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Use of real options to enhance water-energy nexus in mine tailings management

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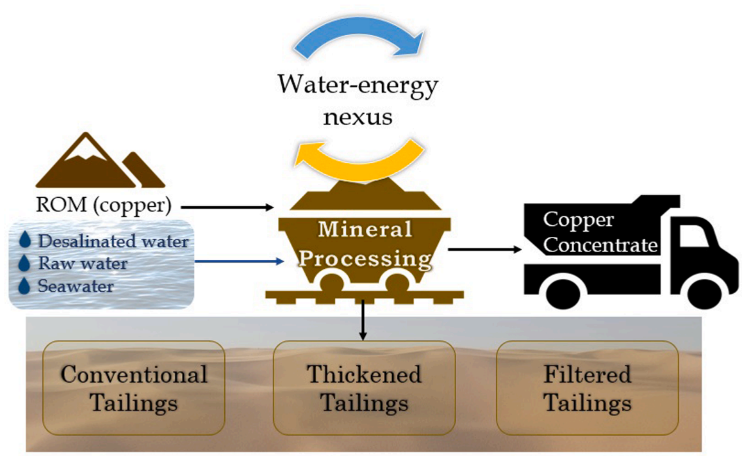
HIGHLIGHTS

- Water-energy nexus in mine tailings and water management is evaluated.
- Real options approach for choosing alternatives of tailings and water management.
- Cost of water transport to the mine is the biggest cost component.
- Thickened tailings are less energy-intensive than conventional ones.
- Energy has high influence in water reuse and recycling for mining sustainability.

GRAPHICAL ABSTRACT



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ABSTRACT

The tailing storage facility is the largest water sink in most mines. An incorrect management of water content in mine tailings can become a threat to their stability, and consequently, their environmental safety. Also, water reuse and recycling are plausible options to mining companies for reasons pertaining to water scarcity. Dewatering technologies for tailings, desalination and water transport are energy intensive. Proper handling of mine tailings and water supply management can considerably improve the water-energy nexus. This article evaluates the water-energy nexus in copper mining companies using a water reduction model focused on mine tailing facilities and water supply to the mine site to find the trade-offs between water and energy. The originality of this work consists in the application of a real options approach, enabling to increase the flexibility of decision-making thanks to quantitative analysis. This approach deploys the Monte Carlo simulation to perform sensitivity and

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uncertainty analysis to evaluate every cost component of water management strategy. Results show that if seawater is the primary source of raw water to the mining plant, water transport represents the largest cost due to the use of energy. So, improving the reuse of water by using dewatering technologies will improve the water-energy nexus, by improving energy consumption. Even though the costs of these technologies are elevated because they are energy-intensive, reduction of water use requirements in the mine will reduce the cost of its treatment and transport.

1. Introduction

Water and energy are essential for the well-being of society. Mining is both water and energy-intensive in its processes. In Chile, the mining industry represents between 2 and 4.5% of the national water demand [1]. Nevertheless, if mines are located in places suffering from water scarcity, water use can impact the local supply. Besides, mining is a particular case due to the following characteristics: high revenues, excess discharge of water, social and environmental performance, water efficiency, and alternative energy sources [2]. Water consumption by the mining industry has increased. In Chile, the copper mining industry consumed 17.35 m^3/s of water in 2018 [3], 13.36 m^3/s of raw water, and 3.99 m^3/s of seawater; back, in 2012 the sector consumed 13.4 m^3/s of water. The decrease in ore grades is one reason why the mining industry has increased its water and energy consumption.

The biggest water sink in a mineral processing plant is the tailing facility [4]. Mine tailings are waste obtained after mineral ore processing to obtain element(s) of interest. They are a mixture of ground rocks with process effluents generated in the processing plant. Their composition depends on the nature of the rock being mined and the recovery process. Mine tailings disposal methods include cross valley or hillside dams, raised embankments/impoundments, dry-stacking of thickened tailings on land, backfilling into abandoned open-pit mines or underground mines, and direct disposal into rivers, lakes, and the ocean (ocean surface and submarine tailings disposal) [5].

Production in lower grade ore mines will be growing, generating larger amounts of mine tailings and, by extension, pressing for the development of a comprehensive framework for mine tailings management [6] that would include adequate water and energy sustainable management. Significant water savings can be achieved by reducing the available wet and open water area, which can be done by carefully managing the placement of the tailings [7,8].

Mining operations are both energy and water-intensive. If all the water supply relies on seawater, water must be treated and transported to the mine site, which leads to high energy consumption. Considering that the biggest water sink on the mine site is the tailings facility, water from tailings can be recovered to diminish the dependence on freshwater sources. Dewatering technologies, such as thickened tailings, paste tailings, and filtered tailings, allow water recovery from the tailings facility. However, they are more expensive than conventional tailing disposal because they are energy-intensive. Though, from the security perspective, reducing water content in mine tailings will improve their stability, lessen future environmental disasters, and lower the storage volume.

1.1. Article's aim

Mining exerts a local impact on water resources. If mining companies are located in an area suffering from water scarcity, water needs to be transported over long distances, and in some cases, to high altitudes above sea level. Proper mine tailings management can optimize the use of water, as well as the use of energy. This article aims to evaluate the water-energy nexus (WEN) in copper mining plants, focusing on tailings facilities to find out about the trade-offs between water and energy and propose a framework for sustainable mine tailings management.

This article aims to answer the following research questions:

- What is the relationship between water and energy in the copper mining industry for different tailing disposal methods?
- How can WEN be improved by using a real options approach?
- In which scenarios can WEN be improved?

A novel approach consisting in the use of real options is introduced to study the relationship between water supply and dewatering technologies and the economic output of every option. A real options approach (ROA) consists in offering the choices that company management can take in order to expand, change or delate investments based on economic, technical, or market conditions. In this study, ROA is used to reduce the risk of mining investments thanks to quantitative analysis of responses to unexpected market developments. The existing methods of managerial evaluation allow optimizing the decisions under the known level of available capital resources and existing investment alternatives. The technique used in this work provides for considering the financial value and the role of timing of decisions. It permits for better assessment of uncertainty and, in consequence, often identifies it as a source of additional value.

1.2. Water-energy nexus in mining

Saving water and energy has become one of the most important premises of global sustainable development. Nowadays, water and energy are interdependent and mutually reinforcing factors. Research has been conducted to explore the interlinks between water and energy, known as WEN [9,10]. WEN is the relationship between water used to produce energy, electricity and fuel sources, and energy consumed in the process of water purification, extraction, cooling, treatment, disposal, etc. Considering WEN in the planning, design, and operation of a water supply system ensures its sustainability, conserves energy and minimizes related greenhouse gas (GHG) emissions [11], which is imperative in mining since it is an carbon intensive sector [12]. This study focuses on the interlink between energy and water at a regional level where energy is used to produce, clean, treat, and distribute water in mineral processing plants.

Water and energy flows are interconnected with different links, and the nexus between them can be of different nature. WEN can be found in production, transportation, and consumption. The heart of the nexus may have several dimensions such as environmental, economic, technological, and social [13]. Various issues need to be addressed, such as water and energy allocation, capacity extension, planning for power plants, and environmental impacts, to manage the WEN [14]. Despite the interdependencies between water and energy flows, policies that consider them are rarely integrated [15].

Tsolas and coauthors introduced a network perspective that considers the interactions between energy and water within a generalized WEN by providing a method to design and optimize WEN using graph theory-based network representation and a novel WEN diagram. This approach considered the interactions between water and energy simultaneously, and it was noted that depending on the objective, the results could be significantly different [16]. As water and energy have an essential role in economic development, a network-based framework for the risk of scarcity of both water and energy, and the nexus between them was developed by Liu and coauthors [17].

Mining operations are both water and energy-intensive, and water demand has increased due to the decrease of grade in new ores [18].

According to Pimentel-Hunt [19] factors such as lower grade, greater haulage, distance, and technological change have made copper mining more energy-intensive. Nguyen and coworkers [20] presented a protocol to recognize water-energy synergy and trade-off potentials in water management in mining processes. They concluded that most water management options in mining have trade-off potentials, and few options will have synergy between water and energy.

1.3. Chilean political energy strategy and GHG emissions contexts

As a small country, Chile releases 0.3% of the global GHG emissions, with a high potential to increase its current energy capacity 70 times as the country enjoys the highest solar radiation on Earth and strong and constant winds [21]. In 2019 Chile produced 81,195 GWh, where 32.6 % came from coal, 3.7% from oil, 18.6% form natural gas, 5.4% from biofuels, 25.7% from hydro, 5.9% from wind, 7.8% from solar PV, and 0.2% from geothermal sources [22]. In 2018 32.3 gCO_2/MJ was the carbon intensity of energy consumption by industry where the industry consumed 60.4% of the energy, 1.6% of energy was consumed by transport, 18.4% went for residential purposes, 16.2% was consumed by the commercial sector, 0.2% by fishing, and 3.3% by agriculture and forestry [22].

