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Integration of Biophysical Aspects in Mine Closure Planning

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Executive Summary

This foundational project focussed on the interconnections between the biophysical aspects at mine closure. These biophysical aspects comprised surface water and groundwater, geochemistry and water quality, biodiversity and ecosystem resilience, landform stability and re-establishment of self-sustaining ecosystems. The key overarching question posed in this project was: what were we missing by looking at each biophysical aspect in isolation from the others and what strategies were available to promote an integrated view of mine closure? In addressing this question, emphasis was placed on the lack of integration of the technical studies that support a closure plan, rather than on the lack of integration within a closure plan in general.

When the project was initiated, its aim was to demonstrate the value of adopting a system-level description of the biophysical components by building a prototype based on a “synthetic” mine that incorporates a range of sources, pathways, and receptors within its zone of influence. As the project progressed, it became clear that the original aim was too narrowly defined and was concerned with different intended users, without articulating who the users might be. Consequently, the project objectives were reviewed to more clearly articulate the aims of the project and its contributions to CRC TiME research priorities:

1. Overview of current regulatory frameworks and associated current practice for selecting closure objectives.
2. Global and national trends shaping future mining with consequences for mine closure and closure objectives.
3. Review current environmental risk assessment practice to determine suitability for mine closure interactions.
4. System-thinking concepts and their application in understanding interactions between biophysical aspects.
5. Categorising the system-thinking approach for different intended user groups.
6. Examples of system-thinking applications for the development of closure plans for different intended user groups.

The project methodology consisted of two stages. Stage 1 methodology concerned the review of literature and documentation to inform objectives 1 to 4 above. Stage 2 methodology comprised defining the groups of intended users and developing examples of prototypes for each group of users. From applying this two-stage methodological approach, five key findings resulted:

1. There are many examples of the sort of model (or approach) that could be used to capture the main dimensions of integration of biophysical parameters through application of system thinking, with the level of detail encapsulated by each model largely guided by the intended users.
2. System thinking and integration of environmental aspects constitutes a complex area of research and as such, further exploration should focus on simpler approaches, namely ones that will deliver the greatest benefits for relatively small investments.
3. For the five foundational projects in the Operational Solutions Program each covering a key technological theme of significant impact on the process of mine closure and relinquishment, their findings will feed into the systems-thinking and integration approach.
4. As the lack of regional planning and lack of a comprehensive national framework for land use planning are preventing selection and assessment of innovative Post Mining Land Uses (PMLUs), there is a strong need for system approaches which would demonstrate how a mine contributes to a region.

5. The requirement to link technical studies has been identified but there is no robust method to achieve this, and thus constitutes a key research gap.

Based on the project's findings, recommendations are that:

- Defining closure and rehabilitation objectives is critical, along with the ability to adjust them to global, national and regional trends. There is no agreed methodology for the selection of post mining land use and it constitutes a key gap with current practices. There needs to be sustained effort to bridge that gap.
- To facilitate effective communication of closure planning with external stakeholders, a robust methodology is required to guide the development of communication and engagement tools. The methodology should consider the potential for these tools to be delivered in spatial form, using land management studies as example.
- The future research activities that are likely to provide the most benefits are those that apply the concepts articulated by this research project to case studies. For instance, a project or operation with a range of complex inter-relations of biophysical parameters could be used to clearly illustrate the benefits of applying system-thinking to closure planning.
- The findings from the foundational projects of the Operational Solutions Program should be compared with the outcomes of this project as they are likely to further outline the interlinking between the biophysical themes. This interlinking would inform key priorities for future research work in operational solutions.

Key Words: *System-thinking, sustainable mining, environmental studies, integration, mining closure*

1 Introduction

1.1 Background

The proposal for this project was developed after the CRC TiME Research Team had compiled all project ideas that had been submitted in response to the ideation process. A portfolio of foundational projects was designed to identify the disconnects in knowledge, behaviour and institutions that inhibit the opportunities for maximising benefits from mine closure. The review of the ideation proposals outlined that there were recurrent technical themes dealing with knowledge gaps about specific biophysical aspects: surface water and groundwater, geochemistry and water quality, biodiversity and ecosystem resilience, landform stability and re-establishment of self-sustaining ecosystems. In response, a foundational project was created for each of these aspects, but the CRC TiME Research Team identified that one topic that was missing was the interconnection between the biophysical aspects. One fundamental question was related to linking or connecting the biophysical aspects: what were we missing by looking at each biophysical aspect in isolation from the others and what strategies were available to promote an integrated view of mine closure?

In response to this fundamental question, a project proposal was submitted, but it focused heavily on the lack of integration of the technical studies that support a closure plan, rather than on the lack of integration within a closure plan in general. The focus on the supporting technical studies was based on the following observations:

A typical mine closure plan defines several operational domains and sets out the rehabilitation objectives so that each domain can sustain the proposed post-mining land use. It requires a wide range of detailed technical studies that demonstrate that the domains will meet their closure objectives, such as “safe, stable and non-polluting”. In most cases, the closure planning timeframe will span several decades. The closure plan is likely to be modified several times during that timeframe, with the requirement to replicate the technical studies along the way to assess the impact of any modification, even minor ones. There is currently no industry standard or process to determine the design change threshold that will trigger a review of detailed technical investigations.

There can be disparities between the level of technical complexity expected from the investigations and the stage achieved within the closure planning process (e.g., the time remaining to scheduled closure). There is a need to educate the various stakeholders about the nature of the technical approaches to ensure their application is based on a comprehensive understanding of the system.

Technical studies are not usually linked: they tend to progress in parallel, with the results from one providing information to the others. If one study is updated and produces different results, all studies require updating. This can be an inefficient process, with no obvious pathway with which to establish the feedback loops between the technical aspects. One example is the need to integrate knowledge from water studies: net groundwater flow into or out of a pit will impact on its water balance whilst the pit water level will influence the net groundwater flow and its direction. With current approaches to groundwater modelling, it can be difficult to establish these connections. There is a need to capture all interdependencies and produce a model of the topological relationships that will allow users to understand effects on the system as particular elements change.

These observations led to the selection of specific project objectives. When the project was initiated, its aim was to demonstrate the value of adopting a system-level description of the biophysical components by building a prototype based on a “synthetic” mine that incorporates a range of sources, pathways, and receptors within its zone of influence. The method of delivery would be such that it could easily be communicated and shared. At the time, it had been envisaged that an open-source platform, ideally in a spatial environment, would be preferred. The intention was that the prototype would be used to:

- Establish a shared understanding of system-level representation of biophysical aspects, relying on outcomes from the other projects in Program 3.
- Test if the Source-Pathway-Receptor (SPR) can be adapted to closure planning to derive system-level variables that can be used to predict the behaviour of the system for a range of scenarios.
- Demonstrate the significance of the interactions or feedback loops between biophysical aspects and the closure planning design options.
- Analyse whether the impact of a change to the design of an operational domain (e.g., change to waste dump design) can be assessed with the system representation and can define the magnitude of change that will require a review of detailed technical studies (“threshold of significance”).
- Communicate key risks and opportunities from closure planning, relying on principles and outcomes derived in Program 2.
- Demonstrate the (positive) impacts of progressive rehabilitation activities through their influence on system-level variables.
- Guide the timeframe to establish and undertake detailed technical studies.
- Identify the critical data requirements for the closure knowledge base, again relying on outcomes from the other projects in Program 3.

The research hypothesis was that adopting a system-level approach would facilitate communication and comprehension of the closure planning process; identify the critical data sets that would contribute to the knowledge base; guide the timeframe for implementation of detailed and complex technical studies; and achieve alignment in the expectations of stakeholders. The project would identify further research priorities that could be pursued at a later stage, particularly in relation to extending the prototype to a wider range of cases and complexity.

As the project progressed, it became clear that the objectives were too narrowly defined and were concerned with different intended users, without articulating who the users might be. They bounce between selecting and communicating closure objectives (objectives c. and e.), high-level conceptual understanding of closure planning processes (objectives a. and b.), application of a new type of conceptual models (objectives d. and f.) and guidance for detailed technical studies (objectives g. and h.). Intended users are not defined and could be external stakeholders (objectives c. and e.), a company or a mine closure planning team (objectives a. and b.) or service providers (objectives g. and h.).

In terms of closure objectives, with current closure planning procedures, post-mining outcomes are generally imposed at the start, usually through regulatory approval conditions, without detailed analysis of all potential options. There could be other outcomes with enhanced local and regional values and opportunities if different post mining land uses (PMLUs) or designs were selected. Foundation Project F1-2 has explored some options with practices that are currently used for selecting closure objectives. It is worth reviewing current regulatory approaches and general trends in land use planning to identify opportunities in relation to the selection of closure objectives and the tools that are required to select the closure objectives; determine their high-level impacts on biophysical aspects and their resilience to long term trends, such as climate change; analyse their suitability given specific mine design and methods; and communicate their performance in terms of compliance with regulatory frameworks and alignment with community expectations.

In terms of conceptual models, the focus on system-level representation is worth pursuing. A system's thinking approach is a way to understand a reality that accentuates the relationship between parts of the system, rather than the parts themselves (Mai & Bosch, 2010). It provides a way to describe and understand complexity and change. Mine closure planning encompasses an array of activities and mining methods, including production, processing, residue disposal, product export, rehabilitation, and monitoring. The mine system has an impact on the environment and can engender feedback loops and cross-scale interactions.

If assessing the sustainability of the closure plan is about understanding these dynamics to gauge the ability of the mine closure system to maintain or enhance its essential objectives, viewing the system as a whole is essential. Systems thinking can be a useful approach to capture causal loops, where the effects of one element can influence the input onto another element. A review of the literature on system-thinking is warranted but it should not be limited to informing the representation of biophysical aspects in supporting technical studies. It should have the broader aim of identifying how system-thinking can influence and transform approaches to mine closure planning.

There are many conceptual approaches that can be adopted and in environmental studies, the Source-Pathway-Receptor (SPR) framework has been used extensively, mostly to describe the flow of environmental pollutants from a source, through different pathways to potential receptors (Holdgate, 1979-1980) as well as in environmental risk assessments. It is usually conceived as a unidirectional, general model with limited detailing, but can be extended into a multidirectional model by adding new insight on sources, transport paths and receptors and more complex relationships between the different components. The domain of application that is of most relevance to mining is environmental risk assessments. A review of current practices related to the use of SPR in environmental risk assessment is warranted, particularly as it is an area of interest to CRC TiME through its Data Integration, Forecasting and Scale program.

Beyond the original shortcomings in the initial objectives, it is worth noting that they were articulated before the CRC TiME Research Prioritisation Plan was finalised. Integration of biophysical aspects through system-thinking can contribute to 5 CRC TiME research priorities:

Priority 2: Informing regulatory excellence for transitions and Priority 3: Delivering post-mining options

Developing innovative approaches to selecting and communicating closure objectives will contribute to Priority 3. It can also support regulatory excellence. One finding from research into High Reliability Organisations (Cote, 2021) is that both regulators and companies need to adopt system-thinking. This project attempts to address this.

Priority 4: Enhancing decisions systems for positive closure

The broader aim of identifying how system-thinking can influence and transform approaches to mine closure planning will provide a novel way to select closure objectives, communicate with different stakeholders about the interactions between the closure plan and its surrounding environment, and establish confidence all risks have been identified and are controlled with suitable management strategies. It will deliver an enhanced decision system for mine closure planning, supported by specific methodologies.

Priority 7: Assessing and predicting cumulative impacts

Establishing a system-level representation of a closure plan’s causal links with biophysical aspects will provide a novel way to compile potential risks at regional level and will support assessment and prediction of cumulative impacts (both negative and positive) of mine closure at regional level.

Priority 8: Demonstration and data solution

By developing prototypes that demonstrate the value of system-thinking, we can provide examples of new digital tools that create new opportunities for sharing data and analytics, which can support planning for healthy and sustainable post-mining ecosystems.

1.2 Revised Objectives

Given the limitations associated with the initial proposal, the project objectives were reviewed to more clearly articulate the aims of the project and its contributions to CRC research priorities, and align them with progress from other CRC TiME foundational projects conducted within programs 2, 3 and 4. Objectives are to:

- Provide an overview of current regulatory frameworks and associated current practice for selecting closure objectives, outlining gaps and opportunities with respect to selection of closure objectives (noting there will be opportunities to review findings against the outcomes from other CRC TiME projects).
- Define the broad global and national trends that are shaping the future of mining with consequences for mine closure and selection of closure objectives.
- Review current practice with environmental risk assessment, with a focus on application of Source-Pathway-Receptor (SPR) frameworks to regional risk assessment in Australia, to determine if this approach would be applicable to describe the interactions between a mine closure plan and its surrounding environment.
- Compile the main concepts used in system-thinking and assess how they can be applied to capture the interactions between the biophysical aspects and communicate them to a range of users.
- Define the intended users for the system-thinking approach and propose options for the level of detail and the type of causal models that will be required for each group of intended users.
- Develop examples of application of system-thinking to the development of closure plans, by proposing a prototype for each group of intended users.

Whilst this represents a significant update to the initial objectives, the project still delivers the initial intent: Objective **1** is broadly aligned with the initial objectives c. and e.; Objective **3** is aligned with the initial objective b.; and Objectives **4**, **5** and **6** are aligned with the initial objectives a., d., f. g., and h. The main differences consist in broadening the assessment to a more comprehensive view of closure planning (Objectives **1** and **2**) and in the nature of the prototype. With different groups of intended users, there cannot be one prototype. Rather, the requirement is better defined as providing an example of prototype that would be beneficial for each group of users.

1.3 Methodology

The methodology consisted of two stages. Stage 1 consisted in the review of literature and documentation that would inform Objectives 1 to 4. Stage 2 consisted in defining the groups of intended users and developing examples of prototype for each group of users.

1.3.1 Stage 1 - Literature, Projects, and Documents review

Stage 1 included:

- A high-level review of Australian regulatory frameworks and some international ones, providing a summary of closure requirements for the main jurisdictions and a detailed description of a new legal instrument in Queensland, the Progressive Rehabilitation and Closure Plan (PRC).
- Consideration of global and national trends that can influence mine closure planning, with a literature review of studies conducted at global scale to identify the major factors influencing the selection of post-mining land use and associated objectives.

- A review of Environment Impact Statements for recently approved resources projects located in the Bowen Basin. This review was performed as part of the Bowen Base case study of the CRC F4.1 project, concerned with strengthening the Shared Analytic Framework for the Environment (SAFE). SAFE has been developed by The Western Australia Biodiversity Science Institute (WABSI) and the Commonwealth Department of Agriculture, Water, and the Environment (DAWE). It provides a structured way to plan and align the data capabilities required for environmental analysis and assessments. It is being developed to provide a nationally consistent way to think about, design, and build the data and analytic capabilities to support environmental assessment in the context of bioregional cumulative impacts. Since the EIS covered all biophysical aspects, this review was used to assess the status of data collection that can inform the knowledge base required for closure planning and the ability of technical studies to support integration of biophysical aspects in closure plans.
- Compiling advice from the Independent Expert Scientific Committee on Coal Seam Gas and Large Mining Development (IESC). The Commonwealth and Queensland regulators seek advice from the IESC at appropriate stages of an assessment process. In providing advice, the IESC will consider whether a proponent’s environmental assessment documentation has used suitable data and information to identify and characterise all relevant water resources and water-related assets; applied appropriate methods and interpreted model outputs in a logical and reasonable way to investigate the risks to those assets from the proposed project; considered potential cumulative impacts from past, present and other reasonably foreseeable actions; adequately described appropriate avoidance or mitigation strategies to avoid or reduce potential impacts to water resources; proposed effective monitoring and management to detect and ameliorate the risk of potential impacts, and to assess the effectiveness of proposed mitigation strategies and other management measures; and addressed the inevitable uncertainties in predictions of potential impacts on water resources and water-related assets. The advice of the IESC is solely focused on water-related matters. However, the level of scrutiny that is applied means that most, if not all, gaps are captured, and this informs the potential requirements for capturing water-related risks in a closure plan. It also outlines where greater integration of surface water and groundwater assessment is required.
- A review of the geological and bioregional assessment for the Cooper geological basin (Holland et al., 2021), which analyses the potential impacts of gas resources development on water and the environment and proposes mitigation and management measures. It represents a large and comprehensive body of work, with an innovative application of the SPR framework for assessing environmental impact. It covers all biophysical aspects, some of which are not relevant to mining (hydraulic fracturing). However, the methodology is of interest to this project as it demonstrates what can be achieved in terms of developing innovative tools to communicate environmental risks.
- A literature review of system-thinking and system-based approaches, with a focus on the aspects that could be applicable to mine closure planning. There are studies that have applied system-thinking to understand interactions between mining and the environment.

In later stages, there will also be opportunities to review findings from other CRC TiME projects, particularly the Program 3 foundational projects.

1.3.2 Stage 2 - Prototype Development

During stage 2, the groups of intended users were defined, and a prototype developed to illustrate how system-thinking could be applied to integrate biophysical aspects into closure plans. The prototypes were based on information available in the public domain. While not within this project, these prototypes should be used to integrate the findings from the five foundational projects covering a key technological theme of significant impact on the process of mine closure and relinquishment: remote sensing and monitoring (P3.2);

mine site water (P3.3); ecosystem resilience (P3.4); mine landform stability (P3.5); and acid and metalliferous drainage (AMD) risk (P3.6).

Given the strong focus on Progressive Rehabilitation and Closure Plan (PRCP) in Queensland, the most suitable case studies were in Queensland. We selected Mount Morgan Mine and the Vulcan Complex Project. The latter has been identified by the regulator as having submitted a conforming PRCP.

2 Regulatory Frameworks

An overview of regulatory frameworks is provided in this chapter for the purpose of contextualising this report. A more extensive mapping of regulatory frameworks in Western Australia, Queensland and Victoria including interactions with the Commonwealth is provided in a separate report (Hamblin et al., 2022).

In Australia, the regulation of mining and resources projects, including closure and rehabilitation aspects, is under State responsibility although, as outlined in a submission to the Senate Standing Committees on Environment and Communications (2019), the Commonwealth Government has certain powers when it comes to environmental matters through the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Under the EPBC Act, the federal government is responsible for the assessment and approval process of proposals falling under matters of 'natural environmental significance'. These include nuclear actions, including Uranium mining, and water resources in relation to coal seam gas and large coal mines development. The Commonwealth Government had bilateral agreements in place with all states and territories for them to consider the EPBC Act as part of their environmental assessment process (Department of Environment, 2013; Senate Standing Committees on Environment and Communications, 2019).

The regulatory requirements vary between Australian jurisdictions. It is often cited that there is a lack of clarity in some jurisdictions with regards to the standard of rehabilitation required to achieve tenement relinquishment. Operators often must discuss expectations with regulators on a case-by-case basis (Allens Linklaters, 2020). Manero et al. (2021) mention an "ill-defined prescription for mine rehabilitation" and Erskine & Fletcher (2013) argue that mines in Australia mostly operate in a self-regulatory environment.

Unger et al. (2012) estimate that there are around 50,000 abandoned, orphaned, or derelict mines around Australia although many of these are small scale historic mining disturbances. For instance, in 2018 the Queensland Government estimated over 15 000 identified abandoned mines but only about 120 were priority site with a combined area of disturbance of about 10 300 hectares[1]. Despite the industry's self-guidance with regards to rehabilitation, very few mine sites in Australia have achieved successful rehabilitation (Lamb et al., 2015). This results in increased risks to humans and the environment and a dent in the reputation of the government and industry (Manero, Standish, & Young, 2021). Hernandez-Santin et al. (2020) argue that knowledge pertaining to mine rehabilitation success and failure is lost in grey literature. This is likely due to this aspect of self-regulation and loose government policies. Heyes & Cooper (2019) posit that closure plans submitted as part of project approvals usually default to the return to native vegetation due to time pressures to obtain approval, a lack of long-term data or a lack of specific detailed consultation on closure alternatives.

