Mine Closure 2025 – S Knutsson, AB Fourie & M Tibbett (eds)

doi:10.36487/ACG_repo/2515_51

# A tool for acid rock drainage and metal leaching prevention and management

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## Abstract

*Improper management of mine waste materials containing sulphide minerals can accelerate natural weathering processes, potentially resulting in the release of acid rock drainage and/or metal leaching (ARD/ML) to the surrounding environment. Unmanaged ARD/ML processes can continue to degrade mine drainage water for decades or centuries and have a direct impact on the success of closure activities and the stability and usability of post-closure environments.*

*Integrating ARD and ML prevention and management throughout the project lifecycle is essential to realising optimised post-closure outcomes, with benefits including:*

- *mitigation of long-term environmental risks*
- *reduction of future liabilities*
- *alignment with sustainability goals*
- *enhancing stakeholder confidence*
- *enabling effective long-term monitoring and maintenance.*

*The International Network on Acid Prevention (INAP) has published international good practice principles in the form of the* Global Acid Rock Drainage Guide *(GARD Guide) (International Network on Acid Prevention [INAP] 2014) to support proactive management of ARD/ML. This resource includes sections on characterisation, prediction, prevention and mitigation and many others. However, despite the technical depth and global relevance of this content, there remains an opportunity to strengthen wider industry implementation of ARD/ML prevention, management, and good practice, throughout life of operations. Professionals on site that are often making mine planning decisions and have the greatest opportunity to incorporate ARD/ML and closure considerations into the project lifecycle are often not geochemists.*

*In 2024, ICMM and INAP collaborated to develop a tool for acid rock drainage and metal leaching prevention and management ('Tool') (International Council on Mining and Metals [ICMM] 2025b) to support non-specialists within mining companies to proactively prevent and manage ARD/ML. The Tool and accompanying user guide span the gap between global-level and site-specific support on the implementation of leading practices with the aim of empowering those responsible for ARD/ML management.*

*This paper provides an overview of the Tool and its functionality in operationalising the principles in the GARD Guide throughout the mining lifecycle. The Tool is targeted at non-specialist mining professionals and aims to*

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*promote and facilitate integrated ARD/ML management and prevention through life of operations so that the potential environmental burden, and closure and remediation costs are reduced.*

**Keywords:** *acid rock drainage, metal leaching, global acid rock drainage guide, prevention and management, monitoring and maintenance*

# 1 Introduction

Water is integral to the healthy functioning of the environment, economy and to human wellbeing. It is a precious, shared resource that everyone has the right to enjoy, underpinned by the United Nations' Sustainable Development Goal 6 to ensure access to water for all.

The mining and metals industry interacts with water across all stages of operations, from extraction to processing and transportation of minerals, to daily use in dust control. The sector's dependency and impact on this shared resource represents a risk that requires effective management though a water stewardship approach. As such, mining and metals companies must consider all potential impacts from operations on the environment and communities close to sites at an early stage of site-level planning and design approaches to prevent and mitigate these risks.

One of these risks to water is acid rock drainage and/or metal leaching (ARD/ML). Acid rock drainage (ARD) is the product of sulphide mineral oxidation and is characterised by sulphate and acidic pH (pH<6). It is often associated with metal leaching (ML), generating elevated concentrations of metals (which may also occur without acid conditions). ARD/ML is preventable with proactive planning and so it is possible to reduce associated environmental and social impacts from it by implementing robust water stewardship practices. This includes thorough site-level planning from the start of a mine's operation through to its closure.

# 2 Project background

ICMM stands for mining with principles. It brings together a third of the global metals and mining industry, along with key partners to drive leadership action and innovation for sustainable development, ultimately delivering a positive contribution to society.

Through ICMM's *Water Stewardship Position Statement* (ICMM 2017), ICMM members have committed to strong and transparent water governance, effective water management at operations and collaboration to achieve responsible and sustainable water use.

To support these commitments, ICMM members have worked collaboratively to address the challenges associated with water stewardship across the mining and metals industry, through developing ICMM's *Water Reporting: Good Practice Guide* (ICMM 2021) and *Water Stewardship Maturity Framework* (ICMM 2023).

