Office of the **Queensland Mine Rehabilitation Commissioner**

Aquatic ecosystems in post-mining landscapes

Technical paper

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Mine water infrastructure such as clean water storages, sediment ponds and residual mine voids may form waterbodies after mining. These areas can retain water intermittently or permanently and may attract bird life and host aquatic biota. It has been suggested that rather than decommissioning these after mining, that it would be better to keep them in place where they have ecological and social value.

There is a variety of water infrastructure found on mine sites and their capacity to develop healthy, viable, functioning aquatic ecosystems can differ. For example, there are some clean water storages and environmental dams which could potentially create viable habitat, function as aquatic ecosystems, or provide ecosystem services after mining. In contrast, structures such as residual mine voids and mine-affected water dams can have physical and chemical characteristics that limit the development of healthy, viable, functioning aquatic ecosystems. Mine water infrastructure such as residual mine voids from both open cut coal mines and metalliferous mines are artificial structures that usually represent a very different environment from what was present prior to mining. For example, residual voids often create deep excavations that fill with water and create permanent water bodies. Water quality in these water bodies can degrade over time due to ongoing inputs of mine-affected water and evapoconcentration. Other constraints can include insufficient habitat to support fringing and riparian vegetation, limited nutrient and carbon inputs and a lack of colonisation by natural sources of flora and fauna.

It can be difficult to define what successful rehabilitation to an aquatic ecosystem looks like. Although the presence of some fish, aquatic plants or birds is sometimes thought to mean that mine water infrastructure has ecological values, it does not necessarily indicate a healthy ecosystem. The objective for rehabilitation of aquatic systems should be to achieve a ‘healthy, viable and functioning ecosystem’ that has environmental and social values comparable to either those present prior to mining or unimpacted aquatic ecosystems found in the local area. This technical paper applies the concept of ‘ecosystem health’ as a basis to define what a healthy, functioning, and viable ecosystem is. Healthy ecosystems display stable water quality, balanced nutrient concentrations, are not toxic to biota, and host diverse communities of aquatic organisms.

The paper describes assessment criteria that can be used to determine whether mine water infrastructure or mine voids proposed to be left in place after mining could be regarded as a healthy viable and functioning ecosystem. To assess whether an ecosystem is ‘healthy’ or not, a comprehensive range of indicators of ecosystem health need to be evaluated. Example monitoring indicators that could be used to assess this are presented. Each of the indicators is linked to the elements of ecosystem health including a) structure (e.g. biodiversity, species composition, food web structure), b) vigour (e.g. primary productivity, nutrient cycling) and c) resilience (e.g. ability to recover from disturbance) and provide a foundation to describe a healthy aquatic ecosystem. Healthy aquatic ecosystems do not encourage the establishment of exotic pests or become a source of or facilitate pests in the landscape hence the presence of exotic fauna is also a useful indicator of ecosystem health. It is recommended that a conceptual model is developed to provide a basis to identify, define and prioritise indicators for monitoring.

The social and economic values of an aquatic ecosystem and its potential to provide ecosystem services should also be considered when assessing the value of the proposed ecosystem. Existing guidance such as the Queensland River Rehabilitation Management Guideline and the International Principles and Standards for the Ecological Restoration and Recovery of Mine Sites provide advice in this regard and should be considered in addition to the information provided here.

1 Introduction

In Queensland, all land disturbed by mining, including water storages, sediment dams, and residual voids must be rehabilitated to be made safe, stable[1] and able to sustain a use beyond mining with few exceptions. Mine water infrastructure and residual voids can have a range of uses beyond mining (McCullough and Lund, 2006; McCullough et al., 2020; Lund and Blanchette, 2023). The guideline for progressive rehabilitation and closure plans (PRC plans) in Queensland recognises ‘habitat and ecosystem services’ as an example of a post-mining land use (PMLU) (DES, 2021). The guideline doesn’t define these terms directly and they are discussed here in terms of aquatic ecosystem[2] health and ecosystem services[3].

Although it is possible to rehabilitate mine water infrastructure and residual voids as aquatic ecosystems which provide social and environmental benefits, it can be difficult to achieve this and demonstrate it in practice. Mine water dams and residual voids encompass artificial or constructed waterbodies which can have different characteristics to natural systems in the local landscape (Côte et al., 2023). Infrastructure such as residual mine voids (also referred to as pit lakes, or simply voids) may lack the physical structure to provide adequate habitat to host a healthy and resilient aquatic ecosystem (Blanchette and Lund, 2016). Water quality within the voids can also inhibit development of suitable ecosystems. Limited catchment size can also restrict external sources of carbon and nutrients which can constrain the development of ecosystem function (Lund et al., 2020). Although some aquatic species can tolerate very high levels of contaminants or may be able to utilise areas with limited habitat values for short periods, such conditions can restrict, prolong, or even prevent the establishment of a sustainable or viable aquatic ecosystem. Geller et al., (2013) states little is known about the aquatic ecology of Australian residual voids. Their review shows that residual voids typically have macroinvertebrate communities with limited diversity, dominated by cosmopolitan and pollution tolerant taxa. Some authors have suggested a ‘sliding scale’ of interacting factors that increase the complexity of rehabilitation, and where ecosystem services become increasingly limited (Blanchette and Lund, 2016; Lund and Blanchette, 2021). Although it can be difficult to achieve, McCullough et al. (2009) provide several examples where water-filled residual mine voids have been rehabilitated for ‘wildlife conservation’.

Effective planning, community consultation, design, monitoring, and management are required to rehabilitate mine water infrastructure and residual voids to be healthy and viable aquatic ecosystems. McCullough et al., (2009) suggest that for a void or pit lake to be a viable option at closure, a management strategy for the development and final form of the void should be considered well before rehabilitation operations have begun. It is widely recognised that planning for closure and the post-mining transition is most likely to be effective when it is undertaken early and continues across the mine life cycle (Measham et al., 2024). In some cases, residual mine voids can be designed and managed to be more conducive to aquatic ecosystems. Examples include providing areas of shallow habitat suitable to establish aquatic plants and linking habitat areas to provide refuge. A study by Seelen et al. (2021) showed terrestrial leaf litter input can improve aquatic biodiversity in gravel voids. Strategies to improve water quality by removing or treating contaminant sources may also help prevent deteriorating water quality. An example is described in Lund and Blanchette (2021) in which management strategies for saline voids as aquatic ecosystems were trialled, including organic matter addition and riparian and aquatic planting. The results reported in that study suggest that there may be positive benefits from adding leaf litter to voids. Earlier studies have also trialled the use of sewage effluent and green waste to improve water quality (McCullough et al., 2008). Studies to evaluate innovative approaches to rehabilitate mine water infrastructure and residual voids such as using ‘floating vegetated islands’ to enhance riparian development at closure and during lake filling are

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[1] The meaning of ‘stable condition’ is defined in the *Environmental Protection Act 1994* (Qld) (EP Act), s111A.

