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Application of Markov chain analysis to reclaimed mining landform portfolio management

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Abstract

The mining industry and regulatory body preference for 'walk away' closure remains an obstacle to relinquishment. Mine operators may choose to maintain dormant mine sites in care and maintenance to defer the prohibitive costs of constructing 'zero maintenance', long-life reclaimed landforms. Alternately, simpler reclamation designs coupled with post-relinquishment monitoring and maintenance may reduce closure costs while providing long-term reliability and societal value.

This work applies stochastic Markov chain analysis to assess projected performance for a hypothetical portfolio of mining landforms by defining asset condition and deterioration. Focusing on covered, vegetated tailings landforms we utilise 5 condition states: (A) exceeding performance targets; (B) performing adequately (good vegetation, some rilling); (C) performing poorly (struggling vegetation, some gullies); (D) imminent failure (poor or patchy vegetation, major gullies, minor tailings exposure); and (F) failed (major tailings exposure or loss of containment).

Twelve scenarios are evaluated at the portfolio level, combining 3 initial design capital expenditure levels (low, moderate and high) with 4 long-term management strategies (walk away, neglect, repair and routine maintenance). Transition and cost matrices are informed by literature case histories and professional experience to develop a statistical description of the financial consequences of the different management approaches. The analysis demonstrates that post-relinquishment monitoring and maintenance to manage event-driven landform degradation is less expensive than robust walk away design over a 100-year period, even when evaluated on an undiscounted cumulative cost basis.

The results imply that a relinquishment policy framework that accommodates monitoring and maintenance through the analysis of residual risk can improve post-operations landform utility. Explicitly allowing these routine interventions can facilitate the transition from care and maintenance to active post-mining land use managed by government or subsequent users.

Keywords: *Markov chains, portfolio management, mine relinquishment, net present cost, residual risk, landform evolution, tailings storage facilities, stochastic modelling*

1 Introduction

Mining provides materials to sustain the modern economy, including critical inputs for food, shelter, clothing, transportation and commerce. However, mining permanently alters the landscape, modifying topography and drainage by creating depressions, mounds and diversions, and changing soil and water quality by exposing rock fragments and ground rock flour to oxygen and moisture, while mixing other chemical constituents with tailings slurry waters.

This paper focuses on the relinquishment of tailings storage facility (TSF) landforms to explore the economics and plausibility of relinquishment, with and without long-term maintenance. Globally, mining produces large volumes of tailings annually, which are commonly deposited in TSF landforms that must subsequently be

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reclaimed. Rana et al. (2022) estimate the cumulative volume of tailings produced between 1965 and 2020 as 2.5×10^{11} m^3, deposited in an estimated 6,810 to 20,230 TSFs constructed over the same time frame. An individual TSF may have a construction and operational life span ranging from a few years to perhaps a decade.

The International Council on Mining and Metals (ICMM) addresses TSF landform relinquishment in its tailings management and mine closure guides (International Council on Mining and Metals [ICMM] 2025a, 2025b). The tailings management guide states that the absence of credible catastrophic failure modes is a prerequisite to relinquishment. The rigorous engineering assessment and classification required to definitively evaluate whether a failure mode is credible (Martens & Kupper 2024) contributes to the inherent regulatory complexity, leading the ICMM to conclude that, for many mines, the case for relinquishment may not exist. Cowan et al. (2013) describe Canadian processes and examples of relinquishment, acknowledging that full relinquishment is rare. Cowan et al. (2013) advocates 'design for relinquishment' for greenfield mine development and the expansion of existing mines. Designing for relinquishment requires thoughtful engineering design choices, from mineral processing methods to tailings and waste deposit development, geometry and post-mining land uses. Early engagement and consensus-building with regulators, local communities and post-mining land stewards are required to ensure the prerequisites for relinquishment are included as a component of the mine design basis.

Mining companies sometimes include the expectation for walk away conditions at closure, implying no ongoing need for monitoring, maintenance or repair. Regulators and local communities are understandably risk-averse, typically demanding that residual risks associated with reclaimed mines are no greater, and sometimes lower, than risks associated with the local natural landscape, requiring rigorous risk assessment methodologies (Pytel 2010). Identifying all credible failure modes and quantifying the residual risk of failure for each mode over time frames extending into perpetuity is practically impossible for all but the simplest sites with the lowest risks. Therefore, local communities, regulators and mine owners rarely agree to relinquishment for walk away closure. Instead, post-operations mines are typically maintained in a state of perpetual care and maintenance, offering little incentive for robust reclamation design. Historically, for many mines, this has been a path to abandonment through the eventual insolvency of the mine owner, resulting in unmanaged degradation where subsequent landform failures have caused severe, globally documented environmental and societal impacts (Islam & Murakami 2021; Pereira 2026).

This paper uses Markov chains to explore alternative pathways to relinquishment. The objective is to spark discussion between mining companies and regulators in their respective operating jurisdictions regarding alternative pathways to relinquishment. These pathways may include perpetual post-relinquishment routine monitoring, maintenance and repair, paid for from dedicated capital pools funded by solvent mining companies during operations. Stevens (2023) recognises that mining companies are transitory entities that create perpetual liabilities through mining. The alternative to the formal transfer of residual liability to the next land user, such as a government or private entity, is unplanned abandonment, where residual liability is transferred to the government and paid for by the broader society. Mines transferred through abandonment have commonly been poorly reclaimed and inadequately managed, and cost billions of dollars to properly reclaim, relying heavily on public funding. The former Giant mine (CIRNAC 2018) and Faro mine (CIRNAC 2021) are 2 prominent Canadian examples.

