Office of the **Queensland Mine Rehabilitation Commissioner**

Leading practice approaches to select post-mining land uses for residual mine voids

Technical paper

Queensland Government

Prepared by: The Centre for Water in the Minerals Industry, Sustainable Minerals Institute, the University of Queensland on behalf of Office of the Queensland Mine Rehabilitation Commissioner

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Executive Summary

The *Environmental Protection Act 1994* (Qld) (EP Act) requires that approval holders for mining activities (both new and existing) describe a plan to progressively rehabilitate land disturbed during mining to a ‘stable condition’. This means that the land is to be made safe and structurally stable, so that it does not cause environmental harm and that the land can sustain a post-mining land use (PMLU). Historically, open cut mining practices have left open pits in place at the end of mining. In some instances, mine voids could be backfilled to create an area of land suitable for a PMLU such as grazing or natural ecosystems. When this is not possible, voids are left in place and typically become filled with water. Water filled voids can potentially be used for a range of post mining uses such as providing water for irrigation of crops or for stock drinking water, supporting the production of pumped storage hydropower, aquaculture or recreational areas.

In practice, mine voids are usually left open and hold water with limited use without treatment. While there are some examples across Australia and internationally where mine voids have been repurposed, in many instances mine voids have limited practical uses and many are likely to remain in perpetuity. Where a mine void cannot be rehabilitated to a stable condition, they may be legally allowed to remain in place without a use and be managed as a non-use management area (NUMA) under some circumstances. The vast majority of residual voids for existing mines are likely to be managed as NUMAs. However, for both new and some existing mines, where a NUMA has not previously been approved, it is important to properly determine whether a suitable PMLU can be achieved for a residual void or not.

This technical paper describes leading practice approaches to identify, assess and compare the feasibility of implementing options for PMLUs of voids. The methodology described here is to assess the viability and suitability of PMLUs for voids through the development and testing of strategic mine planning scenarios. The information is then combined into a multi-criteria analysis that allows mine planning scenarios, as well as the consideration of associated risks and potential benefits, to be weighed up through the lens of multiple stakeholder perspectives. There can be several PMLU options for a void and they must be assessed and compared in a consistent and reliable way. Such a process requires the analysis of multiple mine planning scenarios, as well as the consideration of associated risks and potential benefits to stakeholders.

Evaluating and comparing opportunities and constraints for post-mining uses for voids is linked to the mine planning process as this can influence where a residual void will be left and what form it will take. Early planning to achieve a PMLU is likely to increase the number of possible post-mining uses available. Undertaking assessment and planning in an iterative way is likely to ensure that opportunities for rehabilitation of mine voids are realised where possible and that rehabilitation planning decisions made regarding void management are robust. Plans can also be used to assess the feasibility of backfilling or leaving a void open. This technical paper proposes an integrated planning platform to assess the viability of filling the void with material or water, by analysing three specific strategic mine planning scenarios:

1. Maximise operational value, without specifying a preferred final land use for the void.
2. Deliver a material-filled void, which can support a range of land uses.
3. Deliver a water-filled void, which is non-polluting and can support a range of water uses.

The technical paper describes the architecture and elements of the integrated planning platform. One of its core objectives is to provide a wider range of financial results that can support a nuanced analysis of risks, benefits and values. As such, it considers the impact of variations in corporate assumptions, such as discount rate or commodity price outlooks, captured in scenario parameters. It also proposes a decision-making process that includes a qualitative valuation method for PMLU options and a multi-criteria analysis to compile the outputs from scenario analysis and PMLU valuation and present them in terms of several stakeholders’ perspective.

The approach can be applied to any stage of mining: pre-approval, operational, and prior to closure. The number of options and availability of data and information may vary along this timeframe and may lead to a re-consideration of PMLUs. In general, the earlier the PMLU options are included into the planning processes, the greater the potential for a positive overall outcome, and the lower the cost and risk of implementation.

The approach will be iterative, but the number of iterations will depend on the scenario and on the number of PMLUs that are identified. The scenario that considers a water-filled void is the most

complex and will require detailed understanding of all connections between void design and water assessments, with inputs from multiple teams.

For both new and existing mines, where a NUMA has not previously been approved, leading practice approaches support the identification and comparison of a range of PMLU options for voids. Such an assessment should determine:

- whether it is feasible to backfill the void or not, or
- if the void is not backfilled, whether it will hold a permanent water body.

Where voids are not backfilled, there is a need to assess the value of the PMLU and interaction with surface and groundwater. Water levels and water quality need to be quantified to assess whether the water quality can support a beneficial use into the future and whether there are risks of export of contaminants to the receiving environment (surface water and groundwater).

Void PMLU options are rarely incorporated into strategic mine planning. We propose that leading practice strategic mine planning includes consideration of final void PMLU options to explore the costs and benefits associated with PMLU scenarios. Costs should be assessed using a robust assessment that goes beyond Net Present Value to incorporate future risks, benefits and values.

1 Introduction

The *Environmental Protection Act 1994* (Qld) (EP Act) requires that approval holders for mining activities (both new and existing) describe a plan to progressively rehabilitate land disturbed during mining to a ‘stable condition’. This means that the land is to be made safe and structurally stable, so that it does not cause environmental harm and that the land can sustain a post-mining land use (PMLU). Historically, open cut mining practices have left open pits in place at the end of mining.

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 (Salmon, 2017). Coal is mined in relatively shallow strips, with extraction progressing forward and the waste material being pushed behind the advancing mine front, filling in the void that has been created. At the point where extraction ends, there is no waste left to backfill and this leaves a void. In this guidance document, the term “residual void” refers to the space left after open cut mining has been completed and it applies to coal, hard rock and metal mines.

In some instances, mine voids could be backfilled to create an area of land suitable for a PMLU such as grazing or natural ecosystems. This can help to minimise or avoid closure risks, but it is recognised that backfilling a void may not always be possible or practical to achieve. Voids left in place (i.e. not backfilled) after mining typically become filled with water. In some instances, these areas could potentially sustain some post-mining uses such as providing water for irrigation of crops or for stock drinking water, supporting the production of pumped storage hydropower, aquaculture or recreational areas. Such uses would need to meet any statutory and planning requirements, align with stakeholder expectations and be able to be properly managed into the long term.

Under the EP Act, a mining operation requires an Environmental Authority (EA) which lists conditions regulating impacts such as disturbances to land, soil, water, air, biodiversity, cultural heritage and any other relevant matters. The EAs typically list the currently prescribed PMLU for each type of disturbed area. A recent study commissioned by the Queensland Resources Council (Worden et al, 2021) derived a comprehensive understanding of the status of PMLUs as listed in EAs. The methodology involved searching for the keywords that describe the PMLUs in the EA documents available on the public register maintained by the Department of Environment and Science. This yielded the committed PMLUs from 121 documents and established that there was little diversity. The predominant PMLUs are grazing and native ecosystems (or equivalent wording) with few examples of other potential PMLUs.

A 2021 report prepared by Coffey Services Pty Ltd for the Office of Water Science on behalf of the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) compiled a database of current open-cut coal mine voids in Queensland (Coffey Services Australia Pty Ltd, 2021). Clay et al. (2022) conducted a review of this data to extract the PMLUs specific to void areas and found that the most common was “water storage” (16.5%), followed by “water body/native bushland” (8.2%), “native ecosystem, semi-evergreen vine thicket, hardwood plantation, agriculture” (7.1%) and “accessed by wildlife, used for a water supply or recreational facility” (4.7%).

Both reviews indicate a lack of diversity of PMLUs in Queensland generally, but also the lack of adequate land use planning, which leads to generic land use selection. There is ample scope to expand the potential for other options, including for voids. Regulatory reforms for mine rehabilitation were introduced in Queensland as part of the *Mineral and Energy Resources (Financial Provisioning) Act 2018*. These reforms aimed to strengthen progressive rehabilitation planning and are likely to improve the definition of PMLUs that are prescribed for areas disturbed by mining in the future.

Where a mine void cannot be rehabilitated to a stable condition, the current legislation provides an allowance for these areas to be managed as a non-use management area (NUMA) under some circumstances. However, proposals for a NUMA in a Progressive Rehabilitation and Closure (PRC) plan can only be nominated after all PMLU options have been properly considered and when it is in the public interest for the land not to be rehabilitated to a stable condition. As the reforms are not retrospective, a large proportion of mine voids have historically been approved to remain without a specified use in perpetuity (i.e. where a NUMA is recognised). However, for all PRC plans including those for new and existing mines, where a NUMA has not previously been approved, it is important to properly determine whether a suitable PMLU can be achieved for a residual void or not. At present there is a lack of information and guidance on how to assess and compare PMLU options for a void. Where such assessments are not undertaken in a consistent and reliable way, it may result in unsuitable PMLUs, or proposals for a NUMA that are not necessarily warranted.

The intention of this technical paper is to promote improved practices to support decisions about the rehabilitation and closure of residual mine voids. It proposes a methodology to assess the viability and suitability of post-mining land uses for voids, based on the evaluation of strategic mine planning scenarios and a process for comparing options. There is an emphasis on ensuring the perspectives of multiple stakeholders are included in the consideration of post-mining futures. This requires that a wider range of metrics are produced, along with an assessment of potential value generation.

1.1 Objectives

The aim of this technical paper is to describe leading practice approaches to:

- properly identify, assess and compare the feasibility of implementing PMLU options for voids, including the assessment of the feasibility of a range of possible outcomes; and
- compare options for beneficial use of residual voids.

Such guidance is needed to ensure that rehabilitation opportunities for mine voids are realised where possible and that rehabilitation planning decisions made regarding void management are robust.

The technical paper is concerned with the assessment and comparison of PMLU options for voids that are undertaken prior to, and separate from, a public interest evaluation. Approaches presented here can be applied to decision-making at all stages of mine life, including proposals for new mines, those currently in operation and those approaching closure. This guidance doesn’t apply to voids that are approved as a NUMA.

1.2 Methodology

The technical paper builds from the current knowledge baseline related to the rehabilitation of residual voids, which was compiled by reviewing existing guidance documents and recent research reports and gathering evidence from case studies. The intent was not to produce a comprehensive literature review on the topic of rehabilitation and closure of final voids, as this is included in other documents. Rather, the paper explains how existing tools and knowledge can be adapted to the assessment of potential PMLUs for voids. In some instances, additional investigations will be required, depending on the stage of mining and the PMLU that is being considered. The stage of mining influences the decision-making process in the following ways:

- If the PMLU is to be selected close to closure (i.e., where closure is imminent), it is unlikely that there will be sufficient time to initiate studies that require data collection, interpretation and support complex investigations. The decisions regarding PMLU will need to rely on the current status of knowledge, as described in this technical paper. As a mine approaches closure, the number of viable options for a void’s PMLU will be small and the possible outcomes may be less than ideal.
- If the PMLU selection occurs prior to commencement as part of a pre-approval phase, it is likely that there will be sufficient time to undertake a comprehensive program of work to support decisions on identifying and testing PMLUs. This means that the number of options for a void’s PMLU will be higher and there will be time to undertake investigations to support analysis of the feasibility of the PMLU options.
- If the PMLU is to be selected as part of closure planning during the operational phase, the selection process will be in between the two situations presented above: there will be a range of suitable options, some of which will require investigations, which may or may not be undertaken, depending on the timing of the decision within the mining lifecycle. A process of continuous improvement and adjustment may take place during the operational phase.

1.3 Contents

To achieve effective evaluation of PMLU options, the planning processes will require an integrated and iterative approach that is conducive to achieving collaboration between all relevant technical disciplines. Such a process will require the analysis of multiple scenarios, as well as the consideration of associated risks and potential benefits through the lens of multiple stakeholders. Selecting a PMLU for a void requires consideration of several inter-connected aspects:

- Whether the void can be backfilled or not, and if not, whether it will hold a permanent water body
- If the void is predicted to hold a permanent water body, water levels and water quality need to be quantified to assess whether there are risks of export of contaminants to the receiving environment (surface water and groundwater)
- Whether the predicted water quality is such that it can support a beneficial use
- How social and economic considerations and stakeholder and community expectations are included in the various assessments.

Based on this, the paper includes:

- Strategic mine planning considerations that can influence the potential opportunities and constraints for post-mining uses for voids, including consideration of water-filled and backfilled options
- A methodology that captures the inter-connected aspects that will determine the viability of a PMLU for a void: pit optimisation, mine scheduling, landform and void design, waste characterisation, water balance and water quality
- Description of the technical assessments that are required for each individual aspect, most notably water balance and water quality
- Information about potential land uses and the requirements of specific land uses, such as aquatic ecosystems
- Requirement to determine the value generated by a void's PMLU that is not restricted to standard financial metrics, such as Net Present Value (NPV). NPV has the net effect of delivering a positive outlook for activities that generate high rates of cash over short durations (e.g. mining) compared to activities that generate lower rates of cash but over much longer durations (e.g. agriculture). The analysis of PMLU options for voids cannot be limited to standard NPV calculations: it requires a more robust consideration of future risks, benefits and values; and
- Suggestions for decision-making methods such as a multi-criteria analysis that can be used to compare options and identify whether suitable PMLUs for mine voids can be identified.

The paper has been structured to address these points, in each of the following sections.

2 Influence of mine planning on PMLU selection

Broadly speaking, mine planning is the process of optimising the exploitation of mineral reserves for maximum value, aligned with the strategic goals and objectives of the business enterprise. It constitutes a complex set of activities, which aim to identify the best possible mine design and scheduling of production considering capital investments, operational cost, revenue forecasting and management of cash flows.

Mine design and sequencing are based on a model of the mineral deposit, which is discretised into blocks. Each block consists of a volume of material with its corresponding properties and its value, determined by comparing market prices with extraction and processing costs. Geometrical and geotechnical constraints ensure that the extraction will be carried out in a way that is physically possible.

Traditionally, mine planning is divided in stages according to the required level of detail and the time frame for analysis. A standard distinction is made between:

- Strategic mine planning: the continuous revisions of long and medium term plans, which will determine the future of the operation.
- Tactical mine planning: routine activities, preparation of budgets, equipment deployment and production scheduling on a monthly, weekly and daily basis, as well as grade and quality control.

Whilst strategic mine planning aims at defining the future of an operation and has a bearing on the successful delivery of any PMLU, traditionally, it has not included considerations of PMLU. This is a major oversight and if omitted, means that the outputs from the strategic planning process do not generally provide information that could support assessment of PMLU options.

Given that mine planning is what is used to support decisions about mine design, it can become an important tool to evaluate opportunities and constraints for post-mining uses for voids. It can influence where a residual void will be located and how big it will be, and it can assess the feasibility of different outcomes such as backfilling a void or leaving it open.

Mine planning is complex and influenced by a range of factors such as mining technique, equipment used to mine the resource, handling of waste and overburden. The following sections describe how it can influence final land use and associated rehabilitation activities, and how it has the potential to be undertaken in a way that better incorporates consideration of PMLU options.

2.1 Strategic mine planning

In general, the earlier the PMLU options are included into the planning processes, the greater the potential for a positive overall outcome, and the lower the cost and risk of implementation. Figure 1 provides a visual representation of this.