This work extends to mine closure with ICMM's Integrated Mine Closure Good Practice Guide (ICMM 2025a), Closure Maturity Framework (ICMM 2020) and Financial Concepts for Mine Closure (ICMM 2019).

The International Network on Acid Prevention (INAP) was established in response to an identified need to reduce the liability associated with sulphidic mine materials. INAP brings together the most recent acid drainage experience and knowledge to build on existing research, learn from the achievements and challenges of others and benefit from expert peer review on key acid drainage issues.

In 2009, INAP published the Global Acid Rock Drainage Guide (GARD Guide). The GARD Guide details global leading practices and technologies for the prevention and mitigation of ARD/ML and has been periodically updated since. Despite the comprehensive nature of this guide, there is still significant opportunity for the mining industry to reduce ARD/ML by embedding leading practice ARD prevention and mitigation into day-to-day operations.

ICMM and INAP have collaborated to support mining and metals companies to prevent and reduce water pollution caused by ARD/ML from mines, with the aim of ultimately safeguarding water quality and reducing long-term remediation costs.

The resulting tool for acid rock drainage and metal leaching prevention and management ('Tool') is a new resource to support the implementation of the GARD Guide in mining and metals operations by mine personnel who have responsibilities for ARD/ML prevention and management but are often non-specialised and need to make decisions in a consistent, efficient and practical manner.

This proactive management of ARD/ML is a fundamental aspect of integrated mine closure planning. By addressing ARD/ML early and systematically, mines can significantly reduce the potential for long-term environmental degradation such as water contamination and ecosystem destruction. This approach not only helps to safeguard local biodiversity and water resources but also ensures that mining operations meet regulatory standards and avoid costly remediation efforts in the future.

# 3 Tool for acid rock drainage and metal leaching prevention and management

The Excel-based Tool and accompanying user guide span the gap between global-level and site-specific support on the implementation of leading practices. The aim of these materials is to empower those responsible for ARD/ML management but who are non-specialists in geochemistry.

The Tool provides a clear framework of information and quick access to relevant information from the GARD Guide and supporting information, including examples of typical decisions to make and rationale, asset-specific technical content, technical guidance and links to other documents and resources if needed. Figure 1 illustrates the function of the Tool within the continuum of broad leading practices and site-specific actions as well as the implementation scale, i.e. global versus at the individual asset level. Specifically, the Tool:

- represents a bridge between the guidance provided in the GARD Guide and the site-specific actions that often need subject matter expert input at an asset level (see Figure 1)
- provides a practical approach that assesses and summarises relevant ARD/ML prevention and management information relevant to each asset development stage
- supports and motivates non-specialists to efficiently make asset-level decisions related to the implementation of ARD/ML prevention and management leading practices.

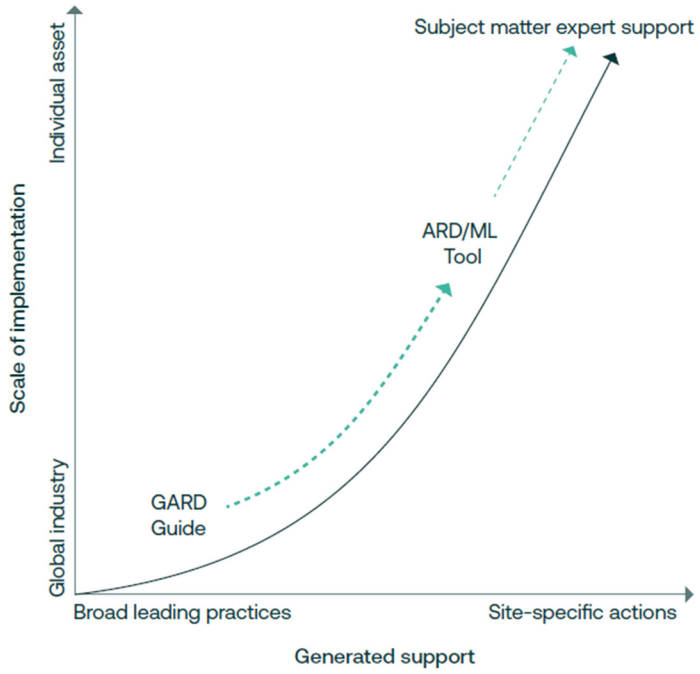


**Figure 1 Where the ARD/ML (acid rock drainage/metal leaching) tool for acid rock drainage and metal leaching prevention and management offers support based on the scale of implementation and the level of support provided**

## 3.1 Tool framework and principles

The Tool is built on a framework of seven leading practice areas and six asset development stages to populate a matrix of available support for the user.