In September 2015, Chile undertook to reduce its CO_2 emissions per unit of GDP by 30% by 2030 compared to the level reached in 2007. This goal is conditional on obtaining financial support from the international community. The country commits to increasing its reduction of CO_2 emissions per unit of GDP by 2030 until reaching a reduction between 35% and 45% compared to the level reached in 2007, considering, at the same time, future economic growth that will allow it to implement the appropriate measures to achieve this commitment [23]. The difficulties that emerged over time have produced changes to the priorities of the country's policy. The crisis that affected the electricity sector due to the drought and rationing in 1999, as well as the Argentine natural gas crisis from 2005, put the security of energy supplies at the top of the policy agenda under strict conditions of economic efficiency and acting in line with the sustainable development of the country [23]. For the development of the methodology for the elaboration of the Energy Policy, *Energía 2050*, the Ministry of Energy decided to adhere to international practices in this field presented, among others, in the New Zealand Energy Development Strategy, the Energy Policy 2005–2030 of Uruguay, the process German Energy Policy, and Australia' s Green Paper and White Paper [23].

The World Energy Council develops the Trilemma index to rank countries on their ability to provide sustainable energy by ensuring energy security, energy equality (accessibility and affordability), and environmental sustainability. In 2020 Chile ranked 37th among 108 countries [24]. Chile has made significant efforts to diversify its energy mix and reduce dependence on hydro and fossil fuels by incorporating power generation from renewable sources into the system, predominantly from wind and solar sources. It has been a solution for mitigating risks associated with importing other types of fuels from neighboring countries [24].

The Chilean national government launched its clean hydrogen strategy in November 2020, which is crucial for Chile to reach carbon neutrality by 2050 [25]. The abundant renewable energy allows the country for having the cheapest clean hydrogen production, enabling the supply of products and services developed with zero GHG emissions and the exports of clean hydrogen, clean ammonia, methanol, and synthetic fuels [21].

As indicated in the Roadmap 2050 document, the country's gross hydroelectric potential corresponds to approximately 16 GW. Energy policy for 2050 offers the opportunity to address hydroelectric development in the country, incorporating sustainability and social and environmental protection. This policy promotes the advantages that this energy source represents for the country, especially the advantages related to energy independence, flexibility, adjustment capacity, and additional services it provides to the electricity system, favoring the incorporation of other renewable sources. Added to all of this are the contributions that hydroelectricity can make to reduce greenhouse gases [23]. Nuclear power energy has not been included as a short-term option. It requires studies in critical aspects, such as long-term economic viability under different legal and market conditions and the legal and institutional adjustments required. These studies must be coordinated and commissioned by the Chilean Nuclear Energy Commission and conducted by competent national organizations.

Chile's energy policy has changed dynamically in recent years. In response to the developments in domestic and international environment, deep institutional and policy reforms and significant infrastructure projects have been carried out. The national energy policy 2050 was adopted in 2015, following an exceptionally inclusive public consultation. The electricity sector, in particular, has developed fast [22]. Chile is a world-class destination for solar and wind energy developers. New legislation supports investment in generating capacity across the electricity sector. The prominent role of the state in energy mix planning has helped to boost project development, especially in electricity transmission. Additionally, Chile has a single interconnected national electricity system [22].

Chile's PV growth is expected to fast-track after 2022. As part of the Covid-19 economic recovery efforts, the government has accelerated the environmental approvals of 55 solar projects. Furthermore, Chile has recently launched a Casa Solar program that supports the development of distributed PV projects by allowing community groups to obtain solar panels at lower prices and receive state co-financing. Chile is well on track to meet its 2025 target of 20% electricity from non-conventional renewable sources [26]. One of the latest example to embrace the zero emission generation of energy is the commissioning of Chile's Cerro Dominador plant with 110 MW and 17.5 h of molten salt storage, the largest in Latin America [27], allowed to carry out the Likana project in Chile, which the Cerro Dominador group acquired in 2019. The group plans to offer a 450 MW concentrated solar capacity project in a power auction in Chile in 2021 [26].

1.4. Water management in mining

As a notoriously water-intensive activity, the mining industry often infringes other forms of water use, and the negative impacts occur at a local level [28]. Mining consumes large amounts of water to process mineral ore. Water is pumped and sometimes treated to be used along the process [29]. To separate the non-valuable minerals from the ore, wet processes, such as flotation, which uses large quantities of water, are often used; 70% of the freshwater used in copper mining in Chile is used in the concentration plant where the flotation process takes place [30]. Nowadays, modern mines reuse or recycle water. In Chilean copper mining, the average total recirculation of water is 74% [30].

As mine sites are usually located in arid zones suffering from water scarcity, their water demand can be fulfilled with a combination of different sources of water, such as groundwater, seawater, freshwater, and recycled water. Transporting seawater to the mine sites is cost-intensive due to the costs of desalination, treatment, and transport of water [31], which involves pumping it over long distances to mine sites located up to 4000 m above the sea level [32], demanding for a large amount of energy [33]. Increasing water recovery in the mine site has a significant effect on reducing the cost of supplying water to the mine [34].

The use of desalinated seawater has increased due to the over-exploitation of water resources in hyper-arid, arid, and semi-arid places where mine plants are usually located [35]. Desalination is still perceived as an expensive and environmentally damaging solution [36]. However, the adverse effects of desalination can be mitigated by carbon-neutrality achieved by using renewable energy. Environmental issues associated with brine disposal can be managed, at a local scale, by an appropriate design of outfalls minimizing its impact through dilution

[36]. Desalination costs have declined over the past decades, thanks to increased plant capacity, higher permeation rates, and improvement of membrane materials [37]. However, achieving further cost reductions is quite challenging despite the continuous enhancements in membrane and energy recovery technologies [38]. Between 1977 and 2015, the capital costs of seawater desalination plants decreased with a learning rate of about 15% [39], which means the capital cost is reduced by 15% when the cumulative capacity has increased twice.

The cost of water treatment can be associated with GHG emissions as energy consumption and CO_2 emissions per unit of water, often referred to as energy and carbon intensity [40]. There is a gap in studies assessing energy use and GHG emissions in the water sector partially due to the absence of clearly defined boundaries [41]. Therefore, some studies strategical define their boundaries to assess GHG emissions' water treatment due to its intrinsic relationship with the energy generation mix [33].

Due to water scarcity in arid and semi-arid regions, there is growing interest in non-conventional water resources as a new alternative [42]. Partial desalination has been proposed to reduce cost, instead of desalination using the reverse osmosis process, as a treatment for seawater to remove only the elements that cause problems in industrial processes [35]. Some mining plants are currently using seawater that is partially desalinated or not treated at all. However, we need to bear in mind that these options may cause operational problems [43].

Several efforts to quantify water and energy in mining processes have been undertaken to reduce the consumption of these resources or improve the efficiency of mining processes. A mine water reduction model was introduced by Gunson and coauthors [1] to improve the mine water system performance in a copper mine plant by comparing scenarios of water reduction with the base scenario that does not consider water savings. Scenarios include tailings dewatering technologies, and water conservation options. Afterward, Aitken and coauthors [44] applied a cost-benefit analysis to the options analyzed by Gunson et al. [1], finding out that elevation is in some cases low, under 1600 m, thickened tailings with the use of raw water is the most effective solution. In comparison, for heights exceeding 1600 m, the most effective solution is the use of filtered tailings. An approach to minimize the energy consumption of water mine processes is called the mine water network design method, developed by Gunson et al. [45]. This strategy describes all water sources and water consumers to put together energy requirement matrices and use linear programming to minimize energy consumption.

1.5. Mine tailings management

The purpose of the mine tailing management approach is to protect humans and the environment from risks associated with mine tailings. Mine tailings management is crucial in mining operations because of the irreversible impacts of mine tailings [6]. Mine tailings storage leaves a significant environmental, temporal, and space footprint, and for its physical and chemical stability, we need to strive to decrease acid mine drainage risk [6]. As tailings contain a multitude of various contaminants, the integrity of these impoundments is a significant issue of global environmental concern [46]. One of the environmental issues related to mine tailings is acid mine drainage [47] which occurs due to the content of sulfide minerals in mine tailings when they are in contact with oxygen and water [48].