Several Australian jurisdictions have recently undertaken reviews or introduced new regulatory frameworks aimed at mining operations, rehabilitation, and closure:

- South Australia has introduced the Statutes Amendment (Mineral Resources) Bill in 2018 to carry out necessary reforms to unlock the opportunities and values of its mineral resources (Government of South Australia, 2016; Senate Standing Committees on Environment and Communications, 2019).
- The New South Wales government released an updated cost estimation tool for mine rehabilitation activities after the NSW Audit Office identified issues with the financial mechanisms for mine rehabilitation (Senate Standing Committees on Environment and Communications, 2019).

1. https://www.resources.qld.gov.au/__data/assets/pdf_file/0008/1454939/policy-abandoned-mines.pdf

- The Western Australian government has recently released a set of guidelines for the preparation of mine closure plans, which include guidance on the standard of rehabilitation required as well as a framework for developing mine site completion criteria (Allens Linklaters, 2020).
- Queensland has recently introduced the Mineral and Energy Resources (Financial Provisioning) Act 2018 (MERFP Act) which required Queensland mines to transition into the Progressive Rehabilitation and Closure Plan (PRCP).

This legislation focuses on the progressive rehabilitation of mined land to a Post Mining Land Use (PMLU) (Cote et al., 2020). Unlike former progressive rehabilitation conditions which only included outcome-based requirements such as 'when practicable' or ‘when areas become available’, a PRCP must now include binding, time-based milestones for actions that achieve progressive rehabilitation (Queensland Government, 2020; Queensland Treasury Corporation, 2017)

In a discussion paper prior to the implementation of the MERFP Act, the Queensland Treasury Corporation (2017) undertook a jurisdictional analysis to examine mine closure requirements across the world. The report considered the Australian mining jurisdictions and

Table 1 outlines the main findings.

It follows that adhering the best practice would be what every legislation aims to achieve. The jurisdictional analysis revealed that only Western Australia, South Australia, and Queensland (post-legislative changes) complied with best practice directives.

Despite the variations surrounding mine rehabilitation expectations around the world, it is universally acknowledged that best practice in mining is when companies take full responsibility for undertaking their operational plans, reach good rehabilitation outcomes and make adequate financial provisions to enable progressive and final rehabilitation (Queensland Treasury Corporation, 2017; Vivoda et al., 2019).

Despite the various reforms with well-defined guidelines, the regulatory frameworks in Australia still lack a clear, quantitative method to guide the selection of post-mining land uses and associated objectives. Post-mining land uses are usually listed in environmental permits and often select the land use that was in place prior to mining, such as grazing or native ecosystems in Queensland.

The regulations in the major mining jurisdictions lack clear and quantitative methods to aid in PMLU selection. This incentivises operators to often commit to unproductive PMLUs as there is no regulatory requirement for them to explore productive land uses. Heyes & Cooper (2019) noted that “there is limited financial incentive for mining companies to drive approval for an alternative land use to extend their responsibility beyond relinquishment, which they may view as more of a long-term host-government responsibility.” For example, regulators in Australia have usually accepted ‘passive’ PMLUs where it is ensured that the site is sufficiently stabilised, revegetated, and self-sustaining (Allens Linklaters, 2020).

In the USA, coal mine operators in the Appalachian region have long chosen grassland and unmanaged forest as PMLUs over planting high value hardwood tree which are able forest services (Burger, 2011).

As such, even with operators having comprehensive PRCPs due to legislative changes, an appropriate framework with measurable metrics and clear definitions about PMLU selection is needed. This will help define the beneficiaries where PMLUs with potential economic benefits are implemented.

In Australia, requirements for Life of Mine plans (LOMP) and Closure plans (PRCP) are well articulated (

Table 1) but are not supported by methods that will deliver what is expected. For instance, there is a requirement to define a future (post-mining) land use but no method to guide the selection of that land use. Items that are relevant to this project are

- Stakeholder consultation and involvement is required during the development of the LOMP

  To facilitate engagement, a representation of the closure plan will be required, outlining interactions with the surrounding environment, and predicted trends. One group of intended users will be the external stakeholders, who will require a conceptual model capturing biophysical aspects and their role in the closure plan.

- LOMP includes closure/rehabilitation objectives

  These objectives will have to be communicated and their relationship with biophysical aspects clearly articulated.

- LOMP includes milestones for closure/rehabilitation

  This requirement indicates that tools that are developed as support to closure planning cannot be static and must be able to include progress through time. This adds to the complexity of integration.

- LOMP describes future land use

  As demonstrated by CRC TiME project 1.2 “Post Mining Land use”, the topic of land use selection remains an issue for most mines and the concept of acceptable post-mining land use is likely to evolve over the next 10 to 50 years. Tools must be designed to enable variations in the selection of post-mining land use and associated objectives.

- LOMP is underpinned by environmental and social baseline data

  The collection of baseline data will remain a constant requirement throughout the life of mine, highlighting the importance of emerging data management frameworks such as SAFE (Shared Analytic Framework for the Environment – refer to CRC TiME project 4.1 “Dynamically transforming environmental assessment through a shared analytics framework) and of data management capability within mining companies. Data requirements will need to be captured by any tool supporting closure planning.

In conclusion, our review of current regulatory frameworks demonstrates that there are expectations with respect to communication of closure objectives to stakeholders, and that methods to select PMLUs are required. This can be facilitated with development of tools that facilitate communication and comprehension of the mine closure and rehabilitation planning process.

Table 1: Mine closure requirements in select jurisdictions (adapted from Queensland Treasury Corporation (2017)

Criteria	New South Wales	Victoria	Tasmania	Western Australia	South Australia	Northern Territory	Queensland*
Mine operators are required to have a LOMP or similar planning document	Y	Y	Y	Y	Y	Y	Y
LOMP is required prior to mining commencement	Y	Y	Y	Y	Y	Y	Y
Stakeholder consultation/involvement is required during the development of the LOMP	Y	Y	U	Y	Y	Y	Y
Clear requirements for mine closure and rehabilitation	Y	Y	Y	Y	Y	Y	Y
LOMP includes closure/rehabilitation objectives	Y	Y	N	Y	Y	U	Y
LOMP includes milestones for closure/rehabilitation	N	U	U	Y	Y	Y	Y
LOMP includes criteria for rehabilitation/closure	Y	Y	U	Y	Y	N	Y
LOMP describes future land use	Y	Y	Y	Y	Y	Y	Y
LOMP is underpinned by environmental and social baseline data	N	Y	Y	Y	Y	U	Y
LOMP includes progressive rehabilitation requirements	Y	Y	Y	Y	Y	N	Y
LOMP includes mine closure cost estimates	N	N	N	Y	Y	U	Y
LOMP links to financial assurances or other financial bonds	Y	Y	Y	Y	Y	Y	Y

LOMP: Life Of Mine Plan, BP: Best Practice, Y: Yes, N: No, U: Information Unavailable, *: Post-Legislative changes

3 Trends

There are broad global trends that are shaping the future of mining with consequences for mine closure and selection of post-mining land use. The list presented below is not exhaustive and only captures the trends that are the most likely to influence post mining futures.

3.1 Climate change

Any aspiration to deliver healthy ecosystems and livelihoods for post-mining futures must consider the consequences of climate change. The changing climate is now dramatically influencing the way land is managed, the value placed on water benefits to regional economies, the demand for new resources and the demand for renewable forms of energy. These issues will influence which options are viable for mines and economic repurposing.

The predicted impacts of climate change in Australia have direct consequences on the sustainability of selected land uses which 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) able to adopt infrastructure standards that withstand severe cyclonic activities, where required.

Anthropogenic carbon dioxide removal (CDR) includes afforestation, agricultural practices that sequester carbon in soils, bioenergy with carbon capture and storage, ocean fertilisation, enhanced weathering, and direct air capture when combined with storage. Of direct interest to the selection of post-mining land uses are afforestation and agricultural practices, which, in the context of mine rehabilitation, concern the re-establishment of vegetation. Consideration of CDR also clearly shows the link between climate change mitigation and biodiversity investment. Re-establishment of vegetation corridors are unlikely to generate income in the current Australian economic system, recognising that this could change if carbon price mechanisms were re-introduced. Climate policy and carbon markets are constantly evolving. Carbon markets are now a key part of an emerging, complex and global policy framework that mixes trading programs and other policies at the subnational, national, and multinational level. Fresh research and policy initiatives are grappling with new issues: linking programs, the consequences and comparability of mixed policies and managing market evolution as policies inevitably change. The future of carbon markets will depend, in part, on how well such efforts address these challenges.

Growing environmental and climate concerns are prompting a global shift in energy use, from a reliance on fossil fuels towards low-carbon energy. This shift is known as the energy transition. This has implications for closure and post-mining land use. The growth/decline scenarios for critical metals and thermal coal leads to rapid development of mines for the former and rapid closure of mines for the latter. With diversification in the energy mix, solar farms and other renewable energy systems can now be considered as potential post-mining land uses.

3.2 Biodiversity investments

There are increasing expectations around risks from the loss of natural capital, requiring assessment of biodiversity and ecosystems needs. For example, the United Nations adopted a new statistical framework in 2021 (https://seea.un.org) to better account for biodiversity and ecosystems in national economic planning and policy decision-making, allowing countries to use a common set of rules and methods to track changes in ecosystems and their services. Additionally, the Dasgupta review (https://www.gov.uk/government/collections/the-economics-of-biodiversity-the-dasgupta-review) suggests that the UK national accounting systems need to include natural capital estimates to enable a more accurate measure of economic progress. Investors in the near term are therefore going to be required to assess the financial risk associated with impacts on nature and will need to find new opportunities to invest in nature-positive projects which enhance ecosystems.

The period 2011-2020 was declared as the United Nations Decade on Biodiversity to promote the implementation of a strategic plan on biodiversity and its overall vision of living in harmony with nature. Governments are encouraged to develop, implement, and communicate the results of national strategies for implementation of the strategic plan for biodiversity. This can influence the selection of a post-mining land use to ensure it better aligns with national approaches to biodiversity investment.

Photosynthetic carbon capture by trees is likely to be the most effective CDR strategy. Consequently, international initiatives, such as United Nations Environment Program Bonn Challenge or the New York Declaration on Forests, have established ambitious targets to promote forest conservation, afforestation, and restoration at a global scale. A recent study analysed the potential to re-establish tree cover across terrestrial ecosystems, using a predictive model based on dominant environmental drivers of tree cover. It shows that eastern Australia has enormous potential for re-establishing tree cover and tree planting can co-exist with grazing (Bastin, et al., 2019). As it is a high-level assessment, it does not consider the constraints imposed by land capability. However, it indicates that restoration of post mine land to woodland can present opportunity for carbon capture and sequestration.

Successful examples of restoration of post mine land to woodland can be found in the USA. In 2004, the Office of Surface Mining Reclamation and Enforcement created the Appalachian Regional Reforestation Initiative (ARRI), a coalition of groups, including citizens, the coal industry, and government, which is dedicated to restoring forests on coal mined lands in the eastern United States. This sort of initiative could be explored in Australia, with support from tested frameworks that seek to support ecological restoration, such as that developed by the Rotterdam School of Management (Ferwerda, 2015).

3.3 International practice for selection of closure objectives

There have been several reviews conducted at the global scale to identify the major factors considered in the selection of a post-mining land use (Mborah et al., 2016; Limpitlaw & Briel, 2014; Soltanmohammadi et al., 2009). These studies show that the selection is primarily driven by government legislation, even though, in Australia at least, regulations in the major mining jurisdictions lack clear and quantitative methods to aid in land use selection.

These reviews examined the most commonly practiced and accepted techniques for land use selection. Factors identified as important in the selection process include land resources (physical, biological, and cultural), ownership, type of mining activity, legal requirements, location, needs of the community, economic, environmental, technical and social factors. In a broad categorisation, almost all post-mining land uses are one of six types: agriculture, forestry, water source, recreational land-use, conservation or construction, as summarised in Table 2. Not all types are equally suitable for every context, however this summary provides a starting point for categorising land use options.

Table 2: Categorisation of post-mining land uses

Land-use types	Typical post-mining land use in each category
Agriculture	Arable farmland, garden, pasture or hay-land, nursery
Forestry	Timber production, woodland, shrubs, and native forestation
Water source (e.g., lake or pool)	Water supply
Recreation	Sport field, sailing, swimming, fishing, hunting
Construction	Residential, commercial (shopping centre), industrial (factory), educational (university)
Conservation	Wildlife habitat, water supply (surface and groundwater)

When conducting literature searches using "post mining land use" as key words, we found that current research could be broadly classified as:

- Technical studies that investigate the performance of rehabilitation activities, often with reference to completion criteria. These represent most of the research, with about 80% of the articles belonging to this category. Rehabilitation activities cover a wide range of technical aspects: flora and fauna re-colonisation, metal mobility, soil fertility and microbial communities, fire impacts and management, erosion.
- Studies that outlined requirements to include various stakeholders, including traditional owners, in decisions about post-mining land uses.
- Policy papers that outline required legislative changes to reduce financial liability of the state (3 papers)
- Development of methods for post-mining land use planning within the mine planning framework: there are very few of these (2 papers) and they lack methodological details.

Most of the international research is still largely focused on developing rehabilitation methods that will deliver pre-determined outcomes (the selected PMLU, often associated with specific completion criteria) without questioning the selection of the PMLU.

3.4 National Trends

Like other similar federalist nations with an extensive area and dependence on natural resources, such as Canada and the USA, the responsibility in Australia for land use policy and planning primarily resides at the sub-national level, with no national policy on land use (Walcott, 2019).

To address this gap, a government panel produced a multiple land use framework (MLUF), primarily as guidance for the mining industry. The MLUF (SCER, 2013) is intended to be used where land access and land use conflict has the potential, real or perceived, to arise. While it has been developed with the minerals and energy resources sectors in mind, the underlying concept can extend to all sectors, including agriculture, environmental and heritage protection, tourism, infrastructure, and forestry.

It introduces the concept of 'multiple and sequential land use': multiple land use is where land is used for different purposes simultaneously and sustainably with a view to maximise the benefits for all Australians; sequential land use involves different use of land over time and may include a return to a former use or the development of an alternative land use. The concept of multiple and sequential land use has strong applicability to the selection of PMLU and there is evidence it has influenced actions at state, industry, community, and individual levels (Walcott, 2019).

Two recent examples of PMLU selection are provided below, but CRC TiME Project F 1.2 will deliver a comprehensive portfolio of case studies.

Latrobe Valley Regional Rehabilitation Strategy

The Victorian government developed the strategy for future land uses around the Latrobe Valley coal mine areas, which will undergo significant change through the closure and rehabilitation of the three major open-cut coal mines and associated power stations. The strategy was prepared by the Department of Jobs, Precincts and Regions in collaboration with the Department of Environment, Land, Water and Planning and had input from many partners. It does not prescribe final landform or final land use, to enable the consideration of rehabilitation options that can be demonstrated to deliver a safe, stable, and sustainable outcome. This allows for adaptability and consideration of environmental conditions, and community and stakeholder views. It focused on the technical aspects that are required to deliver safe, stable, and non-polluting landforms, rather than the PMLU that could be achieved with these landforms.

Hunter Valley Synoptic Plan

The Synoptic Plan: Integrated Landscapes for Coal Mine Rehabilitation in the Hunter Valley of NSW was prepared in 1999 by the NSW Department of Mineral Resources in collaboration with state agencies, local government, and academic contributors. It set out the principles for an integrated approach to landscape management and post-mining rehabilitation for the Hunter coalfield. The NSW government has since launched the Hunter Regional Plan 2036, which commits to reviewing the synoptic plan, in conjunction with the Upper Hunter Biodiversity Assessment to ensure best-practice rehabilitation and visual impact management for closed mines. The review is currently progressing.

In absence of a national land use policy to strongly guide land use planning decisions, state government and their departments have led development of regional land use planning vision and strategies. There are examples in mining regions, most notably in the Hunter Valley, where a vision for mine rehabilitation was established as early as 1999 (recognising that this vision is evolving).

3.5 Scale

Questions are being raised about the appropriate scale for mine closure planning. The state level may be too remote and the individual mine level too insular, not considering the regional context. Globally, governments have started to pay closer attention to subnational levels (Cattan, 2002). However, planning at the regional scale is challenging, both geographically and conceptually. In their study of global mining regions in transition, Everingham et al. (2020) find that the spatial boundaries of mining regions are ill-defined.

Other challenges relate to environmental, socio-economic and governance complexity of the regions (Franks et al., 2013; Measham et al., 2013; Cheshire, 2010), as well as socio-ecological inequalities across mining regions (Sheffer et al., 2017). These inequalities refer to the unequal (re)distribution of ecological risks and environmental costs; the socially unevenly distributed abilities and capacities to access and control natural resources and environmental goods; the uneven range of social abilities and capacities to cope with and react to changing environmental conditions; the unequally distributed causes and responsibilities for socio-ecological crises, and the uneven power relations and asymmetries which shape the production of knowledge, problem-definition and search for solutions (Hackfort, 2012). As a consequence of these challenges, very little attention has been given to the dynamics within mining regions.

3.6 Conclusions

The trends discussed above will influence the selection of PMLU. Given a closure plan will be developed over a long-time frame (typically 10-50 years), it can be expected that these trends may actually require a change or update to the PMLU. This means that tools are required to show the interactions between a closure plan and global and national trends.

In Australia, a critical gap towards selecting innovative PMLUs is the lack of regional planning and the lack of comprehensive national framework for land use planning. This means companies face difficulties when trying to articulate what their closure plan might mean for a region. There is a requirement for instruments that place the mine as part of a region, so that if a regional plan is developed, the role of the mine in this plan can be articulated.

Similarly, development of regional plans is likely to make some PMLUs feasible in the future. For instance, in Queensland, there is no mine with “production of solar energy” as PMLU. However, if the State were to develop a solar energy strategy, this PMLU could become feasible. In addition, companies need to be able to assess the relationship between the potential PMLU and the relationships with biophysical aspects. For instance, selecting “grazing” as PMLU presents specific risks, as the success of grazing as PMLU is highly corelated to rainfall availability. If “production of solar energy” is selected as PMLU, these types of risks will be lower.

4 Environmental Impact Assessments

4.1 Shared Analytics Framework for the Environment

Establishing efficient pathways for data collection at a range of scales will ensure CRC TiME projects can deliver their objectives. The Shared Analytic Framework for the Environment (SAFE) provides a nationally consistent framework to design and build the data and analytic capabilities that will support assessment of bioregional cumulative impacts, and as such, is of critical interest to CRC TIME. Project F 4.1 included a case study undertaken in the Bowen Basin to determine the gaps and opportunities related to the implementation of SAFE in Queensland. It involved an in-depth review of four Environmental Impact Statements (EIS) to identify the information that is currently collected by resource companies and characterise the associated data in terms of type, format, storage location, access protocol:

- Olive Downs Project, approved in 2019: Greenfield metallurgical coal mine with a yield of up to 15 million tonnes of product coal per annum for steel production.
- Byerwen Coal Project, approved 2014: A 15 million tonnes per annum (Mtpa) Run of Mine (ROM) open cut coal mine project with a mine life of up to 50 years.
- Arrow Bowen Gas Project, approved in 2014: Coal seam gas extraction in the Bowen Basin, for the region west of Mackay, extending from Glenden in the north to Blackwater in the south (covering 8,000m^2), aiming to supply gas to the domestic market and for the production and export of LNG.
- Isaac Downs Project, approved in 2021: Greenfield, open-cut coal mine and associated project infrastructure, extracting between approximately 1 and 4 million tonnes per year of run of mine (ROM) metallurgical coal, with an approximate total of 35 million tonnes of coal over 16 years.

