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TOOLS FOR PLANNING REGIONAL WATER SUPPLIES IN MININGS REGIONS: VIABILITY OF MINING THROUGH A CENTRALIZED DESALINATION PLANT SCHEME IN CHILE'S REGION III

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ABSTRACT

Copper mining activity in Chile in recent years has been showing a trend towards changing the production matrix, increasing the extraction of low grade sulphide minerals. The processing of sulphides is carried out by flotation, the main process to produce copper concentrates which has more intensive water demands using significantly greater amounts of water than in the leaching process, which is the main process to produce copper cathodes in oxidized minerals.

At the same time, the droughts that predominate in the northern sector of Chile caused mainly by climate change and over-exploitation of watersheds, have led to the need to cover an interdisciplinary study and the participation of different stakeholders to achieve efficient water management in the Regions.

One of these is the Atacama Region, the second most affected in the country with water scarcity problems, negative current and projected balances of water supply and demands for the mining industry, agricultural and community sectors. Among the solutions, that governance has proposed is the development of sea desalination plants in order to reduce supply risks of the different demands.

This background outline above motivates this research to assess and compare two supply network systems for copper treatment plant operations in Atacama Region. The first system represents the current scenario of demand supplied with both continental and desalinated water, while the second system involves a proposed setup relying solely on desalinated water through a desalination plant scheme. The parameters for conducting this evaluation are derived from a model developed in the ArcGIS program, which integrates tools for optimized cost calculation of routes and distances based on the spatial location of supply and demand points.

The model yielded an Opex and Capex for the current system of 1,310.076 MUSD and 829.151 MUSD respectively. In contrast, for the proposed system with only the desalination plant as the water distributor, the Opex and Capex reached values of 1,950.076 MUSD and 1,115.976 million USD respectively.

RESUMEN

La actividad minera cuprífera en Chile en los últimos años muestra una tendencia hacia el cambio de matriz de producción, aumentando la extracción de minerales de sulfuros por sobre la extracción de minerales de óxidos. El procesamiento de sulfuros para la producción de concentrados de cobre se realiza mediante flotación, el cual tiene demandas de agua más intensivas, utilizando cantidades significativamente mayores que en el proceso de lixiviación.

Paralelamente las sequías que predominan en el sector norte de Chile, provocadas mayoritariamente por el cambio climático y la sobre explotación de cuencas, han originado la necesidad de abarcar un estudio interdisciplinario con la participación de distintas partes involucradas para lograr una gestión eficiente del agua en las regiones.

Una de estas es la región de Atacama, segunda más afectada del país, con balances negativos de oferta y demanda de agua, actuales y proyectadas, para el sector minero, agrícola y comunitario. Una de las soluciones que la gobernanza ha planteado es la construcción de plantas desalinizadoras de mar con el fin de reducir riesgos de suministro. Sin embargo, estos suministros se caracterizan por tener altos costos operacionales debido a la distancia y diferencia de altura que hay entre el reservorio de agua desalada y las operaciones.

Estos antecedentes motivan esta investigación a evaluar y comparar 2 sistemas de redes de suministro hacia operaciones con planta de tratamiento de cobre en la región de Atacama, siendo el primero la representación actual de demanda con suministro de agua continental y desalada, y el segundo un sistema propuesto de solo agua desalada como suministro a través de un esquema de planta desalinizadora. Los parámetros para realizar esta evaluación se obtienen mediante un modelo desarrollado en el programa ArcGIS que integra herramientas de cálculo optimizado de costes de rutas y distancias, según la ubicación espacial de los puntos de ofertas y demanda.

El modelo arrojó un OPEX y un CAPEX para el sistema actual de 1.310,076 MUSD y 829,151 MUSD respectivamente. En contraste, para el sistema propuesto, con solo la planta desalinizadora como distribuidora de agua, el OPEX Y el CAPEX alcanzaron valores de 1.950,076 MUSD y 1.115,976 MUSD respectivamente.

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NOMENCLATURE

MEASUREMENT UNITS:

- (ASL) Above Sea Level.
- (m) Meters.
- (Km) Kilometres.
- (m^3/s) Cubic Meters per Second.
- (L/s) Litres per Second.
- (US$/$m^3$) United States Dollar per Cubic Meter.
- (atm) Atmospheres.
- (KTMF) Thousands of pure metric tons.
- (TWh) Terawatt Hour.
- (TPD) Tons Per Day.

FINANCIAL:

- (USD) United States Dollar.
- (AUD) Australian Dollar.
- (CLP) Chilean Pesos.
- (Capex) Capital expenditure.
- (Opex) Operating expense.
- (GDP) Gross Domestic Product.

INSTITUTIONS:

- (DGA) General Directorate of Water.
- (SMI) Sustainable Minerals Institute.
- (COCHILCO) Chilean Copper Commission.
- (SEA) Environmental Assessment Service.
- (CSIRO) Commonwealth Scientific and Industrial Research Organisation.
- (UN) United Nations.
- (RCA) Environmental Qualification Resolution.

- (SONAMI) National Mining Society of Chile.
- (DEyPP) Department of Studies and Public Policies of Chile.
- (CRHIAM) Water Resources Centre for Agriculture and Mining.
- (ENAPAC) Pacific Energy and Water Company.

LIST OF EQUATIONS

1. INTRODUCTION

1.1 PROJECT BACKGROUND

The current uncertainty in the water supply, regarded to the growing in water demand in Chile, occurs because of four main reasons: the possible effects of climate change, overexploitation of some basins, increasingly demanding environmental regulations and strong social pressure [1]. Climate change has caused extreme events and an increase in the demand for water by productive activities, which results in the overexploitation of the resource in some territories.

One of these productive activities is mining. Its concessions and operations are in areas where water scarcity is a limiting factor for regional development. One such is Atacama Region. Thus, ensure enough water to meet the increase in the production and reduce water consumption and emissions are long-term strategic risks.

In 2017, the mining sector had a 13% increase in continental water consumption in Chile's Region III (Atacama Region) compared to 2015, reaching 1.35 m^3/s because of further mineral processing [2].

Atacama Region has highly production due to the large mining and agricultural activity, but its future is uncertain because it in the most arid desert of the world and water resources have been depleted [3].

This has caused new demanding environmental regulations. One of these is a bill that the government submitted to the Chilean Water Resources Commission that would require all mining companies to use seawater in their operations [4].

Accordingly, the solution that has been adopted by the mining industries in northern Chile, in recent years, is the incorporation of seawater into their supply water sources. These solutions are usually individual and have resulted in a fractional system of low-scale infrastructures that currently cover distances of up to 180 km and reach heights above 3,000 meters ASL. [1].

The cost of desalinated seawater for a mine site at 3,000 meters ASL has been estimated at 4.0 US$/$m^3$. However, the ultimate cost depends on parameter's variation that have generated uncertainty in Chilean mining viability through this system supply. Some of these uncertainties include: ore grades, freshwater supply, regulatory change and energy prices which allow a multiple-scenario approach to inform knowledge about risks and improve robustness of decisions [5].

This research proposes the identification of spatial analysis tools to reduce risks and provide opportunities in solution finding to sustainability issues (from business perspectives) of water supply for copper mining operations, reducing operational costs through process optimization [6].

1.2 OBJECTIVES

1.2.1 Research Question or General Objective

It is proposed to identify how a centralized desalination plant scheme could reduce risk and give opportunities of water distribution to mining operations in the Atacama Region. The Main research questions is:

- Are there significant cost differences between supplies from continental and seawater sources in copper mining operations within the Atacama Region?

1.2.2 Specific Objectives

- To identify key parameters influencing operational water demands in copper mining operations through an extensive review of relevant literature.
- To select potential customers capable of supplying the required water for their operations through a desalination plant scheme in the Atacama Region.
- To analyse water consumption patterns of prospects, examining extraction sources and quantities based on approved environmental studies.
- To utilize the ArcGIS program to pinpoint the locations of the continental and seawater sources, assess current water supply distribution using GIS techniques, and propose an

optimized distribution incorporating a desalination plant, evaluating costs through transport model equations.

1.3 SIGNIFICANCE AND RELEVANCE TO INDUSTRY

Desalination is already considered as the answer to the necessity for water in mining. It is expecting to focus in looking for efficiency alternatives of supply so that the consumption of continental water does not increase, and better yet, decrease.

At the same time under the premise that an indicator of cross-sectional performance to any process includes operating costs and the compliance of environmental regulations, the investment in optimization processes allows the reduction of operational costs but it is also a way of solution finding to sustainability issues. A relevant indicator in these terms is the change in the efficient use of water resources over time, since the efficiency of water at the national level is the sum of the efficiencies in the economic sectors weighted according to the quantity of water extracted by each sector respect of the total extractions. This achievement is established as one of the sustainable development aims in the 2030 agenda for Sustainable Development adapted by the UN.

Technically, one of the main disadvantages faced by desalination plants as an additional water source are the high investment and the high operating costs caused by the requirements of the pumping system and distribution over long distances. Further, the bill of article 111 of the law 18.248 of the mining code in Chile claims the obligation to incorporate the desalination of seawater into the production processes in mining companies whose water extraction exceeds 150 L/s.

Desalinated plants then, between existing and future water supply systems, appear as an alternative that would improve the use of infrastructure, eventual savings in investment cost, eventual savings in operational cost and less vulnerability in water supply providing a reliable source of water for an area where industry and communities are highly vulnerable to drought.

1.4 RESEARCH METHODOLOGY

Below are the stages that were developed throughout the research according to the established objectives.

The first stage involved identifying variables related to water demand and water distribution in the mining industry, such as economic aspects, production, ore grades, mineral processing and their projections. Additionally, it was necessary to gather general information about water aspects to define the parameters required for the supply analysis. This included understanding the state of water resources, the utilization of these resources in mining, recirculation practices, continental and seawater demand in the industry and their projections. Furthermore, a comprehensive review of desalination plants was conducted to examine their economic and general aspects, including operational restrictions and investment cost challenges. Subsequently, a desalination plant scheme was presented as the focal point for developing the proposed water distribution system. Additionally, the significance of Geographic Information System (GIS) techniques was described, along with their functionality and importance in achieving optimal water distribution. Lastly, studies on optimal transport supply were presented to facilitate the economic evaluation process.

The second stage involved representing and characterizing the case study, specifically focusing on the Atacama Region. This included describing the state of water resources, identifying the primary sources of water extraction, and providing an overview of the existing desalination plants as well as the selected desalination plant scheme.

The third stage encompassed the development and analysis of results. It involved collecting the necessary data identified in the general background stage, representing the spatial routes of the current water distribution system with continental and seawater sources as the supply, and mapping out the spatial routes of the proposed water distribution system with the desalination plant scheme as the supply through the GIS tools mentioned in the first stage. Subsequently, the developed model within the program was executed to obtain essential parameters for conducting the economic evaluation using transport model equations.

1.5 SCOPES

- Mining industry in the Atacama Region have different mineral processing, which have different water demands. This study focused on copper mining.

- As the highest water consume occurs during mineral processing and because of data availability, the flows considered in every calculation correspond to the quantities of this task. This means the 85% of the total informed consumption.

- Recognizing that water quality aspects are important and significant in the production, the parameters about biotic and abiotic materials that can affect it are not considered in this study.

- This study didn’t consider land use as another important parameter for developing optimal routes between the demand and supply points.

- While the technical considerations pertaining to the siting of the desalination plants hold significant environmental and economic importance, it will be deferred to future studies, as this thesis focuses on an already developed desalination plant scheme.

2 GENERAL BACKGROUND

A comprehensive review of parameter variations that have engendered uncertainty in the mining viability within Chile due to water demand, encompassing aspects such as ore grades, freshwater availability, governance regulatory alterations and energy costs has been expounded in Appendix 9.1.

The overarching facets pertaining to water in Chile, encompassing the state of resources, consumption, availability, and prevailing drought conditions are delineated in Appendix 9.2.

2.1 WATER RESOURCES IN MINING

It is possible to identify three major sources of water origin: inland water, sea water and recirculated water from mining process [7].

Inland Water: permanent freshwater bodies that it finds on or below the earth's surface away from coast areas. Some correspond to rivers, lakes, reserves and wetlands [7].

Sea Water: large volumes of water on earth, which have the largest liquid part of the planet that surrounds all continents and islands. It is characterized by its high salt content and temperatures [7].

Recirculated Water: Corresponds to all the water flows used or worked on in some tasks that can be used again in the same or another process within the operational model. In mining, for example, from the lagoon of the tailing's dams [7].

There are also 2 water sources that are significantly minor for mining industry:

Water acquired from third parties: Corresponds to water flows obtained through contracts with third parties. The purchase is from the water directly and not from the rights. It can be obtained from municipal, sanitary waters, among other suppliers [2].

"Miner's water": Water found in a mining operation such as pit, tunnel, shaft, etc. and that is necessary to extract to allow mining to advance [8].

2.1.1 Water Consumption and Supply Sources

Regarded to the total water consumption in 2019 by the mining industry to obtain 5,784.4 thousand tons of pure copper produced, it is observed that water of continental origin reached 12.45 m^3/s, the sea water 4.06 m^3/s and the recirculated water 53.32 m^3/s, which in total adds up to 69.83 m^3/s of water [7]. Figure 1 illustrate the percentages of the respective consumed amounts. The blue colour signifies the consumption of continental waters (18%), the orange colour corresponds to seawater (6%), and the grey colour represents recirculated waters (76%).

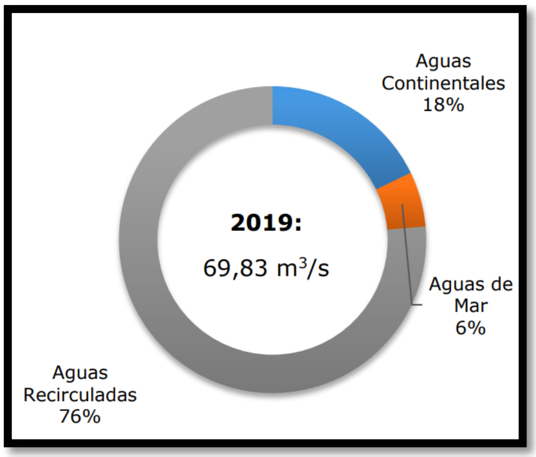


Figure 1: Distribution of total water consumption in the copper mining industry in 2019 (%) [7]

Figure 2 illustrates total water consumption in the copper industry from the three main sources of water origin. It is observed that the continental water reached 13.36 m^3/s (22%), seawater had an increase and reached 3.99 m^3/s (6%), and the recirculated water reached 44.87 m^3/s (72%), which in total adds an amount of 62.22 m^3/s of required water for copper mining and copper mineral processing. Analysing the trend of global consumption, it can be notice that the continental water remains stable in recent years while in seawater an upward trend is observed. The recirculated water maintains variations year to year [7].

