CEEC THE FUTURE

GLOBAL WATER INITATIVE

ESTABLISHING THE WATER KNOWLEDGE BASELINE

The University of Queensland, Australia — Create Change

The University of Queensland, Sustainable Minerals Institute

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Preface

Professor Claire Côte of Sustainable Minerals Institute has coordinated the preparation of this first draft of the Water Knowledge Baseline for the CEEC Global Water Initiative with contributions from Prof Neil McIntyre, Prof Mansour Edraki, Dr Pascal Bolz, Dr Nevenka Bulovic, Dr Robynne Chrystal, Dr Louisa Rochford, Dr Mandana Shaygan. This version remains work in progress and is intended as a starting point for input from sponsors and CEEC affiliated professionals, followed by minor updates and an initial public release.

The knowledge base is expected to evolve as feedback and input are received and will require periodic updates to keep it current. CEEC is determining the best way to gather and validate updates to content, as well as an expected cycle for periodic reviews and updates.

The next update is expected to include additional information on references to regulatory approaches, technical guidelines, and guidance documents from a wider range of jurisdictions. CEEC partners, supporters and sponsors will be well placed to submit references to such documents, based on their experience.

Case studies will strengthen the knowledge base. CEEC partners, supporters and sponsors are encouraged to submit ideas. The team working on the Water Knowledge Baseline can assist with drafting written content describing the case studies, if required.

It has been envisaged that the knowledge baseline will be transposed to an online wiki structure, similar to the GARD Guide. The timing, hosting, and management of the set-up of this wiki is yet to be determined. Input is sought from sponsors and CEEC affiliated professionals on how best to manage the wiki and associated updates.

Contents

1. Purpose and application

1.1 Purpose

The CEEC Water Knowledge Baseline has been developed as a structured, introductory reference to the water-related themes that are relevant to mining and mineral processing. It is intended to support professionals across the industry in acquiring a foundational understanding of topics such as regulatory frameworks, hydrology, hydrogeology, water quality and treatment, operational water risks, monitoring systems, and stakeholder dynamics.

This document is not designed to be exhaustive or prescriptive. Rather, it serves as a practical entry point into technical and strategic issues, guiding readers toward relevant methodologies, case studies, and additional sources of expertise. It reflects practices and insights from a diverse range of mining jurisdictions, including Australia, Chile, Peru, Brazil, Canada, the United States, and others.

Where external sources, service providers, or research institutions are mentioned, these are presented as illustrative references and not endorsements. Users are encouraged to critically assess the relevance and applicability of all referenced tools and materials to their own context.

1.2 Why having a Water Knowledge Baseline matters

Mining operations worldwide are increasingly affected by complex and dynamic water-related challenges. These include technical, environmental, regulatory, and social dimensions that require integrated and context-specific solutions. A shared baseline of knowledge offers several benefits, as it can:

- Enable rapid orientation for professionals who are new to water-related domains or are seeking to update their understanding.
- Establish a common language to support collaboration between technical specialists, project teams, regulators, and communities.
- Promote consistent use of terminology, assumptions, and methods, especially across multidisciplinary and multi-national teams.
- Help identify water-related risks, opportunities, and information gaps early in the mine planning and operational lifecycle.
- Align technical decisions with broader environmental, social, and governance (ESG) frameworks and stakeholder expectations, including those related to transparency and accountability.

For CEEC, this baseline can also serve as a foundation that supports ongoing learning and collaboration, exchange of practices, identification of innovation priorities, and promotion of continuous improvement in water stewardship.

1.3 Who this document is for

This document is intended to support a wide range of professionals and institutions involved in water management in the mineral sector, including:

- Engineers and technical professionals addressing operational risks that involve understanding of hydrology, hydrogeology, water treatment, tailings management, and more generally environmental management.
- ESG and sustainability practitioners seeking to align operational practices with voluntary and regulatory frameworks.
- Regulatory agencies and permitting authorities engaged in the oversight of water management in the mineral sector and the protection of environmental values.
- Academic institutions and students looking for introductory material or practical orientation to water-related challenges in the mineral sector.

- Project managers and operational leaders integrating water-related considerations across the lifecycle of mining projects.
- Community relations and external affairs teams navigating stakeholder concerns related to water access, quality, and legacy impacts.

Whether the reader is seeking to design a more sustainable project, improve existing site performance, understand regulatory risk, or engage effectively with stakeholders, this Water Knowledge Baseline aims to provide a coherent starting point and reference pathway.

1.4 Continuous improvement of the Water Knowledge Baseline

This document represents the initial iteration in the development of the CEEC Water Knowledge Baseline. It proposes an architecture for capturing the elements of mine water management and communicating the status of knowledge associated with these elements. As far as practicable, it aims at describing practices that have been implemented by companies to improve mine management and outlines where progress is still required, proposing potential activities for improvements.

CEEC aims to establish a framework for the ongoing enhancement of this knowledge resource, with the intention of making it widely accessible—most likely in the form of a wiki. A wiki is a type of website or online platform that allows users to collaboratively create, edit, and organise content. The most well-known example is Wikipedia, but wikis can be used for many purposes, including knowledge management. The content is usually accessible to a wide audience, and editing may be open or restricted depending on the platform's settings that are selected.

The Water Knowledge Baseline wiki would serve as a dynamic and interactive repository for water-related knowledge. It is envisioned that the platform will:

- Serve as a vital interface between academic and non-academic sources of knowledge.
- Integrate both formal and informal insights, including contributions from industry professionals.
- Encourage individuals to voluntarily share their expertise and actively engage in the knowledge-sharing process.

2. Introduction

2.1 The water cycle

The water cycle describes the constant movement and endless recycling of water between the atmosphere, land surface, and underground. The water cycle shapes landscapes, transports nutrients and minerals, and is essential to most life and ecosystems on the planet.

While the concept of the water cycle is quite simple at global scale, the practical assessment of its components becomes very complex at more detailed scale.

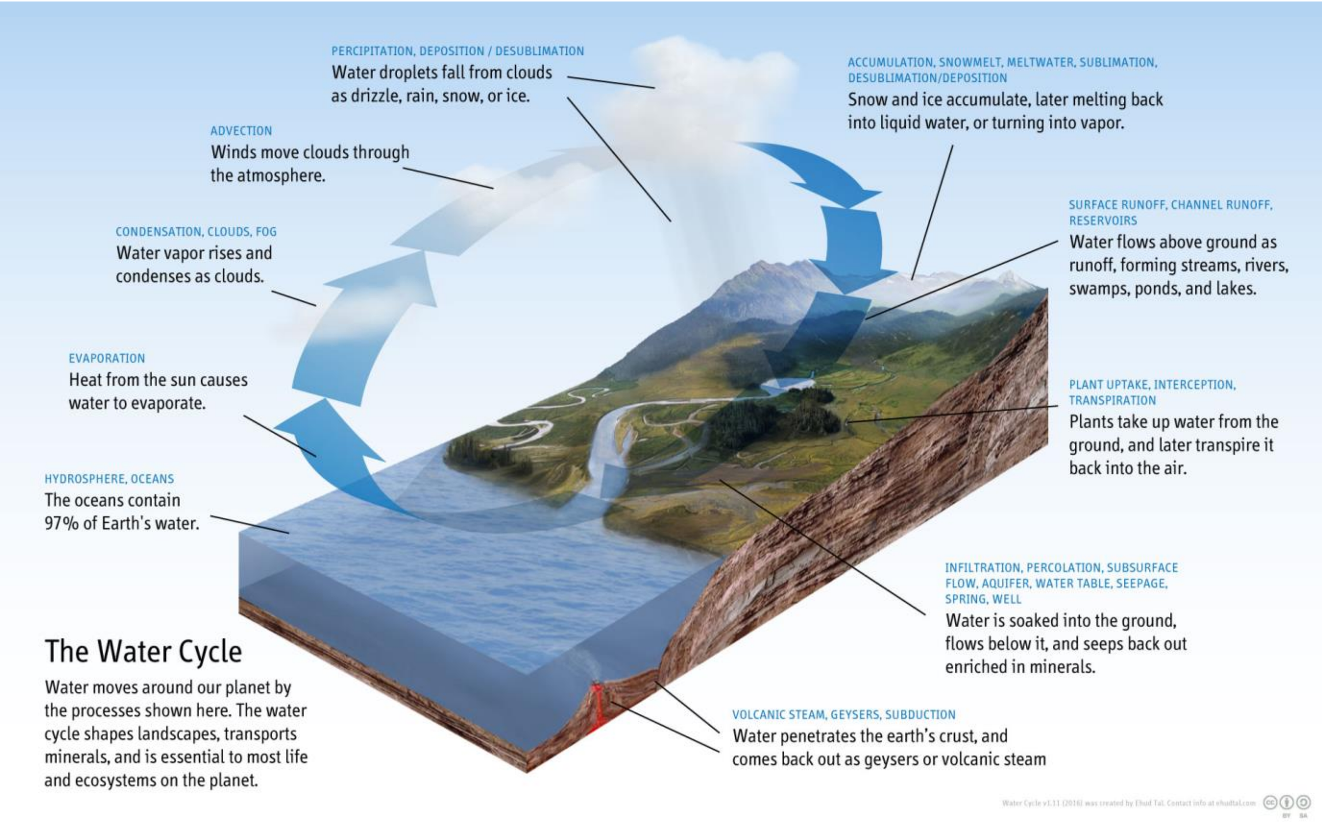

Figure 1: The water cycle (source: ehudtal.com).

Hydrology is the study of the fundamental transport processes that govern the quantity and quality of water as it moves through the water cycle: evaporation, precipitation, streamflow, infiltration, and groundwater flow. This domain of study is subdivided into surface water hydrology (Section 4), groundwater hydrology (called hydrogeology and covered in Section 5), and marine hydrology. As marine hydrology is rarely relevant to mineral extraction activities, it is not included in this knowledge baseline.

2.2 Interactions with mineral extraction activities

Mineral extraction activities create a wide range of interactions with the water cycle, as they are located all over the world, spanning multiple climatic contexts: arid, temperate, tropical, and sub-arctic. These interactions are well understood. They include management of surface water runoff and potentially requirements to divert watercourses, requirements for flood protection, erosion and sediment control, predicting and controlling potential releases of mine-affected water, optimising water supply and/or groundwater extraction, dewatering and storage dams, managing the impacts on water quality, and optimising residue and tailings disposal (Figure 2).

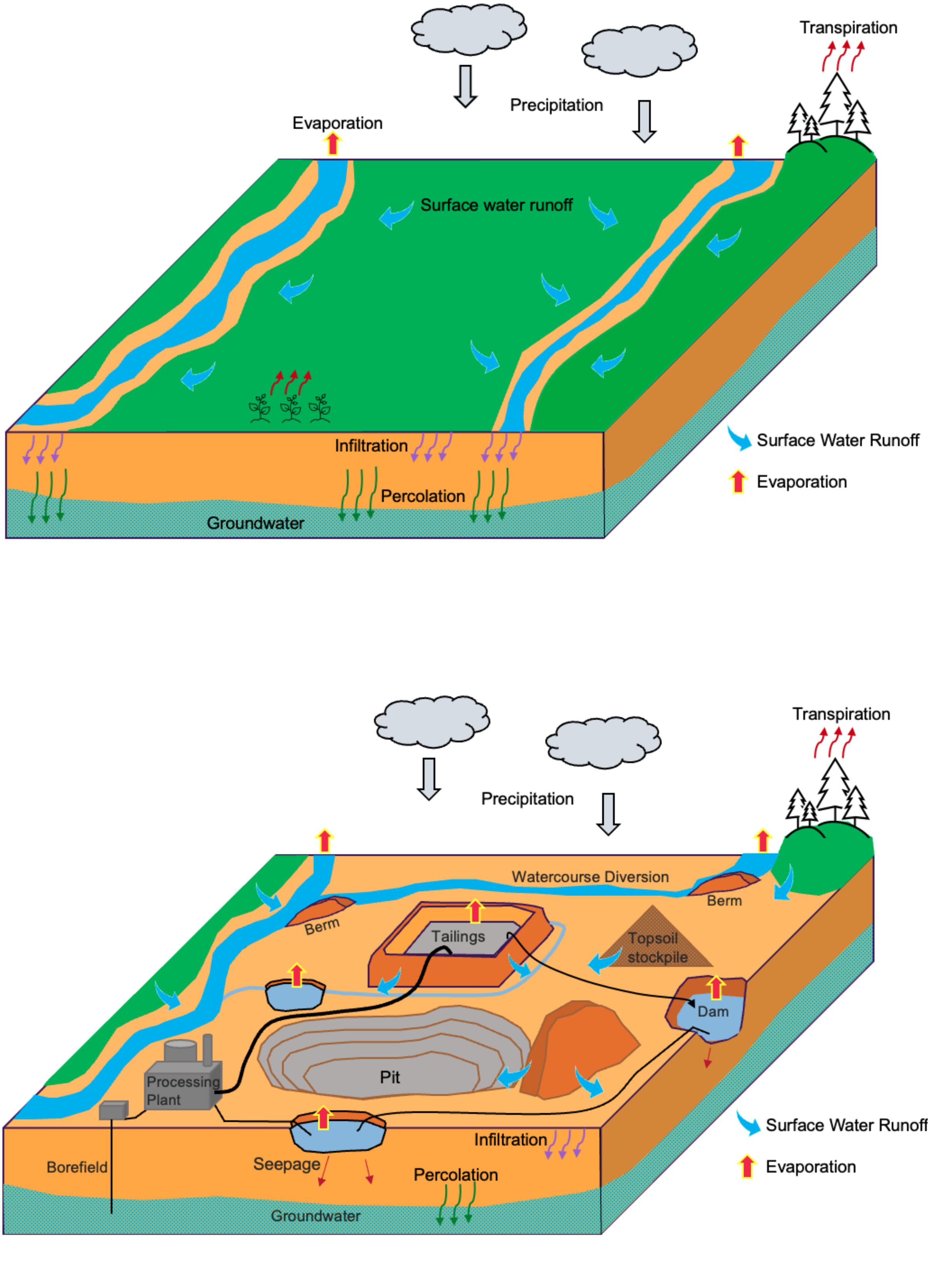

Figure 2: the water cycle before (top) and during (bottom) mining (Source: Centre for Environmental Responsibility in Mining, Sustainable Minerals Institute, University of Queensland).

In addition, despite mining being a relatively small consumer of water on a global scale, in the regions where mining does occur, it can account for a large proportion of consumed water. The local impacts of a mine's water consumption can lead to social tension with other water user groups such as agriculture, communities, or tourism.

The local climate, hydrology, and hydrogeology will dictate the nature and extent of water-related risks faced by mines and their nearby ecosystems. Risks include uncertainty over access to a stable water supply, flooding, instability of waste structures and impoundments, or uncontrolled releases of poor-quality water. Water quality deterioration from mining is different from that generated by other industries, as the contamination can arise from the geochemistry of the ore body, the mining, mineral processing and waste disposal methods, and the strategies for collecting and storing mine-affected water. In most mining jurisdictions, regulatory frameworks have been developed to ensure these risks are identified and mitigated.

The knowledge required to manage these aspects is held by experts, employed by mining companies and/or specialised service providers. There are risks associated with knowledge loss as most of this knowledge is not readily available in the public domain.

There have been efforts to capture some knowledge in guidance documents, for instance:

- International Council of Mining and Metals (ICMM) Water Stewardship Maturity Framework: https://www.icmm.com/en-gb/guidance/environmental-stewardship/2023/water-stewardship-maturity-framework
- Water Stewardship – leading practice management handbook, published by the Australian Federal Government in 2019: https://www.industry.gov.au/sites/default/files/2019-04/lpsdp-water-stewardship-handbook-english.pdf
- The Mining Association of Canada (MAC) water stewardship protocol: https://mining.ca/wp-content/uploads/dlm_uploads/2023/04/Water-Stewardship-Protocol-apr-2023.pdf

However, these guidance documents mostly describe high-level principles of mine water management, with very little direction towards finding detailed technical advice.

The structure of the CEEC Water Knowledge Baseline is organised to address the themes identified above:

- Regulatory frameworks, legal and voluntary commitments;
- Understanding hydrology and how hydrological methods are used to understand and mitigate risks associated with surface water;
- Understanding hydrogeology and how groundwater studies are used to understand and mitigate risks associated with groundwater;
- Understanding the impacts of mining on water quality and options for water treatment;
- Managing stormwater runoff, as well as erosion and sediment export;
- Exploring the risks water can pose to the safety of mining operations and understanding the issues arising from waste disposal, particularly tailings dams;
- Designing a monitoring program as an essential part of risk mitigation and managing water-related data effectively.

The Knowledge Baseline is not meant to be an exhaustive repository of information. It more closely aligns with the concept of providing the first steps towards seeking and finding more detailed guidance. In some sections, links to service providers, research groups, or sources of documentation are provided. These are not to be interpreted as endorsement, but as options that warrant investigation.

3. Legal and voluntary obligations

3.1 Regulation

The mining industry is heavily regulated, with frameworks focusing on safety, environmental protection, and responsible resource management. Broadly, in most mining regions (if not all) the environmental legal system imposes requirements to obtain approval for a mining project, which is a highly complex process, and to comply with any relevant standard imposed by the law. It is beyond the scope of this knowledge baseline to explore regulatory frameworks in detail, as they vary with each mining region. Readers are encouraged to source information about the regulatory framework that is applicable to their region of interest.

It is worth noting however that, generally, leaders and managers at mine sites and corporate offices have extensive accountability under environmental legislation, which may cover responsibility for compliance with environmental legislation. Leaders, managers, and mine workers must know their environmental legal obligations and establish work programs to deliver compliance with these obligations. In most jurisdictions, there is a process for dealing with environmental offences and they will be communicated via media platforms. Whilst the financial consequences tend to be small, the reputational consequences can be severe.

Readers who are seeking general information about the importance of regulating the mineral sector can refer to the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF). It supports more than 80 member countries to advance sustainable development objectives through effective mining laws, policies, and regulations. The IGF's cornerstone Mining Policy Framework (MPF) represents the best practices required for good environmental, social, and economic governance of the mining sector and the generation and equitable sharing of benefits to contribute to sustainable development. The MPF can be accessed here: https://www.igfmining.org/resource/igf-mining-policy-framework/

With respect to water management in the mineral sector, typically there are two main aspects that are regulated:

- The volume of water that can be withdrawn or abstracted from certain sources such as lakes, rivers, or aquifers: this is governed by principles of integrated water resources management, described in Section 3.4.
- The volumes and composition of waters that can be released from a mine site. Threshold concentrations of various species in water (e.g. heavy metals) may be prescribed. In some cases, mines may be required to be zero-liquid discharge, i.e. no water is to be released from the site. Quantifying the volumes of water that may need to be released and the quality of that water forms part of the detailed technical studies described in Sections 4 to 8.

3.2 Voluntary commitments

Beyond legal obligations, organisations like the Initiative for Responsible Mining Assurance (IRMA), the International Council on Mining and Metals (ICMM), the Mining Association of Canada (MAC), the Copper Mark and the World Gold Council have developed and published their own standards and principles to provide guidance to mining companies on environmental, social, and governance aspects. These voluntary standards and principles include commitments to water stewardship and water management. Examples of voluntary standards are provided below. Employees currently working in the mining industry are encouraged to seek information about the voluntary frameworks their company has adopted.

Standards and principles developed by industry organisations

International Council on Mining and Metals (ICMM)

Mining Principles: https://www.icmm.com/en-gb/our-principles

Global Tailings Management Institute: https://www.icmm.com/en-gb/our-collaborations/gtmi, and Global Industry Standard on Tailings Management: https://globaltailingsreview.org/global-industry-standard/

Water Stewardship: https://www.icmm.com/en-gb/our-work/nature/implement-water-stewardship-practices

Both the Global Industry Standard on Tailings Management and the Water Stewardship documents contain extensive commitments to good practice water management.

Mining Association of Canada

The Mining Association of Canada's Towards Sustainable Mining (TSM) standard is a globally recognised sustainability program that supports mining companies in managing key environmental and social risks: https://mining.ca/towards-sustainable-mining/

It includes a protocol for water stewardship: https://mining.ca/wp-content/uploads/dlm_uploads/2023/04/Water-Stewardship-Protocol-apr-2023.pdf

The water stewardship protocol specifies criteria for water governance, operational water management, watershed-scale planning, and water reporting.

The Copper Mark

The Copper Mark is an assurance framework to promote responsible practices across the copper, molybdenum, nickel, and zinc value chains: https://coppermark.org

The Copper Mark includes assessment criteria related to water stewardship to avoid, minimise, rectify, and compensate for adverse impacts on water balance, flow quality, and access and needs of other water users and wildlife from operational activities.

The World Gold Council

The Responsible Gold Mining Principles (RGMPs) provide a framework that set out clear expectations for consumers, investors, and the downstream gold supply chain as to what constitutes responsible gold mining: https://www.gold.org/industry-standards/responsible-gold-mining

Principle 10 of the RGMPs relates to water, energy, and climate change. It aims at improving the efficiency of water use and at ensuring gold mining operations do not adversely affect the overall quality of catchment water resources available to other users.

The Consolidated Mining Standards Initiative

These four organisations have embarked on a project to consolidate their individual standards. This new standard comprises 24 performance areas that cover a wide range of topics related to responsible mining under the four pillars of ethical business practices, worker and social safeguards, social performance, and environmental stewardship. One performance area relates to water stewardship.

Consolidated Mining Standard Initiative (CMSI): https://miningstandardinitiative.org

Standards developed independently from industry

Initiative for Responsible Mining Assurance (IRMA)

The IRMA standard currently offers the only independent, third-party assessment of industrial-scale mine sites for all mined materials that is governed equally by the private sector, local communities, civil society, and workers: https://responsiblemining.net

The IRMA standard contains a chapter dedicated to water management (Chapter 4.2), with the goal of managing water resources in a manner that strives to protect current and future uses of water.

Global Reporting Initiative (GRI)

The GRI 14: Mining Sector 2024 comprehensively addresses the sustainability impacts of the mining sector and meets broad stakeholder demands for transparency to provide mining companies with a unified set of metrics to report their impacts. The standard highlights the balance between the essential role of mining in supplying critical minerals and the need for accountability regarding environmental, community, and worker impacts. The standard was developed through a robust multi-stakeholder approach and covers 25 key topics, promoting significant and sustainable practices. The Standard aligns with general GRI reporting by providing sector-specific metrics and guidelines that complement the broader GRI Standards: https://www.globalreporting.org/standards/standards-development/sector-standard-for-mining/

This standard is effective as of January 2026 and includes reporting indicators related to water.

3.3 Compliance tracking

It is beyond the scope of this project to articulate how to deliver compliance with legal and voluntary commitments. Key messages are that water practitioners working in the mining and minerals industry must:

- Understand the commitments the company they work for have made, with respect to both legal and voluntary frameworks.
- Align and incorporate the principles committed to into water-related strategies, policies, and procedures.
- Regularly report on progress on implementing these principles.
- Undertake audits and/or self-assessments to verify that activities are being undertaken to implement the principles.

This requires that skilled personnel with appropriate budget and resources are allocated to these tasks.

The total number of obligations that a mine must comply with will be very large (the order of magnitude varies but some mines must comply with thousands of obligations). For companies that operate several mines in different jurisdictions, data and information management systems will be required to track compliance performance. This requires specific databases that can compile data and information and produce reports to meet the requirements of compliance tracking. In most cases, a hierarchical approach will be required. For instance, a mine can install a system for compiling their water-related data (e.g. an environmental database) and create reports of aggregated information to send to an environment, health, and safety analytics platform at corporate level.