[2] An ‘aquatic ecosystem’ is defined in the Environmental Protection (Water and Wetland Biodiversity) Policy 2019 as “a community of organisms living within or adjacent to water, including riparian or foreshore area”.

[3] ‘Ecosystem services’ are defined as “the contributions that ecosystems (i.e., living systems) make to human well-being” in Haines-Young and Potschin (2018).

underway (ACARP, 2022). Approaches to enhance aquatic ecosystems in mine voids are discussed here in brief but are not the focus of this technical paper.

At present there is limited guidance on how to rehabilitate mine water infrastructure and residual voids to aquatic ecosystems. Additionally, how to demonstrate successful closure outcomes is not clearly described in the literature (Blanchette and Lund, 2016). A study by Vandenberg et al., (2022) suggests that a lack of published residual mine void relinquishment criteria creates a lack of clarity around what an acceptable outcome may be. Blanchette and Lund (2016) suggest ecological principles may have application to developing more meaningful criteria. To address these knowledge gaps, this technical paper describes the attributes of a viable aquatic ecosystem as a rehabilitation outcome.

2 Characteristics of mine water dams and residual voids

Water infrastructure such as clean water storages, sediment dams, subsidence areas, and residual mine voids present a challenge for rehabilitation to aquatic ecosystems. Clean water storages and sediment dams tend to be relatively shallow structures. They typically hold good quality water where they capture clean overland flow, or hold water purchased from external bulk water supplies. Clean water dams are often proposed to remain after mining as water storages to provide water for agricultural uses such as stock drinking water. Sediment dams are designed to capture and treat sediment-laden water. These tend to be shallow and receive input from surface water runoff. They often hold turbid water and can have thick sludge at the bottom. Many sediment dams will be dewatered and filled in at the end of mining.

Residual mine voids present some unique challenges for rehabilitation to an aquatic ecosystem. Accordingly, they provide a focus for the discussion here. Residual mine voids are associated with open cut mining operations such as hard rock, base metal, silica and mineral sands, bauxite or coal mines. The shape and form of residual mine voids can vary according to the mining method used to extract the target commodity. For example, hard rock mines tend to leave sub circular and very deep voids, while coal voids are comparatively shallow, long and narrow (Salmon, 2017). Figure 1 shows a cross section of a typical coal mine residual void and includes elements of a water balance model (reproduced here with permission). Voids with steep or stepped (benched) walls are often observed in residual mine voids. Without rehabilitation, upon filling, the steep or stepped walls tend to provide limited or no fringing/riparian zones, resulting in insufficient habitat and energy sources to support aquatic biota.

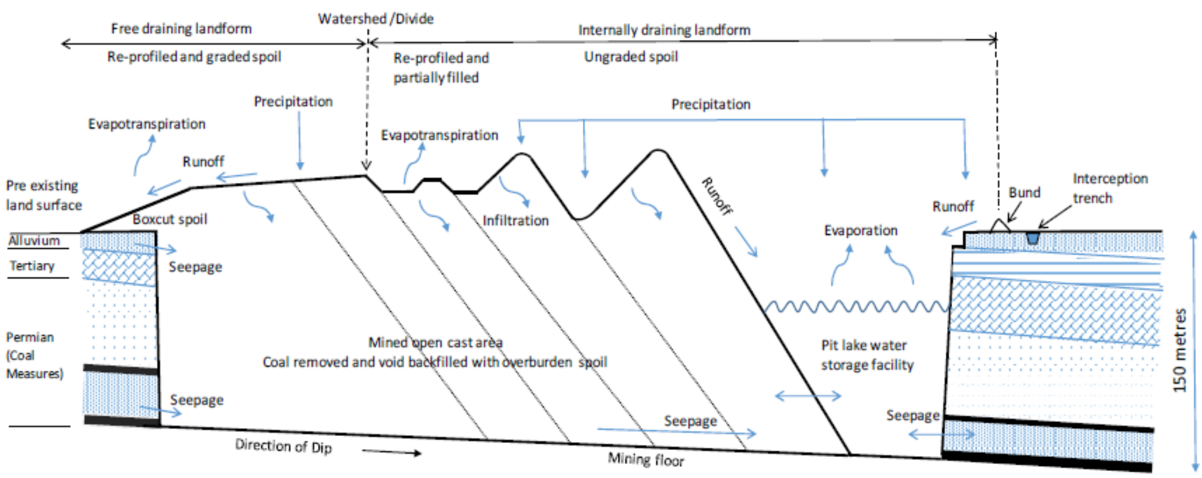

Figure 1. Conceptual model for a residual void water balance (Salmon, 2017)

Regardless of their shape and form, residual voids become permanent modifications to hydrological and hydrogeological systems (Lund and Blanchette, 2023). Mining generally requires dewatering of groundwater prior to and during mining. However, as dewatering ceases after mining, groundwater can flow into a void causing it to become filled with water. It may then take decades or longer for water levels in a residual mine void to reach a steady state (Tomlin et al., 2023). Direct rainfall and surface runoff can also fill voids, in conjunction with or even without groundwater. The long time periods required for filling voids with water creates challenges for rehabilitation, particularly for establishing fringing and riparian vegetation and also for safely managing the site. Additionally, residual mine voids may interact with surface and groundwater in different ways. Where evaporation rates are high and surface and groundwater flows into, but not out of a residual void, they tend to act as contaminant sinks. However, in some instances, residual mine voids can have a positive water balance and release to surface water or groundwater systems following significant wet weather events or via seepage into surrounding groundwater systems.

3 Aquatic ecosystem rehabilitation

While it is recognised that it may not be realistic or achievable to rehabilitate a mine void to exactly match the values of a natural, unimpacted aquatic ecosystem, the goal for rehabilitation should be to achieve similar values to a natural ecosystem known to occur in the local environment (to as great an extent as possible). This is akin to the suggestion by Spain et al. (2023) that rehabilitation of terrestrial ecosystems should target natural historic ecosystems. Where the values of a natural, unimpacted aquatic ecosystem cannot be achieved, then efforts to improve the values, minimise risks and enhance ecological outcomes should still be undertaken.