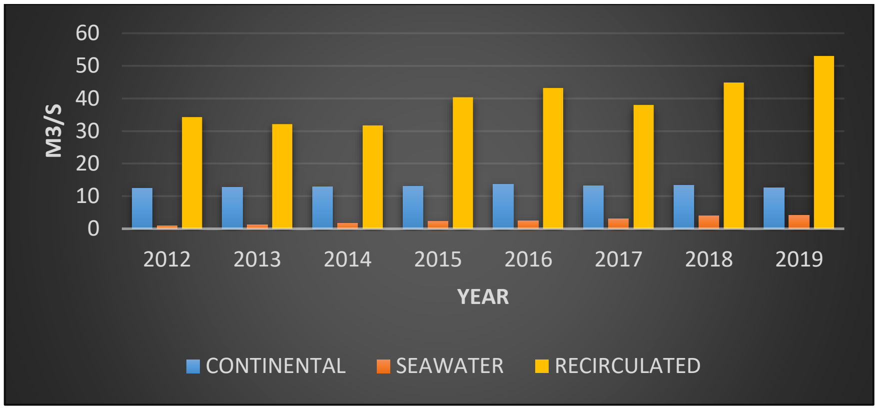


Figure 2: Total water consumption in the copper mining industry 2012 - 2018 (m3/s) [7]

It is important to mention that COCHILCO used another methodology to collect their data, corresponding to data processing, classification and analysis of the information contained in the Mining Survey of Production, Water and Energy (EMPAE), provided by mining companies where the number of these consulted corresponds to 98% of the national copper production of 2019. According to this study, analysing the consumption of 2019 the water of continental origin reached 12.45 m^3/s.

Figure 3 shows a water balance including water sources, users, and recycled water in the copper sector in Chile. Inland water consumption corresponds to 13.1 m^3/s (groundwater, surface waters and Water acquired by third parts), while desalinated seawater corresponds to 1 m^3/s. As it can be noticing the concentration process uses 73% of the total freshwater entrant from the different sources.

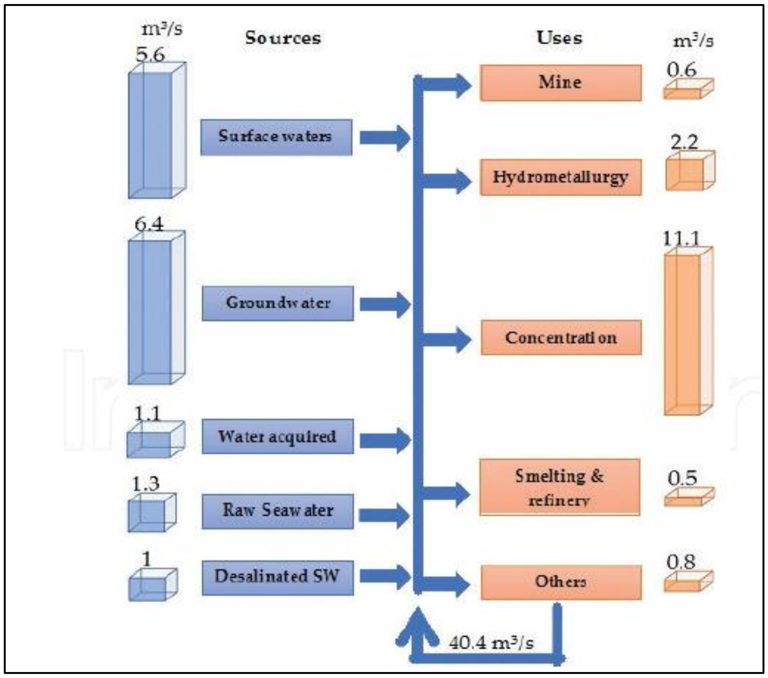


Figure 3: Sources and uses of water in the copper industry in Chile [9]

It is important to highlight that the water used for mine services is not reused or returned to the processing system [9].

In Chile, the extraction water rights can be surface or underground. Surface rights are classified as consumptive and non – consumptive and underground rights as definitive and provisional. Consumptive rights allow the holder to fully consume the water in any activity, therefore due to the characteristics of the process, there are volumetric losses of water. Conversely, non – consumptive rights allow to use the water without consuming it, forcing it to be restored in the manner determined by the act of acquisition or right's constitution. Therefore, there is no loss of water since the quantity that enters is the same or approximately the same as comes out in the process [10] [11].

The mining sector has consumptive use. Until 2017 the major source of water extraction is from underground origin, constituting 41% of the total water extracted. Otherwise, surface water origin reached 33%, marine origin 19% and those acquired by third parties represented 7% [2].

2.1.2 Water Consumption in Copper Mining

In general, five distinct tasks are identified in the copper mineral industry where water consumption occurs: The mine task, the concentrator plant task, the hydrometallurgy plant task, smelting and refinery task and the services task [2]. Figure 4 illustrates the water utilization in these mining processes.

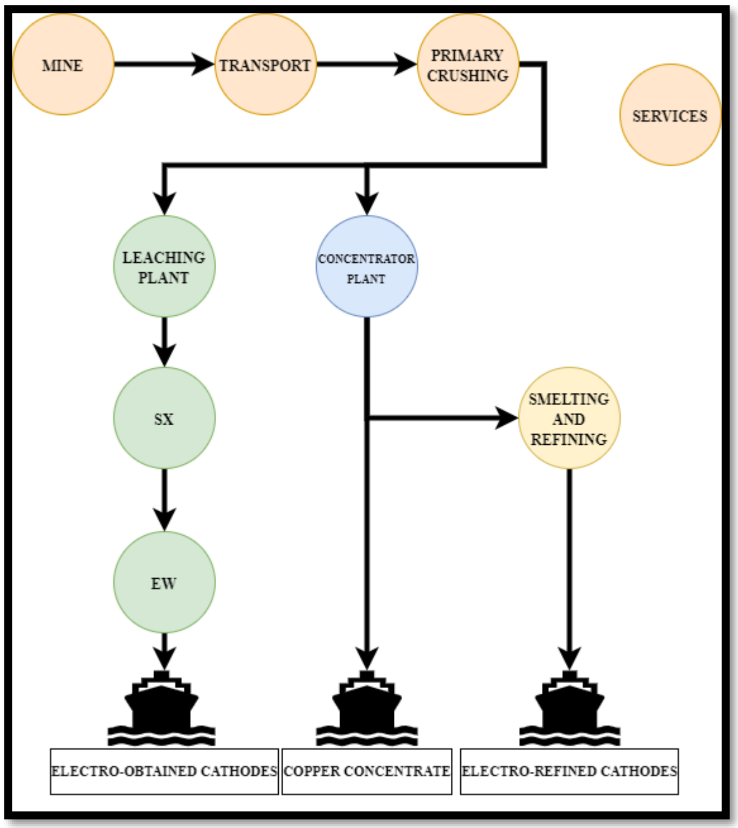


Figure 4: Uses of water in the different tasks of copper processing [2]

In the case of the mine task, it encompasses both open pit and underground mining operations, including material transport to the primary crushing area and associated services. Water usage in this domain primarily revolves around dust suppression on roads extraction and pumping from underground works [2].

The services task comprises activities with relatively low volumes of water consumption compared to the overall consumption in a mining operation. The primary uses of water in this area include drinking, cooking, washing, irrigation, campsite maintenance and other minor purposes [2].

The concentrator plant task involves sulphide mineral processing, which accounts for the highest water consumption in terms of total volumes. This phase encompasses mineral comminution (milling), followed by flotation, classification, and thickening processes. Depending on the proximity between the concentrator and the filtering and storage facilities, wastewater may or may not be recycled back into the process. A significant portion of the water used in flotation becomes part of the tailings, which are then directed to the thickening stage to recover a portion of the water it contains [2].

The hydrometallurgy plant task encompasses heap leaching processes, solvent extraction (SX) and electro winning (EW), for cathode production. In this process, the primary water consumption occurs during the application of acid solution consisting of water and sulfuric acid onto the surface of the ore piles. This acid solution facilitates the infiltration of the piles, dissolving the copper present in the oxidized minerals [2].

The smelting and refining process encompasses subjecting the desiccated concentrate to a pyro metallurgical procedure, yielding voluminous plates with an anode-like structure. These plates are subsequently either directly marketed or subjected to additional refining, which occurs within electrolytic cells immersed in a solution of sulfuric acid. Here, an electric current is applied to induce dissolution of the copper anode and deposition onto the primary cathode, thereby attaining cathodes of exceptional purity [2].

As previously stated, the concentration process of sulphide minerals exhibits the highest water consumption, accounting for 64% of the total inland water utilized in copper mining operations. Following closely, the hydrometallurgical process employed to extract cathodes from oxidized minerals represents the second highest water consumption, amounting to 14% of the overall inland water usage [7].

It is evident that the concentration of sulphide minerals represents the foremost water-intensive process, as illustrated in Figure 5, with water consumption for concentration surpassing that of hydrometallurgy by more than 4.5 times in 2019. These Figures clearly demonstrate the substantial water demand associated with the concentration process for sulphide minerals [7].

In the third position, the category labeled as 'others' or 'various services' accounted for 11% of the total water usage in 2019. This category encompasses water utilized in campsites, irrigation purposes, and other processes characterized by comparatively lower water consumption levels [7].

Mine services accounted for 5% of the total continental water demand, while the smelter and refinery operations represented 3% of the inland water consumption [7].

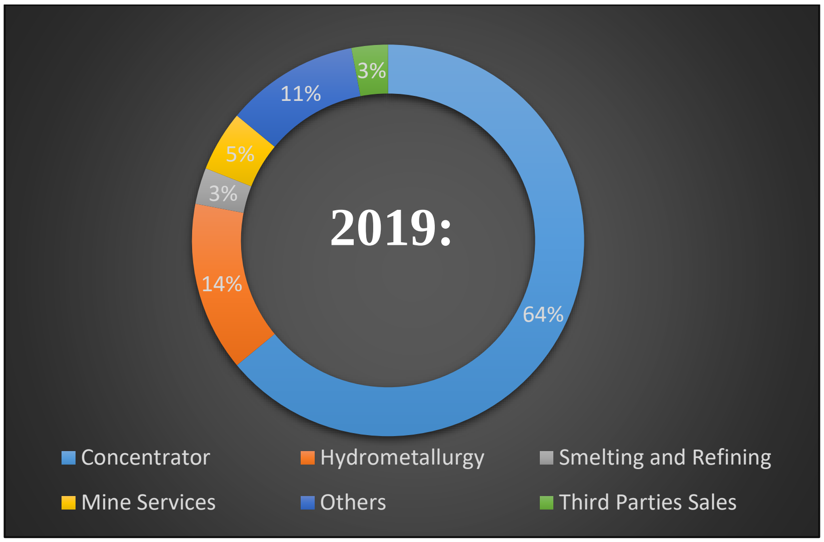


Figure 5: Percentage distribution of water according to mining process 2019 [7]

2.1.3 Seawater Consumption in Copper Mining

The use of seawater in mining has been addressed in numerous studies and publications [12]. It is not new and there are numerous examples of its successful application in the copper, zinc, uranium and iodine mineral processing as is shown in Appendix 9.3.

Specifically, the seawater demand for mining requires energy for its desalination and transportation from the coast to the mine operation, which can be at high altitude. This means that the seawater use generates energy demand, another scarce resource [13].

In regions with significant mining activity, the consumption of electric power varies between 21% and 38%. Furthermore, the utilization of this resource has experienced a substantial increase of 104% in recent years, primarily driven by the processing and desalination of seawater [1]. At a regional level, the Antofagasta Region emerges as the primary consumer of seawater, leading to a consistent reduction in its share of national freshwater consumption by mining operations from 36% in 2016 to 10% in 2030 [9].

Therefore, an action that could be expected from the mining industry is the use of non – desalinated seawater. However, this requires that the process is adapted to new conditions. These new conditions include the possible interactions of the elements dissolved in seawater with the minerals, chemical agents, and materials of the equipment used. Then new technologies are needed to adapt traditional processes to non – desalinated seawater. Also, the cations that are contained in seawater as sodium, magnesium, potassium, and calcium and the anions as chlorine, sulphate, and bicarbonate generates changes that can affect their use in mining processes because its salinity influences the physicochemical properties of water like density and viscosity of it generating a less efficient process. Another alternative is the use of partially desalinated seawater, with the purpose of removing only the elements that cause problems in the process and thus reduce costs and environmental effects. This partial desalination it has not been applied in mining, at least in Chile [12].

Even Though the partial desalination of seawater has been the focus of several studies, there is no obvious application of this process for mining purposes in Chile. In the international literature, several methods for the partial desalination of seawater have been widely proposed. In detail, Castro, Jeldres et al. and Cruz et al. proved for the flotation of Cu-Mo sulphide ores the effectiveness of seawater chemically pre-treated with reagents such as CaO, Na_2CO_3, NaOH and CO_2 with the aim to remove Ca^{2+} and Mg^{2+} ions. High copper and molybdenum recoveries were achieved under high alkaline conditions when the seawater's hardness was reduced [14] .

The use of seawater in mining also challenges geographical aspects as it can see in Figure 6, with a typical situation of a mining company in northern Chile. These ore deposits are located at high altitude and in a hyper-arid Region. The seawater must first be collected from the sea (I), pre-treated, desalinated (D), transported including a pumping system (P), and used in the mining operation (M).

