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The environmental and economic case for valuing water recovery and its relationship with tailings storage conservation

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A B S T R A C T

Alternative tailings disposal methods such as dry stack are often neglected as optimal mine waste disposal methods due to perceived high cost. However, the transition from traditional wet tailings disposal to dry stack and alternative tailings disposal is critical for decreasing freshwater consumption and de-risking projects. This research presents an open-source techno-economic model which allows for the comparison of water use and cost between different tailings disposal-related equipment, addressing a major gap in models available for operators and early technology decision-makers. A case study of a Chilean copper mine is evaluated through the model to optimize the dewatering equipment choice. The findings indicate a substantial technical, environmental and economic return on the thickener control system and hydro-cyclone compared to desalinated and pumped water. Early economic modeling can quickly develop a business case for new water and energy-saving technologies while creating shared de-risked technical, ESG, and business team drivers.

1. Introduction

Water scarcity is a pressing issue facing the mining industry. Climate change is increasing the number of mines in the world facing water stress (Northey et al., 2017). Moreover, studies show that 40% of all copper deposits are located in arid regions and approximately an additional 30% of copper deposits are at risk of ending up in areas classified as arid by 2100 as climate change continues to shift water supplies (Northey et al., 2017). The combination of climate change and increased demand for metals means that the management and conservation of water on mine sites are contentious issues between mining companies, mining stakeholders and water-using processes within mining operations (Gunson et al., 2012).

Miners have four choices when facing local freshwater scarcity: (i) reducing production, (ii) sourcing desalinated water, (iii) sourcing non-local water, or (iv) improving water usage efficiency (Ossa-Moreno et al., 2018). In this paper, we argue that there remain significant opportunities to improve water usage efficiency at mines as a preferable approach to the other three choices available. One of the most critical variables that influences water consumption at a mine is the technology used to process minerals, especially on the nexus between managing post-mineral processing waste and water recovery processing (Gunson et al., 2012). This is because the bulk of the process water used by the concentrator ends up in the tailings management system (Islam and Murakami, 2020, Rodríguez et al., 2023).

Most mines use wet mineral processing, and as a byproduct, they generate a ground rock and a wet, viscous mixture of mine waste called tailings (Northey et al., 2016). Tailings are often deposited behind earthen dams called tailing storage facilities (TSFs; Franks et al., 2021). TSFs are often associated with environmental degradation events due to contaminant seepage or minor stability issues. The failure of TSFs can result in immeasurable environmental and human impact as evidenced by the numerous catastrophic TSF failures over the last decade (Innis et al., 2022; Innis and Kunz, 2020; Rana et al., 2021). Poor water management or the presence of high-water content in the tailings is often associated with stability events which lead to these TSF events (Davies et al., 2000; Owen et al., 2020). Optimizing water management around tailings water recovery has never been more relevant from an environmental, economic and political perspective.

The technical feasibility of conserving water at mine sites is well-understood but is frequently dismissed as being too expensive (Cacciuttolo Vargas and Pérez Campomanes, 2022; Gunson, 2013; Gunson et al., 2012; Luukkanen et al., 2022; Patterson et al., 2020; Valenta et al., 2023). This is likely because techno-economic cases justifying decreased water usage have not been well documented. While current research provides examples on the technical or economic optimization of single equipment option tradeoffs (Baawuah et al., 2020; Furey and Lupo, 2020; Luukkanen et al., 2022; Zamorano, 2020), there are several limitations to those approaches. Importantly, most of the academic research on the economic optimization of water in mining is modelled using

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theoretical mines or unique mines with a single mine optimized solution (Connelly, 2021), and includes two primary assumptions: (1) that mines are making a greenfield capital decision, and (2) they don't have the sunk costs of prior equipment choices (Connelly, 2021; Gunson et al., 2012). These simplifying assumptions are problematic because many mines in water-scarce regions such as Chile are long-life copper porphyry deposits and mine equipment choices must therefore be modelled as a brownfield upgrade or as expansions.

In this paper, we address this gap in the literature by introducing a decision-making framework that can be used for tailings waste and water optimization within brownfields projects. This framework enables an economically-informed decision about which process optimization investments have robust economic and environmental business cases. Consequently, a decision maker will be able to decide which project should get funding for advanced engineering and testing work.

To do this, a spreadsheet-based model was developed to evaluate the early techno-economic feasibility of three different water-saving mine equipment upgrades. We use a case study of a hypothetical Chilean mine with four specific research objectives: (i) to document a parsimonious business case framework for equipment changes, (ii) to test business proposals and models on a case study; (iii) to compare the techno-economic feasibility and water and storage saving of three water-saving mine equipment packages against additional TSF capacity and the cost of desalination, and (iv) to provide an interactive and iterative equipment evaluation framework for financial and technical stakeholders. This research was completed in partnership with FLSmidth, an original equipment vendor who specializes in mining equipment, FLSmidth contributed funding and data on the tested equipment packages. FLSmidth did not contribute to the research or writing of this paper.