The Progressive Rehabilitation and Closure Planning objectives and performance outcomes[4] are that PMLUs are ‘viable, having regard to the use of the land in the surrounding region’. The performance outcomes also require that the proposed use ‘deliver, or be aimed at delivering, a beneficial environmental outcome’, be ‘consistent with how the land was used before mining’ or be ‘consistent with other planning and development approvals’. Views regarding what an aquatic ecosystem should deliver to demonstrate a ‘beneficial environmental outcome’ may differ between stakeholder groups and individuals. For example, the creation of habitat for a single or limited group of species may be regarded as sufficient by some, whereas others may suggest that matching the abiotic and biotic values of a natural aquatic ecosystem or reference analogue is a minimum requirement.

A leading practice objective for a newly created ecosystem is to be a functioning, stable and healthy environment which is suitable for a diverse range of biota, not only highly specialised or tolerant taxa. An ecosystem should also be viable, feasible to construct and create a self-sustaining ecosystem that is resilient to external stressors. Where waterbodies existed prior to mining, then recreating aspects of those original waterbodies provides a worthy goal. Where aquatic ecosystems are established after mining, they would need to target the same or similar ecological values to pre-mining conditions. Water quality would also need to be the same as locally relevant unimpacted systems or meet the scheduled water quality and ecological objectives. Historic mapping may indicate the presence of surface water bodies in the pre-mined landscape. Baseline studies undertaken prior to the mining activity may also identify the condition of aquatic habitats and water quality prior to mining.

3.1 Ecological integrity

Where the aim is to rehabilitate a residual mine void to an aquatic ecosystem, the concept of ecosystem health[5], which is synonymous with ecological integrity, provides a basis to define what a healthy and functioning ecosystem is. The Southeast Queensland freshwater ecosystem health monitoring program (Bunn et al., 2010) provides an example where the concept of ecosystem health has been applied to monitor the condition of aquatic ecosystems since the early 2000’s. The Ecosystem Health Monitoring Program (EHMP) managed by Healthy Land and Water assesses the ‘health’ of South East Queensland’s catchments and produces a report card showing environmental condition (Healthy Land and Water, 2023). This program uses indicators of ‘ecosystem health’ that are linked to ecosystem structure (e.g. biodiversity, species composition, food web structure), vigour (e.g. rates of production, nutrient cycling) and resilience (e.g. ability to recover from disturbance) (Bunn and Smith, 2002; Bunn et al., 2010). Ecosystem health indicators that assess how an

[4] Environmental Protection Regulation 2019 Schedule 8A.

[5] The ‘health’ or condition of an ecosystem is defined as “the ability of an ecosystem to support and maintain key ecological processes and organisms so that their species compositions, diversity and functional organisations are as comparable as possible to those occurring in natural habitats within a region”(ANZG, 2018).

ecosystem functions are also described in DES (2023). These indicators are defined as physical, chemical, biological or socio-economic measures that best represent the key elements of a complex ecosystem (DES, 2023). De Lange et al. (2018) explain the development of a South African rapid assessment protocol for voids used to inform of their ecological integrity and provide an economic valuation of their services. The assessment can subsequently be used to guide rehabilitation. Results can be reported using multi-criteria analysis or other metrics to provide an overall measure of ecosystem health.

Similar programs where aquatic ecosystem health is reported across catchments have become more commonplace since, with programs undertaken in a number of catchments in Queensland and around Australia. Indicators of 'ecosystem health' such as structural habitat (e.g. riparian health, snags and water depth), require consideration when planning for aquatic ecosystem rehabilitation.

3.2 Environmental values and ecosystem services

The Environmental Protection (Water and Wetland Biodiversity) Policy 2019 (EPP) identifies the environmental values to be protected for waters and wetlands in Queensland. Environmental values (EVs) can include biodiversity, aquaculture, stock watering, cultural and spiritual values, and recreation or aesthetic values. Rehabilitated systems could potentially host several EVs. The EPP also establishes management goals and Water Quality Objectives (WQOs) to support EVs in natural waters. These may be used to provide an indication of local water quality. Where water quality does not meet WQOs in the long term, then an aquatic ecosystem is unlikely to be viable and is not supported. For this reason, it is important to assess whether water quality will be stable over the long term and can continue to meet water quality objectives for ecosystem values.

Another consideration is whether the aquatic ecosystem will provide an 'ecosystem service'. Ecosystem services can be defined as 'the contributions that ecosystems (i.e. living systems) make to human well-being' (Haines-Young and Potschin, 2018). There are a range of potential ecosystem services associated with rehabilitating mine water infrastructure. Examples of an ecosystem service include passive water treatment or contaminant removal. Further information on ecosystem services is discussed in the following section.

3.3 Existing ecosystem rehabilitation guidance

The Queensland River Rehabilitation Management Guideline (QRRMG) (DES, 2022b) describes a process to rehabilitate rivers. Although the guidance is not specific to the rehabilitation of mine voids or mine water infrastructure, there are approaches that are applicable from the context of rivers. For example, the QRRMG recommends using a whole of system, values-based framework to identify and describe the components and processes that make up an ecosystem at multiple scales (spatial and temporal). The QRRMG proposes an assessment of biophysical components and processes of rivers in conjunction with the broader social, cultural and economic aspects, which includes the 'ecosystem services' that society may derive from the aquatic ecosystem. A detailed description of the planning process is provided in DES, (2022b). To perform this assessment, the QRRMG details a process that includes:

- describing the system, including its components and processes
- identifying existing and potential ecosystem services
- identifying stakeholders and values (positive and negative) for beneficiaries
- describing existing and potential threats (pressures) and opportunities
- describing the aims and objectives of rehabilitation
- outlining the long-term maintenance and monitoring required to achieve planned objectives.

This process provides a framework that can be adopted for rehabilitation of mine water infrastructure and residual voids. Importantly, the guideline defines rehabilitation as 'an action, or actions to repair, enhance and/or replace ecosystem processes and/or components, to improve intrinsic values and/or ecosystem services. This concept is distinguished from 'restoration' which is regarded as an 'action, or actions to bring back a former, original, normal, or unimpaired condition'. The guideline also states that restoration of river systems back to their pre-disturbance condition is a worthy but often difficult goal to achieve. This is akin to the challenges with mine rehabilitation where restoration to a pre-disturbance or reference condition may not always be feasible, particularly where adequate design and planning has not been undertaken.

