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Pit Impact Risk Assessment Tool: using explicit uncertainty to drive progressive mine closure planning across a portfolio of open pit voids

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Abstract

Mine closure planning is fundamentally a problem of time-bound knowledge applied to permanent landforms. A pit void that will persist in the landscape for millennia must be assessed and managed using information that is incomplete at the time decisions are made and that improves only as the mine advances through its life cycle. The conventional industry response has been to defer detailed closure risk assessment until knowledge is considered adequate. This paper argues that a more effective approach is to make the current state of knowledge explicit at every stage, couple it visibly to a risk and uncertainty rating, and use that transparency to drive knowledge acquisition rather than waiting for it.

This paper describes the development of the Pit Impact Risk Assessment Tool (PIRAT), commissioned by BHP's Western Australia Iron Ore (WAIO) closure planning team to manage closure risks across its Pilbara open pit portfolio (Noonan et al. 2025). The tool applies a source-pathway-receptor scoring framework across 14 risk categories. Its distinctive contribution is a parallel knowledge base (KB) certainty assessment in which every risk score is accompanied by a certainty rating calibrated against the minimum acceptable knowledge standard for the pit's current stage of life. Where certainty falls below the threshold, the tool automatically flags to the user, making knowledge gaps as visible and actionable as the risks themselves. The tool's forward work program output translates these flags directly into a prioritised schedule of studies. PIRAT is a screening and prioritisation tool. It identifies which pits warrant detailed study and in what sequence, and does not replace the detailed hydrogeological, geochemical and ecological studies that follow.

The paper presents the tool's design rationale, risk architecture, scoring methodology and preliminary outputs from 2 pits in the test hub, representing the first test data entered into the tool. The results illustrate how pits with the same closure strategy and life cycle stage can carry meaningfully different risk profiles and how the certainty framework reveals that both are currently relying on an inadequate knowledge base for their most critical closure control. The project is ongoing; findings are presented as at March 2026.

Keywords: *mine closure planning, closure risk assessment, knowledge uncertainty, source-pathway-receptor framework, progressive closure planning.*

1 Introduction

There is a structural tension at the heart of mine closure planning that is rarely acknowledged explicitly. The risks created by pit voids to groundwater (GW) systems, surface water, ecosystems, human safety and cultural values are effectively permanent. Yet the knowledge on which closure planning depends is, by its nature, incomplete at the time it matters most; during the period when mine plans are being made, pit

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geometries are being set and waste management strategies are being designed, often years or decades before the pit closes.

This tension is not unique to mine closure, but it is unusually acute in the context of mine closure planning. In most engineering contexts, uncertainty can be managed through conservative design margins or by delaying commitment until better information is available. Neither option transfers easily to pit voids, for reasons specific to the permanence and scale of pit voids. Conservative margins for groundwater drawdown or pit lake chemistry mean different mine plans, which may conflict with extraction economics. Delaying serious closure risk assessment until knowledge is complete means losing the ability to change the mine design closer to the front end rather than managing the consequences, particularly cost and environmental impacts, after the fact.

The dominant response in practice has been a form of deferral. Closure studies are conducted thoroughly when a pit is approaching its end, and provisionally or not at all in the interim. The consequence, which is now well-documented in the Australian mine closure literature and increasingly reflected in regulatory requirements [Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) 2025], is that knowledge gaps which could have been addressed early at modest cost are instead discovered late, when options for mitigation are severely constrained and their cost is high.

The Pit Impact Risk Assessment Tool (PIRAT) takes a different position. Rather than deferring assessment until knowledge is adequate, it asks what can be assessed now, explicitly flags how reliable that assessment is, and uses the gap between current certainty and the required standard to generate a specific, actionable forward work program. The question the tool asks is not 'is this pit high risk?' in isolation. It asks how risky do we currently assess this pit to be, and how much should we trust that assessment?' Answering both questions simultaneously and making both answers visible on the same page fundamentally changes what a closure planning team does next.

