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Development of an ecosystem model for post-mining land use with a systems dynamics approach

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Abstract

Returning mined land at closure to its pre-mining land use is not always desired or possible due to alterations of the landscape and socio-economic context. Post-mining land use (PMLU) is often promoted as a solution, however, significant effort is required in developing PMLU options with different land uses providing widely different outputs.

The mine site can be a value driver by providing resources (e.g. water, waste and land) that can springboard these activities. A holistic approach to understanding the whole business ecosystem and the interrelationships between different PMLU activities and how these activities reinforce each other (generation of wastes, supply of energy, use of water and benefits developed) thus supports a sustaining system.

This constitutes a complex and dynamic system that can be represented and modelled through system dynamics theory. It is how a change in one variable affects other variables over time through a series of feedback loops. In relation to PMLU, an example of this behaviour is the interrelationship between land, cropping for energy generation, irrigation of the crop with mine water and the impact on biomass generated, and economic activity developed (measured as jobs).

This paper describes the development of an ecosystem model which provides a dynamic tool capable of:

- *integrating extensive amounts of information to simulate a range of processes and interactions across a number of value streams over the life of an asset*
- *identifying flow optimisation pathways and opportunities/solutions that seek to eliminate waste and pollution, circulate products and materials, and regenerate land*
- *identifying major gaps in knowledge so that actions can be implemented to close these*
- *improving the understanding of the whole business ecosystem including major processes, drivers and responses*
- *simulating alternative options in a simple visual way to inform decision-making around PMLU*
- *supporting investment decisions.*

Keywords: *post-mining land use, options assessment, just transition, stakeholder engagement, master planning, economic modelling*

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1 Introduction

Through our experience in closure planning and with miners (supported by Gregory et al. 2023) , we make the following, interrelated arguments:

1. Asset transformation or regeneration can drive regional sustainability and/or regional development.
2. Mining companies can be enablers of post-closure possibilities but cannot singularly or sustainably lead a regional socio-economic transition.
3. Similarly, for legal, liability and financial reasons, stakeholders cannot expect miners to cede all decision-making capacity or control at closure. Nor should this be built into expectations of a successful closure transition.
4. Viewing closure as an opportunity to (re)consider post-closure alternatives is, and will continue to be, critical to reputation building and maintenance; as miners must obtain a social licence to operate, they will increasingly have to obtain a 'social licence to close'.

One of the barriers to planning for closure and developing social transition is determining the value of an investment decision. Therefore, there exists a need to understand the potential outcomes from any investment and value that can be realised. Equally important is developing an understanding of constraints and what enablers need to allow the investment to realise its full impact.

Within a paper presented at the 2023 Mine Closure conference, CRC Time provided thoughts on 'What are we transitioning into?' (Boggs et al. 2023) Recommendation 3 within this paper is: encourage ongoing regional-scale and coordinated planning to support positive long-term resilience and manage risks and impacts. Opportunities for long-term economic resilience in mining regions and communities remains a challenge. Develop new and complementary opportunities from existing infrastructure. Development of:

- an analytical framework to enable individual regions to identify transition capacity drivers and regional resilience components
- tools to support communities in identifying and considering potential future development scenarios.

An ecosystem model can fulfil some of these requirements.

Myriad different land uses have been seen as solutions for post-mining land use (PMLU) (Pearman 2009). Many of them have been implemented not by the mining company but by third parties who have become involved in the sites post-closure. Where PMLU is appropriate and possible the potential business and societal benefits of engaging earlier and developing a seamless transition are self-evident. Organisations are working towards maximising both societal and economic value via diverse interrelated PMLUs, with the Green Engine agri-industrial project proposed by Anglo American (2019) for the Khwezela colliery in South Africa and Veragold's Mina Santa Rosa Gold-Silver Project (Anderson et al. 2023) in Panama being two examples.

This paper presents a modelling approach to understanding the value created across a diverse ecosystem of projects and unlocking how value can be increased through augmentation of the ecosystem.