The review focused on the information describing the existing environment (or baseline) and the potential impacts. The information was organised into the following categories: land and soil; flora; fauna; surface water; groundwater; water quality; air quality.

As EIS are expected to provide a comprehensive assessment of all potential environmental impacts, the biophysical aspects they assess will need to be included in closure planning considerations and this categorisation would suit. Data management frameworks such as SAFE will assist with baseline data.

4.2 IESC Advice

The Commonwealth and Queensland regulators seek advice from the Independent Expert Scientific Committee on Coal Seam Gas and Large Mining Development (IESC) at appropriate stages of an assessment process. The advice of the IESC is solely focused on water-related matters but it provides a lot of recommendations that are directly relevant to improving the integrated understanding of the relationships between mining activities and biophysical aspects. We provide below a summary of the most frequent findings and recommendations:

- Some mining activities require water course diversions, which can potentially alter downstream groundwater recharge, surface water flow regimes and extent of floodplain inundation.
- Mining activities can lead to groundwater drawdown within aquifers (usually alluvial aquifers) which may impact on terrestrial and aquatic groundwater-dependent ecosystems (GDEs). Where riparian vegetation and ecosystems rely on alluvial sediments, drawdown from mining activities can disrupt riparian zone continuity and ecological connectivity and result in the loss of associated water-dependent ecosystems.

- Drawdown may also alter surface water-groundwater interactions in creeks and ecologically important surface flow components, such as the number of low and zero-flow days in ephemeral creeks.
- Residual voids are legacies of coal mining. They are likely to become increasingly saline after mine closure and hydrogeological and ecological legacy effects need to be understood.
- The IESC recognises that rainfall patterns will change over the next 20 years and there may be increased risk of releases of mine-affected water to the receiving environment. There could be long-term changes, post-mining, to water resources due to contaminated water discharges from underground voids, seepages, and surface water storages.
- Subsidence from coal mining can lead to stream-bed fracturing, ponding and long-term water quality issues post closure, including ongoing erosion where subsidence-induced ground deformation occurs. The results from groundwater, subsidence and geotechnical impact assessment reports must be integrated and linked to the mine plan.
- There is often a gap in baseline data collection related to sediment quality (e.g., adsorbed contaminants) in receiving waters

Whilst restricted to water-related aspects, this advice provides strong recommendations for greater integration of biophysical aspects. Models are required to improve understanding of the connections and interactions between:

- groundwater, surface water and water-dependent ecosystems.
- mining methods, landform design and stability, surface water and groundwater.
- climate predictions, rainfall patterns, water balance, water quality and sediment quality and risks of contaminants export to the receiving environment.

4.3 Source Pathway Receptor

4.3.1 Environmental Pollutants

The Source-Pathway-Receptor (SPR) model has been used extensively to describe the flow of environmental pollutants from a source, through different pathways to potential receptors (Holdgate, 1979-1980). It has also been applied to environmental risk assessments of hazardous substances such as mercury (Driscoll, 2013) and PCB (Hoffman, 2003), as it is particularly suitable for this purpose. It provides a system model for the evaluation of pollutants in different environments as it combines the transport pathways with the receptors to assess consequences of pollutants in the environment. It usually takes the form of a unidirectional, general model with limited detailing, but can be extended into a multi-directional model by adding new insight on sources, transport paths and receptors and more complex relationships between the different components.

A major advantage of the SPR model is its simplicity, its flexibility, and the ability to identify relations in complex systems. Another important aspect of this model is that the definition of pathways and receptors is relative (Narayan, et al., 2012). Accordingly, components of the system may act as pathways as well as receptors, which is particularly important in the field of pollutants. For example, aquatic organisms can ingest a pollutant and thus become receptors but can also partially excrete it again and thus take part in the transport. Receptors are defined as media that are affected by the pollutant. This includes firstly environmental areas that serve as sinks, and secondly flora and fauna, that can incorporate or absorb pollutants.

The general methodology for setting up a SPR model is to first divide the sources into generation and production sites of the pollutant of interest, define the entry paths into the environment, and subsequently, the pathways and transport routes into the individual environmental compartments. Since the concentrations of pollutants are critical to ecotoxicological analysis, they are calculated through the steps in the model to enable assessment of impact on the receptors. This represents the most widely used application of SPR frameworks. In this particular form, it has limited application to the consideration of biophysical aspects in mine closure planning, at it places too much emphasis on contaminant concentrations and too little on most other variables.

4.3.2 Flooding

A less common application of the SPR framework relates to its use for describing the propagation of a flood from a source (river or sea) through flood defences (pathways) to the floodplain beyond (receptors). The UK Environmental Agency has adopted this approach to communicate risks from coastal flooding because they found that existing scientific approaches, which rely on detailed flood modelling to produce geographical flood maps, were very useful in conveying specific information to particular users but were not well-suited for describing the complexity of coastal flooding processes to impacted communities. They also found that the nature of the flood models posed several challenges in ensuring their application was based on a comprehensive understanding of the system. Application of the SPR framework aimed at addressing these issues by proposing a system-level analysis of coastal floodplain behaviour.

The combination of SPR with system diagrams was found to be a powerful way of collating a comprehensive description of the state of the flood system, its elements, and their relationships (Narayan, et al., 2012). It first requires identifying the receptors and to build up the network of pathways. As with consideration of pollutant flows, a key principle in this approach is the recognition that the definitions of “pathways” and “receptors” are relative, rather than fixed. Components of the flooding system may simultaneously function as pathways to “downstream” receptors and as receptors in their own right. The methodology that was applied to build the system diagram of a coastal flooding system involved:

- The boundaries of the coastal flood system are defined based on the highest water level being considered, assuming of a worst-case scenario with complete failure (or absence) of engineered defences.
- All elements within the flood system, including flood defences, are mapped as unique entities classified based on land-use.
- The relationships between the identified elements are defined. In the case of flooding, a link is identified between any two elements if they share a geographical boundary.
- Once the complete system diagram is built, the sources of flooding are identified along all boundaries.

A system diagram built with this methodology enables a rapid broad-scale assessment of large-scale flood system, showing the relationships between specific defence elements (e.g., a dike) and urban areas. These relationships will not be as obvious on a flood map, given the defence elements and the urban regions occupy areas that are widely different in scales. A town or city will be easily identifiable, but a flood levee or dike might not be (Narayan, et al., 2012).

The coastal flooding system models could provide complex information about the system and element relationships in a robust and effective manner. It was found to be a powerful means of making key explicit assumptions and considerations about the system, providing users a comprehensive understanding of their flood system. The systems model is not meant to replace flood maps or fully quantitative numerical models; instead, it is intended to be used alongside these, to ensure that a comprehensive understanding of the flood system before undertaking quantitative modelling.

This approach is presented as an application of the SPR framework because it uses similar terminology, but its fundamental conceptual approach is based on system definition and description, with a focus on establishing the relationships between the elements of the model. It applies principles that are typical of system-thinking, which are explored in Section 5. The methodology for constructing the system would be applicable to the mine lifecycle and closure planning:

- The boundaries of the system would be defined as the boundary between the mine and its surrounding environment. There can be uncertainties with locating exact boundaries between these two entities (e.g., a mining lease might not necessarily capture the boundary at which groundwater exits the mine water system), but conceptually, it is reasonably straightforward to establish the separation between them.
- The elements within the mine system could be categorised by “land use”, which in this case is more accurately referred to as operational domain: a waste dump, a tailings storage facility, a residual void, a road, or building. To achieve a closure planning system that integrates all biophysical aspects, this might not be the most suitable approach, as the complexity is not related to the co-existence of various domains (or land uses). With flooding assessment, we do want to understand where dikes or levees are located and whether they are connected to urban areas. With closure planning, we seek to understand how the actions that are implemented to deliver rehabilitation and closure objectives interact with each other. System elements are more likely to be captured as rehabilitation objectives and the actions that will deliver them.
- With this assumption, two elements would be linked if a change in the status of the first one would lead to a change in the status of the second one. For instance, if we consider the two system elements “vegetation cover” and “surface water quality”, they would be linked, because a reduction in vegetation cover can lead to an increase in erosion and export of sediments, which leads to a this would lead to impacts on surface water quality.

The type of approach described for coastal flooding would be applicable to delivering Objective 6 of this project, but we argue that it is an application of system-thinking, and not an application of the SPR framework. System-thinking is discussed in Section 6.

4.3.3 Causal network for bioregional assessment

Environmental impact assessment (EIA) is an application of the SPR framework. An effective EIA should:

- identify all likely hazards and their associated stressors over multiple spatial and temporal scales: this aligns with the concept of sources in the SPR framework;
- specify the mechanisms by which these stressors may negatively impact on valued assets: mechanisms can be conceptualised as pathways and valued assets as receptors;
- assess the risks of these negative impacts (Peeters et al., 2022).

A common weakness of many EIAs is that they suggest broad strategies to mitigate risks, generally presented as general narratives rather than being linked explicitly to specific relevant causal pathways. In addition, they lack clarity about how the risks vary spatially. Spatial risk characterisation is important at regional scale because negative environmental impacts of a given stressor are unlikely to be consistent across a large area.

Recently, CSIRO developed a new approach to undertake environmental impact assessment at regional scale, as part of a study funded by Geosciences Australia to provide a bioregional assessment of the Cooper geological basin. A rapid regional prioritisation process first sought to identify the basins with the greatest potential for shale and tight gas development in eastern and northern Australia and found that the Cooper geological basin had the greatest potential for delivery of conventional or unconventional gas. The Cooper geological basin underlies the Cooper Creek catchment, which forms part of the Lake Eyre Basin. Cooper Creek traverses an arid region and supports complex wetland ecosystems on densely channelised floodplains. There has been relatively low anthropogenic disturbance and a key feature is that there is no major infrastructure to regulate flow. Cooper Creek is characterised by extreme surface water flow variability, with most flow events resulting from variable monsoonal rainfall. During wet periods, habitat complexity and availability is vast with extensive flooding producing a complex system of swamps, channels, billabongs, and waterholes on the floodplains. In dry periods, the creek is usually reduced to a series of waterholes in the channels and isolated wetlands on the floodplain. These habitats serve as refuges for aquatic species but many dry up completely in prolonged drought. The area is internationally recognised as an outstanding example of an unregulated, low-gradient, dryland river system and is one of the last arid-zone water catchments around the globe to flow intermittently without interruption, and therefore is of high conservation significance on a world scale. It is essential that the environmental values be protected.

To support risk assessment in this region of high environmental significance, CSIRO developed an approach to analyse risk along multiple causal pathways, assess potential collective impacts on one or more valued assets, and identify links where there is limited or no capacity to mitigate serious negative impacts (Peeters et al., 2022). They developed a spatial causal network that is essentially an application of the Source-Pathway-Receptor framework with addition of mitigation controls and spatial analysis. Their method involved:

- Systematic identification of activities (sources) and valued assets (receptors), and of the stressors and processes along the causal pathways that link the activities and valued assets.
- Individual evaluations of risk and associated uncertainty for each link along the causal pathways.
- Mitigation options relevant to the link evaluations, from which "residual risk" (risk remaining after a mitigation option has been implemented) could be assessed, for single or multiple causal pathways; and
- Addition of a spatial analysis component that enables users to generate project-specific maps of stressor extent and residual risks.

The activities, stressors, processes, and assets are represented as nodes, and the links along the causal pathways as edges, thereby producing what is called a directed acyclic graph in graph theory. Easers can click on each node to access documentation, which includes the current knowledge base, relevant knowledge gaps and key assumptions. All possible pathways between activities and valued assets were analysed to derive the overall direction of an impact along a pathway (i.e., will an increase in an activity lead to an increase or decrease in a valued asset?).

The causal network can be accessed and used online at:

https://gba-explorer.bioregionalassessments.gov.au/coo/7

Figure 1 is a screenshot showing an overview of the tool, outlining the degree of complexity associated with the numbers of activities (sources), assets (receptors) and pathways.

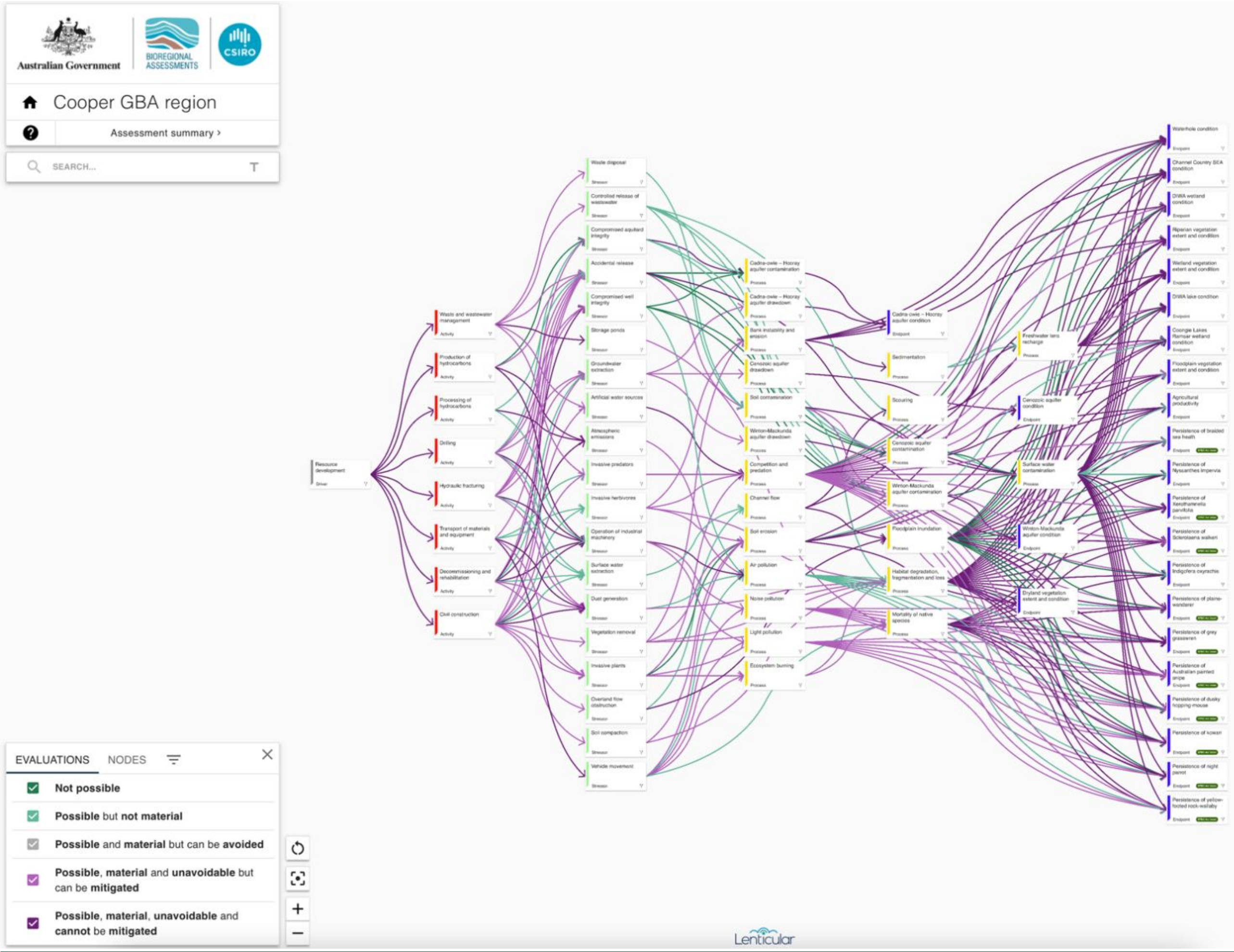


Figure 1: Overview of GBA Explorer

This application is novel and represents a significant addition to the field of EIA. Because it aims at assessing risks, the network that connects activities with valued assets is essentially unidirectional. It seeks to understand the unidirectional pathway that leads from a starting point (the activity) to its end point (the impact on a valued asset). Some of the concepts used in this approach are relevant to closure planning, particularly the systematic evaluation of links. However, research project F3.1 seeks to define all potential interactions between a mine and its surrounding environment, and it is unlikely that the links between the system elements will be unidirectional. There will be feedback loops and a critical objective of this project is to propose methods to identify, describe and establish these processes. As such, this approach is not applicable, but we can draw some guidance, particularly for the definition of system elements. For closure planning, rather than define "activities" as the elements that will create a hazard, we can conceptualise them as the actions that will deliver the rehabilitation objectives ("valued asset"). Similarly, the pathways can be conceptualised as the link or group of links that form the causal chain between an action and the delivery of a rehabilitation objective.

4.4 Conclusion

There have been many advances in EIA and some will directly support closure planning processes. Advances in data collection and data management will probably have the most immediate impact as they will support baseline assessment and can contribute directly to the closure planning knowledge base. From the perspective of project F3.1, we can assume that baseline assessment will pose no particular concern for the development of closure plans.

The GBA Explorer is essentially an application of the Source-Pathway-Receptor model to resource activities, but its domain of applicability to closure planning is likely to be limited. When designing a closure planning system, the items of interest are the behaviour of the system and its interactions with its surrounding environment, rather than unidirectional impacts on assets.

5 System-thinking

In broad terms, system-thinking accentuates the relationships between parts of a system rather than the parts themselves. It is applied to understand complexity and change and provides tools to describe and understand complex challenges.

Environmental systems involve numerous interrelated components and deal with environmental phenomena that change over time. (Clark, et al., 2001) defined four main components in an environmental system:

- Reservoirs: repositories where something is accumulated, stored, and potentially passed to other elements in the system. For mining, examples are lakes storing water or waste rock dumps storing contaminants. Both are designed for storage and can potentially pass contaminants to other elements of the system.
- Processes: ongoing activity in the system that determines the contents of the reservoirs over time. For mining, an example is the design of the mining plan which will dictate the extent of the catchments generating mine-impacted runoff and the volumes of mine-affected water captured in the mine water system.
- Converters: system variables that can play several different roles, but their most important role is to dictate the rates at which the processes operate and therefore the rates at which reservoir contents change. For mining, there will be many system variables, covering hydrological, hydro-geological, geochemical, and geotechnical processes.
- Interrelations: they represent the intricate connections among all components of the system, usually expressed in terms of mathematical relationships. For mining, the challenge will be to define the types of relationships that can be defined to capture the interrelations without introducing too much complexity.

Environmental problems are inherently dynamic systems problems (Clark, et al., 2001) and thus contain sets of interacting elements that change over time. These elements function together as a collective unit, producing outputs in relation to inputs through processes endogenous to the system. Changes in one variable will impact other variables of the system, with possible multi-scale effects. Outcomes thus emerge from the complex interactions among system elements, potentially including natural and human components.

Depending on the complexity of the environmental issue that is the object of study, the system can include different subsystems. For complex environmental issues, subsystems are represented and modelled separately to understand better the details and the dynamics within a subsystem. However, it is important to consider the interrelation between the subsystems to keep consistency in the representation of the system. For a mine closure plan, the detailed technical studies essentially describe the subsystems which separately describe, assess, and model specific aspects.