The seven leading practice areas are mapped in Figure 2 along with various external and company influences that were considered as part of the development process and impact the information or decisions made at each stage gate. The framework considers external influences such as community needs and cultural sensitivities, industry guidelines (GARD Guide/ICMM/Mine Environment Neutral Drainage [MEND]), and regulatory requirements (global/national/regional). External influences are incorporated into the corporate-level ARD/ML governance and strategy which clearly defines accountability and responsibility for ARD/ML prevention and management.

The first leading practice area is ARD/ML governance and strategy which is highly influenced by external factors such as industry and regulatory guidance as well as stakeholders and communities.

The next two stages, leading practice areas two and three, cover setting objectives, standards and key performance indicators (KPI) and development of an ARD/ML management plan, respectively. This marks a transition point from strategic planning to activity-based leading practice areas, but these stages are still highly influenced and informed by external factors such as environmental and social impact assessments, baseline assessments, material characterisation and mine water quality predictions. Leading practice area three, relating to the development of an ARD/ML management plan, can be further broken down into five leading practice activities: characterisation, prediction, prevention mitigation and treatment, monitoring plans, and development and integration with mine, water, waste and closure plans.

When developing management plans and transitioning into implementation (leading practice area three to four), cross project integration with mine planning, water management, mine waste management and closure planning becomes essential.