Inadequate storage of mine tailings may lead to catastrophic consequences. Errors made in the storage and management of mine tailings are the largest source of severe effects experienced globally by the public [49]. Water has a significant role to play in determining tailing's behavior. Therefore, water recovery from tailings impoundments is a common strategy to reuse water and reduce tailings dam risks, especially in places with water scarcity [50]. In the case of coal mining, the trade-offs between water and energy in mine tailings include both the pumping of tailings and the technology used for dewatering tailings [51]. Most mines still use the conventional method for tailings disposal, consisting in transporting mine tailings slurry through pipes to a tailing storage facility or a tailing dam. A typical tailing storage facility includes a dam, a beach produced by the discharge of tailings slurry, and fine sand to silt and clay slimes farthest from the dam in a layer sufficiently impermeable to maintain an overlying pond [52]. This method requires a high percentage of water, approximately 70%, but it is chosen because it is cost-effective [6]. Thickened tailings (TT) and filtered tailings (FT) reduce the water content of tailings but are considered energy-intensive, hence more expensive. Nevertheless, the implementation of these technologies would reduce the costs of mine closure [53,54]. Various studies indicate that emerging technologies, such as TT and FT, represent a breakthrough in the mining industry as they rely much more heavily on recycled water and reduce freshwater consumption [55]. Other benefits of TT and FT, compared to conventional tailing disposal, are a lower footprint, reduced potential of acid mine drainage, reduced risk of potential dam failure, and higher reagent recovery [56].

Pumping tailings to the storage facility is also energy-intensive; it depends on the solid content since the tailing slurry can only be pumped until a certain percentage of solids. Rheology analyses are needed to determine if the tailings can be transported. The yield stress is a parameter that indicates the point at which a material begins to deform plastically. Tailings with high solid content (65 and 70% mass solids) have very high yield stress which means they are difficult to pump. Higher mass solids need to be transported by other means, such as using a filter press [51].

1.6. Real options approach

The costs of putting technology in place can be broken down into capital expenditure (CAPEX) and operational expenditure (OPEX), which depend mainly on the pump type, energy consumption, and the chemicals used [6]. A new mining project is based on many uncertain inputs, such as production costs, price of materials, and supplies. The analysis and modeling of uncertainty enhance the ability to make appropriate decisions [57]. Water management strategies, such as the use of desalinated seawater, include costs associated with water treatment and its transport. Desalinated water must be transported over long distances to the mine sites as they are usually located far away from the coast. ROA can evaluate each cost component of different water management strategies to then analyze the WEN of the proposed methods.

In the project valuation field, a real option is a right, not an obligation, to take any action on an underlying nonfinancial asset, referred to as a real asset [58]. That action can consist of, for example, abandoning or expanding a project or even deferring a decision for some time. Such actions cannot be considered in the traditional discounted cash flow method due to its static nature with a one-off decision-making process. In contrast, ROA considers the strategic management options that may arise for specific projects and the flexibility in exercising or abandoning these options [59]. Real options have been used recently in different fields to assess investments surrounded by uncertainty to provide the flexibility that traditional valuation methods cannot offer. Applications of ROA can be found in several mining investment studies [60]. ROA can be used to model the profitability of new metal mining investments [61], forecasting uncertainties in mining projects [62], and reduce the uncertainty due to commodity price, as well as to give operational flexibility [63].

There are applications of ROA in research related to the energy sector. ROA was used to analyze the uncertainty of CO_2 sequestration in depleted shale-gas [64]. A methodological approach that integrated ROA into multicriteria analysis was developed to assess energy firms [65]. A real options model using system dynamics was built to optimize financial subsidies for renewable energy technologies [66]. The photovoltaic power generation under carbon market linkage has been analyzed with ROA to consider uncertainties such as investment costs, electricity prices, carbon prices, and subsidy payments [67]. ROA was

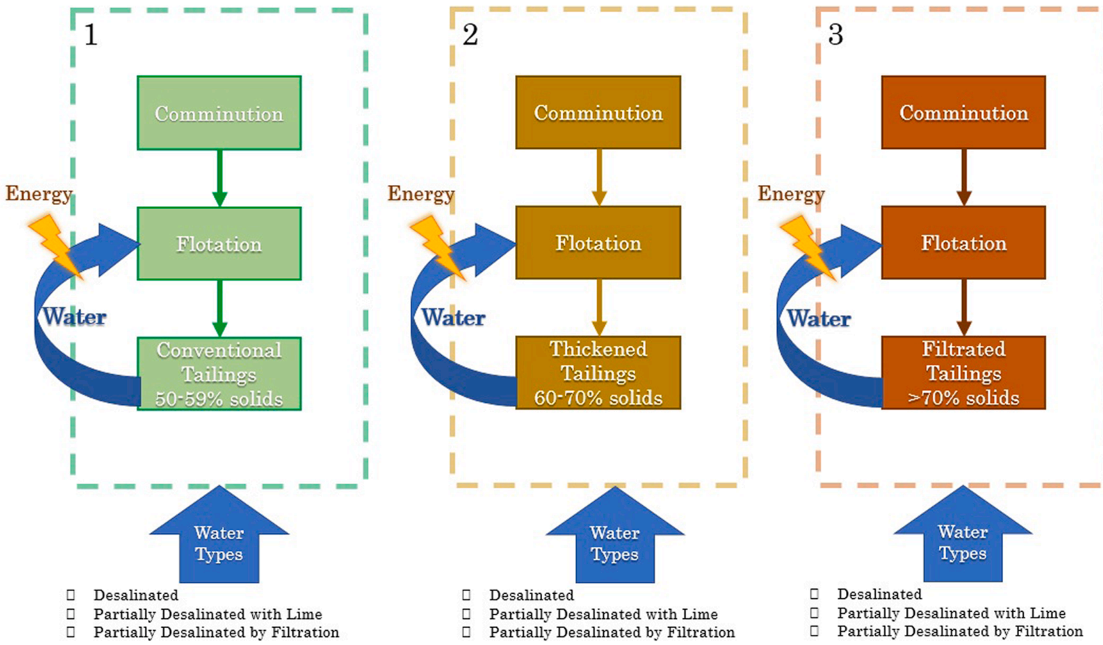

Fig. 1. Simplified scheme of every option of tailings management and water treatment considered in the study.

used to analyze the impacts of government subsidy on the investment decision of full-chain carbon capture utilization and storage projects [68]. ROA was used to analyze the economic feasibility of waste-to-energy projects; this approach considers options such as waiting and the optimal timing of switching technologies [69]. A model that aims to enhance the flexibility in gas-fired power plants with an approach of real options helped assess the future profitability of power plants and support the decision-making process regarding the operation of power plants [70].

ROA supplements traditional tools used to assess investment projects [58]. In this article, ROA is used to assess the uncertainties inherent in the costs of implementing different options and analyzed scenarios. Monte Carlo is applied to perform an uncertainty analysis and the estimation of Sobol' indices is used to perform global sensitivity analysis.

Sensitivity analysis and uncertainty analysis are often used together to ensure the quality of the model and the transparency of the decision-making processes [71]. Sensitivity analysis examines the response of an output variable to variations of input variables [72]. It explores and quantifies the impact of possible errors in the input data in predicted model outputs [73]. Instead, uncertainty analysis assesses the effect of ambiguous values of parameters on the output results [74]. Sensitivity and uncertainty analyses can be used as complementary to valuation tools to study the impact of inputs in investment projects.

Monte Carlo simulation is widely used to perform uncertainty and sensitivity analyses [75], and is a method that consists of a thousand possible scenarios and can be used as a valuation tool to calculate the net present value of a project for each scenario and analyze probability distribution of the net present value result [58], it can also be used for risk analysis by modelling the probability of different outcomes of the process. This simulation approach is relatively simple, each random variable in a process is sampled several times to represent the underlying probabilistic characteristics [75]. It can also be complemented with other statistical tools to study the probability distribution of a function according to different parameters.

2. Methodology

2.1. Water reduction model

Strategies pursued to reduce the amount of water used in a mineral processing plant deploy the water reduction model introduced by Gunson et al. [1] to estimate the raw water requirement for the mine site. These strategies are technologies for dewatering tailings and options for water supply to a large mine plant that produces fine copper. They include technologies such as traditional disposal of tailings, in which tailings contain 35% of solids and the rest is water; TT and FT are considered to reduce water content in tailings. Due to the scarcity of groundwater or water from lakes, mine sites can be supplied only from the sea. A combination of water supply is also considered since some treatment procedures for seawater give water of a higher quality that might be required for processes like flotation. In contrast, lower quality water can be used in other processes. The higher quality water corresponds to seawater desalinated using the reverse osmosis process, and the lower quality corresponds to seawater that is partially desalinated using filtration or precipitation with lime.