The resulting open-source tool will model core variables that are present at most floatation-based mining operations. These encompass the capital costs and operating costs, the performance of vendor-supplied equipment packages modelled against the size distribution of tailing waste, desalinated water cost, the cost of traditional TSFs, and how those variables impact the value of optimizing a reduction in wet tailings and water recovery.

2. Chile as a case-study

Chile was selected as the study context for this work because mining is occurring in water-scarce regions where water constraints are currently managed through desalination and the pumping of water from the sea to the Andes mountains. Current government policy has promoted the mandatory use of desalination as a water source for new projects (Herrera-León et al., 2019a). However, desalination requires capital and energy-intensive inputs, and creates significant socioeconomic inequalities between miners and local water users (Campero et al., 2021).

Mining-process water optimization has been primarily studied through a Chilean lens due to the natural water scarcity of local water in the Atacama Desert. For example, the hydro-economic framework proposed by Ossa-Moreno et al. (2018) established a mine's processing framework to adopt dry stack or alternative tailings structures. Similarly, Gunson et al. explore Chilean water optimization options around equipment package choices in mineral processing and tailings management (Gunson, 2013; Gunson et al., 2012). These findings were extended by Aitken et al. (2016,2017), who financially analyzed Chilean desalination and life of mine techno-economic trade-off options.

Northey et al. (2016,2019) subsequently propose a shifted focus from water quantity to a blended quantity-quality measure of water consumption, specifically on water consumption by different mine types. Araya et al. (2021) modelled a theoretical mine that was roughly the size of BHP Minera Escondida (approximately 400,000 tonnes of production per day). The author proved that a dry stack tailings facility in Chile had a higher project NPV than a traditional TSF with a desalination plant and pumping, when the cost of water is taken into account (Araya et al., 2021).

Despite the research attention on the Chilean context, there has yet to be an analysis which explores the techno-economic trade-offs of sourcing desalinated seawater among improved water recovery equipment packages. This knowledge gap is largely due to difficulties associated with comparing the cost of different mining equipment packages and the lack of transparent cost information. Cox et al. (2022) introduced a unified metric for costing tailings dams using the cost unit of USD per dry metric tonnes (USD/DMT). This metric and the corresponding paper's model allow the user to compare previously disparate CAPEX, OPEX and closure costs of different technical solutions into a single comparable metric, thereby addressing cost comparison issues (Cox et al., 2022).

Herrera-León et al. (2019a) and Odell (2021) reviewed the state of seawater desalination in Chile, including the plants built and the plants under construction and proposed. Their paper mapped the growth of desalination, supply, and demand for water by region. It lists all the desalination plants under operation and lists them by the user, of which 15 out of 23 are for the mining industry. Herrera-León et al. (2019b) continued this work by creating an optimized theoretical model using real data on water systems used by the mining industry in Chile. After analysis, the paper proposes optimizing the use of photovoltaic solar in desalination systems and the economic and environmental value of shared water systems. The range of water costs from existing desalination was \$3.52-\$5.70 per cubic meter. The value of this work is in how the economic cost of desalinated water is between conveyance and the desalination plant. It is also an example of a techno-economic trade-off between water options.

By integrating the cost of desalinated water provided by Herrera-León (2019b), our paper creates a techno-economic model that combines the work of Gunson, Aitken, Northey and Araya on water conservation technologies and uses the comparative costing metric from Cox et al. (2022). The synthesis of these frameworks provides a techno-economic method for comparing water-saving technologies for ore processing at different mine sites. In this paper, we argue that optimizing water use by improved recovery and recycling of processed water may provide better economic and environmental solutions. By producing a smaller CO_2 and economic footprint, water-saving alternatives such as thickeners, cyclones and filter presses can challenge the conventional desalination option as a viable, sustainable model in terms of water management.

3. Methodology

3.1. Model development

The model proposed in this paper represents a techno-economic model that can be used to compare water-saving solutions at a brownfields mining operation during the early stages of a business planning process. The model seeks to promote consideration of multiple options instead of the current standard approach towards water management which focuses on increasing water supply through either local pumped or desalinated water. Other papers have used similar techno-economic trade-off models in the mining industry. Examples include solar energy versus grid energy for mine cooling (Pokhrel et al., 2020), leaching tank optimization trade-off studies (Khalesi et al., 2015; Thompson et al., 2018), and solar optimization for desalination (Khalesi et al., 2015; Mata-Torres et al., 2017; Zurita et al., 2018). The common theme among them relies upon the comparative analysis of two or more technologies in order to find an optimal solution using both financial and technical criteria. Ideally, the decision to optimize a mine's water system is a continuous process. Nonetheless, changes that require capital investment also require an investment case and decision backed with justifiable financial models at every stage. Scoping and pre-feasibility studies on upgrades are conducted for pre-detailed engineering and design. Our model supports that early pre-feasibility studies, backed with a business case, are the first hurdle for a capital project, especially those with an environmental lens.