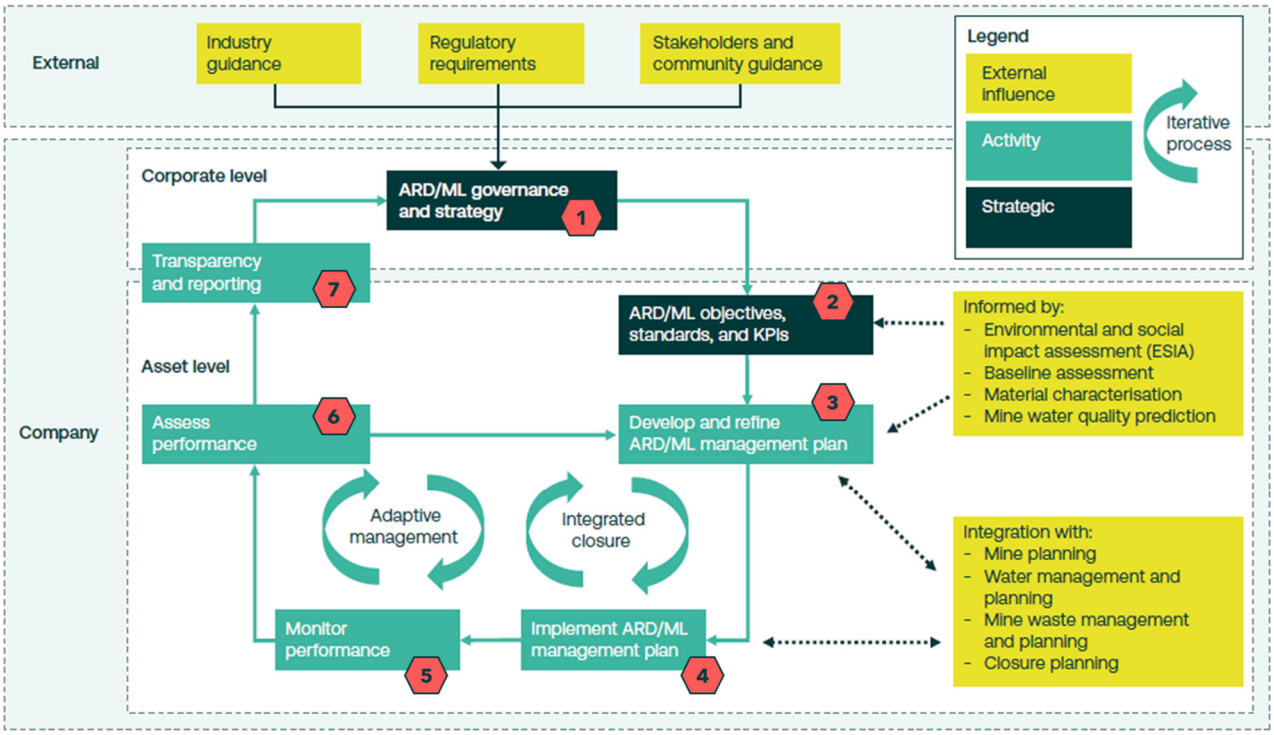


**Figure 2 Leading practice areas and various influences from the tool for acid rock drainage and metal leaching prevention and management**

The next stages (leading practice areas five and six) move into monitoring and assessing performance. This builds in feedback loops for adaptive management and integrated closure into the whole process.

Lastly, leading practice area seven covers transparency and reporting.

Each of these leading practice areas can be considered against six asset development stages: exploration, design, construction, operations, closure and post-closure. Figure 3 shows an indicative level of support for each of the leading practice areas. This support ranges from limited through peak levels depending on the level of prevention and mitigation measures applicable at each stage.

| | | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|---|
| | Leading practice areas | Leading practice activities | Asset development stages | | | | | |
| | | | Exploration | Design | Construction | Operations | Closure | Post-closure |
| 1 | ARD/ML governance and strategy | Define ARD/ML governance and strategy at corporate level | | Yes | | | | |
| 2 | ARD/ML objectives, standards and KPIs | Set ARD/ML objectives, standards and KPIs at asset level | | Yes | | Adaptive | Adaptive | |
| 3 | Develop and refine ARD/ML management plan | Characterisation | Limited | Peak | Yes | Adaptive | Adaptive | |
| | | Prediction | Limited | Peak | | Adaptive | Adaptive | |
| | | Prevention, mitigation and treatment | Limited | Peak | Adaptive | Adaptive | Adaptive | Yes |
| | | Monitoring program plan | Limited | Yes | Adaptive | Adaptive | Adaptive | Yes |
| | | Development and integration with mine, water, waste and closure plans | Limited | Yes | Adaptive | Adaptive | Adaptive | |
| 4 | Implement ARD/ML management plan | Integration with mine planning and operations | | | Yes | Peak | Yes | |
| 5 | Monitor and assess performance | Transparency in data management and reporting | | | Yes | Peak | Yes | Yes |
| 6 | Continual improvement of ARD/ML practices | Adaptive management | | | Yes | Yes | Yes | Yes |
| 7 | Integrated closure | Integrated closure | Yes | Yes | Yes | Yes | Yes | |

**Figure 3 Matrix depicting the indicative level of support for each leading practice and asset development stage within the tool for acid rock drainage and metal leaching prevention and management**

## 3.2 Tool function and capability

The Tool itself is Excel-based and utilises a matrix selection which can be used to select the leading practice area and asset development stage that is applicable to the user's project or needs.

The Tool contains several preamble sections leading the user through the following:

- executive summary
- an introduction to ARD/ML and the Tool framework
- instructions on how to use the Tool
- example scenarios on how the Tool can be applied.

The final two sections contain the Tool and a 'generated support' function. The Tool functions via a selection in a matrix of the leading practice areas and asset development stages, see Figure 4. By selecting an option within the matrix, the Tool auto-populates a table of information relevant to the user.