Feedback is identified in a system when outputs of a subsystem are routed back as inputs as part of a chain of cause and effect that forms a circuit or loop. The system itself adapts and changes over time due to feedback loops between the parts and the subsystems (Chowdhury, 2019). For a mine closure plan, there has been no example to date demonstrating that feedback loops had been defined or included.

5.1 Global Systems

Since the early 1990s, Socio-Ecological System (SES) approaches have been developed and applied to describe complex systems where global environmental and socio-economic changes occur concurrently, and to assess how sustainable such systems would be (Holling, 1996; Turner, 2003; Ericksen, 2008; Ostrom, 2009). Environmental degradation, social distress, and economic fluctuation are worldwide concerns challenging conventional views on development and forcing the assessment of the long-term sustainability of socio-economic systems.

There is no widely accepted definition for sustainability, but in the context of this discussion on system-thinking, an appropriate definition would be the ability of a system to maintain or enhance its essential outcomes among perpetual changes.

5.1.1 Sustainable Food Systems

Socio-Ecological Systems are defined as complex human–nature adaptive systems linked by dynamic processes and reciprocal feedback mechanisms, with a substantial exchange of energy and materials across boundaries (Berkes, 2001; Folke, 2006). They characterise a range of global processes, including many in ecosystem management and ecology, but particularly those where there is a strong inter-dependency between environmental values and economic outcomes. One example relates to assessing the sustainability of global food production systems, which encompass an array of activities from sowing through to waste disposal management, including production, processing, packaging, and distributing, and retail and consumption (Ericksen, 2008).

Food production requires land, water, and nutrients, with impacts on biodiversity and land access. Processes along the food chain from agricultural production to consumption produce outputs other than consumable food that are returned to the natural environment such as pollution or waste. There are large numbers of people suffering from undernourishment, while obesity has become a significant public health issue in developed countries. Building sustainable food systems has become a major endeavour to redesign global food systems that deliver better adjusted goals and improved societal welfare (Allen & Prosperi, 2016).

Food systems have a high level of complexity driven by many economic, socio-cultural, and environmental factors, which are both internal and external to its boundaries. The systemic nature of these interactions calls for systems approaches and integrated assessment tools to guide change. Efforts to define, measure, and model progress towards sustainability have led to the development of a variety of indicators and models that monitor and simulate (some) aspects of sustainability (Allen & Prosperi, 2016).

A crucial challenge is the ability to forecast trade-offs between human wellbeing and ecosystem services, economic performances, and environmental impacts. Vulnerability and resilience have emerged in recent years as key SES framing concepts for research on global change (Allen & Prosperi, 2016). There have been several illustrations of approaches analysing food systems for their vulnerability and resilience to global socio-economic and biophysical changes in order to explore their sustainability, which have highlighted key system processes and characteristics (Ericksen, 2008; Darnhofer et al., 2010; Allouche, 2011).

Allen & Prosperi (2016) propose a four-step method to develop a SES representation of global food systems:

- defining the study area and scale of analysis.
- identifying essential drivers of change.
- identifying essential food systems' outcomes; and
- developing a causal model by selecting essential interactions, drivers, and outcomes, and examining respective systems' exposure, sensitivity, and recovery potential.

They outline those two questions are crucial when defining the system level and spatial scale of analysis:

1. who are the intended users of the measurement set?
2. what is the degree of granularity of the food system's outcomes to be addressed?

The second and third steps require simultaneously identifying the main drivers of change and their potential impacts on the system. For their study they had based this analysis on extensive literature review and discussions with a focus group composed of seven experts.

They retained four drivers of change (water depletion, biodiversity loss, food price volatility, changing food consumption patterns) and four critical food and nutrition security issues as essential systems outcomes (nutritional quality of food supply, affordability of food, dietary energy balance, satisfaction of cultural food preferences).

In the fourth step, a causal model is developed: the four drivers of change and the four food security issues are matched to explore their possible causal relationships. Their proposed framework shows how changes in water, biodiversity, food prices and food consumption patterns are transmitted through the food system, including the sequencing of events and the scale of interactions; determines to what extent it is sensitive to these changes and can adapt to them; and identifies the food system characteristics that make it capable of sustaining food and nutrition security outcomes.

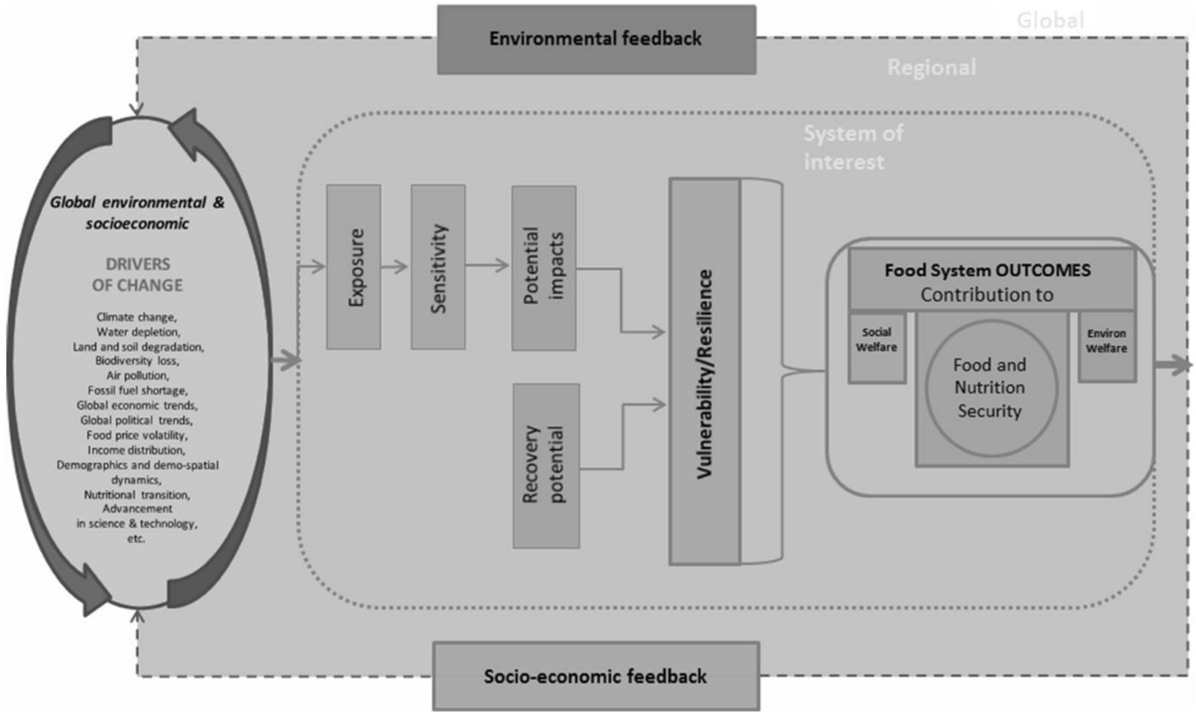


Figure 2: Framework describing Food System (Allen & Prosperi, 2016)

The application of system-thinking to a global complex issue such as food production has great relevance to closure planning, particularly the methodology that was applied for deriving an analysis framework.

The first critical requirement is to define the boundary of the system and the spatial scale of analysis, by identifying the intended users and the degree of granularity with which the system's outcomes will be analysed. With closure planning, there can be several groups of externa users, from external stakeholders interested in understanding the environmental feedback between the closed mine and the surrounding environment, to technical providers focused on integrating their detailed work within the broader description of the closure plan.

The requirement to define the system's outcomes relates directly to the selection of closure objectives, which should be underpinned by analysis of potential options (as discussed in Sections 3 and 4). As with food systems, mine closure planning encompasses an array of activities and mining methods, including production, processing, residue disposal, rehabilitation, and monitoring.

The mine system has an impact on the environment and can engender feedback loops and cross-scale interactions. Assessing the sustainability of the closure plan is about understanding these dynamics to gauge the ability of the mine closure system to maintain or enhance its essential objectives.

A process will need to be defined to guide identification of the drivers of change and their causal relationships, as to date, this has not been done in the context of closure planning.

5.1.2 Land use systems

Another example of application of system-thinking to complex issues relate to decisions about land use, which has some relevance to the selection of post-mining land use (Sections 3 and 4).

In most cases, as with closure planning, stakeholders wishing to develop land use and management change scenarios at the landscape scale and to assess their corresponding impacts on water quality, biodiversity and economic performance, must examine the output of a suite of separate models.

The process is not simple and presents a considerable deterrent to making such comparisons and impedes the development of more sustainable, multifunctional landscapes. To remedy this problem, several tools have been developed, such as the Landscapes Toolkit (Bohnet, et al., 2011), an integrated modelling framework that links spatially explicit models to enable integrated assessment of the water quality, biodiversity and economic outcomes of land use and management change scenarios. Intended users are natural resource managers, policymakers, planners and local communities.

The principal datasets required for use in the Landscapes Toolkit are land use, catchment and sub-catchment boundaries, a digital elevation model (DEM), drainage lines, transport networks and vegetation cover. Additional data sets, such as land suitability and protected areas, are included to support scenario development and/or the definition of parameters relevant to each model. A limited number of disciplinary component models currently linked in the Landscapes Toolkit assess water quality, terrestrial biodiversity and regional economics using a range of indicators.

Model developers argue that to support agriculture-environmental policy decision making, stakeholders need quantitative “back-of-the-envelope” analysis that is timely and sufficiently accurate to make informed decisions. The model is spatially explicit to clearly demonstrate how ecosystem services can be maintained or enhanced in a region. The Landscapes Toolkit strikes a satisfactory balance between the inclusion of component models that sufficiently capture the richness of some key aspects of social-ecological system processes and the need for stakeholders to understand and compare the results of the different models. Decisions that were made about the selection of datasets and sub-systems are relevant to mine closure planning.

Another example is the development of an interactive online tool called the Landscape Futures Analysis Tool (LFAT) (Summers, et al., 2015). Four high priority regional management issues were selected (agricultural production, carbon sequestration, biodiversity conservation and weed management) and simple models developed to explore a range of environmental and economic scenarios that included consideration of climate change, carbon price, agricultural commodity price, and production costs. These models were implemented within the LFAT to allow users to select, query and explore combinations of key variables and examine their impact on each of the management issues through a range of interactive maps and summary statistics. The intended use is to support regional planning.

There is potential for this sort of tool to support communication of the objectives of the closure plan to external and internal stakeholders.

5.2 Application in ecology and environmental management

Ecological management and restoration require consideration and integration of multiple technical assessments. A system-thinking approach that accounts for the interactive and interdependent components of an ecosystem, and feedbacks between them, is useful, if not essential, particularly when ecosystems are exposed to global changes (Hobbs et al., 2011; Lindenmayer et al., 2010). Evans (2011) highlights that ecologists need to embrace the development of truly predictive system models, which can be cast into future conditions. Anthropogenic environmental change is creating new environmental conditions and we need the ability to forecast how these conditions will impact on ecosystems and their components (Clark, et al., 2001).

Hallett (2020) proposes a method based on systems archetypes, borrowed from business management theory. Systems archetypes propose a topology for organising common patterns of systems' behaviour and identifying relationships among them. In ecological intervention, they can assist with identifying scenarios that have the potential to be repeated and suggest more effective interventions. Broadly, there are four system archetypes (

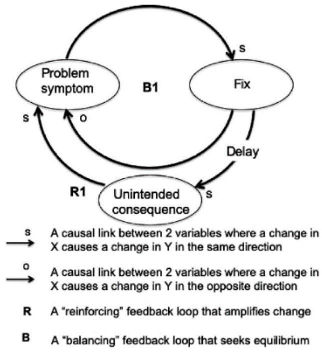
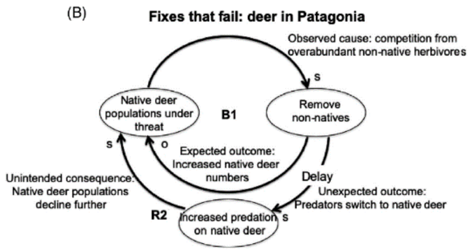
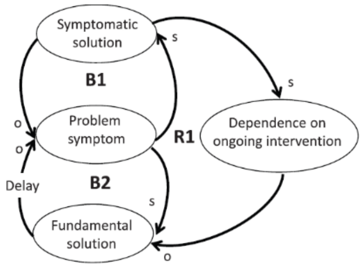
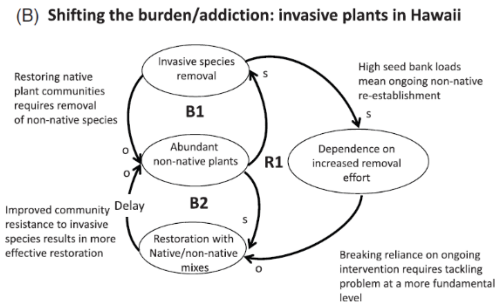
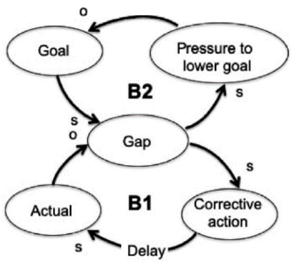
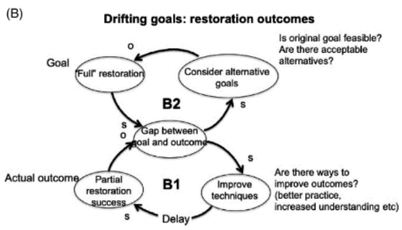
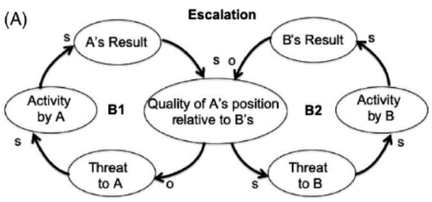
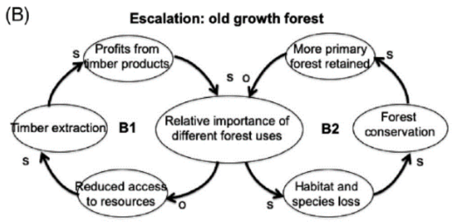
Table 3):

- Fixes that fail when an action is taken that alleviates the problem temporarily, but eventually makes it worse. There are plenty of examples in ecology, the most recent one being the attempt to save the Tasmanian devil by re-locating a small healthy population to Maria Island, where they fed on endemic little penguins and completely eliminated them. In mining, the most extreme example is the practice of storing residue as a slurry with high water content in tailings dams, which is assessed as being cost-effective but can lead to tailings dam failures, with enormous environmental and financial consequences (Burritt & Christ, 2018).
- Shifting the burden: a solution to treat the symptoms diverts attention from the more systemic problem. An example applicable to mining is coal mines in Queensland negotiating for updates to the calculation method of design storage allowance (the volume of mine water that they are allowed to hold in the mine water system before the start of a wet season), rather than implementing strategies to reduce their inventory of mine water, such as treatment.
- Drifting goals: in an effort to close the gap between a goal and current performance, the nature of the initial goal is adjusted. An example applicable to mining relates to the increase in greenhouse gas emissions from some coal mines, with the decision to exploit loopholes in the safeguard mechanism policy to increase the emission baseline, rather than investing in increased gas capture infrastructure. The increase in emission baseline represents the drifting goal.
- Escalation: one actor takes an action that is perceived as a threat by another actor, who retaliates. An example applicable to mining rehabilitation would be the selection of native species to re-establish vegetation on reshaped landform, rather than an improved pasture species to support grazing. Local stakeholders could potentially respond by clearing more land for pasture.

In ecology, there have been many examples of poor outcomes that could have easily been predicted by application of system-thinking in general, and identification of the system archetype in particular. It can be used to rapidly assess, communicate, and ideally optimise the impact of potential management actions, without inadvertently creating unintended negative outcomes.

It is recommended that mines adapt and implement this type of analysis to ensure potential negative feedbacks are identified early in the closure planning process.

Table 3: Systems archetypes and examples of application.

Type	Representation	Example
Fixes that fail It occurs when action is taken that alleviates the problem temporarily, but eventually makes it worse via an unintended feedback		
Shifting the Burden It occurs when a solution to treat the symptoms diverts attention from the more systemic problem		
Drifting Goals It occurs when in an effort to close the gap between a goal and current performance, the nature of the initial goal is adjusted.		
Escalation It occurs when one actor takes an action that is perceived as a threat by another actor, who retaliates		

Source: (Hallett, 2020)

5.3 Applications in Mining

Extractive industries such as mining include complex processes and operational challenges throughout the life of mine. The incorporation of these mining components and processes into the environmental system generates highly complicated system dynamics with a large range of interactions.

5.3.1 Managing Mining Regions

There are some studies that applied system-thinking to understanding the interactions between mining and the environment. Alaoma & Voulvoulis (2018) investigated the potential for re-assessing mineral resource active regions from a systems perspective. Findings of this research demonstrated that the application of systems thinking in resource management has the potential to deliver benefits to all stakeholders as they illustrate the interdependencies between the various players and sectors in the mining regions. This approach offers an alternative to the reductionist end-of-pipe thinking of traditional resource management that usually focus on competition and assessment of impacts separately. Alaoma & Voulvoulis (2018) proposed a preliminary conceptual model for system interactions in a mining active region (Figure 3).

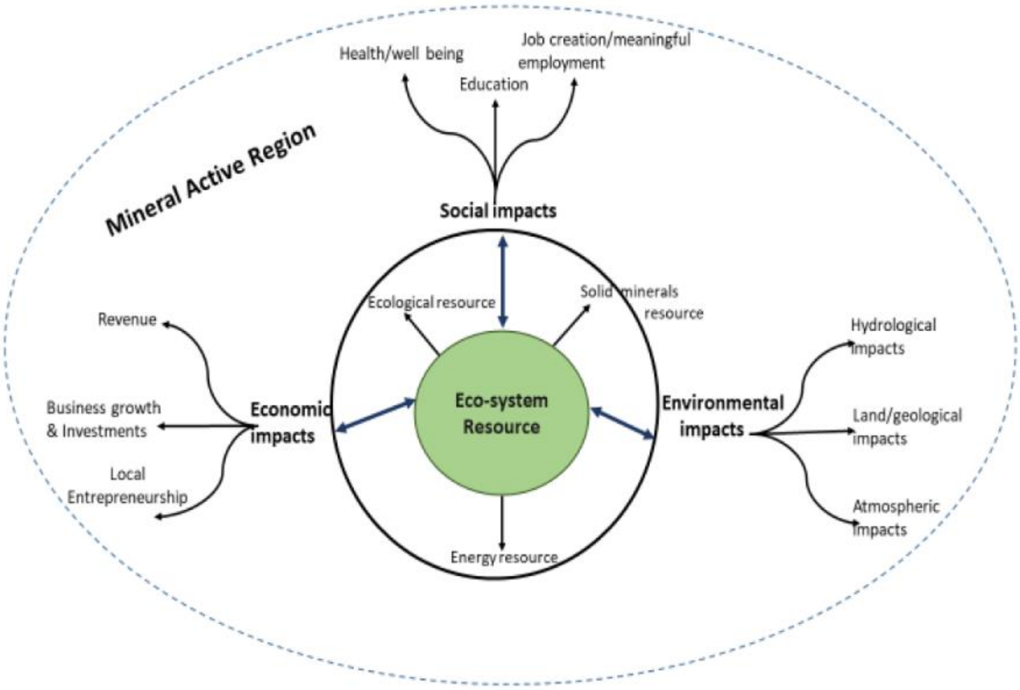


Figure 3: Preliminary conceptual model for system interactions in a mining active region

Authors postulated that system thinking in the management of mining active regions has the potential to deliver benefits through the understanding of the links between system components, their interactions, and interdependencies. Using conceptual models of the relationships and interactions that characterise the regions, and through a multidisciplinary approach, system tools can enable stakeholders to fathom these interactions and interdependencies. Critical gaps and barriers that undermine efforts to sustainable resource extraction and management become visible, allowing for more collaborative and participatory management. Accounting for spatial-temporal and sectorial issues, such participatory approaches involve gathering historical and contemporary views on the regions, creating a collective representation based on the integration of different perspectives.