Traditional costing frameworks used by the mining industry in early-to-mid-life decision-making, such as discounted cash flow and operating cost reporting, overemphasize startup capital utilization (Samis and Steen, 2020). These frameworks do not account for long-term capital utilization costs or charges. Hence, the time value of capital is distorted or leads to an overemphasis on low capital cost instead of a united life cycle costing of equipment (Cox et al., 2022; Ulrich et al., 2019). As a result, these methods result in water recovery equipment packages being priced out early in the decision-making process. Moreover, the work on mine equipment optimization has predominantly focused on optimized cost as opposed to optimizing environmental and cost savings. For example, the value of hydro-clones in diverting construction material from TSFs is known, but the value in water recovery is not as well understood (Kujawa, 2011).

The techno-economic model presented in this paper was created to show the value of the water generated by tailings management equipment package choices. This model is referred to as the tailings economic trade-off (TET) model. The three water recovery equipment packages modelled are (1) optimized thickeners which recover water with active gravity separation and shift the density of the whole waste stream; (2) hydro-cyclones which recover water via separation of large and small size fractions; and (3) filter presses, which recover water using compression to expel water. The equipment packages modelled are then compared to the cost of desalinating seawater and pumping the water to mine sites at altitude. However, the capital and operating costs for these processes are not widely available (Section 2.1). The three types of equipment packages modelled primarily impact three variables: water recovery, tailings deposition type, and economic and environmental resource consumption. The development of this model utilizes work from Cox et al. (2022) through the annualized USD per DMT unit both as an input unit and as an output for its ability to compare equipment packages in techno-economic terms of optimized blended process water and TSF capacity conservation. Table 1. is a comparison of the three water-saving equipment packages modelled and the products produced from the equipment operation.

All the tested equipment packages have different modelling requirements, and a comparable model requires using comparable units. The TET model focuses on achieving operating performance and total cost on a comparable DMT of feed basis. The USD/DMT metric allows the model to be comparable across technologies at a mine site and comparable across mines (Cox et al., 2022).

Fig. 2 is a visual summary of the TET model; the figure shows the inputs, equations used, and outputs of the TET model. We intend the TET model to be open source, and therefore the model is available for download in Supplementary Materials 1. The TET model inputs are categorized by performance inputs, mine inputs, and equipment package cost inputs. These inputs can be sourced from three sources; the mine data may be obtained from company management and published regional sources, and the performance and cost inputs may be obtained from an Engineering Procurement Construction Management Company (EPCM) or an Original-Equipment Manufacturer (OEM). The outputs are categorized by performance outputs and economic inputs. These two outputs will inform how much water can be recovered from each tested equipment package and the total net cost of the marginal water recovered to the mining company. An additional value driver created through the TET model is tailings impoundment resource conservation which impacts the cost of the water recovered by reducing the cost of deposition; this metric is referred to as the TSF capacity savings.

Table 1
Modelled equipment comparison table showing the different separation methods, products produced from the operating equipment and where the equipment lies in the waste stream process.

	Optimized Thickener	Hydro-cyclone	Filter Press
Separation method	Active settling	Physical separation by size	Compression
Products produced from equipment package operation	Water and thickened tailings.	Water and two size fractions of rock. Usually, one size is then suitable for stacking.	Water and tailings cake suitable for dry stacking.
Is this the final process?	No; TSF disposal or dry stacking is required.	Partially, for some materials, a post-cyclone thickener is required.	Yes

3.2. *Case study data and assumptions*

To showcase the applicability of the TET model for decision-making on water-saving equipment package installation, the TET model was applied to a hypothetical case study of a Chilean mine. Data are sourced from an amalgamation of public and company-supplied information. The company-supplied information was provided to the authors; however, client confidentiality requires site-specific or identification-related information to be unidentified.

The theoretical subject is a brownfield copper porphyry mine looking to expand milling capacity with a 100,000 tonnes per day wet flotation concentrator plant that feeds tailings thickeners to produce a thickened tail stream deposited behind a traditional, wet TSF. The mine sits at 3,000 m Above Sea Level (ASL) and has an expected life of mine of 20 years, thereby assuming a time period longer than any functional life of mine equipment. The current primary water source for the operation is desalinated water pumped to the site. The site currently pays for desalinated water. The structure of the water sourcing at the theoretical mine echoes that of many of the actual mines located in the arid Northern Chilean regions (Herrera-León et al., 2019a, 2019b). The assumed current water source is valued at the cost of desalination because the trade-off tested through the TET model is the optimization of water recovery through the tested equipment package against the purchase of more desalinated water to supply water for the expansion project.