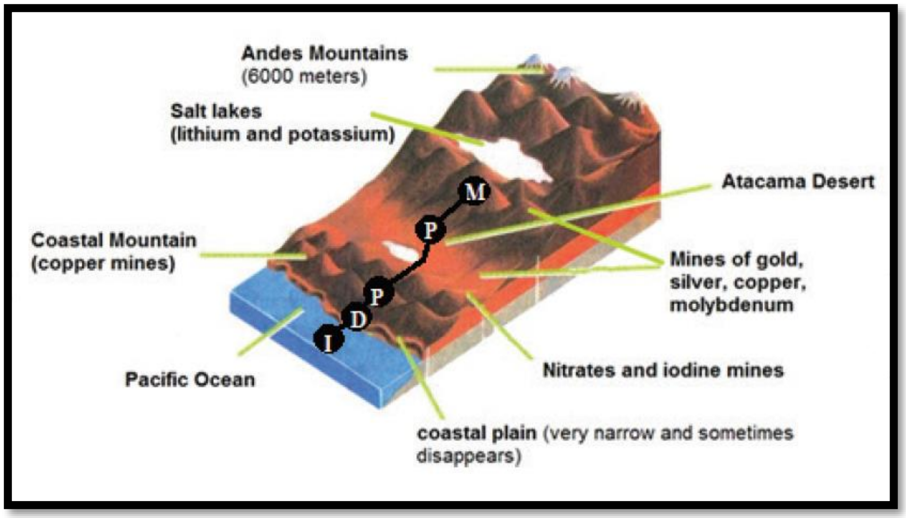


Figure 6: Geographical scheme of the Antofagasta Region, mining activities, and seawater catchment system (I: Intake, D: Desalination Plant, P: Pumping System, M: Mine) [12]

Figure 7 illustrates the evolution of seawater consumption in copper mining from 2010 to 2019, with a growth rate annual average of the order of 43% [7]. It is possible to observe that until 2019, seawater usage in copper mining amounted to 4.06 m^3/s, constituting 25% of the total water utilized in mining operations based on the supply source. Out of this total, 1.84 m^3/s corresponded to direct usage of seawater in processes characterized by high salt content, while 2.22 m^3/s was sourced from previously desalinated seawater. Compared to 2018, the utilization of seawater witnessed a 1.7% increase [7] .

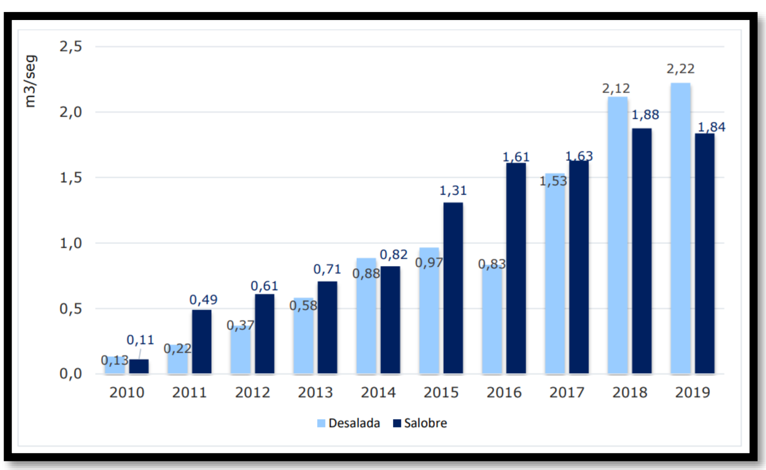


Figure 7: Use of seawater in copper mining 2010 - 2019 (m3/s) [7]

In relation to energy consumption, electrical energy represented 9% of the operational costs of big mining companies in 2016. Moreover, electricity consumption for the pumping and desalination of seawater increased from 369 TWh in 2012 to 753 TWh [15] .

The increase in concentration operations has made it possible to project that the electricity consumption of desalination plants will increase 3.2 times its consumption in the period 2016 – 2027; from 0.86 TWh in 2016 to 2.7 TWh in 2027 [15].

Mining companies in Chile pay an average of \$5 per m^3 for desalinated seawater, whereas the equivalent volume of freshwater costs \$1.6 (*Nueva Minería, 2013*). Consequently, due to the high energy expenses involved, desalination costs in Chile are twice as expensive as in the United States, where it amounts to only \$2.3 per m^3. Additionally, the energy cost in Peru is 6 cents per kilowatt-hour, whereas in Chile, it stands at 16 cents. This discrepancy explains why operational costs are lower in Peru, despite both countries sharing similar capital costs. Figure 8 illustrates the comparative operational and capital costs across various mining countries. Notably, while the total cost of desalination remains relatively consistent, differences in transportation costs are primarily attributed to the varying altitudes where the reservoirs are situated [16]. In this Figure, the x-axis represents the altitude (above sea level) at which mining operations are in different countries while the y-axis represents the operational and capital costs of desalination (gray color), capital costs of transportation (green color), and operational costs of transportation (blue color).

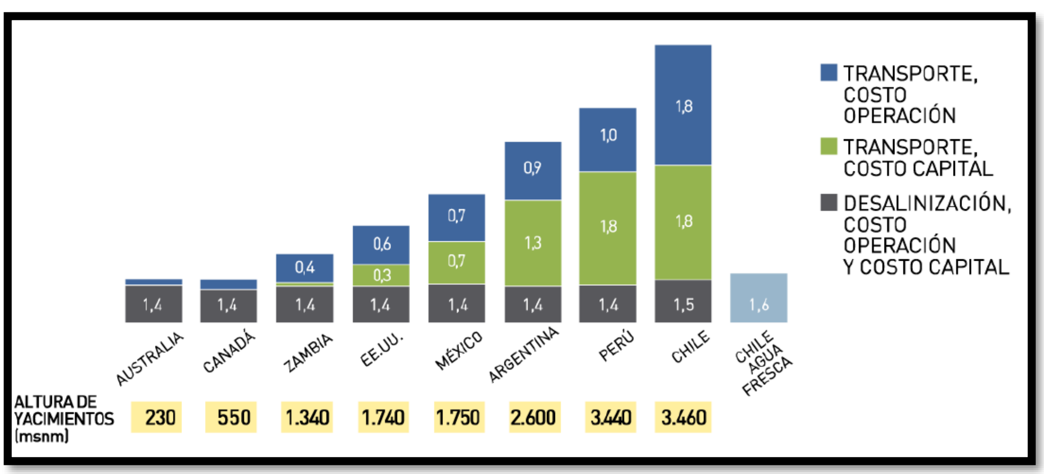


Figure 8: CAPEX and OPEX of desalinated seawater in some mining countries [16]

2.1.4 Continental Water and Seawater Demand Projections

The preceding chapters have demonstrated that mining activity is primarily concentrated from the Metropolitana Region and extends northward, particularly in the region facing severe water scarcity. It is projected that the demand for water in this area will increase by approximately 200% over the next 25 years [9].

The shift in Chile's copper production matrix, focusing on the utilization of sulphide minerals, will have a significant impact on water consumption within the industry. This is because the flotation process, which is more water-intensive, is employed. Additionally, the decline in ore grades will necessitate a larger volume of water to extract one metric ton of pure copper. As a result, a greater quantity of mineral will need to be processed, leading to a heightened demand for water, primarily met through the utilization of seawater [17].

Figure 9 illustrates the causes and consequences of the decreasing availability of fresh water, the decline in ore grades and the emergence of new mining operations. In Chile, desalinated seawater faces significant challenges, including high operational costs, brine emissions, and negative public perception due to its energy consumption [18].

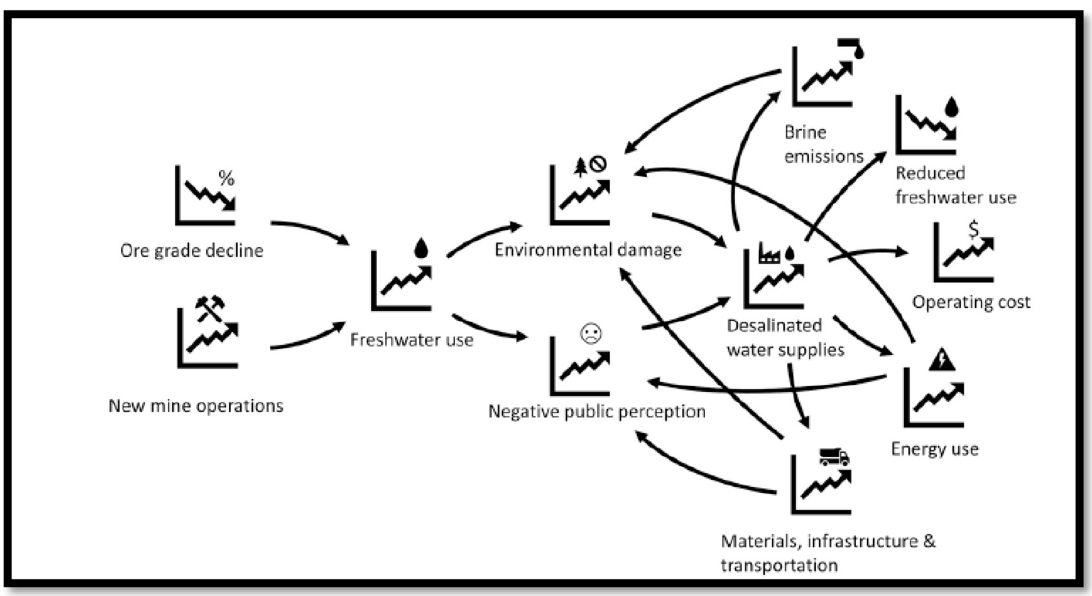


Figure 9: A cause and effect diagram for freshwater and seawater use in the Chilean mining industry [18]

Regarding water demand projections in copper mining, it is anticipated that by 2030 freshwater consumption will decrease at an annual rate of 1.5% compared to the estimated value in 2016 while seawater consumption is expected to increase at an annual rate of 6.6% [9].

A Monte Carlo simulation was conducted to project the demand for continental and seawater in the copper mining industry. The results indicate that the estimated total consumption of continental water in 2029 will reach 14.53 m^3/s, representing a 12% increase compared to the expected consumption in 2018. Seawater, on the other hand, is projected to account for 43% of the total water demand reaching 10.82 m^3/s by 2029, a significant 230% increase compared to the expected value in 2018 [17].

Figure 10 showcases the projected growth in overall water utilization and the anticipated contribution of seawater to meet the total demand. These estimations are derived by considering copper production forecasts, the water consumption per unit for mining operations and companies, and the probability of occurrence for the given forecasts [18].

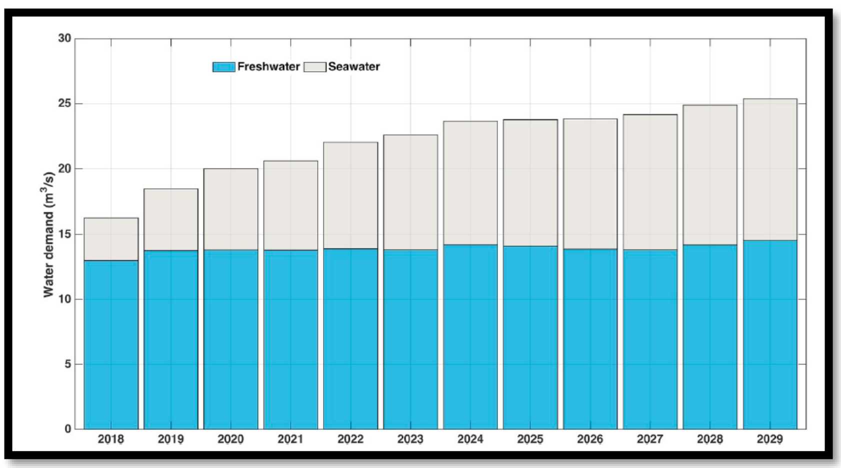


Figure 10: Project demand (2018 - 2029) for freshwater and seawater for the Chilean mining industry [18]

2.1.5 Recirculation Water in Copper Mining

Mining operations, particularly in copper mining, heavily rely on a steady and reliable water supply. The demand for water in the flotation process, the dominant activity in Chile's mining industry, is substantial, accounting for around 70% of the water content required (*Ramos et al., 2013*). As a result, the copper mining sector is increasingly focusing on water recycling efforts to optimize resource usage and reduce water consumption. This chapter discusses the significance of water recirculation in copper mining, the recovery and reuse of water in various processes, and the challenges faced in minimizing water losses.

The efficient management of water resources is of paramount importance in copper mining. The percentage of water recirculation serves as a key indicator for sustainable water use in mining processes. Surplus water from mineral processing can be reutilized within the same process or allocated to different tasks or processes based on their quality and quantity requirements. This approach not only optimizes resource utilization but also reduces the volume of water requiring treatment prior to discharge [2].

In copper sulphide processing, approximately 60% of the water used is recovered through thickeners, with most of the remaining water retained in tailings, eventually lost through evaporation and long-term entrainment (*Gunson et al., 2012*). Smaller amounts of water are utilized for various purposes such as road dust suppression, evaporation from holding tanks, and domestic tasks (*Concha, 2014*). After copper concentrate separation into concentrate and tailings, dewatering of these streams is commonly achieved through gravity thickening and filtration. The water reclaimed from the thickener is recycled for process use, while the sediment is directed to the tailings facility where further settling occurs, and the supernatant water is recovered and recycled [18].

In hydrometallurgy processes, water losses result from evaporation in leaching heaps and ponds, as well as from washing the organic phase and discarding of solutions [2]. To mitigate such losses, mining companies adopt various technologies, including dewatering of tailings, pre-sorting of ore, use of dust binders for road dust suppression, and covering ponds and tanks to reduce evaporation [9].

The copper mining industry had made significant progress in increasing water reuse and recycling rates. From 2012 to 2017, the industry reduced its process water consumption from 0.61 m^3/ton of ore to 0.45 m^3/ton (*Montes, 2016*). This improvement led to an average recycling rate increase from 68% to 75.7%, with some operations achieving recycling rates as high as 87%. Despite these improvements, significant volumes of water are still lost daily due to evaporation, entrainment, and filtration in tailing facilities [18].

Figure 11 illustrates the percentage of seawater and inland water, recycled and consumed, in the two major mining regions in Chile (Antofagasta and Atacama). Remarkably, at national level 73% of the water used corresponds to recirculated water within the process, while the remaining 23%

comprises inland waters, including surface waters, groundwater and water obtained from third parties [12].