Options for systems that compile and manage environmental data are provided in Section 9.3.1.

3.4 Regulating access to water: integrated water resources management

Integrated water resources management (IWRM) promotes the co-ordinated development and management of water to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. It stems from the recognition that difficult decisions must be made to apportion diminishing water supplies between ever-increasing demands and that a fragmented approach is not viable; a holistic approach to water management is essential.

IWRM was built on the experience of practitioners. Although many parts of the concept have been around for several decades (since the first global water conference in Mar del Plata in 1977) it was not until after the World Summit on Sustainable Development in 1992 in Rio that extensive discussions focused on what it means in practice. The stages involved in IWRM planning and implementation are outlined in Figure 3.

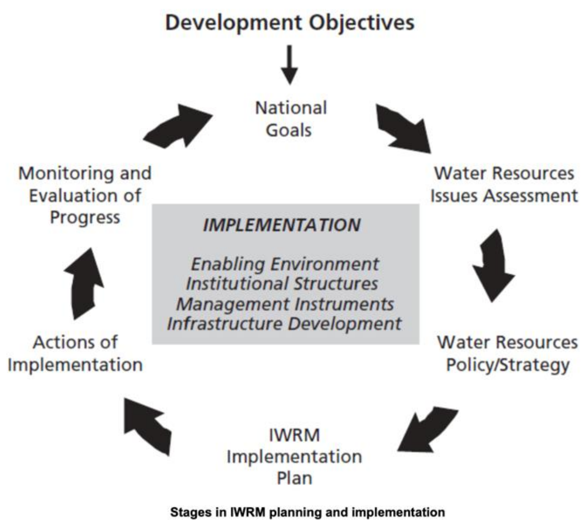

Figure 3: Overview of integrated water resources management[1].

Progress on implementation of IWRM on a global scale is described in this United Nations report:

https://www.unwater.org/sites/default/files/2024-08/SDG6_Indicator_Report_651_Progress-on-Implementation-of-IWRM_2024_EN_0.pdf

Data describing progress is available in this data portal:

IWRM data portal: http://iwrmdataportal.unepdhi.org

As shown in the IWRM data portal and associated maps, almost all countries have embarked on the implementation of the principles of IWRM. The case studies below explore the level of practice in several mining regions: Australia, Canada, Chile, and Peru.

Case study: water resources planning in Queensland, Australia

Australia has achieved a high degree of implementation of IWRM processes. Within the country, the State of Queensland has established a reputation for implementing strong governance processes for the quantification and allocation of water resources, which is the responsibility of the state government. The approach involves:

- Water planning that balances the needs of water users and the environment.
- Ensuring access to safe and reliable drinking water and recycled water supplies.
- Improving water security for both drinking and non-drinking purposes.
- Facilitating efficient water markets to stimulate economic development in regional communities.
- Ensuring the safety of dam infrastructure and downstream people and property.

[1] IWRM Toolbox: https://waterknowledgehub.org/learn/iwrm-tools/national-iwrm-plans

- Enabling fairness, transparency, and accountability of water systems through high-quality data collection and visibility.

The state government manages water resources by:

- Planning the allocation for water—through water plans, water management protocols, and resource operations licences.
- Administering entitlements for access to water—by issuing water allocations, licences, and permits.
- Administering licences to operate water infrastructure—by issuing resource operations licences and distribution operations licences.

A water resource plan states government objectives for a catchment's social, economic, and environmental needs, while a resource operations plan details how water resources will be managed on a daily basis to meet these objectives.

A mining operation seeking to secure an allocation of water needs to:

- Identify in which catchment the mining operation is located.
- Review the water resource plan for that catchment and identify the resource operations plans that are the most likely to be able to supply water to the operation.
- Follow the guidance provided with the water resource plan to apply for a water entitlement.

This information can be found at:

https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning

Case study: water resources planning in British Columbia, Canada

Canada has achieved a high degree of implementation of IWRM processes. As is the case in Australia, water resources are primarily managed at provincial level.

The Water Sustainability Act (WSA) was enacted in 2016 to ensure a sustainable supply of fresh water that meets the needs of British Columbia (B.C.) residents. It establishes the province's ownership of surface and groundwater, clearly defines limits for bulk water removal, and prohibits the large-scale diversion of water between major provincial watersheds (catchments) and/or to locations outside of the province.

The right to divert and use surface water or groundwater is authorised by a licence or approval. Certain streams are designated sensitive to protect fish populations and habitat. Licences and approvals may be granted on sensitive streams subject to strict terms and conditions.

Water allocation plans only exist for specific streams. They review how much water is available within these streams, considering the environmental flow requirements for fish and the existing and potential demands for water licences or water use approvals.

As the relationship between fish, flood protection, recreation, power generation at hydroelectric facilities, and other water uses has received considerable attention, the province now requires development of water use plans for water control structures.

A mining operation seeking to secure an allocation of water needs to identify in which catchment the mining operation is located and whether a water allocation plan is in place for that location. It is highly unlikely that a water use plan will be required, as these mostly concern hydro-electric dams. The operation then needs to apply for a water license.

This information can be found at:

https://www2.gov.bc.ca/gov/content/environment/air-land-water/water

Case study: water resources planning in Peru

Peru has achieved a medium to low degree of implementation of IWRM processes. The 2009 Water Resources Law and the draft National Water Resources Management Strategy provide the framework for IWRM, which includes modernising the allocation of water rights, incorporating climate scenarios, and establishing early warning systems for floods and extreme events. La Autoridad Nacional del Agua (ANA) is responsible for the design and implementation of sustainable water resources policies and irrigation nationally. It has a clear mandate for implementation of IWRM principles.

Consejos de Recursos Hídricos de Cuenca (CRHC) are being created to achieve meaningful and permanent participation of stakeholders in the planning, co-ordination, and agreement for the sustainable use of water resources in their respective areas. The CRHCs are comprised of representatives from ANA, regional and local governments, water users (agricultural/non-agricultural), professional associations, universities, farmers, indigenous communities, and operators of special projects of water infrastructure. Additionally, as appropriate, they can include a representative of the water transfer areas (giving and receiving basins), a representative of peasant communities, a representative of Indigenous communities, a representative of special projects that operate public water infrastructure, and a representative of the Ministry of Foreign Affairs.

Despite significant progress, Peru faces challenges related to its limited institutional capacity, zones of high-water stress in coastal regions, deteriorating water quality, and inadequate access to sanitation.

A mining operation seeking to secure an allocation of water needs to apply for a water right to the ANA. Identifying the relevant CRHC and engaging extensively with its members would support this process.

Detailed information about the status of IWRM implementation in Peru is provided in this document: https://www.oecd.org/content/dam/oecd/en/publications/reports/2021/03/water-governance-in-peru_0980e96a/568847b5-en.pdf

Case study: water resources planning in Chile

Chile has only achieved a low degree of implementation of IWRM processes. However, the country is actively improving its approach to water resource planning, with a growing emphasis on sustainability, equity, and climate resilience. It is addressing its water challenges through policy reforms, institutional strengthening, and the implementation of IWRM principles.

The reform of the Water Code (2022) mandated the creation of Strategic Water Resources Plans for all basins (catchments). These plans will be implemented through Basin Councils, and a participatory governance model will be applied, of an intersectoral nature and with territorial relevance, composed of representatives of the State at the central, regional, and communal levels, the private sector, civil society, and academia. This work is developed jointly with the Ministries of Agriculture and Environment, plus the country's 16 regional governors.

La Dirección General de Aguas (DGA) is the institution responsible for water allocation, hydrological planning, research, measurement, monitoring, and enforcement related to water resources. Any new water rights are granted by the DGA.

A mining operation seeking to secure an allocation of water needs to apply for a water right to the DGA. Identifying the relevant basin council and engaging extensively with its members would support this process.

3.5 What is the role of mining companies in water resource management?

Despite the central role expected of governments in delivering integrated water resources management, there is an increasing idea that corporations should voluntarily step into this space. Companies are tending to shift focus from internal management of water to more proactive external water stewardship. Some argue that corporate water stewardship has arisen not only due to dissatisfaction with state-mandated water resources management but also to a changing role of business in society. There is now pressure for companies to contribute to global social development goals, as they are perceived as political actors. There are difficulties in doing this, for example:

- Corporate entities may be spread over multiple jurisdictions.
- There may be significant gaps in the binding legal frameworks for the corporate group where activities cross state borders.
- Corporations are separate legal entities that are bound by company law and the stock exchanges on which they are traded.
- The duties of directors of corporations may also affect the ability of companies to contribute to the public good, where these activities may be fundamentally at odds with the interests of the company.

The CEO Water Mandate noted that corporate involvement in water policy and management must be approached with caution to avoid policy capture where there may result undue influence on decision making, skewing of public policy priorities, or privileged access to water resources, and highlights many potential integrity risks of water stewardship initiatives. The difficulties in collectively managing water resources are compounded when activities that affect water resources are undertaken by corporate entities that are spread over multiple jurisdictions. Activities affecting water resources in one nation state can, and often do, affect neighbouring states. For example, coal mining in the Elk Valley in British Columbia, Canada, leads to elevated concentrations of selenium in waterways, with negative impacts on biodiversity and fish health. As some of these impacted waterways drain to the USA, there are calls for the International Joint Commission to investigate this transboundary water conflict. This situation has been captured in the media:

https://www.nytimes.com/2023/07/11/science/us-canada-mining-pollution.html

Whilst mining and mineral companies' commitments to water stewardship are laudable, they must navigate this carefully and understand how their activities contribute to established IWRM processes.

The case study below illustrates water stewardship initiatives undertaken by mining companies.

Case study: African Rainbow Minerals

African Rainbow Minerals Limited is a multi-national South African mining company extracting iron ore, manganese ore, chrome ore, platinum group metals, nickel, and coal in South Africa and Malaysia.

The company details engagement around external water governance issues in its report Climate Change and Water 2021. They participate in fora that discuss issues on sustainable water supply, including the influence of climate change and potential shifts in regulation as well as catchment balances. The company also participates in six water-related forums. They are involved in off-tenure activities in collaboration within their catchments and/or activities that actively promote equitable distribution of water resources. African Rainbow Minerals also contributes to industry supported bulk-water infrastructure and invests in community boreholes and water infrastructure for numerous communities.

For more detail, access and read the Climate Change and Water 2021 Report: https://arm.co.za/wp-content/uploads/2025/10/ARM-CCW-Report-2025_Interactive.pdf.

This case study illustrates how a mining company can contribute to IWRM processes, without undue influence on decision making, skewing of public policy priorities, or privileged access to water resources.

Case study: Rio Tinto water platform

Rio Tinto marked World Water Day 2023 by publishing detailed information about annual surface water usage across its global network of managed sites in 35 countries, through an interactive map on its website. For each site that is included in the platform, the database details permitted surface water allocation volumes, the site's annual allocation usage, and the associated catchment runoff from average annual rainfall estimate. The database includes five-year historic comparative data and will be updated annually.

This disclosure aligns with Rio Tinto's water target for 2019-2023. The information is available through an interactive platform, searchable by location, operation, or project.

The Rio Tinto water platform is available here:
https://experience.arcgis.com/experience/6c146e9361814524bb0926ce2871b471

This case study illustrates how a mining company can transparently communicate its water allocations and the impact of these on the broader water availability in the catchment.

Case study: Los Pelambres copper mine desalination initiative, Chile

Facing prolonged droughts, Antofagasta Minerals implemented a desalination plant to supply water to the Los Pelambres copper mine, reducing reliance on freshwater sources. The desalination plant provides 400 L/s of water, with plans to double its capacity, ensuring consistent water supply without depleting local freshwater resources. This initiative represents a proactive approach to climate change, addressing water scarcity in mining operations. By alleviating pressure on the Choapa River, the project benefits both the mining operations and the surrounding communities dependent on the river.

Source: https://www.reuters.com/sustainability/land-use-biodiversity/antofagasta-launches-desalination-plant-los-pelambres-copper-mine-chile-2024-03-21/

This case study illustrates how a mining company can invest in water supply technology to reduce risks to its operations and deliver benefits to communities and ecosystems. It also captures the strategy adopted by many copper mines in Chile to secure water supply, with regulations increasingly restricting access to surface water and groundwater in arid and semi-arid regions.

Case study: legal recognition of the Atrato River's rights, Colombia

In 2016, Colombia's Constitutional Court granted the Atrato River legal rights, recognising it as a subject of rights due to the severe environmental degradation caused by illegal mining activities. The court's decision set a precedent for environmental protection by granting legal personhood to a river, ensuring its protection and restoration. The establishment of "river guardians" empowered local communities to monitor and advocate for the river's health. Despite legal recognition, enforcement remains a challenge due to ongoing illegal mining and limited governmental support.

Source:
https://apnews.com/article/977ad1e171715b8f7fb20a8ac6b9e149
https://www.corteconstitucional.gov.co/relatoria/2016/t-622-16.htm

This case study illustrates that legal frameworks aiming at the protection of water resources are continuously evolving. Mining companies should keep abreast of legal development in the jurisdictions in which they operate and be attuned to any sensitivity related to water.

Case study: direct lithium extraction (DLE) in Catamarca Province, Argentina

The Kachi lithium project in Argentina's Catamarca Province employs Direct Lithium Extraction (DLE) technology, aiming to minimize water usage in lithium mining operations. DLE offers a more water-efficient method of lithium extraction compared to traditional evaporation ponds. Despite this technological improvement, local communities and environmentalists express concerns about potential impacts on freshwater aquifers and ecosystems.

Source: https://time.com/6200372/lithium-mining-technology-argentina-gold/

This case study underscores the importance of transparent environmental assessments and community engagement in mining projects.

3.6 Going further - additional reading

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4. Surface water hydrology

The principles of surface water hydrology are used to estimate or calculate rainfall, evapotranspiration, infiltration into soils, surface runoff, and precipitation. These calculations are required to determine the water balance of a mine, predicting and mitigating flood risks, designing mine water infrastructure, controlling erosion and sedimentation, and more broadly, assessing the impacts of mining activities on water resources. Specific examples of application of hydrological studies in a mining context are:

- Quantifying changes in streamflow: mining activities can alter river flow patterns through water extraction, construction of water and tailings storage facilities, and changes to the landscape (Figure 2). Hydrological studies can quantify these changes and assess their impact on ecosystems.
- Predicting water inflows into excavations, and use of the results to design mitigation strategies, such as:
  - Deciding to collect these inflows for use in mining operations, to reduce withdrawals from other sources.
  - Diverting surface runoff water around mining activities to avoid water accumulation in the mine water system.
  - Designing the drainage network to minimise risks to site infrastructure and waste management facilities and guarantee safety and operational efficiency.
- Assessing flood risks to avoid engulfment of mine excavations and breach of waste management facilities.
- Predicting the volumes of water that the mine will need to contain in appropriate storage facilities and designing an appropriate strategy for mine water releases during extreme rainfall events.
- Deriving a water balance for the mine, using it to track and predict flows into the mine and derive water management objectives, which can vary from collecting as much overland flow as possible to meet demands to diverting overland flow to reduce water accumulation on site, depending on local context and climate variations.
- Simulating hydrological processes after rehabilitation of the mine to assist with designing a closure plan that mitigate risks to water resources.

This section describes the level of practice in hydrology and hydrological modelling with domains of applications, examples of service providers, and commonly used software, including data collection (such as equipment used to collect climate data, Lidar for elevation data etc).

Knowledge gaps and/or areas that require improvement are outlined, particularly in relation to methods to capture risks arising from climate change.

4.1 Key concepts

4.1.1 Extent of catchment area

A catchment is an area of land which is bounded by natural features such as hills or mountains from which all runoff generated from the rain falling over the area flows to a low point. Several words can be used to designate a “catchment”: catchment, watershed, drainage basin, river basin, or basin. They mean the same thing and can be used interchangeably, although river basin tends to only be used when referring to the catchment of major rivers. In this document, we use the term “catchment.” The standard term in Spanish is “Cuenca,” with which many readers will be familiar.

Topography dictates the boundaries of a catchment. A mining operation can affect the topography and thus alter parts of a catchment and associated drainage. In some cases, a mining operation may affect more than one catchment due to the location of mine excavations and mine waste facilities relative to catchment boundaries.

A crucial first step to any hydrological study is to determine the extent of boundaries of the catchment of interest. One of the main advances of the last 20 years is the development and wide adoption of Geographic Information Systems (GIS). GIS has strong capabilities for complex spatial analysis and modelling, has strong integrated data management options, and facilitates collaborative project-based work. Adoption of GIS has completely transformed the water sector, particularly with respect to hydrology.

Defining catchment boundaries in open-cut mine environments is a non-trivial task that requires:

- High quality, high-resolution, up to date and fit-for-purpose elevation data.
- Expert knowledge in Geographic Information Systems and adequate workstation hardware.
- An understanding of basic civil engineering approaches for surface water management infrastructure.

Digital elevation models (DEMs) are digital representations of the topographic surface and are the first essential element of a hydrological study. They can be derived from Light Detection and Ranging (LiDAR) data, collected from aircraft using sensors that detect the reflections of a pulsed laser beam. The reflections are recorded as millions of individual points, called a "point cloud," that represent the positions of objects on the surface, including buildings, vegetation, and the ground. Most mines are now well versed in the acquisition of LiDAR data but tend to use the technology for production purposes. A LiDAR data collection campaign should consider and include the requirements of the team(s) in charge of delivering hydrological studies.

Once topographical data is available, the catchment area needs to be delineated and partitioned into sub-catchments to capture the variations and complexity of the drainage network. On a mine site, this delineation of catchments and sub-catchments needs to be revised regularly, as the mine's progress changes the topography and the drainage network. Some hydrological modelling software now includes fully automated delimitation of basins and sub-basins. The most effective example of this automatic process is the one integrated into the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS):

https://www.hec.usace.army.mil/software/hec-hms/

Section 4.2.6 provides more information about the software tools that are available for undertaking hydrological studies.

ESRI is the global market leader in GIS software (https://www.esri.com/en-us/about/about-esri/overview). They provide guidance for the tools they have developed to support hydrological approaches:

https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-watershed-works.htm

There is also an open access GIS software, called QGIS:

https://qgis.org

QGIS is less intuitive than ESRI ArcGIS and typically requires a greater investment of time to achieve proficiency. It is customisable through addition of plug-ins (e.g. a tool called TauDEM for delineating catchments) and Python scripting. As is the case with most open-source solutions, it requires a higher level of proficiency and coding than commercial options.

As outlined above, the topographic surface will dictate the extent of catchments and sub-catchments within a mine. Areas that are disturbed by mining activities are of particular interest in hydrological studies because rainfall that comes in contact with them can produce runoff of a quality that makes it unsuitable for a range of uses. This poorer quality runoff is often referred to as "mine-affected water" or "contact water." Ideally, a mine should be designed to minimise the flows and volumes of mine-affected water, by diverting runoff away from disturbed areas. If this is not feasible, mine-affected water can be contained in the mine water system and released to the receiving environment under specific conditions, if allowed by local legislation. The mine plan will dictate the extent of areas disturbed by mining activities and the potential for diversions: it is critical that mine planners work closely with their water specialists to ensure risks related to mine-affected water are minimised.

Enhanced integration of mine planning activities with hydrological studies has the potential to significantly reduce inefficiencies and time wastage.

4.1.2 Components of the hydrological cycle

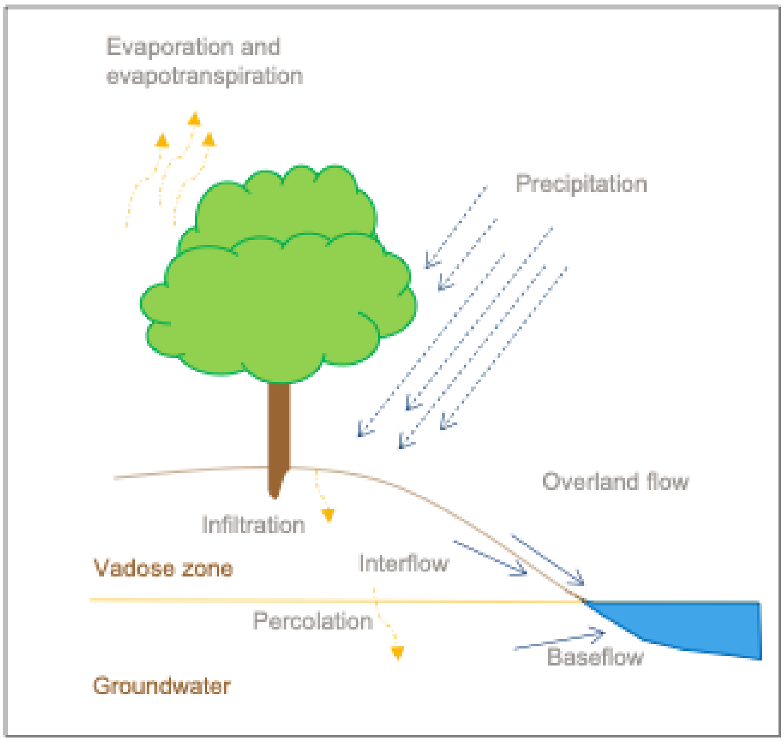

Figure 4: Components of the hydrological cycle (Source: Centre for Environmental Responsibility in Mining, Sustainable Minerals Institute, University of Queensland).

Precipitation, most often in the form of rain, can:

- Be intercepted and held in water storage structures, such as dams, non-operational pits, and tailings storage facilities, from where it can evaporate (Evaporation). Note that in vegetated catchments, evaporation can occur from the vegetation canopy.
- Reach the soil surface and run off relatively quickly towards a stream channel (Overland flow).
- Reach the soil surface and infiltrate into the soil profile (Infiltration), where it can move relatively slowly through the soil profile and contribute to streamflow, evaporate from the soil profile and/or be removed from the soil by plants (Evapo-transpiration), or percolate past the base of the soil profile to recharge groundwater (Percolation).

In cooler climates, if precipitation occurs in both the liquid and solid phase, that is in the form of rain and snow. Snow accumulates on the ground, creating what is referred to as a “snowpack.” When the temperature rises, it melts and creates overland flows. The timing and magnitude of these flows will depend on the snowpack depth, the trends in temperatures, and the terrain. The seasonal increase in stream or river flows due to melting snow is called “freshet.” It typically occurs in spring.

4.1.3 Obtaining data

To assist with quantifying these components, data are required.

Precipitation data is a critical input for hydrological studies and characterises the timing, intensity and spatial distribution of precipitation events. Precipitation time series can range from covering a short time period to multiple years.

Rainfall data may be readily available (e.g. government weather services database, local utilities or weather stations), however issues with accuracy and consistency are common and should always be assessed as the quality and resolution of rainfall data directly influence the reliability of hydrologic assessments and decision-making.

Globally, most rainfall data are obtained by manually recording rainfall depth every day. This is accurate but does not provide the sub-daily time resolution required for some tasks, and it is time-consuming. Pluviometers are rain gauges that record rainfall automatically and continuously, often powered by solar panels and with data sent by telemetry to a data centre. There are two types of rain gauges routinely installed on mine sites:

- Tipping bucket rain gauges record a tip for every unit depth of rainfall (typically 0.1 or 0.2 mm).
- Acoustic rain gauges estimate the raindrop rate and size from the sound of the drops hitting a plate.