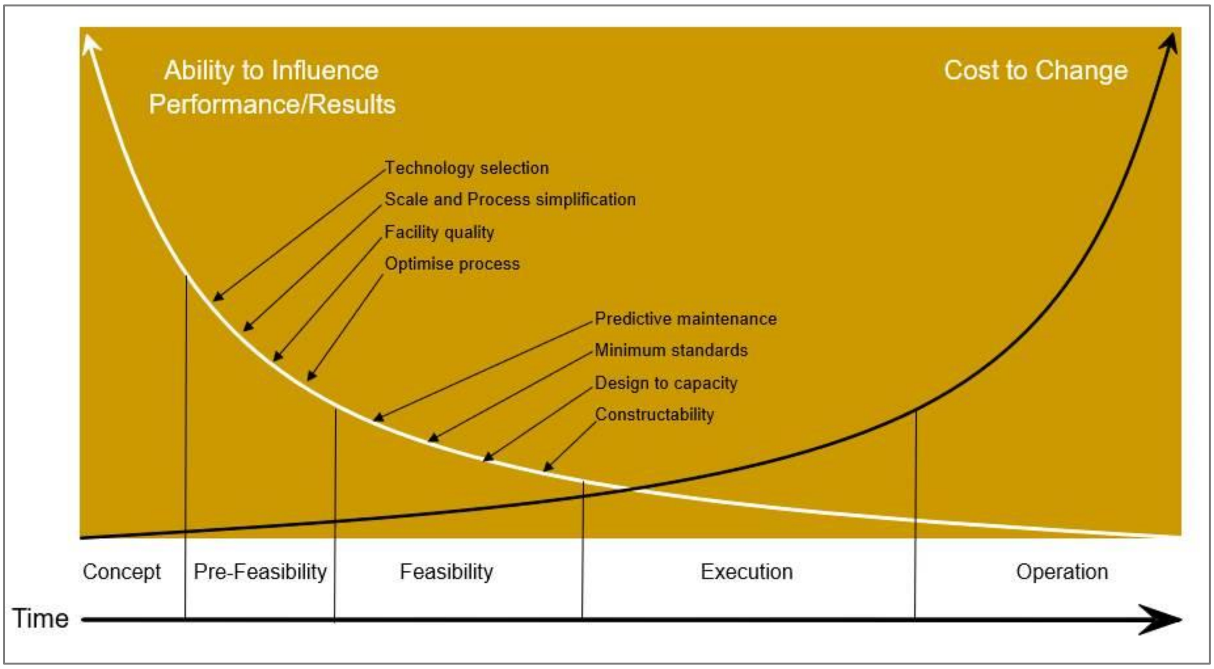

Figure 1. Cost to change at each project stage

The selection of appropriate and viable PMLUs for a residual void will be dictated by whether it will be filled with material (backfilled) or filled with water (not backfilled and maintaining a permanent water body). This means that the strategic mine planning process must be adapted to the assessment of the potential viability of backfilling a residual void. Whilst the intent is not to restrict the applicability of this guidance document, the focus is on voids resulting from open-cut coal mining activities, because in metal mines, there will be much fewer opportunities to backfill a pit. The sections below outline the items that can influence the feasibility of a PMLU because they can impact on:

- the final geometry and stability of a residual void
- the feasibility of backfilling a residual void
- the associated rehabilitation and closure plans.

2.1.1 Ultimate pit selection

A major step in open-pit mine planning is to define the final footprint and location of the mine, often called ultimate pit. There is usually more than one option as most deposits can support a range of pit sizes that are technically feasible and economically profitable. The size and geometry of the ultimate pit can impact on capital requirement, scale and duration of operation, equipment size, profitability and resource utilisation.

The ultimate pit selection will have a significant impact on both the size and location of the disturbed areas at the time of mine closure. The larger the pit, the greater the resource extraction, potential for value generation, quantity of waste generated, and the larger the disturbance area. In this context the “value” being considered is largely financial, with the associated benefits being to the company operating the mine, its employees, and to communities in terms of royalties and taxes. As the pit size increases the potential for “value” increases, along with some risks, e.g.:

- Environmental impacts (greater disturbed area with more waste to store and manage) and associated liabilities
- Exposure to adverse movement in commodity prices.

The selection of the ultimate pit will generally be based on a pit optimisation process. There are standard pit optimisation models: the Lerchs-Grossman (LG) and Pseudoflow algorithms are commonly used and are accepted as industry standards. The algorithms rely on the definition of an objective function, which is the mathematical formulation of the objectives of the pit optimisation process under a set of constraints that can be related to geology, resource knowledge or production targets. The algorithms seek to minimise or maximise the value of the objective function, depending on its definition. In most cases, it seeks to optimise the final pit by maximising the value of Net Present Value (NPV). Pit optimisation models continuously evolve, and we can expect new approaches to be developed by software providers.

The models generate arrays of incremental shells and for each shell, calculate the revenue factor (ratio of incremental cost to incremental revenue). When the value of the revenue factor is 1, the cost is equal to the revenue, meaning that for this incremental shell, there is no profit. Coal mines, more so than metal mines, will often select the ultimate pit as the incremental shell that yields a revenue factor of 1 (this is commonly referred to as RF 1.0 shell). If the coal (or ore) will be accessed during the same period as the waste that must be removed to gain access to the resource, then such a selection is appropriate. However, the greater the time-based disconnect between access to the resource and waste removal, the less appropriate the selection of the RF 1.0 shell as ultimate pit selection.

Regardless of the commodity being mined, the pit optimisation process will focus mining activities to the highest margin material earlier and delay extraction of lower margin material. This is a simple function of the revenue factor analysis. It results in the lowest margin material being mined at the end of the mine life. From the perspective of value generation, this makes sense as it delivers greater profits earlier in the mine life to pay back the capital invested in establishing the operation. This does also mean that the later years of the operation are more exposed to any adverse movements in commodity price and/or operating costs.

Pit optimisation processes provide useful inputs to the overall planning process, but have well-identified shortcomings:

- Limited functionality to incorporate time-based adjustments (including discount rates)
- Limited functionality to incorporate blending
- Limited functionality to incorporate and quantify risks
- A lack of consensus regarding the appropriate revenue factor to use as the basis for the selection of the ultimate pit.

Such risks must be considered in the context of the additional expenses required to successfully close an operation and to establish any PMLU option that the operating mine has committed to. This combination of risks is rarely quantified yet should be considered as being of critical importance to the successful closure of any mine and the management of liabilities, as well as the associated impacts on the successful delivery of the planned PMLU option.

2.1.2 Staging pits

Staging pits refer to the interim stages before the ultimate pit is completed. They can be fully designed pits with ramps and infrastructure but have not yet reached the final pit shell.

The selection of staging pits will impact on options, particularly when closure occurs earlier than planned, for a range of reasons such as lack of community acceptance or adverse movements in commodity prices. If, for example, very large staging pits are selected, then each pit represents a commitment to mine that entire pit and/or rehabilitate the same.

Staging pits also directly impact waste placement, particularly for strip mining operations that are placing waste in the previous strip. This interrelates with equipment selection.

2.1.3 Equipment selection

Equipment selection will impact upon the geometry of the residual void, the flexibility of the operation to implement specific design requirements that will be conducive to supporting PMLU options, and the associated cost profiles. For example, a dragline will typically deliver a significantly lower operating cost profile but will have limited flexibility in the resulting structure and shape of spoil piles. Truck and shovel fleets, by contrast, will typically be significantly more flexible, albeit with a higher operating cost. Backfilling of residual voids would likely require the use of truck and shovel fleets to provide operational and design flexibility. Nevertheless, if established early enough in the mine planning process, it may well be possible to incorporate draglines in the void backfilling process, as they can be more efficient if still in good condition towards the end of the mine life.

Additionally, mining equipment selection does not need to be a static decision and may change through the mine lifecycle to support better outcomes. Larger equipment will generally provide a lower operating cost base, at the expense of selectivity and flexibility, and will have a higher capital cost. Equipment lifecycle replacements can potentially be tailored to suit the implementation of PMLU towards the end of the mine life.

2.1.4 Waste destinations

The selection of the waste location(s) made during the operational phase will impact significantly on the costs associated with potential backfilling of the residual void. If the waste location is a significant distance from the void, the cost to fill the void will be significantly higher. This highlights that a decision to backfill a residual void must be made as early as possible in the planning process as it will yield a greater likelihood of delivering this outcome in a cost-effective manner.

2.1.5 Waste characterisation

Waste characterisation in both interim and final designs is of critical importance. If the operation has a range of classifications of waste type, they will need to be accounted for when assessing the backfilling of the residual void. Reactive or problematic waste types may be preferred as the material used to fill the void. If such material is stored sub-aqueously (i.e., below the post closure water level), it limits (or eliminates) any potential oxidation. Clearly any potential impacts on surface water and groundwater quality would need to be considered. This will be discussed in more detail in the next sections.

If the approach is to stockpile reactive waste, then the planning process must capture this adequately, along with the associated costs of doing so.

2.1.6 Waste dump designs

Waste often represents the bulk of material movement. In the context of selecting a PMLU for a residual void, a critical comparison will be between scenarios where waste dumps are created and reshaped to final landforms and scenarios where waste is used for backfilling the void.

Geotechnical stability will be required to deliver dumps that are safe and stable, and this will be captured by the selection of suitable geotechnical parameters.

Consideration must also be given to interim and final waste dump designs and their impact on the environment, including surface water, groundwater, visual impacts, and transitionary land use. This forms part of standard closure planning.

2.1.7 Tailings storage facilities

Tailings storage facilities, whilst not directly related to residual void, may form a potential source of fill, particularly in operations that plan to process large quantities of low-grade or stockpiled material after the mine excavation has ceased. Staging of pits may also impact the location of tailings storage facilities, particularly if tailings can be used to fill an adjacent pit.

2.1.8 Rehabilitation designs and progressive rehabilitation

For scenarios where waste dumps are created and reshaped to final landforms, their progressive rehabilitation must be valued during ultimate pit selection process.

For scenarios where waste is used to backfill a void, some waste dumps will not be progressively rehabilitated because the waste is being stockpiled until it can be used for backfill. There will be requirements to minimise environmental impacts from dumps that are not progressively rehabilitated, particularly from sediment export. Techniques like hydro-seeding can be used and their cost must be captured in the planning process.

2.1.9 Seams or depth of mining

The designed depth of mining determined during the mine planning phase will impact the extent and shape of the residual void. In the context of an open-pit coal operation, if multiple seams are present, the selection of the lowest seam for extraction is a clear example of where this would be relevant.

If the lowest seam is of lower value, it may be the case that if a PMLU option is being considered that would require the backfilling of a residual void, then it may make sense from a standard financial perspective to leave this in the ground and minimise the effort, cost and risks associated with backfilling the void. In simpler terms, there could be opportunities to decide not to mine the lowest seam as the value it would generate would be less than the cost of re-establishing a PMLU. Mine planning teams must be able to demonstrate that they have analysed this type of option.

2.1.10 Water management

Other considerations in the context of the mine design (including orientation and final structure placement) include water course locations, flood risk management and relationships with the receiving environment. Residual voids located in flood plains present specific risk profiles and PMLU option evaluation for these must be undertaken as early in the planning process as possible. For the scenarios where the void is not backfilled, it will be critical to evaluate whether the void will hold a permanent water body and whether the water held in the void will pose risks to the receiving environment. It will also be useful to determine whether the predicted water quality is such that it can support a beneficial use. Sections 4 to 7 cover water-related aspects in more detail.

2.1.11 Closure liabilities

From a regulatory perspective, there exists the potential for the closure liability to be greater for backfilling options if the final landform and closure milestones are not achieved and the void is not backfilled as planned at the end of mining. With backfilled options, the residual void cannot be filled until mining activities are completed. The liability can reasonably be expected to be the greatest at the point where active mining of the commodity generating cashflow stops. There will also be risks associated with unvegetated waste piles with potential water, dust and visual amenity impacts. Compared to a closure plan that incorporates a progressive rehabilitation program, the profile of the expected closure liabilities can be expected to differ significantly.

This does not imply that this cannot be managed, however managing such liability risks is essential and must form a core component of the framework that is used to assess the preferred options for closure.

2.2 Applying strategic mine planning to define void PMLUs

This overview demonstrates that there are several elements of the strategic mine planning process that can influence the identification of potential opportunities and constraints for post mining land uses for voids. Whilst strategic mine planning aims to define the future of an operation, traditionally, it has not included such PMLU considerations. This guidance document proposes an application of strategic mine planning that captures the inter-connected aspects that will identify these opportunities and constraints, including:

- simplified designs that capture, in the best way possible, the impact of relevant decisions regarding equipment selection, waste disposal options, rehabilitation and void designs;
- pit optimisation and mine scheduling; and
- water-related considerations.

The overview also indicates that the financial information produced by standard planning processes do not provide an adequate consideration of future risks, benefits and values arising from PMLU options. Strategic mine planning should aim to provide a wider range of financial results that can support a more nuanced analysis of risks, benefits and values.

It is recognised that consideration of PMLU options will need to be undertaken in an iterative way throughout the life of mine. As more information becomes available, there may be a need to amend the mine plan and potentially the PMLUs. However, once a PRC plan and associated rehabilitation schedule have been approved, the PMLUs are effectively “locked in”. A formal amendment would be required to make changes to the PRC plan and schedule.

The next section describes a method to incorporate PMLU scenarios for voids into strategic mine planning.

3 Integrated planning platform

Selecting a PMLU for a residual void as part of the PRC planning process requires consideration of:

- Whether it is feasible to fill the void with material at the conclusion of mining activities (“material-filled void” or “backfilled void”), and if not, whether the void will hold a permanent water body (“water-filled void”)
- If the void is predicted to hold a permanent water body, water levels and water quality need to be quantified to assess whether there are risks of export of contaminants to the receiving environment (surface water and groundwater)
- Determine whether the predicted water quality is such that it can support a beneficial use.

In addition, social and economic considerations and stakeholder and community expectations should be included in the various assessments.

Based on this, the guidance proposes a methodology to assess the viability of filling the void with material or water, by analysing three specific strategic mine planning scenarios:

1. Maximise operational value
   The objective of this scenario is to maximise the operational value without specifying a preferred final land use for the void.

2. Material-filled void
   The objective of this scenario is to deliver a material-filled void at the conclusion of mining activities, which can support a range of land uses.

3. Water-filled void
   The objective of this scenario is to deliver a water-filled void at the conclusion of mining activities, which is non-polluting and can support a range of water uses.

The mine planning system will need to be set up with the ability to analyse these three scenarios. As outlined in the previous section, consideration should be given to the elements of the strategic mine plan that can influence the feasibility and cost of each scenario.

3.1 Stages of mining

The integrated planning methodology can be applied to any stage of mining: pre-approval, operational, and prior to closure. However, as discussed in Section 1.2, the number of options and availability of data and information will vary greatly along this timeframe. The integrated planning framework described here will need to be adapted to the requirements arising from each phase of the mine lifecycle.

3.1.1 Pre-approval phase

The incorporation of PMLU options at an early stage of the operation will provide the greatest opportunity for the alignment of outcomes and consideration of options. It can be expected to provide the greatest range of options for consideration. However, this will be limited by an incomplete knowledge base. For example, there may be knowledge gaps with respect to the extent of the deposit or the geochemistry of waste produced from material that will be mined in the future. Such challenges are relatively common during greenfield studies and may effectively undermine the application of the recommended leading practice integrated planning framework. Nevertheless, almost all greenfield projects must manage the issue of incomplete knowledge, and the assessment of PMLU options should still be able to be incorporated. At this stage of the mine lifecycle, there will be a lower level of confidence in the long-term sustainability of PMLU options and the planning framework should aim at outlining key risks associated with planned outcomes.

All PMLU options have the potential to be costly. Partial or complete backfilling of voids will typically incur a significant lump sum financial cost at the end of mine life, whilst leaving a void may result in long term ongoing management and monitoring costs. Both scenarios will impact the ultimate pit selection in terms of the planned ultimate pit size and therefore the reserves contained within. The pit optimisation process will therefore need to be modified to incorporate such costs as well as the associated risks. It is expected that multiple pit optimisation scenarios will be required.

3.1.2 Operational phase and prior to closure

During the operational stage, there will be a continually diminishing range of options available and a concurrent increase in the costs associated with the introduction of any changes in the planned approach to the mine designs and schedule. At the stage where the final pit is being mined, the options are very limited and are almost identical to those available immediately prior to closure. If changes to the mine plan are considered early there may still be significant scope to identify several PMLU options and implement the required changes to the mine plan (including mine design, equipment selection, mine schedule, etc).