2 The Pilbara context

2.1 Scale and setting

WAIO's operations encompass multiple mine sites across the Pilbara, collectively comprising numerous active, inactive and future open pits at various stages of their lives. Many pits extend to depths exceeding 150–220 metres below the ground surface and penetrate significantly below the regional watertable. When active dewatering ceases post mining, these below-watertable (BWT) voids will progressively fill to form pit lakes whose geometry, chemistry, salinity and long-term character will reflect the mineralogy of the surrounding rock mass, the acid and metalliferous drainage (AMD) potential of pit walls and waste materials, and the hydrogeological equilibrium that re-establishes in the absence of pumping (Lottermoser 2010).

The Pilbara's hydrogeological and ecological setting adds layers of complexity. The region's river systems support groundwater-dependent ecosystems, riparian vegetation communities, permanent and semi-permanent pools that are ecologically and culturally important and, in many cases, already under pressure from decades of pit dewatering. Subterranean fauna communities in alluvial aquifers may be sensitive to groundwater level changes and chemistry shifts that propagate well beyond the immediate pit footprint. The proximity of multiple pits within the same catchment system means that cumulative impacts to shared receptors can substantially exceed the contributions of any individual pit (Younger & Wolkersdorfer 2004).

2.2 Traditional owner values and the backfill commitment

A dimension that distinguishes WAIO's closure challenge from many other mining contexts is the clear and active role of traditional owner (TO) groups in defining what a successful closure outcome looks like. TO groups across the Pilbara have expressed an aversion to permanent pit lakes remaining in the landscape and a strong preference for post-mining land use that supports traditional cultural activities on Country. Permanent open water bodies, particularly those with saline or geochemically affected water, are not consistent with this vision.

BHP has responded by maximising pit backfilling to above the post-mining watertable where practicable. This approach has 2 important consequences for how closure risk is framed. First, it makes the feasibility and deliverability of backfilling programs a primary risk question, not a secondary mitigation option. Second, it creates an obligation to understand, early in the mine life, whether backfilling can achieve the intended outcome that requires knowledge of waste balance, geochemical classification of those materials, placement constraints and the water balance needs of managed aquifer recharge (MAR) programs designed to sustain groundwater-dependent receptors during the period of groundwater recovery. These are questions that cannot be usefully answered at the end of mine life. They must be asked and progressively answered from the planning stage onward.

2.3 Regulatory expectations

The 2025 DEMIRS Guidelines for Preparing Mine Closure Plans establish an explicit expectation that mine closure planning is a progressive, life cycle activity. The guidelines require that closure plans demonstrate an understanding of closure risks based on the best available information at each stage of mine development, and that forward work programs be defined and prioritised to address knowledge gaps in sequence with the life of asset (DEMIRS 2025). This is not simply a documentation requirement. It reflects a view, now well established in Australian mine closure practice, that closure outcomes are shaped by decisions made throughout the mine's life, and that operators who engage with closure risk early have more options and lower costs than those who do not.

Against this context, the absence of a consistent, portfolio-wide framework for evaluating pit closure risks at WAIO had created a practical gap. There was no standardised basis for comparing risks across pits, identifying knowledge gaps, prioritising studies or communicating the current state of closure readiness to management, regulators or community stakeholders. The PIRAT was developed to fill that gap.

3 Design principles

3.1 Uncertainty as a co-equal output

The most consequential design decision in the PIRAT was to treat knowledge base certainty not as a caveat appended to the risk rating but as a co-equal and co-visible output that appears alongside every risk score. In conventional approaches to closure risk assessment a moderate risk rating looks the same regardless of whether it is backed by a calibrated numerical model or a desk-based inference from regional geology maps. The confidence of the assessor may vary enormously; the reported score does not.

In the PIRAT, every risk score is paired with a certainty rating derived from the maturity of the knowledge base elements supporting that score. The certainty is evaluated not in absolute terms but relative to the minimum standard expected for the pit's current stage of life; a standard that is explicitly defined and that increases as the pit advances towards closure. Where certainty falls one level below the acceptable threshold, the cell is shaded orange, flagging the requirement for forward work planning. Where it falls 2 or more levels below it is shaded red, supporting prioritisation.