The amount of snow falling can be measured in depth units (mm, cm, m, in) either as it falls (known as snowfall), or once it is on the ground (as snow water equivalent or snow depth observations). The most widespread technique is to place a snow board on the ground (a simple board with a measuring tape on it) and to take readings at regular intervals. However, there are now automated instruments that measure snow depth, such as ultrasonic sensors which send sound waves to the ground and measure the time it takes for the echo to return. Snow gauges collect snow, which is then melted to measure the amount of water. This helps determine how much water the snow contains (snow water equivalent). Satellites provide data on snow cover and extent, especially useful for inaccessible regions.

The most common technique to measure evaporation is to install an evaporation pan—a circular pan of standard dimensions containing water. The water level is automatically or manually read, usually each day, and evaporation is calculated from the difference in water level (subtracting rainfall input if needed). A ‘pan factor’ is used to convert this measurement into the equivalent evaporation at the site of interest (e.g. a lake from a mining pit). Some mine sites employ a floating evaporation pan on pit lakes to give an in-situ measurement of evaporation, from which an accurate pan factor can be calculated. Where suitable pan evaporation data do not exist, evaporation can be calculated using a theoretical equation.

A variety of automatic weather stations (AWSs) are commercially available and in addition to rainfall, they measure air temperature, solar radiation, wind speed and direction, humidity, and snow fall when required. There are many suppliers of weather stations (and monitoring equipment) and providing an exhaustive list is beyond the scope of this document. These suppliers have many customers from the mining and mineral extraction industry:

Campbell scientific: https://www.campbellsci.com.au

Novecom: https://novecom.com.au

HydroTerra: https://hydroterra.com.au

Examples of government websites that provide climate data are:

Australia: www.bom.gov.au

Brazil: https://portal.inmet.gov.br

Canada: https://climatedata.ca

Chile: https://www.meteochile.gob.cl/

Peru: https://www.senamhi.gob.pe/

4.2 Hydrological modelling

4.2.1 Overview

Hydrological modelling is used to predict the hydrological response of a catchment (runoff, evaporation and evapo-transpiration, infiltration) as a function of precipitation and other parameters representing the characteristics of a catchment, such as topography, soil infiltration capacity or extent of vegetation cover. In general, a hydrological model is developed to generate data on runoff volumes and river flows to:

- Fill in gaps in the time series of flows and generate long time series of flow data to estimate the reliability of flows over the long term.
- Estimate flows in watercourses for which there is a paucity of data (these are referred to as "ungauged" watercourses).
- Undertake scenario modelling, for instance to evaluate flood risks.

There are several types of models, which differ in:

1. The calculation methods used to describe the behaviour of the hydrological system: these can range from the relatively simple, in so-called 'conceptual' models, to the relatively complex in models capturing all physical processes (physically-based models). Conceptual models require relatively little data but generally cannot provide very accurate forecasts. Recently, due to the greater availability of data and advances in computing power, models based on statistical analysis have emerged. They are being used more frequently, especially for short-term forecasting of floods and droughts.
2. The way in which the values of the parameters that characterise the physical processes are selected: "grouped" models assume that the value of a parameter is the same for the whole catchment; "distributed" models assume that the value of a parameter varies according to the location within the catchment. Distributed models are used for studies covering very large areas, such as river basins.
3. The period over which the calculations are made. A distinction is made between:
    a. Continuous modelling, used for long-term simulation, often with a daily time step. This approach synthesises the hydrological effects of all the precipitation events that occur during the simulation period.
    b. Event-based modelling, used to simulate an isolated rainfall event. It represents hydrological processes on a finer scale and defines the response of a catchment to a specific event. In general, it provides calculations of total runoff volume, runoff depth, peak flows, and the time slots at which these flows occur. The selection of rainfall events and time steps is an extremely important step in event modelling.

In the mining sector, continuous modelling is used to generate long-term water balances for a mine to:

- Assess whether the mine will have access to sufficient volumes of water to maintain operations.
- Predict the volumes of mine-affected water that will need to be stored and potentially released in accordance with local legislation.

- Evaluate the impact of various climate scenarios on water availability and water accumulation.

Event-based approaches for deriving design floods from design rainfall events are widely regarded as standard practice in many countries. There are several event-based models that can be used to convert rainfall into a flood hydrograph (hydrographs are explained in Section 4.2.5) with the Design Event approach being the most widely used. This method assumes that a specific storm duration will produce the largest flood for a given catchment. Since this critical duration depends on both rainfall and catchment characteristics, it is not known in advance and is usually identified by testing multiple durations and selecting the one that results in the highest flood peak or volume.

Hydrologic inputs to event-based models typically include:

- A design storm of preselected annual exceedance probability (AEP, explained in Section 4.2.2) and duration. Local design standards typically specify which design storms should be used to ensure infrastructure can effectively manage anticipated runoff volumes and flood risks under defined conditions. Note that design standards may vary significantly across regions due to differences in climate, geography, infrastructure needs, and governance structures. These regional variations highlight the importance of context-specific standards that balance technical performance, environmental protection, and climate resilience.
- Temporal patterns to define how design rainfall is distributed over the duration of a storm event. These patterns may also include additional rainfall before and after the main burst to represent the full structure of a complete storm.
- Spatial patterns to represent rainfall variation over a catchment as the result of factors such as catchment topography, storm movement, and local weather dynamics. These patterns help represent the uneven distribution of rainfall during storm events.
- Loss parameters that account for antecedent moisture conditions and the soil's ability to absorb rainfall during a storm event.

This is now a well-established practice in most countries. Numerous software are available and are selected according to the preferences and skills of the service providers.

4.2.2 Annual exceedance probability

Event-based modelling simulates the response of a catchment to specific rainfall events. The concept of annual exceedance probability (AEP) is used to characterise these specific rainfall events. It refers to the probability that a specified flow (or volume of water over a specified period) will be exceeded in a given year.

In practice, for flood management, a desired level of protection is selected, specified in terms of the AEP of the flood flow being exceeded, against which infrastructure, homes, etc. are protected. Event-based hydrological modelling is used to produce maps of water levels resulting from rainfall events with a defined AEP. These are then superimposed on maps of the area, and an acceptable level of risk is defined. Structures such as levees can then be designed to protect specific elements. For example, a flood management plan can be designed so that all buildings on a mine are built above the level of a flood with an AEP of 1 in 1000. These modelling methods are complex, require the addition of hydraulic modelling to convert flows into water height, and are carried out using specialised software.

Event-based modelling can calculate, for the specified AEP:

- The peak flow rate
- Total runoff volume
- Flow rate as a function of time (hydrograph)

4.2.3 Design rainfall: intensity-frequency-duration (IFD) curves

Intensity-Duration-Frequency (IDF) curves are graphical tools that describe the likelihood of a range of extreme rainfall events.

Event-based modelling most commonly relies on IFD curves to assess the magnitude and frequency of rainfall events, which is essential for estimating runoff, designing stormwater infrastructure, and evaluating flood risks under various rainfall scenarios. IFD curves represent the relationship between rainfall intensity, storm duration, and the frequency of occurrence (annual exceedance probability). They are used by a wide range of professionals (e.g. engineers, hydrologists, planners) as a fundamental tool for infrastructure design, risk assessments, and climate resilience planning, for example in:

- Runoff calculations that use the rational method: this method is explained Section 4.2.4.
- Unit hydrograph (Section 4.2.5) and synthetic hydrograph methods (e.g. USDA's NRCS, formerly SCS, Curve Number method).
- Hydrologic modelling software (4.2.6).

These applications rely on accurate and context-specific IDF data to ensure reliable predictions and effective water management planning. To ensure informed decision-making and prevent misuse, it is imperative that practitioners understand how to apply, use, and interpret IDF curves and be aware of the limitations in measuring extreme rainfall and deriving these curves.

In regions with well-established meteorological networks, IDF curves are typically derived from long-term historical rainfall records and are regularly updated to reflect changing climate conditions. However, in many parts of the world, particularly in low-resourced or remote areas, reliable rainfall data and corresponding IDF curves may be unavailable or incomplete. In such cases, practitioners often rely on regional proxies, satellite-derived rainfall estimates, or climate models to approximate IDF relationships. While these approaches can provide useful insights, they introduce greater uncertainty, underscoring the need for improved data collection, capacity building, and methodological transparency when applying IDF curves in data-scarce environments.

4.2.4 Rational method

The rational method is a simple hydrological calculation of peak flow based on catchment area, rainfall intensity and a non-dimensional runoff coefficient.

$Q = C \times Ip \times A$

Q is the peak flow rate.

A is the surface area of the catchment.

C is the non-dimensional runoff coefficient.

Ip is the precipitation intensity for a precipitation duration equal to the time of concentration.

The time of concentration is the time elapsed between the start of precipitation and the time at which the flow rate at the catchment outlet reaches its maximum value. It corresponds to the time needed for water to run off from the furthest point in the catchment to the outlet. The use of the rational method is therefore based on the assumption that the time of concentration and the duration of the rainfall are equal, that the intensity of the rainfall is uniform throughout the duration of the rainfall event, and that the rainfall is evenly distributed over the catchment. For small catchments subject to a relatively regular climate, these assumptions are often justified. However, many mines are in locations with highly variable climates, and the applicability of the rational method needs to be assessed.

Many water practitioners assume that the rational method is not used anymore, as hydrological studies are now performed with the support of hydrological software. However, most of these software do use the rational method in their calculations. It is therefore imperative to understand the assumptions embedded in the software calculations and discuss their applicability to the mine of interest.

4.2.5 Hydrograph method

The hydrograph method analyses the response of a catchment to rainfall. It consists in creating a graph, called a hydrograph, that plots flow (also called discharge) against time, as well as rainfall. An example is shown in Figure 5, with the bars showing the amount of rainfall that was measured during a rainfall event and the line showing the value of the flow measured in a river during and after the rainfall event.

There is a delay between the peak rainfall and the peak flow because it takes time for the water to find its way to the river: this is called lag time. Flow in the river starts to rise when runoff reaches the river and this is shown on the hydrograph as the rising limb. After the peak flow, runoff is still reaching the river but in much smaller volumes; this is shown as the recession limb. The flow that occurs in the river under normal conditions (e.g. when it does not rain) is called the baseflow and its source is groundwater.

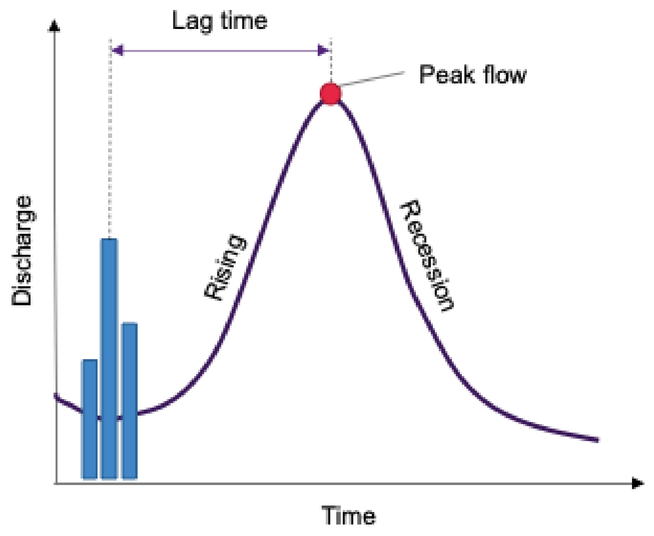

Figure 5: Components of a hydrograph (Source: Centre for Environmental Responsibility in Mining, Sustainable Minerals Institute, University of Queensland).

The characteristics of a catchment will impact on the shape of a hydrograph:

- Smaller catchment areas and steeper slope gradients will lead to shorter lag times.
- Drier soil conditions before the rainfall event will lead to longer lag times.
- Heavy rain can result in rapid saturation of the soil and a steeper rising limb.
- A thick vegetation cover can intercept precipitation, promote higher infiltration rate and slow the movement of water, yielding a flatter rising limb and a lower peak flow.

As discussed in Section 4.1.1, a mine site is usually partitioned into sub-catchments to capture the variations and complexity of the topography, land use distribution, and associated drainage network. A hydrograph can be derived at the outlet of each sub-catchment. Before these hydrographs can be summed to represent the flow at the catchment outlet, the effects of travel time and storage are considered. The process of recalculating the hydrograph at a downstream location from upstream hydrographs is called hydrograph routing or flood routing. These calculations are complex and require the use of specialised software.

4.2.6 Hydrological software

There is a huge range of hydrological software, with every country having invested in hydrological and hydraulic modelling. Software tends to focus on specific aspects: water resource forecasting and management, flood control, and urban runoff management.

The main 'families' of hydrological software with **open-access** options are:

- Software developed by the US Army Corps of Engineers Hydrologic Engineering Centre in the United States: a series of software packages known as HEC, each with a specific application (HEC-RAS for rivers, HEC-WAT for water resources in catchment areas, etc.). The software specialising in runoff calculations is HEC-HMS (https://www.hec.usace.army.mil/software/hec-hms/). The HEC software packages are used extensively in the mining sector, for instance for the design of sediment basins.
- Software from the Cooperative Research Centre for Catchment Hydrology in Australia: all the software is listed on the eWater platform (https://ewater.org.au). This software family tends to focus on water resources and urban drainage, with few applications for the mining sector. There are two exceptions: (1) the Australian Water Balance Model (AWBM), a conceptual model that divides catchments into zones where soils saturate more or less quickly; it is widely used in Australia to predict flows in water courses and has been widely adopted by the mining sector in Australia, mostly due to its simplicity; and (2) RORB, a runoff and streamflow routing program used to calculate flood hydrographs (https://harc.com.au/software/rorb/), widely used in Australia with many applications in the mining sector.
- Storm Water Management Model (SWMM) developed by the EPA in the USA (https://www.epa.gov/water-research/storm-water-management-model-swmm). In its open-source version, it is rarely used in the mining sector. There is a commercial version available, PC-SWMM (see below).
- The Soil Water and Assessment series of tools (SWAT), used widely for assessing and managing water resources in small scale to large scale catchments: https://swat.tamu.edu/software/
- The Large Basin Model (MGB-IPH), a deterministic, distributed, process-based hydrological-hydrodynamic model. It was developed by the Brazilian Institute of Hydraulic Research (IPH) of the Federal University of Rio Grande do Sul (UFRGS), for the characteristics and types of data from tropical regions and with various applications showing good sensitivity and hydrological responses in river basins studied in Latin America, such as Brazil, a continental country with a diverse climate, soil, and vegetation (https://www.ufrgs.br/lsh/products/iph-hydro-tools/).

In addition to these freely accessible tools, there are many **commercial** software packages:

- The MIKE series from DHI (https://www.mikepoweredbydhi.com/products/mike-she) used extensively in Europe and Canada.
- Tools from Innovyze (https://innovyze.com), used extensively by water professionals, but less so for application in the mining sector.
- TUFLOW (https://www.tuflow.com), probably the most widely used software for flood simulation, but is also used for urban drainage, coastal hydraulics, sediment transport, and water quality assessment. There are few examples of free applications of TUFLOW, which has become very widespread and is used on a commercial scale by engineering consultancies, especially for flood studies. TUFLOW is used extensively as part of flood studies commissioned by mines.
- Software developed by Computational Hydraulics International (CHI) based in Canada (https://www.chiwater.com/Home). Their offer includes a commercial version of SWMM, called PC-SWMM. It is used for many applications (flooding, urban drainage, and runoff water quality) and by many government agencies in the USA and Canada. It is less often used within the mining sector.

- The Water Evaluation and Planning (WEAP) tool, an initiative of the Stockholm Environment Institute (https://www.weap21.org) to support integrated water resource management. The tool includes supply, demand, water quality, and ecological considerations at catchment scales.

Selection of the most appropriate package will depend on:

- The objectives of the study: is it about understanding the mine's water balance, risk of insufficient supply to the mine or excess of water accumulation, or flood protection?
- The hydrological processes that need to be considered to deliver the objectives of the study: a flood study will require event-based modelling and will not (usually) be concerned with the overall status of integrated water resources management in the broader catchment.
- The spatial and temporal scale: is the study confined to the mine, or does it extend to the surrounding catchments? Does it require continuous modelling (e.g. water balance assessment) or event-based modelling (e.g. flood study)?
- The desired level of detail and complexity, and the amount and type of data that are available to support them.
- The degree of applicability to the local context. Some jurisdictions are strict about model selection. For instance, in Australia, any modelling undertaken as part of integrated water resource management studies to support development of water plans must use the eWater Source model, a product of the eWater platform. Similarly, many countries have invested in development of hydrological models that are adapted to their climatic, geologic, soil, and biodiversity conditions, and these should be selected as far as practicable.

Whilst there are many hydrological models available for evaluating the components of the water cycle over large catchments, fewer are suitable to support the assessment of flows that contribute to a mine site's water balance. This specific task requires partitioning the mine site into land use types (e.g. run-of-mine stockpile, waste rock dump, industrial area, and tailings storage area) and characterising infiltration and runoff from these land uses through calibration of model input parameters. Ideally, calibration is achieved by comparing calculated and measured flows or calculated and measured volumes of mine water stored in the mine water system. The resulting model can be used to calculate water balances over the operational life of the mine and adjust management methods (e.g. forecast water supply requirements, forecast the capacity required to store water of a quality that cannot be discharged) and size equipment (e.g. pumps). PC-SWMM, SWAT, HEC-HMS and AWBM are widely used for that purpose.

Increasingly, the mineral sector favours development of mine water balance models in a commercial platform called GoldSim, which is designed for visualising and dynamically simulating complex engineering systems. The platform resembles a "visual spreadsheet" that allows the user to graphically create and manipulate data and equations. Hydrological models can be coded into the GoldSim platform. AWBM is the most common model to be included as its computational requirements are not high.

https://www.goldsim.com/Web/Products/GoldSim/Overview/

4.3 Protecting from floods

Methods that must be employed to assess flood risks tend to be mandated by various levels of government, and technical methods will vary among jurisdictions. Readers are encouraged to familiarise themselves with the methods prescribed in their own jurisdiction.

Australia

Australia provides an example of such methods in its national guideline document "Australian Rainfall and Runoff (ARR)," which provides guidance, data, and a software suite that can be used for the estimation of design flood characteristics in Australia. ARR is pivotal to the safety and sustainability of Australian infrastructure, communities, and the environment. It is an important component in the provision of reliable and robust estimates of flood risk. Consistent use of ARR ensures that development does not occur in high-risk areas and that infrastructure is appropriately designed.

Australian Rainfall and Runoff is available here: https://arr.ga.gov.au

The table of contents include:

- Scope and Philosophy
- Rainfall Estimation
- Peak Flow Estimation
- Catchment Simulation for Design Flood Estimation
- Flood Hydrograph Estimation
- Flood Hydraulics
- Application of Catchment Modelling Systems
- Estimation of Very Rare to Extreme Floods
- Runoff in Urban Areas

This provides an outline of what to look for in guidelines applicable to the location of the mine.

While Australia's ARR is a well-established national framework for flood risk assessment and design hydrology, other countries have developed or are developing comparable technical standards. For mining operations outside Australia, it is critical to identify the official hydrological design guidelines mandated in each jurisdiction. Preliminary guidance is provided below.

Canada

Canada's approach to flood protection is evolving towards a more comprehensive, integrated, and nature-based framework. The Federal Flood Mapping Guidelines Series are resources to advance and standardise flood mapping projects and activities in Canada. These guidelines address each step of the flood mapping process and provide advice to individuals and organisations in Canada that need to understand and manage flood risks and their consequences to communities.

https://natural-resources.canada.ca/science-data/science-research/natural-hazards/federal-flood-mapping-guidelines

Chile

No single document as comprehensive as ARR exists, but guidance is derived from:

- Dirección General de Aguas (DGA) hydrological publications and regional rainfall intensity-duration-frequency (IDF) curves.
- Norma Chilena NCh 433 for seismic and structural design often includes hydrological references for safety of critical infrastructure.
- Manual de Diseño de Obras de Drenaje (MOP, Ministerio de Obras Públicas), used for road and mining infrastructure.

Perú

The ANA (Autoridad Nacional del Agua) provides the regulatory basis through:

- Guía Técnica para Estudios Hidrológicos (ANA, 2014), which outlines methods for peak flow, frequency analysis, and hydrograph development.
- Normas para el diseño hidráulico de obras (e.g., PUCP, UNI, MTC) complement ANA documents for infrastructure and mining projects.

Brazil

The Departamento Nacional de Infraestrutura de Transportes (DNIT) issues Normas de Hidrologia Aplicada and the Manual de Hidrologia, which include deterministic and probabilistic flood estimation techniques. ANA (Agência Nacional de Águas) also offers rainfall data platforms (e.g., HidroWeb) and supports model applications like MGB described above.

Regional states (e.g., São Paulo, Minas Gerais) often publish their own hydrological design manuals.

4.4 Vadose zone hydrology

The zone between the soil surface and the groundwater table is called the vadose zone or the unsaturated zone. Unsaturated conditions occur when soil pores start to fill with air as the soil dries and water moves out of the soil. The vadose zone is a dynamic environment where various processes occur, including infiltration, evaporation, transpiration by plants, and redistribution of water. This zone is critical for:

- Groundwater recharge, as it acts as a pathway for water to percolate and replenish groundwater aquifers.
- Water quality, as flow through the soil can influence the quality of water reaching groundwater by mediating the transport and attenuation of contaminants.
- Ecosystems, as it supports plant life through soil moisture availability and root water uptake.

In the vadose zone, water movement is typically vertical but can have large lateral components. Water in unsaturated soil moves from areas with high water potentials (low suction or wetter areas) to areas with low water potentials (high suction or drier areas). Water movement in unsaturated soil conditions is slow compared to that occurring when the soil is saturated.

Soils are characterised by their texture (the proportion of sand, silt, and clay), structure (how particles aggregate), porosity (the amount of void space), and bulk density (mass per unit volume). The water holding capacity of a soil and water movement in a soil are directly linked to characteristics of the pore system (porosity, connectivity, and type of pore). The movement of water through a soil is governed by its hydraulic properties:

- Hydraulic conductivity: the ability of the soil to transmit water.
- Water retention, capturing how much water a soil can hold at different soil water potentials (a measure of the energy status of water in the soil, indicating the tendency of water to move from one location to another). Water retention is represented by a soil water retention curve, plotting water content as a function of soil water potential.

Soil hydrological studies need to be undertaken when there are risks that mining activities will impact on water and solute transport processes in the vadose zone. Examples are:

- Underground mines located under wetlands or swamps can accelerate vertical percolation of soil water, which can lead to drier conditions and impacts on vegetation and ecosystem health.
- Mining activities can introduce pollutants into the soil, which can then leach into groundwater and surface water.
- Subsidence from underground mining can create localised lowering of the land surface with associated changes to drainage patterns. The characteristics of the underlying soil will dictate whether the subsided areas retain water or drain and whether the changes to drainage patterns lead to impacts on ecosystem health.

In addition, the scientific principles of soil hydrology can be applied to analyse water and solute transport in waste rock dumps and tailings storage facilities, through the operational phase, rehabilitation, and closure.

Soil hydrological studies typically require:

- Measurements of soil water content, either via sample collection or installation of continuous sensors, such as TDR moisture sensors (these use time-domain reflectometry to measure moisture content indirectly based on the correlation to electric and dielectric properties of the soil).
- Measurements of hydraulic conductivity (in the field or in the laboratory on representative samples) and water retention curves (in the laboratory on representative samples).