3.2 Planning architecture

The architecture of the planning system will need to support the assessment of multiple scenarios. Thought should be given to how data will be passed between models, in what format, and what software solutions will be the most appropriate.

The following guidance provides a way to ensure consistency in the analysis of scenarios and to avoid the introduction of any bias when comparing between the scenarios being analysed:

- All scenarios must be run using the same models with the same structure.
- All parameters that should be held constant between scenarios must be held constant.
- The construct of the objective function must not be manipulated between scenarios.
- The same basis for the selection of the ultimate pit must be used.
- Any variation in the consideration of risk between scenarios must be detailed and defensible.
- The differences between scenarios must be stated.
- The parameters which are assigned a different value between scenarios should be clearly identified.

For the three scenarios that are required to support the decision regarding the preferred PMLU option, the pit optimisation process should be organised as follows:

1. Maximise operational value
   This scenario is based on a standard pit optimisation process, with standard geotechnical parameters and operating cost assumptions.
2. Material-filled void
   This scenario is similar to the standard pit optimisation process but incorporates the additional costs required to fill the void with material at the conclusion of mining activities. This can be expected to result in a smaller ultimate pit in many instances.
3. Water-filled void
   This scenario assumes the void is not filled with material but with water and adjusts some design assumptions and parameters so that the water-filled void could potentially support a range of water uses, such as supply to agriculture or habitat for aquatic ecosystems.

3.3 Scenario parameters

Strategic mine planning relies on standard corporate assumptions about the economic factors that will affect the financial performance of operations. These include assumptions about commodity price, foreign exchange and discount rate. They constitute key input parameters into the scenarios that will be analysed with the planning system.

One of the objectives of the integrated platform is that it should aim at providing a wider range of financial results that can support a more nuanced analysis of risks, benefits and values. As such, it should consider the impact of variations in the corporate assumptions. As a minimum, the scenario should be analysed with:

- Consumer Price Index (CPI) instead of corporate discount rate. CPI is an accepted measure of inflation and can be an appropriate substitute for estimating the future value of money. By using the CPI in the analysis, rather than the corporate discount rate, the time value of money is maintained but the risks associated with the funding structure are removed. It provides information that is less dependent on the level of corporate appetite for financial risk.
- Different commodity price outlooks: the standard corporate assumption, a higher price outlook and a lower price outlook. Commodity prices will influence closure liabilities, particularly for scenarios that rely on cash input towards the end of mining activities (e.g., material-filled voids).

The scenario parameters must be set at the start of the analysis, as shown in Figure 2.

3.4 Product and schedule optimisation

The scheduling process should be developed using a schedule optimisation model that will support analysis at the strategic level. Such models will solve to an objective function, whose structure should be kept constant between all scenarios analysed. As discussed in the previous section, there are options for the definition of the objective function and all scenarios should use the same one. The use of manual scheduling processes is not recommended. Such processes are time consuming and can be expected to result in inconsistencies between scenarios.

Equipment selection will impact upon several factors relating to the form of the residual void, the flexibility of the operation to implement specific design requirements to support potential PMLU options, and the associated cost profiles. This has been discussed in the previous section. The schedule optimisation should include consideration of equipment selection and the potential to tailor equipment lifecycle replacements to suit the implementation of PMLUs.

3.5 Simplified designs

Developing detailed mine designs for each stage or pit requires significant engineering time. This is not required for the strategic level process concerned with identifying and selecting options for residual voids. Given that the analysis is at a strategic level, tactical level planning detail is not necessary. However, the process should be consistent between scenarios to avoid the introduction of any bias in the analysis.

3.5.1 Staging pits

The selection of staging pits will impact on options in which mine closure occurs earlier than planned, due to a range of external factors, including adverse movements in commodity prices. When very large staging pits are selected, then each pit represents a commitment to mine that entire pit. Staging pits also directly impact waste placement, particularly for strip mining operations that are placing waste in the previous strip. At this strategic level, it would be acceptable to use a series of selected shells from the pit optimisation process as inputs to the scheduling process. In this instance, it is important to ensure that appropriate geotechnical parameters are used and are consistently adjusted to incorporate access (ramp designs) as well as any other operational adjustments that may be required.

3.5.2 Geotechnical parameters

Selection of geotechnical parameters will be critical and will require geotechnical expertise to provide guidance on Factor of Safety[1] and competency of material. Salmon (2017) identified that a key knowledge gap was related to the lack of geotechnical characterisation and classification of void wall material and definition of its stability. This aspect creates uncertainty as to the risk of failure of pit walls and potential safety impacts this may have. It also limits the ability to design stable re-profiled slopes.

When considering the geotechnical aspects, there will be differences between metal mines and coal mines. A residual void in a coal strip mine will be bounded by: a highwall; end walls of undisturbed geology and one face; a low wall, comprised of broken unconsolidated overburden material (shales, mudstones, siltstones, sandstones and possibly other mining wastes). Rehabilitation options for highwalls will depend on the competency of the material. Reshaping the angle of highwalls can facilitate the establishment of some land uses on this section of the void and this aspect should be considered in the simplified designs. Low walls are deposited at angle of repose and need to be reshaped. They can be easily eroded and can rapidly become unstable in high rainfall events. They have different hydrogeological features and parameters compared to the highwall and end walls. Void wall treatments can improve the stability, safety and sustainability of the final landform. Coal mine high walls and end walls may be blasted and re-profiled, topsoiled and revegetated to improve stability, safety and sustainability of the slopes. Re-profiling of void walls will change the geometry of the coal mine final void significantly and it will look notably different if compared to hard rock mine voids.

A hard rock mine final void is normally bounded on all sides by relatively undisturbed rock. The walls of a hard rock pit void are often vertical to sub-vertical, competent and stable geotechnically, mostly because they are composed of hard, strong crystalline rocks. They tend to be less affected by weathering and erosion than the weaker and more erodible sedimentary rocks in the highwall and end walls of a coal void. However, structural features tend to be more common in hard rock mines than coal mines. Fault zones and highly contorted folding can result in areas of weakness in hard rock mine walls. Base metal pit walls are rarely battered back or re-profiled since they are, usually, substantially more stable than coal mine pit void walls.

The features and approaches to achieving landform stability need to be captured in the simplified designs as they are related to PMLU suitability.

3.5.3 Waste disposal

Since the waste disposal strategy will significantly impact on the viability of PMLU options, the simplified designs need to capture it as practicably as possible in terms of waste destination, waste characterisation, and rehabilitation designs for waste rock dumps. For the case where the void is backfilled with material, the scenario needs to include the source of such material, where the material is stored until the final void becomes available, the associated costs, and its ability to sustain a safe and stable landform.

3.6 Water-related assessments

For water-filled voids, a large component of the planning assessment will be dedicated to evaluating the voids' water balance and water quality, including options for water quality mitigations, the potential to support aquatic ecosystems and defining the relationships between the voids and receiving environment. There will be aspects of the simplified designs that can impact on the viability of PMLUs for water-filled voids: for instance, simple adjustments to a void's shape can make it more suitable for the establishment of aquatic ecosystems. The relationships between a void's design and its suitability to support a PMLU are discussed in detail in the water-related sections.

3.7 Iterative process

The process will be iterative, but the number of iterations will depend on the scenario and on the

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[1] Slope stability is controlled by driving forces (e.g. gravity) and resisting forces (e.g. shear strength of the material). The Factor of Safety is the ratio between the resisting and driving forces. If it is less than 1, the slope is not stable.

number of PMLUs that are identified. This is illustrated in Figure 2 and Table 1. The scenario that considers a water-filled void will be the most complex as there are connections between the void's design and water balance (catchment extent, void's shape and storage capacity), waste disposal strategy and water quality, and the void's design and its ability to sustain aquatic ecosystems. There is also a requirement to assess water quality mitigation options. These aspects are discussed in detail in Sections 4 to 7. It will require detailed understanding of all potential feedback loops, with inputs from multiple teams.

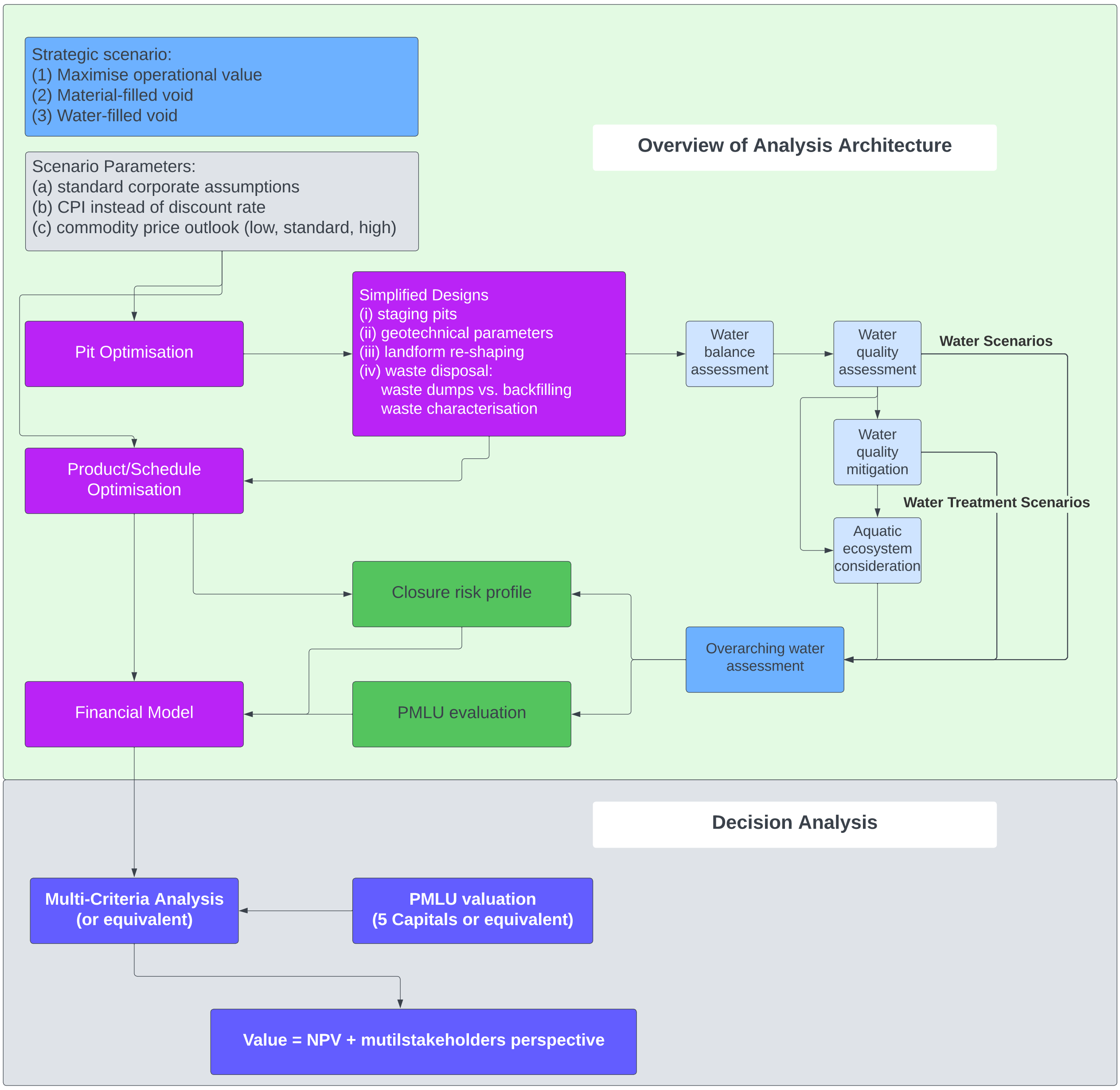

Figure 2. Overview of integrated planning platform

Implicit within Figure 2 is that the parameters for each scenario are used as inputs for the pit optimisation process and then all subsequent modelling processes. It is not sufficient to merely modify the financial model. Changes to inputs such as the waste mining cost have the potential to materially impact the size of the ultimate pit (and therefore the size of the waste storage facilities) as well as material destinations in the schedule optimisation process. To quantify these impacts the framework needs to be completely re-run for each scenario in almost all instances.

Table 1. Illustration of iterative process

Scenario	Examples of required iterations
Maximise operational value	This scenario might yield the option where the void is filled with water of a quality that makes it unsuitable to support any type of land use. The water balance assessment shows that there is no export of contaminants to the receiving environment. In this case, there would be no need to iterate the number of water scenarios (water balance, water quality and aquatic ecosystem consideration).
Material-filled void	This scenario might yield a landform that is safe, stable and non-polluting as it does not hold any water. In this case, there would be no need to undertake any of the water assessments (water balance, water quality and aquatic ecosystem consideration). However, the landform might be suitable for several land uses, and iteration will be required for PMLU evaluation and valuation.
Water-filled void	This scenario is the one that is the most likely to require several iterations as the water assessments can lead to changes to simplified designs (e.g. catchment extent, void shape, waste disposal structures).

4 Water balance

4.1 Overview

A large component of void closure planning will be dedicated to defining its relationship with water resources (surface water and groundwater). In many cases, catchments that drain to a residual void are intentionally minimised to reduce runoff inputs into the void and prevent overflow to the receiving environment. A thorough water assessment is required to assess potential options.

For the purposes of informing the integrated planning approach to identifying and selecting a PMLU, technical studies must be undertaken to:

- Predict whether the void will maintain a permanent water body.
- If it will, predict the water level in the void in the long term and the time required for the water level to reach long-term equilibrium conditions. The water level will fluctuate around an average equilibrium level in response to climate variations. The sensitivity of this equilibrium level to assumptions related to climate scenarios, evaporation calculations and initial water storage volume must be assessed. Any impact of water level fluctuations on geotechnical stability should also be investigated.
- Use the water level predictions to assess whether they will result in overflow to the environment via surface pathways and assess the risk of water being exported to surrounding ecosystems including creeks, rivers, wetlands, and springs.
- Describe the regional groundwater context, through conceptual then numerical approaches. Compare the void’s predicted water level with the groundwater level in the regional system and assess the risk of flow to regional groundwater and groundwater dependent ecosystems.
- Quantify the void’s water quality in the long term, by calculating concentrations of contaminants of interest (e.g., salinity, major ions, metals and metalloids). Use these calculations to review the risk of export of contaminants to surface water and groundwater.

A water balance model must be developed to simulate all flows in and out of the void(s), including interactions with groundwater and prediction of water quality. The Queensland Mine Rehabilitation Commissioner has published guidance on water balance modelling for the purpose of mine rehabilitation planning (Tomlin et al, 2023). Information related to the groundwater regional setting and regional groundwater levels must be compiled. Depending on the complexity of the groundwater setting, this can be generated by conceptual descriptions and simple analytical methods or by a numerical groundwater model. Expectations are that groundwater modelling be made available, but there could be instances where it is not warranted or that simplistic approaches provide an adequate representation for the purpose of assessing the water-filled void scenario. The water balance model (Figure 3) must include:

- Inputs of water: rainfall and runoff, baseflow (infiltration through the spoil pile that eventually drains to the base of the voids) and groundwater flow.
- Outputs of water: evaporation, potential flow to the regional groundwater system and potential flows to the receiving environment.
- Prediction of water quality, in the form of predicted concentrations in key contaminants of interest, which will be site dependent but are likely to include salinity, major ions and some metals or metalloids. Water quality predictions are discussed in Section 5.

Rainfall, runoff and evaporation must be calculated using a hydrological model with climate data derived using standard practices. Catchment details must be supplied by mine planning teams, providing final design for topography to derive catchment areas, spoil volumes and void geometry. The relationships between water level, stored water volume and surface area must be calculated using pit shell geometry, spoil volumes and porosity data. Water balance considerations are included in the integrated planning platform, which captures essential components (e.g., catchment extent) in the simplified designs.