The task was to produce a model that could be utilised globally on any mine site. A systems approach (System Dynamics Society 2024) has been used as this type of method has a wide application and is used in a number of industries, and by researchers, to investigate the impact of policy and support decisions. It provides an analytical tool that aims to understand the connections between the many different potential elements that could be conceived within a complex and dynamic ecosystem. In this case, that complex and dynamic ecosystem involves the various elements that can be represented within the post-mining landscape. the PMLU ecosystem model has been developed using STELLA software developed by isee systems.

2 Model objectives

The model is intended to be used as a tool to build an iterative regeneration approach for closure planning. The tool is intended to support the development of self-sustaining business ecosystems (post-mining) by embedding regenerative solutions into execution planning for both operational and legacy assets. Five value streams (water, mineral and non-mineral waste, land, carbon neutrality and social impact) are seen as key to promoting and developing regenerative PMLUs. The tool assists assets in maximising the cumulative impact across the five value streams so that site-specific regenerative PMLU opportunities/solutions can be identified and successfully implemented to ensure healthy business ecosystems and communities that are sustainable long after the mine has closed.

3 Model coverage/development needs

To build inputs for the model we need to understand:

- site-specific data that defines the site and its asset base, e.g. land and water availability, and how wastes can be utilised through circular opportunities
- the scope of what different PMLUs entail
- what outputs these PMLUs develop and how they can feed into other PMLUs
- compatibilities of the PMLUs with different parts of the mine site, and the uses of different resources.

A PMLU will only be anchored on a mine site if that site provides something. In this respect, mine sites have assets that the businesses do not necessarily recognise as assets. These should be thought of in the widest terms and could include land, access to water — both grey and blue water streams (Heuer et al. 2019; Pocock & Coetzee 2021), the valorisation of different waste types (Kal Tire Mining 2024; Ramos et al. 2017; Kinnunen 2022), waste heat, gravity potential or cultural heritage aspects.

PMLU options are wide-ranging, with a total of 16 different archetypes defined within four categories as shown in Table 1.

Table 1 Post-mining land use defined as customisable archetypes

Category	Archetypes
Circular economy	Mineral waste
	1. Waste to product
	2. Waste to land
	Non-mineral waste with a byproduct
	Tailings as a mineral resource
Social development/socio-economic	Land-based economy
	1. Agriculture
	2. Agriculture with energy input
	3. Livestock
	Tourism
	Residential
	Commercial/industrial
Green energy	Energy generation — land
	1. Solar
	2. Wind
	Energy generation — waste feedstock
	Energy storage system
Nature	Carbon
	Anthropogenic aquifers

Archetype mapping shows how these different land uses could interrelate and provide a service to each other (see Figure 1).

Each archetype defines a construction or start-up period, workforce requirements for construction and operation, a land requirement, and demands such as electrical and water needs; noting how these factors change over time and with the scale of operations. A literature review was undertaken to build the various archetypes and provide a numerical population in relation to the input values — for example, energy production from piggery waste (Theofanous et al. 2014) — and associated algorithms.

The archetypes are customisable to accommodate geographic differences and variances in the production approach, e.g. farming can be defined as either arable or livestock (see Table 2) in relation to input requirements. Various livestock classes have been defined, e.g. cattle, dairy, pigs, sheep and poultry. Differences exist within these classes, both in terms of the approach to farming required and geographic inputs/outputs e.g. the numbers of birds per hectare in a poultry farm varies tremendously between intensive farming systems (e.g. barn-reared and free-range). Even while ostensibly carrying out the same operation, an understanding of different inputs is required, e.g. the number of cattle per hectare at a cattle station in Australia will be lower than at a UK beef farm.

