Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_82

A quantitative and practical method for prioritising contaminated sites to support mine closure planning

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Abstract

Mining operations typically contain hundreds of potential contaminant sources that differ in size, complexity and risk. As mine plans evolve, rehabilitation progresses, and regulatory expectations increase, mining companies need a consistent way to identify which contaminated areas require action first. Without a structured method, prioritisation often depends on expert opinion, which can be inconsistent, difficult to explain, and difficult to align across large operations.

To address this challenge, we developed the risk assessment and prioritisation tool (RAPT), a quantitative, multi-criteria approach that evaluates all contaminated areas against a common set of measures. The method brings together environmental, operational, regulatory and social factors, including geological and hydrogeological considerations, within the scoring criteria and converts them into a transparent risk score. This allows contaminated areas to be compared on a like-for-like basis, even when the risks are very different in nature. It also highlights where early action reduces long-term risk, where investigation adds the most value, and where issues can be safely managed through routine controls.

The approach supports adaptive decision-making by allowing priorities to shift as site conditions, mine plans or regulatory requirements change, while still keeping the contaminated sites program aligned with key milestones such as progressive rehabilitation, closure strategies and approvals. This helps reduce program bottlenecks, improves sequencing and allows limited resources to be directed where they have the greatest impact.

The paper explains how the method evaluates each area, how the criteria are weighted, and how the tool calculates risk scores to create a clear and defensible prioritised list. This includes examples of how contaminant type, exposure pathways, proximity to sensitive receptors, operational constraints and closure dependencies influence the final ranking. The work demonstrates how a structured, quantitative approach improves the way contaminated sites are identified, compared and prioritised, ultimately supporting safer operations, better environmental outcomes, and more efficient mine closure planning.

Keywords: *contaminated sites, risk prioritisation, approvals and planning, multi-criteria decision analysis*

1 Introduction

Contaminated sites are a common feature of mining operations around the world. Over decades of activity, mining operations generate hundreds of areas of potential environmental concern (APECs) through fuel storage, chemical handling, waste disposal, workshops, wash-down areas, sewage treatment and the use of firefighting foams. These areas vary widely in size, contaminant type, environmental setting and level of risk. Some pose immediate threats to human health or ecological receptors, while others represent low-level legacy issues that may not require action for many years.

As operations mature and move toward closure, the management of contaminated sites becomes a central part of planning. Contaminated land can directly affect whether closure milestones are met, whether

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progressive rehabilitation can proceed, and whether regulatory approvals can be obtained. In many jurisdictions, including Western Australia under the *Contaminated Sites Act 2003* (Government of Western Australia 2003) and the *Environmental Protection Act 1986* (Government of Western Australia 1986), mining companies have legal obligations to investigate, manage, and where necessary remediate contaminated land. Regulators such as the Department of Water and Environmental Regulation (DWER) can issue improvement notices or directives if contaminated sites are not being appropriately managed (DWER 2021).

Expert judgement has always been, and will continue to be, a fundamental part of contaminated site management. Experienced practitioners bring valuable knowledge of site history, contaminant behaviour, regulatory expectations and operational context that no tool can fully replicate. However, when a mining company is managing a large portfolio of APECs across multiple operations, the process of comparing and sequencing work across all of those sites can become complex and time consuming. Each APEC has a unique combination of contaminants, exposure pathways, receptors, geological and hydrogeological settings, operational constraints and regulatory requirements. A single operation may have dozens of APECs, and across a portfolio, the number can run into the hundreds. Bringing all of these factors together in a way that is consistent, transparent and easy to communicate to stakeholders outside the contaminated sites team is a significant undertaking.

Various approaches to contaminated site prioritisation have been developed in other contexts. The United States Environmental Protection Agency uses the Hazard Ranking System (HRS) to evaluate sites for inclusion on the National Priorities List, based on likelihood of contaminant release, waste characteristics and receptor proximity (US EPA 1990). In Canada, the National Classification System for Contaminated Sites (CCME 2008) provides a framework for classifying sites based on contaminant characteristics, migration pathways and receptor sensitivity. More recently, Cinelli et al. (2021) demonstrated the application of multi-criteria decision analysis to contaminated site management in a European regulatory context, and Tarnocai et al. (2022) applied a semi-quantitative risk ranking approach to prioritise sites contaminated by perfluoroalkyl and polyfluoroalkyl substances (PFAS) for funding allocation. While these methods share the common goal of bringing structure to contaminated sites prioritisation, they were developed for different regulatory frameworks and operational contexts. In the Australian mining context, the prioritisation needs to integrate not only environmental and human health risk but also mine planning approvals, progressive rehabilitation requirements, closure obligations, traditional owner and heritage considerations, and corporate risk management, which are not fully captured by existing published methods.

This is where a structured, quantitative approach can add real value. Rather than replacing expert judgement, a tool that captures the key risk factors and converts them into a comparable score can accelerate the prioritisation process and make it easier to align the contaminated sites program with mine plans, progressive rehabilitation schedules, closure strategies and budget cycles. It gives practitioners a common language and framework for discussing priorities, and it gives senior decision-makers a clear and defensible basis for understanding where resources should be directed.

With this opportunity in mind, we developed the risk assessment and prioritisation tool (RAPT), a portfolio-level, semi-quantitative decision support tool designed to rank APECs according to relative priority for investigation, management or remediation. The RAPT integrates qualitative and quantitative data across environmental, operational, regulatory, social and business risk dimensions to generate a weighted risk score and classification for each APEC. It is designed to sit alongside expert judgement and detailed site-specific risk assessments, not to replace them, but to bring structure, consistency, and transparency to the portfolio-level prioritisation process. This paper describes how the tool was developed, how it evaluates each APEC, how the criteria are weighted, and how the risk scores are calculated. A conceptual case study is presented to demonstrate how the tool works from start to finish, including the reasoning behind each score selection.