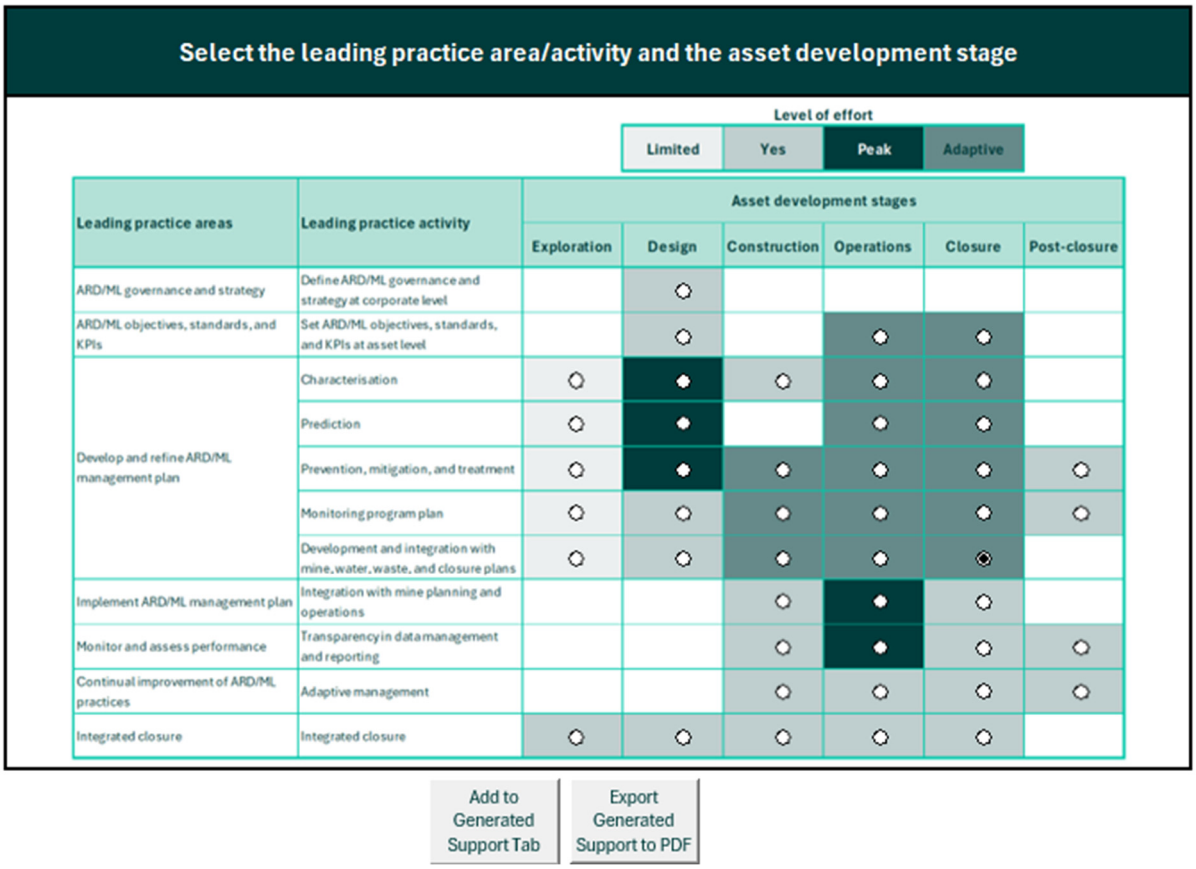


**Figure 4 Tool for acid rock drainage and metal leaching prevention and management matrix selection and functionality buttons**

The presented information runs through:

- Context: an overview of the activities relevant for the asset development stage and leading practice activity selected.
- Decision/s: examples of the typical decisions relevant to the selection.
- Rationale: basis and reasons relevant to the selection.
- Information requirements: outlines the typical information, data and documentation requirements for the selection.
- Technical and process considerations: key technical requirements, constraints and procedural factors that influence the planning, development and execution of activities within the selection.
- Related ARD/ML leading practice areas/activities: other selections within the Tool which may contain pertinent information.
- Useful GARD Guide resources: identifies chapters within the GARD Guide which can provide further detail and rationale, should this be required by the user.
- Figures: relevant figures from the GARD Guide to the information presented as part of this selection.

The generated outputs for a typical selection in the Tool is shown in Figure 5.