This mechanism transforms how the tool's outputs are read and acted on. A moderate risk score paired with an at-threshold certainty rating calls for a management response to the risk. A moderate risk score paired with a red certainty rating calls first for a knowledge investment because the current assessment may be wrong in either direction, so committing to a closure strategy based on it would be premature. The tool does not simply tell you what the risks are; it tells you how much to trust what it says about the risks.

3.2 Progressive assessment through the mine life cycle

The second core principle is that the tool is designed for repeated use across the full mine life cycle, not for single-point completion. The pit register records the current stage of life for each pit, and this designation controls the certainty threshold applied to its knowledge base. An 'in-study for operations' (that is, a pit whose operational studies are underway but which remains years from closure) pit is held to a different standard than a pit in its final years before mining completion. As the pit advances, the tool is updated, the thresholds tighten and the forward work program output automatically identifies the knowledge gaps that now fall below the new standard.

This structure operationalises the progressive planning principle in a concrete way. It does not simply recommend that operators think about closure earlier in the mine life cycle; it makes the current knowledge adequacy measurable, flags deficiencies specifically and generates a direct-action list. The difference between aspiration and genuine operationalisation matters greatly in a planning environment where closure studies must compete for budget and attention against the demands of active production.

3.3 Screening, not substitution

The PIRAT is a screening and ranking tool. Its criteria are simplified relative to the complexity of real hydrogeological, geochemical and ecological systems. Proximity to a receptor is used as a proxy for transport pathway effectiveness; geochemical hazard is classified against categorical criteria derived from AMD screening rather than site-specific modelling. The tool identifies which pits warrant detailed study and in what sequence; it does not replace the detailed studies.

This boundary is important both for the tool's integrity and for how its outputs are used. Risk scores from the PIRAT should not be presented to regulators as definitive characterisations of pit closure risk. They are the basis for prioritisation in deciding where to invest in the detailed studies that will produce the definitive characterisations. This two-tier structure reflects the proportionate use of resources that good management practice and regulatory frameworks both require.

4 Risk architecture

4.1 Risk identification and selection

Risk identification commenced with a structured brainstorming workshop in June 2025, attended by the WAIO closure planning team and technical advisors (Pershke Consulting 2025, 2026). The resulting long list of candidate risks was refined through individual consultations with subject matter experts across groundwater, surface water, geochemistry, biodiversity, cultural heritage and geotechnical disciplines. Each candidate risk was evaluated against 2 criteria: materiality (whether it could be a driver of closure strategy or a concern to regulators or TO groups) and differentiability (whether screening-level information could meaningfully distinguish between pits on the basis of that risk).

Several risks failed the differentiability test. The potential for feral fauna to use pit lakes as a water source, and the broader impact of water quality changes on ecosystem establishment dynamics, could not be differentiated between pits at screening scale. These were excluded from active scoring and treated as qualitative commentary fields. Several initially separate safety risks were merged into a single pit safety criterion, since the key differentiating variable is the nature of the void and its proximity to human receptors rather than the specific mode of potential harm. The resulting register of 14 risk categories is presented in Table 1.

Table 1 Primary risk categories in the Pit Impact Risk Assessment Tool and their key receptors