The International Principles and Standards for the Ecological Restoration and Recovery of Mine Sites

(Young et al., 2022) are also relevant. These standards provide guidance on responsible ecological restoration of mine sites more broadly. While this reference is also not directly applicable to mine water infrastructure rehabilitation, it does provide a good framework to incorporate social and environmental aspects into mine closure planning. These standards present 8 principles:

- engage stakeholders throughout the life of mine
- draw on many types of knowledge
- be informed by reference ecosystems, while considering environmental change
- support ecosystem recovery processes
- assess against clear goals and objectives, using measurable indicators
- seek the highest level of recovery attainable
- gain cumulative value when applied at large scales
- employ a continuum of restorative activities

Existing guidance such as the Queensland River Rehabilitation Management Guideline and the International Principles and Standards for the Ecological Restoration and Recovery of Mine Sites should be considered in addition to the information provided here.

3.4 Community consultation

Community consultation is a key component of rehabilitation planning (DES, 2021). Stakeholder engagement provides an opportunity to seek input and plan rehabilitation in partnership with a range of stakeholders. It can also serve to add different perspectives and provide insights and offer potential solutions. It is important to understand the aspirations of local, regional and First Nations communities regarding the land uses they would like to see after mining. The need to coordinate with regional and First Nations communities across mine life is critical to improving long-term outcomes among other important recommendations (CRC TiME, 2023). Water resources including aquatic ecosystems are recognised to have important cultural and spiritual values, particularly for indigenous peoples of Australia (ANZG, 2018). Cultural and spiritual values are recognised in the Environmental Protection (Water and Wetland Biodiversity) Policy 2019 (EPP). Accordingly, it is necessary to incorporate indigenous knowledge and cultural and spiritual values for planning and managing the rehabilitation of water resources in the landscape. The AIATSIS Code of Ethics for Aboriginal and Torres Strait Islander Research provides a foundation for incorporating indigenous knowledge into land management (https://aiatsis.gov.au/research/ethical-research/code-ethics). The QRRMG (DES, 2022b) suggests identifying and documenting all stakeholders and beneficiaries and how they are affected by or benefit from an ecosystem. This is said to enable clearer definition of the objectives for rehabilitation.

4 Biophysical attributes of an aquatic ecosystem

Information in the following sections describes some of the key attributes of an aquatic ecosystem and defines criteria that may be used as a basis for assessment. It is not intended to provide prescriptive requirements but instead provides examples of the attributes of an aquatic ecosystem which are necessary to ensure a stable, functioning system. Determining whether a rehabilitated mine void or mine water infrastructure resembles an aquatic ecosystem would require a further, more detailed assessment of site-specific components.

4.1 Food webs and biodiversity

Food webs generally include primary producers (photosynthetic organisms), decomposers or detritivores (consume dead organic material), primary consumers (herbivores or grazers), and secondary consumers (predators) (Dodds, 2002). A healthy ecosystem is complex and requires diversity for each of these groups to be present.

The national water quality guidelines (ANZG, 2018) use a food web model of an aquatic ecosystem to define biological effect-based criteria (i.e. effect-based water quality guidelines). Toxicant guidelines for water quality are based on a risk-based assessment of toxicity for a range of organisms representing each of the trophic levels of an aquatic ecosystem. This approach uses a primary producer (such as an aquatic macrophyte or algae), an invertebrate (such as a Cladoceran or shrimp) and a vertebrate (such as a fish or frog) to represent key components of a functioning ecosystem (Dunlop and McGregor, 2007). An example of a simplified conceptual model of an aquatic ecosystem is shown in Figure 2 below (reproduced here with permission).

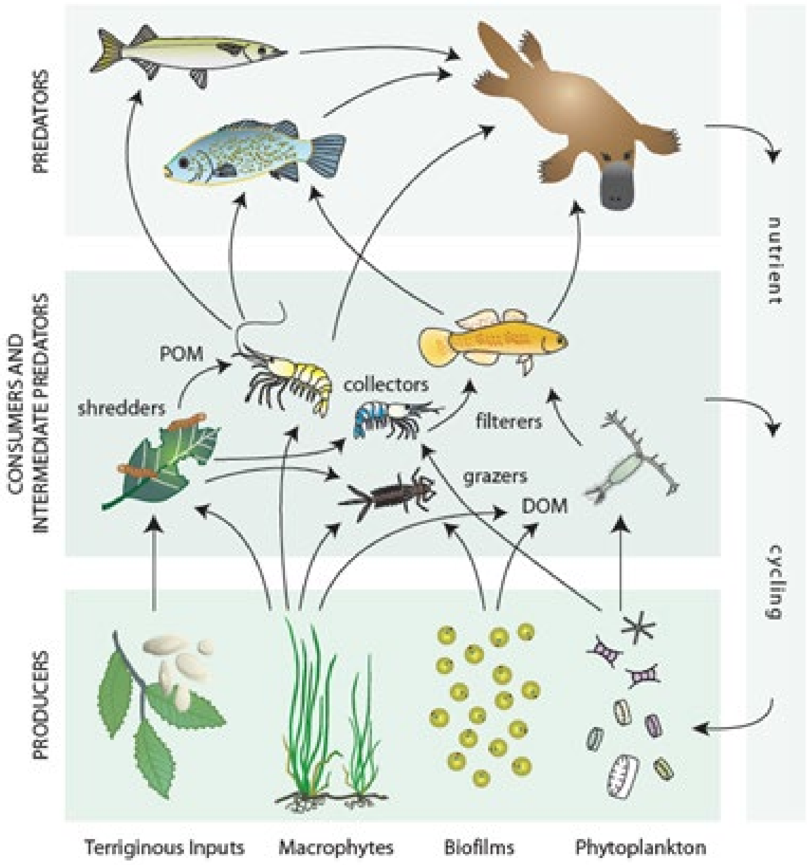

Figure 2. Conceptual model showing the energy exchange pathways of four trophic levels in a freshwater ecosystem (Dunlop and McGregor, 2007)

4.2 Primary productivity and aquatic plants

Primary productivity is essential to an aquatic ecosystem because it drives the flux of carbon, energy and nutrients. Such fluxes can become destabilised for example, in scenarios where there are conditions that lead to cyanobacteria blooms, or there are an excess number of predatory species that consume microcrustaceans or invertebrates and limit organic material cycling.