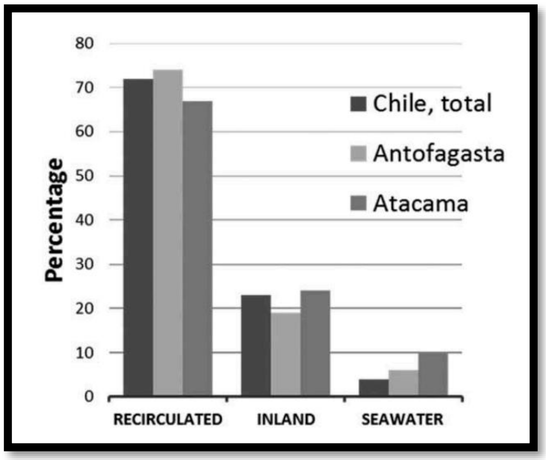


Figure 11: Percentage of type of water consumed in Chile, Antofagasta region, and Atacama Region [12]

Recirculation in operations: This percentage is calculated as the total recirculated water that enters the operation divided by the total flow of water that enters regardless of its source of origin [7].

Equation 1

$$total\ recirculation = \frac{total\ recirculated\ water\ in\ the\ operation}{total\ flow\ of\ water\ entering\ the\ operation}\ \% \qquad \ldots(1)$$

Figure 12 provides a view of water recirculation at the national level for mining operations in 2019. The recirculation rate, calculated based on the production of each region, reached 76.4% during that year. This represents a notable increase of 5% compared to the recirculation rate in 2018. The significant improvement from the previous year's data suggests that mining companies have been actively implementing management strategies to enhance the amount of water recirculated from their processes [7].

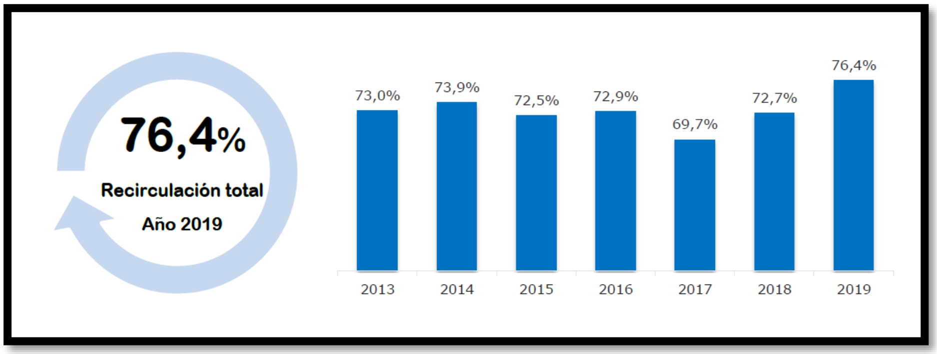


Figure 12: Trend in recirculation rate in copper mining operations 2013-2019 [7]

Recirculation in concentrator plant: This indicator is calculated in equation 2 by dividing the total amount of recirculated water by the overall water used in the process, including both recirculation and the net flow of water reserves [7].

Equation 2

$$concentrator\ recirculation = \frac{total\ recirculated\ water\ in\ concentration\ process}{total\ flow\ of\ water\ used\ in\ the\ concentrator\ plant}\ \% \qquad \ldots(2)$$

Figure 13 provides an overview of the recirculation rate in concentrator plants at the national level. In 2019, the recirculation rate reached 74.8%, indicating a noteworthy increase of 0.6% compared to the previous year (2018). This upward trend highlights the commitment and strategic efforts undertaken by mining companies to further promote the utilization of recirculated water from concentrator plants [7].

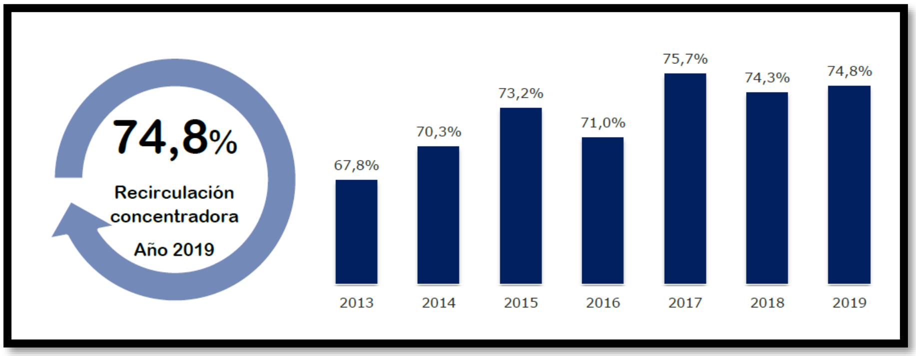


Figure 13: Trend in recirculation rate in the concentrator 2013 – 2019 [7]

Figure 14 depicts the recirculation rate in relation to the production of fine copper, categorized based on the type of processing employed, namely hydrometallurgical and concentration processes. The bubble sizes in the graph represent the production of fine copper, the x-axis denotes the percentage of recirculated water for each process, and the y-axis represents the quantity of mineral processed. The blue-coloured bubbles signify mineral processed through concentration, while the green ones represent minerals processed through hydrometallurgy [2].

An observation from the figure reveals that the hydrometallurgy process exhibits lower rates of water recirculation in comparison to the concentration process. Furthermore, the volume of water used in hydrometallurgy is notably lower, making it technically challenging to achieve high recovery rates through recirculation alone [2] .

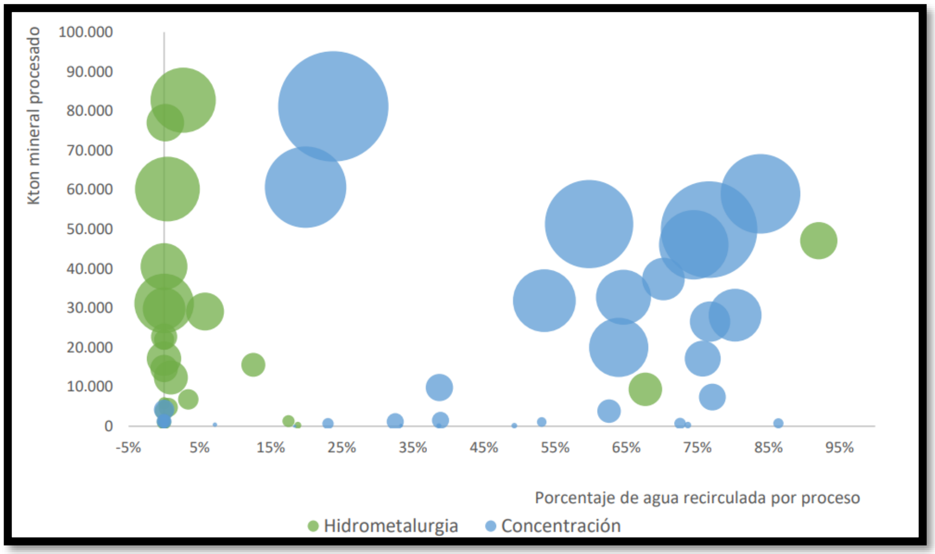


Figure 14: Percentage of recirculation by process according to amount of processing 2017 [2]

2.2 DESALINATION PLANTS FOR MINING

It is evident that the current water resources are insufficient to meet the total water demand required by the mining industry, not only in the present but also in the coming years. Consequently, decisions have been made to utilize seawater sourced from the Chilean coasts, with most of such facilities projected and situated in the northern regions of Chile at varying altitudes ASL [19].

However, the environmental technical considerations regarding the placement of these plants have not been fully considered in the environmental impact assessments submitted to the environmental evaluation service in Chile [20].

To delve further into desalination plants in the country it is necessary to comprehend the general operation of these facilities and to elucidate the projections associated with them.

Most of mining operations in Chile that are currently using seawater employ desalinate through reverse osmosis, producing good metallurgical process water. This is a filtration process, in which the seawater is forced to pass through a membrane, a filter medium with extremely small porosity positioned between two vessels, a process that requires a very high pressure of 60 – 70 atm (*Mehdizadeh, 2006*). All salts in the seawater are retained on one side of the membranes while pure water flows through the membrane to the second vessel. The transportation of the process water requires that the treatment plant be connected to mines operations through a pipe network and that sufficient energy to transport the water to the required elevation be supplied. Once developed, mine sites have a high quality, reliable water supply. Nevertheless, the high capital and operating costs of desalination technology tend to limit investment in this technological solution to large – scale operations that can afford the investment [18].

The existing desalination plants are all located in the north, between latitudes 18°S and 30°S. Figure 15 displays eighteen plants currently operating along the coastline, many of which are close to towns and cities, but most tend to be relatively far from mines [18].

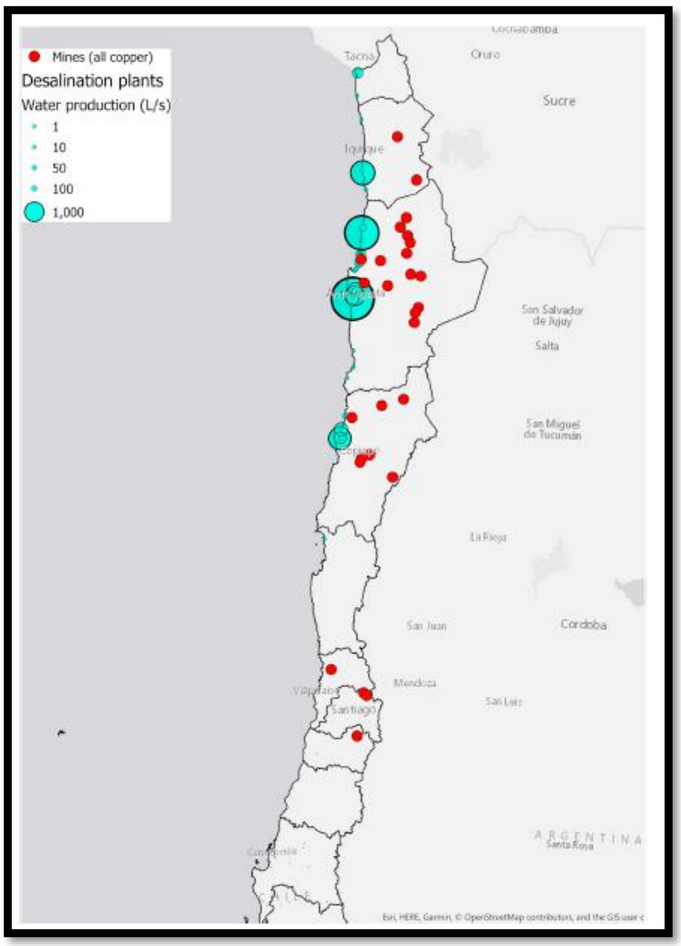


Figure 15: Operational desalination plants and copper mining operations in Chile [18]

2.3 THE ECONOMICS OF CONTINENTAL AND SEAWATER SUPPLY

Investment in water for mining projects and the unit costs of process water production from seawater and continental water are important issues that affect the decision to use the appropriate process of supply [18].

Different cost of water supply in the mining Region of northern Chile are shown in the next tables. Table 1 presents the different costs based in distances to 150 km from the coast and considering an altitude of 3,000 meters ASL. Table 2 displays the costs in desert areas and Table 3 depicted the costs in non-desert areas (*Concha*, *Vergara 2007*).

Table 1: Water type costs to 150 km from the coast and 3,000 m.a.s.l.

Water Type	**US/m^3**
Fresh Water	0.40
Raw Seawater	2.98
Pre-treated Seawater	2.98
Recirculated Water	0.20
Desalinated Seawater	3.64

Table 2: Water type cost in desert areas

Water Type	**US/m^3**
Fresh Water	0.35
Recirculated Water	0.18

Table 3: Water type cost in non-desert areas

Water Type	**US/m^3**
Fresh Water	0.12
Desalinated Water	1.0 – 5.0

Regarded seawater, the development of economic models for a typical large-scale copper mine in Chile, the calculation of water production cost for the use of raw, pre-treated and desalinated seawater for different levels elevations [18], are displayed in Figures 16, 17 and 18.

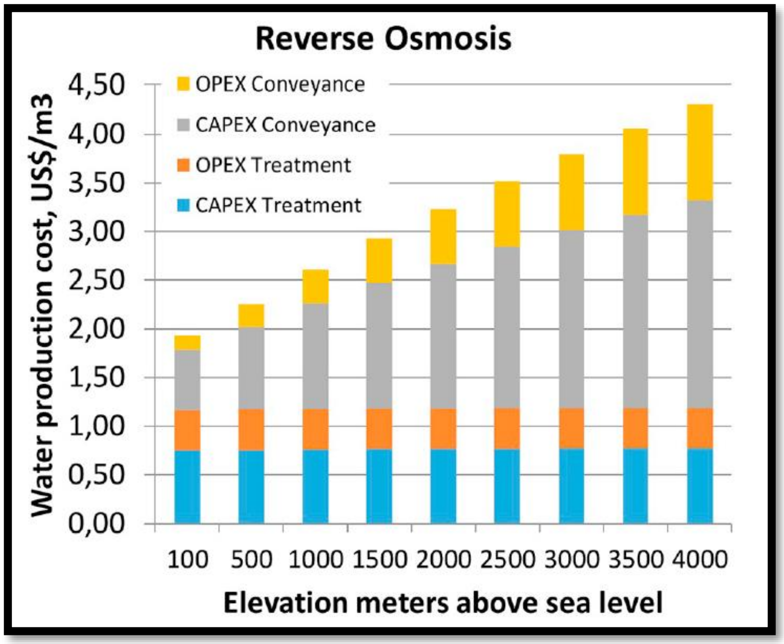


Figure 16: Water production cost of desalinated treatment [18]

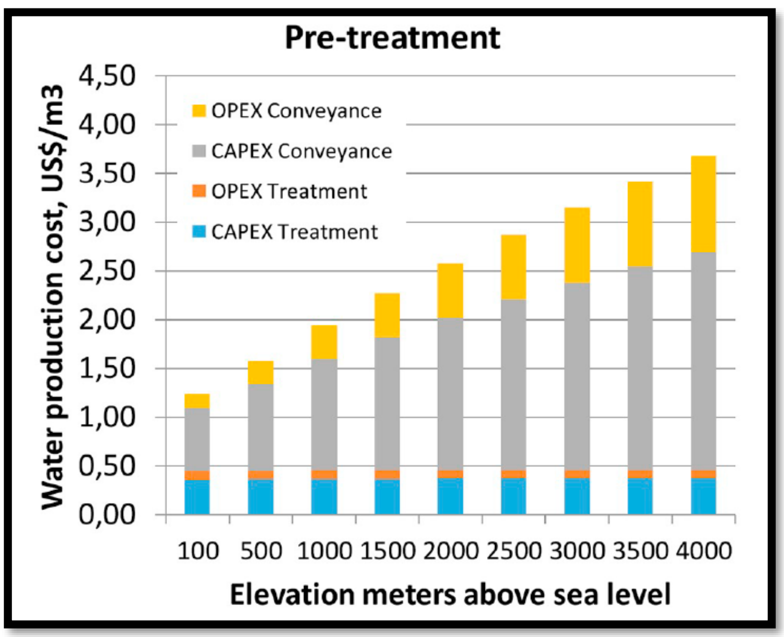


Figure 17: Water production cost of pre-treated seawater [18]