In most instances, it is appropriate for the water balance model to simulate water quantity and quality in the voids on a daily basis with shorter timesteps (e.g., 1 hour) during periods of high transfer (such as a spill between voids). Modelling must include sensitivity analysis to assess the potential impact of:

- Climate change, including conservatively high emissions scenario.
- Uncertainty of evaporation calculations: in many instances, evaporative losses are calculated with a simple approach that combines average monthly pan evaporation rates and a pan factor. There is uncertainty associated with the selection of the pan factor and the impact of a different values must be assessed. Ideally, a more sophisticated approach would be selected.
- Initial water level in the voids.

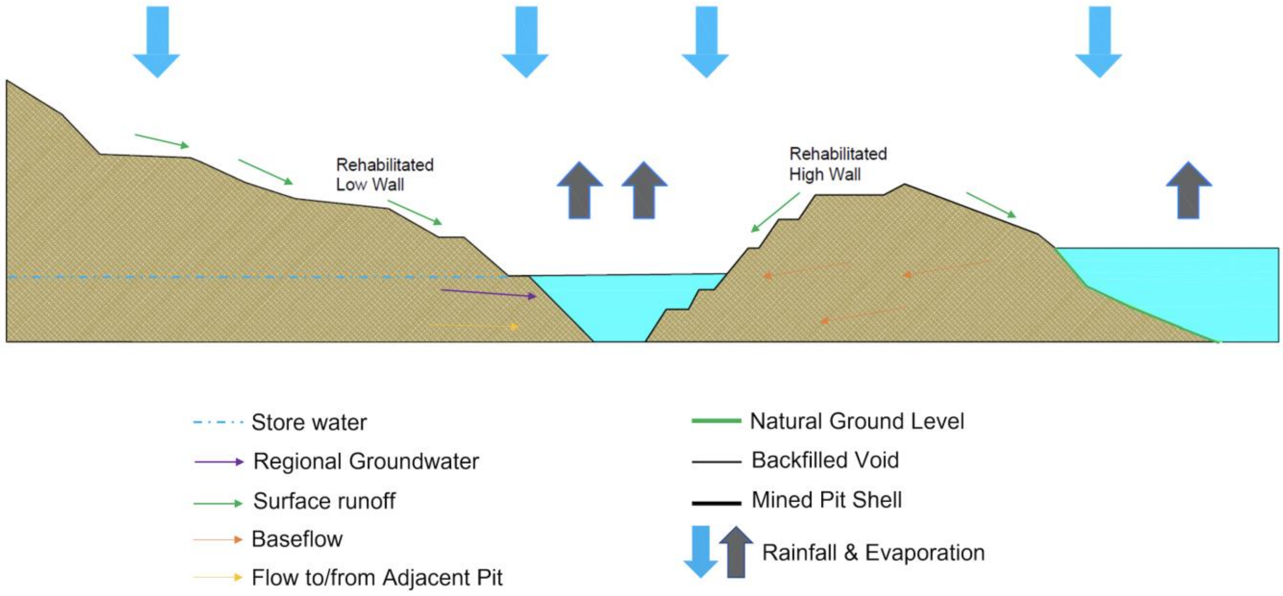

Figure 3. Conceptual model of void water balance for strip mining

For the purpose of predicting final water levels in the voids and analysing the potential interactions between voids and groundwater, a detailed hydrogeological assessment must be undertaken. This assessment must comprise description and modelling of water flow through:

- The main groundwater bearing units: these will vary with locations but can include quaternary sediments (alluvium); tertiary sediments and/or basalt; coal measures if relevant; any other hydrogeological unit. In the Bowen Basin, the most permeable lithological units are frequently the coal seams, which form aquifers with low transmissivities that are confined by overlying and underlying shales and mudstones. Groundwater in the coal seams is also saline and not suitable for stock water supply or irrigation. These groundwater bearing units tend to be referred to as the "regional groundwater system".

- The underground workings if applicable: in all likelihood, groundwater will flow from the seams towards underground workings. When underground workings are in close proximity to surface voids, there can also be pathways with relatively high hydraulic conductivity that convey water from the voids to the underground workings. This will impact on the water levels in the voids, which will only stabilise once the underground workings have filled with water. Groundwater levels in the regional system must be compared with those in the underground workings to assess whether there can be flow from the underground workings to the regional groundwater system.
- Waste material: as open-cut operations progress, pits are backfilled with waste material. Rain infiltrates into the waste piles, which creates a baseflow through the material that drains to the pit. This is effectively a surface water component that is treated independently from the groundwater system and is usually included in the water balance model ("baseflow" in Figure 3). However, water stored in the pits can also flow into surrounding waste material and be conveyed to underground workings or to another pit. In Central Queensland mines, it is very common for pits to be hydraulically connected by flow through porous material. This component is usually incorporated into the net groundwater flow derived from the groundwater model, because this type of flow is through a porous medium and is calculated according to physical principles that are similar to those found in aquifers. It is important to check how flows through waste material are included in the water balance model and/or the groundwater model, and to ensure they are not double counted.

In many cases, a numerical groundwater model will be required to simulate these flow components and provide estimates of:

- Potential drawdown in the regional groundwater system as a function of time and the level at which the groundwater table will stabilise after mining activities has ceased. This level is often referred to as "recovery" level.
- For each individual pit, the groundwater fluxes through the waste material, which can be from one pit to another or to underground mining areas. It is also common for pits to be hydraulically connected by flow through waste material.
- For each individual pit, the relationship between the water level in the pit and the net groundwater flow into or out of the pit. This can be difficult as there are often knowledge gaps.

Hydraulic connections between pits add complexities to detailed calculations, but generally do not impact on overall site water balance and long-term average final water levels. It does pose challenges to the prediction of water quality, as discussed in Section 5.

Where coal voids are backfilled above the elevation of the rebounded water table, drainage paths should be formed but shallow water ponding may still occur. If backfill in the coal void is below the rebound water table elevation, a lake can form but its depth will be dependent on the amount of backfill material deposited. The material-filled scenarios should investigate these impacts.

Beyond the prediction of final water levels in voids, the post-mining water balance must also assess whether there are predicted changes to local stream losses and any impact on the interactions between local streams and aquifers.

The outcomes from the water balance assessment will inform the type of residual voids that will be left at closure (Table 2).

If the void is predicted to contain a permanent water body and there is no risk of export of contaminants to the receiving environment (surface water or groundwater), post-mining land uses associated with water-filled voids should be analysed as part of the planning framework. Catchment extents are therefore an essential component of the simplified designs.

If there is a risk of export of contaminants to the receiving environment via surface water pathways, the catchment extents can be adjusted to reduce or eliminate that risk. If there is a risk of export of contaminants to regional groundwater systems, a water-filled void might not be a feasible option where it has the potential to cause harm or impact on adjacent water users. In such circumstances, backfilling to a level above the regional groundwater level might be required.

There are other situations when a water-filled void might not be feasible, for instance when the void will be relinquished to another party (e.g., neighbouring grazier who might be reluctant to accept the risk of managing such a water-filled void). For these specific cases, backfilling to a level above the regional groundwater level might also be required.

Table 2. Types of water-filled residual voids

Type of Void		Characteristics	Advantages	Risks
Open residual void	Terminal Evaporative sink	Terminal sink flow regimes typically occur in arid climates where evaporation potential is higher than average rainfall runoff. During groundwater level rebound at mining cessation, the void water level rises to a level where inflows are in equilibrium with evaporation losses. In a terminal sink flow regime, the void water level rise is lower than adjacent groundwater levels, and due to the generated lateral hydraulic gradient towards the pit, void water does not seep into the surrounding groundwater system.	The water quality is expected to exhibit increased acidity and metals and salt concentrations over time as solutes introduced through groundwater inflow and pit wall runoff are concentrated by evaporation. A long-term risk of increasing ‘pit lake’ salinity is the potential for density-driven flow to reverse hydraulic gradients promoting seepage into the surrounding groundwater system. These risks will require evaluation on a site-by-site basis.	Flooding Effects of climate change Public health and safety Impacts to wildlife that may interact with contaminated water
	Source Perched above local groundwater levels	Perched above the surrounding water table. Occurs in net positive water balance areas or in cases where surface water run-off is diverted into the residual void once mining has ceased.	Becomes a recharge zone for the regional groundwater system and may overflow during periods of excessive rainfall, if the void spill height is exceeded.	Groundwater levels surrounding the residual void will be elevated above pre-mining levels Export of contaminants to the regional groundwater system Effects of climate change.
	Flow-through or capture of catchment runoff Predominantly to surface waters	Engineered for the purposes of maintaining or improving water quality, by permanently diverting a river or other surface water into the residual void, with discharge into a natural waterway downstream.	Potential to contribute to the improvement or stabilisation in the void’s water quality over long-term time scales, which may make the water held in the void suitable for reuse. This will provide long term storage and prevent waste generation.	Cumulative impacts of multiple flow-through residual voids from the export of contaminants, particularly on downstream users. Effects of climate change. Magnitude and scale of potential impacts to potential receptors is site specific.

4.2 Knowledge gaps

There are two critical knowledge gaps: lack of data regarding the hydraulic properties of waste material and difficulties with combining the calculations from the surface water balance model and the groundwater model to give an indication of overall risk.

4.2.1 Hydraulic properties of waste material

A critical knowledge gap identified in Salmon (2017) is related to the modelling of flow through waste material (the backfilled areas in the void). This information is essential to validate groundwater models and site water balance. There is a lack of data about the hydraulic properties of waste material, which introduces uncertainty because assumptions are used in the numerical groundwater models. Characterising and measuring the hydraulic properties of waste material would assist with:

- Identifying potential flow pathways in the spoil backfill, determining the location of the water table within spoil piles and clarifying hydraulic connections between voids.
- Confirming the relationships between water table in spoil piles and regional groundwater levels. Uncertainty about this aspect limits understanding of physical and chemical characteristics of the regional groundwater regimes and impacts on confidence in modelling of groundwater flows into or out of the void.

4.2.2 Surface water and groundwater interactions

Currently, there is no well-defined method to undertake integrated surface and groundwater modelling for residual voids. It can be done in an iterative way, where results from both models are updated step-by-step. This is not dynamic and is time consuming. This can make it difficult to confidently state how regional groundwater systems interact with voids. In particular, it can be difficult to assess the direction of flow between the voids and the regional groundwater system.

Ideally, a void water balance model should be linked with a groundwater and surface water model. While it will always be necessary to make simplifying assumptions about some components of the water balance, when such assumptions are made, they should be explicitly documented, and the effects of the assumptions should be explored as part of sensitivity analysis.

One simple option is to derive “Stage-Discharge” tables, where “stage” refers to the water level in the void and “discharge” refers to the net groundwater flow. The groundwater system will be the combination of the regional groundwater system and waste material. Groundwater modelling results are usually too complex to split groundwater flow into these individual components and they are summarised as “net groundwater flow”. If the net groundwater flow is positive, the void loses water to the groundwater system. If the net groundwater flow is negative, the void gains water from the groundwater system.

There are research projects underway that are investigating how we can derive more reliable quantification of surface water and groundwater interactions in post-closure water balance assessment of voids.

5 Water quality

5.1 Overview

The range of potential end uses for water from voids is predominantly dependent on its water quality. Water quality is influenced by numerous factors including climate, groundwater quality, void depths, void water balance, local mineralogy and mineralogy of the waste materials (spoil dumps, spoil piles). In Australia, water-filled voids can be classified into four different categories based on their water quality (Kumar et al., 2013):

1. Acidic voids are affected by acid mine drainage (AMD) and require chemical/biological remediation.
2. Saline voids typically occur in drier regions where there is a net loss due to the balance

between evaporation and inflows. This can co-occur with AMD.

3. Neutral pH, but with some degree of contamination which may require treatment to support a land use.
4. Good quality water, but not necessarily comparable to that characterising natural regional water bodies.

The water quality of residual voids (often referred to as “pit lakes” in the international literature, which commonly focuses on metal mines) differs significantly from natural lakes. This is mainly caused by their distinctive morphological characteristics. Residual voids have a relatively high depth to surface area ratio (between 10 and 40 %, compared to less than 5% in natural lakes), which makes them susceptible to stratification. Stratification leads to changes in chemical characteristics with depth, including an increase in total dissolved solids (TDS) and electrical conductivity (EC). Sub-oxic or anoxic (no oxygen) conditions tend to occur in the hypolinium (lower stratum) if the chemical and/or biological oxygen demand is high enough. The steep side slopes of mine voids create sheltering effects which inhibit wind induced mixing (Huber et al., 2008a).

Limiting runoff contribution from catchments with complex mineralogy of exposed geologies may be useful in preventing worsening water quality. However, where exposed geologies are not problematic, it may be desirable for voids to capture high quality water. This will be captured in the simplified designs, as catchment and waste disposal extents.

In areas of Queensland with high evaporation rates, residual voids will commonly be thought to act as a sink for on-site water and the concentration of salts gradually increases due to evaporation. While the water levels in the voids are generally expected to reach equilibrium over time, the time that it takes to reach chemistry equilibrium is unknown and the ionic chemistry before and after equilibrium is uncertain (Willgoose and Hancock, 2016). There is uncertainty about the rate and duration of salt contributed by coal spoil piles. Using hydrological models developed to predict water quality in residual voids with the assumption of unlimited salt availability may predict a trend towards hyper-salinity. Assumptions about the amount of salt that will be leached from a spoil pile can have a large impact on predicted salt concentration in voids and the time to reach equilibrium.

Based on the research work undertaken as part of ACARP research projects (Edraki et al. 2019; 2021) there is general agreement that in spoil piles the salinity of leachate will be initially high and then concentrations will decline over time, although in some cases there may be an initial period of increase. In simple terms, the salt generation involves weathering[2], dissolution, and transport (advection and diffusion). The quasi-steady state condition depends on the relative speed and extent of these processes in the long-term, which in turn depends on the type of spoil, placement, physical and geochemical properties, climate, surface drainage and bulk material drainage properties. The quasi-steady state may be dominated by long-term weathering rates and/or transport (advection and diffusion rates).

Any collapse of leached preferential flow-paths and opening up of new flow paths will give a localised pulse but is not likely to be significant on a whole-of-dump scale unless the collapse is a result of a major geotechnical failure of the spoil pile. In some cases, leaching depends on climatic events that result in a series of high salinity pulses generated by infiltration of high rainfall events. Transport of salts out of the spoil piles tends to be significantly lower in interceding times. Therefore, the concept that is generally adopted is that of quasi-steady state with caveats on time scales and the potential for pulses of higher salinity. In other words, salt leach will asymptote but there will be episodic salt slugs as infiltrating water intersects new unleached areas of the spoil pile.

Currently, given the range of complexity related to the geochemical processes that can impact on water quality, simplified approaches are generally adopted, which involve collecting samples of spoils for analysis and identification of key geochemical processes, for instance dissolution and transport of salts (total dissolved solids and major ions), oxidation of sulfide minerals that will release sulfate and associated metals and metalloids.

Salts are immediately soluble and will be mobilised by water flow. Leaching tests provide data demonstrating how salt concentrations in the leachate will decline over time. A decay curve can be

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[2] “weathering” here encompasses all physical and chemical processes that create soluble salt from the spoil

used to predict the likely evolution of salt concentration in the flow from the spoils.

Oxidation of sulfide minerals will depend on the rate of oxygen ingress into the spoil, which can be calculated to provide an estimate of the depth of oxygen ingress and the time required to fully oxidise sulfide minerals through that depth. After this time, it is assumed that no additional solute can be generated but the accumulated solutes would continue to be flushed from the spoil in a process similar to that defined for salts.