2 Background

2.1 Markov chains

Markov chains are commonly used in deterioration modelling applications to manage the life cycle of pavements, bridge structures, railway networks and pipeline systems. Markov chains can be applied to stochastic processes involving a sequence of random variables where the conditional probability distribution of future states depends strictly on the current state and not on previous states. Each possible state must be defined, with a transition state matrix providing the probability of transitioning from a given state to a different state. In the mining sector, Markov chain applications remain limited but have been utilised for predicting subsurface heterogeneity in contaminated soil management (Moon et al. 2012). The author did not identify pre-existing examples of Markov chain applications specifically developed to support reclaimed mining landform management.

2.2 Relinquishment

The ICMM (2025a) Integrated Mine Closure Good Practice Guide discusses relinquishment in the context of closure planning and execution, emphasising the need for early and ongoing engagement with regulators and stakeholders. ICMM (2025a) states that no credible catastrophic failure scenarios may exist for relinquishment to be viable. Furthermore, ICMM (2025a) notes that, 'the business case for relinquishment must be balanced rationally, with the ongoing costs and liabilities of maintaining ownership of a site weighed against the cost and difficulty of securing relinquishment. Relinquishment may not always be the preferred outcome.'

Conversion from an active TSF to a landform is a prerequisite to reclamation, closure and relinquishment. According to the ICMM (2025b) Tailings Management Good Practice Guide, landforms 'meet the objective of being long-term, stable earth structures which are capable of being closed with surveillance and limited management or maintenance requirements. To be considered a landform, the facility cannot develop a credible catastrophic failure scenario.' Designing for relinquishment, therefore, must include designing to eliminate credible catastrophic failure scenarios present during operations and designing landforms for which no credible catastrophic failure scenarios are projected to develop over time.

2.3 Tailings storage facility failure modes and rates

Rana et al. (2022), supported by updated statistical analyses (Rana et al. 2023; Vidal & Macciotta 2025), report a total of 303 TSF failures between 1965 and 2020 out of an estimated 6,810 to 20,230 TSFs constructed over the same period. The resulting TSF failure rate is 1.5 to 4.4% over the 55-year period, equating to 5.5 TSF failures per year, or 0.03 to 0.08% (i.e. 3 to 8 in 10,000). Vidal & Macciotta (2025) indicate that slope instability, overtopping, and seepage are the most common triggering mechanisms for TSF failure, with more than 90% of failures occurring during the operational phase. Dams constructed by the upstream method have experienced more failures than downstream, water retention or centreline-constructed dams. Key indicators for failure include excessive porewater pressure, reduced freeboard, slope deformation and foundation conditions.

Failure rates for reclaimed or relinquished TSF landforms may be lower than reported for operational facilities as suggested by the 90 to 10% split between reported failures during operations versus post operations, respectively. However, additional failure modes may develop over long time frames, such as blocked outlets, plugged drains, geochemical reactions, slow seepage of poor-quality tailings-affected water, erosion driven by rare storms and seismic deformation by rare earthquakes (Martens & Kupper 2024). In addition, uncertainty regarding the true frequency of extreme seismic and storm events and potential changes in the intensity and frequency of future storm events creates uncertainty in quantifying failure risks for the exposure periods of centuries for relinquished landforms. In the absence of specific statistical analysis for reclaimed TSFs, the range of TSF failure rates described by Rana et al. (2022) is used as the basis for post-reclamation TSF failure in the present study.

3 Methods

3.1 Tailings storage facility landform relinquishment cases

A generic TSF reclamation scenario was developed to evaluate the hypothesis that less robust reclamation, combined with routine monitoring, maintenance and repair, is less costly than robust reclamation designed for walk away closure following a post-reclamation monitoring period of a few years. The assumed starting point is the moment of relinquishment following a post-reclamation monitoring period sufficient to confirm that the reclaimed landform is performing consistently with the design intent. It is assumed that each reclaimed TSF landform has been evaluated and that no credible catastrophic failure mode can develop post relinquishment. Generic reclamation cost estimates were developed for landforms to be reclaimed to upland or shallow water wetland habitat, with a post-mining land use intended to provide habitat for local wildlife.

Table 1 summarises the scenarios considered. Three reclamation cases were evaluated: basic (low capex); typical (moderate capex); and robust (high capex). Four conditions were simulated for each case: walk away (or abandonment); neglect; repair; and routine maintenance. Thus, 12 scenarios were evaluated overall. The scenarios are comparative to explore the relationships between capital costs, operating costs and landform performance. Actual landform design and performance depend on site-specific conditions that inform optimisation and design trade-offs. See Table 1 for additional details regarding each scenario.

Table 1 Relinquishment scenarios and associated costs (AUD thousands)

Case	Construction	Annual monitoring	Maintenance	Repair	Reconstruction
Low capex	5,000	10	500	5,000	100,000
Moderate capex	50,000	10	5,000	50,000	100,000
High capex	100,000	10	10,000	100,000	100,000

3.2 Transition states

Five transition states were defined for each scenario: A (performing well); B (performing adequately); C (degraded); D (failing); and F (failed). In this context, a failed condition is not a catastrophic failure (i.e. the latter causes fatalities or extensive environmental damage), which is assumed to be non-credible. Rather, failure is defined as a non-catastrophic loss of containment due to physical instability or seepage of poor-quality water. Table 2 provides a description of each of the 5 transition states.