Systems tools treat mining active regions as integrated catchments, complex systems with spatial and temporal boundaries. This does not mean that systems-based methodologies can provide an all-encompassing solution, instead, they enable stakeholders to redefine the problems they face and even make the need for management solutions obsolete. This study however was solely conceptual, with no domain of application.

5.3.2 Systems approach for ecological environmental management in coal mining areas

Shi (2020) proposed a system dynamics model for ecological environmental management in coal mining areas in China. First, the whole causal loop diagram of the system was built to illustrate the general system (Figure 4). Five subsystems were presented according to the causal loop diagram. This illustration assisted with assessing different allocation alternatives of investment for ecological environmental management in coal mining areas.

In Figure 4, we can identify a positive feedback loop, where an increase of the first parameter will lead to a higher level of the first parameter. For instance, an increase in the degree of GDP will increase the environmental investment and investment in air treatment leading to higher air quality, which reduces the cost of pollution control in the coal mining area, leading to a higher mining revenue and GDP. Negative feedback loops were also identified, where an increase of the first parameter will lead to a lower level of the first parameter. For instance, an increase in environmental investment will increase investment in air pollution, leading to higher air quality and ecological environment quality in coal mining areas, which leads to a lower environmental investment.

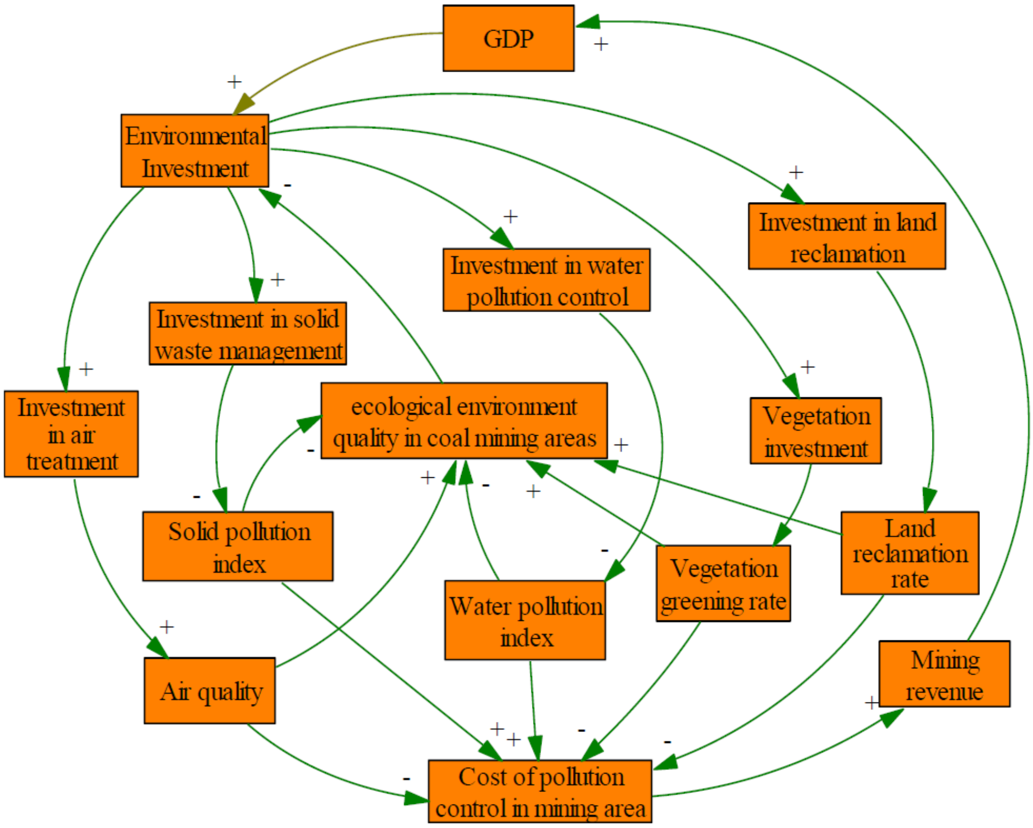


Figure 4: Causal loop diagram of the general system (Shi, 2020)

Figure 5 presents the subsystem 'water pollution', which is one of the 5 subsystems of the general system. Water pollution is the state variable, water pollution production and the amount of water pollution control are the rate of the variables. Here, the amount of water pollution control refers to the quantity of water pollution that is treated.

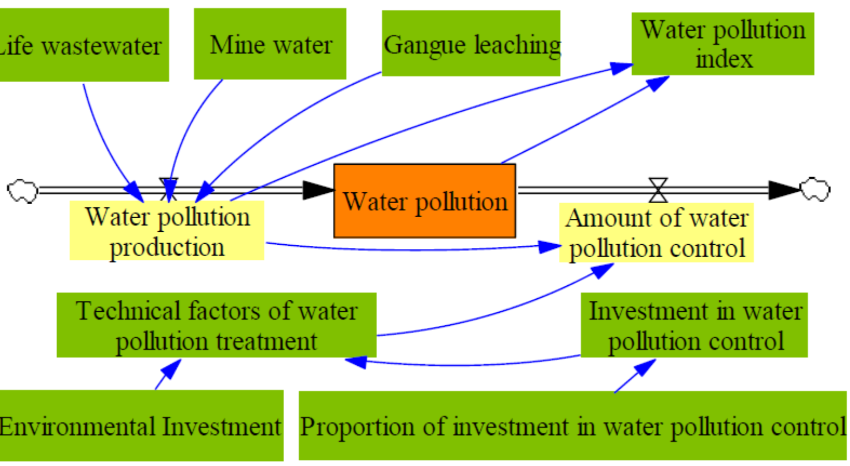


Figure 5: System flow diagram of water resource subsystem (Shi, 2020).

In general, these studies provide good examples as they demonstrate the applicability of the system-thinking approach to different aspects of the mining activity. However, to the best of our knowledge, there are not any studies that aims to deeply understand the interrelation of biophysical parameters and the mining closure plan in a way that assist the planning of the technical studies.

5.4 Conclusions

There is a large body of work in the literature that applied system-thinking to describe and communicate the relationships between parts of a complex system. The objectives of such work are almost always to understand complexity and change, and to provide tools to describe and understand complex challenges.

These tools are largely graphical representation of relationships, using charts and diagrams. These can lead to development of numerical models to calculate the flows of quantities between elements in that chart. There is no set structure or methodology to develop these representations and models. The research team examine the problem at hand, draws list of components and articulates the impacts of one on the others. There can be myriads of models for similar systems, depending on the temporal and spatial scales that is selected.

Given the flexibility of the system-thinking approach, there is no barrier to applying it to the closure planning: the challenge is to define the structure and methodology that will yield the most benefits.

6 Intended Users

Based on the literature review, and Section 6.1.1 in particular, there are four main stages to developing a system-level approach.

Stage 1	• Define study area and scale of analysis • The mine (internal) & its environment (external)
Stage 2	• Identify the main subsystems and associated variables • Identify the main relationships between the variables
Stage 3	• Identify essential drivers of change
Stage 4	• Develop a causal model between the drivers of change, vulnerability, potential impact, management strategy

Figure 6: Stages of the system-level approach

In Stage 1, the two critical aspects are to define the intended users and the degree of granularity of the system's outcomes that will be required. Both are linked. For closure planning, we can envisage three groups of intended users:

- Tier 1 Group would include external stakeholders at local, regional and potentially national level. Communication of system's outcomes would focus on risk assessment and confidence in mitigation measures, with a low degree of granularity. Visual and spatial tools would be preferred. Good examples are described in Section 6.1.2.
- Tier 2 Group would include internal stakeholders from the company. Communication of system outcomes would focus on the behaviour of the environmental system for all analysed mine planning and environmental scenarios, with a medium degree of granularity. Tools will be used communicate to internal stakeholders that the project team has envisaged all potential outcomes and has implemented adequate mitigation measures, thereby providing confidence in the resilience of the closure plan. The example discussed in Section 6.3.2 gives a good example of the level of detail that should be captured, although it is likely that the full causal model will be too complex to be fully captured in a diagram. A tabulated form might be more appropriate.
- Tier 3 Group would include the service providers who are assisting the project team. Outcomes would focus on the behaviours of the sub-systems with a high degree of granularity. Tools will be used to ensure consistency and coherence between the technical studies, with a high degree of granularity.

At Stages 2 and 3, graphical models will be required to identify and represent the individual elements and their topological relationships. System diagrams are a popular and effective means of conveying topological relationships and feedbacks between elements in various fields. Topological maps can be useful in communicating complex information at the right level of abstraction. These models will have to be developed for each tier described above.

At Stage 4, the causal model can be elaborated for a range of scenarios and the results analysed to determine if the model can demonstrate the significance of the interactions or feedback loops between biophysical aspects in the different technical studies; if it captures the impact of a change in one of the biophysical aspects for the other environmental studies, and if it can be used to define thresholds of significance.

The challenge will be in defining the mathematical relationships that link the variables. Each technical study will produce sets of complex results and innovative approaches will be required to establish the influence of one set of results on the other aspects of the system. Appendix A gives an example of a suitable approach for developing a causal model.

In developing causal models, a distinction can be made between perturbation or stress. Perturbations are major spikes in pressure (e.g., a tidal wave or hurricane) beyond the normal range of variability in which the system operates, and commonly originate beyond the system or location in question. Stress is a continuous or slowly increasing pressure (e.g., soil degradation), commonly within the range of normal variability. Stress often originates within the system, and stressors often reside within it. For simplicity, we selected the term “vulnerability issue” and organised them as internal to the system or external to the system.

Following these steps for each group of intended users will produce a “Project Planning System”, as described in Table 4.

Table 4: Elements of the Project Planning System

Level	Title	Description
Tier 1 External Stakeholders	Communication and Engagement	High level diagram and tools to facilitate communication and comprehension of the mine closure and rehabilitation planning process.
Tier 2 Internal Stakeholders	Objectives, Drivers, Variables and Management Strategies	Description of system elements to capture interactions and feedback loops between biophysical aspects and the project planning design options. Can be used to demonstrate the impacts of design options on system-level variables, supported by detailed causal models Will include a range of tools to support assessment of specific aspects. For instance, a water assessment tool will be required to capture the objectives, drivers and management strategies for the project’s water-related risks.
Tier 3 Service Providers	Technical Studies Integration	Description of relationships between supporting technical domains, to assess impact of a change to the design of an operational domain, and magnitude of change that will require a review of detailed technical work. Will be supported by a specific causal model that identifies where data and results from one study impact on the scope and results of another. Will ensure consistency and coherence between the different technical studies and guide the timeframe to undertake them.

6.1 Testing applicability of the system-thinking approach in mining

A previous step before the application of the system-thinking approach consists of testing the applicability of this approach in mine closure and rehabilitation strategies. For this purpose, the case of the rehabilitation of Mount Morgan Mine (Queensland) was considered. An example of system diagram was developed to illustrate how the rehabilitation strategy can be defined based on the objectives and the main drivers.

The Mount Morgan region has sub-tropic, sub-humid climate with an annual average rainfall of 793mm. Heavy rains, typically during December to February, increase the flow of acidic sediment throughout the catchment, adversely altering water quality. Acid mine drainage (AMD) is the result of a natural oxidation process that occurs when rocks containing sulphide materials are exposed to air. Vicente-Beckett et al. (2015) reported that AMD contamination in the Dee River extended to about 80km downstream of the mine and at a 30cm depth of the riverbed and floodplains. As a result of acidic minerals lowering the pH of the catchment upstream and interacting with freshwater downstream, water colouration can occur.

In 2013, a cyclone caused the mine to overflow, spilling acidic runoff and heavy metals into the river (Mount Morgan Mine, 2018). This caused devastating losses to species diversity in the area.

In 1992, the Queensland Government obtained control of the legacy issues of the mine and restricted operations to the reprocessing of tailings and stockpiles. Several projects have been proposed and they are expected to support the economy and local community through employment opportunities, enhancement of adventure tourism activities and environmental rehabilitation. The State Government currently spends $3 million annually to manage the site, which is vital to safeguard ecosystem services.

As a first step, a diagram of the closure objectives was developed (Figure 7) and the main drivers and rehabilitation actions were identified (Figure 8).

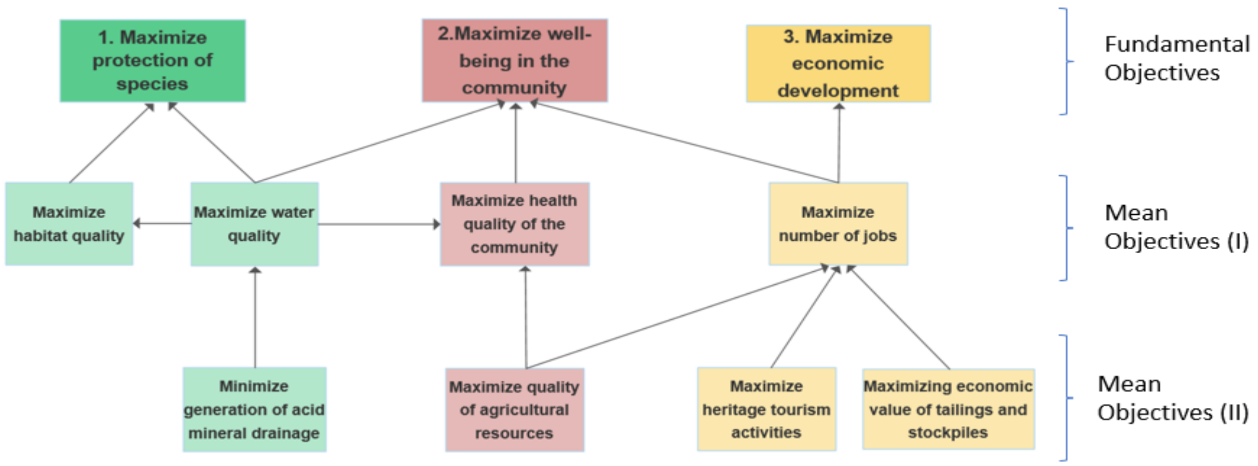


Figure 7: Objective's diagram for Mount Morgan Mine

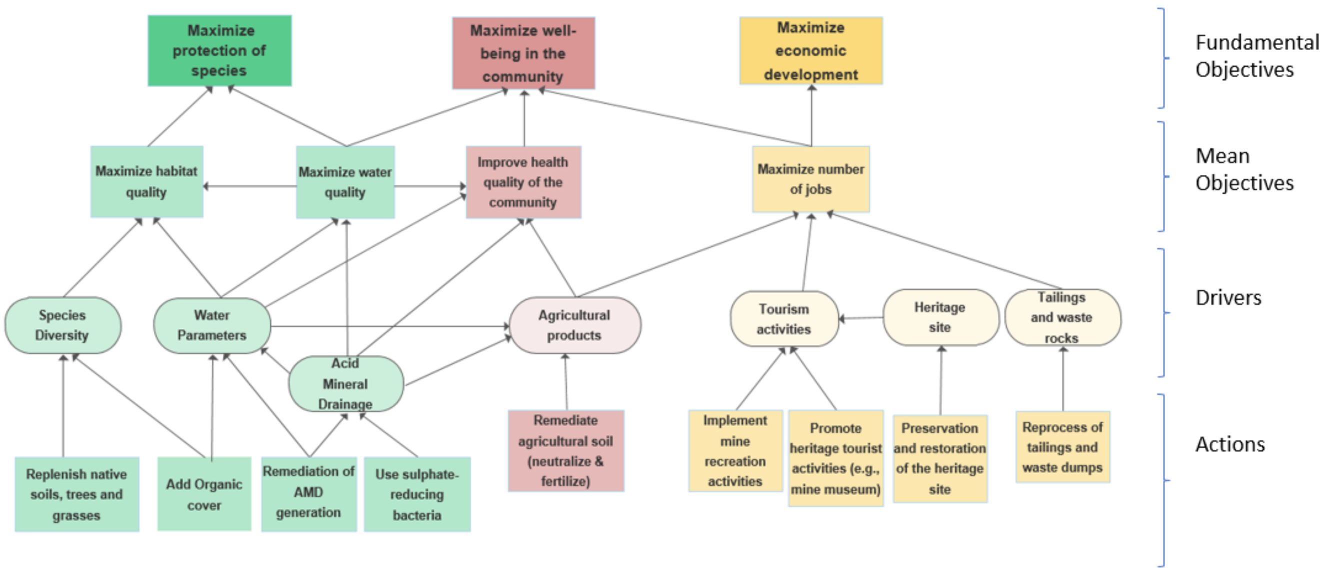


Figure 8: Objectives, drivers and actions

7 Prototype Examples

7.1 Tier 1 - Communication and Engagement for External Stakeholders

7.1.1 Methodology

For this group of intended users, the objectives are to address some of the barriers that have been identified as part of the literature review, particularly as part of the discussion related to communication of flood risks: the UK Environmental Agency had adopted a system approach to communicate risks from coastal flooding because they had identified that existing scientific approaches, which rely on detailed flood modelling, were not well-suited for describing the complexity of coastal flooding processes to impacted communities. They also found that the nature of the flood models posed several challenges in ensuring their application was based on a comprehensive understanding of the system (Narayan, 2014). Complex models are scientifically robust but do not work well as communication tools.

The first component at this level should be a high-level diagram or tool that will communicate the mine closure and rehabilitation planning process to external stakeholders. Figure 9 provides a simplified generic diagram, which can be adapted for a specific mine to highlight the relevant elements of that particular system.

The diagram presents the main tasks to develop the mine closure and rehabilitation plan in green boxes. The main inputs for these tasks are in grey boxes. The arrows represent the sequence of tasks and the transfer of information from the input boxes.

The blue arrow shows that rehabilitation objectives should be an input for the mine design. This interaction is important as designing for closure will maximise the progressive rehabilitation of the land and will minimise the long-term closure costs and management requirements. This diagram also highlights the relevance of the outcome of consultation with the community in developing the plan as it determines the first task.

It is important to notice that some input processes (mine design, climate change and regulatory, and any other as applicable) can change throughout the closure and rehabilitation program. Therefore, they can be considered as relevant drivers of change that should be monitored to identify if updates are required in the technical studies.

Once this step is complete, the system outcomes should be defined, which, in the case of closure planning, is likely to be captured mostly as rehabilitation objectives.