Risk domain	Primary risk description	Key receptors
Groundwater levels	Below watertable (BWT) void reduces regional groundwater levels, impacting groundwater-dependent receptors	Permanent pools, groundwater-dependent ecosystem (GDE), stygofauna, TO values
Alluvial baseflow	Above watertable (AWT)/BWT void intercepts alluvial aquifer, reducing baseflow to riparian systems	Semi-permanent pools, riparian vegetation, stygofauna
Pit lake – water quality	Poor pit lake water quality (salinity, metals) impacts humans, wildlife and cultural values	Avifauna, humans, fauna, TO values
Pit lake – through-flow	Pit lake becomes groundwater through-flow system, releasing contaminants to surrounding aquifer	Stygofauna, water abstraction, GDE
Density-driven flow	Density-driven flow from saline pit lake contaminates surrounding groundwater	Stygofauna, water abstraction, GDE
Pit lake overtopping	Pit lake overtops, releasing saline or contaminated water to surrounding environment	Riparian ecosystems, TO values, humans
AWT seepage	Contaminant seepage from AWT pit walls or floor reaches groundwater or surface water	Stygofauna, water abstraction, GDE
Backfill through-flow	Backfilled pit releases contaminants to surrounding groundwater	Stygofauna, water abstraction, GDE
Creek capture	Pit wall instability or flooding causes creek capture	Riparian ecosystems, stygofauna, TO values
Catchment reduction	Pit intercepts catchment of sensitive receptor, reducing inflows	Riparian vegetation, GDE, semi-permanent pools
Pit wall stability	Pit wall failure beyond zone of influence destroys post-mining infrastructure or sensitive receptors	TO heritage, protected vegetation
Pit safety	Inadvertent human or fauna access to BWT void or pit lake causes injury or death	Humans, terrestrial fauna, settlements
Cultural values	Pit void incompatible with post-closure cultural land use, access or values	Traditional owners, cultural heritage
Rehabilitation	Backfilled surface cannot sustain vegetation; managed aquifer recharge water unavailable during groundwater recovery	Vegetation communities, ecohydrological receptors

4.2 The source-pathway-receptor scoring framework

Each risk is scored as the product of 3 components:

- a hazard score (H, maximum 5) reflecting the magnitude of the risk source
- a distance score (D, maximum 5) reflecting the proximity of the pit to the receptor as a proxy for pathway effectiveness

- a receptor significance score (R, maximum 5) reflecting the ecological, social, cultural or safety importance of the receptor.

The resulting score H × D × R has a maximum of 125 and is colour coded for very low (≤ 8), low (9–17), moderate (18–31), high (32–52) and very high (53–125). Where a risk draws on multiple hazard factors, scores are normalised to a maximum of 5 to ensure comparability across risks.

The source-pathway-receptor (SPR) framework was chosen because it is conceptually transparent, communicable to non-specialist audiences and directly decomposable into its contributing factors. Identifying whether an elevated risk score is driven by a high hazard, a close receptor or a sensitive receptor indicates the type of management response most likely to reduce it. Source management, pathway modification or receptor protection are fundamentally different interventions. The SPR structure makes this distinction visible in the output.

4.3 Pit safety scoring

Pit safety required an adaptation specific to the Pilbara context. The standard assumption that remote location reduces inadvertent access risk does not apply here without qualification. Community members may travel 150 km or more to reach a body of water (pit lake) perceived as having recreational value. Recreational encounters with open voids along such routes are a genuine risk and this scenario is presented here as an illustrative example of the pit safety risk type rather than the sole basis of the safety assessment. The safety hazard score therefore distinguishes risk between 4 void types based on their inherent physical condition and special relation to local remote communities: backfilled-to-surface; above-watertable void; BWT void greater than 150 km from a settlement; and BWT void within 150 km of a settlement. The last category attracts the highest hazard score, reflecting the combined hazards of drowning, chemical exposure and difficult egress from a steep-sided, water-filled void in a remote setting.

5 The knowledge certainty framework

5.1 Structure and derivation

For each pit, the pit knowledge base records the maturity of information across a standardised set of knowledge base elements corresponding to the 14 risk domains. Each element is assigned a certainty rating on a 5-level scale (very low through very high) that is automatically generated from the type and currency of information entered, with a user-overridable option supported by mandatory justification text. The certainty rating for each risk output is then derived conservatively as the lowest certainty rating among all knowledge base elements contributing to that risk.