Biodiversity is important for ecosystem functioning (Loreau et al., 2001) and needs to be maintained. Cyanobacteria can cause poor water quality and can be toxic to aquatic life and impact human health. Cyanobacteria can reproduce quickly in favourable conditions, where there is abundant sunlight, still or slow-flowing water and sufficient levels of nutrients, especially nitrogen and phosphorus (WQA, 2023). Although nutrient concentrations can be low in residual voids, other structures such as sediment dams or environmental dams could potentially have comparably higher concentrations. Ammonium nitrate (NH_4NO_3) mixed with fuel oil is commonly used for blasting in mining. The decomposition and oxidation of undetonated explosives can result in high NO_3 concentrations in waters expressed from waste rock dumps (Hendry et al., 2018). Nitrogen-based explosives have been found to result in the presence of soluble N in mining waste rock dumps and catchment areas in in the Elk Valley, British Columbia (Mahmood et al., 2017; Hendry et al., 2018).

Aquatic plants (submerged, fringing and riparian) make a substantial contribution to the structure, function and service provision of aquatic ecosystems (O'Hare et al., 2018). For example, they provide critical habitat, provide oxygen, cycle nutrients and provide an input of carbon, an important source of energy. Aquatic and terrestrial plants have also long been used to treat water and remove contaminants from water and have application to mine void rehabilitation.

4.3 Water quality

In many cases water held in mine water infrastructure is influenced by mining. Mine-affected water quality is impacted by the geochemical characteristics of the surrounding rock and catchment area.

Mine-affected water in mine voids is often contaminated with metals, metalloids, salinity or is acidic/alkaline and its chemistry rarely approaches natural water body chemistry (Kumar et al., 2009). Residual mine voids can receive contaminant inputs from a range of sources including weathering of pit walls and seepage from groundwater and waste rock dumps. Water quality in mine water storages and residual voids can also have been influenced by operational requirements such as the transfer of water between pits or water storage during wet weather events.

Geller et al. (2013) define four major categories for Australian mine void water quality including a) acid mine drainage, saline (which can co-occur with acid mine drainage), neutral pH with metal and metalloid contamination, and good water quality (though not necessarily equivalent to natural wetlands). In Queensland, coal mines generally result in neutral to alkaline void water with high salinity and sulfate and potentially elevated concentrations of some metals. Metalliferous mining in mineralised areas also generally results in acid mine drainage with high acidity and high concentrations of soluble forms of metals and dissolved salts. There are, however, some site-specific exceptions to these generalisations. For example, the Collinsville coal mine has highly acidic mine lakes with high sulfate levels (McCullough et al., 2008). Geller et al., (2013) also suggest that void water quality at the Mary Kathleen and Thalanga mines in Queensland have relatively good water quality but are contaminated by copper and zinc, respectively. Common water quality indicators associated with coal mines include salinity, aluminium, zinc, copper, sulfate and pH (Jones et al., 2019). A review of the coal mine void water quality data in Queensland found that elevated salinity can limit the reuse of mine void water in the Fitzroy Basin for irrigation and stock watering without treatment (Clay et al., 2022). Many coal mine voids in Queensland are alkaline (Clay et al., 2022) though there are examples where voids can have high acidity and elevated metals. In contrast, most metal mines with acid forming parent rock tend to have acidic water with elevated metals and salinity (Kumar et al., 2009; Salmon, 2017).

Mineral processing and in-pit disposal of waste and tailings can also impact the quality of mine-affected water. Water quality in storages such as residual mine voids may be expected to decline over time where there is continued input of excessive contaminants from surface runoff, waste rock dumps or groundwater inputs (typically saline) and sustained evaporation (see conceptual model in Figure 3). There are a range of physical processes and chemical reactions that can influence water quality such as stratification of the water column due to temperature or chemical gradients, adsorption of dissolved metals and precipitation of salts (Lottermoser, 2003). McCullough et al. (2020) indicate that void water depth can influence the occurrence of seasonal thermal stratification and the amount of oxygen available at depth, and is therefore an important consideration for final void design.

The water quality in many residual coal mine voids across Queensland is brackish or saline (Clay et al., 2022). Although saline lakes occur naturally in dry landscapes in Queensland (Gardiner, 2005), their existence alone would not be considered sufficient to justify creating a different environment that is in stark contrast to the environments around it as a mine rehabilitation outcome. Instead, the objective is to achieve environmental values and water quality in the rehabilitation area that are consistent with or better than pre-mining conditions and the surrounding landscape. In such instances a determination of what is suitable should be made applying the Water Quality Objectives scheduled under the Environmental Protection Policy (Water and Wetland Biodiversity) 2019 (DES, 2022a). Where necessary, site-specific trigger values should be developed applying the frameworks outlined in the National and Queensland water quality guidelines.

It is also common for acid rock drainage to lead to low pH and elevated concentrations of metals in metalliferous mining areas. Changing levels of oxygen may also alter the redox potential of water, resulting in a shift in the oxidative state of compounds affecting solubility, thus influencing the toxicity of metals (Lottermoser, 2003).

Modelling is often used to assess void water balance and water quality. Both water balance and quality influence how the void will interact with the surrounding environment, what management activities may be necessary and which potential post-mining uses will be identified. An example schematic of a cross section of a coal mine void and water balance including inputs and outputs is shown in Figure 3 (reproduced here with permission).

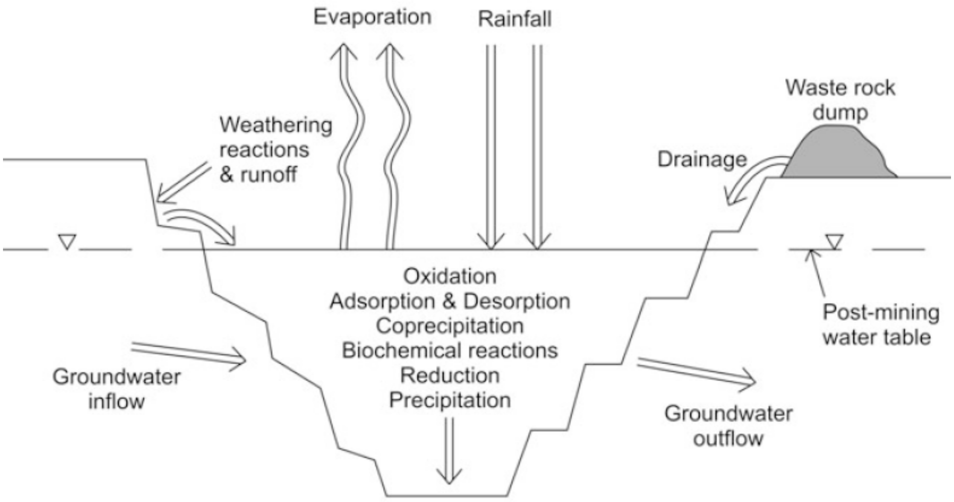

Figure 3. Simplified cross section of a mine pit showing the processes affecting water quality (Bowell, 2002)