2 Methodology

2.1 Overview

We developed the RAPT to provide a consistent, repeatable and transparent method for prioritising contaminated sites across a mining portfolio. At its core, the RAPT is a semi-quantitative priority ranking system that uses a structured set of environmental, operational, regulatory and social criteria with derived weightings to produce a single comparable score for each APEC. The tool is implemented as an Excel-based application with VBA support. We chose Excel because it is widely available across mining operations, does not require specialist software licences, and allows practitioners to interact directly with the data, scoring and outputs without needing programming skills. The VBA component automates calculations, manages data validation and generates summary outputs, which reduces manual effort and the risk of errors.

The tool is not intended to replace detailed human health or ecological risk assessments. It is a portfolio-level screening and prioritisation tool that sits alongside those assessments and helps direct limited resources toward areas of greatest environmental, operational and business impact. It is designed to be used by experienced contaminated land practitioners who understand the technical context of each APEC and can apply professional judgement when selecting scores.

The RAPT is a portfolio-level screening and prioritisation tool. It is used to compare and sequence work across many APECs within a mining portfolio. It is not a contaminated site risk assessment. Formal contaminated site risk assessment under the National Environment Protection (Assessment of Site Contamination) Measure 2013 (NEPC 2013) is a site-specific process that characterises risk to human health and the environment at a single APEC using detailed exposure modelling, site-specific data and tiered assessment criteria. The 2 processes are complementary. The RAPT directs limited resources toward the APECs that warrant further work, and the site-specific risk assessment then provides the detailed technical basis for that work.

The development of the tool was guided by 6 principles, as follows:

- Enable holistic decision-making by aligning the priorities of each operation to an overarching strategy.
- Articulate what is important by agreeing a single suite of prioritisation criteria to keep the contaminated sites program aligned.
- Quantify and balance competing factors to reduce bias and undue influence on decisions, and to sequence work rather than create bottlenecks.
- Optimise and deliver value by making the logic visible, allowing scrutiny and improvement, and bundling interdependencies to drive efficiency.
- Recognise that resources are finite by directing budget where most needed, when most needed, within the funding envelope.
- Be agile by redirecting effort proactively, reprioritising when new risks are identified, and enabling mining, progressive rehabilitation and closure.

Figure 1 presents an overview of the RAPT workflow, showing the 8-step process from data collection through to decision support.

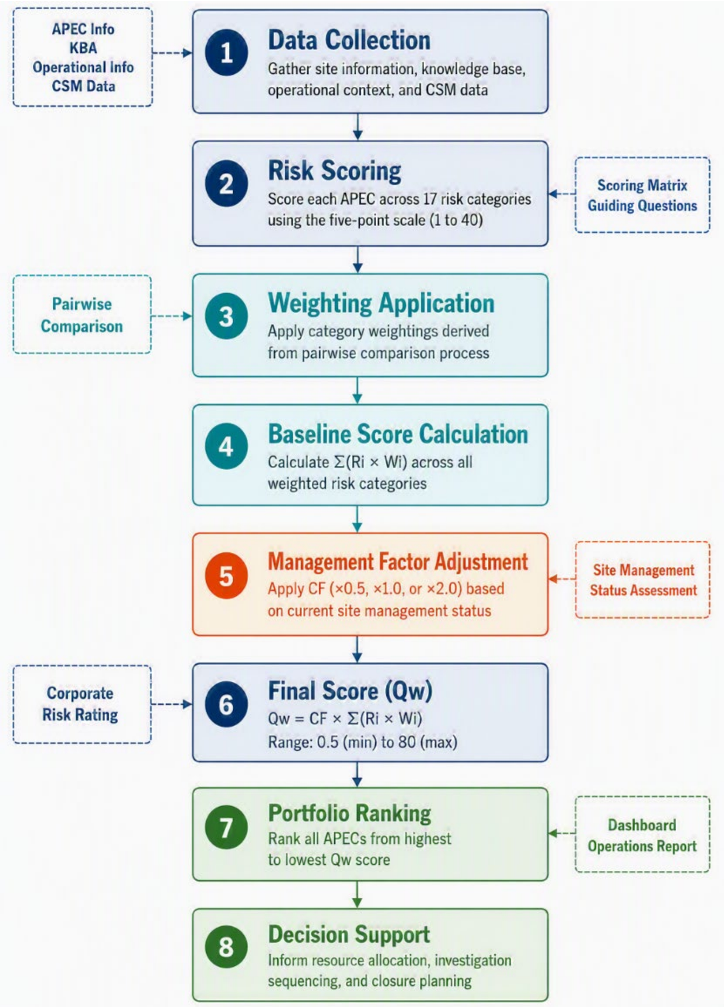

Figure 1 RAPT workflow showing the 8-step process from data collection through to decision support, including key inputs at each stage

2.2 Tool structure

The tool is organised into several integrated components, each serving a specific purpose in the prioritisation workflow.

The login page manages user access and ensures that only authorised personnel can enter or modify data. This is important for data integrity and audit trail purposes, particularly when the tool is used across multiple operations where different teams may be entering data at different times. It also allows the tool administrator to control who has read-only access and who can edit scores, which supports quality assurance.

The RAPT data entry and scoring sheet is the core of the tool. This is where practitioners enter site-specific information for each APEC and select scores for each risk category. The sheet is structured so that all inputs for a single APEC are captured in one place, making it easy to review the full risk profile of any site. The scoring is supported by guiding questions, reference examples built into the scoring matrix, and a set of predefined options for each category that the assessor selects from, based on the site conditions. For example, when scoring migration potential, the assessor is presented with options that describe different combinations of contaminant mobility, depth to groundwater, aquifer permeability and proximity to surface water, and selects the option that best matches the conditions at the APEC. This approach ensures that scoring is consistent across different assessors and operations, because everyone is selecting from the same set of technically defined options rather than assigning numbers without a common reference point. The outcome of this sheet is a weighted risk score and classification for each APEC, which forms the basis of the prioritisation.