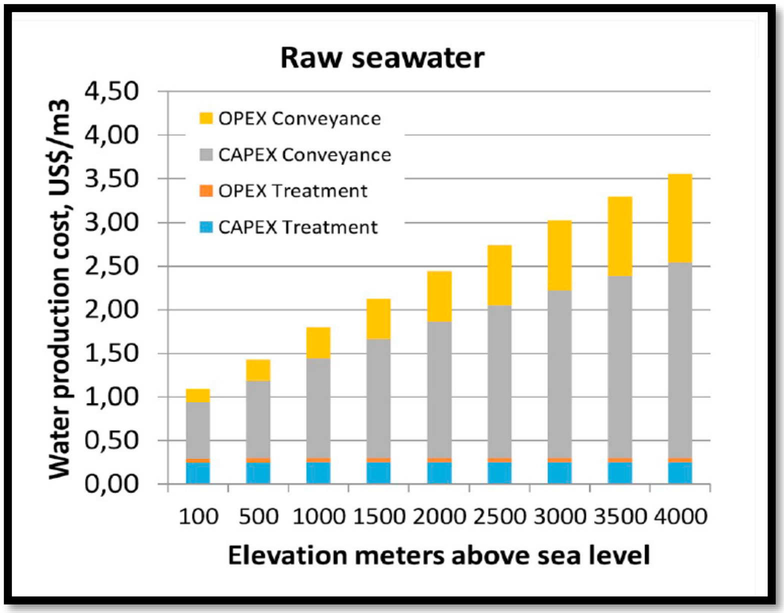


Figure 18: Water production cost of raw seawater [18]

It can be observed that the production costs of the processing methods vary and that the differences between costs are most pronounced at low elevations. At high elevations, the cost of water conveyance greatly outweighs the costs associated with treatment. This is a reason why mines operating at low elevations, which in Chile are often smaller-scale mines, often opt to use of raw seawater and those at high elevations, generally the larger-scale mines, invest in desalination systems [18].

Moreover, it is possible to determine that in any of the 3 situations, the highest cost is the water transport to the mines and that the difference in total cost between the production of pre-treated water and raw water at high altitudes is minimal. This could be the reason of why the introduction of pre-treated water production has not been occurred in Chile yet.

Fig. 19 illustrates the variation of total water costs from different sea water reverse osmosis plants over time. Even with similar plant capacities total costs have fallen below 0.50 US$/m^3 for a large scale at a specific location and conditions while in other operations the costs reached more than 1 US$/m^3 [19].

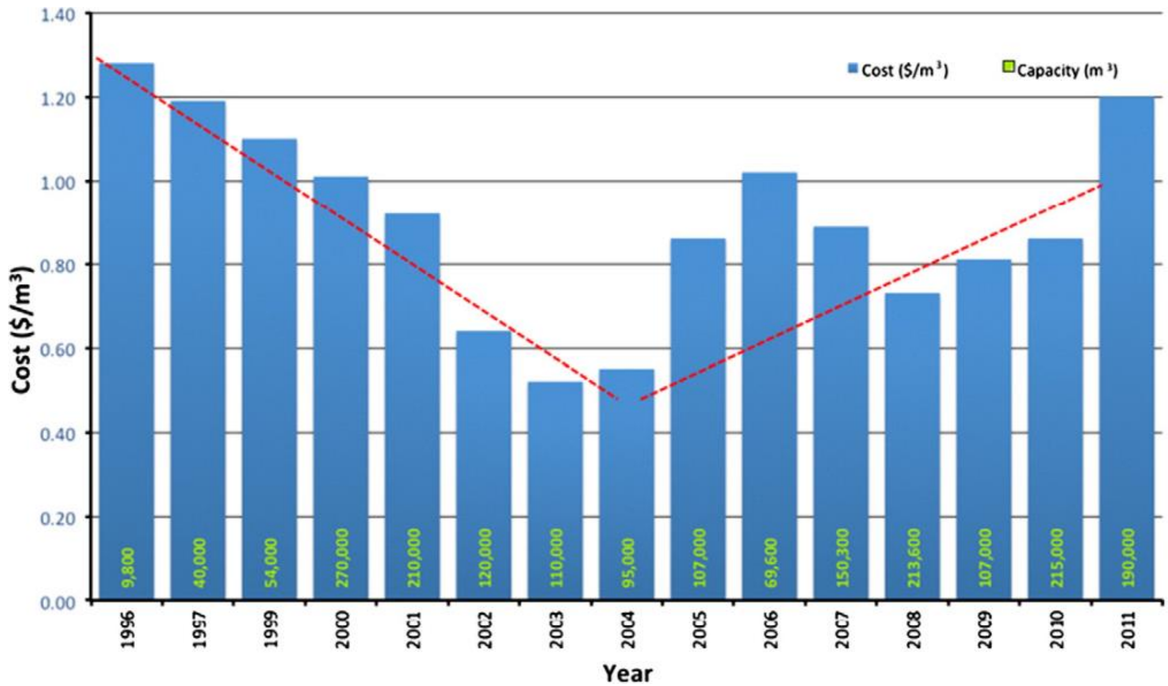


Figure 19: Total water cost of different SWRO plants in operation and contracted [19]
Average capacity: m^3/d
Average cost: US$/$m^3$

2.4 Spatial Analysis ArcGIS Tools

Cost and distance planning for the development of optimal routes with the use of Geographic Information Systems (GIS), allows to face a restrictive aspect of the territory by tracing the optimal route between two points to incur the least cost of effort during a displacement [21].

In fact, the water diversion route planning is a typical least cost path solution [22].

GIS least cost path analysis is a method to find a least-cost path from the source and destination points according to the cost per raster unit and it is based on Dijkstra's algorithm, which is widely applied for creating a path on an accumulated cost surface. The least-cost-path algorithm works on corridor analysis cell by cell. This can be used to connect the source and destination cells and then to form a least-cost path on the accumulated cost surface [22]. The composition of the steps of Dijkstra's algorithm is:

Suppose that in a raster data format a grid cell has three attributes: The cell cost C, the back-link cell B and the accumulated cost P. Among them, B is the previous cell used for calculating the accumulated cost of the current raster cell [22].

For example, if cell i could be the back-link cell 3, then $B_i = 3$. The initial value of P is 0, and after the calculation P is the accumulated cost from the source to the current cells [22].

The Dijkstra's algorithm is composed of the following steps:

Step 1. Build a stack and put the source cell into the stack.

Step 2. Select cell A in the stack whose accumulated cost P_i in the minimum and delete cell A in the stack. Then get 8 adjacent cells of cell A.

Step 3. Set $j = 0$, $j = j + 1$. If $j = 9$, then proceed to Step 7; otherwise, proceed to Step 4.

Step 4. If $P_j = 0$, then put cell j into the stack and calculate C_{ij} using the following equation and then set $P_j = C_{ij}$, $B = 9 - j$, and return to Step 3; otherwise, proceed to Step 5.

Equation 3

$$C_{ij} = \begin{cases} \dfrac{C_i + C_j}{2}, & j = 2,4,6,8 \\ \dfrac{\sqrt{2}(C_i + C_j)}{2}, & j = 1,3,5,7 \end{cases} \quad \ldots (3)$$

Step 5. If cell j is in the stack, then proceed to Step 6; otherwise return to Step 3.

Step 6. If $P_j < P_i + C_{ij}$, then return to Step 3; otherwise set $P_j = P_i + C_{ij}$, $B = 9 - j$, and return to Step 3.

Step 7. If the stack is empty, then proceed to Step 8; otherwise return to Step 2.

Step 8. Export the accumulated cost surface and the back-link life [22].

In addition, 3 tools about cost surface that represent a path in water diversion routes are described. One of them is described in Appendix 9.5 as it was not considering to developing the model.

2.4.1 The path distance tool

The path distance tool is generally used to create the least-cost path between a source and a destination, while accounting for the surface distance and the horizontal and vertical factors. In other words, it calculates, for each cell, the least accumulative cost distance from or to the least cost source. An example problem solved by path distance analysis is to calculate the actual cost and distance for a proposed road adjusting for the uphill and downhill changes in the landscape [23].

Generally, the required inputs to run this tool are: raster or feature source data, cost raster and surface raster.

- Raster or feature source data: The input source locations. This is a raster or feature (point, line or polygon), identifying the cells or locations that will be used to calculate the least accumulated cost distance for each output cell location.

- Cost raster: A raster defining the impedance or cost to move metrically through each cell. The value at each cell location represents the cost-per-unit distance for moving through the cell. Each cell location value is multiplied by the cell resolution while also compensating for diagonal movement to obtain the total cost of passing through the cell. To get this mathematically is necessary to reclassify the values and to create the raster, it is requiring to identify the cost of constructing a road through each cell [24].

- Surface raster: A raster defining the elevation values at each cell location. The values are used to calculate the actual surface distance covered when passing between cells. Generally, a digital elevation model (DEM), in consider as a surface raster parameter [23].

The outputs of the tool are: Cost backlink raster and cost distance raster. The process is represented in Figure 20.

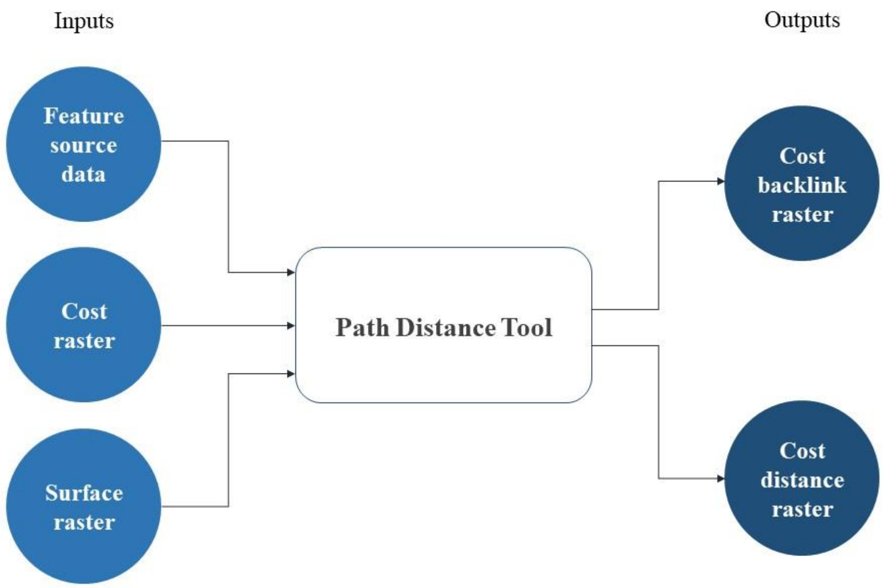


Figure 20: Inputs and outputs of the path distance tool
(Own elaboration)

2.4.2 Cost Path as Polyline tool

The cost path as polyline tool calculates the least-cost path from a source to a destination as a line feature. It produces an output polyline feature that records the least-cost path or paths from sources to the closest destination [25].

The inputs necessary to run this tool are: Raster or feature destination data, cost backlink raster and cost distance raster [25].

The output of the tool is the least cost path (routes), between the demand and the supply points. The process is represented in Figure 21.

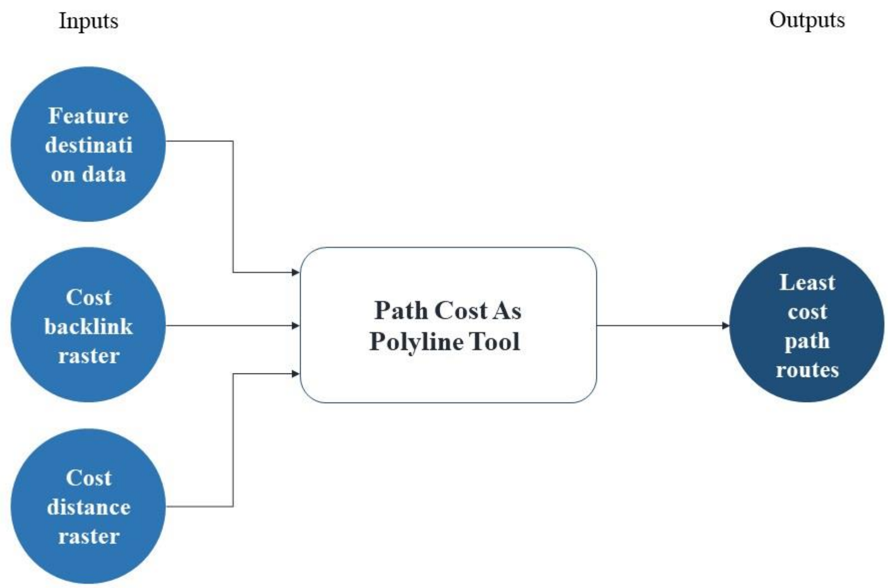


Figure 21: Inputs and output of the path cost as polyline tool (Own elaboration)

2.5 The Transport Model

Transportation problem solution attempts to minimize total transportation cost and at the same time satisfy the destination requirement given the transportation cost per unit. The transportation algorithm is specially designed to provide optimal solutions to problems arise because of transporting product or allocation of services or delivery from several origins to various destinations, where the total requirements at each destination are knows quantities, thus, deciding along which routes are the best they should be dispatched [26]. Appendix 9.5 has general aspects of this type of problems.

Research conducted by SMI introduced a transportation model as a proposal within a multi-objective optimization framework. This model serves as an alternative approach to efficiently distribute water between demand and supply points, with the primary goals of minimizing energy costs, selecting appropriate pipe diameters, conserving water resources and optimizing both the capital expenditure (CAPEX) and operational expenditure (OPEX) associated with the network pipe system. The underlying assumption is that through the successful implementation of this model it becomes feasible to rectify the prevailing water distribution scenario and even facilitate water preservation for recharging certain aquifers [27].