Table 2 Transition states

State	Description
State A	Exceeds performance targets, with established, healthy vegetation and stable drainage; any erosion features are minor and not progressing. Overall condition is better than the design performance criteria
State B	Meets design performance criteria, with good vegetation cover and early-stage erosion features such as some rilling. No significant gully development is present and tailings are not exposed
State C	Falls below design performance criteria, with patchy or struggling vegetation and more advanced erosion including some gullies. Containment is still maintained and tailings are generally not exposed
State D	Indicates imminent failure, with poor or patchy vegetation and major gullies and/or other advanced erosion features approaching loss of function. Minor tailings exposure may be present, and the landform is likely to transition to failure without intervention
State F	Indicates non-catastrophic failure, with major tailings exposure and/or loss of containment (e.g. breach or uncontrolled seepage). Condition is beyond acceptable performance and requires reconstruction or other major corrective works

Transition matrices were defined for each of the 12 scenarios (Table 3). An annual timestep was used to calculate state transitions. The typical walk away transition state matrix was calibrated to produce a TSF failure rate between 0.03 and 0.08% per year at year 50, consistent with the historical TSF failure rate (Rana et al. 2022). The basic walk away transition state matrix was calibrated to 10× the typical failure rate.

The robust walk away failure rate was calibrated to 0.5× the typical failure rate. Succession (States B to A transition) and self-armouring (States C to B transition) were considered plausible, with failure (State F) representing a trapped state for the walk away case. The transition state matrices for the basic and robust cases were adjusted from the typical case, based on the author's judgement.

The neglect case reflects ad hoc, periodic monitoring with post-failure repairs only. Repairs are modelled to require 10 years and restore the TSF from State F to B, accounting for the time required for discovery, design, permitting, construction and initial post-construction monitoring. The repair case reflects routine monitoring, with repairs causing a transition from State D to B over 5 years. The maintenance case reflects routine, active monitoring and maintenance, with annual activities facilitating a transition from State C to B over 2 years. This reflects efficient landform triage and repair processes funded by an annual budget.

3.3 Estimated costs

Initial construction costs, routine monitoring, maintenance and repair costs were developed based on general experience in the Canadian context. Post-failure repair costs were set at 2× the initial construction cost for robust reclamation to reflect the costs associated with legal action, regulatory consequences and reputational damage caused by TSF landform failure. The 2x estimate is based on the expectations of less efficient repair than initial construction due to the passage of time and corresponding loss of institutional knowledge, use of contractor rather than mine fleet construction equipment, and an increased level of review and scrutiny for design and construction that would be anticipated after a failure.

Post-failure repair to a robust reclaimed standard is expected, even though catastrophic failure is non-credible for the considered scenarios. Table 1 summarises the initial construction costs, annual monitoring costs to maintain States A and B, maintenance costs (State C to B transition), repair costs (State D to B) and reconstruction costs (State F to B transition). The costs to transition states were multiplied by the conditional transition probabilities to derive an annual cost for each transition.

4 Results

4.1 Landform deterioration

Figure 1 illustrates the evolution of the distribution of transition states for the 12 scenarios over 100 years for a hypothetical portfolio of TSF landforms. Table 4 provides a summary of the distribution among performing (States A and B), degraded (States C and D) and failed (State F) landforms. The walk away cases will continue to evolve until 100% of the landforms eventually fail, as State F is defined as a trapped state. The possibility that a failed TSF landform could self-heal over very long time periods (e.g. centuries) was not modelled. Mathematically, 100% of the walk away relinquished TSF landforms eventually fail under the assumption of a non-zero annual probability of failure. In reality, spontaneous recovery from a failed state may occur through natural processes and ecological succession that were not considered in the present study. The time for 50% (t50) of the landforms to fail under walk away conditions is sensitive to the transition state matrix assumptions, with t50 of 90 years for the low capex case, 800 years for the moderate capex case and 1,400 years for the high capex case. Other landform stabilisation mechanisms that could potentially stabilise landforms over very long time periods, such as physical and chemical weathering, cementation, and soil and vegetation development, were not represented. Such mechanisms could conceivably create self-healing conditions for walk away scenarios over time periods of centuries to millennia.

Table 3 Transition state matrices

a. Low capex – walk away

From/to	State A	State B	State C	State D	State F
State A	0.9780	0.0100	0.0060	0.0040	0.0020
State B	0.0025	0.9805	0.0100	0.0020	0.0050
State C	0.0000	0.0040	0.9790	0.0090	0.0080
State D	0.0000	0.0000	0.0000	0.9780	0.0220
State F	0.0000	0.0000	0.0000	0.0000	1.0000

b. Low capex – neglect

From/to	State A	State B	State C	State D	State F
State A	0.9780	0.0100	0.0060	0.0040	0.0020
State B	0.0025	0.9805	0.0100	0.0020	0.0050
State C	0.0000	0.0040	0.9790	0.0090	0.0080
State D	0.0000	0.0000	0.0000	0.9780	0.0220
State F	0.0000	0.1000	0.0000	0.0000	0.9000