**Generated support: Develop and refine ARD/ML management plan**
**Activity: Development and integration with mine, water, waste, and closure plans**
**Asset development stage: Closure**

| | |
|---|---|
| **Context** | The closure stage presents the final opportunity to update and refine the ARD/ML management plan. While the closure plan should have been regularly updated throughout operations to provide for closure execution in this phase, if this has not yet been completed, it is during this stage that there might be the highest reliance on the ARD/ML management plan to inform and support more detailed closure planning.<br><br>Information in the ARD/ML management plan is used to support the implementation of closure measures based on predicted post-closure drainage chemistries from residual mine landforms/facilities. The ARD/ML management plan is updated with new drainage chemistry predictions, final closure ARD/ML prevention and mitigation measures, and information from any additional geochemical characterisation studies (eg closure construction materials). |
| **Decision(s)** | (1) Are there any changes or updates required to the ARD/ML management plan for the closure stage? |
| **Rationale** | The closure stage presents the ultimate opportunity to use the information that has been captured in the ARD/ML management plan during preceding stages to support closure planning. It is also critical to update the ARD/ML management plan with the final closure measures (as they relate to ARD/ML prevention and mitigation during the post-closure stage). The updated ARD/ML management plan becomes a record of all ARD/ML related information for the asset, is a consolidated technical reference for the closure plan and is used to communicate ARD/ML prevention and mitigation strategies. |
| **Information requirements** | (1) Results from geochemical verification and/or characterisation programs during operations<br>(2) New or updated drainage chemistry predictions<br>(3) Relevant mine waste and water operational data (eg production records, material masses stored, water volumes managed)<br>(4) ARD/ML monitoring data<br>(5) Any changes to (integrated) mine waste and water management strategies or measures<br>(6) Closure plan, including outcomes, objectives and criteria<br>(7) Regulatory requirements related to ARD/ML management during closure |
| **Technical and process considerations** | The ARD/ML management plan is updated during the closure stage to consolidate and be an updated repository of all ARD/ML data, information, measures, and commitments associated with the asset. The updated ARD/ML management plans also acts as a technical reference for ARD/ML components of the closure plan.<br><br>The ARD/ML management plan should be updated with the following information:<br>(1) Changes to the closure plan, specifically any changes to residual mine landforms/facilities ARD/ML prevention and mitigation measures.<br>(2) Results of geochemical verification and characterisation programs (eg closure construction materials).<br>(3) ARD/ML management performance assessment.<br><br>It is essential that all functions responsible for ARD/ML planning, mine planning, mine waste planning, mine water management planning, closure planning, and social engagement communicate on a regular basis and develop a record of topics discussed, decisions made, required actions, and responsible/accountable parties for execution of those actions. |
| **Related ARD/ML leading practices areas/activities** | (1) Develop and refine ARD/ML management plan → All leading practice activities<br>(2) Integrated closure → Integrated closure |
| **Useful GARD Guide resources** | (1) Chapter 3: Corporate, Regulatory, and Community Framework<br>(2) Chapter 9: Acid Rock Drainage Management and Performance Assessment<br>(3) Chapter 10: Acid Rock Drainage Communication and Consulting<br>(4) Chapter 11: Sustainable Mine Closure |

**Figure 5 Generated output for a typical selection within the tool for acid rock drainage and metal leaching prevention and management**

The Tool has several functions to enhance usability and functionality as well as tailor it to a specific site. For example, the generated guidance can be added to the 'generated support' tab via the button function which allows multiple selections to be viewed in a table.

The 'generated support' tab also allows the user to add project information and user notes before exporting the file as a standalone Excel document. Individual guidance sections (i.e. from one selection on the matrix) can also be exported directly as a PDF.

# 4 Examples of tool application

The Tool can be used in a variety of different ways to suit the user and specific asset functions. This section presents some example scenarios in which it could be applied.

## 4.1 Example #1: continuous improvement and adaptive management

In this scenario, a mining company is in the early stages of operations. The operation has an existing ARD/ML management plan, and potentially acid forming material has been placed in a waste rock storage area, designed to minimise infiltration and oxygen ingress, per the management plan.