4.4 Structural habitat

The physical structure of mine water infrastructure influences the type and availability of aquatic habitat. Blanchette and Lund (2016) state that steep, highly mobile banks and absence of fringing and riparian vegetation can create an aquatic 'desert,' starving the lake of nutrients and habitat complexity. The volume and permanency of water also affects habitat availability. It is important to understand what the long term equilibrium conditions will be for the water body such as whether it will maintain a permanent water body (Côte et al., 2023). Important structural considerations to rehabilitate mine water infrastructure to aquatic ecosystems are the establishment of littoral zones, pelagic zones and profundal zones. A littoral zone provides habitat for aquatic plants and breeding and nursery areas for fish recruitment. The littoral zone of a natural lake is the nearshore interface between the terrestrial ecosystem and the deeper pelagic zone of the lake (Côte et al., 2023). Planktonic food webs are typical in pelagic zones and microbial mats may occur in the profundal zone. Each of these structural elements provides valuable habitat needed to sustain a diverse range of taxa. The creation of large areas of open water without habitat such as islands or littoral zones may impede the movement and migration of aquatic fish species.

5 Approaches to enhance aquatic ecosystem values

Mine water infrastructure including residual voids can provide habitat and refuge for some species. In many cases these systems may not have the same level of ecological values as natural, unimpacted systems but may still provide some values. Lund and Blanchette, (2023) argue that residual mine voids will eventually develop ecosystem values and that the time required to do so depends on the level of intervention and the values ascribed by the community. There are many strategies that have been employed to improve water quality and habitat in residual mine voids. For example, a study by Lund et al., (2014) investigated the addition of nutrients and organic matter on biodiversity in residual coal mine voids. A study by Bylak et al. (2019) found that improving habitat, plant communities and littoral areas of residual mine voids appeared to improve biodiversity. That study reported improvement may occur up until a point, although poor water quality was likely to remain a constraint to the development of a healthy, functioning ecosystem. Although a water filled residual void will develop some level of aquatic ecosystem values over time, the time taken to develop into a functioning ecosystem without interventions could be multi-generational. The timeframe to achieve rehabilitation outcomes or to establish a demonstrable trajectory of improvement is an important consideration for rehabilitation.

6 Conceptual model of aquatic ecosystems

Where mine water infrastructure or a residual void is proposed to become an aquatic ecosystem or habitat, a conceptual model can be developed to help define the components of the ecosystem, key ecological and physical processes and how they interact. A conceptual model can also be used to identify and prioritise indicators for monitoring. Conceptual models also provide a way to describe any stressors acting on an ecosystem over time such as contaminant inputs or evapoconcentration that can both impact water quality. Site-specific conceptual models would most likely need to be developed to describe the characteristics of mine water infrastructure and residual voids. Conceptual models developed for aquatic ecosystems in mine water infrastructure can be used to describe issues such as:

- the shape and dimensions of the structure
- habitat zones such as littoral, profundal and pelagic zones
- surface and groundwater hydrology
- flora and fauna
- nutrient dynamics
- carbon and nutrient inputs and cycling
- contaminant inputs via surface or groundwater (e.g. catchment runoff and seepage from waste rock dumps or in-pit tailings disposal)
- contaminants (acid, metals, salts, hydrocarbons, suspended sediments, nutrients)
- evaporation and evapoconcentration
- adsorption/desorption processes associated with pH
- connection/disconnection from surrounding environment
- any treatment mechanisms to improve water quality
- fringing vegetation (riparian shading, littoral zones, deep water)
- precipitation of contaminants to form unconsolidated sediment.

7 Criteria used to describe a healthy ecosystem and indicators for monitoring

This section describes assessment criteria that can be used to assess whether mine water infrastructure or a residual mine void that is proposed to be left in place after mining could be regarded as a healthy, viable, functioning aquatic ecosystem. This can apply in both the rehabilitation planning and implementation phases. The assessment criteria and indicators described here serve both purposes. Monitoring provides a tool to assess ecosystem health (or condition) and whether it is stable over time.

There are many indicators that can potentially be used to assess water quality and ecosystems. The indicators that are used to set water quality guidelines for Queensland waters are described in DES (2022a). Ecosystem health monitoring indicators and approaches to assess ecosystem function are also described in DES (2023). Indicators relevant to aquatic ecosystems can include:

- physical and chemical indicators (e.g. pH, nutrients, suspended solids, water clarity, salinity, dissolved oxygen)
- biological indicators (e.g. in-stream biota—fish, macroinvertebrates, turtles, frogs and toads, aquatic macrophytes, phytoplankton, zooplankton, diatoms and microbes)
- ecosystem processes and function (e.g. gross primary production or daily respiration, chlorophyll a, stable isotopes C and N)
- toxicant and toxicity indicators as described in ANZG (2018)
- physical form indicators (e.g. beds, banks, in-stream habitat, refuge waterholes and ground cover)
- habitat indicators (e.g. measures of the health of the riparian zone such as width, continuity, species composition)
- hydrological indicators and environmental flows (e.g. measures of alteration to hydrology, seasonality, and groundwater interaction)

It may not be necessary to monitor all indicators listed here and instead a targeted approach could be used, whereby a refined suite of indicators is selected from each criterion to represent each of the attributes of ecosystem health. A risk-based approach should be undertaken when prioritising indicators similar to the approaches used to identify contaminants of potential concern (COPCs) in contaminant risk assessment. Other indicators not listed may be relevant where it can be demonstrated that they fit the attributes and criteria required. Adequate monitoring data collected across wet and dry periods using a suite of relevant indicators are needed to incorporate natural variability and to demonstrate the presence of a healthy ecosystem with adequate structure, function and resilience.