2.2. Real options approach

A ROA approach is used to assess the cost of each option by analyzing every cost component, which includes the costs of the technologies used for water and tailings management. The annual cost of each strategy is calculated considering a 20-year project life. The uncertainties in the cost of CAPEX and OPEX are considered in all the options assessed as these costs are subject to change. OPEX includes the cost of electricity and materials for operating different technologies. CAPEX and OPEX have uncertainties connected to the price of electricity and water for the implemented technologies. The price of copper is also an uncertainty considered in the revenues of the process. The system is shown in Fig. 1, which illustrates its boundaries.

2.3. Uncertainty and sensibility analysis using Monte Carlo

The application of ROA consists in applying Monte Carlo simulation to perform uncertainty analysis and calculate the Sobol' indices as a global sensitivity analysis. Sobol' indices or Sobol' method is a variance-based sensitivity analysis, a form of global sensitivity analysis [76]. The analysis is completed using RStudio, an open-source software. The function of the annual cost is analyzed; its components are the CAPEX and OPEX of the different technologies included in each strategy, such as tailings dewatering technology, water treatment of water supplied to the

Table 1
Major parameters of the mineral processing plant described in the case study.

Parameters	Mine site
Feed (tpd)	405,712
Grade (%)	0.86
Process water requirement (m^3/d)	567,151
Water recycled (m^3/d)	106,274
Recycled water (%)	0.187
Raw water requirement (m^3/d)	473,288

mine, and the transport of water from the water treatment plant located on the coast to the mine site.

2.4. Energy consumption and GHG emissions

Energy consumption of each dewatering technology for tailings is calculated and compared to the water reclaimed by each technology, additionally water supply and treatment for water management is calculated. Energy consumption involved in pumping the water from the water treatment plant to the mine site can be estimated from a basic theoretical physical relationship represented by Equation (1) [41]:

$$Energy\ \ consumption(kW\ \ h) = \frac{9.8\left(\frac{m}{s^2}\right)*lift(m)*mass(kg)}{3.6*10^6*efficiency(\%)} \tag{1}$$

GHG emissions are calculated to determine the environmental impact of the different sources of energy deployed in the generation of electricity used by the technologies involved in tailings disposal, water treatment, and water transport To calculate the GHG emissions, the CO_2 equivalent emissions were determined for different percentage share of energy sources; the energy mix can be powered by different sources like coal, oil, hydroelectrical, natural gas, Photo Voltaic, wind, biofuel, geothermal, nuclear, among others. CO_2 emissions vary within a certain range for every energy source; hence three cases of CO_2 emissions were used, minimum, median, and maximum. Therefore, CO_2 equivalent emissions were estimated for every option under study. The data were obtained using secondary sources from the International Energy Agency [22] and the World Nuclear Association [77], and the calculation is presented in the Appendix A.

In general terms, the methodology can be described by the following stages:

– Determination of the boundaries of the studied system. It includes the selection of the dewatering technologies, types of water, size of mine, project lifespan, energy mix, among others.
– Modelling the amount of water used in the system under study using a water reduction model.
– Calculating CAPEX and OPEX for different options.
– Application of a ROA approach, implementation of sensitivity and uncertainty analysis for every option.
– Calculating energy consumption and GHG emissions for the options assessed.

3. Case study

Chile's Geochemical and mineralogical characteristics have made mining one of the main economic activities in the country. Chile is the leading world producer of copper, whose production in 2018 reached 5872 K tons of copper, which corresponds to 28.3% of the world's production [78]. Furthermore, Chile is the second world producer of molybdenum, with 60,248 tons produced in 2018 [78]; molybdenum is a by-product of copper mining. Most of these mining activities have developed in the Atacama Desert, the driest non-polar desert on earth, and it extends all over the northern parts of Chile.

The Atacama Desert is an area where demand for water has been growing due to the water scarcity that this area suffers from. Desalination is seen as the best option to meet the water demand. Hence, the Chilean government has proposed new policies to promote desalination processes in different sectors; moreover, Chile has got the largest desalination system in South America [43].

Methods used in Chile to store mine tailings are conventional tailings stored in tailing dams, TT, FT, and paste tailings [79], being tailing dams, the most common type of tailing storage facility in the country. By 2015, approximately 70% of tailing storage facilities were dams constructed using cyclone sand tailings, 7% by earth fill or rock fill, and 3%, by FT, paste, or TT, for the remaining 20%, no information is available [80].

The developed framework was applied to a case study of a large mine plant. It resembles an actual open pit mine operation in the Antofagasta Region, an area located in the Atacama Desert, Northern Chile, that hosts several mining operations of the copper industry. The mine site uses water supplied from a water treatment plant located on the coast. In this study, we assumed that the demand for water represented by the mine must be fulfilled with seawater since freshwater is not available due to the water scarcity in the nearby areas.

At the mine site, copper is recovered by flotation, which is the separation process that generates mine tailings. The water reduction model was used to calculate the raw water requirement for each scenario, including tailings dewatering technologies. The mine site covered by the study has the same feed and grade as the Escondida mine, which is the world's largest copper mine, located in the Antofagasta Region. Data on the main water streams of Escondida Mine were obtained from reports of the company [81]. Escondida mine produced 906.8 ktpa of payable copper in 2019 [82]. Copper price of 2.60 US$/lb is considered, which is the price of copper in 2019 used in the BHP report [82]. Table 1 includes the main values of parameters of the case study used to estimate different outcomes with the water reduction model.

Process water requirement refers to the water flow used in the mineral processing plant. Raw water requirement refers to the water flow input, which is equal to water losses in the process, which can also be called consumption water or withdrawal. Recycled water refers to the water used in the process and can be recycled to be used again. Mine process operations are considered a black box, as shown in the different figures. The different dewatering scenarios lead to different water content in tailings which implies a reduction in the raw water requirement of the mine site. The surplus water, i.e., the overflow water of tailings that will not be used inside the mine plant, is available for other uses outside the plant.

4. Results

Water management strategies within the framework are applied to different scenarios to analyze the impact of each alternative. When scenario 1 is a base case, no water-saving approach is used because tailings go through a traditional tailing dewatering method and disposal. Scenario 2 considers the strategy of TT technology to enhance the dewatering of tailings. Scenario 3 uses filtering tailings as a dewatering technology for tailings disposal. CAPEX and OPEX of tailings dewatering technologies were obtained by scaling the equipment costs stated in the Ajax Project Report [83]. The costs of equipment were scaled using the 0.6 rule [84]. For the feed considered, the costs of conventional tailings disposal are: CAPEX of 669 M US$ and OPEX of 369 M US$; for TT, CAPEX is 678 M US$ and OPEX is 396 M US$; and FT has a CAPEX of 1,326 M US$ and OPEX of 1,290 M US$. The same report was used to estimate energy consumption of each tailings management technology, however, the numbers were adapted to the case study presented here.

Mining companies can take seawater from the coast and transfer it to their locations, subjecting it to different treatment processes dictated by their specific requirements. In this case study, water treatment options include seawater partially desalinated with filtration, seawater precipitated with lime, and desalinated water with reverse osmosis, as

Table 2
Raw water requirement for dewatering tailings technologies and the base case of conventional tailing disposal.

Technology	Raw water requirement (m^3/d)
Conventional tailing disposal	473,288
Thickened tailings	406,436
Filtered tailings	313,046

Table 3
Cost of implementing different scenarios and options for tailings dewatering and water supply management.

Scenario and option	Annual cost (M US$/ year)	Total cost (M US$)
Conventional tailings + option 1	629	12,578
Conventional tailings + option 2	660	13,200
Conventional tailings + option 3	853	17,069
TT + option 1	549	10,984
TT + option 2	576	11,518
TT + option 3	742	14,841
FT + option 1	512	10,249
FT + option 2	533	10,660
FT + option 3	661	13,220
FT + 50% option 1 + 50% option 3	587	11,733
FT + 50% option 2 + 50% option 3	597	11,940

Table 4
Values of the variables used for sensitivity and uncertainty analyses.