This conservative aggregation is deliberate. A hydrogeochemical pit lake model may be confidently constructed, but if it relies on a very low certainty groundwater level prediction and an unvalidated source hazard assessment, the overall reliability of the pit lake quality risk rating should reflect the weakest link in the chain. The tool enforces this logic automatically, ensuring that confidence is not overstated by the presence of a sophisticated model built on uncertain inputs.

5.2 Stage-of-life thresholds

The minimum acceptable certainty standard for each knowledge base element is calibrated to the stage of the pit’s life cycle, as summarised in Table 2. The thresholds are explicitly defined and tighten progressively as the pit approaches closure. A pit in early study is held to a very low or low standard; a pit in its final years is held to a high or very high standard. Where current certainty falls one level below the applicable threshold, the cell is shaded orange (flagging a deficit that should be addressed in the near-term work program). Where it falls 2 or more levels below, the shading is red (flagging a critical gap relative to the expected standard for this stage of pit life).

Table 2 Knowledge base certainty thresholds by stage of pit life

Stage of pit life	Minimum acceptable certainty	Typical knowledge base at this stage
Pre-study for operations	Very low	Geological formation, regional geographic Information system (GIS) datasets, legacy drillhole data
In-study for operations	Low	Preliminary hydrogeological model; regional AMD screening; optimised mining model catchment data
Operations > 5 years to completion	Moderate	Site-specific calibrated groundwater (GW) model; geoenvironmental source hazard assessment; detailed pit design
Operations < 5 years to completion	High	Pit lake water and salt balance; density flow modelling; pit lake quality modelling; backfill stratigraphies confirmed
Mining complete	Very high	Validated predictive models; completed closure studies; confirmed waste balance

The progressive tightening of thresholds creates the right incentive structure. It does not demand impossibly high certainty at early stages when information is genuinely limited. But it also does not allow low certainty to persist indefinitely: as the pit ages, the same knowledge base that was adequate at an earlier stage becomes flagged as deficient. The flags are specific, they identify the individual knowledge base element that is below threshold and they translate directly into the forward work program output, which lists the studies needed to bring each flagged element up to the required standard.

5.3 Forward work program

A dedicated output sheet identifies, for each pit, the knowledge base elements that need to be acquired at each stage of life to meet the applicable certainty threshold. This is the tool's most directly operational output: a structured, pit-by-pit list of named studies, matched to the current life cycle stage, which provides a ready-made basis for scoping and prioritising the closure study program. It can be used to brief study teams, to prepare scope-of-work documents for studies, and to present to management and regulators a transparent account of what is known, what remains unknown and what is being done about the latter.

6 Tool implementation

6.1 Architecture

The PIRAT is implemented as a macro-enabled Microsoft Excel workbook (XLSM). Excel was chosen for accessibility: the tool must be usable and maintainable by the WAIO closure planning team and their consultants without specialist software or programming capability. The workbook uses a colour-coded tab architecture – green for data entry, blue for dropdown lookup tables, pink for intermediate calculation tables and red for output sheets – and a macro-enabled front page that controls navigation and protects the calculation architecture.

The data entry workflow is structured in 4 sequential modules. The hub or site receptor register establishes all receptors for a hub, their type, significance rating and the impact pathways to which each is susceptible. This last field controls which risks are active in the output tables for each receptor, preventing spurious scores for impact pathways that are physically irrelevant to a given receptor. the pit register links each pit to its relevant receptors with distance classifications. The pit knowledge base captures knowledge maturity data. The risk register contains risk criteria selections made from dropdown menus that are dependent on knowledge base entries, enforcing consistency between the stated knowledge and the applied criteria.

6.2 Outputs

At the time of writing this paper, 5 output sheets serving distinct purposes have been developed. The residual environmental and safety (E&S) risks sheet; provides a full breakdown of risk scores and certainty ratings by pit and receptor, filterable by hub, orebody or pit level. The residual E&S risks aggregated sheet; sums risk scores across all receptors per pit, using graduated conditional formatting to show relative portfolio ranking without implying spurious precision. The residual E&S risks to receptors sheet; shows the cumulative load on each receptor from all contributing pits, which is essential for understanding the aggregate pressure on shared regional receptors from a hub or portfolio of hubs. The risk to achieving closure sheet; rates risk to the achievability of the proposed closure strategy on a separate 1-5 scale. The knowledge base (KB) by Stage of Pit Life sheet; generates the forward work program described in Section 5.3.