The dashboard provides a portfolio-level summary of all APECs and their scores. It presents the ranked prioritisation list and allows users to quickly identify the highest risk sites, compare scores across operations and see how the portfolio is distributed across risk categories. This is particularly valuable for communicating priorities to senior decision-makers, closure planners and finance teams who need a clear picture of where resources should be directed without needing to review the detail behind every score.

The scoring matrix defines the criteria, weightings and scoring scales for all risk categories. It includes guiding questions, real-world examples and explanatory notes for each score level. This component is critical for ensuring consistency across different assessors and operations. By providing a common reference point, it reduces the variability that can occur when different practitioners are scoring sites independently. The scoring matrix can also be updated if organisational priorities change, such as when a new regulatory framework is introduced or when closure timelines are brought forward.

The spend tracker allows users to record and monitor expenditure against each APEC. This is important because one of the key outputs of the prioritisation is a recommended sequence of work, and that sequence needs to be linked to available budget. By tracking actual spend against planned spend for each APEC, the tool supports financial planning and helps demonstrate return on investment to senior stakeholders.

The operations report provides a formatted output for sharing information with operational stakeholders such as mine planners, closure planners and site managers. It presents the key information for each APEC in a format that is easy to read and understand without needing to open the full tool. This supports cross-functional communication and helps ensure that contaminated site priorities are integrated into broader operational planning.

2.3 Data input categories

For each APEC, the tool captures data across 4 main categories. Each category serves a specific purpose in building the risk profile and ensuring that the prioritisation reflects the full context of each site.

APEC information captures the basic identification and location data for each site. This includes the entry date, risk assessor name, mine name, APEC identifier, description, location coordinates, location summary, tenure information, highest level of investigation completed (such as preliminary site investigation, detailed site investigation, or remediation), and year of investigation. This information provides the foundation for tracking and reporting. The entry date and assessor name support the audit trail. The level of investigation is important because it indicates how much is known about the site, which directly influences the confidence in the risk scores. A site that has only had a desktop review will have greater uncertainty in its scores than a site that has had a detailed site investigation with laboratory analysis.

Knowledge base assessment (KBA) information captures the source–pathway–receptor (SPR) linkage assessment and uncertainty scores derived from desktop reviews or previous investigations. The SPR linkage is a fundamental concept in contaminated land assessment. A complete SPR linkage means that a source of contamination, a pathway for migration or exposure, and a receptor that could be harmed are all present and connected. An incomplete linkage means one or more of these elements is missing or broken. The KBA section captures whether each linkage is complete, potentially complete or incomplete, and also records the level of uncertainty in that assessment. This is important because the presence and completeness of SPR linkages is a primary driver of risk. A site with a confirmed complete linkage to a sensitive receptor requires a very different response than a site where the linkage is theoretical or incomplete.

Operational information captures the interactions between the APEC and current mining and infrastructure operations. This includes mine planning requirements and timelines, site infrastructure needs, approval requirements (both mine plan related and other regulatory approvals), progressive rehabilitation timelines, and closure requirements. This category is critical because contaminated site management does not happen in isolation. An APEC that sits in the path of a planned mine expansion has a very different urgency than one that is located in an area with no planned activity. By capturing these interactions explicitly, the tool ensures that the prioritisation reflects real-world operational constraints and opportunities, not just environmental risk in isolation.

Conceptual site model (CSM) information captures the risk profile of the APEC in terms of contaminant fate and transport, migration potential, affected media, contaminants of potential concern, impacted area and data gaps. The CSM is the foundation of any contaminated site assessment. It describes what contaminants are present, how they behave in the environment, where they are going, and what receptors they could affect. By capturing CSM information in the tool, we ensure that the risk scores are grounded in the technical understanding of each site. The data gaps field is particularly important because it identifies where the current understanding is incomplete and where further investigation would add the most value.

2.4 Risk categories and scoring

The tool evaluates each APEC against 17 risk categories that together capture the full spectrum of factors influencing whether a contaminated site requires priority action. The categories were selected to reflect how contaminated land risk is assessed in practice under Australian regulatory frameworks, including the National Environment Protection (Assessment of Site Contamination) Measure 2013 (NEPC 2013), the *Contaminated Sites Act 2003* (Government of Western Australia 2003) and the PFAS National Environmental Management Plan Version 3 (HEPA 2025). They also reflect the operational and business realities of managing contaminated land within an active mining portfolio, where environmental risk is only one of several dimensions that determine when and how a site should be addressed. In practice, the RAPT is applied by entering site information for each APEC, assigning scores across 17 predefined risk categories using a guided matrix, applying category weightings derived through pairwise comparison, and calculating a single weighted score that allows all APECs to be ranked relative to one another. The derivation of the category weightings is described in Section 2.5. Figure 2 illustrates the 5-point scoring scale and the type of site conditions that correspond to each level.

The 17 categories were structured so that each one captures a distinct part of the risk profile and the overlap between them is minimised. SPR linkage establishes whether a credible risk mechanism exists at all. Migration potential captures contaminant behaviour and the rate at which contamination is moving. Proximity of receptor captures the spatial relationship between the source and the receptor. The human health and ecological health categories capture the magnitude of consequence against published criteria for current and future land use. The pairwise comparison process was also used to check that no single dimension of risk was given disproportionate weight by being represented in more than one category, which further reduces the risk of double counting.

Figure 2 Five-point scoring scale used in the RAPT, ranging from 1 (very low) to 40 (very high), with representative site conditions for each level

Each category is scored on a 5-point scale of 1, 10, 20, 30 and 40, representing a progression from not applicable or very low risk through to very high risk. The scoring matrix provides guiding questions, real-world examples and explanatory notes for each score level to ensure different assessors are applying the same logic and thresholds across the portfolio.