Variables	Value	Value × 0.9	Value × 1.1	Value × 0.8	Value × 1.2
CAPEX filtered tailings (MUS$)	442	398	486	354	530
OPEX filtered tailings (MUS$)	430	387	473	344	516
CAPEX thickened tailings (MUS$)	226	203	249	181	271
OPEX thickened tailings (MUS$)	132	119	145	106	158
CAPEX conventional tailing disposal (MUS$)	223	201	245	178	268
OPEX conventional tailing disposal (MUS$)	123	111	135	98	148
CAPEX water treatment – filtration (US$/$m^3$)	0.230	0.207	0.253	0.184	0.276
OPEX water treatment – filtration (US$/$m^3$)	0.070	0.063	0.077	0.056	0.084
CAPEX water treatment - precipitation with lime (US$/$m^3$)	0.350	0.315	0.385	0.280	0.420
OPEX water treatment - precipitation with lime (US$/$m^3$)	0.130	0.117	0.143	0.104	0.156
Cost water treatment - reverse osmosis (US$/$m^3$)	1.600	1.440	1.760	1.280	1.920
Cost water transport - supply system (US$/$m^3$)	3.040	2.736	3.344	2.432	3.648

considered by Aitken et al. [44]; these options replace the raw water requirement of the mine site. Additionally, a combination of water supply sources was considered since some operations require water of higher quality, which is relatively expensive. Therefore, water supply options consist of 50% of water desalinated with reverse osmosis process, and 50% of filtered seawater or 50% of seawater desalinated with reverse osmosis and 50% of seawater precipitated with lime are also considered. Water desalinated with reverse osmosis is designated as having higher quality, while filtered seawater and seawater precipitated with lime is of lower quality.

The annualized cost, which included both capital and operating expenses, of using seawater partially desalinated with filtration, which is option 1, and using seawater precipitated with lime, option 2, were taken from Aitken et al. [44]. The costs of filtration can be broken down into CAPEX (0.23 US$/$m^3$) and OPEX (0.07 US$/m^3), and for precipitation with lime, 0.35 US$/$m^3$ for CAPEX and 0.13 US$/$m^3$ for OPEX.

For option 3, in which seawater desalinated with reverse osmosis is used, the annualized cost of a reverse osmosis plant was taken from Herrera-León et al. [31] and it amounts to 1.6 US$/$m^3$. The cost of the water supply system, i.e., pipelines and the pumping system to carry the water from the coast up to the mine sites, was calculated from the model validation performed by Herrera-León et al. [31] and it amounts to 3.04 US$/$m^3$.

Each scenario of tailings dewatering technology can be combined with water supply options 1, 2, and 3. These options are meant to meet the plant's water requirement with seawater treated using different methods described in the options above. For the mine site, calculations were made for the three scenarios combined with each option of water supply. The results are presented in Table 2. FT has been found out to be the most effective technology for tailings dewatering because it dramatically reduced the raw water requirement from 473,288 m^3/d to 313,046 m^3/d, which is a 33.86% reduction of the water requirement. In the case of TT, the water requirement is reduced to 406,436 m^3/d, which is 14.14% less.

Table 3 contains the costs for each combination of scenarios and options. The most economical water supply system for a mine is using filtered seawater, followed by a solution using water precipitated with lime. However, water quality for these two options is low, which is why we considered a combination of 50–50% of water desalinated with reverse osmosis, and filtered seawater and 50–50% of water desalinated with reverse osmosis and seawater precipitated with lime, more detailed results are included in the Appendix A.

On the other hand, CAPEX and OPEX for TT and FT are higher than conventional tailings dewatering technologies. Still, since the raw water requirement for these technologies is considerably lower, the annualized costs are lower.

Assuming annual production of 906.8 ktpa of payable copper at a price of 2.6 US$/lb, the revenue would be 5,239 M US$/y, investment in tailings management, and water supply represents between 9.77% and 16.28% of annual costs of mine site operation for a 20-year project life.

Equation (2) represents the cost of water and tailings management. This equation was modelled in RStudio using Monte Carlo simulation and the estimation of the Sobol indices.

$$Annual\ \ cost = CAPEX_d + OPEX_d + CAPEX_w + OPEX_w + COST_{RO} + COST_t \tag{2}$$

where $CAPEX_d$ and $OPEX_d$ are the annual costs of dewatering technologies; $CAPEX_w$ and $OPEX_w$ are the annual costs of water treatment, be it filtration or precipitation with lime, $COST_{RO}$ is the annual cost of reverse osmosis, and $COST_t$ is the annual cost of the transport of water from the water treatment plant to the mine site. In the case of filtered tailings and water supply that consists of 50% of water representing higher quality, which is desalinated with reverse osmosis, and 50% of water representing lower quality, which is filtered seawater, the annual cost is 587 M U$/year.

Sensitivity and uncertainty analyses were performed as ROA for the implementation of water management options. The Monte Carlo simulation models the probability of different outcomes from the options assessed. Fifty thousand simulations were run. To carry out these analyses, we assumed the value of variables that ranged between a minimum and maximum considering a range of ±10% and ±20%, these values are presented in Table 4. The investment was planned for 20 years, which is a usual timeframe for a project of this magnitude. The results considering TT and conventional tailing disposal are included in the Appendix B.

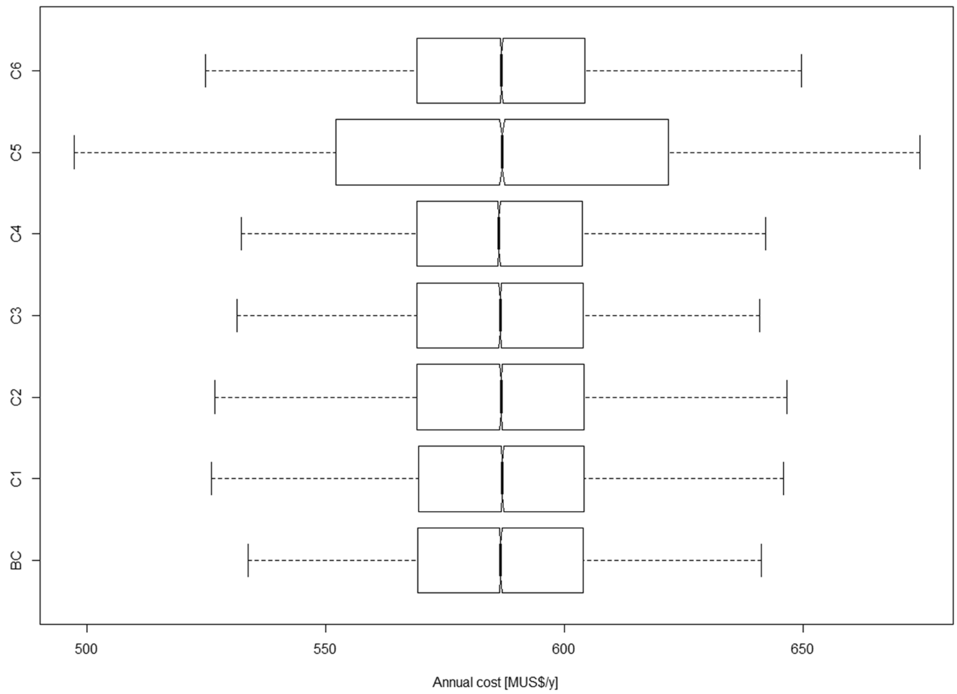

Fig. 2. Boxplot of the annual costs of implementing filtered tailings technology and water supply of 50% of higher quality and 50% of lower quality water. BC represents the base case, C1 $CAPEX_d$ ± 20%, C2 $OPEX_d$ ± 20%, C3 $CAPEX_W$ filtered seawater ± 20%, C4 $OPEX_W$ filtered seawater ± 20%, C5 $COST_T$ ± 20%, and C6 $COST_{RO}$ ± 20%.