Once suitable data are acquired, hydrological processes through soils can be simulated with appropriate software. The most widely used is HYDRUS, for simulating water, heat, and solute movement in one-, two- and three-dimensional variably saturated media. https://www.pc-progress.com/en/Default.aspx?hydrus. Other options are listed here:

https://ucanr.edu/site/groundwater/vadose-zone-modeling-web-links

4.5 Climate change

Climate change introduces large uncertainties in rainfall and evaporation predictions and thus challenges the robustness and adaptive capacity of mine systems built under climate assumptions that may not remain valid. Consequently, alongside an increased focus on climate change adaptation within broader society, it is critical that mine planning accounts for a non-stationary and uncertain future climate.

Several climate indices have been used to represent specific sectoral hazards and to assess how climate change may impact future business activities and risks. Examples of widely used climate indices include those arising from daily extremes, droughts, heatwaves, flooding, and erosion.

In 2013, a guide called “Adapting to climate risks and extreme weather: a guide for mining and minerals industry professionals” was published in Australia. This guide and accompanying report synthesised case studies, options, and skills needed for minerals industry professionals to adapt to climate change in the areas of flood, drought, bushfire, and high temperatures. It emphasised that changes to historical climatic conditions are likely to increase the efforts required to protect physical assets, worker and community health and safety, and improve the environmental performance of operations before, during, and after extreme weather events. Mining and mineral professionals have key roles to play in meeting the challenges of changing climatic conditions, through adapting mine infrastructure: tailings storage facilities, processing plants and thickener systems, design of open pits and underground workings, and water management networks.

https://www.researchgate.net/publication/323357353_Climate_change_adaptation_for_Australian_minerals_industry_professionals_Final_Project_Report#full-text

Generally, mining companies are investing in capacity building to address these challenges, notably through the appointment of climate change experts, but there are needs and opportunities for improved approaches to understanding climate change risks to the mineral sector operations:

i. How do climate change projections translate into changes to rainfall, runoff, and hydrological extremes?

ii. What is the uncertainty in climate data sets and how does it translate to risk?

iii. How do risk and uncertainty vary over mining regions?

iv. Can regulatory frameworks adapt to these risks and uncertainty?

To estimate the impact of climate changes on rainfall and runoff, methods being applied include:

- Scaling existing IDF curves: this involves adjusting the historical IDF curves by a factor (e.g., percentage increase) based on climate change projections. This method is being used in Chile and Brazil for the design of tailings dams.
- Using climate models downscaled to a mining region: there are several global climate models, which are complex numerical models that attempt to account for all the processes that drive

climate dynamics, including processes in the atmosphere, oceans, land, and ice. Their spatial resolution is too coarse for mining regions (or mine sites) and they need to be "downscaled" to adjust them to smaller areas. This downscaling work is usually undertaken by national or state governments. Downscaled models can be used to assess climate risks at the scale of a mining region or mine.

Information about downscaling global climate models for Queensland, Australia: https://theconversation.com/our-new-high-resolution-climate-models-are-a-breakthrough-in-understanding-australias-future-216739

Research and applied studies are being undertaken to better understand climate risks for mining regions and implications for regulatory frameworks.

Climate change will impact on infrastructure resilience. There is an opportunity for "climate-smart" mine design that embeds climate risks in design decisions.

4.6 Case studies

It is envisaged that inclusion of case studies on this topic will be a key point of discussion after input from sponsors and CEEC affiliated professionals.

4.7 Going further – additional reading

Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors). Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019.

Bulovic, N., Johnson, F., Lievens, H., Shaw, T.E., McPhee, J., Gascoin, S., Demuzere, M., McIntyre, N., 2025. Evaluating the Performance of Sentinel-1 SAR Derived Snow Depth Retrievals Over the Extratropical Andes Cordillera. Water Resour. Res. 61. https://doi.org/10.1029/2024wr037766

Bulovic, N., McIntyre, N., Trancoso, R., 2024. Climate change risks to mine closure. J. Clean. Prod. 465, 142697. https://doi.org/10.1016/j.jclepro.2024.142697

Chow, V.T., Maidment, D. and Mays, L. (1988). Applied Hydrology, McGraw Hill, p. 229

McCuen, R. (1982). A Guide to Hydrologic Analysis Using SCS Methods, Prentice Hall. Chapter 7, Estimating the Time of Concentration, p.192

Smithers, J.C. (2012). Review: Methods for design flood estimation in South Africa. Water SA Vol. 38 No. 4 July 2012.

U.S. Army Corps of Engineers, AED Design Requirements: Hydrology Studies

5. Hydrogeology

Hydrogeology, or groundwater hydrology, investigates the processes that govern groundwater, including how water infiltrates beyond the vadose zone, flows through aquifers, and interacts with the surrounding geology. Excavations required to extract mineral resources often interfere with aquifers: this is why understanding hydrogeology is essential for managing the impact of mining on water resources. Specific examples of application of hydrogeological studies in a mining context are:

- Quantifying the lowering of the groundwater table: safely accessing an ore body often involves pumping groundwater out ("dewatering"), which can lead to a drop in the groundwater table.
- Evaluating the impacts on aquifer properties: excavation, drilling, and subsidence can physically alter aquifers, reducing their ability to store and transmit water.
- Assessing contamination risks: extraction activities can introduce heavy metals, acids, and other pollutants into groundwater through seepage from tailings and waste rock.

This section describes the level of practice in hydrogeology and hydrogeological modelling with domains of applications, examples of service providers, and commonly used software, including data collection.

5.1 Key concepts

As with surface water hydrology, hydrogeology is underpinned by key concepts with which water practitioners in the mining and mineral extraction sector must be familiar.

Groundwater

Groundwater is water that exists underground in saturated zones beneath the land surface. A more technical definition is that groundwater is the saturated part of subsurface water that has a pressure greater than or equal to 0 (atmospheric pressure being taken as 0 pressure by convention).

Recharge

The process by which water infiltrates the ground and replenishes groundwater.

Aquifers

Aquifers are defined as porous media that will readily yield water in a usable quantity to a well or spring.

Unconfined aquifers

An unconfined aquifer is an aquifer whose upper water surface (the water table) is at atmospheric pressure and thus is able to rise and fall. The time scales for groundwater movement in unconfined aquifers typically vary from days to years.

Confined aquifers

A confined aquifer is placed between layers of impermeable material, causing it to be under pressure. When a confined aquifer is penetrated by a well (or bore), the water will rise above the top of the aquifer. The level to which water will rise in bores tapping a confined aquifer is known as the potentiometric surface. The time scales for groundwater movement in confined aquifers typically vary from centuries to millennia. Unconfined aquifers are usually closer to the surface than confined aquifers, and as such are impacted by climatic conditions and contamination sooner than confined aquifers.

Aquitard and aquicludes

There are types of porous media that do not allow easy transmission of water through them. They are called aquitards, which are semi-impervious, or aquicludes, which are effectively impervious.

Aquitards and aquicludes separate aquifers and partially disconnect the flow of water underground. Although water cannot flow very fast through an aquitard, significant quantities of water can seep through aquitards in some conditions.

Bore (or well)

A bore (or well) is a hole in the ground that intersects an aquifer and is used to extract groundwater. A bore is constructed by drilling a hole in the ground and then installing a casing with a screened or perforated area through which water from an aquifer can enter the bore. Water is brought to the surface using a pump or under natural pressure. Bores can range in depth from a few metres to hundreds of metres and may be up to 2,000 metres (for instance in the Great Artesian Basin in Australia).

Artesian bores

An artesian bore (or well) is a bore tapping a confined aquifer where the groundwater is under pressure and the groundwater level in the bore rises above the aquifer. These bores often require headworks (e.g. valves, fittings, and instrumentation) to control the flow of water from the bore.

Drawdown

Drawdown is the lowering of the water table in an unconfined aquifer, or the lowering of the potentiometric surface in a confined aquifer, caused by:

- Pumping of groundwater from a bore tapping the aquifer (or uncontrolled flow from a flowing artesian bore).
- Dewatering due to the intersection of mine workings with the aquifer.

Both open cut and underground mines can cause drawdown. The cone of depression is the area around the bore or mine where groundwater levels are drawn down. Drawdown in confined aquifers may also be referred to as depressurisation.

Measuring hydraulic head

A piezometer (otherwise known as an observation bore/well or a monitoring bore/well) is a tube that is placed in the ground to depths below the water table and that extends to the ground surface and is open to the atmosphere. The bottom of the piezometer is perforated to allow groundwater under positive hydrostatic pressure to enter the tube. The depth to the water level in the bore is measured relative to the ground surface using an electric water level metre or a steel tape with bell sounder. Water levels measured in piezometers completed in the upper part of an unconfined aquifer indicate the elevation of the water table, which is the top of the saturated zone. For confined aquifers, the water level in a piezometer will rise above the elevation of the top of the aquifer. These water levels define an imaginary surface, referred to as the potentiometric surface.

Note that piezometers can be used for other purposes, for instance for measuring pore pressure in tailings embankments or pit slopes.

Flow direction

Groundwater flows from high to low values of hydraulic head. To determine the direction of groundwater flow, measurements of hydraulic head are compiled to generate contour maps of groundwater level. These maps define the potentiometric surface, which is much like a topographic contour map but defines the distribution of potential energy in the groundwater system. Each contour, or equipotential, represents a line of equal hydraulic head. Groundwater flows down-gradient, perpendicular to equipotential.

There can be exceptions to this. For example, if the hydraulic conductivity of the aquifer is much higher in one direction than another, or dominated by fractures with particular orientations, then these can redirect groundwater flow askew to the maximum gradient. But in general, groundwater will flow in the direction of steepest gradient.

5.2 Managing groundwater studies

The study of groundwater is complex and requires input from technical specialists: hydrogeologists and groundwater modellers. Water practitioners in the mining and mineral extraction sector are likely to have to manage groundwater studies, requiring them to:

- Coordinate field investigations, which can occur at all stages of the mine lifecycle including exploration, operations, and closure.
- Provide input into development of conceptual models representing the aquifers and their connections (eg., provide data on inflows for any existing mine workings).
- Provide input into the development and application of groundwater models (eg., provide proposed mine plans, mine layouts, plans for water supply, etc.).

They will also need to collaborate with mine planning teams to develop plans that will control groundwater risks to operations, such as the development of dewatering plans. This is discussed in more detail in Section 10.1.

Dewatering and depressurisation is a multi-disciplinary effort as it requires strong interactions between mine planning, geotechnical, environment, geology, and mine operation teams. Collaboration is essential.

In the last 20-30 years, in mining regions like Australia and Canada, the quality of groundwater assessments has increased dramatically, as well as the capability of service providers. Groundwater modelling guidelines have been published (e.g. in Australia). Environmental Impact Studies (EIS) are often available in the public domain, and they provide a vast repository of reports with excellent examples of groundwater modelling.

There is now a wide range of documents to assist with managing and delivering groundwater assessments, but it is critical to clearly articulate the objectives, methods, and deliverables of these assessments.

Delivering a successful groundwater study first requires that its goal and objectives are clearly stated: what are the problems that we are trying to solve? Then a detailed scope of work must be developed, covering items such as:

- Background about the site, its water management strategy and the groundwater issues.
- The data sets that are available, in what format: topography, geology, mine plans, monitoring, any previous groundwater assessment, etc.
- Development of a conceptual model.
- Construction of a numerical model: numerical method, software, model domain, initial and boundary conditions (with links to mine plan).
- Calibration and sensitivity analysis.
- Scenarios for prediction.
- Methodology for result analysis.

- A preferred timeframe, but it is better to be flexible. If the timeframe is too short, the suppliers will not have sufficient time to critically analyse the results.

Many groundwater assessments will require the development of a conceptual model, which can then lead to construction of a numerical model, if this is required to meet the objectives of the study.

Conceptualisation involves identifying and describing the processes that control or influence the movement and storage of groundwater. It should gather all available information that will help understand and potentially quantify the heads and flows of groundwater, as well as its interactions with surrounding features (Figure 6). It should also capture how the mine is expected to impact on the groundwater and the ecosystems that depend on groundwater. The conceptual model must explain (qualitatively and quantitatively) all observed groundwater behaviour in the region of interest. It should be regularly re-assessed, when additional data are available and refinements can be made. The conceptual model may not be unique (i.e. there could be different conceptual models that can all explain groundwater observations) and it is usually encouraged to propose and maintain alternative conceptualisations for as long as possible through the study. In some cases, this may lead to the development and use of alternative numerical models.

If numerical modelling is required, there will be a stage defining how to best implement the conceptualisation in a mathematical and numerical modelling environment. The decisions required at this stage include selection of a numerical method and modelling software, selection of an appropriate model dimension, definition of a model domain, and the spatial and temporal discretisations to be used in the model. Modellers are encouraged to take a pragmatic approach to these issues and to explore simple modelling options where these may be appropriate.

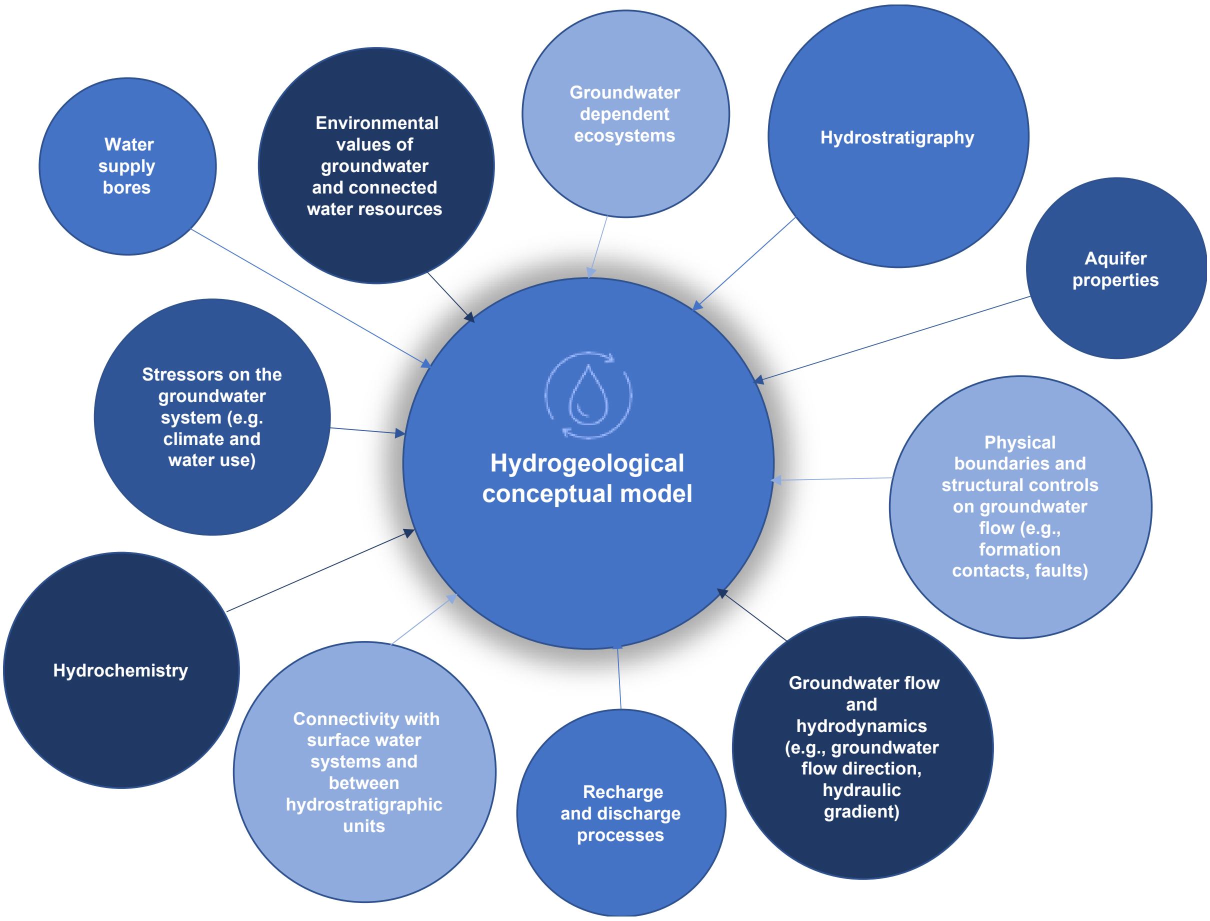

Figure 6: Elements of a hydrogeological conceptual model (Source: Centre for Environmental Responsibility in Mining, Sustainable Minerals Institute, University of Queensland).

In the mining sector, a groundwater model generally serves two functions:

- It provides a tool to aid in the interpretation of field data and to refine conceptual understanding of the hydrogeological system and system response to changed conditions associated with mine development.
- It provides a decision support tool to aid in the evaluation of design options.

In the mining sector, these two software are widely used for groundwater modelling:

MODFLOW developed by the US Geological Survey and available as open-source: https://www.usgs.gov/software/modflow-6-usgs-modular-hydrologic-model. The MODFLOW code can be embedded in commercial products, e.g. those proposed by Waterloo Hydrogeologic: https://www.waterloohydrogeologic.com

FEFLOW, a commercial product developed by the DHI group: https://www.dhigroup.com

Selection of the numerical platform will be highly dependent on the objectives of the groundwater assessment:

- What is the model for?
- What data are available?
- How complex and uncertain is the conceptualisation?
- What kind of results need to be produced to achieve the objectives?
- What kind of scenarios need to be defined?

For example, if the objective of modelling is to quantify the impacts of a mining project on environmental values, including groundwater-dependent ecosystems that access groundwater from alluvium, the model would need to be able to:

- Accurately represented the alluvium and water table.
- Simulate and predict drawdown in the alluvium.
- Simulate and predict whether drawdown in other hydrostratigraphic units would lead to drawdown in alluvium.
- Provide results in a template that can facilitate interpretation.

A standard problem with hydrogeological studies based on development and implementation of groundwater models is that the specialists undertaking the study ("groundwater modellers") can become caught up in the complexity of their numerical issues and "forget" the objectives. They can spend a lot of time getting the model to "work," with not much energy left to critically analyse the outcomes. For instance, they can produce prediction for groundwater recharge, flows, levels, and drawdown but can struggle to translate the findings into what they mean for environmental values in general, groundwater-dependent ecosystems in particular. Hydrogeological assessments should include expertise and interpretation of results from other specialists, particularly ecologists.

5.3 Reference documents

Australia

In Australia, multiple guidelines have been published to support groundwater assessments.

Groundwater modelling guidelines

Australian Groundwater Modelling Guidelines
https://www.researchgate.net/publication/258245391_Australian_Groundwater_Modelling_Guidelines

The objective of the Australian groundwater modelling guidelines is to promote a consistent and sound approach to the development of groundwater flow and solute transport models in Australia.

Note that in 2025, these guidelines were being reviewed:
https://www.nationalwatergrid.gov.au/projects/australian-groundwater-modelling-guidelines-revision

Revisions to the groundwater modelling guidelines will support groundwater modelling practitioners, as well as end-users of groundwater modelling. This includes regulators, industry proponents, water managers, and water resource planners.

Guidelines and standards for groundwater monitoring and testing

There are a range of guidelines and standards that apply to groundwater field investigations.

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) are proposing National Minimum Groundwater Monitoring Guidelines. These guidelines are currently in draft format and are undergoing public consultation. The guidelines are proposed to apply to projects where there is potential for impacts to groundwater resources and related assets and ecosystems, such as water supply bores and groundwater dependent springs. The guidelines recommend a risk-based approach be used to design groundwater monitoring networks and develop groundwater monitoring and testing programs for both the pre-approval and post-approval phases of a project.

https://www.iesc.gov.au/sites/default/files/2023-04/consultation-national-minimum-groundwater-monitoring-guidelines.pdf

Guidelines for drilling and construction of monitoring bores

The design, drilling, and construction of groundwater monitoring installations should be undertaken in accordance with relevant sections of the Minimum Construction Requirements for Water Bores in Australia, developed by the National Uniform Drillers Licensing Committee (NUDLC).

The document focusses on bores used for water supply, however there is a section on groundwater monitoring bores. It is important to note that monitoring bores differ from water supply bores in several ways (for example they are often used for water quality analysis) and this needs to be considered when referring to the NUDLC document.

https://adia.com.au/wp-content/uploads/2020/09/Minimum-Construction-Requirements-Edition-4.pdf

National industry guidelines for hydrometric monitoring

These guidelines were developed by the Bureau of Meteorology (BOM) and provide Australian industry best practice for groundwater level and quality monitoring. They also provide guidance on the establishment of monitoring sites and data management.

http://www.bom.gov.au/water/standards/niGuidelinesHyd.shtml

Field guide for groundwater sampling and analysis

This field guide was developed by Geoscience Australia and provides standard groundwater sampling protocols and procedures.

The guidelines cover drilling and installation of monitoring bores, measurement of groundwater levels, and collection of groundwater samples for water quality and gas analysis. They provide good guidance on selection of an appropriate groundwater sampling method and quality assurance and quality control procedures.

https://www.phosynanalytical.com.au/wp-content/uploads/2012/04/GeoscienceAustralia.pdf

International standards

There are a range of International Organization for Standardization (ISO) standards on groundwater field investigation methods, including:

- ISO 5667-22:2010 *Water quality — Sampling — Part 22: Guidance on the design and installation of groundwater monitoring points*.
- ISO 21413:2005 *Manual methods for the measurement of a groundwater level in a well*.
- ISO/TR 23211:2009 *Hydrometry — Measuring the water level in a well using automated pressure transducer methods*.
- ISO 5667-11:2009 *Water quality — Sampling — Part 11: Guidance on sampling of groundwaters*.

North America

Standards from the US Geological Survey (USGS) are widely adopted in North America. The USGS has established standards and guidelines for groundwater modelling, primarily using the MODFLOW family of models. These standards cover various aspects, including model development, documentation, and calibration, ensuring consistency and scientific rigor in groundwater studies.

https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs

Europe

Groundwater modelling in Europe is guided by the Water Framework Directive (WFD) and its associated directives, including the Groundwater Directive (2006/118/EC), which sets standards for groundwater quality and requires Member States to assess and manage groundwater bodies. European regulations also influence the type and quality of data used in models, such as the requirement for applicants to conduct degradation and sorption studies for pesticides. Additionally, there are efforts to develop pan-European datasets and models for groundwater recharge and other hydrological processes. These are not specific to mining application, but rather, focus on agricultural impacts.

https://environment.ec.europa.eu/topics/water/water-framework-directive_en

Brazil

Brazil’s groundwater modelling guidelines are overseen by the Agência Nacional de Águas e Saneamento Básico (ANA), which provides open access to hydrological data and regulatory frameworks.

The ANA Open Data Portal provides datasets on hydrographic divisions, water quantity and quality, hydrological monitoring, and critical hydrological events. It also includes tools for hydrogeological modelling.

https://dadosabertos.ana.gov.br

Chile

The Servicio de Evaluación Ambiental publishes methodological guides to establish minimum standards for environmental modelling studies, including one directed at groundwater modelling. ‘

https://www.sea.gob.cl/sites/default/files/migration_files/guias/Guia_uso_modelo_aguas_subterraneas_seia.pdf

Peru

Peru doesn't have a single, comprehensive, national guideline document for groundwater modelling but the regulatory framework, particularly for mining and other large-scale water-affecting projects, refers to principles from international best practices and guidelines. These principles emphasise the importance of robust conceptual models, uncertainty analysis, and a clear demonstration that models are "fit-for-purpose" in decision-making.

South Africa

The National Hydrological Services are responsible for directing the assessment of groundwater resources, data acquisition, and data management for capacity building and the development and maintenance of information systems. They provide access to publicly available groundwater data and a range of documentation, guidelines, and standards.

https://www.dws.gov.za/Groundwater/data.aspx

https://www.dws.gov.za/Groundwater/Documents.aspx

5.4 Case studies

It is envisaged that inclusion of case studies on this topic will be a key point of discussion after input from sponsors and CEEC affiliated professionals.