To minimize the energy required for water transport between each supply and demand point, this study employs the empirical Hazen-Williams formula to determine the hydraulic slope for calculating hydraulic pump power. Additionally, the model selects the appropriate diameter for each specified discharge, ensuring that the maximum velocity (V) does not exceed 1.6 m/s (*M. Maya Senzano).*

Another report conducted an economic evaluation of a desalination plant in Antofagasta Region using the same formula for getting the head loss in the pipes and subsequently the hydraulic pump power [28].

Both studies propose an Opex and Capex evaluation following the next steps:

1. To get the first input parameter: Quantity of water demanded by the company *i*.
2. To calculate the second input parameter: Diameter necessary of each pipe between the supply and demand node through the equation:

Equation 4

$$V = \frac{4 * Q_i}{\pi * d^2} > 1.6 \qquad \dots (4)$$

3. To calculate the hydraulic slope of energy line using the parameters mentioned before through the next equation:

Equation 5

$$S = \frac{\left(10.674 * Q_i^{1.852}\right)}{\left(C^{1.852} * \ d^{4.871}\right)} \qquad \dots (5)$$

Where

S: Hydraulic slope of energy line (-)

Q: Discharge (m^3/s)

C: Pipe roughness coefficient (-)

d: Diameter (m)

4. To calculate the friction factor with the equation:

Equation 6

$$h_f = S * L_i \quad \text{... (6)}$$

Where

h_f: Head loss for water over total length of pipe (m)

L_i: Length of pipe (m)

5. To calculate the hydraulic pump power (MW) with the equation:

Equation 7

$$\sum_{i=1}^{N} P_h = \frac{Q_i * \rho * g * \left(h_f + h_i\right)}{1{,}000{,}000} \quad \text{... (7)}$$

Where

P_h: Hydraulic pump power (MW)

Q: Discharge (m^3/s)

ρ: Density of fluid (Kg/m^3)

g: Gravity (m/s^2)

h_i: Head (m)

6. Calculation of the operating expense:

Equation 8

$$OPEX = \frac{P_h * Energy\ cost * 24 * 365 * Life\ of\ Project}{1{,}000{,}000} \quad \text{... (8)}$$

7. Calculation of the capital expenditure:

Equation 9

$$CAPEX = L_i * C_p \quad \dots (9)$$

Where

C_p: Cost of pipe: 736 (USD/m) [9]

3 BACKGROUND OF THE CASE STUDY

3.1 ATACAMA REGION

The Atacama Region limits to the west with Pacific Ocean, to the East with Argentina, to the North with the Antofagasta Region and to the South with the Coquimbo Region. It has a surface of 75,573 km^2, equivalent to 9.94% of the national territory and a mean annual precipitation of 82.4 mm/year [29]. Its natural characteristics allow it to be defined within the national territory as a transitional region, since, although the desert climate predominates, winter rainfall is registered [30]. Figure 22 displays the geographic location.

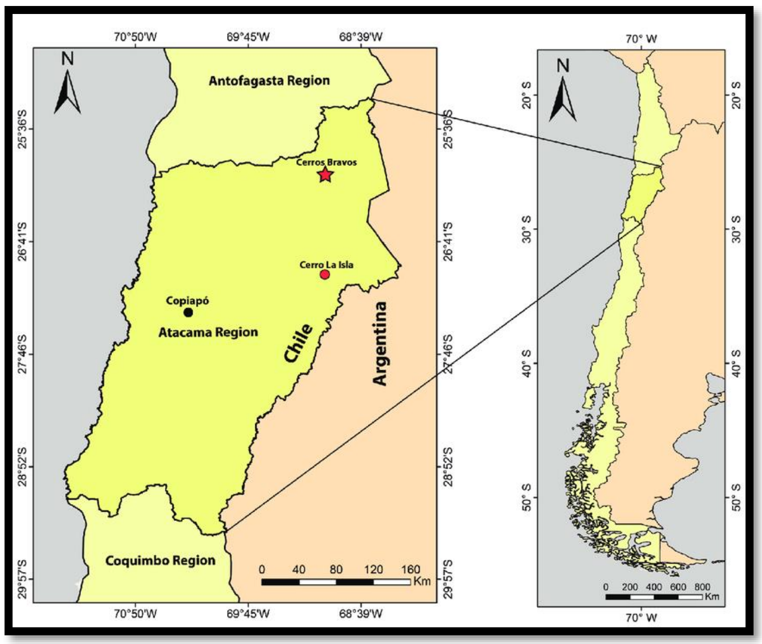


Figure 22: Map of the Atacama Region [30]

Regarded mining resources and projects, this economic activity provides 40.6% of regional GDP where the territory has estimated US$10,977 million in mining investment between years 2017-2026. In this Region there are small, medium and large mining operations and there are also large iron and gold mining operations [31].

3.2 WATER RESOURCES AND CONSUMPTION

According to the classification of the General Water Directorate (DGA), the Atacama Region comprises 10 extensive basins, further divided into 35 sub-basins and 110 sub-sub-basins. The basins exhibiting the most considerable surface area relative to the regional expanse are the “Río Copiapó” with 18,704.07 km^2, the “Endorreica entre Frontera y Vertiente del Pacífico” with 15,619.02 km^2 and the “Río Huasco” with 9,813.7 km^2 [32]. Figure 23 displays the primary basins in the region with their spatial locations within the territory.

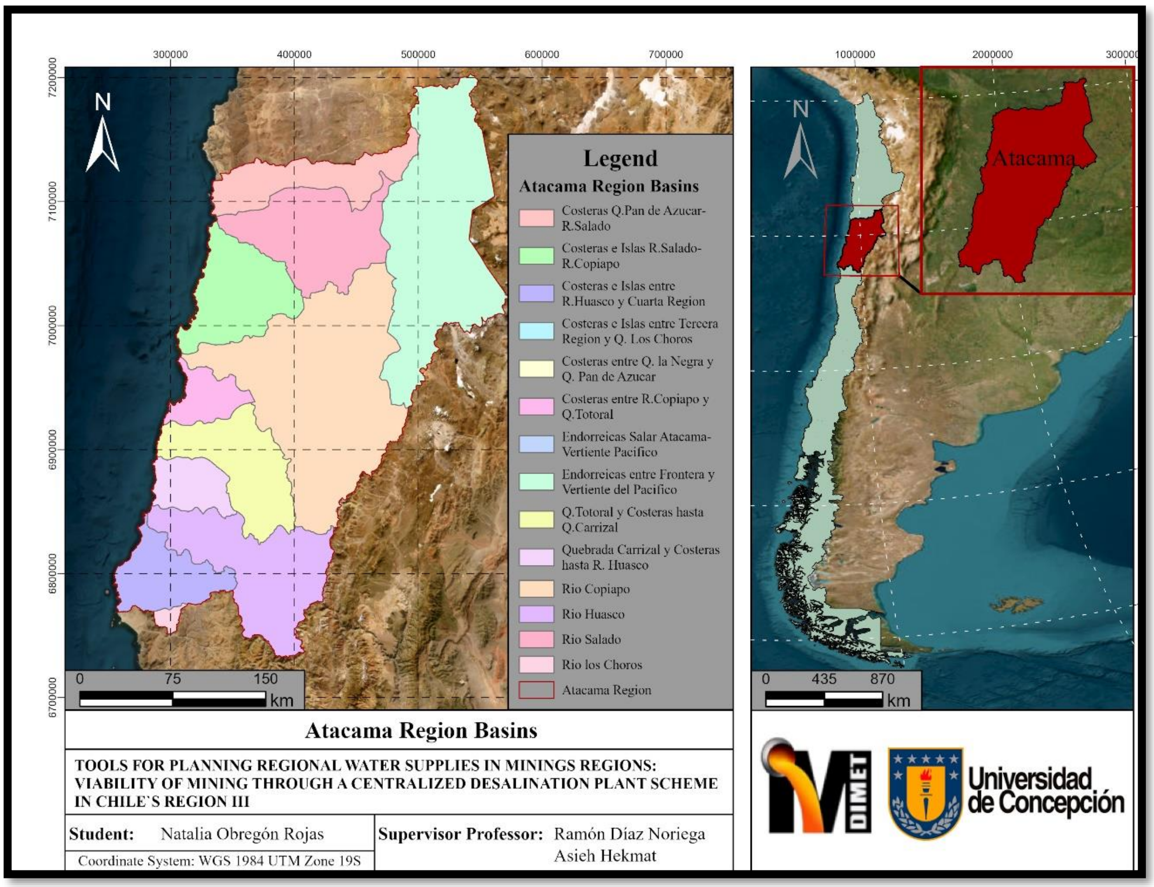


Figure 23: Basins in Atacama Region
(Own elaboration)

According to DGA Water Cadastre from November 2013, there are a total of 1,209 water use rights in the Atacama Region, encompassing both surface water and groundwater rights. Among these, 1,165 water use rights are classified as consumptive, meaning the water is utilized and not returned to the source. Conversely, only 44 water use rights are categorized as non-consumptive, indicating that the water used can be returned to the source. Figure 24 visually represents this distribution of water use rights, with orange colour denoting consumptive use and blue colour representing non-consumptive use [32].

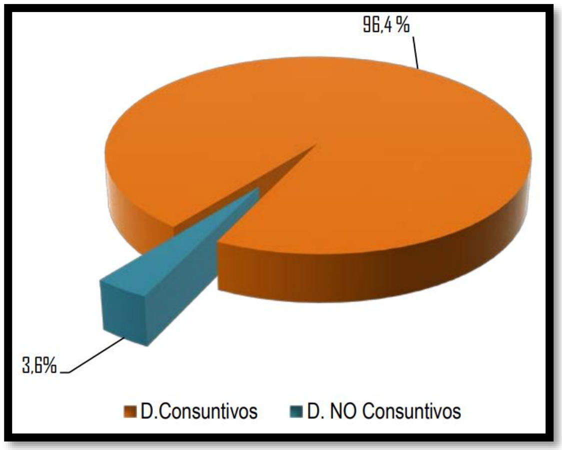


Figure 24: Surface and underground water rights in Atacama Region [32]

Considering consumptive and non-consumptive water use, the sector with the greatest demand is the agricultural with 73.3%. The second greatest demand is mining sector with 9.8%. Then the health and industrial sector with 4.9% and 3.1% respectively. In the case of the energy sector, it demands only 1.5% of the water being used mainly by thermoelectric plants for their respective generation processes as depicted in Figure 25 [32].

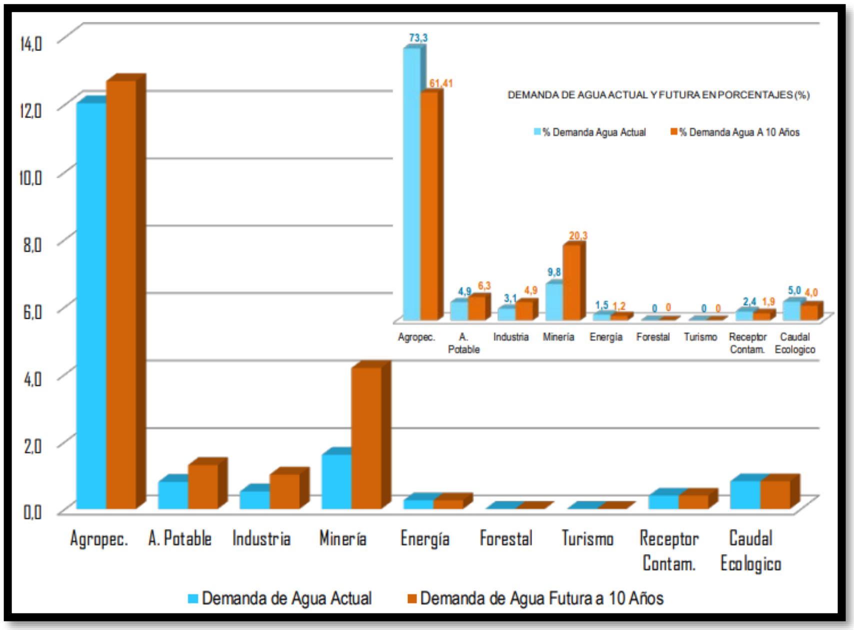


Figure 25: Current and future 10-year water demand by sector in m^3/s and % [32]

In the year 2020, the primary source of water extraction for large-scale mining activities in the Atacama Region was continental water, with an average extraction rate of 0.96 m^3/s. Among continental water sources, surface channels accounted for the highest extraction volume with an average of 0.568 m^3/s. Additionally, underground water extraction contributed 0.36 m^3/s while miner's water extraction amounted to 0.032 m^3/s. Regarding non-continental water sources, both desalinated and non-desalinated seawater were utilized with an average combined extraction rate of 0.175 m^3/s. This information is visually depicted in Figure 26 [8].

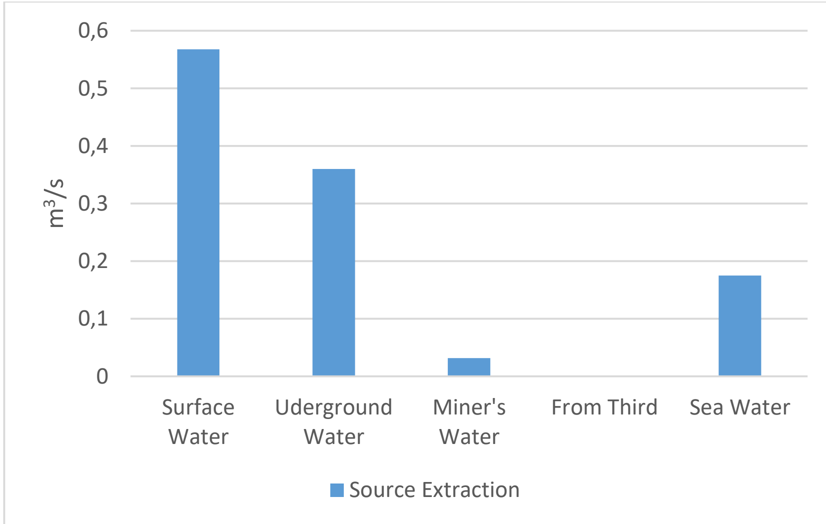


Figure 26: Water source extractions from large mining in Atacama Region [33]

In the upcoming years, the Atacama Region is projected to experience a significant increase in water demand within the mining sector. It is expected that the water demand will rise by 10% until the year 2030, reaching a total demand of 4.183 m^3/s. Furthermore, the demand is anticipated to grow by 14% until 2040 with a projected water demand of 6.057 m^3/s [33].