c. Low capex – repair

From/to	State A	State B	State C	State D	State F
State A	0.9780	0.0100	0.0060	0.0040	0.0020
State B	0.0025	0.9805	0.0100	0.0020	0.0050
State C	0.0000	0.5000	0.4830	0.0090	0.0080
State D	0.0000	0.2000	0.0000	0.7780	0.0220
State F	0.0000	0.1000	0.0000	0.0000	0.9000

d. Low capex – maintain

From/to	State A	State B	State C	State D	State F
State A	0.9780	0.0100	0.0060	0.0040	0.0020
State B	0.0025	0.9805	0.0100	0.0020	0.0050
State C	0.0000	0.5000	0.4830	0.0090	0.0080
State D	0.0000	0.2000	0.0000	0.7780	0.0220
State F	0.0000	0.1000	0.0000	0.0000	0.9000

e. Moderate capex – walk away

From/to	State A	State B	State C	State D	State F
State A	0.9928	0.0040	0.0020	0.0010	0.0002
State B	0.0050	0.9875	0.0050	0.0020	0.0005
State C	0.0000	0.0080	0.9882	0.0030	0.0008
State D	0.0000	0.0000	0.0000	0.9988	0.0012
State F	0.0000	0.0000	0.0000	0.0000	1.0000

f. Moderate capex – neglect

From/to	State A	State B	State C	State D	State F
State A	0.9928	0.0040	0.0020	0.0010	0.0002
State B	0.0050	0.9875	0.0050	0.0020	0.0005
State C	0.0000	0.0080	0.9882	0.0030	0.0008
State D	0.0000	0.0000	0.0000	0.9988	0.0012
State F	0.0000	0.1000	0.0000	0.0000	0.9000

g. Moderate capex – repair

From/to	State A	State B	State C	State D	State F
State A	0.9928	0.0040	0.0020	0.0010	0.0002
State B	0.0050	0.9875	0.0050	0.0020	0.0005
State C	0.0000	0.5000	0.4962	0.0030	0.0008
State D	0.0000	0.2000	0.0000	0.7988	0.0012
State F	0.0000	0.1000	0.0000	0.0000	0.9000

h. Moderate capex – maintain

From/to	State A	State B	State C	State D	State F
State A	0.9928	0.0040	0.0020	0.0010	0.0002
State B	0.0050	0.9875	0.0050	0.0020	0.0005
State C	0.0000	0.5000	0.4962	0.0030	0.0008
State D	0.0000	0.2000	0.0000	0.7988	0.0012
State F	0.0000	0.1000	0.0000	0.0000	0.9000

i. High capex – walk away

From/to	State A	State B	State C	State D	State F
State A	0.9964	0.0020	0.0010	0.0005	0.0001
State B	0.0050	0.9917	0.0020	0.0010	0.0003
State C	0.0000	0.0080	0.9901	0.0015	0.0004
State D	0.0000	0.0000	0.0000	0.9990	0.0010
State F	0.0000	0.0000	0.0000	0.0000	1.0000

j. High capex – neglect

From/to	State A	State B	State C	State D	State F
State A	0.9964	0.0020	0.0010	0.0005	0.0001
State B	0.0050	0.9917	0.0020	0.0010	0.0003
State C	0.0000	0.0080	0.9901	0.0015	0.0004
State D	0.0000	0.0000	0.0000	0.9990	0.0010
State F	0.0000	0.1000	0.0000	0.0000	0.9000

k. High capex – repair

From/to	State A	State B	State C	State D	State F
State A	0.9964	0.0020	0.0010	0.0005	0.0001
State B	0.0050	0.9917	0.0020	0.0010	0.0003
State C	0.0000	0.5000	0.4981	0.0015	0.0004
State D	0.0000	0.2000	0.0000	0.7990	0.0010
State F	0.0000	0.1000	0.0000	0.0000	0.9000

l. High capex – maintain

From/to	State A	State B	State C	State D	State F
State A	0.9964	0.0020	0.0010	0.0005	0.0001
State B	0.0050	0.9917	0.0020	0.0010	0.0003
State C	0.0000	0.5000	0.4981	0.0015	0.0004
State D	0.0000	0.2000	0.0000	0.7990	0.0010
State F	0.0000	0.1000	0.0000	0.0000	0.9000

Table 4 Summary of year 100 condition state distributions and annual management costs

Case	State A	State B	State C	State D	State F	Annual cost (AUD thousands)
Low capex – walk away	3.5%	18.7%	15.7%	9.7%	52.3%	0
Low capex – neglect	5.6%	48.8%	24.7%	13.5%	7.4%	740
Low capex – repair	6.4%	58.2%	28.0%	1.8%	5.6%	580
Low capex – maintain	8.7%	83.9%	1.7%	1.0%	4.7%	490
Moderate capex – walk away	20.8%	38.7%	18.4%	16.6%	5.5%	0
Moderate capex – neglect	21.5%	42.0%	19.0%	17.0%	0.6%	60
Moderate capex – repair	24.0%	53.3%	21.3%	1.0%	0.5%	110
Moderate capex – maintain	28.4%	69.6%	0.8%	0.8%	0.4%	100
High capex – walk away	29.1%	49.8%	9.7%	8.4%	3.0%	0
High capex – neglect	29.5%	51.8%	9.9%	8.5%	0.3%	30
High capex – repair	31.0%	57.9%	10.4%	0.4%	0.3%	80
High capex – maintain	33.3%	65.7%	0.3%	0.4%	0.2%	80

For the neglect and repair cases, the state distribution continues to evolve at year 100, as State B transitions to State A, as well as to States D and F. For the maintain cases, the distribution between States A and B is still evolving at year 100 due to dynamics between landform development (States B to A) and degradation (States A to B), while the distribution of degraded and failed states has stabilised.