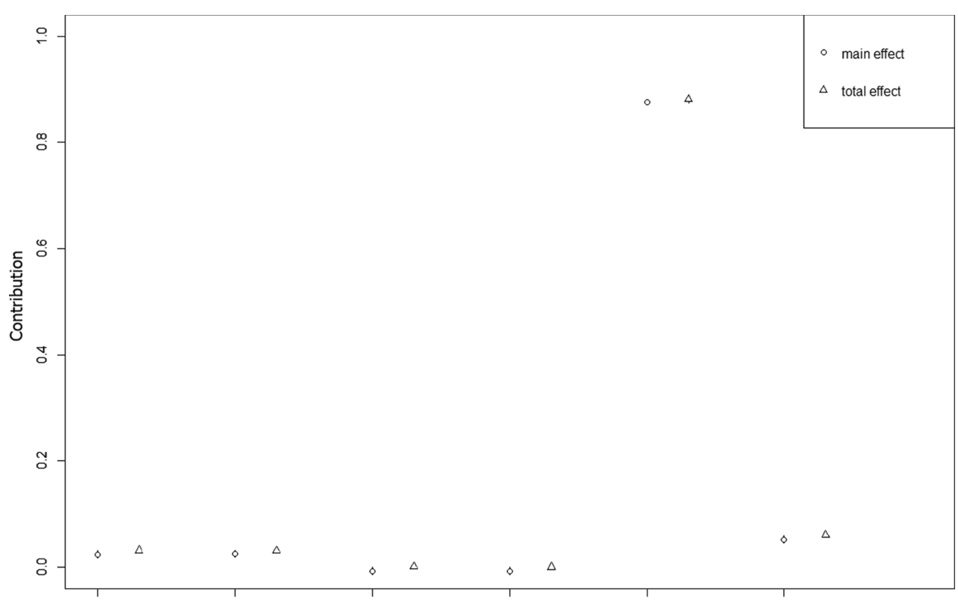

Fig. 3. Sobol' indices of the annual costs of implementing filtered tailings and water supply of 50% of higher quality water and 50% of lower quality water. Where 1 $CAPEX_d$ 2 $OPEX_d$,3 $CAPEX_W$ filtered seawater, 4 $OPEX_W$ filtered seawater, 5 $COST_{T,}$ and 6 $COST_{RO.}$

The summary of results delivered by RStudio, considering the option of using filtered tailings and a combination of 50% desalinated water and 50% partially desalinated water of lower quality obtained by filtration, shows a minimum value of 531.7 M US$/y and a maximum value of 640.1 M US$/y, mean of 586.6 M US$/y and median that equals 586.6 M US$/y. Boxplots represent the summary and the primary data; they visualize the minimum, lower quartile, median, upper quartile, and maximum data set [85]. They are a straightforward and informative method of data interpretation [86]. A boxplot is presented in Fig. 2 to visualize the characteristics of data used to calculate the annual cost. BC stands for the base case using a ±10% variation for each input. For the rest of the boxplots, the uncertainty of one input was expanded to ±20%, leaving the rest of the inputs in the previously settled ±10% range.

With Monte Carlo simulation, global sensitivity analysis is performed by estimating the Sobol' indices with independent inputs. Fig. 3 shows the main and total effects of the inputs of the annual costs of implementing filtered tailings and water supply, combining 50% of higher quality water and 50% of lower quality water obtained using the Soboljansen function of RStudio. This method decomposes the model output variance into fractions that can be attributed to each input.

Table 5
Energy consumption and CO_2 emissions of dewatering technologies and a base scenario of using reverse osmosis.

	Conventional tailing disposal	Thickened tailings	Filtered tailings
Energy consumption dewatering technology (kW h/d)	708,593	474,314	1,169,755
Energy consumption water supply (kW h/d)	4,380,540	3,761,792	2,897,418
Energy consumption water treatment (RO) (kW h/d)	1,467,192	1,259,952	970,444
Energy consumption dewatering technology + water supply + treatment (RO) (kW h/d)	6,556,326	5,496,058	5,037,616
CO_2 emissions (gCO_2 eq/d) $\times 10^9$ median	2.683	2.249	2.061
CO_2 emissions (gCO_2 eq/d) x10^9 min	2.277	1.909	1.750
CO_2 max (gCO_2 eq/d) x10^9 max	6.940	5.818	5.333

Therefore, in the case of using filtered tailings method and water supply combining 50% of higher quality and 50% of lower quality water, the main contribution to the variance, 0.84, is due to the cost of transporting the water from the water treatment plant located on the coast to the mine site. If the main effect and the total effect of each input are close to each other, then there are no significant interactions between them.

Results of uncertainty and sensitivity analyses for the rest of the options show similar results that the cost of the water supply system exerts the bigger impact on the cost of investment in implementing a dewatering technology and having a water supply system that combines seawater with desalination or other treatment method leading to partial desalination. Results of the other options assessed are included in the Appendix B. In the case of traditional tailing disposal and TT, the differences between the contribution of each input are more noticeable. Because the cost of traditional tailing disposal is lower than FT and since the raw water requirement is much higher when using traditional tailing disposal, the costs of the water supply system and water treatment are increased.

The WEN can be divided into energy for producing water and water for producing energy. In this study, the energy component needed to produce water is examined since it is part of the energy used in water treatment, water transport, and tailings dewatering technology. Improving energy efficiency will reduce GHG emissions. Energy consumption for each dewatering technology, TT and FT, and for the base case of conventional tailings disposal was estimated to assess the energy component of each strategy proposed. It was then compared to the amount of energy consumed in pumping the water from the water treatment plant to the mine site. Table 5 presents energy consumption and CO_2 emissions of each technology. FT consumes 1,169,755 kW h/d, which represents 65% more energy than conventional tailing disposal. TT consumes less energy than conventional tailing disposal, showing a reduction of 33.063%. Energy consumption associated with water supply was estimated in each case as the energy consumption of pumping the water from the water treatment plant located on the coast to the mine site. Considering the transport of water to the mine site and the technology chosen to deal with tailings, using FT represents a 20% reduction in energy consumption compared to the conventional tailings disposal method. In the case of TT, a decrease of 17% of energy consumption is achieved compared to the conventional tailings disposal method.

In Table 2, we can see that the raw water requirement of the mine site is different depending on how tailings are handled. FT is energy-intensive; however, the raw water requirement of the mine site is minimized; hence the cost of transporting water to the mine site is lower, so is energy consumption, which can be seen in Table 5. Total energy consumption considers each option of tailings management and energy consumed in transport as there is a trade-off between them. As to reverse osmosis, it is known that it is energy-intensive and costly compared to other treatment methods. Data concerning energy consumption of precipitation with lime and filtration treatment were not found in literature, hence we considered a scenario where water supply relies only on reverse osmosis, using for energy consumption a value of 3.1 kW h/m^3 obtained from literature [87]. Data from the International Energy Agency were used to calculate CO_2 emissions [88]. These data contain CO_2 emissions per energy source for Chile's energy mix and are included in the Appendix A. A minimum, median, and maximum value of 374.34, 409.2, and 1058.56 g CO_2 eq/kWh respectively were used to estimate the CO_2 emissions of the water supply system and tailings disposal technologies. The GHG emissions were determined for the Chilean energy mix. This scenario conforms to different sources of energy 32.6% coal, 25.7 hydroelectrical, 18.6% natural gas, 7.8% Photo Voltaic, 5.9% wind, 5.4% biofuel, 3.7% oil, and 0.2% geothermal [22].

5. Discussion

There is a trade-off between water and energy in choosing the tailings dewatering technology. Even though dewatering technologies, such as FT and TT, are more expensive than conventional tailings disposal, in terms of both CAPEX and OPEX, they reduce the raw water requirement of the mine. These technologies decrease the cost of water treatment and water transport to the mine site and, ultimately, reduce the overall cost of the mine site operation. Furthermore, the use of FT and TT technologies, by removing additional water from the mine tailings, improves the stability of deposit, diminishes the risk of acid mine drainage, and reduces the deposit site volume as a mining liability.

Suppose mine plants use seawater and are located far away from the coast; having TT or FT could be more economically viable than conventional tailings disposal due to the costs involved in transporting water to high altitudes. The costs of technologies to manage tailings are directly related to the energy they consume. FT is highly energy-intensive, but the final product is tailings with the lowest percentage of water, meaning that the raw water requirement of the mining plant decreases more considerably than when using conventional tailings disposal. Additionally to the dewatering technologies as a strategy to save water in the mining plant, it has been demonstrated that the use of road dust suppressant products is a cost-effective solution to save water [89].

Chile is a developing country that is highly dependent on coal [88]. However, this is a struggle that several developing and under-developed countries have faced [90]. For developing countries, economic growth raises energy consumption [91]. Hence, Chile should adopt energy-efficient technologies and use renewable energy sources to achieve sustainable development with lower CO_2 emissions [90]. Additionally, Chile as a seismic region, cannot rely on the safe use of nuclear energy as a source for its energy mix.

In areas suffering from water scarcity, seawater is the primary source of water for mining sites. There are insufficient water resources in the North of Chile to cover environmental, domestic, and industrial requirements [92]. In this study, we assumed that the whole water supply relies on seawater and that continental water is not available due to the water scarcity situation that most areas where mines are located suffer. This assumption is based on the Chilean legal context, where every new mineral process plant should be operated by seawater only. In the future, 70% of the desalination capacity in Chile will meet the demand of the mining industry [43].