8 Conclusion

Mine water infrastructure and residual voids may retain water intermittently or form permanent waterbodies, remaining as persistent features in the landscape after mining. In some cases, these may be able to be rehabilitated to create aquatic ecosystems. The aim of rehabilitating mine water infrastructure is to provide aquatic habitat that has the same or better ecological integrity as comparable or local aquatic ecosystems. In general terms the objectives are to:

- demonstrate achievement of a healthy, viable, functioning ecosystem
- be representative of aquatic ecosystems found locally, either those present prior to mining or unimpacted systems found locally
- have the same or better water quality than local unimpacted aquatic ecosystems
- have stable water quality that meets water quality objectives in the long-term
- not harbour exotic pest species

Although rehabilitation to an aquatic ecosystem or habitat is a worthy goal, it is often a difficult task and can be challenging to demonstrate. Effective design, planning and management practices and ongoing monitoring is needed to rehabilitate such areas. While this may be possible in some cases, unrehabilitated mine water structures can have physical or chemical characteristics that make them unsuitable to host a healthy, functioning and resilient aquatic ecosystem. While these areas may develop some level of aquatic values over long timeframes, they are likely to differ from natural unimpacted ecosystems. Although those areas may not meet the objective of being a healthy, viable, functioning aquatic ecosystem, attempts to rehabilitate them to as great an extent as possible should still be undertaken to minimise risks associated with them and maximise ecological outcomes. Emerging research on rehabilitation options for mine voids provide promising solutions in this regard. For example, see project C29049 ‘Saline Pit Lakes as Aquatic Ecosystems: A Design Manual for Closure’ as described in the Australian Coal Association Research Program’s Annual report (ACARP, 2022).

Criteria are needed to benchmark rehabilitation success and monitor outcomes over time. It is suggested that monitoring indicators are selected to demonstrate a healthy ecosystem with adequate structure, function and resilience. Where the aim is to demonstrate successful rehabilitation, adequate monitoring data collected across wet and dry periods using a suite of relevant indicators can provide a basis for assessment.

9 References

ACARP (2022) *2022 ACARP Annual Report*. Australian Coal Association Research Program, Available at: https://www.acarp.com.au/Media/ACARP 2022 Report.pdf.

ANZG (2018) *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Canberra, ACT, Australia: Australia and New Zealand Governments (ANZG), Available at: https://www.waterquality.gov.au/anz-guidelines/guideline-values/default.

Blanchette ML and Lund MA (2016) 'Pit lakes are a global legacy of mining: an integrated approach to achieving sustainable ecosystems and value for communities', *Current Opinion in Environmental Sustainability*, 23:28–34, doi:10.1016/j.cosust.2016.11.012.

Bowell RJ (2002) 'The hydrogeochemical dynamics of mine pit lakes', *Geological Society Special Publications*, 198(1):159–185, doi:10.1144/GSL.SP.2002.198.01.11.

Bunn SE, Abal EG, Smith MJ, Choy SC, Fellows CS, Harch BD, Kennard MJ and Sheldon F (2010) 'Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation', *Freshwater Biology*, 55(SUPPL. 1):223–240, doi:10.1111/j.1365-2427.2009.02375.x.

Bylak A, Rak W, Wójcik M, Kukuła E and Kukuła K (2019) 'Analysis of Macrobenthic Communities in a Post-Mining Sulphur Pit Lake (Poland)', *Mine Water and the Environment*, 38(3):536–550, doi:10.1007/s10230-019-00624-2.

Clay M, Dunlop J and Gagen E (2022) *Review of open-cut coal mine void rehabilitation planning practices in Queensland*.

Côte CM, Holloway E, Dunlop J and Chrystal R (2023) 'Leading practice approaches to select post-mining land uses for residual mine voids', Available at: https://www.qmrc.qld.gov.au/__data/assets/pdf_file/0030/315849/leading-practice-approaches-select-pmlu-residual-mine-voids.pdf.

CRC TiME (2023) *Beginning with the end in mind : Submission – Australia ' s Critical Minerals Industry Discussion Paper*. Perth, Australia, Available at: https://crctime.com.au/macwp/wp-content/uploads/2023/02/Beginning-with-the-end-in-mind-CRC-TiME-Submission-Feb-23-3.pdf.

de Lange WJ, Genthe B, Hill L and Oberholster PJ (2018) 'Towards a rapid assessment protocol for identifying pit lakes worthy of restoration', *Journal of Environmental Management*, 206:949–961, doi:10.1016/j.jenvman.2017.11.084.

DES (2021) *Guideline - Progressive rehabilitation and closure plans (PRC plans)*. Department of Environment and Science, Queensland Government.

DES (2022a) *Guideline: Environmental Protection (Water and Wetland Biodiversity) Policy 2019 Deciding aquatic ecosystem indicators and local water quality guideline values*. Queensland Department of Environment and Science, Available at: https://environment.des.qld.gov.au/__data/assets/pdf_file/0029/88148/deriving-local-water-quality-guidelines.pdf.

DES (2022b) *Queensland river rehabilitation management guideline*. Version 1. Brisbane, Qld.: Department of Environment and Science (DES), Queensland Government.

DES (2023) *Ecosystem health indicators*, *Department of Environment and Science*, Available at: https://environment.des.qld.gov.au/management/water/health-indicators (Accessed: 21 November 2023).

Dodds WK (2002) *Freshwater Ecology: Concepts and Environmental Applications*. Elsevier Science and Technology, Available at: http://ebookcentral.proquest.com/lib/uql/detail.action?docID=294137.

Dunlop J and McGregor G (2007) *Setting water quality guidelines for salinity and sediment in freshwater streams in Queensland: An applied approach within a natural resource management context*. Queensland Department of Natural Resources and Water.

Gardiner S (2005) *Wetland Management Profile Arid and Semi-Arid Lakes*. Queensland Government.

Geller W, Schultze M, Kleinmann R and Wolkersdorfer C (2013) *Acidic Pit Lakes: The Legacy of Coal and Metal Surface Mines*, *Environmental Science and Engineering*, doi:10.1007/978-3-642-29384-9.

Haines-Young R and Potschin M (2018) *Common International Classification of Ecosystem Services (CICES) V5.1 d Guidance on the Application of the Revised Structure*, Available at:

https://cices.eu/content/uploads/sites/8/2018/01/Guidance-V51-01012018.pdf (Accessed: 16 May 2023).

Healthy Land and Water (2023) *Report Card: Methods Manual*. Brisbane, Australia, Available at: https://reportcard.hlw.org.au/public/assets/pdfs/2023-Report-Card-Methods-Manual.pdf.

Hendry MJ, Wassenaar LI, Barbour SL, Schabert MS, Birkham TK, Fedec T and Schmeling EE (2018) 'Assessing the fate of explosives derived nitrate in mine waste rock dumps using the stable isotopes of oxygen and nitrogen', *Science of the Total Environment*, 640–641:127–137, doi:10.1016/j.scitotenv.2018.05.275.

Jones CE, Vicente-Beckett V and Chapman J (2019) 'Coal mine-affected water releases, turbidity and metal concentrations in the Fitzroy River Basin, Queensland, Australia', *Environmental Earth Sciences*, 78(24):1–16, doi:10.1007/s12665-019-8734-x.