2.4.1 Source–pathway–receptor linkage

SPR linkage for current land use assesses whether a credible risk mechanism exists at the APEC. Under the NEPM 2013 and WA DWER guidelines, risk is only realised where a complete linkage exists between a source of contamination, a pathway for migration or exposure, and a receptor that could be harmed. Scoring ranges from no identified linkage (score of 1) through to a confirmed complete linkage demonstrated by field evidence (score of 40). The weighting is moderate because SPR linkage establishes whether risk exists at all, while the severity and consequence of that risk are captured by the other categories.

2.4.2 Operational and planning interactions

These categories capture the interactions between contaminated land and the operational requirements of the mining business. In practice, many contaminated site investigations and remediation actions are triggered not by environmental risk alone but by the need to obtain approvals, clear land for development, meet rehabilitation commitments, or prepare for closure.

Mine planning and associated approvals assesses how urgently a mine planning requirement is affected by the APEC. When contaminated land sits within or adjacent to a planned mining area, it must be characterised and managed before the approval can proceed. Delayed approvals delay production, often at a cost that far exceeds the investigation itself. Scoring is urgency based, from no requirement (score of 1) through to immediate requirement within 6 months (score of 40).

Site infrastructure assesses whether the APEC affects planned construction, modification or decommissioning of infrastructure. Construction activities can also mobilise contamination if contamination is not identified and managed beforehand. Scoring follows the same urgency scale as mine planning.

Approvals excluding mine plan captures the broader regulatory context beyond mine planning, including clearing permits, works approvals, licence amendments and approvals under *the Environmental Protection Act 1986* (Government of Western Australia 2003). Multiple WA regulators – including DWER, the Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) and the Environmental Protection Authority (EPA) – can impose conditions.

Progressive rehabilitation assesses whether the APEC is preventing progressive rehabilitation from proceeding in an area that is otherwise ready. Progressive rehabilitation is increasingly expected by regulators and is a key component of reducing closure liability. The lower weighting reflects that rehabilitation delays generally carry less immediate financial and regulatory consequence than delayed mining or approvals.

Closure ensures that APECs with specific closure implications are visible in the prioritisation, even if closure is many years away. For example, PFAS contamination may require a long-term monitoring strategy that needs to be planned well in advance. The low weighting reflects the typically longer timeframes but ensures closure relevant APECs are not overlooked.

2.4.3 Contaminant behaviour and migration

Migration potential evaluates whether contamination is stable or actively spreading. This is one of the most technically significant categories because the cost and complexity of managing contamination increases significantly once it has spread beyond the source area. Scoring considers the solubility and mobility of contaminants, whether the source area is exposed or covered, depth to groundwater, aquifer permeability, preferential flow paths, proximity to drainage and surface water, and contaminant volatility. A PFAS plume in a shallow alluvial aquifer with confirmed offsite migration would score 40, while total petroleum hydrocarbon (TPH) in clay soil with groundwater at 30 m and no surface water nearby would score 1 or 10. The high weighting reflects that early action on high migration potential sites can prevent much larger costs and impacts later.

2.4.4 *Human health risk*

Human health for current commercial industrial land use assesses whether contamination exceeds Tier 1 health investigation levels under the NEPM 2013 Schedule B1 for the current land use. Protection of human health is the primary objective of contaminated site management under both federal and state legislation, which is why this category carries one of the highest weightings. Scoring ranges from below Tier 1 (score of 1) through to significantly exceeded with credible health risk (score of 40). For example, a site where all soil and groundwater results are below Tier 1 investigation levels would score 1, while a site where multiple contaminants exceed Tier 1 by more than 10 times in areas accessible to workers would score 40.

Human health for future open space land use assesses whether contamination would meet Tier 1 values for the anticipated post-closure land use. The low weighting reflects the longer timeframe, but the category gives closure planners early visibility of sites that meet current criteria but will not meet future land use criteria.

Agreed post-mining land use and closure domains directly influence the future land use scoring. Where the closure plan specifies a domain such as open space, conservation, grazing or low-density development, the future land use scores are aligned with the corresponding NEPM 2013 health investigation and ecological investigation levels for that land use. Where the post-closure land use is still under negotiation with regulators, traditional owners or other stakeholders, a conservative open space criterion is applied as the default until the final land use is confirmed. This ensures that APECs which meet current land use criteria but would not meet a more sensitive future land use are visible in the prioritisation well before closure.

2.4.5 *Ecological health risk*

Ecological health for current commercial industrial land use assesses whether contamination exceeds Tier 1 ecological investigation levels. In the mining context, ecological risk is particularly relevant where contamination may affect waterways, groundwater-dependent ecosystems or areas of ecological significance (ANZG 2018). The weighting is lower than human health, reflecting the regulatory hierarchy, but ensures ecological risks are visible in the prioritisation.

Ecological health for future open space land use assesses whether contamination would meet ecological criteria for the anticipated future land use. Similar to the human health future category, the low weighting captures closure relevant ecological risks without dominating the prioritisation.

2.4.6 *Regulatory, reputational, and social risk*

Reputational or legal risk exposure assesses the organisation’s exposure to public, media, legal and regulatory attention arising from the APEC. Certain types of contamination, particularly PFAS, asbestos and impacts to drinking water, attract disproportionate public concern that can be more costly and damaging than the environmental impact itself. Scoring ranges from no exposure at a remote site with no public access (score of 1) through to severe and potentially global exposure such as a PFAS plume affecting a community water supply with active media coverage (score of 40). This category carries a relatively high weighting. For example, a contained hydrocarbon spill at a remote site with no public access would score 1, while a PFAS plume with confirmed offsite migration generating media coverage and community opposition would score 40.