The impacts of initial landform design and the degree of monitoring and maintenance are evident in Figure 1. The low capex cases transition to failed states, with 52.3% of the TSF landforms failing by year 100 under walk away conditions, compared to 5.5% of the moderate capex landforms and 3.0% of the high capex landforms. The combination of a relatively high annual probability of failure and an assumed 10-year reconstruction timeline for failed landforms results in a steady-state level of 4.7% for failed landforms in the low capex case with routine monitoring and maintenance. This compares to 0.4% for moderate capex and 0.2% for high capex landforms under conditions of routine monitoring and maintenance.

For the high capex case, 79% of the relinquished landforms are performing (States A + B) at year 100 under walk away conditions, which is similar to the 81% performing under neglect, but less than the 89% performing under repair and 99% under maintenance conditions. The moderate capex case achieves a 98% level of performing landforms under maintenance, declining to less than 80% for repair, neglect or walk away conditions. The low capex case achieves 93% performing landforms under maintenance, declining to less than 65% under repair due to the higher probability of failure.

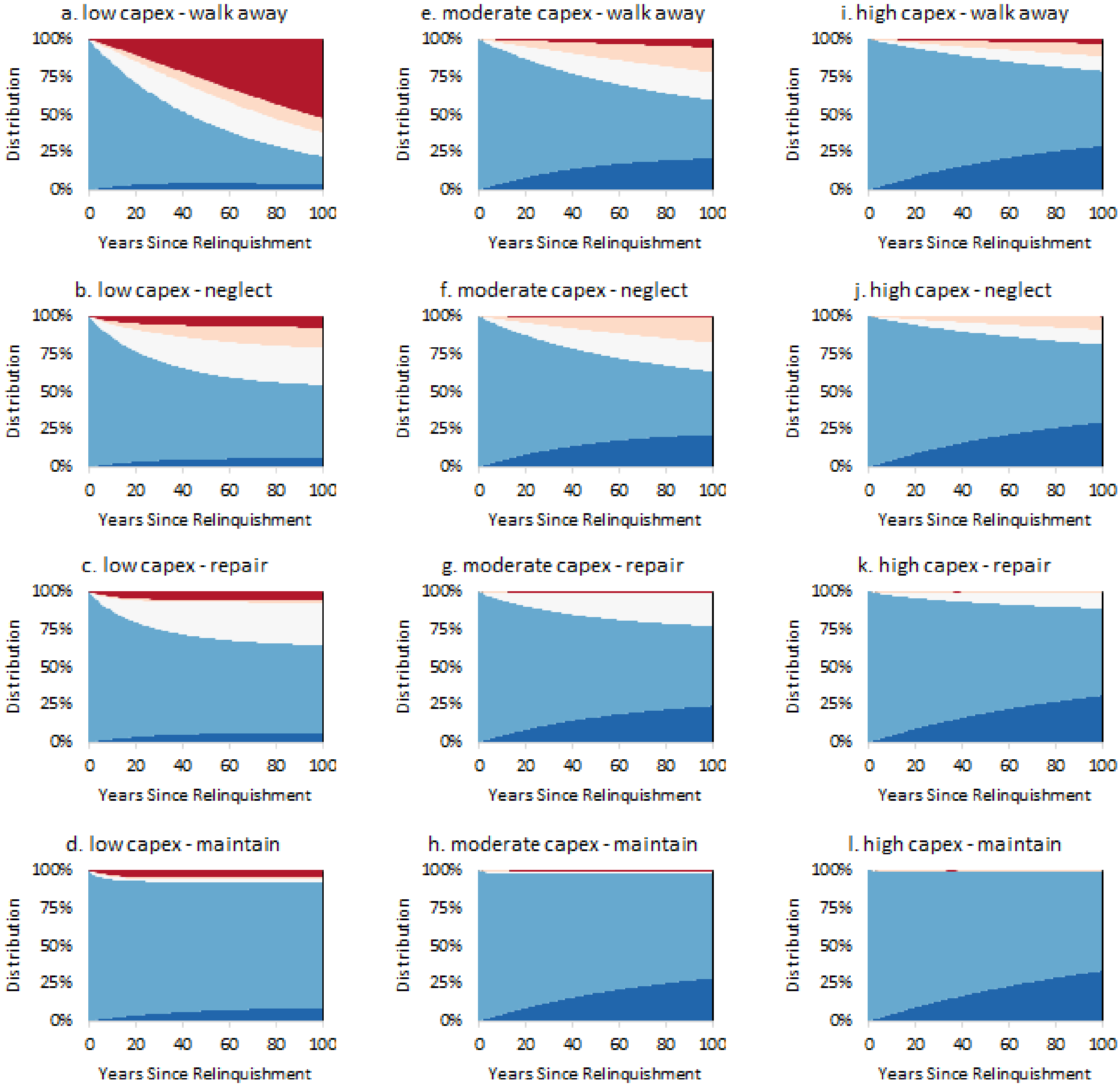

Figure 1 Condition state evolution over a 100-year post-relinquishment period for a hypothetical portfolio of reclaimed tailings storage facility (TSF) landforms. The 12 subplots illustrate performance trajectories for low, moderate, and high capex reclamation (columns) with walk away, neglect, repair and maintain long-term management strategies (rows). Landform conditions are State A (dark blue), State B (light blue), State C (pale grey), State D (pink), and State F (red)