7 Preliminary application: test hub

The test hub was the first to be populated with real pit data during the initial testing phase of the PIRAT, providing the first genuine illustration of the tool's outputs in context. Two pits are under active assessment: test pit 1 (scheduled mining closure FY32, maximum depth 220 m, BWT, planned backfill to 5 m above the post-mining watertable) and test pit 2 (closure FY36, 150 m depth, BWT, same backfill strategy). Both are currently classified as 'in-study for operations', for which the acceptable knowledge certainty threshold is low. Both pits are assessed against 2 shared regional receptors: test receptor 1 (threatened ecological community, TEC) is a groundwater-dependent vegetation community classified as Ecosystem at risk, located 5–20 km from both pits; and test receptor 2 is a public drinking water source area (PDWSA), a Priority 1 water catchment within 1 km of both pits.

7.1 Environmental and safety risk profile

Table 3 presents selected key E&S risk scores for both pits against both receptors. The certainty column notes whether the certainty for each risk element is at or above the low threshold required for the in-study stage.

Table 3 Selected residual environmental and safety risk scores, test hub (H × D × R, maximum 125)

Risk/certainty	Test pit 1 → Test receptor 1 (TEC)	Test pit 1 → Test receptor 2 (PDWSA)	Test pit 2 → Test receptor 1 (TEC)	Test pit 2 → Test receptor 2 (PDWSA)
GW drawdown risk score	19 Moderate	32 High	0 N/A	0 N/A
GW level KB certainty	Moderate (at threshold ✓)	Moderate (at threshold ✓)	Moderate (at threshold ✓)	Moderate (at threshold ✓)
AWT seepage risk score	38 High	10 Low	10 Low	16 Low
AWT seepage KB certainty	Low (at threshold ✓)	Low (at threshold ✓)	Low (at threshold ✓)	Low (at threshold ✓)
Backfill through-flow risk score	24 Moderate	16 Low	12 Low	20 moderate
Backfill through-flow KB certainty	Low (at threshold ✓)	Low (at threshold ✓)	Low (at threshold ✓)	Low (at threshold ✓)

Note: E&S = environmental and safety; H × D × R = hazard × distance × receptor; TEC = threatened ecological community; PDWSA = public drinking water source area; GW = groundwater; KB = knowledge base; AWT = above watertable; N/A = not applicable.

The first notable finding is the differentiation between 2 pits sharing the same closure strategy. Test pit 1's AWT seepage risk to the test receptor 1 (TEC) scores 38 (high), the highest single risk score in the register, reflecting the substantially larger volume of spontaneous combustible and/or acid and metalliferous drainage

(SC-AMD) material in test pit 1's pit walls and overburden compared with test pit 2, where the same risk scores only 10 (low). GW drawdown at the test receptor 2 (PDWSA) is rated high (32) for test pit 1, reflecting modelled cumulative drawdown at the PDWSA exceeding 1 m; test pit 2 registers zero here because groundwater is predicted to fully recover to pre-mining levels.

These are not trivial differences: test pit 1 carries a significantly higher geochemical legacy risk to a Priority 1 drinking water source and closes 4 years earlier than test pit 2. A portfolio review without a consistent scoring framework might not have surfaced this distinction or might have treated the 2 pits as interchangeable, given their common closure strategy. The PIRAT makes the difference visible and attributable.

Importantly, all the E&S certainty ratings in Table 3 are shown as 'at threshold' for the in-study stage. The risk scores for both pits are based on knowledge that is currently adequate for this stage of their lives. The E&S certainty picture is orange and red elsewhere in the register, but not here. This is the correct reading: adequate certainty does not mean complete certainty; it means the knowledge base is sufficient for the current stage of planning. It will need to be improved as the pits advance.