Risk of regulator improvement notice assesses the likelihood of DWER issuing a formal improvement notice requiring specific actions within prescribed timeframes. This is one of the most heavily weighted categories because an improvement notice creates an immediate, non-discretionary obligation that overrides other priorities. It also triggers public disclosure, potential enforcement action, and signals to the broader regulatory community that the company is not meeting its obligations. Scoring ranges from no regulatory interaction (score of 1) through to improvement notice already issued (score of 40). For example, a site where DWER has formally requested a remediation action plan following a compliance audit would score 30, while a site with no regulatory interaction and no contaminated sites register entry would score 1.

Potential impact on traditional owner, heritage or social values assesses whether contamination could affect culturally significant land, waterways or food sources. In the Australian mining context, relationships with traditional owners are central to ongoing operations and eventual closure. Contamination that affects heritage values can have lasting consequences for trust and social licence. Scoring ranges from no identified values in the area (score of 1) through to confirmed impact on a culturally significant site with breakdown in relationships (score of 40).

2.4.7 Investigation status and data quality

Current simple data gap impeding reclassification identifies opportunities where a relatively low cost action, such as developing a site management plan or completing a validation report, could move the APEC to a more favourable classification under the *Contaminated Sites Act 2003* (Government of Western Australia 2003). This category highlights straightforward opportunities for risk reduction that might otherwise be overlooked. A score of 40 means the site could almost certainly be reclassified immediately if a straightforward action were completed.

Magnitude of exceedance differentiates between marginal and severe exceedances of Tier 1 investigation levels. A site where contamination is 1.1 times the screening value represents a very different situation to a site where it is 20 times the value. Scoring ranges from no exceedance (score of 1) through to more than 4 times the guideline value (score of 40). This adds granularity to the human health and ecological categories, which on their own do not distinguish between minor and major exceedances.

Proximity of receptor assesses the distance between the APEC and the nearest sensitive receptor, including people, ecological receptors and cultural receptors. Even highly contaminated sites may pose limited immediate risk if receptors are far away, while moderately contaminated sites can pose significant risk if a receptor is on or adjacent to the source. Scoring ranges from no receptor within 1.5 km (score of 1) through to receptor located on the APEC itself (score of 40). This category works in combination with migration potential, human health and ecological health to build a complete picture of whether contamination is reaching or could reach a receptor.

2.5 Weighting determination

The weightings for each risk category were determined through a pairwise comparison process, a well-established technique in multi-criteria decision analysis (Saaty 1980). The specific percentage weightings are not presented in this paper for confidentiality reasons. The following describes the process by which they were derived. In this process, each of the 17 risk categories was compared against every other category. For each pair, the assessor answered the question: is category A much less important, less important, equally important, more important, or much more important than category B? The responses were recorded on a 5-point scale where 0 means much less important, 1 means less important, 2 means equally important, 3 means more important, and 4 means much more important.

Because there are 17 categories, the pairwise comparison generates 136 unique pairs (calculated as 17 multiplied by 16, divided by 2). The results of all 136 comparisons were compiled into a matrix and normalised to produce the percentage weightings. Normalisation was done by summing the scores for each category across all its pairwise comparisons and dividing by the total sum of all scores across all categories.

This approach has several advantages over simply assigning weightings directly. It forces the assessor to consider the relative importance of every possible pair of criteria, which reduces the tendency to over-weight familiar or salient risks. It produces a mathematically consistent set of weightings that reflects the collective judgement of the assessment team. Furthermore, it provides a transparent and auditable record of how the weightings were derived, which supports defensibility if the prioritisation is challenged.

The weightings can be updated if organisational priorities change. For example, the introduction of new PFAS regulations or a change in closure timelines could warrant a reassessment of the pairwise comparisons to ensure the weightings remain fit for purpose.

A formal sensitivity analysis of the category weightings is planned as part of future development. The analysis will examine how changes in individual weightings, particularly across the high weighted categories of human health for current land use, migration potential, regulator improvement notice, and reputational or legal risk, influence the final ranking. The aim is to confirm that the prioritisation outcomes are robust and not driven by a small number of dominant categories, and to identify any categories where a change in weighting would materially change the order of priority.

While the specific percentage weightings are not disclosed, the categories can be grouped into 3 broad weighting bands to provide transparency on relative importance. High weighted categories include human health for current land use, risk of regulator improvement notice, migration potential and reputational or legal risk exposure. Moderate weighted categories include SPR linkage, mine planning and associated approvals, approvals excluding mine plan, and proximity of receptor. Low weighted categories include progressive rehabilitation, closure, site infrastructure, ecological health for current and future land use, human health for future land use, magnitude of exceedance, simple data gap, and traditional owner, heritage or social values. These bands reflect the pairwise comparison outcomes described in Section 2.5 and are consistent with the regulatory hierarchy under the NEPM 2013 and *Contaminated Sites Act 2003* (Government of Western Australia 2003).

2.6 Risk score calculation

The qualitative weighted score is calculated using the weighted sum model (WSM), one of the most widely used multi-criteria decision-making methods (Triantaphyllou 2000). The WSM aggregates the performance of each alternative across multiple criteria by multiplying the score for each criterion by its corresponding weight and summing the products. This approach has been applied in various environmental decision-making contexts, including contaminated site remediation (Cinelli et al. 2021) and contaminated site portfolio risk ranking (Tarnocai et al. 2022) using the following formula:

$$Q_w = C_f \times \sum_{i=1}^{17} (R_i \times W_i) \tag{1}$$

where:

Q_w = qualitative weighted score for the APEC

R_i = risk category score for category i(selected from the 5-point scale of 1, 10, 20, 30 or 40 based on the scoring matrix)

W_i = weighting of risk category i(expressed as a decimal, where all 17 weightings sum to 1.0)

C_f = mitigating or aggravating factor.