Water quality in voids will also be influenced by flows from the regional groundwater system, which are captured in the water and solute balance model as a net groundwater flow (the combination of flow from the regional groundwater system and flow through waste material). This poses a challenge as solute concentration in the regional groundwater system may not be the same as that in the waste material. This limitation is generally not significant in the context of the geochemical simplifications that have to be adopted to produce water quality estimates.

There are challenges related to the quantification of long-term water chemistry, with several research projects investigating how we can derive more reliable quantification of a water-filled void’s long term water chemistry.

5.2 Knowledge gaps

In Queensland, the main barrier to using water from voids to support a PMLU is its quality, governed largely by the chemistry of the water leaching from spoil piles. The void’s water quality in the long term needs to be determined, as this will govern the types of land use that can be supported by water sourced from the void. The main elements that can influence the void’s water quality are the distribution and type of waste material. The extent, shape and location of waste disposal structures are an essential input into both the water quality prediction tool and the simplified designs. Characterising waste material from sample analysis and leaching tests will assist with determining the impacts of waste disposal structures on void’s water quality. Similar data should be collected for material that will be used for backfilling.

The range of PMLUs that can be supported by water from a residual void will be highly dependent on the water quality from that void. It might require remediation technologies to achieve the required water quality targets (see next section on water quality mitigation). The evolution of water quality in voids can be complex to understand. Currently, the models that are used to predict water quality in coal mine voids tend to over-predict salt concentrations as they have not incorporated recent findings from ACARP research (Edraki et al. 2019; 2021).

6 Water quality mitigation

6.1 Overview

Most mine voids contain poor quality water that is unsuitable for a use post mining. Salinity is the most common water quality constraint in voids of the Fitzroy Basin, which are often expected to become terminal sinks (Coffey Services Australia Pty Ltd, 2021) due to saline spoils and an arid climate. A highly saline water body presents various challenges for identifying PMLUs, as it prevents the establishment of autochthonous ecological communities (Nielsen et al., 2003) and is not suitable as a water source for crops or livestock (Zörb et al., 2019).

There are few examples where desalination has been implemented at coal mines in Queensland, despite great progress on developing fit-for-purpose technology. Research funded by ACARP (ACARP projects C21043 and C23031) has delivered an integrated forward osmosis (FO) and reverse osmosis (RO) system and demonstrated that this technology offers a readily controllable onsite water treatment method that can be tailored to each site’s water management requirements. Because the brine is used to keep a high salt concentration in the draw solution for the forward osmosis component, this integrated treatment technology produces negligible volumes of brine (less than 1%).

There might be water quality issues other than salinity that require consideration of different treatment options. For completeness, an overview of water treatment technologies is provided in Table 3 and Table 4. Further information can also be found in a study by Fonseca-Teodoro et al. (2022) that reviewed approaches to treat coal mine affected water in Queensland.

The quality of mine affected water may be improved by dilution with better quality water sourced from onsite water storages, capture of overland flows or diversion of river or creek flows into mine voids. In some cases, proposals consider diluting water with or without releasing water into a stream. While such a strategy can improve the quality of mine-affected water, it can have undesirable outcomes. Lake Kepwari in the Collie region in Western Australia provides an example of a coal mine void that functions as a 'flow-through' system. This void became connected with the river system after a diversion was accidentally breached during a high flow event. The pit has since become connected to the stream and releases water back into the river, creating a flow-through system. Research on Lake Kepwari has shown that creating a flow-through void diluted the concentration of analytes resulting in a net improvement of its water quality (ACARP Project C23025). It also showed that the flow-through system altered the hydrological regime of the area downstream by reducing the intensity of flooding, delaying the onset of flows and prolonging the cessation of flows. Without the additional inflows from the nearby rivers, the void water would have been acidic. There were site-specific factors that influenced the success of this case, and such results might not be feasible in other regions. Despite the potential improvement in water quality within the void, flow-through systems can alter hydrological regimes, can lead to the release of contaminants and can present risks to downstream users or ecosystems. Some of the potential concerns associated with creating a flow-through void that both receives inputs from riverine flows and releases back into a stream include:

- reducing the quality of downstream water resources
- increasing contaminant loads in other parts of the catchment
- reducing stream flows and potential impacts to groundwater ecosystems
- increased water losses though evaporation
- creating a sink that alters geomorphic characteristics and prevents sediment transport
- creating habitat that can favour exotic species and prevent dispersal of native species
- impacting other water users and water rights
- potential impacts from the construction of a weir and associated infrastructure within a waterway.

Accordingly, a proposal that involves diluting mine affected water with stream flows requires careful consideration of the risks and benefits. In some cases, the risks may be outweighed by the benefits resulting from improved void water quality. This type of option can be captured in the integrated planning framework, through the water quality and quantity assessment and the decision-making process that includes regional social and economic considerations. In Queensland, there has been no regional assessment of the risks and benefits associated with flow-through voids.

6.2 Knowledge gaps: treatment options

Further and ongoing research is required to better inform treatment technologies that are specific to Queensland conditions and post-mining land uses. International studies are generally focussed on treating highly toxic, acidic pit lakes which are characterised by low pH and high sulfate and metals concentrations, whereas saline lakes have received much less research attention. In addition, a one-size fits all approach might not be suitable as void water treatment can become complicated due to site-specific conditions that result from the limnology of the void water body and underlying geochemistry. An understanding of how these factors influence void water quality is essential for the implementation of appropriate remediation technologies.

Long-term closure strategies for residual voids require remediation methods that are self-sustaining and require no or limited management inputs and maintenance (e.g., pump and treat remediation, nutrient addition, in-lake liming). Treatment technologies can be classified as either active or passive treatment. Active treatment requires continuous operation and maintenance and is often used in operating mines when there are personnel on site and revenue is dedicated to water treatment. Passive treatment is intended to be self-sustaining after an initial set-up phase and is ideal for treating mine water after closure although some level of management is inevitable. Active treatment technologies are generally only implemented post-closure where there is a risk of contamination to social or environmental receptors or as a requirement in the beneficial reuse of void water.

In summary, for water-filled voids, the number of feasible PMLUs will be greater if the void's water is mitigated to a suitable quality. Water quality mitigation scenarios should be included to identify if active mine water treatment during the operational phase or other mitigation options can yield a water quality at closure that is suitable for a range of land uses. The assessment should include the cost of mitigation options.

Table 3. Overview of active treatment technologies

Physicochemical treatment	
Chemical - pH modification, neutralisation and precipitation	pH is raised by adding ameliorants (e.g., lime, limestone caustic soda, sodium carbonate). Oxidation occurs concurrently and iron and then other metals precipitate out of solution. 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. Examples: Liming, ViroMine technology, hydrotalcite precipitation
Physical process technology	Membranes, reverse osmosis (RO), forward osmosis (FO) and filtration used to separate water from ions. In Baal Gammon mine pit (pH 2.9), North Queensland, a mobile RO plant was used to remove residual salts remaining after in-situ remediation and prior to filtrate discharge to an adjacent creek (Douglas, 2014). Site trial of integrated FO-RO unit was used to eliminate extensive pre-treatment steps generally required for conventional RO. Further work required to determine long-term durability and membrane fouling propensity (Thiruvenkatachari et al., 2020).
Ion Exchange	Reversible exchange of contaminant ions with more desirable ions of a similar charge adsorbed to solid surfaces known as ion exchange resins. Hardness removal, desalination, alkalinity removal, radioactive waste removal, ammonia removal and metals removal. Selective metal recovery may be an option depending on type of water. Limitations include suspended solids plug the resin bed and increase head loss and increase fouling potential, degradation due to organics, strong oxidants and high temperatures, high disposal costs for resin. Most effective for water with pH range of 4 to 8, low suspended solids and low concentrations of iron and aluminium.
Biological treatment	
Bioremediation - Bacteria	Cost effective with locally available materials. Sensitive to physico-chemical conditions.
Microalgae biofilm technologies	Microalgae cultivation is a low-cost method for desalinating void water. Bio-desalination of brackish and seawater using halophytic algae.
Biochemical reactor (also passive)	Use microorganisms to transform contaminants and to increase pH. Removal of elevated levels of selenium, nitrate, mercury and metals and can easily accommodate reasonably high flow rates. Most used are sulfate-reducing bioreactors (SRBRs, SRBs) and are operated anaerobically.

Table 4. Overview of passive treatment technologies

Phytoremediation (flow through)	Use plants to treat or capture contaminants in various media and include extraction of contaminants from soil or groundwater. Require root contact so plants must be able to extend roots to the contaminants. Examples include halophytic plants, aquatic macrophytes, tidal wetlands and marshes, mangroves, carbon sink wetlands. Can remove metals, including chromium, and radionuclides, including uranium, caesium and strontium. There are six basic phytoremediation mechanisms that can be used: phytosequestration, rhizodegradation, phytohydraulics, phytoextraction, phytodegradation and phytovolatilization.
Anoxic Limestone Drains	Neutralising mine water and precipitating metals without addition of materials, by allowing the water to flow through: 1) beds of limestone in an anoxic environment so that there is no oxidation leading to precipitates that will clog the system; 2) open limestone channels on relatively steep slopes with high flow rates, so that precipitates can be entrained; (3) other proprietary products. Ideal for remote areas, cost effective and can treat a range of flow rates. Needs replenishment once depleted. Chemical characteristics of the influent mine water can cause variations in alkalinity generation and metal removal.
Biochemical reactors (also active)	Use microorganisms to remove contaminants and can have various designs. Able to treat a wide range of mine water with the use of local materials. Low operation and maintenance requirements. Do not typically require any external power and can operate without continual maintenance.
Permeable Reactive Barriers	Contaminated water flows through a permeable treatment zone which contains reactive material (e.g. limestone, compost, zeolites, activated carbon and apatite). Capable of remediating an array of contaminants. Have extremely low maintenance costs for at least 5- 10 years and no operational costs other than routine compliance and performance monitoring.
Constructed wetlands	Combines naturally occurring biogeochemical, geochemical, and physical processes and are either subsurface flow wetlands or free water surface wetlands. Can be used for the long-term remediation of AMD (Pat-Espadas et al., 2018). Wetlands can capture or treat sulfate and various metals, including iron, manganese, arsenic, aluminium, copper, zinc, cadmium, selenium, nickel and lead. Wetlands can treat acidic, neutral or alkaline mine drainage. Low cost and able to tolerate unforeseen fluctuations. They require a large amount of land per unit volume of water; a constant and sufficient supply of water is necessary to support the wetland. Pre-treatment may be required. Release of captured contaminants may occur during high-flow periods or periods when vegetation decomposes, if pH changes and resolubilisation or resorption occur.
Microbial desalinisation cell	Low-cost, sustainable option which can simultaneously treat water, desalinate saline water, produce electrical energy, and recover valuable chemicals (refer Gujjala et al., 2022). Best suited to pre-treatment step for the conventional desalination processes. Examples include *Bacillus* and *Paenibacillus* phylotypes (Sharma et al. 2021); Salt-tolerant (halophilic) organisms (*Bacillus sp*. strain) (Zhuang, et al., 2010); saline wastewater treatment with purple phototrophic bacteria (Hülsen et al., 2019).
Bioremediation (Natural biogeochemical processes)	Self-neutralising approach, however, may take years until the decisive biogeochemical processes are naturally established in a lake scale.

7 Aquatic Ecosystems

Demonstrating that aquatic ecosystems are a sustainable PMLU for a void is of great interest to industry, as it can justify not considering other, more costly, options (such as backfilling or treating water) and it avoids declaring a void as a NUMA.

With respect to coal mine voids, there is not a lot of recorded or easily accessible knowledge about the type of ecosystems that can be sustained by water bodies with elevated salt concentrations. In general, where water is present, it tends to support biota that may be considered as simplified or complex ecosystems that are adapted to the water conditions present. In the case of residual voids, there is not extended knowledge about what this type of ecosystem might include, with unresolved research questions.

Where a residual void becomes a permanent waterbody in a semi-arid environment with ephemeral flow regime such as occurs in many parts of Central Queensland, it can be distinctly different from the surrounding environment. Risks can include providing habitat that favours pest species.

7.1 Current knowledge baseline

Most of the available knowledge has been derived from studies in metalliferous mines, where the void is normally bounded on all sides by relatively undisturbed rock. The walls of a hard rock pit void are often vertical to sub-vertical and the resulting void's geometry is different from that of coal mine voids. In this context the term "pit lake" is used rather than water-filled void. The knowledge base is therefore mostly related to pit lakes.

Typically, pit lakes present several key constraints that make them unsuitable for the establishment of aquatic ecosystems. In terms of their morphology, they have a high relative depth to surface area and an unnatural geometry with minimal natural slopes. The high relative depth to surface area promotes stratification which leads to changes in chemical characteristics with depth and the steep side slopes of mine voids create sheltering effects which inhibit wind induced mixing (Huber et al., 2008). Pit lake catchments were often intentionally minimised to reduce catchment inputs and prevent overtopping of the pit, thereby decreasing the potential to capture high quality water where exposed geologies are benign. On the other hand, the benefit of this is to reduce the inputs of lower quality runoff from problematic exposed geologies (Lund et al., 2020).

7.1.1 Stratification

Stratification can occur in some circumstances and leads to changes in chemical characteristics:

- TDS and EC tend to increase with depth.
- Hypolimnion (lower stratum) has the tendency to contain low dissolved oxygen (DO) concentrations, if oxygen demand (chemical and/or biological) is high enough.

For coal mine voids, stratification remains a risk but anecdotally, it is not as prevalent as with metal mine pit lakes, potentially due to the different shape, depth and timeframes for reaching water level equilibrium.

7.1.2 Connection to catchments

Pit lake sediments typically consist of residual crushed rocks from mining which are typically devoid of organic matter. This is exacerbated by the lack of fringing or riparian vegetation, which is required for stability and erosion control, and low inputs of allochthonous carbon (leaf litter). It is therefore important to establish connections to a vegetated catchment which can increase benthic organic matter and potentially promote autochthonous carbon (Laskov et al. 2002). Over time, benthic organic matter in pit lakes can develop similarly to natural waterbodies, which is likely to be a key part of ecosystem development (Lund and McCullough, 2011).

The littoral zone of a natural lake is the nearshore interface between the terrestrial ecosystem and the deeper pelagic zone of the lake. These areas are biodiverse, spatially complex, and are generally the most productive area of the lake as they contain increased levels of dissolved oxygen and organic matter relative to the rest of the water body. These areas also influence the movement and processing of allochthonous carbon. Therefore, designing gently sloping banks with a variety of depths helps to create these heterogeneous edges that receive inputs of terrestrial organic matter from the wider catchment. Landscape contouring can also extend beyond the lake shoreline to facilitate passive input of allochthonous carbon (Blanchette and Lund, 2016).

7.1.3 Influence of biomass

The carbon availability in most water bodies generally increases over time, however this is generally not the case for pit lakes that are characterised by acidic conditions, as nutrients bind to pit substrata thereby limiting primary production (Blanchette and Lund, 2016). The addition of large quantities of nutrients is therefore required to support primary production. This requires on-going management, which presents numerous challenges post closure. Biomass additions may cause the void to act as a carbon source or sink, depending on site specific factors, therefore further research and site-specific analysis should be considered (Blanchette and Lund, 2016).

7.2 Knowledge gaps

Most of the available information has been acquired for metal mines. In Queensland, there is not as much information about sustaining aquatic ecosystems in water-filled voids, although research projects are underway. Nevertheless, the information for metal “pit lakes” can be used to inform the simplified designs: it is important to establish connections to a vegetated catchment, which can increase benthic organic matter and potentially promote presence of organic carbon, although trials are likely necessary to determine whether a void will act as a carbon source or sink. To promote ecosystem development, voids should be shaped to match the critical components of natural lakes, namely the formation of littoral areas and integrated catchments. Partial backfilling could be considered, with material short-hauled at the end of life of mine. This could be used to create shallower benches or construction of islands that would support a greater proportion of habitat and a more diverse aquatic ecosystem. Rafts are often used to facilitate biodiversity outcomes. These requirements can be included in the pit optimisation and the simplified designs.