7.2 Risk to achieving closure

The risk-to-closure results, summarised in Table 4, tell a more urgent story. Both pits score 13 out of a possible 35 on the combined risk-to-closure assessment.

Table 4 Risk to achieving closure, test hub (⚠ = below acceptable certainty threshold; ✓ = at or above threshold)

Risk to closure element	Test pit 1 score (1–5)	Test pit 1 KB certainty	Test pit 2 score (1–5)	Test pit 2 KB certainty
Backfill strategy risk	4 High	Very low ⚠ (2 below threshold)	4 High	Very low ⚠ (2 below threshold)
Backfill waste balance risk	3 Moderate	Very low ⚠ (2 below threshold)	3 Moderate	Very low ⚠ (2 below threshold)
Revegetation strategy risk	3 Moderate	High (above threshold ✓)	3 Moderate	High (above threshold ✓)
Cultural values impact risk	3 Moderate	Moderate (at threshold ✓)	3 Moderate	Moderate (at threshold ✓)
Total risk to closure (out of 35)	13 of 35		13 of 35	

Taken at face value, a total of 13/35 with individual component scores of 3 and 4 on a 5-point scale might read as a manageable set of moderate-to-high risks with a stated closure strategy in place. But the certainty column inverts this reading. The 2 highest-risk components, backfill strategy (4/5, high) and backfill waste balance (3/5, moderate), are both rated as very low certainty: 2 levels below the low threshold expected for in-study pits. The red flags signal that these scores are based on preliminary, highly conceptual waste balance analyses that do not account for AMD geochemistry constraints on material placement, hub-level interactions or water balance requirements for MAR during groundwater recovery. The moderate-to-high risk scores may be understated, overstated or approximately correct, but the current knowledge base cannot determine which.

Revegetation, by contrast, is rated as a moderate risk (3/5) with high certainty, well above the threshold. Revegetation trials have been established and outcomes are beginning to emerge. The distinction between the red backfill certainty and the green revegetation certainty in the same row is the tool performing its central function: not simply telling you the risk is moderate but telling you which parts of the closure strategy are well supported and which are currently operating on uncertain ground.

The forward work program implication is direct and specific. For both test hub pits, the priority knowledge task is a hub-level integrated waste balance that accounts for AMD geochemistry constraints on backfill material placement, volumes available at different classification levels, sequencing with pit void requirements at the hub scale, and the water balance requirements for sustaining groundwater-dependent receptors during the recovery period. This is a concrete, scoped and schedulable study, not a general observation that more work is needed. The study needs to be commissioned immediately, given test pit 1’s closure in FY32 and the time required to generate and validate the outputs of a study of this complexity.

8 Discussion

8.1 What the results demonstrate

The test hub results illustrate all 3 of the tool’s design principles in action. The consistent SPR scoring differentiates between 2 pits with the same strategy, surfacing test pit 1’s substantially higher geochemical risk to the test receptor 2 (PDWSA); a finding that has direct implications for study prioritisation given test pit 1’s earlier closure date. The progressive life cycle framework ensures that the same risk register will be reassessed as both pits advance, with certainty thresholds tightening to reflect the increased urgency of knowledge acquisition as closure approaches. The certainty assessment identifies, with specificity, that the current closure strategy rests on a backfill knowledge base that is inadequate for the current stage of life; a finding that is actionable immediately in a way that a qualitative statement about uncertainty in the closure strategy is not.

8.2 Implications for mine closure practice

The challenge illustrated by the test hub example is not unique to WAIO. Across the Australian mining sector and in many international jurisdictions, the demand for progressive, life cycle-based closure planning is growing in response to regulatory reform, rising community and traditional owner expectations, and the growing recognition that options foreclosed by the late identification of closure risks cost more to recover than risks identified and addressed early.