The summation component of the formula captures the baseline risk profile of the APEC by combining the scores across all 17 categories with their respective weightings. This produces a single number that reflects the combined environmental, operational, regulatory and social risk of the site. However, 2 APECs with identical contamination, identical receptors and identical operational drivers can still present very different levels of priority depending on how well the risks are currently being managed. A site where contamination is contained within a bunded area, monitored regularly and covered by a site management plan is a different proposition to an identical site where no controls are in place and the contamination is unmanaged.

The mitigating or aggravating factor (C_f) accounts for this by adjusting the baseline score up or down based on the current management status of the site. Where the site is inactive and risks are managed under existing controls or a site management plan, $C_f$is set to 0.5, which halves the baseline score. The rationale is that effective controls reduce the immediacy of the risk, even though the underlying contamination remains. The same factor of 0.5 applies where the site is still operational and risks are managed under existing controls, because the ongoing operational management provides a layer of protection that reduces the urgency for additional intervention.

Where the site is operational but risks are not well managed, C_f is set to 1.0, meaning no adjustment is applied and the baseline score stands as calculated. This is also the case where the site is inactive and risks remain uncontrolled or not well understood, because the absence of active management or adequate knowledge means the baseline risk profile is the best representation of the current situation.

Where there is a change in land use or where the APEC is linked to a known affected site with confirmed offsite impacts, C_f is set to 2.0, which doubles the baseline score. This is the most aggravating condition in the tool and reflects the elevated urgency that comes with changing exposure scenarios. A change in land use can introduce new receptors or new exposure pathways that were not present under the previous land use, fundamentally changing the risk profile. Similarly, confirmed offsite migration means the contamination is no longer contained within the APEC boundary, which typically increases the regulatory, reputational and remediation consequences significantly.

The C_f is deliberately kept simple with only 3 possible values (0.5, 1.0 and 2.0) to ensure it is easy to apply consistently across the portfolio. It is not intended to be a detailed assessment of management effectiveness but rather a broad adjustment that recognises the difference between a well-managed site, an unmanaged site, and a site where conditions have materially changed. The specific values of 0.5, 1.0 and 2.0 were selected to provide a practical adjustment range where the mitigating factor halves the baseline score and the aggravating factor doubles it, creating a clear and intuitive scale. Sensitivity testing of alternative C_f values could be explored in future applications to determine whether a more granular scale would improve the prioritisation outcomes.

The values of 0.5, 1.0 and 2.0 were chosen to provide a clear and intuitive halving and doubling scale that practitioners can apply consistently across the portfolio. A halving factor represents a meaningful reduction in immediacy where effective controls or active operational management are in place. A doubling factor represents a meaningful increase in urgency where land use has changed or offsite migration has been confirmed. Alternative scales using values such as 0.25, 0.75, 1.5 and 3.0 were considered during development but were not adopted because they added complexity without improving the prioritisation outcome at the screening level. Sensitivity testing of alternative C_f values is flagged as part of future development.

The theoretical minimum score occurs when all 17 categories are scored at 1 and the mitigating factor of 0.5 is applied, giving a Q_w of 0.5. The theoretical maximum score occurs when all 17 categories are scored at 40 and the aggravating factor of 2.0 is applied, giving a Q_w of 80. In practice, scores will fall somewhere between these extremes, and the distribution of scores across the portfolio provides the basis for ranking and prioritisation.

In addition to the qualitative weighted score, the tool also calculates a corporate risk rating based on severity level and risk likelihood inputs, aligned with the company's risk management framework. This provides a second lens through which to view the risk, linking the contaminated site assessment to the broader corporate risk register and ensuring that the contaminated sites program speaks the same language as other risk management functions within the organisation.

3 Conceptual case study

To demonstrate how the tool works from start to finish, we present a conceptual case study involving 4 hypothetical APECs at a mining operation. No real site data are used. The purpose is to show how the tool takes raw site information, applies the scoring framework, and produces a prioritised ranking with clear reasoning behind each score. The 4 APECs were deliberately selected to represent a range of risk profiles from very low to very high, to demonstrate the full scoring range of the tool. In real-world portfolios, the distribution of scores is typically more clustered, and the tool is equally effective at differentiating between sites with similar overall risk levels through the granularity of the 17 individual category scores.

3.1 Site descriptions

APEC A is a former vehicle workshop that was decommissioned 5 years ago. During operation, hydraulic fluids and diesel were stored and used on site. A preliminary site investigation (PSI) identified TPH contamination in soil at concentrations exceeding the Tier 1 health investigation level for commercial industrial land use by approximately 2–3 times. Shallow groundwater (approximately 8 m below ground level) was found to contain dissolved phase hydrocarbons. The aquifer is moderately permeable alluvium. An ephemeral creek is located approximately 400 m to the north. No site management plan is in place. A mine planning approval for an adjacent pit expansion is required within 18 months. The regulator has not raised specific concerns but the site is classified as *possibly contaminated – investigation required* under the *Contaminated Sites Act 2003* (Government of Western Australia 2003).

APEC B is an active fuel storage facility with secondary containment, regular inspections and an environmental management procedure. A targeted soil investigation found minor TPH staining in soil beneath the bunded area at concentrations below Tier 1 investigation levels. Groundwater is deep (approximately 25 m below ground level) in low-permeability rock. There are no identified complete SPR linkages. No mine planning, progressive rehabilitation or closure requirements are imminent. The site is well managed under existing operational controls.