8 Identifying post-mining land uses

8.1 Identification of PMLUs

The selection and justification of appropriate and viable PMLUs is a key statutory obligation within the PRC plan. Mine operators are required to propose suitable land uses following consideration of the surrounding landscape, community views and the objectives of local and regional planning strategies. Worden et al. (2021) show that local knowledge derived from stakeholders can be used to inform expert-driven assessments of PMLU suitability and provide valuable insights into the collaborative potential and opportunities for each option. There are opportunities for early strategic planning, identification of innovative PMLU options and collaborative use of post-closure mine assets, such as infrastructure (power, road/rail, buildings), dams and voids.

A list of potential PMLUs for residual voids and the key criteria that can be used to assess their suitability have been summarised in Table 5. The list of options is based on those identified during a comprehensive review as part of baseline works commissioned by the Queensland Resources Council (Worden et al., 2021) but has been framed for the purposes of this report. While the list may not represent all possible PMLUs for a given site, it can assist with broadening the number of options. The suitability of each will be influenced by the time left until mine closure, as some PMLUs will require investigations over a long timeframe (e.g., 5 to 10 years). In Table 5, suitability is assessed at the following three phases of mine life: “Pre-approval”, “Operational” and “Prior to closure”, which are described in Section 3.1.

Table 5. Potential Post Mining Land Uses for residual voids and suitability at mine lifecycle phases

Potential PMLU	PMLU Description	Suitability assessment criteria	Suitability for each mine lifecycle phase
Options for Material-Filled Voids			
Native ecosystem	Land used primarily for conservation purposes, based on maintaining the essentially natural ecosystems or investing in re-establishing the natural ecosystems. In the context of PMLU, the latter is more relevant and will often take the form of creating native ecosystem corridors that aim to reverse habitat fragmentation.	Many mines in Queensland have existing commitments to return some land to native ecosystems. If the mine is located in close proximity to remnant ecosystems that are not part of the formal protected areas network, there will be significant benefits from this land use.	Pre-approval: yes Operational: yes Prior to closure: yes Sufficient knowledge is available to consider this for all 3 phases
Grazing	Of native or modified pastures. The most common livestock in Queensland is cattle.	Most mines in Queensland have existing commitments to return some land to grazing. Factors that should be considered include sensitivity to climate change and rainfall variability, re-establishment of growth medium and pasture.	Pre-approval: yes Operational: yes Prior to closure: yes Sufficient knowledge is available to consider this for all 3 phases
Cropping	Refers to the planting of trees, shrubs or suitable crops in a dryland farming setting, with the option of access to irrigation when feasible. It also refers to types of cropping that will enhance carbon sequestration.	Suitability of growth medium to support proposed crops. Economic returns will depend on carbon mitigation policy Results from site trials, particularly when considering using mine water for irrigation.	Pre-approval: yes Operational: yes Prior to closure: no Additional knowledge is required (1-5 years)
Renewable energy - Solar	Solar farms are an alternative that can increase the value of land where it is of marginal value. Two to three hectares are generally needed to produce 1 MW.	Alignment with state strategic plans Requires high solar radiation, low annual rainfall, and low cloud coverage. Most areas in Queensland meet this requirement. Proximity to energy transmission lines or substation Open land / sparse landcover / free from shading Suitable topography (slope < 5%)	Pre-approval: yes Operational: yes Prior to closure: no Additional knowledge is required, particularly in addressing regulatory barriers (1-5 years)
Renewable energy - Wind farms	Wind farms are an alternative that can increase the value of land where it is of marginal value.	Alignment with state strategic plans Suitable climate characteristics (strong and consistent winds): average annual wind speeds of 6.5m/s or greater at 80m are generally considered commercially viable	Pre-approval: yes Operational: yes Prior to closure: no Additional knowledge is required, particularly in addressing regulatory

Potential PMLU	PMLU Description	Suitability assessment criteria	Suitability for each mine lifecycle phase
		Proximity to energy transmission lines or substation Open land / sparse landcover Suitable topography (flat) Accessibility for maintenance	barriers (1-5 years)
Renewable energy - Pumped hydro energy storage (PHES)	Operates similarly to a traditional hydropower system where water from a high elevation is channelled through a turbine to spin a generator. The difference is that water is pumped to the high elevation using a form of renewable energy, usually solar. During the day, solar panels produce electricity which is used to pump water from a storage at low elevation to another at higher elevation. At night, water is channelled down to the turbine. While it is not itself a source of energy, it enables direct control over the timing of electricity generation and addresses the key constraint of renewable energy production. For example, the Kidston Pumped Storage Project at the disused Kidston Gold mine in North Queensland. Located 280km north-west of Townsville, the project generates up to 330 MW of rapid response electricity for delivery into Australia's National Electricity Market.	Alignment with state strategic plans Head availability (elevation difference available to drive flow between highest and lowest storage) Water volumes – require a minimum of 1GL Distance between upper and lower reservoirs to minimise cost of infrastructure.	Pre-approval: yes Operational: potentially Prior to closure: no Additional knowledge is required, particularly in assessing available head difference between voids and assessing whether underground workings can be used as lower elevation storage. (5-10 years)
Renewable energy - Hydrogen	Hydrogen gas ('hydrogen') is a versatile energy carrier and feedstock, derived primarily by splitting water or by reacting fossil fuels with steam or controlled amounts of oxygen. Hydrogen may be produced via two mature pathways: • Thermochemical: this uses a fossil fuel feedstock to produce hydrogen. Mature technologies include steam methane reforming, which relies on natural gas as an input, and coal gasification.	Mine water quantity and quality Capital costs Proximity to infrastructure (gas pipelines, transport corridors)	Pre-approval: yes Operational: potentially Prior to closure: no Additional knowledge is required, particularly in assessing how void water can support hydrogen production (1-10 years)

Potential PMLU	PMLU Description	Suitability assessment criteria	Suitability for each mine lifecycle phase
	• Electrochemical: it involves the use of an electrical current to split water into hydrogen and oxygen and requires the use of low or zero emissions electricity to produce clean hydrogen. Hydrogen can be used for transport fuel, an export energy, electricity generation, wastewater treatment.		
Phytomining	The harvest of metals from the living tissue of a group of plants known as hyperaccumulators, which retain metals in high concentrations after absorbing them through their roots. These plants can absorb metals from mining wastes and tailings facilities that contain valuable metals, such as cobalt. Phytomining is an innovative solution because it can complement the global supply chain for critical minerals while promoting circular economy concepts by utilising mining waste.	Presence of valuable trace elements in the waste materials (including mine water) Presence of hyperaccumulators in region	Pre-approval: yes Operational: yes Prior to closure: yes
Protected horticulture Intensive livestock	The intensive growing of food products, mainly fruit and vegetables, in structures that protect the crops (e.g. greenhouses or mine buildings that have been adapted for this purpose). It is the fastest growing food producing sector in Australia. Modern approaches to protected horticulture include a range of technologies, such as automatic control of temperature and of water and nutrient delivery. Mine sites usually have water storage facilities that could be re-purposed to support requirements for water	Water availability Proximity to infrastructure (transport corridors) Environmentally controlled and not climate dependent	Pre-approval: yes Operational: yes Prior to closure: yes Only requires pilot project to demonstrate feasibility
Regenerative cropping	The use of a combination of techniques to restore soil health, such as planting cover crops and perennials to protect the soil, not using tillage, pesticides or synthetic fertilisers, and establishing multiple crop rotations. Generally, regenerative cropping is only	It is highly supported by regional stakeholders and could deliver socio-economic benefits	Pre-approval: yes Operational: potentially Prior to closure: no There is no precise definition of what it entails, with a range of practices

Potential PMLU	PMLU Description	Suitability assessment criteria	Suitability for each mine lifecycle phase
	applicable to land that is free from severe soil constraints.		being implemented. As such, it requires investigation.
Manufacturing	A manufacturing hub is a section of a town that has been designated, planned and zoned for industrial development. It is structured to bring together complementary services and features that benefit the companies that occupy space there.	Socio-economic potential Proximity to infrastructure (transport corridors, electricity supply network, gas and water pipelines)	Pre-approval: potentially Operational: potentially Prior to closure: no The location of mine sites in Queensland limits the potential for such land use but there could be opportunities in some areas. It will require extensive engagement with a range of stakeholders (5-10 years)
Tourism	Advancing tourism is a key aspiration for many local governments across Queensland. There is potential to enhance tourism opportunities post-mining by connecting with mining heritage and leveraging off existing tourism destinations.	Socio-economic potential Collaborative potential Proximity to infrastructure (transport corridors, electricity supply network, gas and water pipelines)	Pre-approval: potentially Operational: potentially Prior to closure: no The location of mine sites in Queensland limits the potential for such land use but there could be opportunities in some areas. It will require extensive engagement with a range of stakeholders (5-10 years)
Options for Water-Filled Voids			
Aquaculture	Commercial production of fish and/or crustaceans using ponds, cages, raceways or floating tanks	Water quality suitability Assessment of contaminant uptake by fish Additional investment in terms of food sources Scale of production Existing infrastructure	Pre-approval: yes Operational: potentially Prior to closure: no There have been assessments undertaken at some mines but it would require demonstration of suitability via pilot projects. It will require support and engagement with aquaculture industry (5-10 years)
Smart water supply systems Agricultural systems irrigated	Use of mine water for agricultural irrigation (grazing and cropping) by using advanced water quality control and water delivery technologies. This can also deliver increased carbon capture by locking it in soils and plants.	Water quality suitability and mitigation options Soil constraints	Pre-approval: yes Operational: potentially Prior to closure: no The suitability of using mine water for irrigation must be assessed and

Potential PMLU	PMLU Description	Suitability assessment criteria	Suitability for each mine lifecycle phase
by water from the void			is likely to require treatment or other form of mitigation.
Mine water trading	Addressing water management issues by treating mine water and trading it to support new projects, such as urban water supply, irrigation, fire fighting	Proximity to infrastructure Water demand Water quality suitability	Pre-approval: yes Operational: potentially Prior to closure: no The suitability of using mine water must be assessed and is likely to require treatment or other form of mitigation
Aquatic ecosystems	Establish a vibrant ecosystem in the void by ensuring it is designed according to best available knowledge	Water quality suitability Presence of, or ability to generate, benthic organic matter and organic carbon. Presence of littoral areas and connection to vegetated catchments.	Pre-approval: yes Operational: potentially Prior to closure: potentially Research is required to define the characteristics of vibrant ecosystems established in voids (1-5 years)
Production of algae, seaweed, biomass or microalgae	Use voids to grow species of algae or seaweed that can be harvested and used for a range of purposes. There is potential for using seaweed (Asparagopsis) as methane-mitigating fodder. Microalgae are increasingly being recognised as offering a low-cost alternative for saline water treatment. They can be harvested and processed to create a liquid biofertiliser. Many of the halophytic (salt tolerant) microalgae are rich in lipids and can be used as precursor for biofuels.	Supply/availability of nutrients (nitrogen and phosphorous) Water quality suitability. Lifecycle of the salt or other contaminants uptaken by algae.	Pre-approval: yes Operational: potentially Prior to closure: no The suitability of using residual voids for commercial cultivation is unclear at this stage as most research has been undertaken in laboratory conditions. Research is required to establish the suitability of water quality and to develop harvesting techniques (5-10 years)

8.2 PMLU evaluation: suitability assessment

8.2.1 Technical feasibility

Assessing the technical feasibility of a PMLU requires compiling information about:

- Biophysical parameters such as soils, climate or water availability, as some PMLUs require specific biophysical characteristics. Agricultural systems are examples of such PMLUs.
- Infrastructure networks as many PMLUs require inputs of energy or water, as well as the means to export their production.

A comparison of the different PMLU options will help to determine which option would be most suitable on a site-by site basis. An understanding of the site characteristics and its regional context is important for assessing the feasibility of the different options for PMLUs for residual voids. A potential methodology is to assign a score against selected technical parameters (rainfall amount and variability, soil suitability, access to power or water, and any other relevant ones). Scores can be from 1 to 5, where 1 indicates that the technical aspect is a severe constraint and 5 indicates that it poses no constraint. Scores can then be complied and ranked to compare the suitability of the PMLU options. There is flexibility in the assessment methodology and this advice is not prescriptive.

However, given the closure timeframe, climate change must be included in the feasibility assessment. The Queensland government regularly publishes information about predicted impacts of climate change, based on updated modelling. Under the current emission trajectory, it is expected that maximum, minimum and average temperatures will continue to rise and:

- there will be a substantial increase in the temperature reached on the hottest days, an increase in the frequency of hot days and the duration of warm spells
- there will still be high variability in rainfall and the intensity of heavy rainfall events is likely to increase
- the south of the state is likely to experience more time in drought
- there will be harsher fire weather, reflecting fuel dryness and hot, dry, windy conditions; and
- there is a projected decrease in mean rainfall, but with more extreme rainfall events.

Changes in climatic attributes such as rainfall and temperature are known to fundamentally affect crop yield and pasture productivity. Shifts in rainfall volumes and timings, increases in temperature, and more severe droughts and hot spells predicted under climate change all have the potential to significantly alter agricultural production (Worden et al., 2021). The selection of PMLUs for residual voids will need to consider these projections. PMLUs will need to (1) be adapted to rainfall variations; (2) be able to handle extreme rainfall and flooding; (3) be able to sustain extreme temperatures; (4) be fire resilient; and (5) adopt infrastructure standards that withstand severe cyclonic activities, where required. Assessing resilience in the context of climate change predictions is critical and PMLU designs should consider climate change challenges and scenarios.

8.2.2 Socio-economic aspects

A socio-economic baseline assessment provides a snapshot of a context at a particular point in time. The assessment can be undertaken at any stage of the mining lifecycle. At the project stage, social impact assessments are often used to provide the socio-economic context ahead of mining. Socio-economic baselines can also be conducted during operations or to understand what may happen once mining ends and the host community transitions to a post-mining alternative. A desktop assessment can provide a baseline of PMLU priorities and aspirations for companies, local communities, regional councils and the Queensland Government by analysing qualitative and quantitative data.

Once the list of suitable PMLUs has been established, they need to be added to the scenario analyses.

9 Closure risk profile

The closure risk profile can be expected to vary between scenarios and through time. These profiles must be quantified through time (annually as a maximum time increment) and for each scenario. The method of quantification must be consistent and comparable between scenarios. The costs of establishing and maintaining the selected PMLU, including costs associated with sourcing material, water quantity and quality management, design and construction, and monitoring will also need to be quantified.

At this strategic level of analysis, the goal is to produce a high-level assessment of financial liability. The estimated rehabilitation cost guideline and associated tool[3] can be used but will need to be adjusted for that strategic purpose. In addition, it is not intended that liability be assessed for the whole site: the aim is to compare liability between scenarios for the final voids. With reference to the estimated rehabilitation costing tool, the items that are most likely to have an impact on the liability associated with a PMLU for a residual void are:

- Infrastructure (e.g., pipes, weirs and pumps)
- Water storage
- Water treatment
- Waste rock dumps
- Tailings storage facilities
- Pits.

It is suggested to assess the differences between scenarios in terms of these items, as far as practicable.

There will also be costs and expenses arising from residual risks. These are the risks that remain at completion of rehabilitation activities and require ongoing management activities, such as monitoring and/or remedial actions. An assessment of residual risks will be required and should be based on the identification of credible risk events (DES, 2022). As several credible risk events can arise from residual voids (e.g., wall failure, contaminated discharge), the costs associated with residual risks should be included in the closure risk profile of the PMLU options.