The practical challenge is implementation; how to make the principle of progressive planning operational for teams managing large and complex pit portfolios where the demands of active production compete constantly for the budget and attention that closure studies require. The PIRAT offers a specific answer to this challenge, not by removing that competition but by making the consequences of deferral visible and specific enough to be managed. A red certainty flag on a backfill waste balance, attached to a pit closing in 6 years, is a different kind of management information from a general note in a closure plan that the waste balance requires further development. The former demands a decision; the latter defers one.

The consistent methodology across the portfolio also provides something that pit-level assessments, however thorough, cannot: the ability to compare. The comparison of test pits 1 and 2 is only meaningful because both assessments use the same scoring criteria, the same certainty scale and the same life cycle thresholds, extending this consistency across the full WAIO portfolio.

8.3 Current limitations and planned development

At the time of writing, the tool’s limitations fall into 2 distinct categories: output capabilities still under development and methodological gaps that require more substantive work beyond the current project phase.

8.3.1 Incomplete outputs

The inherent risk register is not yet complete. Without it, the tool shows only the residual risk profile after the proposed closure strategy is applied and cannot demonstrate how much risk reduction that strategy achieves. Completing the register will enable 2 additional output sheets: a side-by-side comparison of inherent and residual risk scores for each risk domain, and a corresponding comparison at receptor level that includes the certainty of the closure strategies themselves. The cultural values output sheet is also absent, a particularly notable gap given the centrality of TO values to the PIRAT's purpose. When complete it will follow the same format as the residual E&S risks to receptors sheet but will record risks to culturally significant receptors rather than environmental or safety receptors. Both outputs are planned for early Phase 2.

8.3.2 Methodological gaps

Two limitations go deeper than missing outputs and will require more substantive development. The cultural values assessment methodology has not yet been developed. Completing the output sheet will provide the format, but the criteria, weighting and language used to characterise cultural values risks need to be developed in direct consultation with traditional owners and WAIO's Indigenous affairs team before the outputs can be considered meaningful or appropriate for external use. Separately, the relationship between the tool's H×D×R scoring scale and BHP's material risk framework, which uses a conventional consequence-likelihood matrix, has not yet been formally resolved. Mapping between the 2 systems may require methodological work beyond configuration and, until that work is done, the tool's outputs cannot be used directly as inputs to the formal BHP risk register. Both of these are Phase 2 priorities. A third consideration, not addressed elsewhere in this paper, is the long-term operational question of how the tool will be maintained as pit data matures, mine plans change and new studies are completed. Clear ownership, version control protocols and a refresh schedule will be needed to ensure the tool remains current and credible as a portfolio management instrument over time.

9 Conclusions

The Pit Impact Risk Assessment Tool (PIRAT) addresses a real and persistent gap in mine closure practice: the absence of a consistent, portfolio-wide framework for assessing pit closure risks that is calibrated to the current state of knowledge and that makes the adequacy of that knowledge visible alongside the risk ratings themselves. Its central innovation is the explicit coupling of every risk score with a knowledge base certainty rating benchmarked against a stage-of-life standard; an approach that makes knowledge gaps as actionable as the risks they affect, and that generates a specific, prioritised forward work program directly from the assessment outputs.

The preliminary application at the test hub demonstrates the tool working as intended. Two pits with the same closure strategy present different environmental risk profiles, driven by differences in geochemical hazard and hydrogeological behaviour that a consistent scoring framework makes visible and attributable. The certainty assessment reveals that both pits are currently relying on an inadequate knowledge base for their most critical closure commitment, their backfill program, and identifies a specific study, at hub scale, which needs to be commissioned now to address this deficiency.

More broadly, the PIRAT illustrates that the principle of progressive mine closure planning, now embedded in Australian regulatory requirements and in the expectation of traditional owner groups, requires more than a commitment to revisit closure plans periodically. It requires a structured and consistent method for measuring the adequacy of knowledge against the demands of each stage of mine life, and for translating that measurement into action. The PIRAT is offered as one approach to meeting that requirement, and the authors welcome engagement from practitioners across the industry on its methodology and its potential wider applicability.

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Use of artificial intelligence disclosure statement

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