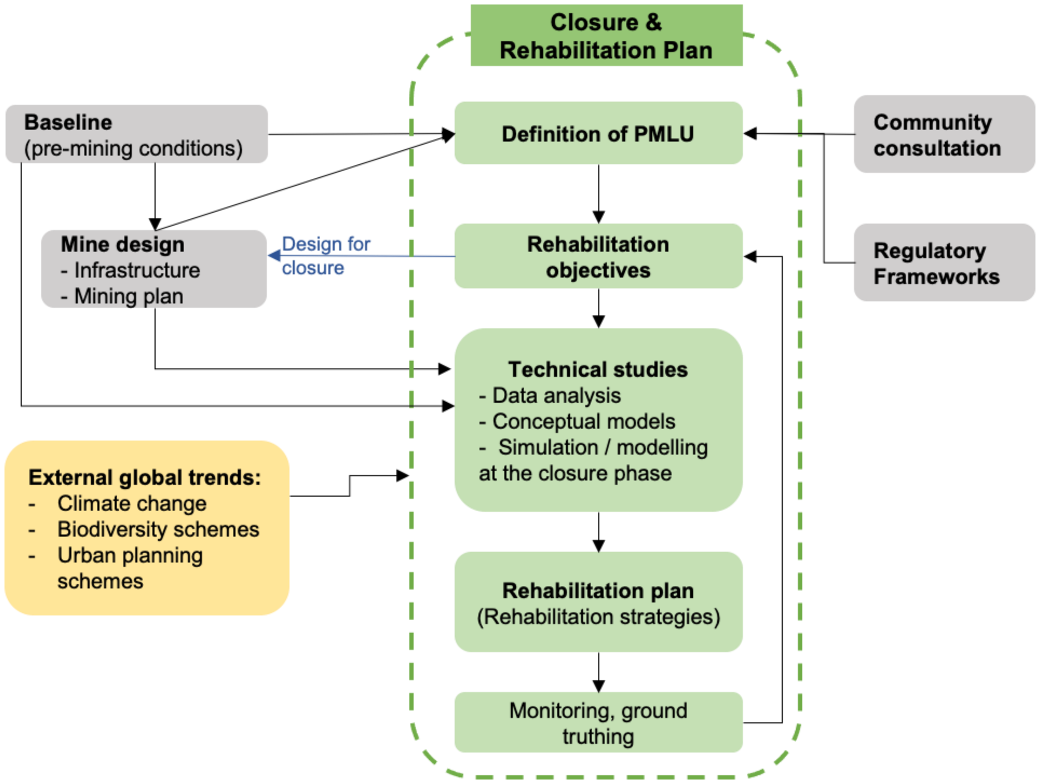


Figure 9: Mine closure and rehabilitation planning process

7.1.2 Example - Mount Morgan Mine

For the purpose of providing an example of a prototype that would communicate system's outcomes, the case of the rehabilitation of Mount Morgan Mine (Queensland) was considered. An example of a system diagram was developed to illustrate how the rehabilitation strategy can be defined based on the objectives and the main drivers.

Based on Keeney & Raiffa (2003), a diagram of the objectives was developed (Figure 10) as a first step to outline the key outcomes for the closure plan for Mount Morgan Mine.

The fundamental objectives represent the overall goals of the closure plan, while the means (lower level) objectives provide pathways to achieving these.

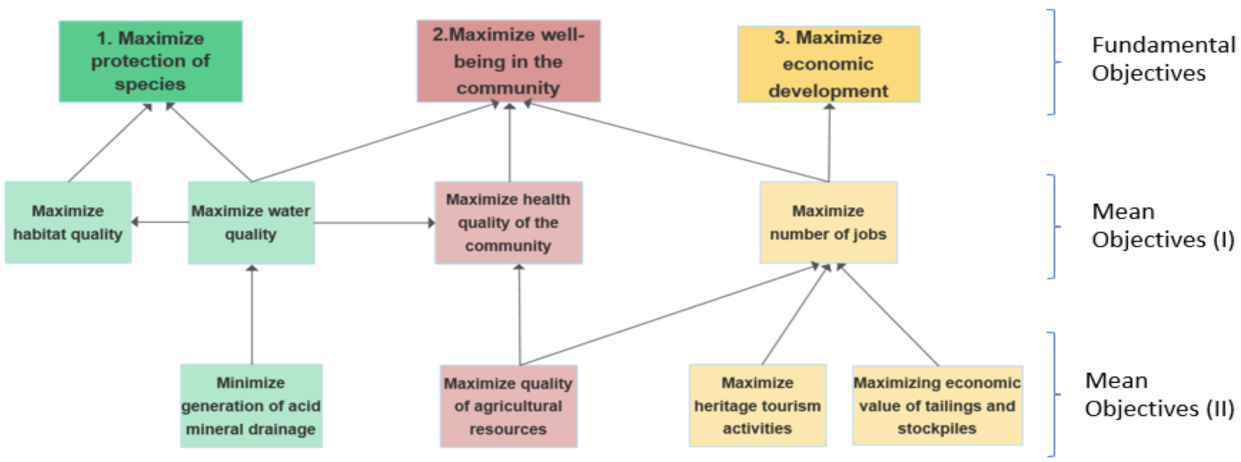


Figure 10: Objectives diagram for Mount Morgan Closure Plan

For the system-approach to remain effective as a means to describe and understand the complex challenges embedded in closure planning, it will be important to limit the proliferation of objectives in the horizontal direction, so as to maintain the relative significance of each of the objectives. However, more details can be provided to describe which drivers and associated actions will deliver the objectives. Figure 10 was expanded to capture this level of information (Figure 11). The drivers identify the key biophysical parameters that influence the delivery of the objectives, while the actions influence the drivers.

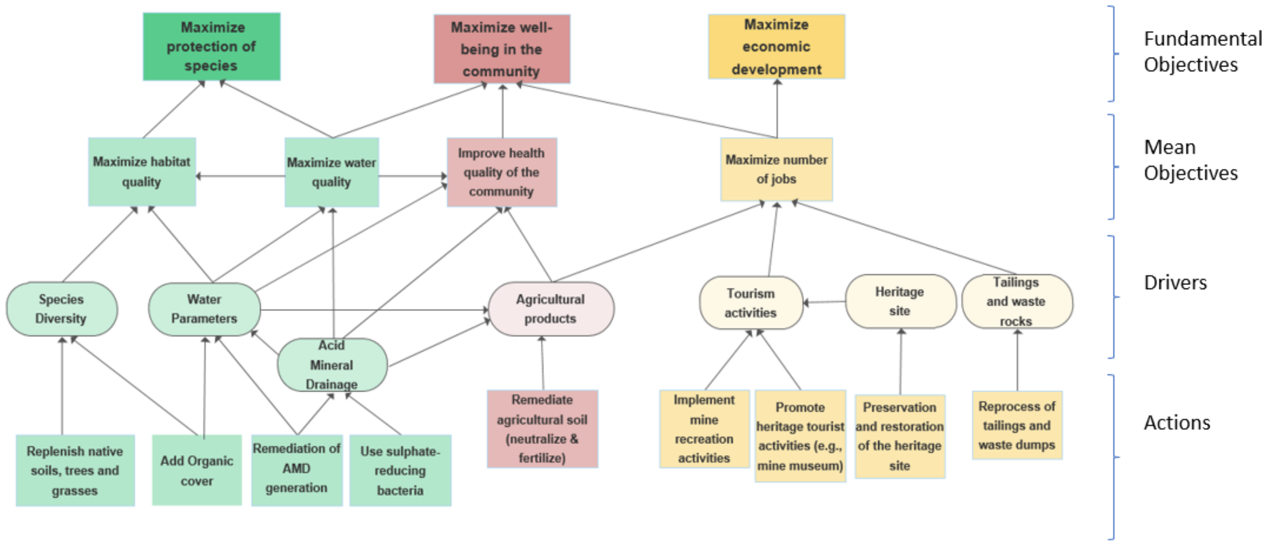


Figure 11: Objectives, drivers and actions for Mount Morgan Closure Plan

7.2 Tier 2 – Internal Stakeholders

7.2.1 Part I: Defining objectives, drivers, variables and management strategies for closure and rehabilitation

For this group of intended users, the outcome should be a diagram or tool that presents the main objectives, drivers, variables and management strategies for closure and rehabilitation (see Figure 12 and the full-size figure in Appendix B). This diagram could be used as a tool to communicate the main elements of the closure and rehabilitation plan. For illustration purposes, the recently approved Progressive Rehabilitation and Closure Plan (PRCP) of the Vulcan Complex Project was considered as an example to represent a simplified version of the result expected in this stage; however, further analysis will be needed to fully represent the system elements and interactions.

Under the Mineral and Energy Resources (Financial Provisioning) Act 2018 (MERFP Act), when submitting a site-specific application for an Environmental Authority (EA) for a new mining activity, applicants are required to submit a proposed PRCP as part of their application. The development of a PRCP aims to: (i) require the EA holder to plan the activities that will be carried out to maximise progressive rehabilitation of the land to a stable condition; and (ii) provide for the condition to which the land must be rehabilitated before the EA may be surrendered. A PRCP consists of two parts:

- Rehabilitation planning, which provides evidence and justification to support the schedule. It should include information about the site and operation, community consultation, analysis of post-mining land use (PMLU) or non-use management area (NUMA), and rehabilitation methodologies.
- PRCP Schedule, which includes the rehabilitation milestones.

Selecting and justifying appropriate PMLUs is fundamental to the PRCP and underpins the obligations in the PRCP schedule. Some examples of PMLU are native ecosystem, habitat and ecosystem services, grazing, agriculture, forestry, cropping, industrial, land fill and water storage (see Section 4 for the trends that may impact on the selection of PMLU).

The content requirements for a PRCP are established in the section 126C(1)(b) and (c)(ii) of the Environmental Protection Act. In addition to the legislative requirements, the guideline "Progressive rehabilitation and closure plans" (Queensland Government, 2021) presents additional information required to approve the PRCP.

This guideline identifies a number of studies or reports that must be provided in the proposed PRCP because they are necessary to underpin the development of the rehabilitation or management methodologies. For specific operations, any of the required information might not be relevant. The applicant must include the information as appendices to the rehabilitation planning part. The range of required studies is separated into those that may be applicable to the whole site and those that are relevant to specific infrastructure (such as TSFs, voids, and underground mining).

As the studies required are representations of different elements of the same study area, it is appropriate to apply the system-thinking approach in the development of the studies to assure consistency and coherence in the representation of the environmental systems where the mine rehabilitation will take place. The application of the system-thinking approach in this context is presented in Section 8.3.

A prototype example for Tier 2 is provided in Figure 12 (the full-size figure in Appendix B). It represents the main objectives, drivers, variables and management strategies for closure and rehabilitation from the Vulcan Complex PRCP. This diagram could be a tool to communicate with all internal teams the main elements of the closure and rehabilitation plan.

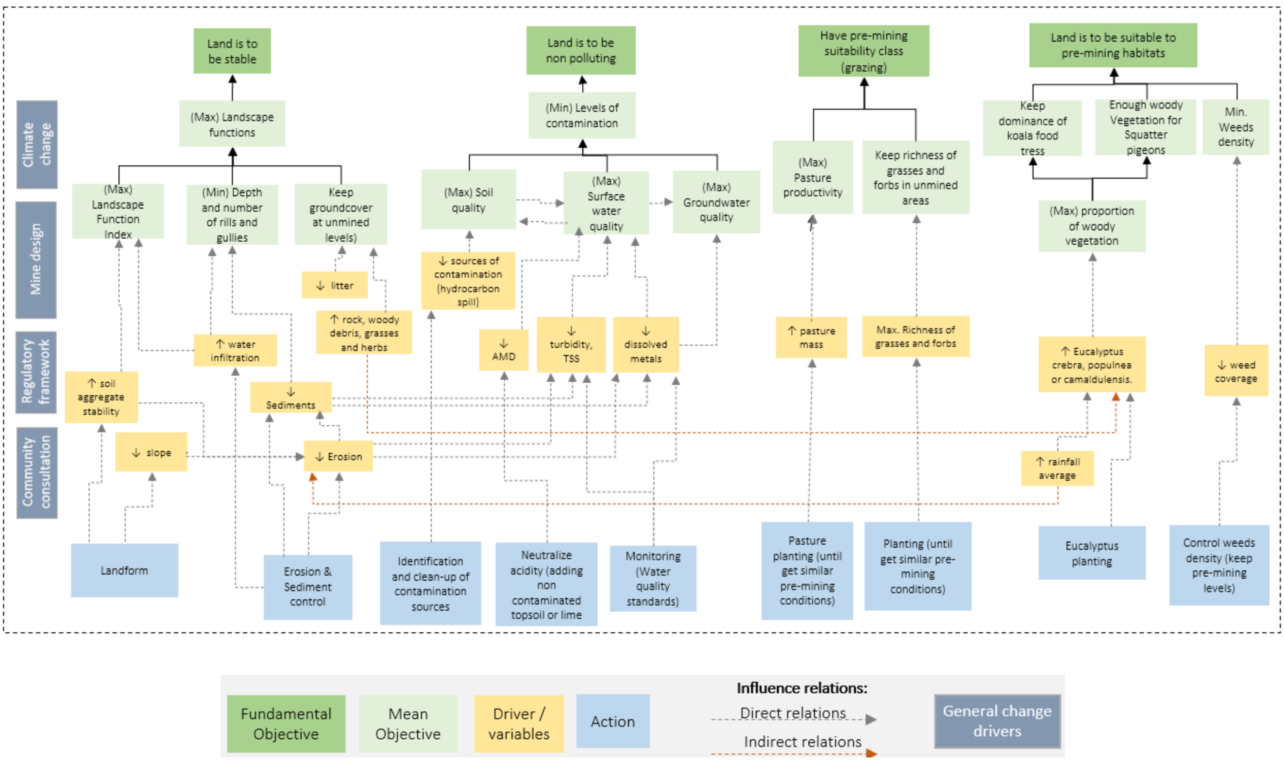


Figure 12: Main objectives, drivers, variables and management strategies for closure and rehabilitation in Vulcan Complex Project

Firstly, the objectives for closure and rehabilitation are identified: they will be directly related to the selected PMLUs. Secondly, one or more means objectives are identified to support delivery of each fundamental objective. Thirdly, the drivers or variables are identified, which are the specific parameters that can drive direct or indirect influences in achieving the means objectives.

Based on the objectives, drivers and variables, actions can be defined (presented in the diagram as blue boxes). The diagram also indicates whether an action will lead to an increase in the parameter value (for instance, pasture planting will lead to an increase in pasture mass) or a decrease in parameter value (for instance, investment in erosion and sediment control will lead to a decrease in erosion and sediment export).

The relationships between the elements of the system are represented by two types of influences, direct (black arrows) or indirect (red arrows). Direct influence means that a change in the variable will be positively impacting on the objective, whilst an indirect influence will be detrimental.

There are general drivers of change that might affect different elements of the system. The drivers are represented as grey boxes in the diagram and in this case include climate change, mine design, regulatory framework, and community consultation. These should be considered throughout the rehabilitation plan, and changes in them will require the review of the other elements.

This description can support a quantitative "back-of-the-envelope" analysis that is timely and sufficiently accurate to make informed decisions (as mentioned in Section 6.1.2).

7.2.2 Part II: Defining the key information required for a PRCP

Beside communication with internal stakeholders about the closure and rehabilitation objectives and actions, it is important to share with them a high-level framework about the key information required to define the closure and rehabilitation plan.

The guideline "Progressive rehabilitation and closure plans" (Queensland Government, 2021), presents the content requirements to approve the PRCP. This guideline identifies a number of studies or reports that must be provided as part of the proposed PRCP. However, the applicants need to define a strategy about how to develop the technical studies in a way that comply with the legal requirements that is fully suitable for the specific operation, and that assure consistency between the study results and efficiency in the elaboration of the studies.

The system thinking approach is highly appropriate to assist in developing the strategy for developing the technical studies required to support the PRCP, as the studies provide a representation of different elements of the same system.

The suggested steps are to:

1. Review the regulatory framework to identify the main studies that are required and identify if any of them is not applicable to the project;
2. Identify additional studies that are not legally required but that could be important for the characteristics of the project;
3. Identify interrelationships between the different studies;
4. Identify the main drivers of change.

At this stage the system would not be represented with too much detail so that internal stakeholders can easily understand the main studies and the interrelations between them. The internal stakeholders will be team leaders from various specialised areas within the company. The outcomes from this stage of the analysis are meant to assist with clarifying the level of team coordination that will be required to deliver an effective PRCP. It will also assist with defining the plan and schedule of the development of the PRCP.

Figure 13 provides an example of representation of the key studies required for the PRCP, outlining inter-relationships. There are three main groups of studies (i) the baseline studies that represent the pre-mining environmental conditions, (ii) the project description that includes the mining plan and design of the infrastructure required for the mining operations on site, and (iii) the rehabilitation plan reports that justify the rehabilitation strategies. In the last group there are two different types of studies, those that are applicable to the whole site and the studies for specific infrastructure elements.

Table presents the minimum content of the rehabilitation studies according to the guideline "Progressive rehabilitation and closure plans" (Queensland Government, 2021).

Additionally, there are other important elements of the system that will define the rehabilitation strategies, such as community consultation and regulatory framework. These should be represented in the system as reference, but they are not technical biophysical reports.

Companies will need to identify the processes that will deliver this kind of information representation. One option is to organise workshops with members from most teams and combine their knowledge to draw the diagram. This will ensure there is shared understanding of PRCP requirements and strong commitment to the delivery of agreed objectives. This will also lead to teams that are collectively mindful of their risks and commitments.

In the next stage (Tier 3) further analysis is undertaken to identify the specific variables in the different studies that are connected and the main interdependencies between the studies.