5.5 Going further - additional reading

The Groundwater Project provides free-of-charge online educational materials on groundwater and how groundwater relates to ecological systems and humanity.

https://gw-project.org/

Reference textbook: Hydrogeology and Mineral Resource Development by Leslie Smith.

https://gw-project.org/books/hydrogeology-and-mineral-resource-development

6. Mine water quality

6.1 Water contamination from mining

Mining and mineral extraction activities can lead to alteration in the chemical composition of water in the receiving environment. This is usually the result of different interrelated factors, such as the nature of the local geology, climate, geochemistry and biochemistry, commodity being extracted, and the mining and processing methods.

Waste rock dumps (or spoil piles), tailings storage facilities (TSFs), and heap leach pads are major sources of contamination due to the hydrology and geochemistry of these waste storage structures. Waste rock dumps or spoil piles are usually considered as an acute source of contamination: they can create sudden exposure to a contaminant, resulting in short-term impacts. TSFs are considered to be a long-term chronic source of contamination. Geomembranes are impermeable liners made from synthetic materials like high-density polyethylene (HDPE) or polyvinyl chloride (PVC), which are engineered to prevent the migration of contaminants, creating barriers that protect against seepage into soil or groundwater. Such liners can be, and often are, used to prevent leaching of contaminants.

The impact of mining on the quality of receiving surface waters and groundwaters should be evaluated through all phases of the mine life cycle. After mine closure, underground workings and open pits are often filled up with water, depending on the hydrology and hydrogeology of the site. In this case, discharge of contaminated water from flooded mines can cause pollution of surface water and groundwater.

6.1.1 Acid and metalliferous drainage

Acid and metalliferous drainage (AMD), the outflow of acidic water from metal mines or coal mines, has occupied technical teams of geochemists, hydrologists, water treatment specialists, and engineers for many years. They have produced technical guides (such as GARD: Global Acid Rock Drainage Guide), numerous research projects and associated findings, have promoted and delivered workshops and conferences, and have published 1000+ research papers. There has been a lot of effort towards understanding the scientific processes, identifying solutions, and communicating them at a range of forums.

AMD continues to be a significant environmental challenge through the life of a mine and after mine closure. It is generated by the natural oxidation of sulfide minerals, particularly pyrite (FeS2). The oxidation of pyrite causes the release of metals and sulphate from the leaching of minerals into waters. Mining and mineral processing wastes are the major sources of AMD.

AMD is characterised by high concentrations of sulphate, heavy metals (cadmium, cobalt, chromium, copper, iron, mercury, nickel, lead, and zinc), metalloids (antimony and arsenic), as well as other elements (aluminium, barium, calcium, magnesium, manganese, potassium, sodium, and silicon). Generally, concentrations may exceed 1000 mg/L for sulphate, 100 mg/L for dissolved iron or aluminium and 10 mg/L for trace metals (copper, chromium, nickel, lead, and zinc). AMD can have extreme impacts on the ecology of streams, e.g. making water toxic to fish, affecting the beneficial use of waterways downstream of mining operations.

The best way to manage AMD is to prevent it from starting, for instance by preventing potentially acid generating (PAG) materials from being exposed to oxygen. This may be done by segregating PAG materials and encapsulating it with non-acid generating (NAG) materials, using engineered covers, or by keeping PAG materials saturated and buried under water covers.

The design of a waste management strategy that minimises risks of AMD requires collaboration between mine planning teams and environmental and geochemistry specialists. Mine design should aim at minimising the occurrence of AMD.

Acidic drainage usually is treated with lime using the high-density sludge process:

https://www.sgs.com/en-ca/services/high-density-sludge-hds-process

However, if there is a requirement to reduce sulphate concentrations, additional treatment methods such as reverse osmosis (RO) may also be required. Section 7 provides more detailed information about treatment options.

Readers are encouraged to familiarise themselves with the GARD Guide.

GARD Guide: https://www.gardguide.com/index.php?title=Main_Page

Case studies

It is envisaged that inclusion of case studies on this topic will be a key point of discussion after input from sponsors and CEEC affiliated professionals.

6.1.2 Salinity

Some mines can generate saline drainage. This is for instance the case of most coal mines in Australia. Rainfall infiltrates spoil piles and dissolves salts that are present in the waste material (sodium, calcium, magnesium, potassium, chloride, sulphate, and carbonates). Salts are then transported into mining voids or towards surrounding watercourses. Coal mine spoil has the potential to contribute significant salt loads to the surface water and groundwater of the receiving environments: this risk is usually mitigated through regulation, with mines having the legal obligation to minimise releases of saline water to the receiving environment. At closure, in most cases, the residual mining voids will be left as saline water bodies, with few options for use of that water, as the salinity level will be too high.

Case study: Queensland's open-cut coal mine void rehabilitation planning practices: challenges and opportunities:

https://www.qmrc.qld.gov.au/__data/assets/pdf_file/0030/326379/qld-open-cut-coal-mine-void-rehab-plan-practice-challenge-opps.pdf

6.1.3 Cyanide

Cyanidation is the predominant leaching method for extracting gold or silver, with two main types of flowsheets – heap leaching or agitation leaching. Typically cyanide leaching is combined with the carbon adsorption, in which the formed gold-cyanide complex is adsorbed on an activated carbon surface. Subsequently, gold can be desorbed from the carbon surface by elution and the final recovery performed by electrochemical methods such as the Wohlwill process. Cyanidation has significant drawbacks as cyanide is a highly toxic compound. It can form complexes of varying strengths and longevity with metals. The major environmental issue arising from the use of cyanide occurs from spills from tailings ponds, trucks, or pipes, before cyanide has decomposed. A cyanide spill can kill fish and wildlife immediately, and there are also long-term consequences from heavy metal contamination arising from the decomposition of metal cyanide complexes.

Many gold processing operations now include cyanide detoxification into their flowsheets to minimise the risk of cyanide contaminating surrounding waters and affecting fauna. Detoxification typically uses sulphur dioxide and air to oxidise residual cyanide and break it down into low-toxicity byproducts, e.g. cyanate (CNO^-).

The International Cyanide Management Code for the Manufacture, Transport, and Use of Cyanide In the Production of Gold (Cyanide Code) is a voluntary, performance driven certification program of best practices for the management of cyanide in gold and silver mining. Participation is open to gold and silver mining companies, manufacturers of cyanide, and transporters of the chemical. The Cyanide Code was one of the earliest standards and certification programs developed for the minerals sector, and today it is amongst the most established certification programs in the mining industry. It is estimated that more than half of the world's annual commercial gold production from primary gold mines using cyanide is produced by mining companies participating in the Cyanide Code program.

The Cyanide Code can be found here: https://cyanidecode.org

6.1.4 Selenium

Coal mining activities, particularly the exposure of waste rock to air and water, can lead to the release of selenium into the environment. Selenium can accumulate in aquatic ecosystems, potentially causing harm to fish and other aquatic life. British Columbia in Canada is a region where coal mining has resulted in elevated selenium levels, particularly in Elk Valley. Some impacted waterways drain into the USA, which has led to conflicts between the two countries.

Selenium is also released during the combustion of coal in power plants and can be a source of environmental pollution.

In Elk Valley, Glencore (previously Teck Resources) has constructed four water treatment facilities to treat 77.5 million litres of water per day. They are constructing six additional water treatment facilities and expect to increase the water treatment capacity to 150 million litres per day: https://www.glencore.ca/en/evr/sustainability/water-quality.

6.1.5 Water quality classifications

Classification of mine-affected water is predominantly focused on water chemistry, using physico-chemical parameters to distinguish between different types of mine water. The most prominent example can be found in the GARD guide (Table 1). This classification is simple and does not necessarily capture specific water quality risks.

Table 1: Mine water classification according to GARD guide

Type of mine-affected water	Description	Threshold values
Acid rock drainage or Acid and Metalliferous mine drainage	Acidic, moderate to elevated metal concentrations, elevated sulphate concentrations	pH < 6
Neutral mine drainage	Near neutral to alkaline pH, low to moderate metal concentrations, low to moderate sulphate concentration	pH > 6 Sulphate < 1,000 mg/L TDS < 1,000 mg/L
Saline drainage	Neutral to alkaline pH, low metal concentrations (potentially moderate concentration in Fe), moderate concentrations in sulphate, magnesium and calcium	pH > 6 Sulphate > 1,000 mg/L TDS > 1,000 mg/L

Another example of classification is that proposed by the Water Accounting Framework (Section 11). The framework defines three categories, based on the level of treatment that would be required to transform mine water into drinking water.

Table 2: Mine water classification according to WAF

Category of mine-affected water	Description	Threshold values
Category 1 High water quality	Minimal effort necessary to achieve drinking water quality	6 < pH < 8.5 Total Dissolved Solids (TDS) < 1,000 mg/L No turbidity after sedimentation No (or no traces) of pesticides/herbicides or harmful constituents Coliforms < 100 cfu/100ml
Category 2 Medium water quality	Moderate treatment necessary to achieve drinking water quality	4 < pH < 10 1,000 < TDS < 5,000 mg/L Coliforms > 100 cfu/100ml
Category 3 Low water quality	Significant treatment necessary to achieve drinking water quality	pH < 6 or pH > 10 TDS > 5,000 mg/L

Both the GARD Guide and WAF classifications use pH and TDS as a primary water quality indicator. The GARD Guide is focused on AMD and, as such, includes sulphate concentration. The WAF classification uses parameters that can be harmful to human health and provides a decision tree for simple categorisation.

It is worth noting that stakeholders calling for mine water classification systems tend to require them for reporting purposes. In practice, they are not particularly useful to the mining and mineral industry. This is because risks arising from water quality degradation are specific to a location and its geology, climate, and environmental values. Controls for mitigating these risks are included in legal licenses and permits, usually in the form of release (or discharge) conditions, which outline how and when a mine can release mine-affected water to the receiving environment. Release conditions are determined on a case-by-case basis and vary significantly with location and jurisdiction.

6.2 Geochemical modelling

Geochemical modelling can be used to assist with predicting mine water quality by simulating the chemical reactions and processes occurring within the mine, particularly at the interfaces between water, pit walls, and mine waste. The processes usually included in geochemical models are:

- Dissolution and precipitation of minerals
- Adsorption and desorption processes, particularly for metals
- Redox reactions affecting elements like iron and sulfur
- Interaction of water with acid-generating or neutralising wall rocks

Whether a mine needs to undertake geochemical modelling will be dictated by site-specific conditions (geology, climate, mining and processing methods etc).

Because water quality is directly dependent on water quantity, geochemical models require information about surface water and groundwater and are often linked to the hydrological and hydro-geological models developed for the mine. Many geochemical models are predictive models of pit-lake water quality, but they can be applied to compare various mining scenarios (e.g. backfilling a pit vs. maintaining a water body in the pit), to evaluate potential impacts from waste rock drainage, or to predict groundwater geochemistry, for example.

As with groundwater assessments, the first step in site-specific geochemical modelling is the development of a conceptual model, capturing the prevalent geochemical processes that occur on the site. The conceptual model should be based on geologic, climatologic, geochemical, hydrogeological, and hydrologic data. Conceptual models should be reviewed against observed conditions and revised as additional data are collected or the mine plan changes. There should be an iterative process whereby the conceptual model improves over time by incorporating new data and any mine plan revisions. Examples of processes that would be included in a pit-lake geochemical conceptual model are:

- groundwater inflow and outflow
- limnology and potential for turnover or permanent stratification of the water column
- surface runoff on highwalls
- interaction with water in underground mine voids and pore-waters in highwall fractures impacted by blasting
- mineral equilibria (e.g., precipitation and dissolution)
- adsorption of aqueous species to mineral phases
- gas equilibrium
- biogeochemical reactions
- redox reactions

Geochemical modelling requires data that characterises the overburden, waste rock and ore, and the groundwater and surface water resources. Adequate characterisation would include the characteristics and spatial distribution of all potential sources, pathways, and receptors for contaminants of concern, such as groundwater aquifers and mineralisation units that will remain in the immediate vicinity of the pit walls. Geochemical characteristics of interest include hydraulic properties, mineralogy, and leachable quantities of constituents.

Once the conceptual model is complete, a modelling code will be used to perform the required complex calculations. Several are available, but the United States Geological Survey (USGS) code PHREEQC is the most widely used. It is open-source and well documented:

https://www.usgs.gov/software/phreeqc-version-3

Additional software include:

EQ3/6: https://github.com/LLNL/EQ3_6

MINTEQA2: https://www.epa.gov/hydrowq/minteqa2-equilibrium-speciation-model

6.3 Going further – additional reading

Castendyk, D.N. and Webster-Brown, J.G., 2007a, Sensitivity analyses in pit lake prediction, Martha Mine, New Zealand 1: Relationship between turnover and input water density, Chemical Geology, v. 244, pp. 42-55, DOI: 10.1016/j.chemgeo.2007.06.004.

Castendyk, D.N. and Webster-Brown, J.G., 2007b, Sensitivity analyses in pit lake prediction, Martha Mine, New Zealand 2: Geochemistry, water-rock reactions, and surface adsorption, Chemical Geology, v. 244, pp. 56-73, DOI: 10.1016/j.chemgeo.2007.06.005.

Castendyk, D.N., 2009a, Conceptual models of pit lakes, pp. 61-76, in: Castendyk, D.N. and Eary, L.E., eds, Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability, Society of Mining, Metallurgy, and Exploration, Littleton, Colorado, pp. 304.

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Castendyk, D.N., Eary, L.E., and Balistrieri, L.S., 2015, Modeling and management of pit lake water chemistry 1: Theory, Applied Geochemistry, v. 57, pp. 267-288, DOI: 10.1016/j.apgeochem.2014.09.004.

Lottermoser, 2007. B.G. Lottermoser. Mine wastes: characterization, treatment and environmental impacts (2nd edition), Springer, Berlin

Opitz, J., Timms, W., 2016. Mine water discharge quality - a review of classification frameworks, in: Drebenstedt, Carsten, Paul, Michael (Eds.), IMWA 2016: Mining Meets Water - Conflicts and Solutions. Freiberg, Germany, pp. 17–26.

Younger, P.L., Banwart, S.A., Hedin, R.S., 2002. Mine Water: Hydrology, Pollution, Remediation. [Book]. Environmental Pollution Series, vol. 5. Springer, The Netherlands. http://dx.doi.org/10.1007/978-94-010-0610-1.

7. Mine water treatment

For the minerals sector, there are two broad domains of applications for water treatment:

1. Treatment of mine-affected water to quality standards that meet compliance requirements for release to the receiving environment.
2. Treatment of water supply sources or intermediate water streams to achieve process or safety quality requirements. For instance, a mine might rely on desalinated sea water as a source of water supply or decide to treat mine-affected water to supply a processing plant.

Water quality control measures that can be carried out at various stages of the mining cycle are to:

- Prevent or control the reactions that lead to contaminants being produced (at source control). This can be achieved by eliminating one or several of the essential components of the undesirable chemical reaction(s) (e.g. removing water or oxygen to prevent oxidation of sulfides) or establishing an environment that will impact on the rate of the reaction(s) (e.g. adjusting the temperature, pH, or bacterial activity).
- Prevent or control the migration of contaminants (e.g. diversion of water, prevention of infiltration).
- Collect and treat contaminated water.

In many cases, water treatment will be required. In very broad terms, the aims of mine water treatment will be aligned with regulatory conditions and can include removal of suspended and/or dissolved solids, metals, and neutralisation of acidity or alkalinity. Treatment processes often yield a by-product consisting of organic and/or inorganic solids that settle out of the water. This semi-solid, slurry-like material is referred to as "sludge" and treatment optimisation will aim at reducing volumes of produced sludge. The efficacy of a treatment process can be considered in terms of the chemistry of the resultant water, the nature of the sludge (volume, toxicity, long-term stability, disposal requirements), and whether any marketable products can be recovered and used to offset the costs of treatment (for example recoverable metals). There are two types of treatment:

- Active, which requires continuous operation and maintenance. This is often used in operating mines when there is a workforce on site and revenue to dedicate to treatment plants.
- Passive, which is intended to be self-sustaining after an initial set-up phase. This presents advantages for treating mine water after closure.

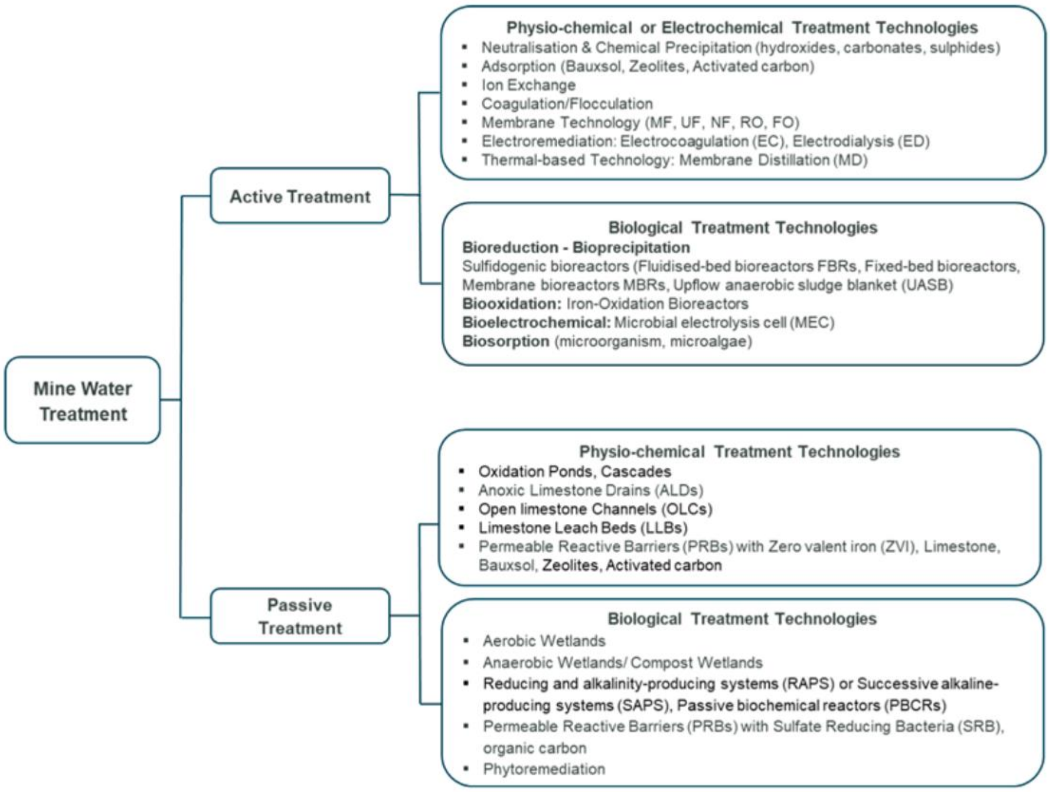


Figure 7: Overview of water treatment technologies (Source: Centre for Environmental Responsibility in Mining, Sustainable Minerals Institute, University of Queensland).

7.1 Active treatment

Active treatment methods involve the use of mechanical or chemical processes to remove contaminants from wastewater. These methods often require energy input and regular maintenance. A distinction is made between the treatment technologies that are based on physico-chemical processes and those based on biological processes. The most common technologies employed by the mining sector are described in Table 3.

A key limitation of treatment technologies is the flow rate they can handle. Mine water flows are typically highly variable and can vary extensively with climate conditions. Most technologies are developed for a fixed flow rate and are difficult to upscale to handle larger rates. In Table 3, Low denotes “laboratory scale,” Medium denotes “field scale” that should be applicable to mine conditions where flow rates are not too variable, and High denotes applicability to a range of mine site conditions.

Table 3: Overview of active treatment processes

Category	Description	Complexity	Flow rate
pH modification Neutralisation and precipitation	pH is increased by adding a material (lime, limestone caustic soda, sodium carbonate). As the pH is raised a concurrent step oxidises iron (and then other metals) which then precipitates out of solution. There are many options for facilitating oxidation. This is a tried and tested technology, but equipment maintenance is relatively high due to scaling. Sludges tend to be chemically complex and unstable, with low to no commercial value. This can be addressed by coagulation and flocculation processes, or high-density sludge processes.	Simple to complex	Medium to High
Ion exchange	Various proprietary processes that rely on ion exchange media to remove metals from solution. The processes differ by the type of ion exchange media, which can include various types of resins and polymers.	Complex	Low
Electrochemical methods	As the behaviour of metals in solution is often controlled by their electro-chemistry, electrical technologies can be applied to facilitate deposition of a metal.	Complex	Low
Adsorption methods	Use of non-biological particles to adsorb metals from solution and use physical processes for separation of solids later in the treatment process.	Simple	Medium
Physical process technology	Use of membranes, osmosis and filtration to separate water from ions.	Complex	Low
Biology-based methods	Use of biofilters, or equivalent type of reactors, seeded with selected strains of naturally occurring non-pathogenic microorganisms that reduce some metals. The end product usually is a fine precipitate that can be removed with periodic backflushing. There is a range of applications, but Selenium removal is a well-known example.	Simple to complex	Medium

There are many service providers who provide advice and support for selecting, designing, and installing a mine water treatment process:

- Consulting firms, mostly for the selection and engineering design of a mine water treatment solution. Examples are WSP (wsp.com), SLR (slrconsulting.com), GHD (ghd.com), Stantec (Stantec.com), etc.
- Technology suppliers, who will design, build and install a water treatment solution. Examples are Veolia, (veoliawatertechnologies.com), Suez (suez.com), EnviroGen Technologies (envirogen.com), Xylem Water Solutions (xylem.com), Mintek (mintek.co.za), etc.
- Research groups who continue to design and test novel technologies. Universities located in mining regions tend to have a strong capability in mine water treatment, particularly in Canada and South Africa. The following universities have established a strong reputation for their research excellence in seeking solutions to mine water quality issues: University of Cape Town, University of British Columbia, University of Toronto, University of Queensland, Columbia

University, Colorado School of Mines, and Pontificia Universidad Católica del Perú. CSIRO in Australia also conducts extensive research in mine water treatment. Canada has established a Research Chair on Treatment of Contaminated Mine Waters. It is currently held by Carmen Mihaela Neculita at the Université du Québec en Abitibi-Témiscamingue: https://www.uqat.ca/services/personnel/fiche.asp?Fiche=110353

A treatment solution is often a combination of several treatment processes, called a "treatment train." Many companies have patented the design of a specific treatment train, for instance:

- SAVMIN, Mintek: Mintek.co.za
- DESALX, CleanTeQ Water: cleanteqwater.com

Research in mine water treatment often leads to the commercialisation of the treatment solution through creation of start-up companies. Two well-known examples are:

- Virtual Curtain Technology, developed and tested by CSIRO: https://virtualcurtain.com.au. It involves the synthesis and application of hydrotalcites which increases the pH, removes metals from the water, and results in low volume of sludge.
- Viromine technology, which utilises the addition of a proprietary product (Bauxsol), processed from the red mud waste of bauxite refining to alumina: https://research.usq.edu.au/item/q55v8/viromine-technology-a-solution-to-the-world-s-mining-waste

Reducing brine volume

If there is interest from CEEC partners, the knowledge baseline could include a section containing information about options to reduce the volumes of brines. This can be of great interest when there is no space available to install evaporation ponds.

7.2 Passive treatment

Current technologies for passive treatment are summarised below.