In cases where the mine site is located far away from the coast, water needs to be pumped over long distances up to the mine site. Water transport is one of the main cost components of water supply, having a bigger impact than water treatment. Reverse osmosis is the leading technology applied to desalinate seawater, and it is still quite expensive as a way of fulfilling the total requirements of a mine site. However, some mining processes do not require high-quality water produced with reverse osmosis [35]. Other technologies applied in this study are filtration and precipitation with lime, in which water quality is inferior but still satisfactory for some processes.

Additionally, the combination of water was considered since relying only on the supply of seawater through a filtration process can be unrealistic since some operations in the mine site require high-quality water, such as the one obtained with reverse osmosis. Currently, some mine sites use a combination of water that includes recycled water, freshwater, and desalinated water. Water transportation and treatment are energy-intensive processes that generate a large amount of GHG and threaten the competitiveness of the copper price by increasing the production cost in mines geographically located in water scarcity places [18].

Using ROA allowed us to study every cost component of the combinations analyzed to better assess the uncertainty inherent in each component. Results of sensitivity and uncertainty analyses indicate that water transport to mine sites located far away from the coast contributes more to the overall uncertainty of the applied model, despite implementing tailings dewatering technologies, such as thickened tailings and filtered tailings, that reduce the water requirement of the plant. In the near future, seawater will be the primary water source for mining due to the scarcity of freshwater sources. Therefore, reducing the water requirement by maximizing the recycling and reuse of water inside the mine is essential.

Waste reduction is crucial for achieving a circular economy. Circular economy principles include reducing and, whenever possible, reusing waste generated by the industry. The potential utility of tailings is enormous since secondary sources are nowadays increasingly more often viewed as sources of minerals and metals for production due to the declining grades in primary ore bodies and the negative impact of mining on the environment. A geophysical study of the Aijala tailings ponds, a combination of Cu, Pb-Zb, and Ni-Cu tailings, showed that the concentration of elements did not change significantly between samples taken in 1982 and 2016 [93]. One may suppose that in arid regions, where acid drainage has a lower chance to occur, the composition of tailings may not change significantly over time. Therefore, the resource estimation of mine tailings performed now will not change in the future. Dewatering technologies will allow storing mine tailings so that they facilitate re-processing them to obtain certain metals or recycle tailings to use them as construction material or ceramics in the near future. Chilean mine tailings contain quantities of critical raw materials such as rare earth elements, whose recovery could be feasible in the future [94], ROA can also be applied in this case. Mine tailings also have the potential for the sequestration of CO_2 via ex-situ mineral carbonation, which could be a way to reduce CO2 emissions from power plants [95].

6. Conclusions

Continental water sources in areas of mine sites are usually scarce or semi-scarce; therefore, part of the water demand must be satisfied by desalinated or partially desalinated seawater. The transport of water from the coast to the mine sites is expensive, and its cost can be 3–4 times higher than that of water treatment. The mining industry has made efforts to reduce the freshwater requirement by recycling several water streams in the process; in copper mining, the average percentage of recycled water is close to 70%. However, the mining industry must reduce water consumption as mine plants are usually located in places suffering from water scarcity. Additionally, this sector in Chile must gradually switch to seawater to comply with the law.

The water reduction model was used to estimate the water requirement of different options and scenarios to reduce the water requirements applied to a case study that consists of a large mine company using the data of an actual mine site. Three dewatering technologies for tailings were considered: traditional tailing disposal, thickened tailings, and filtered tailings. To ensure water supply to the mine site, we examined using seawater treated in different ways and representing different quality. Seawater that is filtered or precipitated with lime is a low-quality resource. Higher quality water can be obtained when desalination is performed using reverse osmosis, but its cost is more than three times higher than that of other technologies; hence a combination of water seems more reasonable to fulfill the mine site requirements.

The novelty of this study consisted of assessing the economic output of various options to supply water and treat mine tailings by applying an approach based on real options. It allows the identification and transparent presentation of existing investments and management options. The method used gives the flexibility to choose between different water management options, as it includes combinations of different water treatments for the water supply to the mine. Investments in mining are characterized by great uncertainty due to the nature of markets and the complexity of new projects. A real options approach enables to assess the uncertainty of every cost component and evaluates each option to make a decision. Real options methods allow for the analysis of consequences of delaying or speeding up managerial decisions and could contribute to the reduction of financial and operational risks.

Uncertainty and sensitivity analyses were carried out for the results of the water reduction model to investigate the uncertainties about costs of the different options of dewatering technologies for tailings management and water supply. These analyses were implemented using Monte Carlo simulations as a real options approach to study the influence of the uncertainties of the inputs on the overall cost of the system.

The following main conclusions can be drawn:

- Results indicate that water transport costs are one of the biggest cost components; hence, efforts to reduce the water requirements are crucial. Since most water can be found in tailings, investing in dewatering technologies is vital to reduce the water requirement of the mine.
- Mine tailings disposed using the traditional disposal method contain approximately 70% of water. It makes the tailing facility the biggest water sink in the mine site. As water is a scarce resource, efforts to reduce water content in tailings are crucial in lowering the demand for water in the mine sites.
- The water-energy nexus is a major component of the total cost for different options of water supply management systems in mines, including water used by the tailing dewatering technologies. On the other hand, energy is needed to transport water, to desalinate or partially desalinate seawater, and in technologies used to recover water from the mine tailings.
- Switching from conventional tailings disposal to thickened tailings or filtered tailings solutions would reduce the water requirement of the mine site. Still, it would increase the amounts of energy needed because these technologies are energy-intensive. However, if the water requirement is reduced, as the results show, the cost of water treatment and transport is reduced, and less energy is required in these processes, which are also energy-intensive.
- The amount of seawater used in the mining industry has been rising, and it is expected that the seawater demand will increase, intensifying the demand for energy. Therefore, to reduce greenhouse gas emissions is mandatory to use low emitting sources of energy.

CRediT authorship contribution statement

Natalia Araya: Conceptualization, Methodology, Investigation, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Yendery Ramírez:** Conceptualization, Methodology, Investigation, Writing – original draft, Visualization. **Luis A. Cisternas:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Andrzej Kraslawski:** Conceptualization, Methodology, Writing – review & editing, 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.

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Appendix A

See Tables A1 and A2.

Appendix B

Sensitivity and uncertainty analysis figures

See Figs. B1-B4.

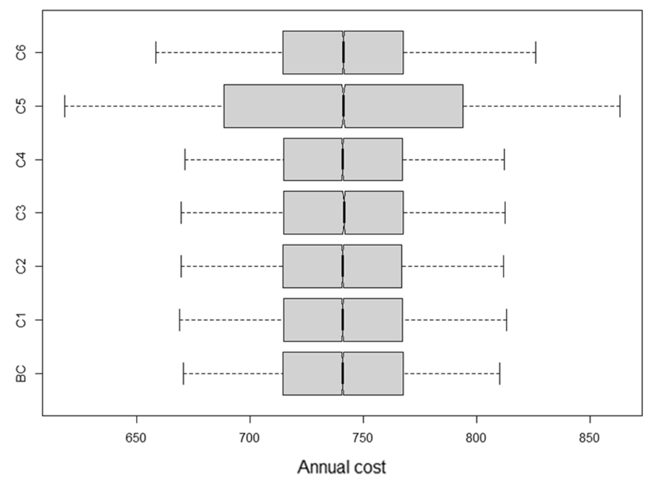

Fig. B1. Boxplot of the annual costs of implementing conventional tailing disposal technology and water supply of 50% of water quality 1 and 50% of water quality 2. BC represents the base case, C1 $CAPEX_d \pm 20\%$, C2 $OPEX_d \pm 20\%$, C3 $CAPEX_W$ filtered seawater ± 20%, C4 $OPEX_W$ filtered seawater ± 20%, C5 $COST_T \pm 20\%$, and C6 $COST_{RO} \pm 20\%$.

Table A1
Summary of costs of each dewatering technology and water treatment option.

	Dewatering technology cost		Dewatering technology water flow (m^3/d)	Water treatment and supply technology [†]			Water treatment and supply costs	Water treatment and supply costs (20 years)
Dewatering technology [§]	CAPEX $M	OPEX $M	Raw water requirement	1	2	3	$M/y	$M
1	669	369	473,288	x			577	11,540
1	669	369	473,288		x		608	12,162
1	669	369	473,288			x	802	16,031
2	678	396	406,436	x			495	9,910
2	678	396	406,436		x		522	10,444
2	678	396	406,436			x	688	13,767
3	1,326	1,290	313,046	x			382	7,633
3	1,326	1,290	313,046		x		402	8,044
3	1,326	1,290	313,046			x	530	10,604
3	1,326	1,290	313,046	50%		50%	456	9,116
3	1,326	1,290	313,046		50%	50%	467	9,320

[§] Dewatering technologies: 1 Conventional tailings disposal; 2 Thickened tailings; 3 Filtered tailings.
[†] Water treatment and supply: 1 Water partially desalinated with filtration and supply until the mine site; 2 Water partially desalinated using precipitation with lime and supply until the mine site; 3 Water desalinated with reverse osmosis and supply until the mine site.