APEC C is a legacy landfill where general waste and asbestos-containing material (ACM) were disposed of over a 15-year period. The landfill was capped with compacted fill approximately 10 years ago, but recent inspections indicate the cap is deteriorating, with visible erosion and some ACM fragments on the surface. The site is located approximately 800 m from a registered heritage area. There is no site management plan. Groundwater beneath the landfill has not been tested. The site could potentially be reclassified from *possibly contaminated – investigation required* to *remediated for restricted use* if an ongoing management plan and updated site management plan were developed. There is a moderate likelihood that the regulator will raise concerns about the deteriorating cap condition at the next compliance review.

APEC D is a former emergency response training area where aqueous film forming foam (AFFF) containing PFAS was used over a 20-year period. A detailed site investigation (DSI) confirmed PFAS contamination in soil, surface water and groundwater. The PFAS plume in groundwater has migrated approximately 300 m from the source area toward a production bore that supplies water to a nearby camp. Perfluorooctane sulfonate (PFOS) and perfluorohexane sulfonate (PFHxS) concentrations in groundwater exceed the PFAS NEMP Version 3 (HEPA 2025) human health screening values by more than 10 times. The regulator has issued a formal improvement notice requiring further delineation and risk assessment within 12 months. The site has significant reputational risk due to the proximity of the affected bore to a community and the current public attention on PFAS nationally. Traditional owners have raised concerns about potential impacts to a culturally significant waterway downstream.

3.2 Scoring

Figure 3 presents the scoring results for all 4 APECs across the 17 risk categories. The scores were assigned by an experienced contaminated land practitioner based on the site descriptions in Section 3.1, using the scoring matrix and guiding questions described in Section 2.4. The colour scale indicates the severity of each score, from very low (green) through to very high (red). The mitigating or aggravating factor and the final qualitative weighted score are shown at the bottom of Figure 3.

Theme	Risk Category	APEC A *Former Workshop*	APEC B *Active Fuel Storage*	APEC C *Legacy Landfill*	APEC D *Former AFFF Training Area*
SPR Linkage	SPR Linkage – Current Land Use	20	1	20	40
Operational & Planning	Mine Planning & Associated Approvals	30	1	1	10
	Site Infrastructure	1	1	1	10
	Approvals Excl. Mine Plan	10	1	10	30
	Progressive Rehabilitation	10	1	10	10
	Closure	10	1	10	20
Contaminant Behaviour	Migration Potential	30	1	20	40
Human Health	Human Health – Current Land Use	20	1	20	40
	Human Health – Future Land Use	10	1	20	30
Ecological Health	Ecological Health – Current Land Use	20	1	10	30
	Ecological Health – Future Land Use	10	1	10	20
Regulatory, Reputational & Social	Reputational / Legal Risk	10	1	20	40
	Simple Data Gap Impeding Reclassification	10	1	30	1
	Risk of Regulator Improvement Notice	10	1	20	40
	Traditional Owner / Heritage / Social	10	1	20	40
Investigation & Data Quality	Magnitude of Exceedance	20	1	10	40
	Proximity of Receptor	30	1	20	40

	APEC A	APEC B	APEC C	APEC D
Mitigating / Aggravating Factor (Cf)	×1.0	×0.5	×1.0	×2.0
Qualitative Weighted Score (Qw)	16.1	0.5	14.5	71.6
Priority Rank	2nd	4th	3rd	1st
Priority Class	High Priority	Low Priority	Moderate Priority	Critical Priority

Score Legend: 1 Very Low 10 Low 20 Moderate 30 High 40 Very High

Figure 3 Scoring matrix for 4 conceptual APECs across the 17 RAPT risk categories, showing individual scores, mitigating or aggravating factors, and the final qualitative weighted score used to determine priority ranking

4 Discussion

The conceptual case study demonstrates several important features of the RAPT.

The tool allows sites with fundamentally different risk profiles to be compared on a common basis. APEC D involves PFAS in groundwater migrating toward a production bore, while APEC C involves asbestos in a deteriorating landfill near a heritage area. These are completely different contaminants, pathways and receptors, but the scoring framework converts the relevant factors into comparable numbers. This is particularly valuable when communicating priorities to stakeholders who may not have deep contaminated land expertise but need to understand why one site is prioritised over another.

The tool captures not just environmental risk but also operational and business risk in a balanced way. The mine planning approval deadline for APEC A contributes meaningfully to its overall score, meaning that a site with moderate environmental risk but an urgent operational requirement is appropriately flagged. Without this integration, the contaminated sites team might prioritise based on environmental risk alone, potentially missing the operational consequence of inaction. Conversely, the operational categories do not dominate the scoring. APEC D scores highest despite having limited operational drivers, because the environmental, regulatory, reputational and social risk factors are so significant.

Future development of the RAPT will focus on several areas. Sensitivity analysis will be undertaken to test how changes in individual category scores and weightings affect the overall ranking, with the aim of identifying which inputs have the greatest influence on prioritisation outcomes. Validation using real operational portfolios across multiple mining operations is underway and will be used to assess whether the tool produces prioritisation outcomes consistent with expert judgement and operational experience. A formal inter-rater consistency assessment will involve multiple practitioners independently scoring the same set of APECs to quantify the level of agreement and identify categories where additional scoring guidance may be needed. Integration with GIS platforms is planned to enable spatial visualisation of the prioritised portfolio, supporting communication with mine planners and closure teams. Finally, integration with corporate closure management systems will be explored to allow the RAPT outputs to feed directly into closure liability estimates and long-term planning tools.

The mitigating and aggravating factors provide a practical and defensible mechanism for adjusting scores based on current management conditions. APEC B scores very low partly because it is operational and well managed, with secondary containment and regular inspections in place. If those controls were removed or the site was decommissioned without a management plan, the C_f value would change from 0.5 to 1.0 and the score would double. Similarly, APEC D scores very high partly because the C_f value of 2.0 reflects confirmed offsite migration. This mechanism ensures that the prioritisation is sensitive to the current state of management, not just the inherent characteristics of the contamination.