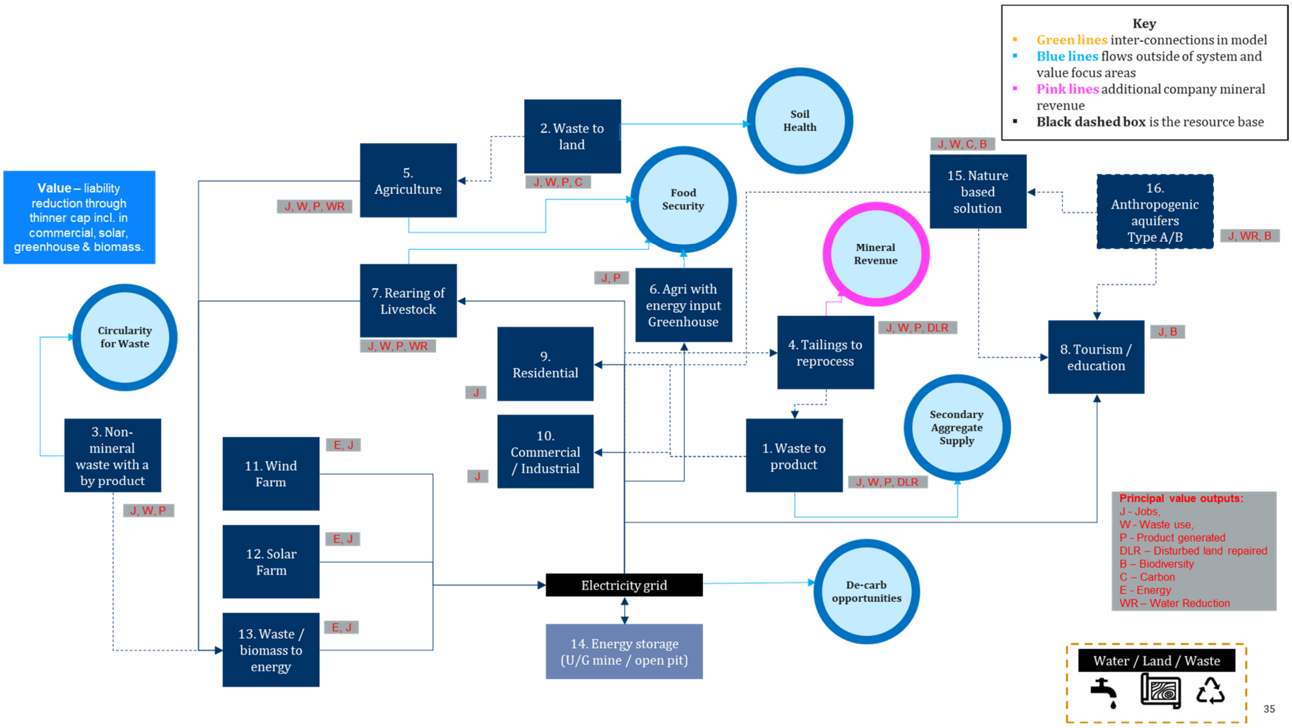

Figure 1 **Interrelationship between archetypes**

Archetypes also have compatibility with various elements within the mine. For instance, solar power can be deployed on land and on tailings while wind energy can only be deployed on land. Similarly, water needs for the various archetypes can be derived from a number of sources, not all of which are compatible.

Data is collated via a linked spreadsheet, which allows specific input of variables and customisation of all the value creation projects. In practice, modelling efforts can be advanced by using the default data embedded in the spreadsheet or further refinement based on estimates of productivity or specific project details. Global resources are available for some of the inputs, e.g. electricity consumption per capita (Statista 2024).

Table 2 Example inputs and outputs for selected archetypes

	Agricultural	Agriculture with energy input	Livestock
Inputs	Internal land required External land optional Dry production rate Irrigated production rate Non-irrigated wet season production rate Water demand during the dry season Water demand during the wet season Permanent crew size Seasonal crew size Storage area Product sale value Water distribution (fresh versus grey) Crop seasons per year	External land optional External energy input Water demand Water distribution (fresh versus grey) Greenhouse area Crew size Storage/processing area Production rate Product sale cost	Internal land required External land optional Crew size Production area Stock number for meat or secondary product e.g. eggs or milk Production rate (meat, secondary products) Water demand for grassland Water demand per head Sale price
Outputs	Total production Production value Jobs Water demand Land demand	Total production Production value Jobs Water demand Land demand Energy demand	Total production milk (l) Total production meat (kg) Production value Jobs Water demand Land demand

This is translated into a system dynamics model via a causal loop diagram (Figure 2) and a depiction of stocks and flows (Figure 3) via a series of algorithms that are developed and connected using the STELLA Architect package. STELLA allows a standalone model to be developed and simulations performed via run-time software on a desktop PC without recourse to the full software package.