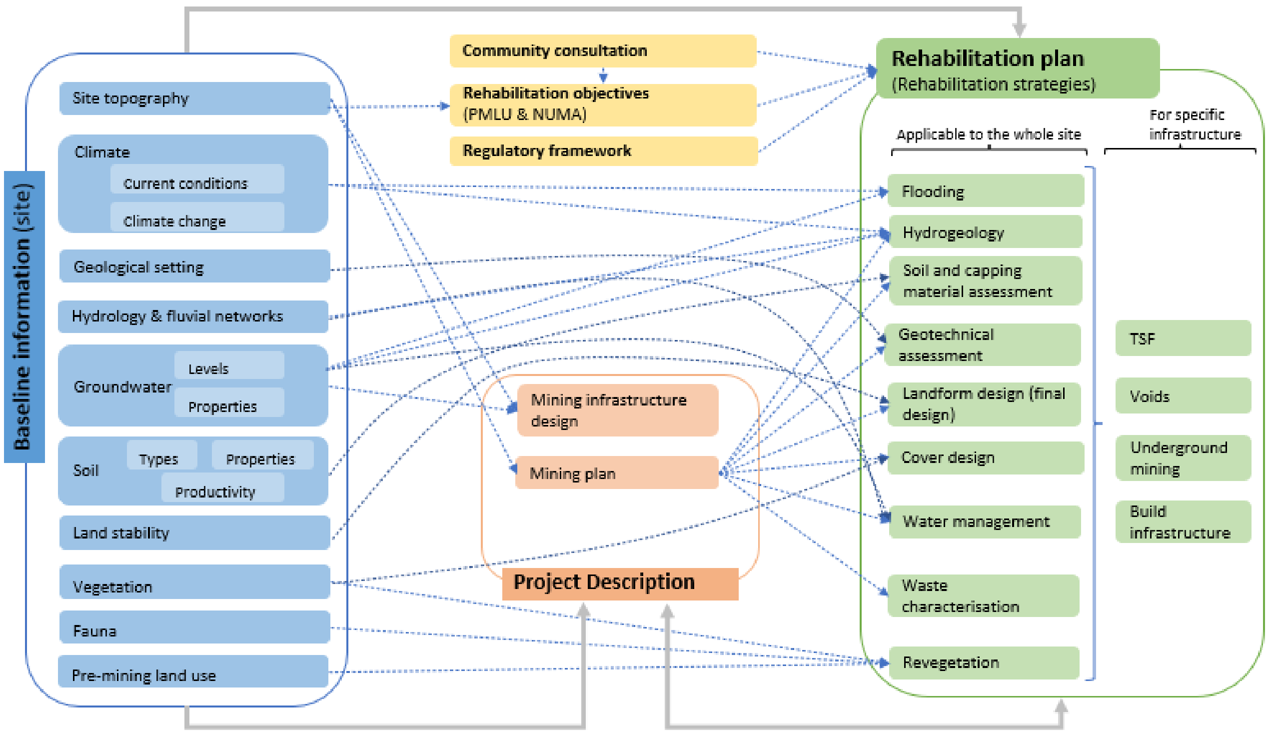


Figure 13: Key studies required for a PRCP

Table 5: Minimum content of the rehabilitation studies

Report	Key information
Hydrogeology	• occurrence, recharge and discharge, flow direction and velocity, • groundwater quality within aquifers and surface expressions, • future uses, • potentiometric mapping and hydro-stratigraphic cross sections • contaminant transport modelling
Flooding	• location of domains and alteration of flow upstream and downstream • model flood levels for a range of design storm events • flooding risk profile
Soil and capping material assessment	• quality and quantity of available resources (e.g., topsoil, clay, competent rock) required for the rehabilitation • location and accessibility of cover material • need for ameliorants and fertilisers • relationship between soils and vegetation ecosystems for the PMLU and rehabilitation methodology.
Waste characterisation	• chemical composition and mineralogical analysis • acid base accounting and net acid generation • water extraction • humidity cell leach testing or column leach testing.
Landform design	• 3D design plans of the final landform • method of determining landform design • modelling predicting the long-term stability of the final landform design
Cover design	• design including the thickness of each layer • construction methodology including any proposed staging of the cover system
Water management	• contaminants that pose a risk to environmental values • source, pathway and fate of potential contaminants • infiltration and seepage intervention and collection controls • surface water diversions and dewatering requirements • water management requirements
Revegetation	• key flora species representative of the proposed PMLU • species of conservation significance relevant to the mine's approval • identify any fauna habitat and use requirements • works for establishing and managing the revegetation
Rehabilitation plan per main components	• Rehabilitation plan for specific components such as underground mine, voids, TSF

7.3 Tier 3 - Service providers

7.3.1 Meta description of Technical Studies

Administering authorities require a substantial range of information and studies to underpin the development of rehabilitation or management methodologies. A portion of these studies are applicable to the whole site while some are relevant to specific infrastructure only. These studies contain numerous components with various outputs. The key outputs from each of the required studies is summarised in Figure 14**Error! Reference source not found.**.

Given the high number of studies, there is a requirement to produce a "meta" description of technical studies, which will capture their critical components: the type and extent of data sets, objectives, methodology, modelling approach when applicable, extent of spatial and temporal domain, results and limitations. This information provides data about the data used in the study, and as such is referred to as "metadata". It is recommended that studies' metadata always be compiled to demonstrate coherence between the assessment of biophysical aspects.

Beyond this, there is also the need to develop specific causal models that identify how and where data and results from one study impact on the scope and results of another as shown in Figure 15.

For the Tier 3 intended user, a critical requirement is the development of a database tool that can be used to identify the data requirements and determine the data dependencies of the different technical studies required for a project study. The database tool shown in Figure 16 has adopted aspects of Leontief's economic input-output analysis and the methods used for ecological network analysis (Fath & et al, 2007). Input-Output analysis explains the interdependence and interrelationship of inputs and outputs of various components of a system. The various components are represented by the technical studies, the required data for the study as in input and the resulting data as an output. This exercise also highlights possible feedback loops for the data. The technical studies and their outputs are arranged in columns and rows and data 'flows' are assigned where column *j* is dependent on row *i* (Figure 16). The project can therefore be summarised as an adjacency matrix where a_{ij} =1 if there is a "data flow" (or data requirement) from column *j* to row *i*, and a_{ij} =0 if there is none. The adjacency matrix can be used to apply sensitivities to each data flow to represent the dependency or reliance of the accuracy of the study on that data, to develop data flow diagrams and illustrate key interdependencies of the different types of studies.

The critical unresolved issue is defining methods to link the results of these studies so that the impact of a change to the design of an operational domain can be quickly quantified to assess whether it requires a review of detailed technical studies. The requirement to integrate studies is well articulated by the IESC (Section 5.2) but no recommendation has been provided to guide how this might be achieved.

7.3.2 Linking Models

One option is to link all the detailed models with each other. The literature review produced some examples, with the most relevant one being related to an environmental impact assessment undertaken for the Gahcho Kué mine in northern Canada (Vandernberg et al, 2016). This project presented a unique set of challenges from a modelling perspective owing to: (1) the dynamic nature of the mine plan and water management plan; (2) the dominance of aquatic features in the region; (3) the different water characteristics between the groundwater and surface waters that will be mixed during operations; and (4) the sensitivity of the pristine waters that will be affected by mining operations. These challenges required an unusually large number of models to interact together, with each model operating within a sub-domain of the overall spatial–temporal domain of the project (Vandernberg et al, 2016).

The project mine plan was designed with the objectives of minimising discharges to the environment and limiting the extent of surface disturbance. These objectives were to be achieved by isolating and dewatering a lake, mining open pits in sequence, and using the isolated lake for most of the operational water and waste management purposes. Mined-out open pits were to be used to store mine materials or water as mining advanced to the other pits.

There is currently no set template or universal framework for developing models for assessing aquatic effects of large, complex mining projects. There is no single model that can simulate the multitude of potential effects in groundwater and surface waters over the various spatial and temporal domains of interest. Instead, environmental assessment practitioners must collaborate to integrate specialised models developed from within their discipline into a linked or coupled set of models. Each model may have different data requirements, time-steps, spatial and temporal domains, and output formats, reinforcing the requirement to collate the meta description of all technical studies (Section 8.3.1). The feedback loops that characterise the complex systems discussed throughout this CRC research project can be simulated through iterative model simulations.

For the Gahcho Kué mine project, eight models were developed to assess the potential impacts of mining operations on groundwater and surface water, in terms of both flows and quality:

1. A groundwater model was used to predict the quantity and quality of groundwater inflows to the open pits over the life of the mine, and the groundwater flow regime during closure.
2. A geochemical and water quality model was used to predict surface water quality and geochemical loading from mine materials during operations and closure in the isolated lake and the downstream lakes.
3. A near-field dispersion model was used to evaluate water quality in a lake that would receive mine water discharges.
4. A hydrologic model was used to predict flows in the downstream receiving environment.
5. A suspended sediment transport model was developed using a combination of fundamental wave and sediment resuspension equations and a three-dimensional hydrodynamic component to determine concentrations in suspended solids during operations.
6. A hydrodynamic model was developed for some of the pits that would be refilled to determine the amount of water and associated constituent load that would circulate upwards and re-enter the surface water system at closure.
7. A vertical slice model was developed to predict long-term salinity in the pits that would be refilled, up to 15,000 years after closure, based on groundwater inflows to the pits predicted by the groundwater model.
8. A three-dimensional nutrient and dissolved oxygen model were used to evaluate concentrations of these constituents in the isolated lake.

Outputs from one of the models were then used as inputs into others: an example is the groundwater flow predictions that were used to estimate long term water quality in the refilled pits, or the flows in the receiving environment that were used to evaluate the potential to dilute mine water discharges. Whilst Vandernberg et al. (2016) describe each of the 8 models in detail, they do not provide an outline explaining how the models are related: a matrix as per the template provided in Figure 16 would have been a strong addition and would have assisted with understanding the connection between the studies. In addition, the models are not linked by code, they remain independent of each other, with a set of outputs from one being used as inputs into others. As such, it can be argued that they have not produced a fully integrated model, but rather a suite of models that must be run iteratively to assess interactions between processes.

In addition, each of the individual models required several inputs and assumptions, which all carried inherent variability and uncertainty that are propagated through the numerous iterations. While methods such as Monte Carlo simulations can be used to quantify uncertainty surrounding a single prediction, there is no method that would meaningfully quantify the effects of propagating error through a system of models. The absolute value of any single variable predicted by these models would probably prove to be incorrect once post-validation monitoring is available. As such, the success of the modelling would be measured by whether the models have correctly identified the actual risks, and whether they predicted values of key variables in ways that are protective of the physical and biological environment. If the aim is to ensure protection of environmental values, there might be more effective ways to achieve it, as continuous iterations of complex models is resource intensive.

Provided the interactions between the various technical studies are well documented and captured, as per templates in Figure 14, Figure 15 and Figure 16, establishing connections between biophysical parameters by running iterations of several studies and models is an option. However, it is resource intensive, and all it is likely to deliver is a detailed risk assessment, with weak confidence in the absolute values of the various variables. Given that the outcomes will remain in the realm of probable events, there could be simpler methods that would produce similar outcomes. However, there is currently no example of such simpler methods, and it constitutes a knowledge gap.

7.3.3 Transfer Functions

In engineering, a transfer function (also known as system function or network function) of a system, sub-system, or component is a mathematical function which theoretically models the system's output for each possible input. They are widely used in electronics and control systems. In some simple cases, this function is a two-dimensional graph of an independent scalar input versus the dependent scalar output, called a transfer curve or characteristic curve. Transfer functions for components are used to design and analyse systems assembled from components, particularly using the block diagram technique, in electronics and control theory.

There is a very large body of work on the topic of transfer function development, applied to a range of subjects, from soil science to economic theory. A detailed review of this research is beyond the scope of this project. Nevertheless, given the number of technical studies and relationships between inputs and outputs of these studies (as per Figure 16**Error! Reference source not found.**), it is worth investigating the applicability of the concept to produce estimates of the impact of a change in one output onto several other inputs.

One example relates to groundwater and surface water interactions. In many cases, hydrogeological units interacting with mining operations would entail:

- Regional groundwater bearing units: alluvium (e.g., quaternary sediments), confined and unconfined aquifers, water supply or irrigation. These constitute a “regional groundwater system”.
- Waste material: as open-cut operations progress, pits are backfilled with waste material. This creates a porous medium through which water can flow. This water is treated as groundwater. Similar to an aquifer, the waste material is assigned hydraulic properties to simulate the interaction with water in the pit.

The relationship between the water level in the pits and the net groundwater flow into or out of the pits can be represented as Stage-Discharge Tables, where “stage” refers to the water level in the pits and “discharge” refers to the net groundwater flow. If the net groundwater flow is positive, the pit loses water to the groundwater system. If the net groundwater flow is negative, the pits gain water from the groundwater system. The stage-discharge tables are an example of a simple transfer function that can be used to capture interactions between two studies (water balance assessment and hydrogeological assessment).

This approach might be applicable to the other studies. The requirement for a “transfer function” is captured by Figure 16, with the number 1 indicating where there is a data flow from one study to the other, and hence the potential to establish a transfer function between these studies. Testing the applicability of this approach was beyond the scope of this study.

It requires access to all technical studies undertaken for a mining project or operations, including all input data, all results and in all likelihood, access to the models themselves to perform additional scenarios, which will produce additional information to refine the transfer function.

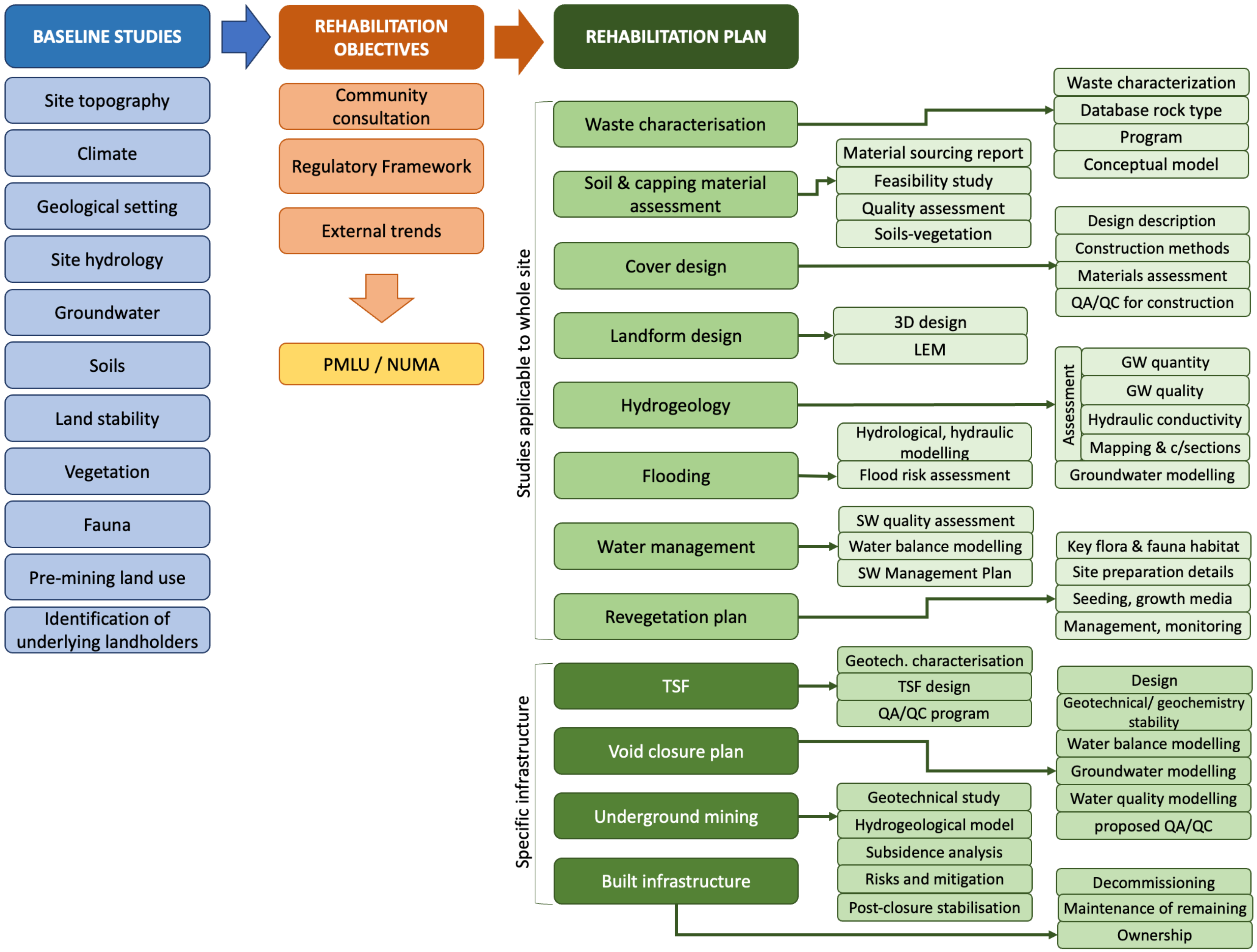


Figure 14: Outputs from technical studies required to support PRCP

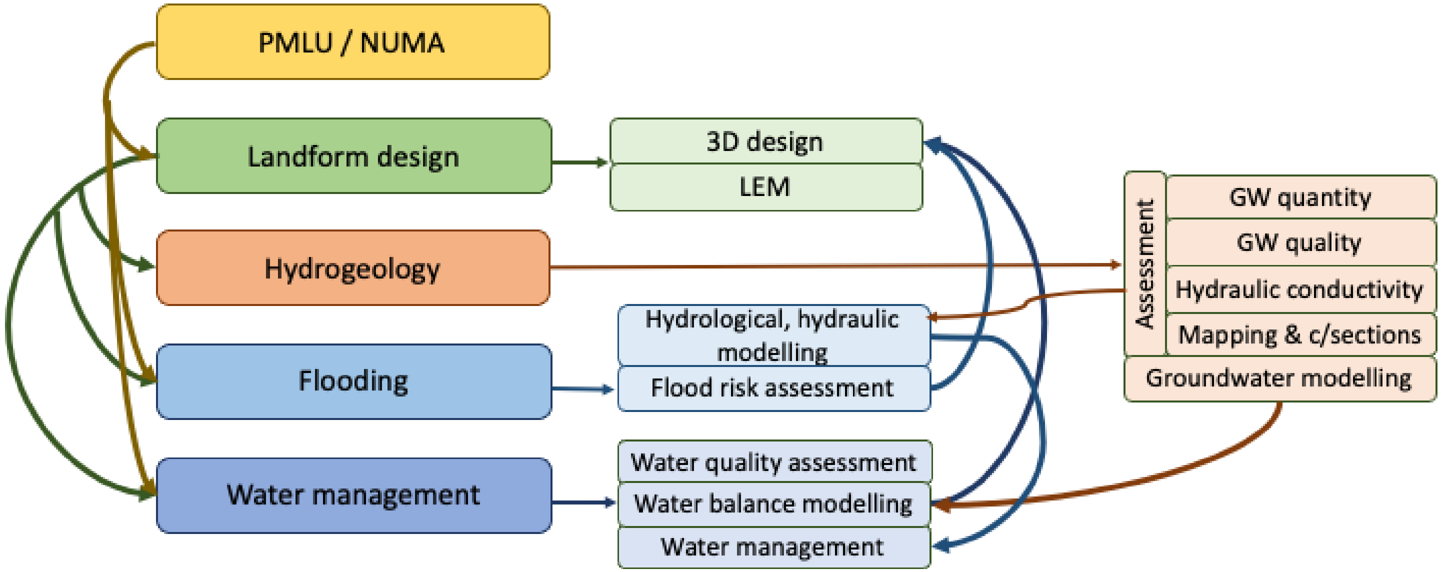


Figure 15: An example of the interrelationships between four studies

TECHNICAL STUDIES AND OUTPUTS		LAND USE	Landform Design		Waste Characterisation				Soil and Capping Material Assessment				Cover Design				Flood Modelling		Water management			Hydrogeology					Revegetation			
			3D design	LEM	Characterisation	Database rock type	Program	Conceptual model	Material sourcing report	Feasibility study	Quality assessment	Soils - vegetation	Design	Construction methods	Materials assessment	QA/QC	Flood model	Risk assessment	Surface water assessm	Water Balance Modelling	SWMP	Quantity	Quality	hydraulic conductivity	Mapping, cross-sections	GW modelling	Key flora & fauna	site prep details	Seeding, growth media	Management, monitori
LAND USE			1	1	0	0	0	0	1	0	0	0	1	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	1	1
Landform Design	3D design	0		1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	1	0	0	1	0	1	0	0	0
	LEM	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Waste Characterisation	Characterisation	0	0	1		0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1	0
	Database rock type	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0
	Program	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Conceptual model	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
Soil and Capping Material Assessment	Material sourcing report	0	1	0	0	0	0	0		1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0
	Feasibility study	0	0	0	0	0	0	0	0		0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Quality assessment	0	0	0	0	0	0	0	0	0		1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Soils - vegetation	1	1	0	0	0	0	0	0	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Cover Design	Design	0	1	1	0	0	0	0	0	0	0	0		1	0	0	0	0	1	0	1	0	0	1	0	1	1	0	0	0
	Construction methods	0	0	0	0	0	0	0	0	0	0	0	0		1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Materials assessment	0	0	0	0	0	0	0	0	0	0	0	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	QA/QC	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Flood Modelling	Flood model	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0		1	0	1	1	0	0	0	0	1	1	0	0	0
	Risk assessment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	1	1	0	0	0	0	0	0	0	0	0
Water management	Surface water assessment	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1	1	0	0	0	0	0	1	0	0	0
	Water Balance Modelling	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1		1	0	0	0	0	0	0	1	0	0
	SWMP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1		0	1	0	0	0	1	0	0	0
Hydrogeology	Quantity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0		1	1	1	1	0	0	0	0
	Quality	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
	hydraulic conductivity	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0		1	1	0	1	0	0
	Mapping, cross-sections	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1	0	0	0	0
	GW modelling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1		0	0	0	0
Revegetation	Key flora & fauna	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1	1	0
	Site prep details	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			1	0
	Plan: Seeding, growth media	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1		1
	Management, monitoring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 16: Example of database matrix

8 Conclusions and Recommendations

8.1 Delivery of Research Objectives

The objectives of the project were to:

1. Provide an overview of current regulatory frameworks and associated current practice for selecting closure objectives, outlining gaps and opportunities with respect to selection of closure objectives.
   This was delivered in Section 3.
2. Define the broad global and national trends that are shaping the future of mining with consequences for mine closure and selection of closure objectives.
   This was delivered in Section 4.
3. Review current practice with environmental risk assessment, with a focus on application of Source-Pathway-Receptor (SPR) frameworks to regional risk assessment in Australia, to determine if this approach would be applicable to describe the interactions between a mine closure plan and its surrounding environment.
   This was delivered in Section 5.
4. Compile the main concepts used in system-thinking and assess how they can be applied to capture the interactions between the biophysical aspects and communicate them to a range of users.
   This was delivered in Section 6.
5. Define the intended users for the system-thinking approach and propose options for the level of detail and the type of causal models that will be required for each group of intended users.
   This was delivered in Section 7.
6. Develop examples of application of system-thinking to the development of closure plans, by proposing a prototype for each group of intended users.
   This was delivered in Section 8.