Table 4. Overview of passive treatment processes

Category	Description	Complexity	Flow rate
Chemical Anoxic	Neutralising mine water and precipitating metals without addition of materials, by allowing the water to flow through: • beds of limestone in an anoxic environment so that there is no oxidation leading to precipitates that will clog the system. • open limestone channels on relatively steep slopes with high flow rates, so that precipitates can be entrained. • Other proprietary products.	Simple to complex	Low to High
Biological	Derives from the abilities of some microorganisms to generate alkalinity and immobilise metals, thereby essentially reversing the reactions responsible for the genesis of acid-mine drainage. Requires in-depth understanding of microbial geochemistry and geomicrobiology. Examples are aerobic wetlands, permeable reactive barriers, and a range of bioreactors.	Complex	Low to Medium
Bioaccumulation by microorganism or microalgae	Relies on the ability of bacteria or microalgae to accumulate metals. Microbial and algae growth is enhanced with addition of nutrients, typically nitrogen and phosphate, which in turn increases the mass of metals accumulated by the biota. The bioconcentrated metals in cells of the biota can then be recovered and used as a livestock feed supplement, pharmaceutical, or biofuel. Research is still in its early stages of development.	Complex	Low to medium
Biodesalination by halophytic organisms	Relies on the ability of halophytic (salt-tolerant) species to remove dissolved salts. This is a relatively new and low-cost approach for saline water treatment, in early stages of development.	Complex	Low

Passive treatment is an attractive proposition for closed mines as, in theory, it does not require as much input in terms of capital investment, workforce, and operational costs. As such, there are many research programs and activities assessing the potential for implementing such approaches as part of mine closure.

This overview shows that there has been development of numerous technologies for treating mine water. Whilst the overall principles of the main technologies are understood, a successful treatment scheme will require implementation of several treatment steps. Incremental improvements have been achieved, essentially by investigating new approaches for individual treatment steps. Many are now available as proprietary solutions, and it has become increasingly more difficult to identify which technology would be the most appropriate for a given water treatment problem.

Mine water practitioners seeking guidance on mine water treatment should identify all their contamination issues and then canvas the knowledge acquired by international water treatment experts with experience in the mining sector for these contamination issues. It is easier to receive independent advice from researchers, as they are not normally bound by commercial interests.

8. Erosion and sediment control

As outlined in Section 4, mine water managers will usually be concerned with two broad objectives:

1. Capturing stormwater runoff (overland flow) for use in mining operations, to reduce withdrawals from other sources.
2. Diverting stormwater runoff to discharge points to manage water accumulation and peak flows from floods.

The balance between these two objectives will be dictated by local context, including regulatory frameworks. It is possible for the same mine to adjust its objectives according to seasonal weather forecasts, for instance with a stronger focus on diversion of stormwater runoff when extreme rainfall is predicted.

In most jurisdictions, there will be requirements to ensure that the strategy for managing stormwater runoff does not lead to soil loss and export of sediments to the receiving environment. To this end, mines must design and implement an erosion and sediment control plan. Guidelines vary with each jurisdiction. Mine water practitioners are encouraged to source the guidelines applicable to their jurisdiction. It should be noted that in many cases, such guidelines were initially developed for the construction sector and may pose challenges when implemented at a mine site. Examples are:

- From the International Erosion Control Association https://www.austieca.com.au//publications/best-practice-erosion-and-sediment-control-bpesc-document
- From the USA: https://www.epa.gov/npdes/national-menu-best-management-practices-bmps-stormwater-construction
- From British Columbia, Canada https://www2.gov.bc.ca/assets/gov/driving-and-transportation/transportation-infrastructure/engineering-standards-and-guidelines/environment/references/erosion-and-sediment-control-manual.pdf
- From Brazil: https://www.gov.br/dnit/pt-br/assuntos/planejamento-e-pesquisa/ipr/coletanea-de-normas/coletanea-de-normas/especificacao-de-servico-es/dnit_074_2006_es.pdf

In British Columbia, Canada, erosion and sediment control at mine sites has received a lot of attention and the Ministry of Environment has published documents specifically for the mining sector, such as:

- https://www2.gov.bc.ca/assets/gov/environment/waste-management/industrial-waste/industrial-waste/mining-smelt-energy/erosion_sediment_control_plan_guide.pdf
- https://www2.gov.bc.ca/assets/gov/environment/waste-management/industrial-waste/industrial-waste/mining-smelt-energy/assessing_design_size_and_operation_of_sediment_ponds.pdf

The information provided in these documents is intended to help mine water practitioners exercise their professional judgment in developing site-specific management strategies.

8.1 Erosion modelling

The quantification of soil loss is critical for the design and implementation of ESCPs, including erosion risk assessments and the design of sediment control structures (e.g. sediment basins). There are many erosion models available for use, but very few are suitable for the prediction of erosion from mine sites where there is high heterogeneity, large distances (i.e. slope lengths), and steep mine waste and spoil stockpiles.

The only model that is used widely in the mining sector is RUSLE: an empirical model used to estimate soil loss from a range of landscapes. It has limited capability as it ignores the effects of gully erosion and dispersive soils and does not represent fundamental hydrologic and erosion processes explicitly, but it provides a good starting point for estimating erosion risk from mined landscapes and is suitable for providing coarse erosion estimates when limited data are available. RUSLE can be easily integrated with GIS, and it is possible that progress in GIS analysis may even address the limitations of the model.

RUSLE is described in detail here: https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research/docs/rusle/

8.2 ESCP controls

The implementation of appropriate erosion and sediment control measures is key to managing erosion and minimising sediment loads from mine sites. It is generally simple to identify the need for erosion and sediment control on mine sites; however the selection of the most appropriate control may pose some difficulties. There can be misalignment between available reference material and existing guidelines, which have not been developed specifically for the type, scale, and duration of disturbances that occur on mine sites. For example, the use of sediment fences is unlikely to be effective at the base of a large waste rock dump.

The fundamental principles of erosion and sediment control should be integrated into disturbance planning and need to be suitable to site conditions, such as the climate, soil type, vegetation, and topographic features. These principles apply to all jurisdictions, and they include:

- The integration of erosion and sediment control principles into mine and construction planning.
- Creating flexible plans to meet site conditions.
- Minimising the extent and duration of the disturbance.
- Maximising sediment retention on site.
- Minimising contamination of non-mine-affected water by diverting it around disturbance activities.
- Prioritising the implementation of erosion and sediment control according to implementation hierarchy (drainage, erosion, and sediment control; see below).
- Providing timely and adequate maintenance.
- Monitoring the effectiveness of the controls.

Effective erosion and sediment control should be implemented using a treatment train approach with the primary aim of minimising erosion. This should be prioritised in the following order:

1. Drainage control includes the diversion of non-mine-affected surface water away from disturbed areas wherever practical. It is based on the prevention or reduction of soil erosion caused by surface water flows such as reducing the scour potential of concentrated flows and diverting surface water around disturbed areas.
2. Erosion control focusses on the prevention or minimisation of soil erosion (from dispersive, non-dispersive, or competent material) caused by raindrop impact and overland flow on disturbed surfaces. It involves minimising the extent and duration of disturbances.
3. Sediment control includes trapping or retention of sediment either moving along the land surface or contained within runoff (i.e. from up-slope erosion).

All efforts to minimise the extent and duration of land disturbances must be made by clearing the smallest practical area of land ahead of recovery activities and rehabilitation. All proposed erosion and sediment control measures must be implemented prior to clearing and stripping operations. It is important that erosion and sediment control be incorporated into mine planning strategically to minimise land disturbance.

Careful consideration of erosion and sediment control in mine planning can provide numerous cost savings benefits, including implementing fewer erosion and sediment control devices and reducing rehabilitation costs.

Drainage design standards for temporary drainage works are generally based on the anticipated design life, while permanent works must be designed in accordance with the local stormwater drainage standards. It is common practice that the design of drainage controls is based on the selection of an appropriate annual exceedance probability (AEP). The permissible flow velocity of the channel surface material is also an important consideration in the design of effective drainage control.

The selection of appropriate erosion control measures depends on the expected erosion risk and the sensitivity of receiving waterways. The erosion risk is typically informed by the timing (likelihood and intensity of expected rainfall and wind conditions) and the degree of land stabilisation (vegetation cover, slope etc.).

A key gap is an understanding of the removal efficiency of the various controls (catch drains, fences, mulches, blankets, etc.) because there is rarely independent testing of these commercial products.

8.3 Sediment basins

Sediment basins are used extensively on mine sites for sediment control. The design criteria for sediment basins on mine sites is generally adopted from available guidelines and they vary widely.

The storage capacity of a sediment basin is the sum of:

1. The volume required to store stormwater runoff and enable settlement of suspended sediments.
2. The volume required to store the sediments that have settled until the basin has been dredged and cleaned out.

To determine the volume required to store stormwater, guidelines recommend using one of these two methods:

- The peak flow method, which calculates this volume based on a rainfall event of a specified annual exceedance probability (AEP). This method is generally recommended for basins collecting coarse-grained sediments. The specified AEP varies widely, from 1:1 AEP to 1:50 AEP.
- The rainfall method, which calculates this volume based on the decile of rainfall over a specified period. This method targets flood control rather than particle settling and is therefore generally recommended for basins that collect finer sediments. The specified rainfall deciles range from 75th to 90th percentile and rainfall duration from 2 days to 20 days.

Estimating the sediment storage zone allows the provision of adequate storage for settled sediment to prevent the need for frequent desilting. This can be estimated by calculating the expected sediment yield over the desired maintenance period (for instance, by using RUSLE). In general, guidelines recommend a basin de-silting frequency of once every 5 years; however, this is not frequent enough for mine sites and should instead be incorporated as part of pre-wet season preparations.

9. Monitoring

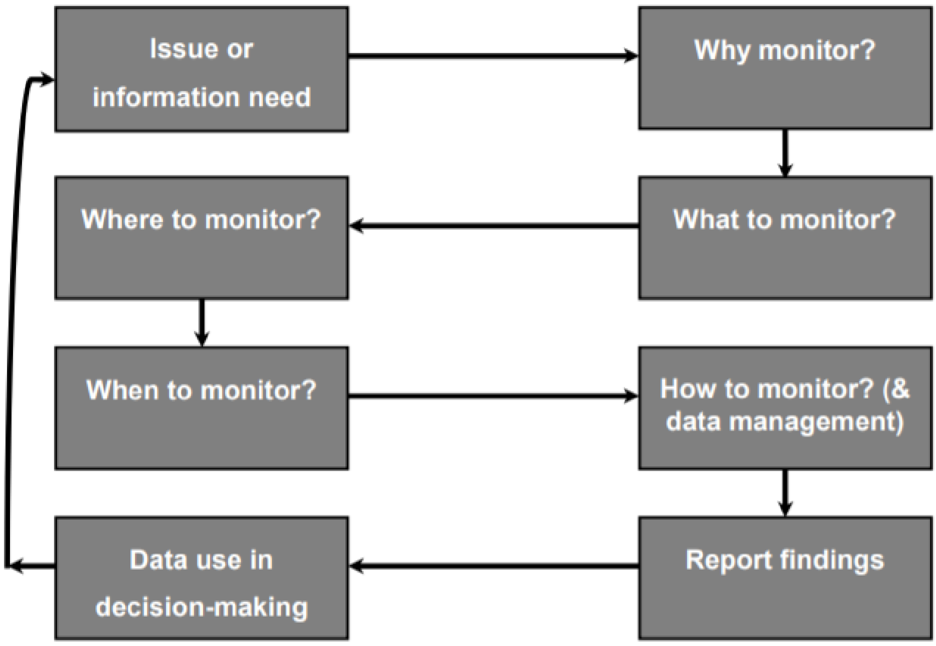
9.1 Purpose of a water monitoring program

Monitoring is defined as the "consistent, regular, long-term gathering of data". It involves recording field observations, making measurements and taking water samples, then analysing data and reporting.

For water monitoring, both quantity (e.g. flows in water courses, groundwater levels, volume stored in inventory) and quality (e.g. concentrations in specific physico-chemical parameters) are subject to monitoring requirements. Flow and volume measurements are used to support and refine water studies or derive a site water balance. Water quality data is used for informing compliance reporting, catchment management, or environmental management decisions.

The challenges associated with monitoring relate to the costs of installing and maintaining the monitoring network, accessing sampling locations (particularly in adverse weather conditions), storing and analysing the quantity of data that are generated, and communicating the results in reports. Companies must dedicate resources to data management, data analysis, and reporting mechanisms.

At its simplest level, a monitoring program can be described as the why, what, where, when and how of sampling.



A successful monitoring program requires:

- Clear objectives, which often aim at identifying sources of contamination, quantifying the loads of contaminants leaving a site, obtaining trends for the values of some parameter concentrations, and/or assessing the effectiveness of a specific water management strategy.
- Adequate training of the personnel who will undertake the sampling tasks.
- A thorough sampling protocol supported by standard operating procedures based on national standards.
- Sample analysis by accredited laboratories, with quality assurance and quality control protocols.

- An adequate data management system, which ideally includes functionalities for data analysis (plotting of time series and box-whisker charts).

The design of a monitoring program should consider:

- The various land uses on a site and the emplacement of waste storage structures, such as waste rock dumps and tailings storage facilities.
- Seasonal variations, particularly variations in precipitation and flow patterns.
- Water quality parameters that go beyond compliance requirements, to support complete hydro-geochemical studies.

Sampling sites should be representative of the spatial extent of mining activities to identify 'hotspots' (areas of elevated levels of contaminants). Development of a water monitoring program begins with review of the mine plan, the geographical location, and the geological setting. The mine plan provides information on the location and magnitude of the following components:

- surface and subsurface disturbances
- ore processing and milling procedures
- waste disposal areas
- effluent discharge locations
- groundwater withdrawals
- surface water diversions.

9.2 Monitoring techniques

It is crucial to:

- Document the monitoring program, with a detailed sampling and analysis plan, outlining objectives, sampling methods, costing, sampling locations and frequency, laboratory analysis methods and limits of reporting;.
- Use standardised methods and protocols for data collection and analysis with a strong emphasis on quality assurance and quality controls to minimise sample contamination and ensure data are of sufficiently high quality.
- Provide adequate training to all personnel involved in monitoring, including training in the maintenance, calibration and correct usage of the equipment being used.
- Use analytical laboratories that are both accredited in the local jurisdiction.
- Review data regularly to validate the data early and often, including the quality control sample results.

The most robust monitoring plans include a temporal and spatial component (i.e., Before-After-Control-Impact [BACI]) to compare nonimpact versus potentially impacted areas. Sampling frequency will be dictated by the objectives of the monitoring programme. For trend analyses in particular, long time series of data will be required.

Guidance on how to design a monitoring program is provided here: https://www.waterquality.gov.au/anz-guidelines/monitoring/study-design/study-type

A distinction is made between sampling during "baseflow," when the flow in the water course is mostly governed by groundwater inflows, and during rainfall events, when flow is governed by rainfall, possibly intense and sustained. The monitoring program must ensure sampling occurs during both baseflow and rainfall events. Many mines are located along water courses which are "ephemeral" or "intermittent;" flows in those streams only occur after sustained rainfall. This poses specific challenges to the design of a monitoring program and currently constitutes a critical knowledge gap, particularly in the context of climate change, which is leading to an increase in the number of ephemeral streams.

9.2.1 Water levels and flow measurements

There are many techniques for measuring water levels in water courses. This represents a complex skill set, with standards varying in each jurisdiction. For instance, the government of British Columbia has produced a manual of hydrometric standards that describes how water quantity parameters should be measured:

https://www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/nr-laws-policy/risc/man_bc_hydrometric_stand_v2.pdf

This manual describes the B.C. Ministry of Environment and Climate Change Strategy procedures for all aspects of hydrometric surveys in an open channel: fundamentals of hydrometric operations, stage measurement, discharge measurement, and stage-discharge rating and discharge calculations.

Australian hydrometric standards are provided by the Bureau of Meteorology:

http://www.bom.gov.au/water/standards/niGuidelinesHyd.shtml

(These are also mentioned in the sections on hydrogeology and groundwater monitoring).

In Chile, the Dirección General de Aguas (DGA) publishes a "Manual de Normas y Procedimientos para la Gestión y Administración de Recursos Hídricos," colloquially referred to as "el Manual DGA." The manual can be downloaded here:

http://www.dga.cl/legistlacionynormas/normas/Paginas/default.aspx

Mine water practitioners are encouraged to seek the equivalent manual for their jurisdiction.

These documents provide extensive information, but it is critically important to understand that methods are adapted to the local climate. If there is no equivalent guidance available in the local jurisdiction, it is recommended to use guidance from another location with a similar climate, as far as practicable.

9.2.2 Groundwater

The assessment of impacts to groundwater requires an understanding of the aquifer system that hosts the groundwater, including its depth, physical and chemical properties, and hydrologic interaction with surface water systems. In Section 5.3, we provided a list of sampling standards for most mining regions.

Mine water practitioners are encouraged to seek the equivalent guidance for their jurisdiction, noting that the Australian guidance is thorough and can be applied in other locations.

9.2.3 Water quality

Queensland, Australia

The Queensland government in Australia has produced a comprehensive manual to describe the common techniques, methods, and standards for sample collection, handling, quality assurance and control, custodianship, and data management:

https://environment.desi.qld.gov.au/__data/assets/pdf_file/0031/89914/monitoring-sampling-manual-2018.pdf

It covers all sampling techniques:

- Sampling scope and design
- Preparation for sampling
- Record keeping
- Quality controls
- The concepts of "control" and "reference" sites

- How to use a GPS
- Choosing a laboratory and analytical method
- Physical and chemical assessments using in-situ methods and various methods for water sampling
- The difference between monitoring during baseflow and during a flow event
- Sediment sampling
- Groundwater sampling
- How to sample for stable isotope analysis
- Using biological indicators, including fish sampling and macrophyte data collection
- Data handling

Peru

La Autoridad Nacional del Agua (ANA) has published a "Protocol for Monitoring the Quality of Water Resources in Peru." This document outlines the protocol for monitoring water quality in continental and marine environments. It aims to standardise technical procedures for water resource monitoring, ensuring consistency across government entities and promoting integrated water resource management. The protocol covers procedures for sampling and analysis in rivers, lakes, coastal zones, and effluent discharges. By implementing this protocol, ANA seeks to create a unified database for water quality information within the National Water Resources Information System, supporting informed decision-making and environmental protection.

Many jurisdictions will have equivalent documentation. Mine water practitioners are encouraged to seek the equivalent manual for their jurisdiction, if available.

9.3 Data analysis

Site personnel must review their monitoring data to extract the information it provides and use it for planning and management. They must receive adequate training to sort and analyse laboratory results.

The common reasons for analysis and interpretation of water quality data include:

- Baseline characterisation of water quality
- Establish pre-mining conditions (geogenic sources and historic mining)
- Identify ecologically sensitive receiving environments
- Understand upstream or regional water quality
- Source identification by identifying water types and geochemical signatures
- Quantify the contribution of various sources to a catchment
- Spatial distribution and extent of contamination
- Fate and transport of contaminants to and through the receiving environment
- Comparison with environmental regulatory standards
- Derive site-specific water quality guidelines
- Assess potential impacts
- Understand the hydrological and geochemical processes (for example inside a tailings storage facility)
- Develop empirical models for water quality predictions
- Treatment options
- Verification of expected water quality and hydrochemical models
- Assess the performance of site-wide waste and water management systems

The general goals of data analysis are to:

- Understand trends: if and how the data vary with time (time series).
- Analyse the distribution of data values, for instance by calculating the frequency of given values, identifying how the values are distributed and whether that distribution qualify as "normal" (basic statistics, box-whisker charts). Site personnel should be asking: is the average representative of the whole dataset? Or has it been artificially skewed down by unusually low or high values?
- Derive correlation: identifying whether concentrations in some analytes are "linked" with each other (correlation analysis).
- Test hypotheses about the data sets. For instance, if we have concentration data for two analytes (Analyte 1 and Analyte 2), we might want to test whether there are statistical differences between the mean concentration of Analyte 1 and the mean concentration of Analyte 2. If there is, we might be able to conclude that the two analytes behave differently from each other, and this will inform the understanding of processes impacting on water quality (statistical tests). The most well-known parametric test is the t-test, which is used to compare the means of two groups. This is useful for water quality, as we might want to compare an average concentration in an analyte to a reference value (e.g. from a reference stream) or to the average value from another monitoring point. ANOVA (Analysis of Variance) generalises the t-test beyond two means. These are complex analyses and environmental personnel need to receive training.

9.3.1 Data management

With implementation of well-designed monitoring programs, mines will collect large amounts of environmental data which is not restricted to water-related data, as they also often collect data related to emissions, dust, noise, flora and fauna, and rehabilitation. There are extensive requirements for data reporting, including to voluntary schemes. An effective data management system is essential and should include these functionalities:

- Collection of data from multiple sources.
- Manual data capture in the field from portable devices.
- Automatic uploading of data from automated instruments installed in the field (e.g. flow gauges and groundwater levels).
- Advanced sample management to assist with planning sampling activities, maintaining the supplies that are required for sampling (e.g. bottles for water sampling), recording that all analyses have been performed on time and results have been loaded in the environmental database, and storing documents related to Chain of Custody (the trail of paperwork that records the steps in the samples analysis).
- Automatic uploading of laboratory reports (e.g. water quality data from various samples).
- No restriction on the amount and type of monitoring data that it can store, flexibility in defining monitoring programs and associated data types.
- Spatial capabilities to support integration with geospatial database.
- Extensive reporting capability with options for users to build customised reports.

Many environmental permits state that all monitoring records must be kept for long periods (e.g. not less than 5 years). If a mine does not have a suitable data management system in place, there is an increased risk of non-compliance. Ideally the data management system would also support compliance tracking with an ability to:

- Store all compliance documents, with tools to capture document versions, which may change as a result of corrections, amendments, and renewals.
- Extract conditions from each compliance document, to organise them by environmental aspect and to display the actions that are required with associated timeframe.

- Manual and automated options for compliance assessment: many conditions state that “X must be measured and must be less than Y.” The compliance system should have the capability to read the value of X in the environmental database and automatically record the condition as compliant if it is less than Y.

Examples of available software are:

- WaterSuite: restricted to water-related data, not specifically developed for the mining sector with no capability for compliance tracking and reporting. https://www.watersuite.com
- Aquatic Infomatics: restricted to water-related data, with capability for compliance tracking and reporting, and used in the mining sector. https://aquaticinformatics.com
- Intelex: restricted to water-related data, with capability for compliance tracking and reporting and used in the mining sector. https://www.intelex.com
- SiteHive: provision of monitoring devices and data management software. https://sitehive.co
- EnviroSuite: initially designed for dust monitoring and prediction, but now expanded to the capture of data from a wide variety of sensors, including noise, air quality, odour, dust, vibration, and water quality. https://envirosuite.com/industries/mining
- EnviroSys: compliance-focused software to efficiently capture, validate, monitor, analyse, and report any type of environmentally-related data; highly flexible model for monitoring aspects including air quality, groundwater, surface water, potable water, meteorological, noise, waste, emissions, soil, land disturbance and rehabilitation activities, and flora and fauna; collection of field, laboratory, and device data; Interface with GIS; can build custom reports to automate reporting requirements. https://www.acquire.com.au/products/envirosys/

10. Managing water for safe operations

Whilst all previous sections have focused on the impact of mining and mineral processing activities on water resources, the inverse is equally true: water can interfere with mining and mineral processing activities.

10.1 Pit slope stability

When ore bodies intersect aquifers, dewatering strategies need to be put in place to:

- Create dry operating conditions in mining pits.
- Maintain geotechnical stability of pit slopes.
- Reduce the in-situ ore moisture content to facilitate material handling requirements.