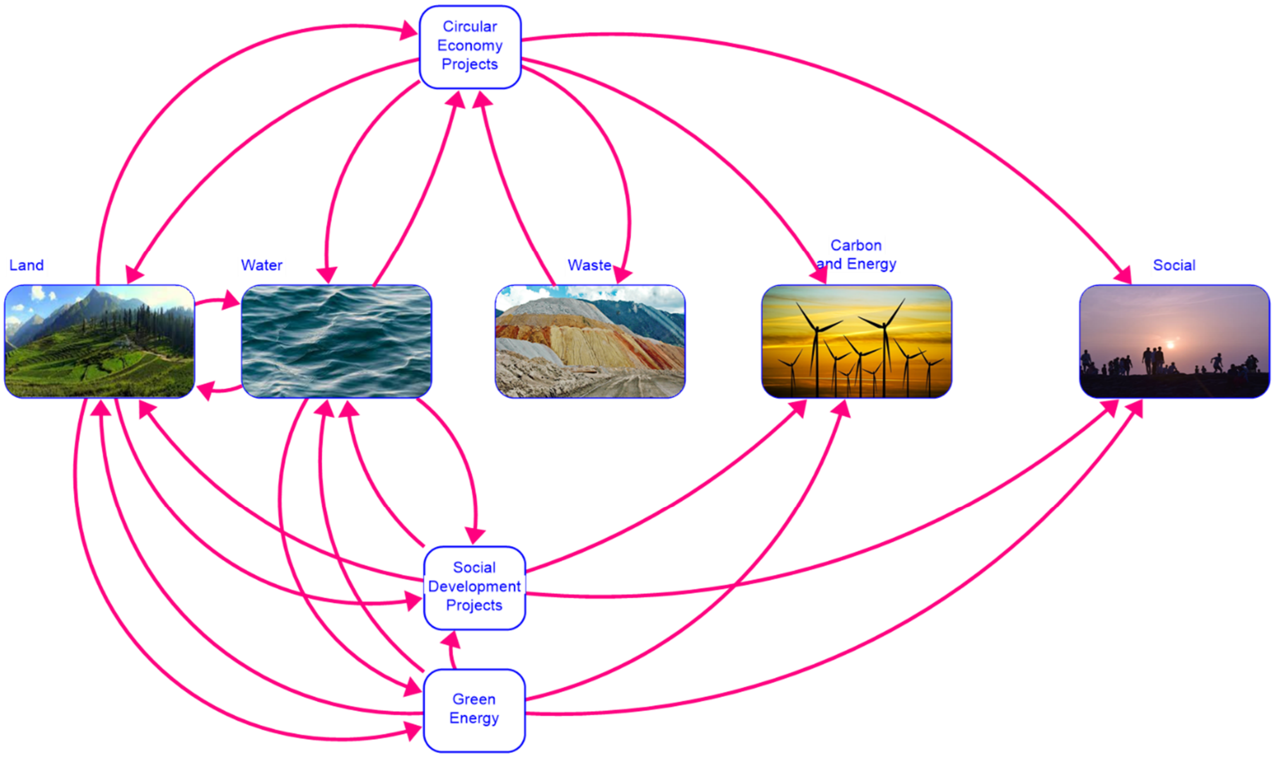

Figure 2 A causal loop diagram showing the relationship between the different value streams