Table 2 outlines the baseline data and sourcing for the theoretical mine. Where authors are listed as the source, the number is constructed from authors' assumptions and averages of similar mines. The technical equipment upgrade performance and base mine case are documented in the supplementary model and materials are a blend of real mine data, author assumptions, and FLSmidth assumptions. For the site water balance, particle size distribution and equipment technical performance assumptions were also made.

The authors used the calculated cost of TSF savings of $2.29 per DMT proposed by Cox et al. (2022), which is the only published number on tailings cost on a unified basis. The non-quantified value of tailings storage capacity savings is the ability of the mine to use the marginal capacity saved to mine more without the need for permitting for raises, local social contracts, geotechnical risks and geo-political risks. To date, the economic value of tailings storage capacity is a largely unquantified and understudied metric.

3.3. *Model application to case study*

This section details the equipment-specific inputs required for the application of the model. Equipment performance changes were different for all three technologies.

Thickener control system: a net density change to the TSF was assumed to shift from 57% to 62% solids. The authors maintained all other assumptions, including the percent of net water recovered from the TSF. The increased average density assumed is due to the control system reducing the range of operational performance by controlling the flocculant dosing, rake speed, and other variables (Kosonen et al., 2017; Ruhanen et al., 2018; Ruuska et al., 2021).

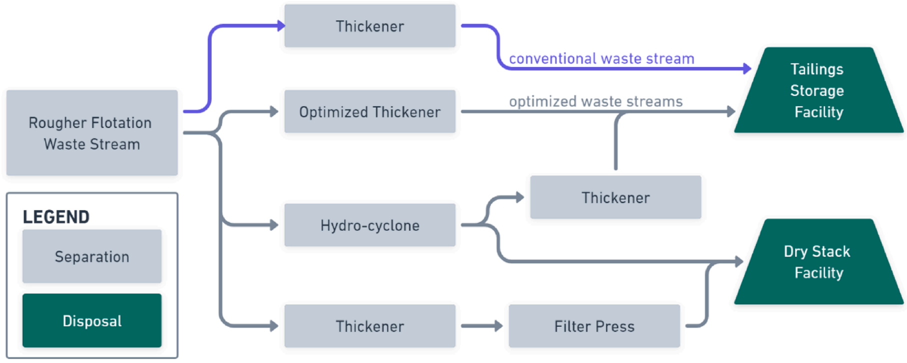

Fig. 1. Modelled equipment packages relative to location in a standard mine waste stream.

