above.

To prevent ponding, the final TSF surface will be shaped to shed water via a spillway on the southern side of the facility, discharging directly to the natural environment (see Figure 3). Given that the final tailings surface in this area is relatively low, the spillway will require a deep cut into the embankment; consequently, adequate flow capacity can be provided even with a relatively narrow spillway. A wider spillway (see Figure 3) was also considered to increase capacity, provide greater robustness and create a more natural landform profile, consistent with the principle of avoiding reliance on delicate engineered structures in perpetuity. While a larger spillway would incur higher costs, the incremental benefits are difficult to quantify in probabilistic terms.

Figure 3 Direct-shed overflow example concepts

As noted earlier, the final surface shape will maximise removal of surface run-off from the facility. However, water shedding alone is insufficient to minimise recharge to the underlying tailings. To further reduce net infiltration the landform will be complemented by an engineered soil cover. Feasible cover options are constrained by available materials, climate and the required long-term performance. A synthetic cover was rejected due to the limited design life under the site conditions and replacement requirements. Given the arid environment, a clay barrier cover was not considered feasible due to the likelihood of clay barriers drying and desiccating during extended drought, and the limited availability of suitable non-reactive clays. A store-and-release cover was therefore adopted as the preferred conceptual option.

The engineered soil cover will:

- further limit infiltration from rainfall
- reduce oxygen ingress (a secondary objective to mitigate AMD generation)
- support the establishment of vegetation.

Therefore, the combination of a direct-shed landform and a store-and-release cover was identified as the most practical way to limit long-term hydraulic loading and recharge, thereby aligning physical and chemical stability with the overarching closure objectives.

5 Limitations

The work presented is subject to several limitations for which practical directions for improvement (e.g. better methods, systematic monitoring and decision-support tools) that highlight areas for further research and development are proposed as follows:

- climate and hydrologic uncertainty. Long-term projections of rainfall intensity, storm sequencing and catchment response remain uncertain beyond a few decades. Closure designs inevitably rely on extrapolation and scenario analysis. Improved methods for representing deep uncertainty (e.g. through robust decision-making and ensemble climate projections) would support more defensible closure criteria
- long-term performance data. There is limited empirical data on the performance of TSF spillways, embankments and covers over the multidecadal to centennial timescales relevant to closure. Systematic monitoring of closed facilities, combined with back-analysis of performance under extreme events, would help refine design assumptions for erosion, degradation and geomorphic evolution
- decision-making frameworks. Existing and emerging decision analysis tools must be used correctly and consider the hierarchy of closure needs. Appropriate decision-making frameworks must

translate the hierarchy-of-needs concept into everyday decision-making, helping practitioners and regulators distinguish between constraints (e.g. physical stability requirements) and objectives (e.g. revegetation, downstream flow restoration) in a transparent way without resorting to overly simplistic scoring or weighting approaches. Further, there is a need for practical tools to support decision-making between unquantifiable options (i.e. a wider, more robust yet costlier spillway).

6 Conclusion

Framing tailings storage facility (TSF) closure water management in terms of 3 idealised strategies – Type 1 (non-discharge), Type 2 (direct-shed) and Type 3 (store-then-spill) – provides a simple basis for comparing options and clarifying trade-offs in storage, discharge and long-term risk. Non-discharge and hybrid concepts can be attractive where some ponding supports revegetation, dust control or site water balance, but the additional stored water must be assessed carefully for its effects on the drivers of physical instability, such as elevated phreatic levels, internal erosion and overtopping. In some cases, directing water off the facility via robust spillways and infiltration-limiting covers may be essential to maintain both physical and chemical stability.

The examples illustrate how the hierarchy of closure needs can be applied in practice: options that cannot meet robust physical stability criteria are screened out before optimising for higher-order benefits. In one case, a predominantly non-discharge concept is strengthened by adding an emergency overflow that may never operate but provides a defined, armoured route for any extreme overflow. In the other example, a direct-shed landform with a store-and-release cover was selected to limit long-term recharge to reactive tailings despite higher cost, reliance on spillway performance and ongoing surface water discharge.

Given significant uncertainty in future climate, landform evolution and human use over centuries, finely optimised designs tuned to a single ‘best-estimate’ future are inherently fragile. For many closed TSFs, providing a controlled overflow path or emergency spillway, conservative freeboard and redundant safety functions should be regarded as good practice to deliver robust, resilient closure outcomes over the very long term.

References

APEC Mining Task Force 2018, Mine Closure Checklist for Governments, Asia-Pacific Economic Cooperation, https://www.apec.org/docs/default-source/Publications/2018/3/Mine-Closure-Checklist-for-Governments/218_MTF_Mine-Closure_Checklist-for-Governments.pdf

Australian National Committee on Large Dams (ANCOLD) 2019, *Guidelines on Tailings Dams-Planning, Design, Construction, Operation and Closure-Revision 1*.

Ball, J, Babister, M, Nathan, R, Weeks, W, Weinmann, E, Retallick, M & Testoni, I (eds) 2019, *Australian Rainfall and Runoff: A Guide to Flood Estimation*, Geoscience Australia, Version 4.2.

Barsi, D & Slingerland, N 2025, ‘Complete closure landforms: geomorphic design with commingled tailings and waste rock’, in S Knutsson, AB Fourie & M Tibbett (eds), *Mine Closure 2025: Proceedings of the 18th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, https://doi.org/10.36487/ACG_repo/2515_78

Government of Western Australia Department of Mines and Petroleum (DMP) 2015, *Guide to the Preparation of a Design Report for Tailings Storage Facilities (TSFs)*, Perth.

International Commission on Large Dams (ICOLD) 2025, *Tailings Dam Safety (ICOLD Bulletin 194*, Chatou.

Rana, NM, Ghahramani, N, Evans, SG, McDougall, S, Small, A & Take, WA 2021, ‘Catastrophic mass flows resulting from tailings impoundment failures’, *Engineering Geology*, vol. 292, https://doi.org/10.1016/j.enggeo.2021.106262

Stark, TD, Moya L, & Lin, J 2022, ‘Rates and causes of tailings dam failures’, *Advances in Civil Engineering*, https://doi.org/10.1155/2022/7895880

Thomson, HM, So, J & Walls, J 2026, ‘How long is long enough? Assessing the critical storm duration for non-discharge TSFs’, in *International Mine Water Association Congress 2026*, International Mine Water Association (IMWA), South Korea, in press.