Kumar RN, McCullough CD and Lund MA (2009) 'Water resources in australian mine pit lakes', *Mining Technology*, 118(3–4):205–211, doi:10.1179/174328610X12682159815028.

Loreau M, Naeem S, Inchausti P, Bengtsson J, Grime JP, Hector A, Hooper DU, Huston MA, Raffaelli D, Schmid B, Tilman D and Wardle DA (2001) 'Ecology: Biodiversity and ecosystem functioning: Current knowledge and future challenges', *Science*, 294(5543):804–808, doi:10.1126/science.1064088.

Lottermoser B (2003) 'Mine Water', in Lottermoser, B. (ed.) *Mine Wastes*. Berlin, Heidelberg: Springer Berlin Heidelberg, 83–141, doi:10.1007/978-3-662-05133-7_3.

Lund M and Blanchette ML (2021) *Towards closure of potentially saline pit lakes: understanding biophysical processes for condition assessment and remediation options*. C27043. Australian Coal Association Research Program, Available at: https://www.acarp.com.au/abstracts.aspx?repId=C27043.

Lund M, van Etten E, Polifka J, Vasquez MQ, Ramessur R, Yangzom D and Blanchette ML (2020) 'The Importance of Catchments to Mine-pit Lakes: Implications for Closure', *Mine Water and the Environment*, 39(3):572–588, doi:10.1007/s10230-020-00704-8.

Lund MA and Blanchette ML (2023) 'Closing pit lakes as aquatic ecosystems: Risk, reality, and future uses', *Wiley Interdisciplinary Reviews: Water*, 10(4):1–18, doi:10.1002/wat2.1648.

Lund MA, Blanchette ML and McCullough CD (2014) *Enhancing ecological values of coal pit lakes with simple nutrient additions and bankside vegetation*. ACARP project C21038. Australian Coal Association Research Program (ACARP).

Mahmood FN, Barbour SL, Kennedy C and Hendry MJ (2017) 'Nitrate release from waste rock dumps in the Elk Valley, British Columbia, Canada', *Science of the Total Environment*, 605–606:915–928, doi:10.1016/j.scitotenv.2017.05.253.

McCullough C, Hunt D and Evans L (2009) 'Sustainable Development of Open Pit Mines: Creating Beneficial End Uses for Pit Lake, Chapter 22 in Mine Pit Lakes - Characteristics, Predictive Modeling, and Sustainability, Volume 3 - Management Technologies for Metal Mining Influenced Water', in Castendyk, D.N. and Eary, L.E. (eds). Society for Mining, Metallurgy, and Exploration (SME), Available at: https://app.knovel.com/hotlink/pdf/id:kt008KQVC7/mine-pit-lakes-characteristics/sustainable-conclusions.

McCullough C, Lund M and May J (2008) *Treating Acidity in Coal Pit Lakes Using Sewage and Green Waste: Microcosm and Field Scale Trials at Collinsville Coal Project (Queensland)*. ACARP C14052. Australian Coal Association Research Program, Available at: https://www.acarp.com.au/abstracts.aspx?repId=C14052.

McCullough CD and Lund MA (2006) 'Opportunities for sustainable mining Pit lakes in Australia', *Mine Water and the Environment*, 25(4):220–226, doi:10.1007/s10230-006-0136-0.

McCullough CD, Schultze M and Vandenberg J (2020) 'Realizing beneficial end uses from abandoned pit lakes', *Minerals*, 10(2):133, doi:10.3390/min10020133.

Measham T, Walker J, Haslam McKenzie F, Kirby J, Williams C, D'Urso J, Littleboy A, Samper A, Rey R, Maybee B, Brereton D and Boggs G (2024) 'Beyond closure: A literature review and research agenda for post-mining transitions', *Resources Policy*, 90(October 2023):104859, doi:10.1016/j.resourpol.2024.104859.

O'Hare MT, Aguiar FC, Asaeda T, Bakker ES, Chambers PA, Clayton JS, Elger A, Ferreira TM, Gross

EM, Gunn IDM, Gurnell AM, Hellsten S, Hofstra DE, Li W, Mohr S, Puijalon S, Szoszkiewicz K, Willby NJ and Wood KA (2018) ‘Plants in aquatic ecosystems: current trends and future directions’, *Hydrobiologia*, 812(1):1–11, doi:10.1007/s10750-017-3190-7.

Salmon D (2017) *Guidelines for coal mine open pit final void closure and relinquishment: addressing uncertainty in coal mine environmental planning*. ACARP Project C25030. Australian Coal Association Research Program (ACARP).

Seelen LMS, Teurlincx S, Bruinsma J, Huijsmans TMF, van Donk E, Lürling M and de Senerpont Domis LN (2021) ‘The value of novel ecosystems: Disclosing the ecological quality of quarry lakes’, *Science of the Total Environment*, 769, doi:10.1016/j.scitotenv.2020.144294.

Smith M, Harch G, Bunn S, Clapcott J, Storey A and Dwyer C (2001) *'Ecosystem Health Monitoring Program for SEQ’ in Design and Implementation of Baseline Monitoring (DIBM3) final report*.

Spain CS, Nuske SJ, Gagen EJ and Purtill J (2023) *Evaluating Native Ecosystem Rehabilitation Options in Queensland*, Available at: https://www.qmrc.qld.gov.au/__data/assets/pdf_file/0021/303438/evaluating-native-ecosystem-rehabilitation-options-in-qld.pdf.

Tomlin J, Phillipson K, Lenahan M, Durick A, Manewell N, Newton D, Briody M and Dunlop J (2023) *Review of current approaches to model residual mine voids for rehabilitation planning: Technical paper 1*. Brisbane: Office of the Queensland Mine Rehabilitation Commissioner, Queensland Government.

Vandenberg J, Schultze M, McCullough CD and Castendyk D (2022) ‘The Future Direction of Pit Lakes: Part 2, Corporate and Regulatory Closure Needs to Improve Management’, *Mine Water and the Environment*, 41(2):544–556, doi:10.1007/s10230-022-00868-5.

WQA (2023) *Water Quality Australia*, *Department of Agriculture Water and the Environment*, Available at: https://www.waterquality.gov.au/issues/blue-green-algae (Accessed: 17 May 2023).

Young RE, Gann GD, Walder B, Liu J, Cui W, Newton V, Nelson CR, Tashe N, Jasper D, Silveira FAO, Carrick PJ, Hägglund T, Carlsén S and Dixon K (2022) ‘International principles and standards for the ecological restoration and recovery of mine sites’, *Restoration Ecology*, 30(S2), doi:10.1111/rec.13771.