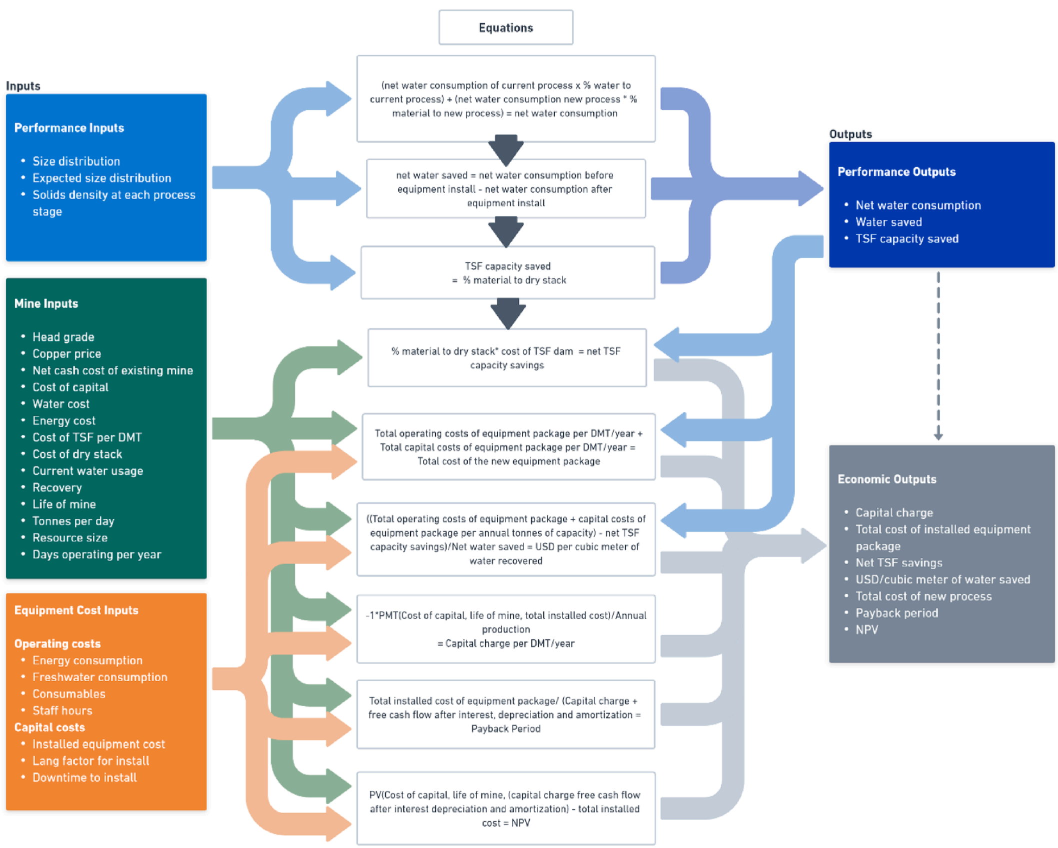

Fig. 2. TET model flowchart outlining the performance, mine and equipment cost inputs, and the equations used to generate either the performance or economic outputs.

Hydro-cyclone: a cyclone performance curve was supplied by FLSmidth and inserted into the model, resulting in 31.5% of the material diverted to the hydro-cyclone overflow to a dry stack with 85% of the water freely recovered by gravity. The second assumption was that the oversized fraction contained the same water-to-solids ratio as the original tailing slurry.

Filter-pressed tailings: the assumption is that thickened tailings are 100% sent to a dry stack filter press that produces a 15% moisture tailings cake and that 0% of the water from that cake is recovered. Operating input data for the filter press case were supplied by FLSmidth.

Capital and operating cost assumptions were provided by FLSmidth for the hydro-cyclone and the filter press; for the thickener control system, data were requested from other equipment manufacturers but not provided; therefore, authors assumed order of magnitude numbers. The lang factor for construction costs and assumed days of lost production were authors' conservative assumptions based on work history experience and verified by FLSmidth.

4. Results

4.1. Case study results

As outlined in Fig. 2, two types of outputs are generated through this model: performance outputs and economic outputs. Table 3 summarizes the case study results from the TET model application.

The total mine cost for desalinated water ranges from $3.52-$5.70 per cubic meter depending on the elevation of the mine and water quantity requirements (Herrera-León et al., 2019b). At 3000 m ASL, the cost of desalinated water is recorded to be $3.75 per cubic meter (Alvez et al., 2020). Given this, the three modelled technologies delivered

Table 2
Inputs to the TET Model.

Input Type	Inputs	Units	Case Study	Source		
Performance Inputs	Size distribution	PSD in µm	Supplementary Material 1	FLSmidth		
	Density of solids at each mineral processing stage	% solids	Supplementary Material 1	FLSmidth		
Mine Inputs	Head grade	% copper	0.50 %	Authors		
	Copper price	USD/tonne	$ 8,000.00	Authors		
	Net cash cost of existing mine	USD/lb	$ 1.50	Authors		
	lbs to tonnes	–	2,204.00	Unit Conversion		
	Cost of capital	%	6.01%	Damodaran		
	Water costs	USD/m^3	$ 3.75	Alvez Et Al (2020)		
	Energy costs	USD/kWh	$ 0.16	Statista.com		
	TSF costs	USD/tonne	$ 2.29	Cox Et Al. (2022)		
	Cost of dry stacking post filter press	USD/tonne	$ 1.00	Authors		
	Water use in m^3	m^3/tonne ore	0.58	Authors		
	Recovery rate	% metal recovery	85 %	Authors		
	Life of mine	Years	20.00	Authors		
	Tonnes per day	TPD	100,000	Authors		
	Resource size	Tonnes	5,000,000,000	Authors		
	Days operating	Days/year	345	Authors		
Input Type	**Inputs**	**Units**	**Equipment Package Information**			**Source**
			Optimized Thickener	**Hydro-Cyclone**	**Filter press**	
	Operating Costs					
Equipment Cost Inputs	Energy consumed	kWh/DMT	0.0005	0.397	1.45	FLSmidth
	Net fresh water consumption	m^3/DMT	0	0	0.05	FLSmidth
	Software license	USD Annual	$ 35,000	–	–	FLSmidth
	Flocculant	USD/DMT	$ − 0.010	–	$ 0.063	FLSmidth
	Filter cloth	USD/DMT	–	–	$ 0.121	FLSmidth
	Wear parts and consumables	USD/DMT	$ 0.000	$ 0.023	$ 0.109	FLSmidth
	Staff hours	FTE/day	−0.3	0.50	5.00	FLSmidth
	Capital costs					
	Cost of equipment	USD/LOM	$ 175,000	$ 2,547,116	$ 42,678,350	FLSmidth
	Lang factor for install	Factor	1	10	8	Authors
	Days down to install	Days	0	5	10	Authors

Table 3
Results from the application of the hypothetical Chilean mine case study to the TET model.