4.2 Estimated costs

Figure 2 illustrates the undiscounted cumulative costs to manage the portfolio of landforms for each case, normalised on a per-landform basis. Because the TSF landform portfolio will comprise landforms of various ages at different times, the initial capital costs (Table 1) and steady-state annual costs (Table 4) are of primary interest. Defining a representative discount factor for a perpetual environmental liability portfolio is highly contested in the literature; standard positive commercial discount rates mathematically diminish long-term intergenerational liabilities to near zero, and if the cost escalation of specialised remediation outpaces trust yields, the real discount rate effectively becomes negative. To avoid these distortions and establish a conservative boundary condition, this analysis evaluates the economic scenarios on an undiscounted cumulative cost basis. Under this framework, monitoring, maintenance and repair costs dominate the cumulative costs for the low capex cases (except for the walk away scenario), whereas capital costs dominate the moderate and high capex cases.

Walk away is the lowest-cost scenario for each of the 3 design cases (Figure 2). Neglect is the next lowest cost for the moderate and high capex cases, while repair and maintenance costs remain similar to one another. For the low capex case, routine maintenance represents the second lowest cumulative cost after 100 years. The annual costs at year 100 are consistent with the cumulative cost trends. Aside from the walk away scenario, annual costs for the low capex cases are approximately an order of magnitude higher than annual costs for the higher capex scenarios. Annual costs for the moderate and high capex cases are on the same order of magnitude. Notably, the annual cost of neglect for the high capex case is approximately half the cost of repair or maintenance.

Figure 3 illustrates the sensitivity of the overall management cost to post-failure reconstruction costs. If post-failure reconstruction can be completed after relinquishment at the same cost as the initial reclamation, then the cost of failure plummets. In this case, the low capex reclamation approach is the least expensive because the cost penalty for failure is small. Neglect is the lowest-cost active management approach (after walk away) for all 3 cases in the absence of a cost premium for reconstruction. In practice, post-relinquishment reconstruction costs would be expected to be much higher than initial reclamation costs. Progressive reclamation by mine fleet equipment, supported by institutional knowledge, is generally more efficient than one-off construction projects. Regulatory, legal, reputational and land use interruption costs would be expected to further increase the cost of failure. Overall, this sensitivity scenario is not considered to be plausible.

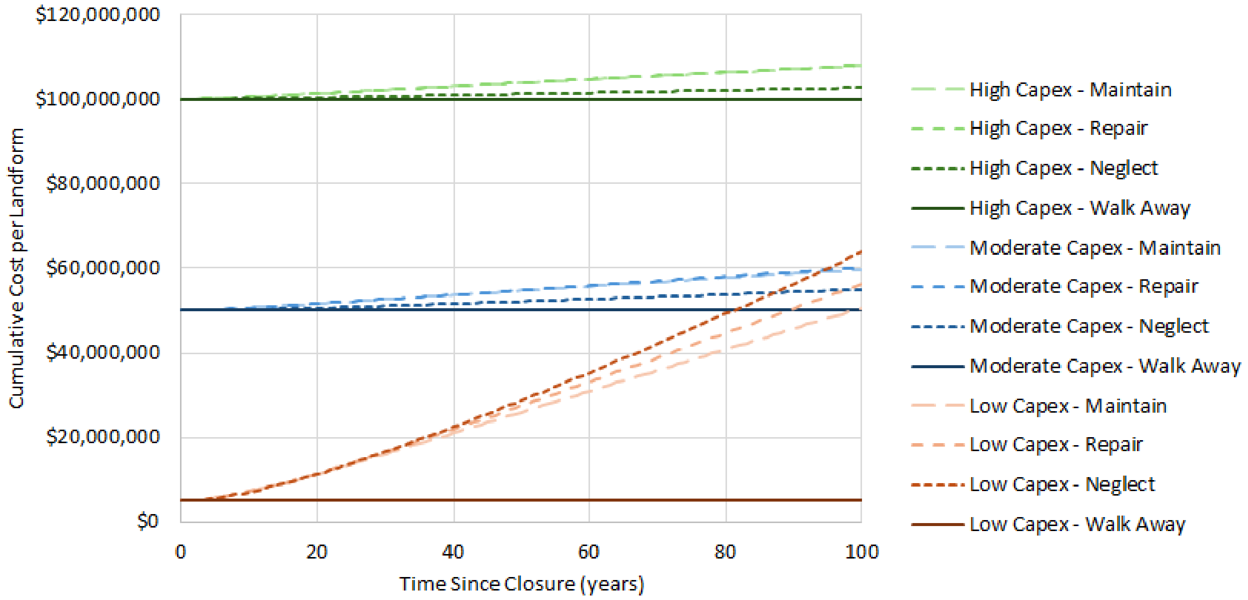

Figure 2 Undiscounted cumulative cost per landform over a 100-year post-closure period