3.2.1 Water Efficiency and Recirculation in Copper Mining

Regarding the identification of gaps in water efficiency for the Atacama Region, aims are established for the mining sector and basins within Region. The primary focus is on prioritizing and identifying actionable measures to close these gaps and develop a comprehensive program with measurable indicators to track progress [3].

As part of this program, Table 4 presents a comparative analysis between the water consumption of mining operations in the Atacama Region and those in Australia. The table highlights the differences in water usage between the two regions, shedding light on potential areas for improvement [3].

The expected scenario for the Atacama Region’s water efficiency improvement is estimated to be achieved within a timeframe of 5 to 10 years. This projection considers an average ore grade ranging from 0.8% to 0.94%. It provides a realistic timeframe for implementing water-saving measures and optimizing resource utilization in the mining processes [3].

In contrast, the expected water efficiency situation for Australia is projected to be achieved within a timeframe of 5 to 6 years, considering an average ore grade between 0.8% to 1.5%. This indicates that Australia's mining sector is on track to achieve greater water recirculation and conservation results in a relatively shorter period [3].

It is essential to note that the recirculation of water, as mentioned in this context, refers to the percentage of total water consumed in the mining processes that can be effectively recycled and reused.

Table 4. Comparison between Atacama Region and Australia of current and expected water used in medium-sized copper mining [3]

		Atacama Region		Australia	
		Current Situation	Expected Situation	Current Situation	Expected Situation
Efficiency (m^3/ton)	Concentration	0.59	0.5	0.15	0.13
	Hydrometallurgy	0.15	0.08	0.08	0.05
Water Source (%)	Recirculation Water	40	60	20-40	20
	Desalinated Water	No Reported	10	0	0
	Continental Water	No Reported	90	100	100

Table 4 also presents a comparison of water sources used in medium copper mining operations between the Atacama Region and Australia. The results indicate that the Atacama Region demonstrates superior water performance, with higher utilization of recirculated water both in the present and projected future scenarios. Specifically, Atacama's recirculated water usage is expected to increase from 40% to 60% over 5 to 10 years, while Australia's recirculation remains constant at 20%. Additionally, Atacama plans to incorporate 10% of seawater as water source in the near future, contrasting with Australia's intention to maintain 100% reliance on freshwater sources.

Conversely, Table 4 reveals that in terms of water efficiency, medium copper mining in the Atacama Region has a lower performance compared to Australia. Notably, Australia demonstrates significantly higher efficiency in concentration processes, both presently and in expected situations. Although the difference in hydraulic efficiency between both locations is less significant in hydrometallurgy processes, it is crucial to highlight that expected water efficiency for Atacama is equivalent to the current situation in Australia.

In this aspect, a viable approach to attain reduced consumption rates for oxide minerals, predominantly treated via hydrometallurgical methods, involves the recirculation of solutions. This method entails the prevention of infiltration and minimization of evaporation losses. Similarly, for sulphide minerals, which are predominantly processed through concentration procedures, optimizing recirculation from thickeners and tailings while mitigating the occurrence of leaks and evaporation becomes pivotal in achieving diminished consumption levels [3].

Given the intensive water utilization during concentration processes, particularly in the context of flotation, it becomes highly desirable to maximize water reutilization. By doing so, not only it is possible to curtail the consumption of freshwater resources but also minimize the volume of discharged water, thereby promoting a more sustainable and eco-friendly mineral processing practice [3].

3.3 DESALINATION PLANTS

As of the current information available, the Atacama Region has a total of five desalination plants that have received environmental approval and are actively operational. These desalination plants are specifically utilized for the processing of copper mining operations in the Region as depicted in Table 5 [34].

Table 5: Desalination plants for copper mining processing in Atacama Region [35]

Operation	Start up	Life of Mine (Years)	Capacitance (L/s)	East (UTM)	North (UTM)
Candelaria	2018	13	500	317260	7006142
Manto Verde	2014	20	120	330827	7063429

Santo Domingo	2019	19	400	324060	7037800
Diego de Almagro	2020	15	315	333951	7092608
Relincho y El Morro	2022	26 and 5 respectively	700	292606	6917243

3.3.1 Desalination Plant Scheme

ENAPAC is a self-sustaining seawater desalination project designed to provide water to various stakeholders in the Copiapó catchment area within the Atacama Region. It holds the distinction of being the largest desalination plant not only in Chile but also in Latin America. With a flexible capacity, ENAPAC achieves an average water production of 1,000 L/s and can reach a maximum capacity of 2,630 L/s. This pioneering project is focused on supplying multiple customers in the Region and stands as one of the most technologically advanced initiatives globally, utilizing a combination of reverse osmosis for desalination [35].

The desalinated water is transported to a reservoir with a substantial capacity of 600,000 m^3 from where it will be distributed to various end-users. To power the system during the day, a 100 MW photovoltaic power plant is employed, harnessing solar energy as a sustainable energy source. At night, the national grid supplements the power requirements. It has an estimated initial investment of approximately USD 500 million [35].

The project is in the communes of Caldera and Copiapó within the Copiapó Province of the Atacama Region represented in Figure 27.

The primary infrastructure, which includes the desalination plant is situated approximately 38 km to the southwest of Caldera city. On the other hand, the photovoltaic plant and the seawater reservoir are positioned at distances of 29 km and 19 km respectively, to the west and southwest of Copiapó city as visually depicted in Figure 28. In this representation, the fuchsia-coloured icon corresponds to the desalination plant, the light blue icon represents the reservoir area, and the orange icon symbolizes the location of the photovoltaic power supply [35].

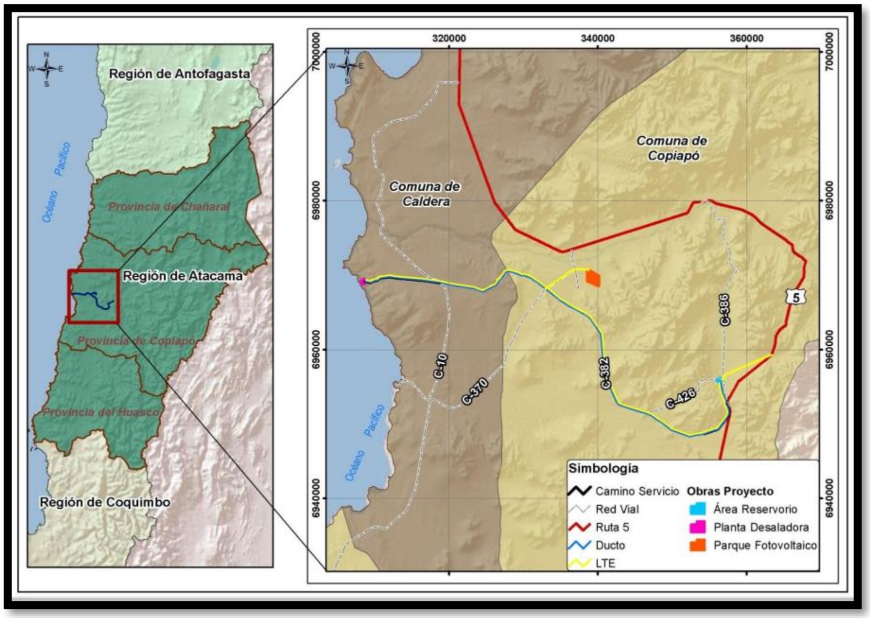


Figure 27: Localization of ENAPAC's project [35]

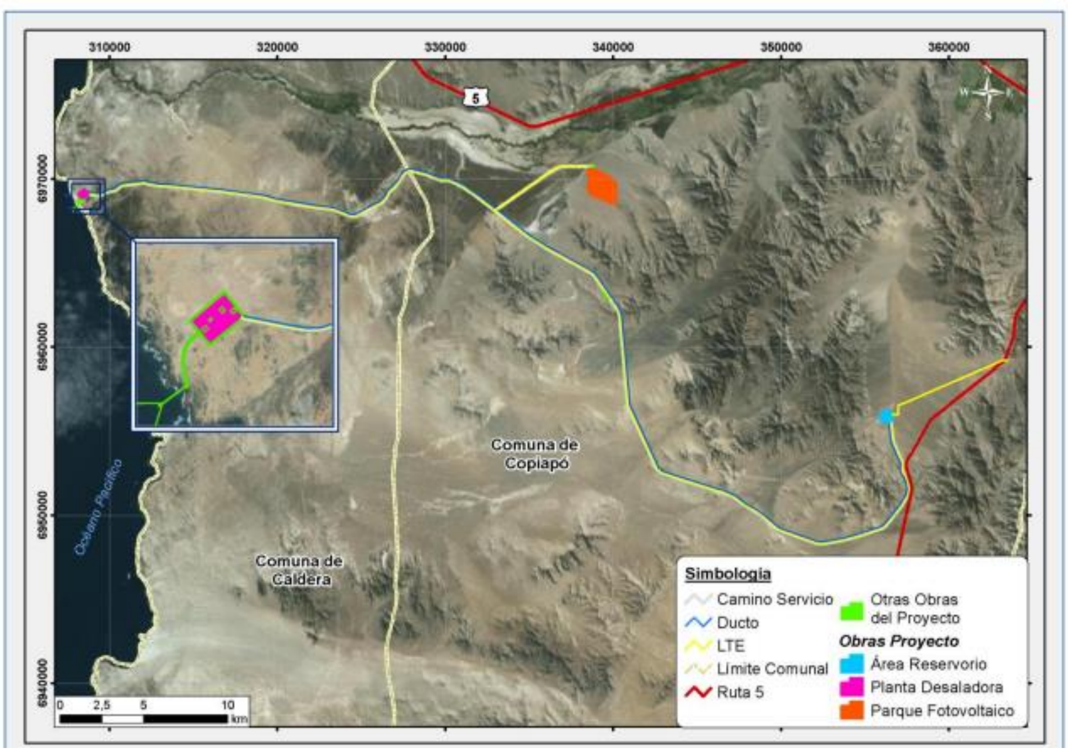


Figure 28: Cartographic representation of the project [35]

4 DEVELOPMENT

4.1 COLLECTION DATA

In accordance with specific objectives, the initial step involves the identification of suitable prospects in the Atacama Region for conducting an economic analysis of water distribution.

The primary criterion for selection involves choosing mining copper operations that engage in ore processing, as most of the water consumption, as indicated in the background information, occurs within mineral processing plants. The second criterion is to target plants that process more than 5,000 TPD as water consumption is directly correlated with the volume of processed minerals. This consideration aligns with future governance policies as previously discussed in the background as well. Lastly, the third criterion entails the selection of prospects whose projects have obtained approval from the SEA to ensure a focus on sustainability matters.

In this manner, a total of 14 selected prospects were identified, and their spatial locations can be observed in Figure 29. For relevant information regarding these operations, please refer to Appendix 9.6.

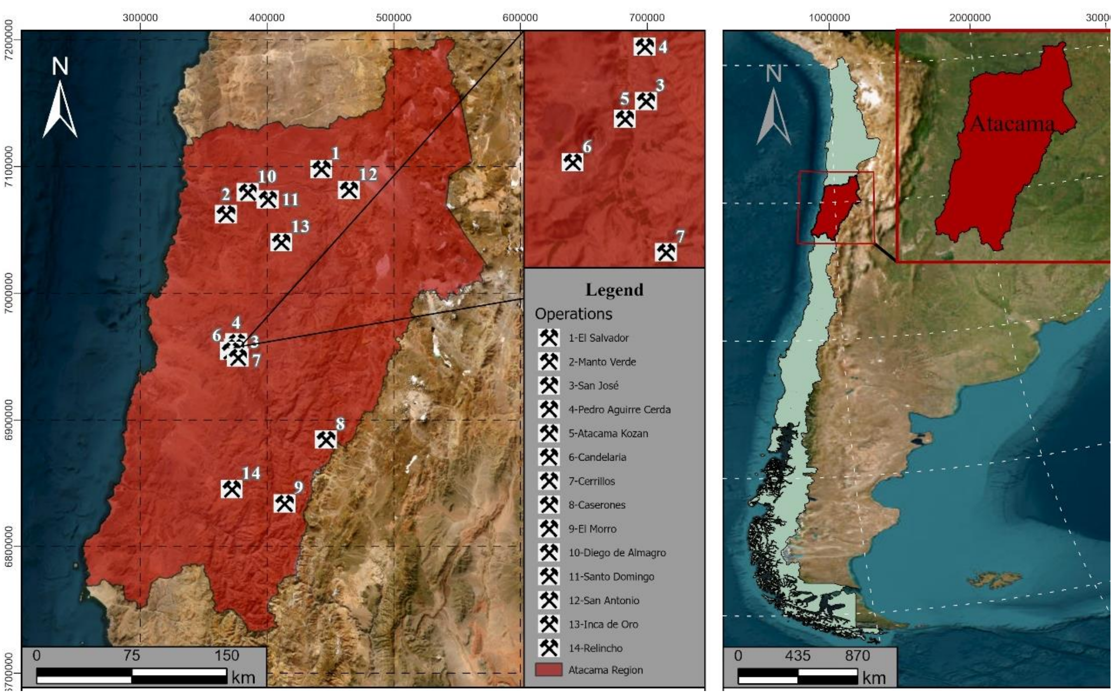


Figure 29: Prospects selected in Atacama Region (Own elaboration)

As expounded in the preceding chapter, there exist pivotal parameters germane to the assessment of water distribution costs, aimed at facilitating an economic appraisal. The quantification of these parameters can be drawn from diverse founts of information, albeit their concurrent identification within a singular source is not ubiquitous. This phenomenon is illustrated in Fig 30, where corporate reports are disseminated on online platforms, albeit not comprehensively encompassing all parameter data. Contrastingly, certain pieces of information, such as the quantum of water consumed, can be derived from corporate reports, mathematical formulations entailing the interpolation of water consumption rates in correspondence with processed tonnage, as well as from oversight institutions like DGA/SEA. On the other hand, 7 of 8 parameters that are necessary to analyze an economic evaluation can be obtained through the environmental impacts assessments (EIA).

Table 6 and 7 present the water source and the demand of the prospects from the data collected through SEA website.