			Base Case	**Results**		
Output Type	**Output**	**Units**	**Desalination with thickener**	**Optimized Thickener**	**Hydro-cyclone**	**Filter press**
Performance outputs	Net water consumption	m^3/DMT	0.58	0.46	0.45	0.18
	Net water saved	m^3/DMT	0	0.12	0.13	0.40
	Material to TSF	%	100 %	100 %	69 %	0 %
	Material to dry stack	%	0 %	0 %	31 %	100 %
Economic Outputs	Total operating costs	USD/DMT	–	$ − 0.010	$ 0.40	$ 1.74
	Capital charge per annual tonne of capacity	USD/DMT	–	$ 0.0009	$ 0.10	$ 1.02
	Total cost of new process	USD/DMT	–	$ − 0.009	$ 0.50	$ 2.76
	Net TSF capacity savings	USD/DMT	–	$ 0.00	$ 0.72	$ 2.29
	Cost per DMT feed	USD/DMT	–	$ − 0.009	$ − 0.22	$ 0.47
	Cost per m^3 marginal water recycled	USD/m^3	–	$ − 0.08	$ − 1.68	$ 1.17
	Total cost of water	USD/DMT	$ 2.17	$ 1.72	$ 1.67	$ 0.66

recycled water at a lower economic cost than marginal desalinated water. The economic benefits of lower TSF capacity requirements and higher water recovery capabilities offset the capital and operating costs across all modelled technologies. The hydro-cyclone and the thickener control system recovered water, where the net cost of the water was paid for by the positive effects of reducing overall mining operating costs, thereby supplying recovered water with a zero or negative marginal cost of water to the operation.

In terms of cubic meters of marginal water recovery per DMT of feed, all technologies materially improve water recovery compared to the desalinated base case (Fig. 3a). Filtered tailings maximize the total water recovery to 31% of the desalination base case at the theoretical mine site. The model also outputs the net cost of recovered water provided by each installed equipment package; costs range from -$1.68 to $1.18 per cubic meter (Fig. 3b). The hydro-cyclone recycles water for the lowest cost when compared to other modelled equipment packages and the desalination base case.

As discussed in Section 2.2, the focus on total CAPEX to start up a mine to drive net present value (NPV) to price tailings-related water savings equipment packages lends to the implementation of wet tailings and desalination equipment due to its low initial capital cost at startup. However, when comparing equipment packages on a lifecycle basis

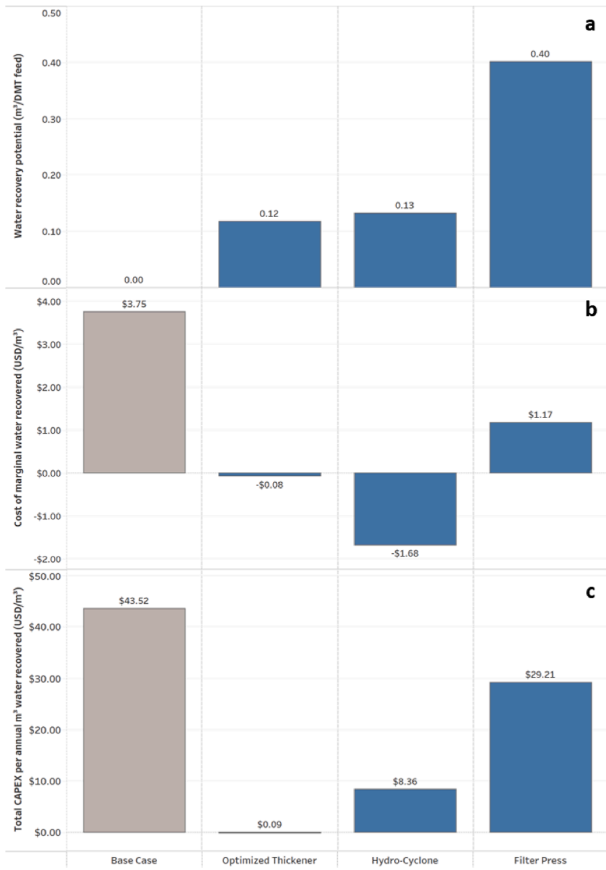

Fig. 3. (a-c) TET model results of the Chilean mine case study for (a) the water recovery potential; (b) the cost of marginal water recovered; and (c) total CAPEX per annual m^3 water recovered for each installed equipment package compared to the desalination base case.

using metrics from Cox et al. (2022), the cost across the lifecycle of the equipment is demonstrated on a unit of water recovery versus desalination capital cost basis. Fig. 3c. shows the total CAPEX and OPEX annualized and discounted per total amount of cubic meters of water recovered. For the desalination base case, the total CAPEX per cubic meter of water per year for desalination and pumping is $43.53, whereas all other modelled equipment packages are less than $30 per cubic meter of water recovered per year with the optimized thickener as the lowest CAPEX at $0.09 per cubic meter year.