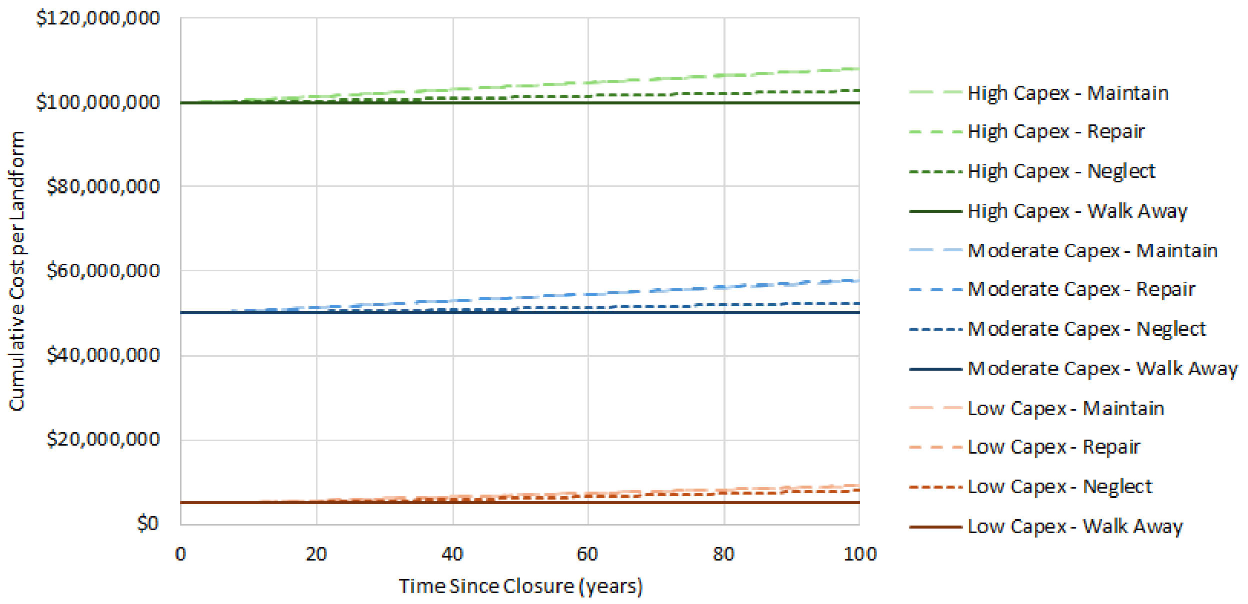

Figure 3 Undiscounted cumulative cost per landform over a 100-year post-closure period, with reconstruction costs set equal to initial capex

Table 5 provides a sensitivity analysis of the impact of discount rate for operating costs. As the discount rate increases from 0 to 5%, the net present cost (NPC) of the 100-year annual monitoring and maintenance costs decreases. The impact on total cost is modest for the moderate and high capex cases because the costs for those cases are dominated by the initial capital costs. For the low capex cases, capital costs are small compared to the annual costs, resulting in a significant reduction in total NPC as the discount rate increases.

Table 5 Sensitivity of 100-year net present costs monitoring, maintenance, and repair to changes in discount rate

	Costs by discount rate (AUD thousands)			
Case	**0%**	**1%**	**3%**	**5%**
Low capex – neglect	74,000	46,600	23,400	14,700
Low capex – repair	58,000	36,600	18,300	11,500
Low capex – maintain	49,000	30,900	15,500	9,700
Moderate capex – neglect	6,000	3,800	1,900	1,200
Moderate capex – repair	11,000	6,900	3,500	2,200
Moderate capex – maintain	10,000	6,300	3,200	2,000
High capex – neglect	3,000	1,900	900	600
High capex – repair	8,000	5,000	2,500	1,600
High capex – maintain	8,000	5,000	2,500	1,600

5 Discussion

The Markov chain analysis reveals critical trade-offs among the level of design, monitoring and maintenance, and acceptable performance. The low capex cases illustrate that a fragile design (e.g. incurring significant damage from a 1:10 year event) suffers from a chronic inventory of degraded and failed relinquished landforms, even when routine monitoring and maintenance are applied. The combination of a 0.5% annual failure rate and a 10-year reconstruction timeline results in a 4.7% steady-state failed inventory (State F) of relinquished landforms. This outcome is unlikely to be palatable to local communities, regulators or land stewards, except for landforms characterised by very low consequences of failure. However, at high discount rates or low reconstruction costs, the low capex design is significantly less expensive than moderate or high capex designs. If lower physical performance, the application of positive discount rates and expectations for cost-effective reconstruction can all be justified, then the low capex design approach, combined with active monitoring, maintenance, repair and reconstruction, may represent the optimal strategy.

The high capex cases illustrate the limitations of robust design in the context of historical TSF failure rates. At 100 years post relinquishment, 3.0% of the landforms are in a failed state (State F) under the walk away scenario, with 78.9% performing (States A + B) and 18.2% degraded or failing (States C + D). The analysis assumes that robust design can reduce the failure rate to half of the historical average, an assumption that may or may not be realistically achievable in practice. Any degree of repair or maintenance is adequate to reduce the failed inventory to 0.3% or lower. Furthermore, a 99.0% landform performance rate is achievable with routine monitoring and maintenance at an annual cost of only 0.08% of the initial capital cost.