Table A2
Chile's electric matrix, source: IEA Electricity Information 2020.

Energy source –2019	GWh	%	gCO_{2eq}	$gCO_{2\ min}$	$gCO_{2\ max}$
Coal	26,494	32.6	$2.1725 \times 10^{+13}$	$1.960 \times 10^{+13}$	$2.411 \times 10^{+13}$
Oil	3,033	3.7	$2.2232 \times 10^{+12}$	$1.6591 \times 10^{+12}$	$2.8359 \times 10^{+12}$
Natural gas	15,128	18.6	$7.4127 \times 10^{+12}$	$6.2025 \times 10^{+12}$	$9.8332 \times 10^{+12}$
Nuclear	0	0	0	0	0
Hydro	20,874	25.7	$5.0098 \times 10^{+11}$	$2.0874 \times 10^{+10}$	$4.5923 \times 10^{+13}$
Biofuels	4,351	5.4	$1.0007 \times 10^{+12}$	$5.6563 \times 10^{+11}$	$1.8274 \times 10^{+12}$
Wind	4,809	5.9	$5.2899 \times 10^{+10}$	$3.3663 \times 10^{+10}$	$2.693 \times 10^{+11}$
Geothermal	202	0.2	$7.6760 \times 10^{+9}$	$1.2120 \times 10^{+9}$	$1.5958 \times 10^{+10}$
PV	6,304	7.8	$3.0259 \times 10^{+11}$	$1.1347 \times 10^{+11}$	$1.1347 \times 10^{+12}$
Total	81,195	100	$3.3226 \times 10^{+13}$	$2.8202 \times 10^{+13}$	$8.5949 \times 10^{+13}$

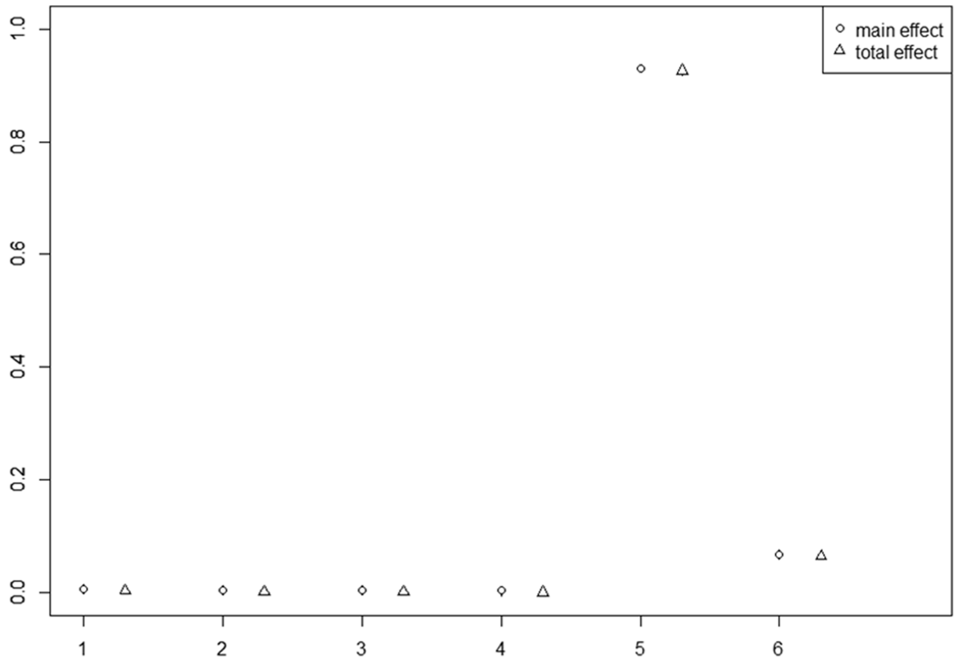

Fig. B2. Sobol' indices of the annual costs of implementing conventional tailing disposal and water supply of 50% of water quality 1 and 50% of water quality 2. Where 1 $CAPEX_d$ 2 $OPEX_d$,3 $CAPEX_W$ filtered seawater, 4 $OPEX_W$ filtered seawater, 5 $COST_T$, and 6 $COST_{RO}$.

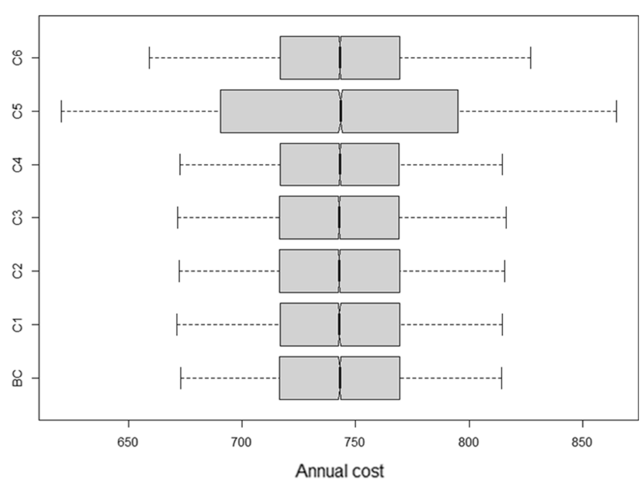

Fig. B3. Boxplot of the annual costs of implementing thickened tailings technology and water supply of 50% of water quality 1 and 50% of water quality 2. BC represents the base case, C1 $CAPEX_d$ ± 20%, C2 $OPEX_d$ ± 20%, C3 $CAPEX_W$ filtered seawater ± 20%, C4 $OPEX_W$ filtered seawater ± 20%, C5 $COST_T$ ± 20%, and C6 $COST_{RO}$ ± 20%.

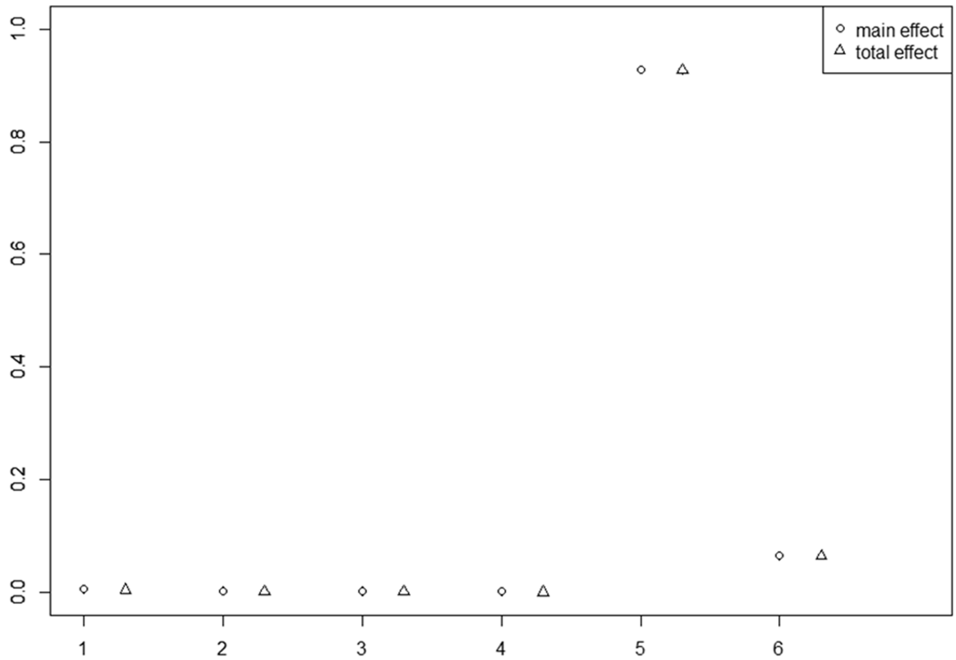

Fig. B4. Sobol' indices of the annual costs of implementing thickened tailings and water supply of 50% of water quality 1 and 50% of water quality 2. Where 1 $CAPEX_d$ 2 $OPEX_d$,3 $CAPEX_W$ filtered seawater, 4 $OPEX_W$ filtered seawater, 5 $COST_{T,}$ and 6 $COST_{RO.}$

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