In large open pit mines, excavation usually takes place in a series of benches. Each bench can be many metres high. Geotechnical engineers must evaluate the stability of individual benches as well as that of the overall pit slope.

Excavating and disposing of material constitute major costs in operating the mine. The simplest way to optimise the cost of excavation is to reduce the volume that needs to be excavated: slopes are built as steeply as possible, but the steeper the slopes, the greater the danger of slope failures. Slope stability risks must be assessed and managed. This requires:

- Estimating the geotechnical properties of the materials.
- Calculating the stability of the slope geometries.
- Monitoring the performance of the slopes as the pit is developed.

The presence of water has an impact on slope stability. Water pressure within the pore spaces or fractures in the material will reduce the strength and stability of those materials. This can be done by:

- Agreeing that the slope can be designed with a lower factor of safety.
- Redesigning the slope with a flatter profile.
- Reducing pore water pressures in the pit slope materials: this is called "depressurisation."

Since the first two options are rarely acceptable or desirable, large open pits rely on extensive programs of depressurisation.

Example of slope failure: https://www.odt.co.nz/business/time-will-tell-waihi-mine

The general objective of a mine **dewatering** program is to lower the groundwater table below the pit floor.

The general objective of a mine **depressurisation** program is to locally dissipate pore pressure within the pit slope to improve slope performance (this leads to an increase in the Factor of Safety; in other words, we make the slope more stable).

The two objectives are related and at many mines both dewatering and depressurisation are required.

Dewatering

In general, the mines that require the largest dewatering rates are located in regions with extensive groundwater aquifers. The deeper the mine will go below the pre-mining groundwater table, the more critical it will be to have a well-designed dewatering plan. The hydrogeological characteristics of the regional groundwater systems will dictate the volumes and rates of groundwater that will be intercepted by the mine.

The most common tools for dewatering are:

- Pumping wells: these can be located outside the pit, and sometimes a long way away from the pit; this will be dictated by the extent of the regional groundwater system.
- High-volume drain holes: these are drilled laterally from the lower pit walls and let groundwater drain by gravity.
- Dewatering tunnels: these are dug below the pit floor and are often built in conjunction with drain holes. The groundwater usually drains by gravity.
- Seepage faces: groundwater is left to naturally drain into the pit through the rock faces with sumps collecting it.
- Sumps and pumps: a system designed to collect water once it has reached the surface and move it away from the pit.

Depressurisation

Designing the depressurisation program relies on calculations from geotechnical and hydrogeological studies that are used to design and install networks of drains. It requires an accurate description of the hydrogeological system and definition of targets for the depressurisation. Cost-benefit analyses are often undertaken to select the most appropriate dewatering plan.

The following tools can be used to reduce pore pressure:

- Pumping wells: these are the same as those used in dewatering programs. Pumping wells can be used both for dewatering and depressurisation.
- Horizontal drains: these are commonly constructed behind pit slopes in rock units that are not accessible for pumping wells.
- Vertical (or angled) drains: these are considered when there is a large hydraulic gradient within the slope or units within the slopes with varying permeability. They are mostly used to establish a connection between less permeable units requiring drainage and more permeable units that have already been drained.
- Drainage tunnels: just like dewatering tunnels, these are dug below the pit floor and are built in conjunction with drain holes. The drain holes can be installed and operated from within the tunnel itself, without interfering with mining operations.

Integrated planning

Dewatering and depressurisation are multi-disciplinary efforts as they require strong interactions between mine planning, geotechnical, environment, geology, and mine operation teams. Maintaining pit slope stability is a core function of mining engineering teams, with geotechnical specialists undertaking the data collection, providing input into the design, installing monitoring systems, and conducting inspections. Because the presence of water can influence slope stability, the geotechnical specialists collaborate with hydrogeologists. In many cases, the hydrogeologists are part of the same technical team as the geotechnical specialists. Environmental teams tend to oversee the understanding of the regional groundwater context and assessing whether mining operations impact on the regional groundwater systems.

Dewatering and depressurisation are multi-disciplinary efforts as they require strong interactions between mine planning, geotechnical, environment, geology, and mine operation teams.

Going further – additional reading

Guidelines for Evaluating Water in Pit Slope Stability

https://www.lopproject.com/groundwater-guidelines/

Case study

Ahumada Calderon, C 2020, 'BHP mine water management: an integrated approach to manage risk and optimise resource value', in PM Dight (ed.), Slope Stability 2020: Proceedings of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering, Australian Centre for Geomechanics, Perth, pp. 3-16, https://doi.org/10.36487/ACG_repo/2025_0.01

https://papers.acg.uwa.edu.au/p/2025_0.01_Ahumada/

10.2 Inrush and inundation of underground mines

An inundation or inrush occurs when a liquid, gas, or other substance that can flow enters a workplace at a rate or volume or concentration that creates an emergency and presents a risk to health and safety of mine workers. An inundation or inrush hazard could be caused by:

- Significant quantities of water or other fluid material, including precipitation
- Any material that flows when wet
- Material that may be fluidised as a result of vibrations such as earthquakes, blasting, or other means
- Irrespirable atmospheres or flammable gases
- Paste or hydraulic filled stopes
- Water storage dams, tailings dams, or other man-made water bodies
- Rivers, lakes, the ocean, or other natural water bodies

In the Australian mining industry there have been at least nine fatal incidents resulting from inundation or inrush with the loss of 19 lives. For instance:

1996 Gretley Colliery Inrush: https://www.resourcesregulator.nsw.gov.au/safety/safety-events-and-education-programs/learning-from-disasters/learning-from-disasters/1996

This type of incident outlines the importance of geological characterisation and identification of faults, which are difficult to identify and conceptualise in hydrogeological models. They also pose large risks to underground mining.

Some people prefer to refer to “inundation” when the material is water and the event is associated with extreme rainfall. For instance, if a flood event leads to rainfall infiltrating the ground and finding a pathway to an underground mine, the preferred term might be “inundation.” Inrush would then be used for scenarios that do not involve rainfall.

Risk assessment forms the basis for developing an effective mine inundation and inrush management plan.

- Identification of all possible significant inrush and inundation hazards.
- Identification of the mechanism and magnitude of the identified inrush or inundation hazard.
- The path of the inundation or inrush, including off the mine site if that is a possible outcome.
- The number and location of people who may be affected by inrush and inundation, including people off the mine site that could be affected by an inundation or inrush.
- Prevention: controls to prevent an inrush or inundation event.
- Monitoring: controls to monitor status of inrush and inundation hazard to identify changes.
- First response: controls to respond to an inrush or inundation event in the early stages.
- Emergency response: controls to respond to a principal inrush or inundation event.

Sources of hazards include:

- Natural surface features: rivers, creeks, lakes, swamps, and floodplains.
- Man-made surface features: dams, tailings facilities, water storage areas, and levees.

- Natural underground features: voids containing fluids, strata/ground that will freely release fluids.
- Other mining operations including those above or below the mining horizon, highwall mining, and open cut voids.
- The proposed mining systems and the potential to create inundation and inrush hazards in the mine; this could include water storage underground, paste and hydraulic fill operations, or sealing of waste areas that may contain irrespirable atmospheres or flammable gases.
- Man-made or natural unconsolidated material that could flow when wet, including tailings dams and mine water dams.
- Aquifers, buried channels and other natural sources of ground water, old workings, or excavations.
- Bore shafts or boreholes, dump holes.
- Connection to the surface (e.g. portals, adits, and escape-ways).

Controls include:

- Elimination:
  - Removing redundant water storage structures.
  - Draining areas of the mine that have an inundation and inrush hazard.
  - Ensuring water storage is at the lowest part of the mine so the hazard is eliminated.
  - Keeping old workings ventilated to prevent the build-up of irrespirable atmospheres or flammable gas.
- Diversions: directing potential flows away from working areas.
- Barriers, which can be any structure that separates working areas from an inundation or inrush hazard:
  - Levee banks
  - Dam structures
  - Septum between seams (coal) or crown pillar between stopes (metalliferous)
  - Solid strata or ground between mines
  - Solid strata or ground between workings and the inundation and inrush hazard
  - Ventilation seals erected against areas that contain irrespirable atmospheres or flammable gases
  - Sealing or otherwise isolating potential man-made conduits such as boreholes
- Monitoring and inspections.

10.3 Subsidence

Subsidence is a localised lowering of the land surface. It occurs when underground voids or cavities collapse, or when soil or geological formations (including coal seams, sandstone, and other sedimentary strata) compress due to changes in moisture content and pressure within the ground.

Whilst subsidence can occur due to any type of underground mining, it is prevalent with longwall coal mining. It is however worth noting that changes to topography resulting from subsidence can lead to:

- Structural damage to buildings and services (including pipelines and sewers) and reduced serviceability of roads and railways.
- Surface cracking, especially in areas towards the edges of subsidence zones.
- Fracturing and vertical drainage of groundwater from shallow aquifers, reducing the water available to springs, peat swamps, and other ecosystems.

- Surface water diversion, reducing the water supplied to features such as streams, lakes, and peat swamps.

Changes to topography can also lead to cascading impacts on streams. It can alter the geomorphology of streams and can lead to changes in water quality, with associated impacts on biota and ecosystems.

Where subsidence is predicted to occur, a Subsidence Management Plan will be required.

Readers are encouraged to enquire about subsidence risks and relevant local regulation.

10.4 Pit lakes

Metal ore deposits are generally mined in pits reaching depths greater than hundreds of metres and covering relatively small areas. It is not common to backfill the pit as part of closure planning. Rather, when the dewatering program ceases, the pit is left to fill with water, creating a "pit lake."

Optimising pit closure outcomes for water quantity, quality, and dependent-ecosystems and environments requires detailed knowledge of groundwater and surface water systems and their connectivity to potential pit lakes.

When mine dewatering ceases, the water table near the mine pit will begin to rise. However, the water level may not stabilise for tens or hundreds of years and may stabilise at a level that is different from the original water table level. If the pit is not connected to a river network, and evaporation from the pit lake exceeds precipitation and runoff into the pit, the final lake level will be below the original water table level. In this case, the regional water table will also remain below the original water table, and this may have long-term implications for groundwater-dependent ecosystems. If the pit is connected to a river network, then rapid filling of the pit may occur, but the groundwater level may still take many years to recover.

The water quality of a pit lake will be largely determined by the rate and chemistry of groundwater flowing into the pit, runoff from the pit walls and lake catchment, the time required for the pit to fill, and the evaporation rate. Pit lake water quality may also be affected by the composition of waste rock and its proximity to the pit. For partially backfilled pits, in-pit storage of waste rock will also affect pit lake water quality. If evaporation exceeds precipitation and runoff into the pit, then the salinity of the pit lake will increase over time. Concentrations of other dissolved solutes will also increase over time. Potential uses of pit lakes will be determined by the water quality and by access and community safety issues.

Understanding pit lake evaporation rates, lake stratification cycles, and how surface water and groundwater inflows to the pit changes over time, are essential for accurate prediction of the final pit lake water level, the time for the pit lake water level to stabilise, and the development of pit lake water quality. Changes in water flows over time due to landscaping and revegetation of pit surrounds need to be considered, together with changes over time in the chemical composition of waste rock leachates and runoff from waste rock and pit walls.

The transient dynamics of pit lake hydrology are often overlooked. Almost all pit lakes will be terminal lakes immediately following closure, with long-term dynamics often taking many years or even hundreds of years to develop. Even then, seasonal or inter-annual changes in rainfall and evaporation can result in lakes fluctuating between terminal, flow-through, and net groundwater recharge conditions.

Prediction of post-closure pit lake water levels is often based on numerical groundwater models, but few of these models are linked to validated numerical lake models that incorporate realistic estimates of pit lake evaporation. Pit lake models that are not coupled to groundwater models often make simplifying assumptions about groundwater inflow to the lakes and how this changes with time. The importance of such simplifying assumptions is rarely tested. How climate change impacts interactions between pit lakes and regional groundwater has rarely been explored. Many pit lake water quality models do not consider changes in groundwater inflows and other water balance components over time, or changes in the chemical composition of surface runoff.

Assessing pit lake remains a focus of research activities, with many research and consulting studies progressing.

The Mine Water and Environment Research Centre has conducted extensive research on pit lakes: https://miwer.org/?page_id=67

The CRC TIME has a program dedicated to pit lakes: https://crctime.com.au/research/projects/project3c/

Going further – additional reading

Kemanga, B., McIntyre, N., Bulovic, N., 2024. Hydrological classification of mine pit lakes using modelling experiments. J. Environ. Manag. 370, 123057. https://doi.org/10.1016/j.jenvman.2024.123057

10.5 Regulated structures and tailings

Regulated structures refer to "land-based containment structures," for instance:

- A dam that is built for the purpose of storing mine-affected water.
- A non-operational pit that is used for storing mine-affected water.
- A tailings storage facility.

These structures pose risks. The main ones are:

- Failure to contain: mine-affected water is released from the structure, through seepage to the surrounding soils or by "overtopping," for instance by flowing over a dam wall.
- Dam break: A dam failure or dam break is a catastrophic type of structural failure characterised by the sudden, rapid, and uncontrolled release of impounded water or tailings slurry.

Because of these risks, the structures are regulated: in most jurisdictions, there are conditions and standards that must be complied with. Companies often use the term "Mineral Residue Facilities" instead but apply it to storage facilities for water, process wastes, and by-products: water dams, water stores, tailings storage facilities, waste rock dumps, stockpiles, and heap leach pads. This means that the range of risks is not confined to water. For instance, with waste rock dumps, there are significant risks associated with geotechnical stability. Applying the same standards to structures that store water or tailings and to structures that store waste rock often leads to confusion.

Because this document is focused on water, the term "regulated structures" is used. It excludes:

- Levees: structures that are built to protect the mine from flooding. Construction of levees is part of flood risk management.
- Waste rock dumps, stockpiles, heap leach pads as these do not store water.

Tailings storage facilities and tailings dams are specific types of regulated structures: they store slurries that are a mix of water and fine particle mineral residue.

Tailings dam failures have disproportionately shaped the reputation of the industry, with several significant disasters in the last five years, including Mount Polley in Canada, Samarco and Brumadinho in Brazil. Beyond the human fatalities, the volume of pollutants released to the environment and the extent of ecosystems affected reached unprecedented proportions.

A timeline of tailings dam failures is available here: https://www.wise-uranium.org/mdaf.html

Case study: Mount Polley tailings dam failure, British Columbia, Canada

In August 2014, the Mount Polley copper and gold mine in British Columbia experienced a catastrophic tailings dam failure, releasing millions of cubic metres of tailings into nearby water bodies. This incident prompted significant regulatory and operational changes in mine water management across Canada.

An independent review panel of three geotechnical experts was established to investigate the failure. The final report was delivered in 2015 and is available here:

https://www.mountpolleyreviewpanel.ca

One of the objectives of the independent review was to determine the cause of the dam failure, which included the interaction of water with the embankment (this relates to tailings breach management) and water management within the facility. Outcomes from the review also included:

- Regulatory review: the breach led to the establishment of the Independent Expert Engineering Investigation and Review Panel, which recommended best practices for tailings storage facilities, emphasizing water balance management and the adoption of stacked filtered methods.
- Enhanced monitoring, with significant increases in real-time water quality monitoring and transparency with local communities.
- Collaborative frameworks: the event spurred collaborations between mining companies, Indigenous communities, and regulators to develop more robust water management strategies.

Source: https://www2.gov.bc.ca/gov/content/environment/air-land-water/spills-environmental-emergencies/spill-incidents/past-spill-incidents/mt-polley

Case study: Fundão and Brumadinho tailings dam failures, Brazil

In November 2015, an upstream tailings dam owned by the mining company Samarco, a joint venture between Vale and BHP Billiton, collapsed in the city of Mariana (Minas Gerais, Brazil), releasing about 33 million cubic metres of tailings down the valley, which killed 19 people. This event is considered one of the largest accidents in the history of mining when evaluated by the volume of wastes released and the geographical extension of the environmental damage.

In January 2019, 150 km away from Mariana, 11.7 million cubic metres of iron mining tailings flooded the installations and offices of Vale and other rural proprieties in the city of Brumadinho (Minas Gerais, Brazil), causing the death of 270 people. Given the scale of this second disaster, Parliamentary Commission of Inquiries (PCIs) were conducted during 2019, aiming to investigate the causes of it. It is worth noting that attempts to initiate a PCI after the first accident in Mariana were not successful.

In response to these events, Brazil updated its tailings regulations, with new resolutions issued by the National Mining Agency (ANM). Key areas of focus include stricter dam safety requirements, regulations for the exploitation of mining waste and tailings, and measures to address the environmental and social impacts of mining activities.

Global Industry Standard on Tailings Management

In response to these disasters, a Global Industry Standard on Tailings Management was developed and released in 2020: https://globaltailingsreview.org/global-industry-standard/

GISTM covers all aspects of managing tailings storage facilities. Readers are encouraged to familiarise themselves with GISTM.

10.5.1 Consequence category assessment

Good practice engineering for regulated structures is about ensuring that the impacts of potential failures are identified and considered in their design and operation. The early identification of the potential consequences of failure of these structures is important in determining the standard of reliability required for design, construction, and operation of the structures. It is this identification of potential consequences from failure that we call “Consequence Category Assessment.”

There are guidelines available for conducting consequence category assessments. Mine water practitioners are encouraged to find the guidelines that apply in their jurisdiction.

As an example, ANCOLD is the Australian and New Zealand Committee on Large Dams. They publish a range of guidelines: https://www.ancold.org.au/?page_id=334

- Guidelines on Selection of Acceptable Flood Capacity for Dams (2000)
- Guidelines on the Consequence Categories for Dams (October, 2012)
- Guidelines on Tailings Dams: Planning, Design, Construction, Operation and Closure (July 2019)

The documents are not free but service providers (e.g. consultants undertaking specific studies) will have access to these documents.

Guidelines are not a design code or standard. They are produced for the guidance of experienced practitioners who are required to apply their own professional skill and judgement in their application. Users must keep abreast of developments in the management and design of water and tailings dams and take those developments into account when using these guidelines.

Another example is the Canadian Dam Association Dam Safety Guidelines:
https://cda.ca/publications/cda-guidance-documents

In Brazil, legislation was updated after the two significant tailings dam disasters, with new resolutions issued by the National Mining Agency (ANM).

10.5.2 Failure mechanisms

There are three main failure mechanisms:

1. Failure to contain: seepage
   This refers to the accidental release of mine-affected water to soils and/or groundwater via seepage through the floor or sides of the structure. This process is governed by the principles of soil science and is highly relevant to tailings dams.
2. Failure to contain: overtopping
   This refers to the accidental release of mine-affected water from the structure due to the volume of water stored in the structure exceeding the storage capacity of the structure. In the case of dams, this means that the water flows over the crest of the dam. In the case of pits that are used as water storage, this means that the water flows over a containment wall and/or the level at which the pit connects to a groundwater or river system. For regulated structures, this failure mechanism would lead to unintentional release of mine-affected water and associated impacts on communities and environmental values.
3. Dam break
   This refers to a structural failure that leads to sudden, rapid, and uncontrolled release of mine-affected water or tailings. It is only applicable to dams. Dam failures can occur with or without a wet weather event. A sunny day failure occurs when a dam fails without a wet weather event. A flood failure occurs when a dam fails with a flood event, which can result in flooding from both the dam catchment and catchments and tributaries downstream.

When undertaking a consequence category assessment, experienced practitioners assess the failure scenarios for their likelihood of leading to, for example, harm to humans, including health and social impacts; environmental harm; and economic loss or property damage.

Based on the predicted impacts, mitigating controls will need to be implemented. Some controls might be imposed by legislation and conditions:; mine water practitioners are encouraged to familiarise themselves with local requirements.

These assessments are complex and must be undertaken by suitably qualified personnel. Methods used are outlined below.

10.5.3 Methods

To determine impacts from a failure to contain mine-affected water, a standard approach is to undertake a Downstream Reach Analysis: using a hydrological model to determine the length of waterway that will be affected by the release. The analysis usually includes two scenarios:

- An intense but short duration rainfall event which leads to an unplanned release of mine-affected water, but no concurrent flow in the receiving waterway. There is no dilution of the mine-affected water release, but flows are captured in pools and depressions or dissipate into the stream bed and as a result do not travel far downstream. This scenario represents the highest concentration of contaminants, but shortest affected reach.
- An intense burst of rainfall at the peak of a large storm after months of above average rainfall which has saturated the regional catchment and leads to an unplanned release of mine-affected water. The release occurs in a fast flowing receiving waterway and is significantly diluted but is conveyed a greater distance downstream. This scenario represents the lowest concentration of contaminants, but the longest affected reach.

To determine impacts from a dam break, flood modelling is undertaken to determine the extent of the zone that could be impacted by the failures. In the case of flood failure, a range of flood scenarios are assessed. The ANCOLD 2012 guidelines provide a structured approach to determining the sunny day and flood failure consequence categories as a result of a possible dam break scenario.

10.5.4 Management of regulated structures

Regulated structures should be governed by an operation and maintenance manual that includes:

- A description of protocols and responsibilities for operation of the mine water system and its storage structures.
- Detailed instructions on how to operate and maintain individual pieces of equipment (e.g. pumps).
- A recording system that is capable of issuing and tracking work orders issued to operational staff and others (such as external contractors), then recording the outcomes.
- Emergency Action Plans as applicable.
- Surveillance protocol: routine, annual and comprehensive inspections.

A critical part of managing these structures is to track the inventory of mine water they store, with a Trigger Action Response Plan in place when inventory reaches certain levels.

It is critical to assess the impact of any water management strategy on inventory. For instance, implementation of a technology to recover water from tailings will require additional storage capacity to contain the retrieved water.

Going further – additional reading

Armstrong, M., Petter, R., Petter, C., 2019. Why have so many tailings dams failed in recent years? Resour Policy 63, 101412. https://doi.org/10.1016/j.resourpol.2019.101412

Saes, B.M., Muradian, R., 2021. What misguides environmental risk perceptions in corporations? Explaining the failure of Vale to prevent the two largest mining disasters in Brazil. Resour. Polic. 72, 102022. https://doi.org/10.1016/j.resourpol.2021.102022

10.6 Diversions

Resource deposits frequently extend beneath streams and rivers. The viability of a resource project can depend on the feasibility of diverting a watercourse to allow access to a resource deposit. Diverted water can be transposed to another location when its quality is not affected by the management activities, with disposal in surface water systems or re-injection in aquifers.

Here we are referring to the diversion of **surface water**. There are mines that are located below the water table and must implement extensive dewatering programs to access the ore. The most well-known example of this situation is iron ore mining in the Pilbara region, Western Australia. A significant portion of iron ore deposits in the Pilbara are located below the water table. This leads to large dewatering volumes that are displaced into neighbouring creeks or made available for beneficial reuse. BHP describes their mine dewatering and surplus water network for their Western Australia Iron Ore business unit: https://www.bhp.com/news/case-studies/2023/08/pilbara-water-scheme-success. The displacement of these volumes of groundwater is technically a "diversion" but is not normally referred to as such. In the Water Accounting Framework (Section 11), it is referred to as "managed water."

Surface water diversions specifically refer to the diversion of a water course. They must be stable, self-sustaining, and must not impact on the adjoining upstream and downstream reaches of the existing watercourse. This is a complex discipline that requires a multi-disciplinary approach: hydrology, hydraulics, geomorphology, and ecology. There are guidelines available for Queensland, Australia, but they are not widely adopted beyond Queensland. As far as we are aware, there is no equivalent guideline available anywhere else. We see this as a significant gap; there is requirement to expand knowledge with regards to best practice design of water course diversions.