With routine monitoring and maintenance, the moderate capex cases provide a level of overall post-relinquishment performance similar to that of the high capex cases. The moderate capex scenario achieves 97.9% steady-state post-relinquishment landform performance (States A + B), with a 0.4% inventory of failed landforms (State F) undergoing repair. Under the conditions assumed for this analysis, the moderate capex maintenance scenario outperforms the high capex walk away scenario at 60% of the cost.

Annual routine monitoring and maintenance costs equate to only 0.2% of the initial capital costs for the moderate capex scenario. Therefore, robust design intended to facilitate a walk away scenario would only be expected to be less costly than more modest design coupled with routine monitoring and maintenance if the incremental construction costs were minimal. Under most realistic scenarios, designing for reasonable operational events – such as 1:50- to 1:200-year storms – combined with a well-funded mechanism for routine post-relinquishment monitoring and maintenance is expected to be optimal. In accordance with ICMM (2025b), designing for relinquishment must eliminate all credible catastrophic failure modes. Beyond that prerequisite, the analysis suggests that landforms designed to accommodate common weather events, while allowing for long-term monitoring, maintenance and repair following rare events, cost less to manage and perform better than either fragile designs requiring extensive care or overly robust designs carrying high initial capital costs.

The requirement to eliminate credible catastrophic post-relinquishment failure modes introduces a critical limitation. The ICMM integrated mine closure good practice guide poses the following key question: 'Are residual risks compatible with relinquishment and/or the identified post-mine land use, and do all stakeholders understand the residual risks?' (ICMM 2025a)

Martens & Kupper (2024) stress the importance of identifying credible failure modes and assessing their risks while acknowledging the challenges and uncertainties associated with the risk assessment. According to ICMM (2025b), 'To be considered a landform, the facility cannot develop a credible catastrophic failure scenario.' Therefore, identification, assessment and elimination of credible catastrophic failure modes is a prerequisite to relinquishment. In addition, the assessment must demonstrate that no such failure modes could develop in the future. This requirement could be addressed for a particular credible catastrophic failure mode either by eliminating the failure mode altogether or reducing the potential consequences to a sub-catastrophic level through changes in design or post-construction mitigation. Good practice requires design for relinquishment, as advocated by Cowan et al. (2013), to address potential TSF failure modes early in the design process. For many as-built TSFs, eliminating all credible catastrophic failure modes may be cost prohibitive or practically impossible.

At a portfolio level, identifying pathways to eliminate credible catastrophic failure modes is a key priority for mine owners and the mining industry in general. For greenfield sites, including the explicit requirement for no credible catastrophic modes as part of each landform design basis would support this objective. For legacy sites, perpetual care and maintenance may continue to be optimal as the mining industry continues to develop innovative methods to stabilise tailings deposits and other landforms.

In addition to technical and financial considerations, the closure approach would need to be consistent with regulatory frameworks. Current financial assurance requirements may or may not account for perpetual maintenance costs. Mechanisms to transfer responsibility for long-term monitoring and maintenance to a third party may be undefined in some mining jurisdictions. Mine owners, regulators, long-term landform stewards and local communities will need to work together to develop overall policies and site-specific closure approaches that meet the objectives of each stakeholder group.

6 Conclusion

The mining industry requires a standardised framework for relinquishment to manage the large and continually growing global tailings storage facility (TSF) inventory. Designing for relinquishment explicitly requires the permanent elimination of all credible catastrophic TSF landform failure modes. For those landforms where catastrophic failure is definitively non-credible, relinquishment can release a mining company from ongoing liability; facilitating more productive allocation of capital. Simultaneously, relinquishment liberates the landform, enabling a beneficial next use and producing tangible value for society.

The analysis presented here suggests that reasonable landform design criteria, combined with routine, long-term monitoring and maintenance, is both more cost-effective and higher performing than robust design criteria intended solely to force walk away closure. Provided that credible catastrophic failure modes are eliminated prior to relinquishment, the residual risks and long-term costs to maintain post-mining landform performance can be successfully managed by the subsequent steward.

Regulatory frameworks that demand overly robust design and low residual liability on the day of relinquishment may inadvertently lead to poorer performance at higher societal costs, particularly if TSF landforms with minimal design are simply abandoned and returned to the responsibility of the government. Financial assurance frameworks that lack mechanisms for post-closure landform stewardship transfer may inadvertently create incentives for mine operators to maintain their facilities in a state of care and maintenance with low ongoing value and high residual liability. The absence of a mechanism to transfer financial assurance responsibility to the next steward through a negotiated process would be an additional barrier.

Regulatory frameworks that promote sound design and legally allow for ongoing monitoring and repair to manage residual risk after relinquishment (e.g. through structured financial bonding) are expected to yield superior outcomes. These outcomes include better reclaimed landform performance with greater public benefit (e.g. ecological, recreational, industrial utility) alongside lowered permanent liability for mining companies, promoting financial health and continued resource development to meet global public needs.

By aligning structural incentives for the public, mining companies and governments, the industry can achieve higher actual reclaimed TSF landform performance at a lower overall cost. This alignment allows mining operators to focus capital on resource development rather than managing balance sheets perpetually weighed down by large and growing liabilities associated with residual TSF risks.

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