High-level financial liability and residual risks cost calculations should be derived for each scenario. This will need to be converted into a time series of liability amounts for input into the financial model (Table 6). It is critical to distribute the amounts over time as it will capture the differences between the options with a progressive rehabilitation program and those with rehabilitation activities scheduled at the end of the mining activities (Section 2.1.11).

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[3] These documents are accessible at: https://www.business.qld.gov.au/running-business/environment/licences-permits/rehabilitation/resource-activities

Table 6. Illustration of financial liability input into financial model

Scenario PMLU selection	Material-filled void Grazing	Water- filled void Supply to irrigated cropping	Water-filled void Aquatic ecosystems
Liability from void PMLU Including consideration of residual risks, ongoing monitoring costs and best practice management costs as per the PRC guideline	Amount 1	Amount 2	Amount 3
2020	X1	Y1	Z1
2025	X2	Y2	Z2
2030	X3	Y3	Z3
2040	X4	Y4	Z4

10 Valuation

10.1 Financial analysis

Valuation is likely to be a key driver of the consideration of the three strategic scenarios. It is also likely to be one of the most contentious and subjective points. Standard financial considerations emphasise nearer term financial returns, and aggressively devalue longer term costs, investments and options. This can be expected to impact significantly on any PMLU option that sits further in the future. For example, if we consider the same PMLU option at two different operations, where the second operation has a longer mine life, standard valuation approaches would devalue the PMLU to a greater extent at the second operation. Pure financial decision-making drivers sit at the core of misalignment between mining shareholders and community stakeholders.

The analysis of the value proposition must consider the comparison between the value generated by mining activities and the PMLU options. One issue fundamental to the assessment of almost any PMLU option is the financial metric used to compare the options. Standard Net Present Value (NPV) analysis produces a wide range of issues that have been well-identified in literature and are not specific to mining (Martin, 1994; Halliwell, 2011; Espinoza and Morris, 2013; Weitzman, 1998; Weitzman, 2001; Weitzman, 2010; Robichek and Myers, 1966; Lilford, Maybee et al.; 2018; Damodaran, 2007; Halliwell, 2001). The crux of the issue relates to the application of the discount rate as a simplified metric to capture both the perceived risk profile of an investment and the opportunity (time) cost representing what could have been earned on a similar investment. It is only a “best guess” about what can happen in the future. This approach has the effect of significantly reducing the ascribed value associated with any longer life value stream, particularly those with a lower cash generation intensity. Similar issues regarding discount rates and timeframes not adequately supporting decision making are present in other areas of society, such as those relating to the storage of nuclear waste, aspects of societal infrastructure, and investments in forestry, for example.

Another issue relates to the order of the valuation calculations. In strategic planning frameworks, mining activities occur first and the value generated by the PMLU commences once the mining operations have ceased. Therefore, the value generated by the mining operations will be subject to a significantly lower level of impact from discounting than the PMLU. Not only is there likely to be a contrast in the intensity of cashflow generation, but it will also be exacerbated by the timing of these activities and the associated discounting profiles.

The problems outlined above have been long identified, with a multitude of alternative approaches explored. To date none of these have gained significant traction, and NPV remains the preeminent approach that is used in the mining industry to support financial and investment decisions.

This structural disconnect in the perspective of value, until resolved, will remain a source of contention between stakeholders. It will also serve to obfuscate the discussions and analysis of PMLU options and therefore present as a barrier to efficiently achieving consensus between the increasing range of active stakeholders. The resolution of this is beyond the scope of this document but it is important that mine planners are aware of the limitations that NPV analysis poses to PMLU evaluation.

Different PMLU options will have impacts on the potential value of the asset to both the company investing in the mining operation and to those who would benefit from the PMLU option. A backfilled void can be expected to negatively impact the value to the mine stakeholders but can potentially positively impact regional stakeholders. All PMLU options would need to be assessed and valued using an impartial approach that considers the potential value to all stakeholders.

Within the current NPV-based decision-making framework, certain observations can be made that could be expected to remain to a greater or lesser extent, even if the discounting mechanism were to be modified. For example, backfilling the void will result in a reduction in royalties and taxes payable, due to the mathematics of the pit optimisation process likely driving towards the selection of a smaller ultimate pit. The costs associated with backfilling can reduce the profitability of the operation and therefore the taxes and royalties payable. These reductions, from a societal perspective, could be directly compared to the potential value to be generated by a PMLU.

The following highly simplified example is included to illustrate the impact of backfilling on the value generated to both society (through taxes and royalties) and to the mine operator. The example is based on a hypothetical coal mine with a 10 year mine-life, with royalties calculated as 5% of profit and taxes as 30% of profit remaining after royalties are paid. Table 7 presents the NPV-based value generated for society and the mine operator if a residual void is left as a non-backfilled void (potentially a non-use management area (NUMA)).

Table 8 presents the same information for the equivalent scenario where the residual void is backfilled. Table 9 provides a summary of the financial impacts. Note that no adjustment has been made in this simplified example to the ultimate pit size. This simplified example does not cover all the issues identified in this guidance (e.g residual risk and management costs post closure), however it illustrates the key point: standard financial analysis based on NPV would conclude that leaving the residual void as NUMA is preferable, for both society and the operator. In a purely NPV-based analysis and decision-making framework, any PMLU option would need to generate additional value to compensate for the NPV reduction resulting from the costs of backfilling the void. Sole use of NPV to assess PMLUs for voids is not recommended as it may not reflect the true costs and benefits. Accordingly, it is important to recognise both current and future costs and benefits to stakeholders.

Again, given that the standard valuation of a PMLU option would be discounted to a future point in time (in all likelihood to some time after the closure of the mining operation), standard financial theory and the associated underlying mathematics will make the case for PMLU selection challenging and contentious. In situations where the ultimate pit is driven by incremental economic factors, backfilling a void may also result in sterilisation of potential future resources. This would need to be assessed to determine the value at risk (VAR) for various pricing scenarios. This is particularly pertinent in coal mines, where historical final highwalls have been re-developed due to changing economic conditions. This type of analysis would also need to consider any potential in risk reduction and post-closure liabilities. This would also need to consider more qualitative factors such as the aesthetics of waste dumps and the alignment with the natural surroundings.

10.2 Resource sterilisation

Society continues to demand commodities at an ever-expanding rate. Recent research (Valenta et al., 2019) as well as price houses (WoodMac, SNL) have provided some compelling analysis and data outlining potential commodity supply shortages over the medium term (10 – 50 years). There is, therefore, potential for structural changes in commodity price levels.

One risk to filling voids is that it can be expected to effectively sterilise any resources remaining in the ground. Given that society has access to currently finite resources, this presents as a risk at both a societal level, and to the operating company in terms of a forfeited value under multiple lenses. Associated with this are the royalties and taxes that would otherwise be delivered should the operation continue under favourable financial circumstances. Numerous instances exist of operations that have been placed in care and maintenance and then re-established under conditions in which the resource price is high or operating costs decline.

Whilst history provides no guidance as to what will happen in the future, volatility in commodity prices can be expected to continue, along with structural changes in the price base of commodities as the relationship between supply and demand changes. Current analysis implies that commodity prices have the potential to increase, which would then potentially result in a forfeited opportunity where voids have been filled leaving resources in the ground. This risk will be exacerbated if the pit optimisation process had incorporated a requirement to fill the void, and a smaller ultimate pit was selected.

For metalliferous deposits, there is the potential that mineralisation peripheral to the primary deposit may contain commodities of potential future value, depending on the specific geological formation of the deposit. As society’s requirements for a wider range of commodities expands (e.g. to support production of batteries), the risk of sterilising resources might become even more of a concern.

The scenario with material-filled voids should consider the resource sterilisation risk, ideally quantifying it under a range of plausible future commodity prices. This risk assessment will be an input into the final decision-making process: it cannot be the sole consideration.

Although resource sterilisation risk is a possibility, according to the Progressive Rehabilitation and Closure plan guideline (DES, 2021), disturbed land that is not being mined is required to be rehabilitated when the land has been identified as containing a probable or proven ore reserve that is to be mined in the next 10 years after the land would otherwise become available for rehabilitation (section 126D(5) of the EP Act). There may be issues with delaying rehabilitation for this reason, such as the removal of landform shaping machinery and degradation of topsoil.

10.3 Financial model

The financial model would typically be the corporate financial model (or equivalent). It is important that the same financial model be used with the same structure between scenarios to ensure they are consistent and can be compared. There will clearly be differences between scenarios, relating particularly to costs and risks, and these differences should be defensible and clearly detailed for each scenario. Evaluation of PMLU options for voids cannot be limited to standard NPV calculations. It requires indicators that incorporates a more robust consideration of future risks, benefits and values. The financial model should be used to provide a wider range of financial results. It is suggested to analyse the three strategic scenarios in terms of:

- Standard NPV
- NPV adjusted for inflation (e.g., Consumer Price Index, as discussed in the section on scenario parameters)
- Streams: Owner/operator, Taxes, Royalties, Employment, PMLU options

Table 7. Hypothetical financial analysis for a non-backfilled void under Net Present Value

Year	1	2	3	4	5	6	7	8	9	10
Tonnages	25	25	25	25	25	25	25	25	25	25
Revenue	$6,250	$6,250	$6,250	$6,250	$6,250	$6,250	$6,250	$6,250	$6,250	$6,250
Costs	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750
Profit	$2,500	$2,500	$2,500	$2,500	$2,500	$2,500	$2,500	$2,500	$2,500	$2,500
Royalties	$125	$125	$125	$125	$125	$125	$125	$125	$125	$125
Taxes	$712.50	$712.50	$712.50	$712.50	$712.50	$712.50	$712.50	$712.50	$712.50	$712.50
Society	$838	$838	$838	$838	$838	$838	$838	$838	$838	$838
Operator	$1,663	$1,663	$1,663	$1,663	$1,663	$1,663	$1,663	$1,663	$1,663	$1,663

Table 8. Hypothetical financial analysis for a backfilled void under Net Present Value

Year	1	2	3	4	5	6	7	8	9	10
Tonnages	25	25	25	25	25	25	25	25	25	25
Revenue	$6,250	$6,250	$6,250	$6,250	$6,250	$6,250	$6,250	$6,250	$6,250	$6,250
Costs	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750	$3,750
Void Fill	$0	$0	$0	$0	$0	$35	$53	$88	$175	$875
Profit	$2,500	$2,500	$2,500	$2,500	$2,500	$2,465	$2,448	$2,413	$2,325	$1,625
Royalties	$125	$125	$125	$125	$125	$123	$122	$121	$116	$81
Taxes	$712.50	$712.50	$712.50	$712.50	$712.50	$702.53	$697.54	$687.56	$662.63	$463.13
Society	$838	$838	$838	$838	$838	$826	$820	$808	$779	$544
Operator	$1,663	$1,663	$1,663	$1,663	$1,663	$1,639	$1,628	$1,604	$1,546	$1,081

Table 9. Summary of financial impacts of the two scenarios (residual void as NUMA vs. backfilling)

		Non-backfilled	Backfilled	Difference	Variance
Net Present Value	Society	$5,146	$4,979	-$167	-3.25%
	Operator	$10,215	$9,883	-$332	-3.25%
Undiscounted Cashflow	Society	$8,375	$7,965	-$410	-4.90%
	Operator	$16,625	$15,810	-$815	-4.90%

11 Decision-making process

The intention of this guidance document is to influence the practices that are implemented to make decisions about the rehabilitation and closure of residual voids. It suggests implementation of an integrated planning platform that has been designed to assist with:

- Identifying all potential opportunities and constraints for post mine uses of voids, including consideration of land uses for water-filled and backfilled voids
- Understanding and assessing the aspects of mine planning and void design that can influence the feasibility of a PMLU for a void, such as the impacts of catchment extent on the water balance, of waste placement on water quality, and slope design on potential to support aquatic ecosystems
- Developing and selecting scenarios that can be compared based on their closure risk profile and financial performance indicators.

Implementing this platform will ensure that all potential options have been considered and that their relative risks have been assessed. It will deliver the knowledge base to support the selection of the most suitable option.

As outlined in the section on identifying PMLUs, mine operators are required to propose suitable land uses following consideration of the surrounding landscape, community views and the objectives of local and regional planning strategies. The perspectives of multiple stakeholders must be included in the consideration of the most suitable PMLU option. In particular, the evaluation of the regional benefits that can be derived from the PMLU options are essential and should feature in the decision making. Broadly, the decision-making process should include perspectives related to:

- Regional communities, their goals and aspirations
- Landholders
- Local indigenous groups
- The environment: the spectrum of natural assets that provide environmental benefits through ecosystem services such as clean air and fresh water
- The operator: the company operating the mine
- Government structures, particularly at state and local level.

In general, communities and local governments will expect options that support regional economic activities, mostly employment opportunities and regional investment, whilst maintaining and enhancing environmental outcomes; the operator may seek the solution with the most advantageous financial outcome that delivers corporate policy goals on environmental, social and governance commitments; the State government may be concerned with resource sterilisation, which may stifle future economic development, and risks associated with mine closure; an environmental perspective will focus on the environmental benefits that can be derived, such as increase in biodiversity value, carbon capture, or improvement in water availability or quality.

The risks and benefits that can be derived from the PMLU options need to be evaluated with these perspectives in mind. There is no widely accepted method to do this and there are several options. Many companies have already tested and applied structured approaches to analyse opportunities related to integrated closure planning (Grant et al., 2018). The methods that are already embedded in business processes could be suitable for the purpose of evaluating PMLU options, provided they include the elements outlined above.

In the absence of well-established decision-making processes, two qualitative approaches are proposed:

- A PMLU valuation method to assess the value generated by the PMLU options
- A multi-criteria analysis to compile the outputs from the financial model and the PMLU valuation and present them in terms of several stakeholders' perspective.

The outcomes from these approaches can then support the final decision, but this has not been tested for the purpose of selecting a PMLU for voids. The approaches are described to illustrate how the perspectives of multiple stakeholders can be included in the consideration of post-mining futures. A potential subsequent phase of work could test the applicability and validity of this decision-making process, if required.

11.1 PMLU valuation: Five Capital Framework

One approach is to apply the Five Capitals framework. It is a widely recognised framework that is usually applied to regions to characterise the goods and services that are needed to maintain regional prosperity and improve residents' quality of life. Sustainable land uses will maintain and where possible enhance stocks of capital assets, rather than deplete or degrade them. The five types of capital are:

- **Natural capital** including renewable and non-renewable materials, and processes such as neutralising waste or regulating climate
- **Human capital** consists of people's health, knowledge, skills and motivation. These can be enhanced through education and training and other human services
- **Social capital** or the institutions and relationships that help maintain and develop other forms of capital in partnership with others; e.g. families, communities, businesses, trade unions, and voluntary organisations
- **Manufactured or built capital** comprises material goods, infrastructure or fixed assets that regional residents and businesses can utilise; e.g. tools, machines, communications and transport and buildings
- **Financial capital** plays an important role in regional economies, enabling the other types of capital to be owned and traded. The financial resources at people's disposal and available to local businesses and human services and civil society organisations influences their well-being and signals the degree of social equity.

Given there is no agreement on the method that should be adopted to "go beyond NPV", it is suggested that the mine planning scenarios and associated PMLU selection can be assessed with a Five Capitals framework, which can be adjusted to an operation's specific goals, objectives and context. It can provide and communicate the values that can be derived from suitable PMLU selection, through a concise and consistent assessment of non-financial aspects.

In practice, the planning team would derive the impact of each scenario on each category of capitals, outlining whether the option would lead to an increase or a decrease in the capital stock and providing an indication of the extent of the variation in capital stock (e.g., Low, Medium, High). This is illustrated in Table 10, for 5 PMLUs (3 from the material-filled void scenario, and 2 from the water-filled scenario). The assessment can also be converted to scores. For instance, in Figure 4, the qualitative assessments have been converted to numerical values:

- Increase (High): +3
- Increase (Medium): +2
- Increase (Low): +1
- Neutral: 0
- Decrease (Low to Medium): -1

It is recognised that the assessment of the five capitals for each scenario will be highly qualitative and outcomes might be difficult to communicate. The qualitative findings can then be used as input into a multi-criteria analysis.