System thinking is used extensively for a range of applications, including environmental impact assessments. Essentially, within the confines of the broad literature review we have conducted, which aimed at gathering evidence relevant to the mining sector in general and mine closure planning in particular, system thinking concerns the development of conceptual models using specific types of charts to identify, demonstrate and analyse key relationships (or feedback loops). It is about conceptualising relationships and has potential for addressing for addressing the complexity and uncertainty challenges associated with long-term closure planning.

8.2 Project Findings

Finding 1

Modelers are generally faced with the dilemma of how comprehensive a model to build: "one with many variables that ends up as a qualitative description, or one with a few key variables that acts quantitatively but lacks comprehensiveness". This applies to mine closure planning. This project has provided many examples of the sort of model (or approach) that could be used to capture the main dimensions of integration of biophysical parameters through application of system thinking. The level of detail encapsulated by each model will largely be guided by the intended users.

Finding 2

System thinking and integration of environmental aspects constitute a complex area of research and can require a high level of investment. The model built by CSIRO for the GBA Explorer cost $35 million. It is highly unlikely that this level of resources will be allocated to research in mine closure planning. As such, further exploration of the topic should focus on simpler approaches, the ones that will deliver the greatest benefits for relatively small investments. One example would be the application of the key concepts presented in Section 8 to a case study.

Finding 3

There were five foundational projects in the Operational Solutions Program each covering a key technological theme of significant impact on the process of mine closure and relinquishment: remote sensing and monitoring (P3.2); mine site water (P3.3); ecosystem resilience (P3.4); mine landform stability (P3.5); and acid and metalliferous drainage (AMD) risk (P3.6). Each project established a baseline for its theme and identified research gaps and barriers that would inform target areas for further developing larger research projects for transformational change. While the findings from each of these foundational projects are useful in their own right, they also feed into the systems-thinking and integration approach described in Section 6 and highlighted in Finding 2 above. In particular, these outcomes have direct connections with Tier 2 and Tier 3 as shown in Figure 13 and Figure 14 respectively.

Finding 4

The selection of post mining land use has not been resolved and it constitutes a key gap with current practices.

Lack of regional planning and lack of a comprehensive national framework for land use planning are preventing selection and assessment of innovative PMLUs. This means companies face difficulties when trying to articulate what their closure plan might mean for a region. System approaches would greatly assist with bridging this communication gap, as they can demonstrate how a mine contributes to a region.

Finding 5

The requirement to link technical studies has been identified but there is no robust method to achieve this. It constitutes a key research gap.

8.3 Recommendations

Recommendation 1

Mine systems can be conceptualised as systems of variables connected to each other through causal pathways, which are further complicated by operating on different geographical or time scales. These connections need to be grasped and theorised, which is how system thinking should be used. The simplest way to achieve this is to develop prototypes to establish a Closure Planning System, addressing at a minimum Tier 1 and Tier 2 requirements:

- Develop robust methodology to build Tier 1 tools and investigate the potential for build them in spatial form, using land management studies as example. This will facilitate effective communication with external stakeholders.
- Establish a process to develop Tier 2 tools, such as workshops with site teams. All internal stakeholders would present their view, understand all issues and links between biophysical aspects. This will break down silos and all internal stakeholders will “own” the closure plan. An activity related to the identification of system archetype (Section 6.2) will generate valuable discussion and will assist with achieving shared understanding.

Recommendation 2

Defining closure and rehabilitation objectives is critical, along with the ability to adjust them to global, national and regional trends. The selection of post mining land use has not been resolved and it constitutes a key gap with current practices. There needs to be sustained effort to bridge that gap.

Recommendation 3

Given the level of complexity associated the topic, the research activities that are likely to provide the most benefits are those that apply the concepts articulated by this research project to case studies.

It is recommended to select a project or operation with a range of complex inter-relations of biophysical parameters, and build a Closure Planning System to clearly illustrate the methodology and the benefits. The case study will need to be supported by existing technical studies.

Recommendation 4

There is no robust method to link the technical studies, and creating connections between all models would be resource intensive. As such, the option of exploring the potential for defining “transfer functions” that would use the outputs from one model as inputs to the others is attractive. Testing the applicability of this approach will require access to all technical studies undertaken for a mining project or operations, including all input data, all results and in all likelihood, access to the models themselves to perform additional scenarios, which will produce additional information to refine the transfer function. It is recommended to explore the potential for such a project.

Recommendation 5

At the time of finalising this report, the findings from the five thematic foundational projects, mentioned in Finding 3 above, had either just been released or were yet to be released. Given this, it was not feasible to fully consider and incorporate all the findings from these projects into the tiered and staged approach introduced in Section 7 and detailed as prototypes in Section 8. A natural next step would be to analyse, understand and integrate the findings from the five thematic foundational projects (P3.2 to P3.6) with the outcomes of this project. While the outcomes of this project need further work as indicated by the recommendations above, incorporating the findings from the five thematic foundational projects into one or more of the presented prototype examples in Section 8 would show in a systematic manner how the research gaps and barriers from the five thematic foundational projects are interlinked. This interlinking would inform the key touchpoints between the future research work in the areas of the thematic foundational projects.

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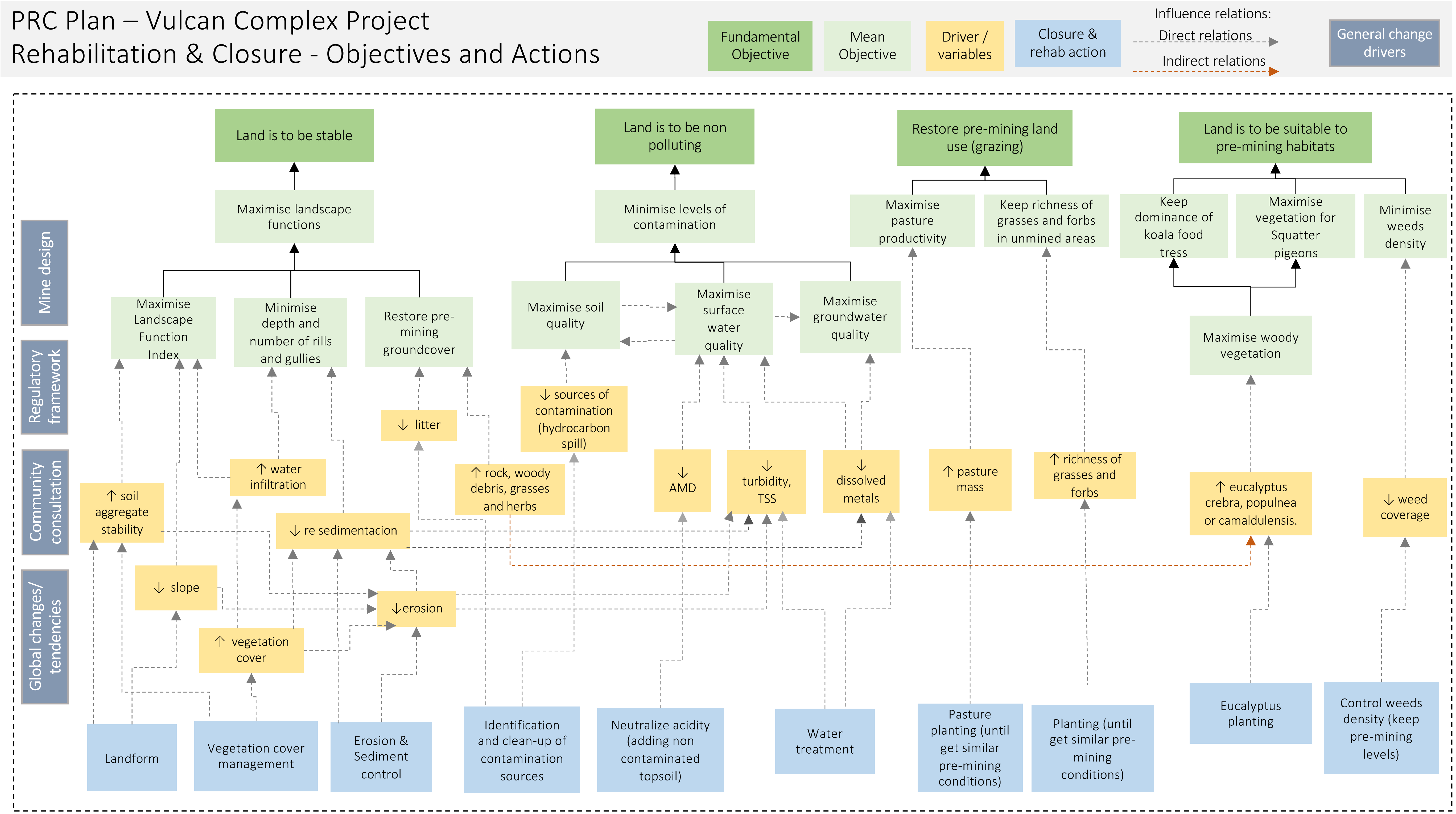
Appendix A

Causal model.

			INTERNAL		EXTERNAL		Supporting tools and studies	
Biophysical Aspect	**Driver of change**	**Vulnerability Issue**	**Variables**	**Recovery Potential**	**Vulnerability Issue**	**Variables**	**Recovery potential**	
Groundwater	Open-cut mining (pit) Mining plan	Pit slope stability Waste rock dump stability Leaching under regulated structures or TSF	Pore pressure Hydraulic gradients Water level / location of phreatic surface Location of seepage face	Slope depressurisation Dewatering plan	Viability of groundwater-dependent ecosystems (GDEs)	Groundwater drawdown / level in relevant hydro-geological layers (e.g. Alluvium)	Make-good agreements	Conceptual model Groundwater numerical model with calculation of groundwater flows Maps of maximum and cumulative drawdown extent of water table
Groundwater	Underground mining Mining plan	Inflows into underground workings (potentially inrush) Post-closure flooding of underground workings	Groundwater flow Equilibrium head / level	Dewatering plan	Subsidence leads to altered surface runoff, flooding patterns and groundwater recharge Export of contaminants to regional groundwater system	DEM Equilibrium head / level	Re-shaping landforms Infilling cracks, grading or channel re-profiling	Conceptual model Groundwater numerical model with calculation of groundwater flows Prediction of groundwater flows into the mine
Groundwater (quality)	Mining plan Dewatering plan				Groundwater contamination	Head difference between void water level and regional groundwater level Salinity and pollutants concentration	Various complex strategies, to be tested with groundwater modelling and monitoring	Groundwater flow directions
Surface water	Land disturbance Mining plan	Flooding Erosion Insufficient mine water storage capacity	Rainfall Runoff Streamflow Water balance	Levees Dams and stores	Catchment modification Modification of geomorphology Modification of flood levels Surface water availability	Streamflow Flood levels Flow velocity, shear stress	Erosion and sediment control Watercourse diversions Compliance with release criteria Prioritise the use of poor-quality water over better quality water	Map of local catchments and watercourses Streamflow records in downstream and upstream gauging stations Water inventory during operations Modelling of site water balance Design of water management infrastructure (e.g., drainage, erosion and sediment control infrastructure, levees, mine water storages) Climate change assessment
Water quality		Not suitable to support a post-mining land use	Concentrations in contaminant of interest	Treatment Blending Dilution with flood flows	Export of contaminants to receiving environment	Water balance (void water level) Concentration of contaminants	Freeboard levels Compliance with water quality release criteria Erosion and sediment control Minimise disturbance Collect, contain, and treat mine affected water	Geochemical analysis of fresh and weathered overburden (pH, non-acid forming (NAF), acid neutralising capacity (ANC), salinity, EC. Water quality records in downstream and upstream gauging stations (e.g., EC, turbidity, TSS, metals) Engineering design: separation of mine affected water, sediment water, clean water and raw water
Water supply	Import of high quality water from external sources (e.g. River)	Insufficient water availability	Water balance	Secure sufficient supply	Extraction of water impacts on ecosystems or regional water needs	Water availability	Extract water from other sources. Reduce reliance on external water	Participation in catchment-based initiatives Modelling of site water balance
Soils	Mining plan Mining methods	Erosion	Rainfall, Slope, Cover, Management Practices,	Minimise disturbance Increase vegetation cover	Erosion leads to sediment export to receiving environment	Rainfall, Slope, Cover, Management Practices, Soil	Erosion and sediment control Minimise soil degradation Rehabilitation	Erosion modelling (e.g. RUSLE)

			INTERNAL		EXTERNAL		Supporting tools and studies	
Biophysical Aspect	**Driver of change**	**Vulnerability Issue**	**Variables**	**Recovery Potential**	**Vulnerability Issue**	**Variables**	**Recovery potential**	
			Soil properties (physical and chemical)			properties (physical and chemical)		
Land Use	Mining plan Mining methods		Disturbance footprint		Post mining land use not feasible	Range of variables depending on selection of PMLU e.g. for grazing land use: Plant available water capacity, nutrient deficiency, soil physical factors, salinity, topography, pH, water erosion	Rehabilitation	Land suitability analysis and ranking, corresponding agricultural land class
Flora (terrestrial)	Mining plan Mining methods				Impact on ecological connectivity Vegetation clearing Loss or alteration of habitat for threatened species Invasive species Groundwater drawdown, Changes in flow regimes Habitat fragmentation Erosion and sedimentation Dust	Species diversity Species of remnant vegetation (areas and status) GDE - Groundwater dependant ecosystems (in function of vegetation ecology, plant physiology, groundwater function) Biodiversity corridors Threatened ecological communities Threatened species	Clearing protocols Maximise the salvage of suitable topsoil Species management plan Rehabilitation Weed control Erosion and sediment control Offset strategies	Listed flora species in the EPBC Act and/or NC Act: likelihood of occurrence, description and maps showing habitat Tables of remnant vegetation clearing Map of GDE
Fauna (terrestrial)	Mining plan Mining methods				Loss or alteration of habitat for species (vulnerable, threatened) Invasive species Habitat fragmentation Erosion and sedimentation Noise and dust	Population characteristics Species diversity Biodiversity corridors	Clearing protocols Species management plan Rehabilitation Pest control Erosion and sediment control Offset strategies	Listed flora species in the EPBC Act and/or NC Act: likelihood of occurrence, description and maps showing habitat
Aquatic Ecology	Surface water and groundwater degradation				Water quality degradation Discharge of mine affected water to waterways Increases in sedimentation, turbidity and TSS in waterways Introduction of aquatic weeds in waterways	Water quality (T, pH, EC, dissolved oxygen, turbidity) Habitat condition Disturbances to the riparian vegetation Existence of GDEs Aquatic flora and fauna	Controlled releases to waterways Erosion and sediment control Restrict disturbance areas Appropriate storage of topsoils for rehabilitation Rehabilitation	Water quality measures in monitoring stations (T, pH, EC, dissolved oxygen, turbidity) Aquatic flora and fauna identified Habitat condition (riverine bioassessment score) Abundance and richness of macroinvertebrates, fish, turtles, stygofauna Wetlands: description and maps
Air – Dust emissions	Mining plan	Poor visibility prevents on site activities	Dust concentration,		Air quality degradation Impacts on vegetation with low tolerance of dust deposition	Dust PM10 PM2,5	Use of water sprays, chemical suppressants in routes and handling areas	Air quality modelling Maximum ground level concentrations and deposition rates of dust across the sensitive receptors Isolines maps of annual and 24-hour average concentration of TSP, PM2.5, PM10 and dust deposition
Air – Greenhouse gas emissions	Mining plan				Climate change Impacts on sensitive receptors (surrounding communities) and biodiversity	tCO_2 equivalent	Production of renewable energy Purchase of green energy Reduce energy consumption	GHG emissions estimation per year Scope 1: fugitive methane, diesel Scope 2: electricity usage
Noise	Mining plan, mining fleet	Impact on fauna			Impact on communities and fauna	Noise levels	Exhaust silencers for trains Build noise bund	Modelling using Isolines maps of noise contours
Vibration	Mining plan				-	Ground Vibration mm/s	-	Predictive modelling Ground Vibration mm/s at different distances
Final landform	Rehabilitation Rehabilitation option analysis Mining plan	Stability	Slope – externally draining Slope – internally draining	Reduce slope	Export of contaminant	Slope – externally draining Erosion and sediments	Geochemical characterisation Erosion and sediment control infrastructure	

Appendix B


PRC Plan – Vulcan Complex Project
Rehabilitation & Closure - Objectives and Actions
Fundamental Objective
Mean Objective
Driver / variables
Closure & rehab action
Influence relations:
Direct relations
Indirect relations
General change drivers
Mine design
Regulatory framework
Community consultation
Global changes/ tendencies
Land is to be stable
Land is to be non polluting
Restore pre-mining land use (grazing)
Land is to be suitable to pre-mining habitats
Maximise landscape functions
Minimise levels of contamination
Maximise pasture productivity
Keep richness of grasses and forbs in unmined areas
Keep dominance of koala food tress
Maximise vegetation for Squatter pigeons
Minimise weeds density
Maximise Landscape Function Index
Minimise depth and number of rills and gullies
Restore pre-mining groundcover
Maximise soil quality
Maximise surface water quality
Maximise groundwater quality
Maximise woody vegetation
↓ litter
↓ sources of contamination (hydrocarbon spill)
↑ water infiltration
↑ rock, woody debris, grasses and herbs
↑ soil aggregate stability
↓ AMD
↓ turbidity, TSS
↓ dissolved metals
↑ pasture mass
↑ richness of grasses and forbs
↑ eucalyptus crebra, populnea or camaldulensis.
↓ weed coverage
↓ re sedimentacion
↓ slope
↓erosion
↑ vegetation cover
Landform
Vegetation cover management
Erosion & Sediment control
Identification and clean-up of contamination sources
Neutralize acidity (adding non contaminated topsoil)
Water treatment
Pasture planting (until get similar pre-mining conditions)
Planting (until get similar pre-mining conditions)
Eucalyptus planting
Control weeds density (keep pre-mining levels)