The tool supports adaptive decision-making. If new information becomes available, such as a change in groundwater conditions at APEC A or the completion of a site management plan for APEC C, the relevant categories can be re-scored and the prioritisation updated. This is essential for a large portfolio where conditions change regularly. Mine plans are revised, new investigation data become available, regulations evolve and progressive rehabilitation progresses. The RAPT is designed to be a living document that is updated as conditions change, while maintaining a consistent and transparent framework. The structure of the tool also allows for sensitivity analysis, where individual category scores or C_f values can be adjusted to test how changes in assumptions affect the overall ranking. This can be used to identify whether a particular APEC's priority is robust or sensitive to specific inputs, which supports better-informed decision-making. A formal sensitivity analysis is planned as part of future development.

The tool also highlights opportunities that might otherwise be missed. APEC C scored relatively high on the simple data gap category, indicating that a targeted and relatively low cost action such as developing a site management plan could achieve reclassification and meaningfully reduce the portfolio risk. Without a structured framework that explicitly captures this dimension, such opportunities can be overlooked in favour of more visible or urgent issues.

It is important to acknowledge the limitations of the conceptual case study presented in this paper. The 4 APECs are hypothetical and the scores were assigned by the development team rather than by independent practitioners. In a real-world application, different practitioners may assign different scores to the same APEC depending on their interpretation of the available data and their familiarity with the scoring matrix. Inter-rater variability is a known challenge in any scoring based assessment, and the RAPT addresses this through the use of guiding questions, predefined score options and reference examples in the scoring matrix. However, the extent to which these measures reduce variability has not yet been formally tested through an inter-rater reliability study. Future work should include a structured comparison where multiple practitioners independently score the same set of real APECs to quantify the level of agreement and identify categories where additional guidance may be needed.

Two practitioner calibration workshops have been held to date. In each workshop, contaminated land practitioners independently scored the same set of APECs using the scoring matrix, and any differences were worked through as a group to identify the source of the variation. Common causes of variation included different interpretations of receptor proximity at sites with diffuse receptors, and different views on whether a partial SPR linkage should be scored as potentially complete or incomplete. The scoring guidance for these categories has since been refined based on the workshop outcomes. A formal inter-rater reliability study is planned to quantify scoring consistency across a larger group of practitioners and to identify any remaining categories where additional guidance is needed.

The case study uses hypothetical data rather than real operational data. While this is appropriate for demonstrating the mechanics of the tool, it does not demonstrate the full range of complexities that arise in practice, such as incomplete data, conflicting information from different investigations, or APECs where the CSM is poorly understood. The tool has been trialled on real portfolios across multiple mining operations, and the results of those applications support the prioritisation outcomes presented here, but the real-world validation is not included in this paper for confidentiality reasons.

The tool has been trialled across multiple mining operations managing portfolios of 30 to over 100 APECs. Key lessons from implementation include the importance of completing the scoring in a workshop setting with input from contaminated land practitioners, mine planners and closure leads to ensure all operational context is captured. The scoring process itself has proven valuable as a structured conversation that improves shared understanding of site risks across disciplines. In practice, the prioritised output has been used to allocate annual investigation and remediation budgets by directing resources to the highest-priority APECs first, and to sequence work programs so that APECs with hard approval or closure deadlines are addressed ahead of those with lower time pressure. The tool has also supported discussions with regulators by providing a transparent and documented basis for explaining why certain sites are being addressed before others.

It is also important to emphasise that the RAPT is designed to complement, not replace, expert judgement. The scoring requires an experienced contaminated land practitioner to interpret site conditions, assess SPR linkages and select appropriate scores. The tool provides the structure and consistency, while the practitioner provides the technical knowledge and contextual understanding. This combination produces a prioritisation that is both technically sound and practically useful.

5 Conclusion

This paper has presented the risk assessment and prioritisation tool (RAPT), a quantitative, multi criteria method for prioritising contaminated sites across a mining portfolio to support mine closure planning. The tool addresses the practical challenge of comparing and sequencing work across hundreds of APECs with diverse risk profiles by providing a structured, transparent, and repeatable framework that integrates environmental, operational, regulatory, social, and business risk factors into a single weighted score.

The tool evaluates each APEC against 17 risk categories with weightings determined through a pairwise comparison of 136 unique pairs, a 5-point scoring scale supported by detailed guidance and examples, and mitigating or aggravating factors that account for current site management conditions. The qualitative weighted score is calculated using a transparent formula that can be readily understood and verified by practitioners and stakeholders.

The conceptual case study demonstrated how the tool works from start to finish, taking raw site information, applying the scoring framework and producing a prioritised ranking with clear reasoning behind each score. The case study showed that the tool can differentiate between sites with fundamentally different risk profiles, integrate operational and environmental drivers in a balanced way, identify opportunities for low-cost risk reduction, and support adaptive decision-making as conditions change.

The tool is designed to sit alongside expert judgement and detailed site-specific risk assessments, not to replace them. It accelerates the prioritisation process, provides a common language for communicating priorities to stakeholders across the organisation, and supports alignment of the contaminated sites program with mine plans, progressive rehabilitation schedules, closure strategies and budget cycles.

The tool has been developed and trialled across multiple mining operations and is being adopted as part of the standard contaminated sites management process. Future development will focus on 2 priorities: a formal inter-rater reliability study to quantify scoring consistency across different practitioners, and integration with spatial data systems to enable geographic visualisation of the prioritised portfolio.

Acknowledgement

The authors acknowledge the support and leadership of the Head of Western Australia Asset Projects, the Technical Manager, and the Discipline Engineering Area Lead. The authors also thank the many stakeholders whose knowledge, experience and feedback informed and strengthened the development of this approach. The authors also acknowledge WSP Australia Pty Ltd for their collaborative support during the development of the RAPT application.

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