All three technologies have different cost drivers. For the optimized thickener, 100% of the capital cost was covered by reduced operating costs, resulting in "free" water. The hydro-cyclone also delivered water at "zero" cost because the capital and operating cost were more than offset by the $0.72 per DMT of TSF saving capacity of the equipment package. Despite the high financial capital charge associated with the installation of the filter press, when valuing both the TSF capacity saving of $2.29 per DMT and water recovered valued at $3.75 per cubic meter of the capacity of the technology, the capital and operating costs are justified by a positive NPV. All equipment packages have a short payback period after valuing TSF capacity savings and water recovery (Table 4), with the optimized thickener having a payback period of only eight days.

Table 4
NPV and Payback Period among equipment packages.

		Optimized Thickener	Hydro-cyclone	Filter press
Total Installed Capital Cost	USD	$ 350,000	$ 37,993,026	$ 404,054,650
NPV	USD	$ 178,112,324	$ 282,527,920	$ 408,300,931
Payback	Years	0.02	1.36	5.70

5. Discussion

5.1. Case study

The study is an extension of the recent study by Cox et al. (2022) to unify the cost of the TSF to comparable performance metrics (USD/DMT) and (USD/m^3) for alternative tailings and water recovery technologies. The results from the TET model (Fig. 3a-c) indicate that there is a strong techno-economic argument for the installation and operation of water recovery systems.

The application of the TET model to the hypothetical Chilean mine case study shows that the implementation of water recovery technologies will not only materially reduce water consumption but also incur a positive NPV of the capital cost of installation against operating costs, water and tailings recovery. Furthermore, the TET model creates a strong case for early techno-economic work before testing and shifts in design choices. On an individual equipment package basis for the Chilean case study, the optimized thickener returned the highest return on investment capital, the hydro-cyclone delivered the lowest cost of water on a USD/m basis, and the filter press delivered the largest shift in NPV.

The model found that filter press economics are heavily dependent on the interest rate and cost of capital, whereas other equipment packages are cost-of-capital agnostic. Although the TET model application to the Chilean case study shows water recovery equipment packages on an individual basis, the equipment should be viewed as a ladder of real options. As shown in Fig. 1, all or some equipment packages can be installed at the mine site to optimize water recovery and tailings storage savings capacity. Future work remains to advance a techno-economic model on the optimization of multiple stacked water recovery equipment packages using real test data from mine sites.

5.2. Implications

The application of the TET model on the hypothetical Chilean mine shows a ladder of positive economic and environmental options. The three equipment packages tested allow for both the water recovery and TSF conservation capacity while developing a mine, meaning that a mine can install one or all of the equipment packages and benefit from the water recovery and tailings cost savings from each equipment package harmoniously.

Given that this model is tested on a hypothetical mine site with limited data, the results of the case study should not be applied directly to decision-making without specific data from the mine under consideration. Therefore, we suggest the TET model can be used in three ways: (i) to make a real economic decision, (ii) to decide to fund test work, or (iii) quickly rule out possible technical solutions on economic grounds for water and TSF capacity conservation. The TET model can be used to facilitate questions on what tests have been done in the past and then justify research to garner what technical information is currently available and what information is needed in order to deploy the TET model for future uses with improved data and findings. For sites with sufficient technical and engineering data, the TET model can be used to justify feasibility and project finance. In any stage of development, the TET model provides operators with a quantitative tool which generates an economic and environmental water and tailings argument to an argument which previously was hard to model due to the different process silos the equipment packages fit within.

While the use of desalinated water looks, at face value, to be an environmentally logical solution to the fundamental water constraint issue facing Chilean mines, the environmental and economic trade-offs associated with the water source have not been quantified in past research. The TET model argues that all water, including desalinated water, is delivered at an economic cost. The costs modelled in the TET model are tailings capacity and water recovery potential. However, there are other unmodelled and unquantified costs, including CO_2 emissions and political and license-to-operate risks. Given these trade-offs and costs, the TET model shows that in arid regions such as Chile, the standard operating procedure of pumping and desalinating water and using a traditional TSF can be materially economically and environmentally optimized. The equipment packages modelled quickly generate a positive economic impact even without quantification of the environmental and social cost or the inherent risks associated with traditional TSFs.

The TET model reduces the discussion around water and tailings to a quantifiable argument around the cost of increased water recovery, the cost of TSF reduction, and the value against the de facto use of a desalination plant and a TSF. Using the TET model requires a paradigm shift, from the lowest capital cost solution being the core driver to optimizing natural capital utilization over the life of mine, resulting in alternative decisions being considered.

5.3. Limitations & impacts of technical assumptions

There are inherent limitations associated with simple, early-stage high-level techno-economic models (such as the TET model) compared to more detailed post-engineering and test work late-stage economic studies.