The operations team wishes to assess the performance of the control systems on an ongoing basis. The following workflow, integrating aspects of consulting the Tool, may apply:

1. Consult the ARD/ML objectives, standards and KPIs for the asset.
2. Consult the ARD/ML management plan and its associated monitoring plan and execute the described monitoring program.
3. Compile and interpret the collected monitoring data to assess if the evolution of ARD/ML under the applied control measures is developing in accordance with model predictions and how well the ARD/ML management plan is preforming against expected performance values.
    a. The user selects the ‘monitor and assess performance’ leading practice activity for the ‘operations’ asset development stage.
    b. The provided information can be used to assess the results of the performance data. For example, under the technical and process considerations, an overview of the types of deviations and variances from the expected conditions that could warrant further evaluation is given.
    c. This includes aspects such as the ARD/ML properties are different from those designed for in the mine plan, seepage water quality from the waste rock pile is different from what was anticipated or modelled, or receiving the groundwater quality is different than expected.
    d. Where necessary, the Tool also prompts the user to undertake adjustments to models, maintain data recording protocols and incorporate any changes into monitoring plans.
4. If the performance assessment results indicate the performance objectives are not being met, adaptive management processes should be initiated.
    a. The user selects the ‘adaptive management’ leading practice activity for the ‘operations’ asset development stage.
    b. The technical and process considerations for this activity can be viewed, along with a figure detailing adaptive management implementation by phased approach from the GARD Guide, to guide the user through this process.
    c. This helps to address uncertainties identified in the deviation from the performance objectives and prompts a review, and where necessary adjustment, of the management plans. Monitoring programs can also be revised to improve the performance assessment process.

## 4.2 Example #2: legacy asset risk management

In this scenario, a mining company is responsible for a legacy mining asset where the ARD/ML risks are not known and have not been quantified. The team responsible for this asset wants to know how to assess and quantify the ARD/ML risks with the view to closing and managing the site.

The Tool may be applied using the following workflow:

1. Define the ARD/ML objectives, standards and KPIs for the legacy asset:
    a. The user selects the ‘define ARD/ML governance and strategy at corporate level’ and ‘set ARD/ML objectives, standards and KPIs at an asset level’ leading practice activities during the ‘design’ asset development stage.

   b. Due to the lack of information available for the legacy asset, it is necessary to utilise the earlier asset development stages (e.g. design or exploration to adequately address the ARD/ML issues in this scenario).

   c. Relevant information from these selections is used to define feasible ARD/ML objectives, standards and KPIs for the legacy asset.

   d. Relevant information provided will prompt the user to consider the regulatory requirements, industry best practice, corporate standards and stakeholder considerations in developing these aspects as well as the information requirements against which any existing documentation can be assessed.

2. Identify the ARD/ML risks associated with the legacy asset:

   a. The user can use a combination of the decision support provided in the 'develop and refine ARD/ML management plan characterisation' leading practice activity for the 'exploration' and 'design' asset development stages.

   b. The information here will aid the user in assessing the available ARD/ML related information and define the ARD/ML risks. The technical and process considerations outline the suitable data, as well as the characterisation requirements for the materials present and the necessary documentation of findings.

3. Assess the need for characterisation and prediction:

   a. The user selects 'develop and refine ARD/ML management plan- characterisation' and develop and refine ARD/ML management plan- prediction' leading practice activities for the 'design' asset development stages.

   b. Key decisions and information requirements from the generated support can be used to further gather information and quantify the ARD/ML risks to a level sufficient to estimate the long-term requirements of managing the ARD/ML risks of the asset. This is crucial for the ongoing management of the legacy asset and understanding the costs of closing and maintaining the site adequately.

# 5 Conclusion

ICMM and INAP's Tool is a new resource designed to promote leading practice management of ARD/ML in mining and metals operations by mine personnel who have responsibilities for ARD/ML prevention and management but are often non-specialists and need to make decisions in a consistent, efficient and practical manner.

The information presented in the Tool aligns with the leading practice as detailed in the GARD Guide but is delivered in a concise and user-friendly format that supports site-specific decision-making. Designed for versatility, the Tool can be applied across a wide range of activities at various asset development stages, including closure-related projects. Its primary aim is to support the mitigation of long-term environmental risks, reduction of liabilities, alignment with sustainability goals and facilitation of long-term monitoring and maintenance.

# Acknowledgement

The authors wish to thank all the contributors to the Tool for Acid Rock Drainage and Metal Leaching Prevention and Management.

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