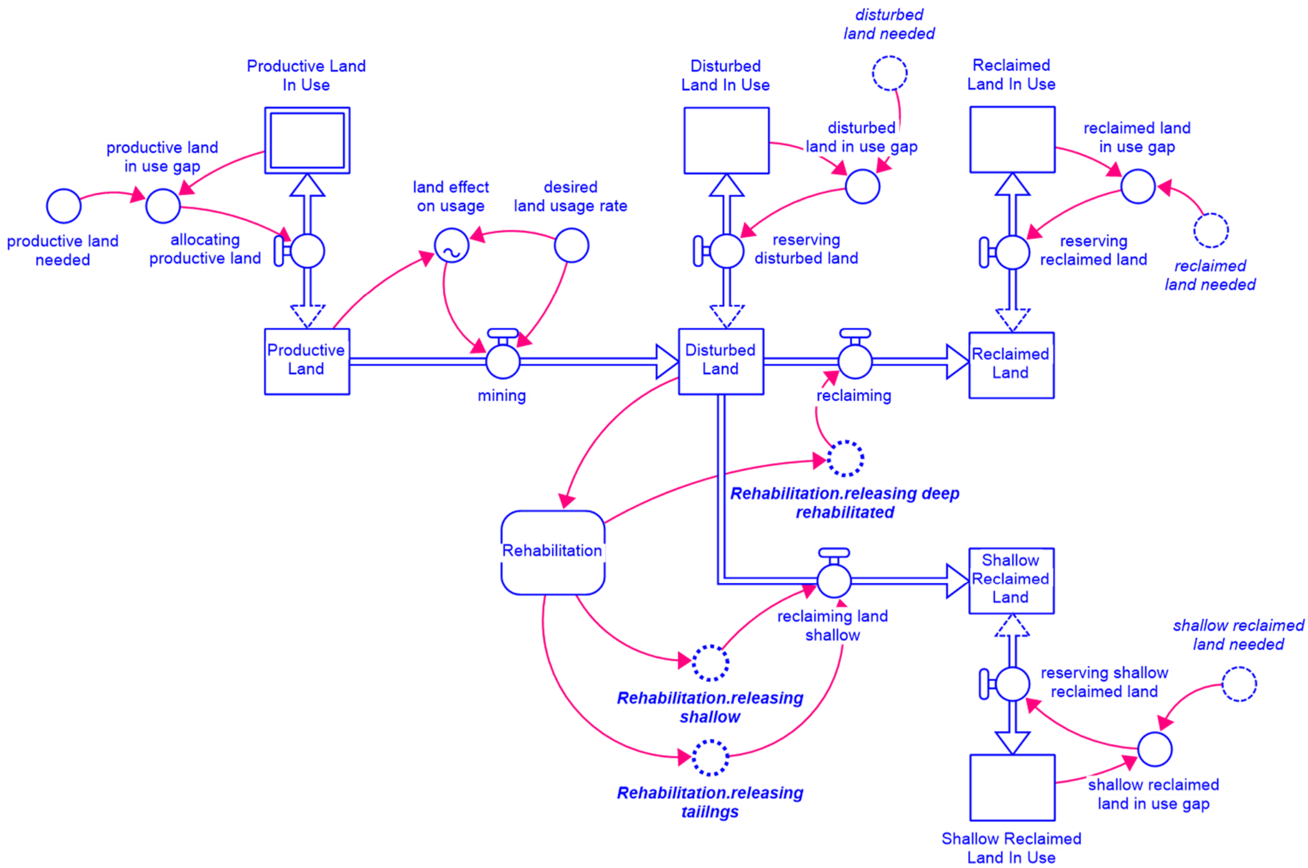

Figure 3 Stock and flow model depicting the land module

4 Conclusion

The model allows any combination of the 16 archetypes to be selected and modelled, providing 65,536 project combinations. Mixed combinations of an archetype, e.g. a mixed livestock system, can be simulated via an averaging approach. Projects are selected via a graphical user interface, with data input via a linked spreadsheet. Some parameters can also be set through archetype pages within the model interface, allowing the sensitivity of different simulations to be assessed. A selected set of project archetypes within a single simulation could be referred to as a basket of projects.

Model outputs are provided via a dashboard (see Figure 4), with a high-level view of how the simulation meets any demands. Figure 4 shows that four archetypes have been selected (the basket contains projects dealing with waste to product, agricultural crops, residential and solar elements), and that with this combination of projects this scenario's water demand is not met. Drill down allowing further data interrogation can be undertaken to provide detail on each of the five value drivers. Figure 5 provides an example of water supply and demand, showing that demand has not been met in this specific simulation, with each peak representing the need for seasonal irrigation.