There are several technical and financial assumptions required to develop and apply the TET model. The implications of these assumptions and limitations are listed below:

- The model was not tested on real plant data due to lack of accessible and transparent test data.
- The model assumes that all the equipment is operating as expected and does not take into account the variation in mineral suspension properties due to differences in mineralogy or water chemistry.
- The TET model boundary limits do not incorporate detailed capital and operating costs of stacking filtered tailings. The model uses a $1.00 USD/DMT or $2.00 per cubic meter (s.g. = 2) of tailings to transport, stack and compact the tailings post filter press.
- Sensitivity testing on the costs of stacking filtered tailings delineates that the upper limit of the cost to stack filter cake per cubic meter is $4.00 per cubic meter to retain an economic argument for the equipment package when compared to the desalination and conventional TSF case. Previous studies show that the total cost of filtered tailings, which includes OPEX for the filter press equipment package and stacking, ranges from between $4.00 and $7.00 per cubic meter of tailings (Carneiro and Fourie, 2018; Mine Environment Neutral Drainage Program, 2017, pp. 44–5). Therefore, the authors find this assumption reasonable. However, future work is needed to understand and quantify the total and combined cost of filter press, haulage and stacking.
- This study assumes that the scale of filter presses needed for this size of mine (100,000 tpd) is feasible. While existing equipment can be packaged to process the throughput of the hypothetical case study, to date, no mine of this size has been constructed and operated with filtered presses and stacked tailings.
- FLSmidth estimated technical performance for the equipment packages; FLSmidth has done hundreds of cyclone tests, thickener tests, and filter press tests, but until the site-specific material is tested, the water recovery, the assumed final density, and percent of feed that can be dry stacked are projected.
- The dry-stacking oversized fraction from the hydro-cyclone is assumed to have no construction material value in the model. This assumption might undervalue the relative benefit of hydro-cycloned tailings on mine sites that rely on it for construction material generation for impoundments, roads, and other site works.
- The water recovery equipment is assumed to be able to produce usable process water without further water recycling treatment. This assumption may lead the output of the value water function of the model to overestimate the relative value of recovered water because the cost of water treatment is not included.
- No research to date exists which allows for reliable and citable capital and operating costs before a detailed engineering study backed by test work. Therefore, these costs are estimated with low belief. The equipment and installation costs are assumed but with high belief based on the use of OEM inputs (FLSmidth Ltd., correspondence, March 17, 2022). The financial assumptions used in the TET model are placeholders prior to test work, site visits, geotechnical and scoping study engineering. The assumptions can be improved with site-specific real numbers. Operating costs also can be significantly different depending on the processed tailing stream, the expected performance, and the spares and wears consumption.
- Another important assumption is that on an annual basis, technical performance is assumed to be static based on a uniform waste stream. Therefore, this inhibits the ability of the model to be applied to highly variable throughput mines, and caution must be used with mines that have variations in ore types and material clay zonation.
- The model tests the economics of competing water recovery solutions instead of one solution over time. That limits the model from generating an internal rate of return and does not consider IRR, debt vs equity financing, asset amortization, IFRS, or tax considerations.

These assumptions limit the accuracy of using the model in this early-stage case study. Users can reduce the technical performance and financial cost limitations by remodeling new data as it is collected. Given the technical assumptions and the limitations of the TET model, caution must be used when applying the model.

6. Recommendations and conclusions

The mining industry faces a unique threat from water scarcity and climate change. Water-saving technology and equipment improvements related to tailings creation and storage present potential solutions for net positive environmental and economic gains. One of the current obstacles for the implementation of water-saving technology at operating mine sites is the lack of financial arguments that value both the water inputs, TSF capacity and time value of embedded capital.

This research created a techno-economic model to evaluate the early techno-economic feasibility of three different water-saving equipment packages and then applied the model to a hypothetical Chilean mine. Our model found that hydro-cyclones and optimized thickener control systems make economic sense on a water recovery basis at any site globally. The high capital and operating cost requirements of filter-pressed tailings make an economic equipment application location-specific to regions with local water scarcity and political risk profiles.

The added advantage of the TET model is that trade-off studies can be done earlier, and the decision to go with the status quo water-intensive equipment in the future can be more broadly challenged on an economic basis. Further economic refinement might be possible with pre-set regional data resulting in regional economic best practices around economic water conservation. The use of the model presented in this paper should not extend to final decision-making stages unless combined with more detailed test work, engineering, and financial modelling. The recommendations for future work are to use this model with engineering teams on real projects and further test its application.

CRediT authorship contribution statement

Benjamin Cox: Conceptualization, Methodology, Data curation, Writing – original draft, Funding acquisition. **Sally Innis:** Writing – original draft, Writing – review & editing, Visualization, Project administration. **John Steen:** Supervision. **Nadja Kunz:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used is found in the paper, supplementary materials, and cited in the references.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mineng.2023.108157.

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