Diversions can cause environmental and social impacts if not implemented and managed appropriately. The physical changes around the diverted channel can impact on flow velocity, with an increased risk of bed and bank erosion. This can lead to physical and biological connectivity issues, with changes to sediment supply regime, lack of vegetation establishment, or reduction in flows to sections downstream of the diversion, with consequences for water quality, biota, and biodiversity.

Once the diversion has finished functioning as an operational structure, further creek rehabilitation works are required. The specifications associated with the closure design may differ from the operational phase.

Queensland guidelines:

Works that interfere with water in a watercourse for a resource activity—watercourse diversions authorised under the Water Act 2000. DNRME, 05/02/2019

https://www.resources.qld.gov.au/?ver=2.00&a=109113%3Apolicy_registry%2Fwatercourse-diversions-water-act.pdf

Going further – additional reading

Flatley, A. and Markham, A. (2021). Establishing effective mine closure criteria for river diversion channels. Journal of Environmental Management 287

Flatley, A., Rutherford, ID and Hardie, R. (2018). River channel relocation: Problems and prospects. Water 10:1360. https://www.mdpi.com/2073-4441/10/10/1360

11. Water accounting framework

Water accounting describes the application of a consistent and structured approach to identifying, quantifying, understanding, and communicating water interactions using a common set of metrics and approaches.

Water accounting differs to water reporting. Water accounting is the consolidation of operational water balance information and provides the data to support water reporting for a variety of audiences and interests. In contrast, water reporting is the presentation of both water accounting and broader water related information in formats tailored to the needs of various reporting uses and users.

The mining industry has developed its own water accounting framework:

https://minerals.org.au/wp-content/uploads/2022/12/MCA-Water-Accounting-Framework-User-Guide-2.0-2022.pdf

It provides a system-level representation of a mine's water balance, which enables clear understanding and communication of risks, as well as identification of performance indicators. It also supports water reporting. Figure 8 provides an overview of the framework, which:

1. Establishes a water balance of a mine: mine water practitioners will need to define the boundaries of the mine for the purpose of deriving the account.
2. Tallies the input of water into the mine from:
   - Surface water: can be derived from surface water studies, Section 4.
   - Groundwater: can be derived from surface water studies, Section 5.
   - Third-party: from an allocation of water obtained as part of integrated water resources management, Section 3.4.
   - Insite ore moisture, which will be provided by the mineral processing team.
3. Tallies the outputs of water into the mine from:
   - Evaporation, Section 11.1.
   - Releases to the environment, which will be measured .
   - Moisture content in products and waste materials, including tailings.
   - Any other losses incurred by the mine, such as haul road dust suppression.
4. Records the change in inventory in water storage structures (Section 10.5) from the start to the end of the reporting period and compares it with the differences between inputs and outputs.
5. Assigns a water quality category to each input and output as far as practicable.
6. Considers any form of diversion as "managed water" that is not included in the water balance.

In essence, the water account summarises the information that has been described in all previous sections of this document. Mine water management can present a range of technical complexities. The water account provides a synthesis of water-related aspects so that key risks can easily be identified and communicated.

Throughout this document, it has been mentioned that the broad objectives of mine water management are to capture overland flow for use in mining operations and/or divert it to avoid water accumulation. The water account captures this well. It compiles all inputs and outputs, so that water deficit and/or accumulation can quickly be assessed. It shows how much water storage capacity is available to manage water accumulation. It quantifies all losses so that water supply requirements can be evaluated. Importantly, it clearly communicates the relationships between a mine and the water resources with which it interacts.

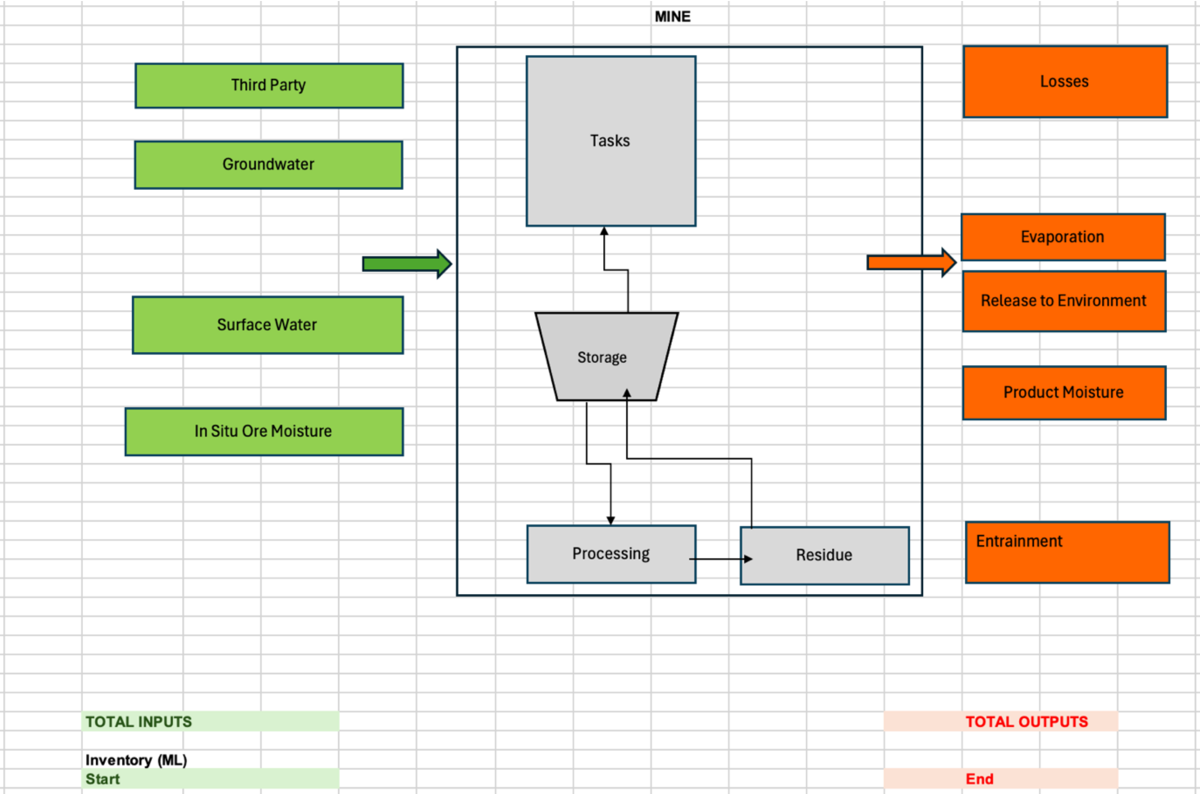


Figure 8: Overview of Water Accounting Framework (Source: Centre for Environmental Responsibility in Mining, Sustainable Minerals Institute, University of Queensland).

The framework has been widely adopted by the mining sector, which has greatly improved understanding of mine water balances and associated risks. However, companies tend to report their accounts in an aggregated manner, at the scale of a business unit or a company. The water account of a single mine is rarely available in the public domain. The example of the BHP overall water account from 2018 is provided below.

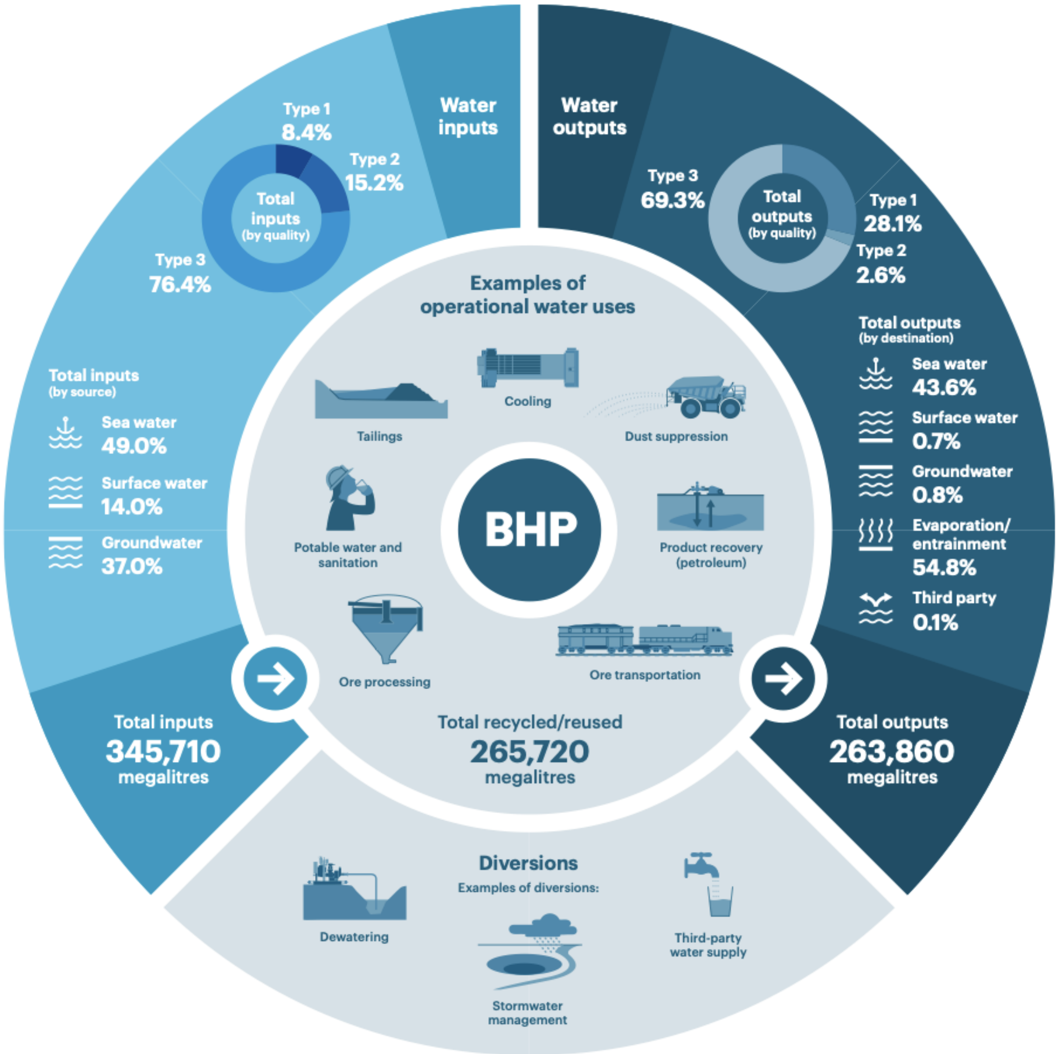


Figure 9: BHP Water Account (2018).

Source: https://www.bhp.com/-/media/documents/investors/annual-reports/2018/180828_bhpwaterreport2018.pdf

Note that there are mines for which implementing the framework will not provide much benefit. For instance, there are mines for which water management is essentially limited to stormwater management and erosion and sediment control, with installation of diversion infrastructure and sediment basins, and which do not have a processing plant or only produce dry residues. In this case, inputs and outputs are negligible. The mine only performs activities to manage water. In these cases, producing a water account is not particularly useful.

The following sections provide information about elements of the water account which have not yet been addressed in this document.

11.1 Evaporation loss from water storages and tailings dams

Evaporation from water and tailings storage structures often constitutes a major component of the water balance (depending on the climate and how much water is stored). At some mines, it can represent the largest output. Mines that lose large volumes of water through evaporation investigate options such as covers. Examples can be found here:

https://www.awtti.com/evaporation-control-floating-cover/

Recently, Escondida mine in Chile has trialled use of spheres to cover the surface area of their water storage structures (“piscinas”) achieving an 80% reduction in evaporation losses:

https://www.linkedin.com/posts/bhp_chile-mining-optimisation-activity-7351007923675746304-ZyO2?utm_source=share&utm_medium=member_desktop&rcm=ACoAAAbVY54BiWKf1FL0FQlWB533G5rweHrU180

An ongoing issue with the supply of technologies to the mining sector is the lack of independent testing.

11.2 Entrainment in tailings

There has been extensive research and development of technologies to recover mine water form tailings. They include

- Thickeners: concentrate tailings solids, allowing for easier water separation and reuse.
- Filtration: vacuum or pressure filters that can extract water from tailings, resulting in a drier, more stable material.
- Centrifuges: machines that rapidly dewater tailings, achieving high solids content and water recovery rates.
- Decant ponds in tailings storage facilities that collect and pump off the supernatant water for reuse.

Some practices have become common in industry: use of thickeners, management of tailings deposition to maximise capture, and reuse of decant water from tailings facility.

Research and development are ongoing for dewatering and drainage techniques (e.g. large-scale tailings filtration and hydraulically dewatered stacking).

Industry has published a guide on filtered stack tailings.

Filtered tailings have come to the forefront of options for consideration by mine operators to significantly reduce the amount of water sent to, and stored on, a surface tailings facility. Filtered stacked tailings is an alternative tailings management system that builds a geotechnically and geochemically stable structure from tailings that have been filtered to produce an unsaturated, soil-like building material. A guide has been published for the design of filtered tailings systems, specifically using pressure filtration technology, to produce a self-supported filtered tailings stack, also known as stacked filtered tailings.

Filtered Stacked Tailings, A Guide for Study Managers, 2024. BHP and Rio Tinto Tailings Management Consortium.

11.3 Benchmarking the components of the water balance

With growing interest in the mining sector’s “water use, tools have been developed to benchmark the performance of the industry with respect to some water balance inputs and outputs.

An example is the database produced by Skarn Associates.

https://www.skarnassociates.com/products/methodology-water

The domain of application of such a tool at mine level is not clear, given the status of practice achieved with water balance modelling.

12. Future Work

12.1 Organisational factors

Organisational factors will greatly influence a mine's performance with respect to water management.

This section will be added as ultimately the success of any operational water strategy depends on the execution capacity of the organisation.

Findings from organisational research to outline aspects that can lead to stronger environmental outcomes in general, and benefits to water management in particular, such as:

- Ensuring water management objectives are included in a company's shared sense of purpose.
- Identifying and addressing organisational issues that prevent communication and collaboration on water-related matters.
- Building teams that meet increasing technical complexity and stakeholders' expectations.
- Ensuring contributions from water personnel are valued and clarifying the role of water specialists inside mining organisations.
- Developing a clear understanding of what must not happen with respect to water.
- Training pathways, professional development,

This section will

- highlight academic programs, technical institutes, and industry partnerships that help build capability (e.g., UBC, PUCP, Sernageomin, ANA).
- Include examples of how companies have structured water governance teams or embedded water leads within operations and projects.

12.2 Cultural values of water

Cultural values of water should be included in the knowledge baseline because water holds deep spiritual, social, and livelihood significance for many communities, particularly Indigenous peoples. Recognising these values ensures that water management decisions respect cultural connections, strengthen trust, and support equitable stewardship.

Indigenous and Western perspectives on water can differ. As outlined in this knowledge baseline, Western frameworks conceptualise water as a resource to be allocated, regulated, or engineered for human use. In contrast, many Indigenous knowledge systems understand water as a living entity with which people hold reciprocal responsibilities and integrate hydrology, ecology, climate, and community values into a unified understanding, treating water, land, plants, animals, and people as part of the same connected system. Decisions about water are embedded in responsibilities to ancestors, future generations, and the broader landscape, rather than being framed only through economic utility, compliance, or engineering feasibility.

These differing views can create tension in project planning, particularly where cultural, ecological, and spiritual values are not captured by conventional regulatory or technical assessments. Recognising these perspectives will support more inclusive, respectful, and durable approaches to water stewardship.

This section of the Water Knowledge Baseline will aim at including:

- An introduction to the cultural values of water, with short explanations of why cultural values matter in water management and why they are included in the baseline (e.g., their relevance to social licence, community relationships, risk management, and stewardship).

- A short overview noting that many jurisdictions now include cultural values in water regulation or environmental approval processes, and that international ESG frameworks increasingly require disclosure of community and cultural water impacts.
- Descriptions of Indigenous knowledge systems in relation to water, outlining how Indigenous communities conceptualise water (e.g., water as a living entity or kin, responsibilities rather than rights, holistic and place-based understanding).
- Discussion of the differences between Indigenous and Western water frameworks, outlining how different worldviews can lead to different expectations, priorities, and interpretations of impacts, supporting the need for early dialogue and culturally aware assessments.
- Cultural Impacts of Water Disturbance: An outline of the types of harm that may arise from water quality changes, flow alterations, groundwater drawdown, or loss of access to culturally significant water places—beyond ecological or chemical impacts.
- Practical guidance on what respectful water-related engagement looks like, such as early involvement of communities, recognition of cultural protocols, and transparent data sharing.
- Suggestions on how mining companies can integrate cultural values into water stewardship strategies, groundwater and surface water assessments, closure planning, monitoring design, and cumulative impact evaluations.
- Acknowledgement of common challenges, such as lack of formalised processes for identifying cultural values, uneven regulatory guidance across jurisdictions, and the need for capacity building on the topic.

This section will be illustrated by case studies, illustrating where cultural values shaped water management decisions.

This section will connect technical water management to human systems and social license to operate.

12.3 Lifecycle assessment of water

Principles of life cycle assessment (LCA) of water should be included in the knowledge baseline because it supports a comprehensive understanding of water-related risks across all stages of a mining project, from exploration through closure and post-closure, and potentially through the supply chain.

LCA can be used to compare technologies (e.g., conventional flotation, coarse particle recovery, heap leaching, paste backfill systems, and filtered tailings) to determine which configurations reduce water demand over the life of mine.

Copper producers have applied LCA to quantify water consumption from extraction through smelting, refining, and product manufacture, enabling comparison of water intensity across mines and identification of hotspots such as concentrate transport, concentrate drying, and refining.

Some companies use LCA-derived water “footprints” to respond to supply-chain reporting requirements (e.g., automotive and electronics manufacturers), enabling customers to compare water intensity between gold, copper, nickel, and battery-mineral suppliers.

Applying LCA can help identify hidden dependencies, long-term liabilities, and opportunities to reduce cumulative impacts, supporting more resilient and sustainable water stewardship.

This section of the Water Knowledge Baseline will aim at including:

- An introduction to Life Cycle Assessment methods as applied to water (ISO 14046-based Water Lifecycle Assessment principles), and why a lifecycle perspective matters for mining projects.
- How water-related risks can shift through exploration, operations, closure and post-closure.
- How lifecycle thinking integrates with ESG frameworks and emerging disclosure obligations.

This section will be illustrated by case studies, providing examples of where life cycle assessment has shaped water management decisions.

12.4 Capacity building

This section of the Water Knowledge Baseline will provide information to guide capacity building and professional development of personnel.

Maintaining high standards of practice in mine water management requires ongoing investment in professional development and capability building across operational, project, and corporate teams. The increasing technical complexity of water-related challenges, ranging from hydrology and hydrogeology to water treatment, closure planning, climate adaptation, and stakeholder engagement, demands that personnel have access to contemporary knowledge, evidence-based methods, and opportunities for continuing education.

A wide range of mechanisms support capacity building, including formal university qualifications, postgraduate programs, technical conferences, industry seminars, and short courses delivered by specialist organisations. These opportunities allow practitioners to deepen technical expertise, stay current with emerging research, and learn from peers working across different commodities, climatic regions, and regulatory contexts. Many universities in major mining regions (including Australia, Canada, Chile, Peru, South Africa, and Brazil) offer targeted programs in water resources engineering, hydrogeology, geochemistry, environmental management, and mine closure, providing pathways for developing specialist capability.

Short courses and practitioner workshops play an important role in bridging academic knowledge with operational requirements. CEEC and its partners have developed short course material designed to support learning across disciplines and organisational levels, ensuring that teams engaged in planning, operations, and closure have a shared understanding of key concepts and good practice approaches. These materials can be further expanded or tailored with input from CEEC sponsors and affiliated professionals to ensure alignment with industry needs.

Collaboration is central to sustained capability development. Mining companies, research institutions, service providers, regulators, and community organisations each hold different forms of expertise essential to effective water stewardship. Forums that enable shared learning supports the exchange of knowledge and the co-development of solutions. Strengthening these collaborative mechanisms helps ensure that emerging technologies, regulatory updates, and improvements in good practice are rapidly disseminated and consistently applied across the sector.

Continued investment in professional development, combined with strong collaboration and knowledge exchange, will be critical to building the capacity required to address evolving water challenges and support the transition to more resilient, transparent, and responsible water management practices.

This section will aim at including water-related training and professional development opportunities across key mining regions, with a country-by-country listing of relevant programs (e.g., PUCP in Peru, Universidad de Chile, UBC in Canada, UFMG in Brazil, SMI in Australia).

13. Glossary

Acid and Metalliferous Drainage (AMD)
The outflow of acidic water from metal mines or coal mines

Annual Exceedance Probability (AEP)
The probability that a specified flow (or volume of water over a specified period) will be exceeded in a given year.

Aquifers
Aquifers are defined as porous media that will readily yield water in a usable quantity to a well or spring.

Aquitard
Aquitards, in contrast to aquifers, are compacted layers of clay, silt or rock that retard water flow underground and act as a barrier for groundwater. Aquitards separate aquifers and partially disconnect the flow of water underground.

Artesian bores
An artesian bore (or well) is a bore tapping a confined aquifer where the groundwater is under pressure and the groundwater level in the bore rises above the aquifer.

Bore (or well)
A bore (or well) is a hole in the ground that intersects an aquifer and is used to extract groundwater.

Catchment
A catchment is an area of land which is bounded by natural features such as hills or mountains from which all runoff generated from the rain falling over the area flows to a low point. Several words can be used to designate a "catchment": catchment, watershed, drainage basin, river basin, or basin.

Confined aquifers
A confined aquifer is placed between layers of impermeable material, causing it to be under pressure.

Drawdown
Drawdown is the lowering of the water table in an unconfined aquifer, or the lowering of the potentiometric surface in a confined aquifer, caused by:

Depressurisation
A program of work to locally dissipate pore pressure within the pit slope to improve slope performance.

Dewatering
A program of work to lower the groundwater table below the pit floor.

Digital elevation model (DEM)
Digital elevation models (DEMs) are digital representations of the topographic surface and are the first essential element of a hydrological study.

Groundwater
Groundwater is water that exists underground in saturated zones beneath the land surface.

Hydrology
Hydrology is the study of the fundamental transport processes that govern the quantity and quality of water as it moves through the water cycle: evaporation, precipitation, streamflow, infiltration, and groundwater flow.

Intensity-Frequency-Duration (IFD) curves
Graphical tools that describe the likelihood of a range of extreme rainfall events.

Inrush
When a liquid, gas or other substance that can flow, enters a workplace at a rate or volume or concentration that creates an emergency and presents a risk to health and safety of mine workers.

Subsidence
A localised lowering of the land surface.

Soil hydraulic conductivity
The ability of the soil to transmit water.

Soil water retention
how much water a soil can hold at different soil water potentials (a measure of the energy status of water in the soil, indicating the tendency of water to move from one location to another). Water retention is represented by a soil water retention curve, plotting water content as function of soil water potential.

Recharge
The process by which water infiltrates the ground and replenishes groundwater.

Unconfined aquifers
An unconfined aquifer is an aquifer whose upper water surface (the water table) is at atmospheric pressure, and thus is able to rise and fall.

Water Cycle
The water cycle describes the constant movement and endless recycling of water between the atmosphere, land surface, and under the ground. The water cycle shapes landscapes, transport nutrients and minerals, and is essential to most life and ecosystems on the planet.

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