The model provides a simulated output over a 30-year period.

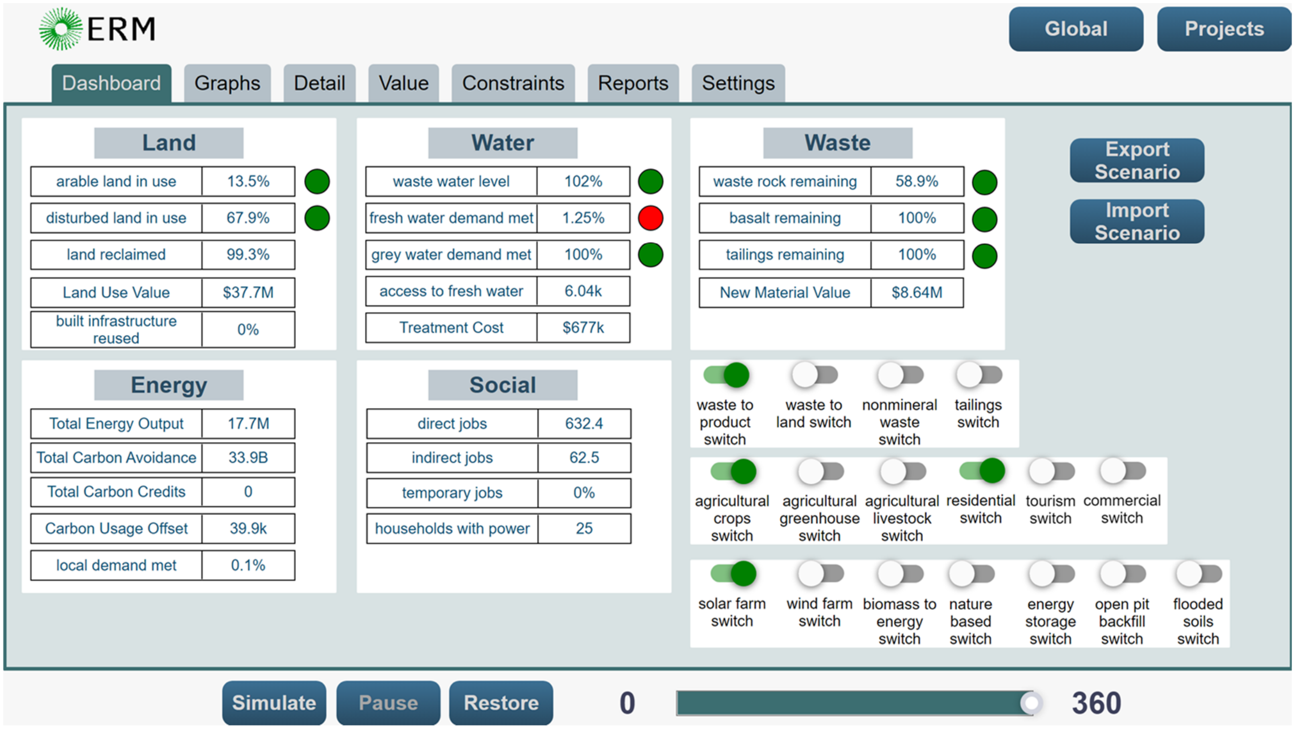

Figure 4 Model dashboard

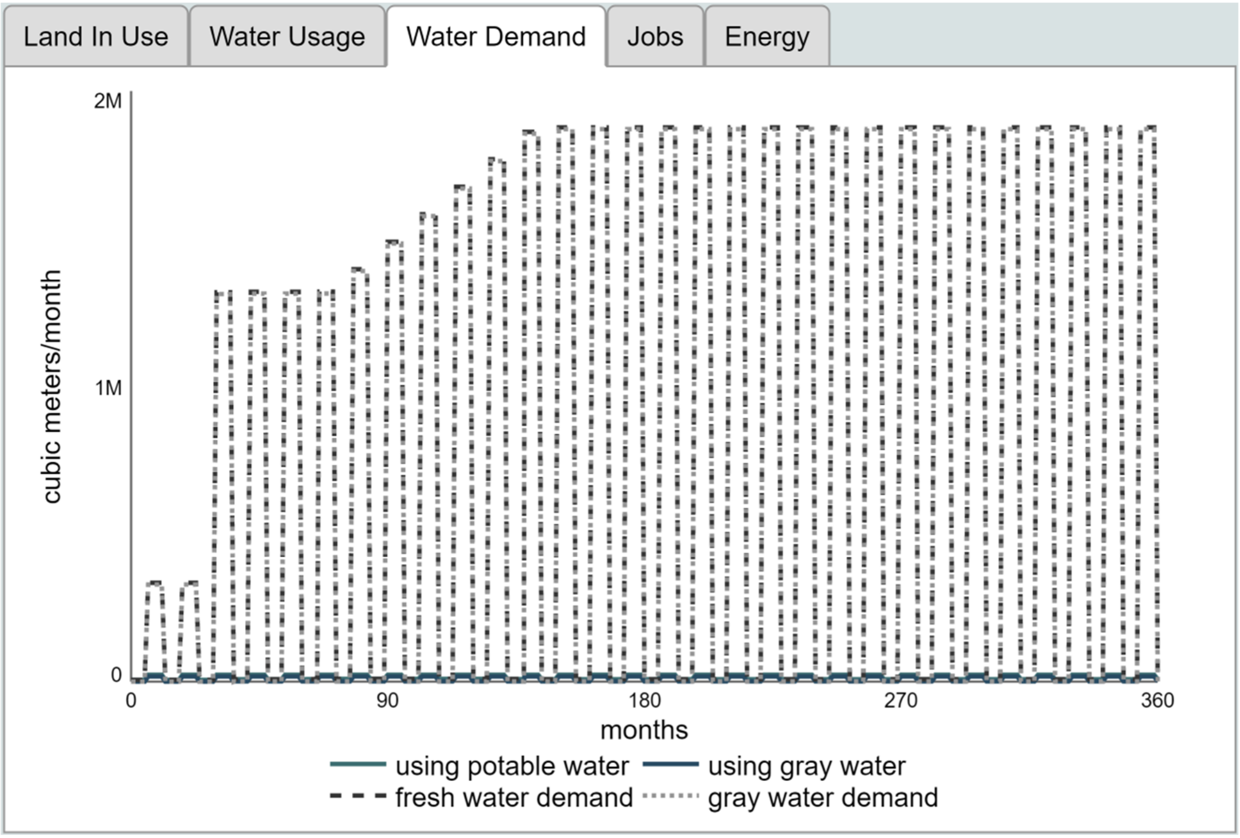

Figure 5 Predicted water demand

Different model simulations need to be compared. The model has some economic outputs ($) but is not a project viability tool. Instead, the outputs are predictions of outcomes, and these vary across the environmental and social spectrum of a mine's closure/regeneration. A combined environmental and social value system has been developed.

The model provides an objective prediction over the 30-year simulation period in relation to each of the five value streams. However, the aim of the regeneration planning also needs to be considered. This requires some initial objective setting to determine the relevancy of any action (e.g. a preference for jobs over energy production) and areas where the mine site can focus to provide impact. This identifies how each of the five value streams equates to an ambition statement for the site (e.g. the site will prioritise social outcomes over waste) and provides an ambition score as a reference point. The value produced through the model is assessed via a statistical test determining the goodness of fit in relation to the ambition score.

Specific targets should also be set against each of the five value streams (e.g. number of jobs created, land repurposed, water treatment avoided, energy produced, etc.) to ensure that outputs meet minimum requirements.

Further work to undertake site-specific testing and to embed the model within a workflow is currently being undertaken. The model:

- optimises asset protection and the re-use of resources by better understanding interdependencies and constraints at the site and allowing better-informed short-term investment plans and decisions
- helps focus efforts and resources pre- and post-closure, decreasing closure costs through better project selection, reducing bias and allowing assessment against value streams
- helps establish a more realistic PMLU vision and promotes partnership with key stakeholders that could reduce costs, along with improving value determination and goal setting.

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