Table 10. Illustration of the application of Five Capitals assessment framework

Scenario:	**Material-Filled Void**	**Material-Filled Void**	**Material-Filled Void**	**Water-Filled Void**	**Water-Filled Void**
PMLU:	**Native ecosystem**	**Grazing**	**Cropping**	**Supply to irrigated cropping**	**Aquatic ecosystem**
Natural	Increase (High) Large contribution to ecosystem services	Increase (Low) Small contribution to ecosystem services	Increase (Low) Small contribution to ecosystem services	Increase (High) The void contributes to natural assets	Increase (High) The void contributes to natural assets
Human	Increase (High) Contribution to mental and physical well-being through connection to nature.	Increase (Medium) Contribution to knowledge and skills for establishing grazing on mined land	Increase (High) Contribution to innovation related to the establishment of cropping on mined land	Increase (High) Contribution to knowledge and skills for irrigated agriculture and recycling water.	Increase (High) Contributes to knowledge and education related to aquatic ecosystems.
Social	Increase (High) Opportunities for nature-based organisations, such as Landcare or wildlife management.	Increase (High) Grazing contributes greatly to the regional social fabric	Increase (Medium) Agricultural activities contribute to the regional social fabric	Increase (Medium) Agricultural activities contribute to the regional social fabric	Increase (Medium) The void provides recreational areas
Manufactured	Decrease (Low to Medium) No contribution to infrastructure and man-made equipment	Neutral Negligible contribution to infrastructure and man-made equipment	Increase (Low) Small contribution to agricultural infrastructure	Increase (Medium) Medium contribution to agricultural infrastructure	Decrease (Low to Medium) No contribution to infrastructure and man-made equipment
Financial	Decrease (Low to Medium) No revenue is generated, based on current economic system. This could change with carbon-based markets.	Increase (Low to Medium) Grazing generates revenue	Increase (Low to Medium) Cropping generates revenue	Increase (Medium to High) Irrigated cropping generates revenue, and potentially higher revenue than non-irrigated cropping	Decrease (Low to Medium) Aquatic ecosystems do not generate economic productivity the current system

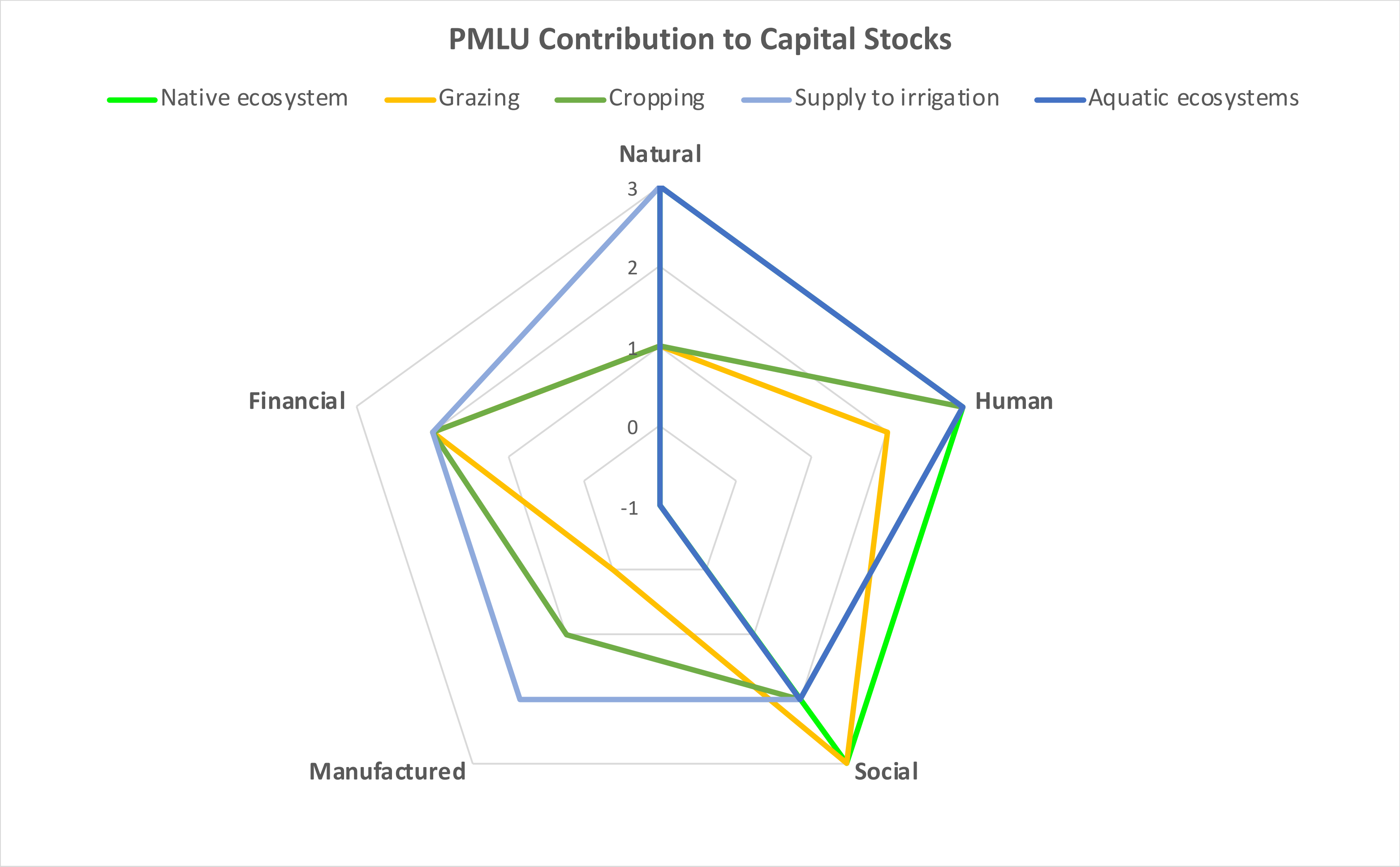

Figure 4. Conceptual representation of Five Capitals assessment framework (hypothetical data)

11.2 Multi-criteria analysis

When applied consistently and transparently, multi-criteria analysis (MCA) is also a suitable approach for comparing options where benefits and impacts are not easily quantifiable. There are a range of ways to apply MCA, but in all cases the analysis should be robust, transparent and defensible. MCA uses objectives, criteria, measures, weightings and scoring approaches to rank and compare options. The selection of weighting is subjective and can impact on overall scoring: it will be critical to develop a transparent process for assigning weighting values.

An example is provided here as an illustration. It considers the three strategic scenarios (maximise operational value, material-filled void, water-filled void) as well as a “no mine” scenario to provide a baseline scoring. For this example, it is assumed each scenario is analysed with standard corporate financial assumptions (related to e.g., discount rate, commodity outlook, as outlined in the discussion on scenario parameter selection).

The outcomes from scenario modelling are complemented with qualitative assessments of other aspects relevant to each stakeholder group, for instance:

- Societal outcomes: additional employment that the scenario will create, regional development (from PMLU valuation), taxes and royalties (from financial model)
- Environmental outcomes: water quality, ecosystem services (from PMLU valuation)
- Operator outcomes: NPV, resource sterilisation risk (from financial model)
- Government outcomes: closure risk profile, resource sterilisation (from financial model).

Scores can be assigned to each of these outcomes. Assumptions supporting the scoring system will need to be explained and justified. For the purpose of illustration, with this example we have assigned to each outcome a score between 1 and 5, where 1 represents the least favourable result and 5 the most favourable result. For instance:

- “Additional employment” is assigned a score of 1 when the scenario does not bring additional employment (e.g., no mine scenario) and 5 when the scenario brings the highest additional employment (e.g., maximise operational value scenario)
- “Ecosystem services” is assigned a score of 1 or 2 when the scenario decreases the ability for the ecosystems to support services (e.g., maximise operational value scenario) and a 4 or 5 when it enhances this ability (e.g., material-filled void);
- “Closure risk profile” is assigned a score of 1 when the risk profile is highest (e.g., material-filled void) and 5 when it is lowest (e.g., no mine).

The scores from all scenarios can be captured in a diagram (Figure 5). Again, this is provided as an illustration: weightings and scoring approaches will need to be tested.

The advantage of multi-criteria analysis is that it can be adapted for a range of stakeholders, interests and outcomes. For instance, construction costs are often an important factor for industry, but they would not be for regulators, who would be mostly concerned with environmental risks. The MCA approach provides a mechanism to include and consider multiple perspectives.

11.3 Further work

Whilst there are options to develop a transparent decision-making process, they will need to be tested through case studies. One area of uncertainty relates to how the results produced by the integrated planning platform can be used to support the broader decision-making process. Testing through case studies might find that additional guidance is required to better outline the types of results that the platform needs to produce to support the decision-making strategies.

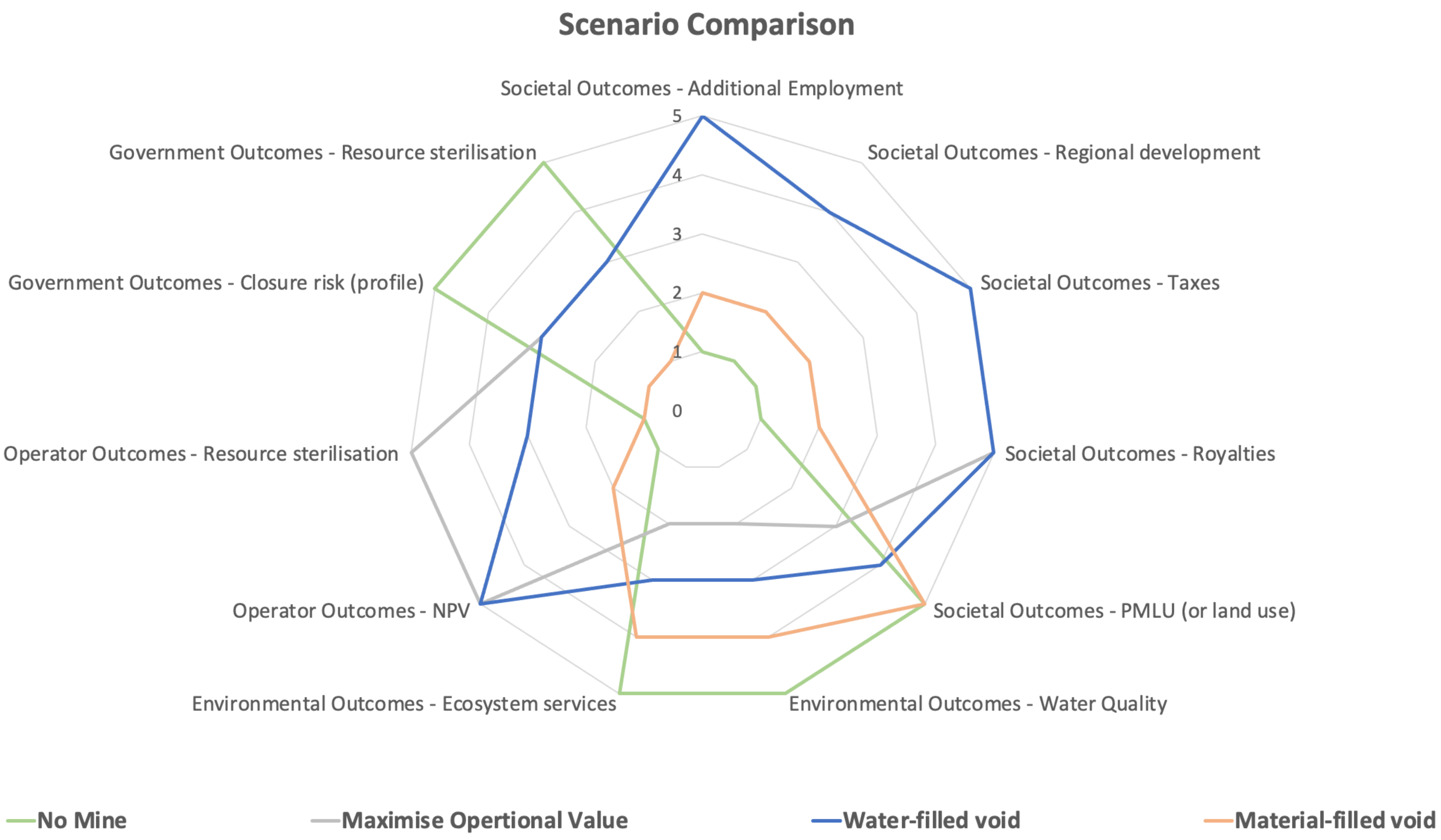

Figure 5. Conceptual representation of a multi-criteria analysis for comparing planning scenarios

12 Summary

This guidance proposes a novel methodology for assessing options for post-mining land uses of residual voids, based on the representation and analysis of various scenarios in an integrated planning platform (Table 11). It is an integrated and iterative approach that is conducive to achieving collaboration between all relevant technical disciplines. It can reasonably be expected that this process will require a greater level of work from these teams and significant testing of this approach will be required. This guidance allows for a consistent and reliable assessment and comparison of PMLU options for voids.

The integrated approach can be applied to any stage of mining: pre-approval, operational, and prior to closure. The number of options and availability of data and information may vary along this timeframe and may lead to a re-consideration of PMLUs. However, once a PRC plan and associated rehabilitation schedule are approved, the PMLUs are effectively locked in. A formal amendment would be required to make changes to the PRC plan and schedule.

The approach will be iterative, but the number of iterations will depend on the scenario and on the number of PMLUs that are identified. The scenario that considers a water-filled void is the most complex and will require detailed understanding of all connections between simplified designs and water assessments, with inputs from multiple teams.

Table 11. Overview of recommended approach

Elements of Integrated Planning Platform	Description
Strategic mine planning	Includes standard pit optimisation and scheduling algorithms. Quantifies implications of modifying mine plans to integrate void PMLU rehabilitation activities. Analyses mine planning scenarios with several variations in financial assumptions.
Simplified designs	Tactical level details are not required to inform the assessment of PMLU options. Simplified designs can be assessed to determine the suitability of a PMLU. Considerations include: • staging pits • geotechnical aspects (stability) • landform shapes • catchments draining to void • distribution and type of waste material • waste disposal strategy.
Water balance assessment	Predicts whether the void will maintain a permanent water body. If it will maintain a permanent water body, estimate whether this will pose risks to the receiving environment via surface or groundwater pathways. Requires catchments assessments from simplified designs.
Water quality assessment	Included quantitative predictions of long term void water quality to enable PMLU decision making. Predictions are based upon distribution and type of waste material from simplified designs. Requires collection of waste characterisation data.
Water quality mitigation	Water quality mitigation scenarios should be examined with aim to produce water of suitable quality for PMLUs. Assessment to include the cost of mitigation options.
Aquatic ecosystem considerations	Assessment of the aquatic ecosystem PMLU to include pit optimisation and simplified designs with a void shape with: • lowered slope angles of the upper sections of the walls • establishing connections to vegetated catchments.
PMLU evaluation	Identify potential PMLUs and assess their suitability. An understanding of the site characteristics and its regional context will be required.
Closure risk profile	Predict costs to establish and maintain the selected PMLU, including those of:

Elements of Integrated Planning Platform	Description
	• sourcing material • water quantity management • water quality management • design • construction • monitoring • residual risks. Derive high-level financial liability calculations for input into the financial model.
Decision-making process	Combine the outputs from the financial model with qualitative approaches to evaluate the option from the perspectives of multiple stakeholders.

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