Table 6 depicted the location of the water sources where the prospects extract the water to their processing plants. To see mining parameters aspects regarded mineral processing and the production of the prospects proceed to Appendix 9.6

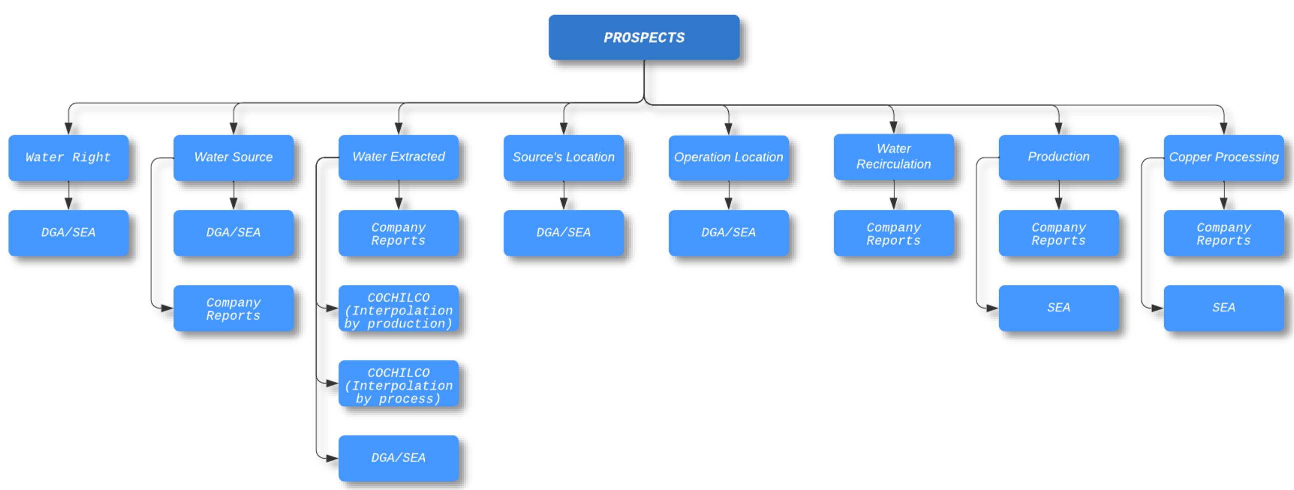


Figure 30: Diagram of prospect's relevant parameters (Own elaboration)

Table 6: Mineral processing characteristics of prospects

ID	Operation	Mineral Treatment	TPD Processed	Av. Ore Grade
1	El Salvador	Leaching	25000	0.6
		Concentration	32000	0.9
2	Manto Verde	Leaching	15000	0.27
		Concentration	36111	0.6
3	San José	Concentration	20000	0.81
4	Pedro Aguirre Cerda	Concentration	70000	0.86
5	Atacama Kozan	Concentration	5000	0.81
6	Candelaria	Concentration	75600	0.81
7	Cerrillos	Concentration	8000	0.81
8	Caserones	Leaching	41667	0.3
		Concentration	125000	0.34
9	El Morro	Concentration	50000	0.58
10	Diego de Almagro	Leaching	2000	0.95
		Concentration	24000	0.81
11	Santo Domingo	Leaching	65000	0.3
12	San Antonio	Concentration	40000	0.5
13	Inca de Oro	Leaching	30000	0.59
		Concentration	37000	0.59
14	Relincho	Concentration	50000	0.38

Table 7: Location and quantity of the water source extraction

ID	Operation	Source	North (UTM)	East (UTM)	Water Extracted (L/s)
1	El Salvador	GW	7073637	417111	603
		SW	7090997	488647	165
2	Manto Verde	Seawater	-	-	380
3	San José	GW	6977271	388258	241
		GW	6938946	388281	
4	Pedro Aguirre Cerda	SW	6931586	395478	95
		GW	6977271	388258	

5	Atacama Kozan	GW	6977271	388258	129
6	Candelaria	Seawater	-	-	400
		GW	6977271	388281	150
7	Cerrillos	GW	6938946	388281	40
8	Caserones	GW	6913193	399495	518
		GW	6898751	439685	
9	El Morro	Seawater	-	-	250
10	Diego de Almagro	Seawater	-	-	315
11	Santo Domingo	Seawater	-	-	463
12	San Antonio	SW	7090997	488647	94
13	Inca de Oro	SW	7090997	488647	470
14	Relincho	Seawater	-	-	250

4.2 DATA REPRESENTATION AND CHARACTERIZATION OF ROUTES

Data is processed in ArcMap to representing visually 2 cases, the actual system of water distribution and a proposed system.

Subsequently, a cost-weighted distance model in a raster data format is built, using path distance tool and cost path as polyline tool through a visual programming language for building geo-processing workflows called Model Builder. The workflow diagram is in Appendix 9.8. The accumulative costs are calculated from the source to the destination's points. The sources in the first case are the continental and seawater extraction informed from each approved EIA's project of the prospects and the source in the second case is the proposed system with the plant scheme presented. The destinations points are the selected prospects. Finally, a least cost path of water diversion route is identified in both cases, to get the minimum cost distances and altitudes between each source and destination. These output parameters from the model are used to develop the economical evaluation. Both cases are visually represented in Fig 31 and Fig 32.

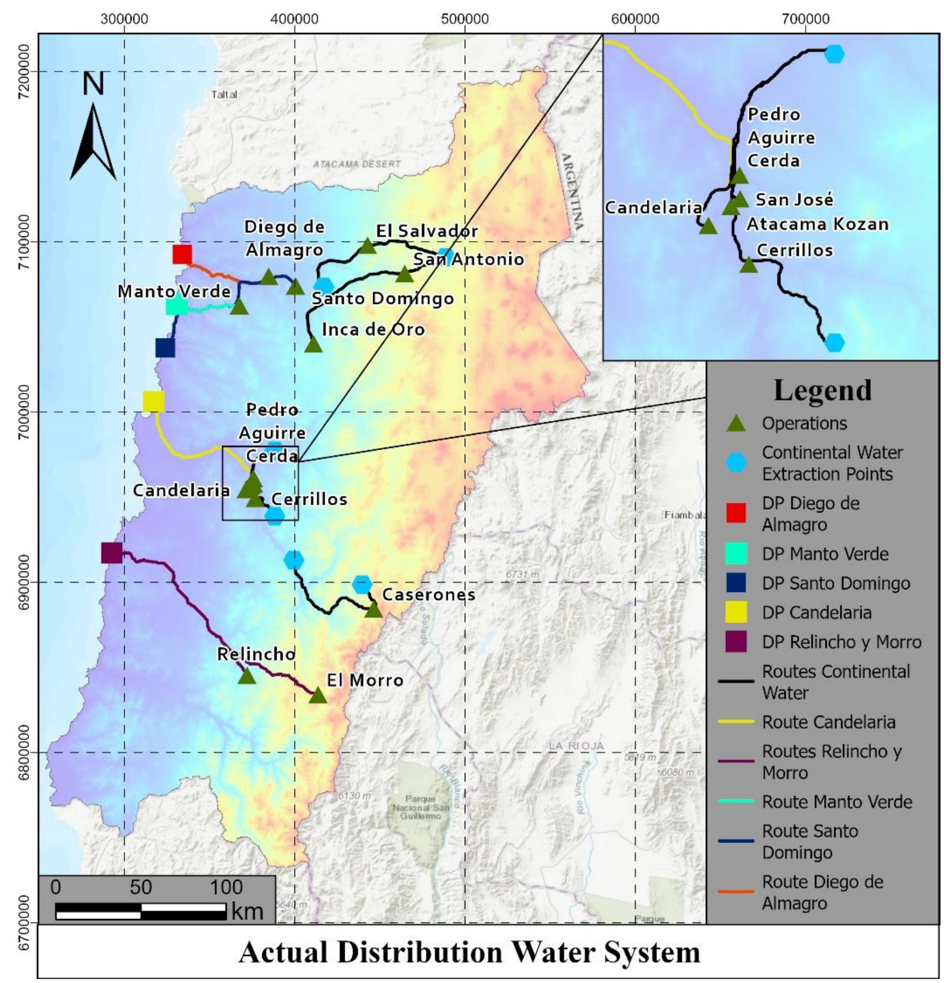


Figure 31: Actual system with desalination plants and continental water as distribution (Own elaboration)

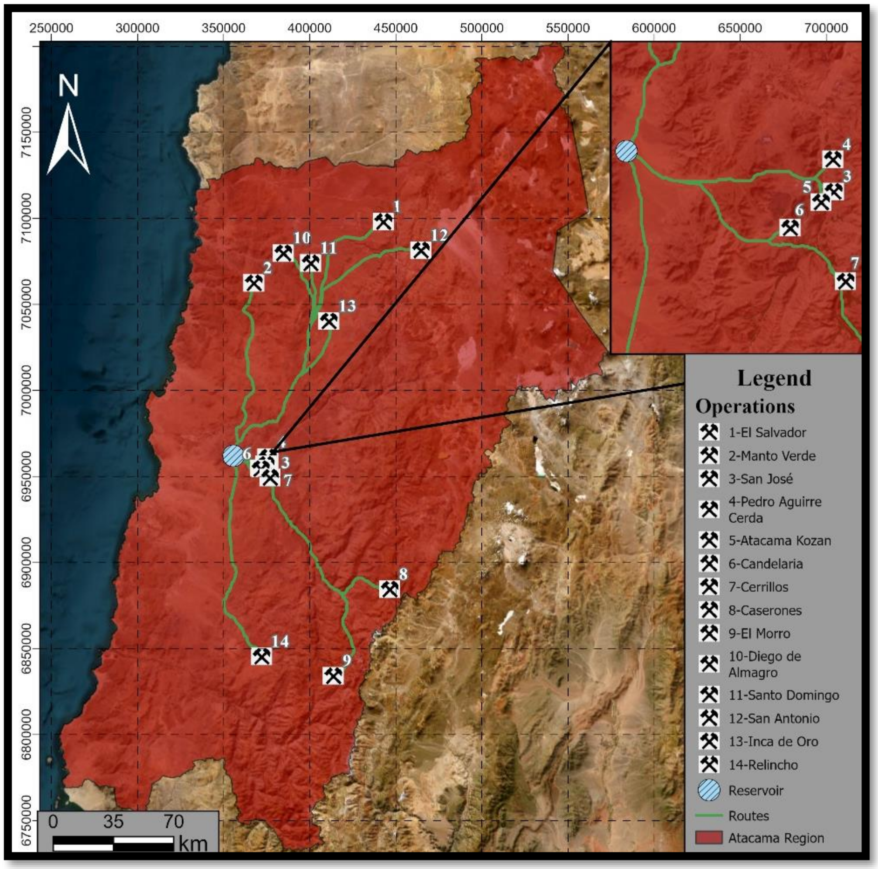
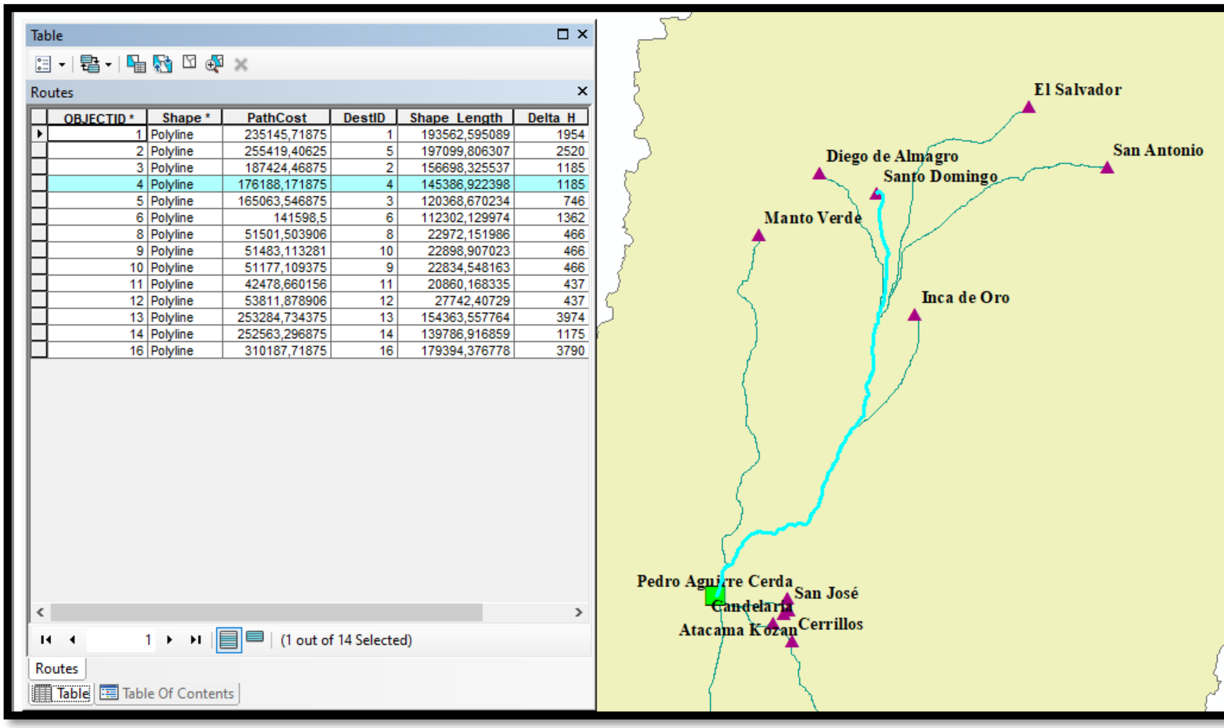


Figure 32: Proposed system with a desalination plant as distribution (Own elaboration)

When the results of the model execution are stored in a geodatabase, the total length of the least-cost path is saved in the 'shape_length' field, along with the elevation difference between the start and the destination nodes. Figure 33 illustrates an example with the results of the distance (Shape_length) and elevation (Delta_H) fields between the studied desalination plant and Santo Domingo as the outputs of the model builder.



Table

Routes

OBJECTID *	Shape *	PathCost	DestID	Shape_Length	Delta_H
1	Polyline	235145,71875	1	193562,595089	1954
2	Polyline	255419,40625	5	197099,806307	2520
3	Polyline	187424,46875	2	156698,325537	1185
4	Polyline	176188,171875	4	145386,922398	1185
5	Polyline	165063,546875	3	120368,670234	746
6	Polyline	141598,5	6	112302,129974	1362
8	Polyline	51501,503906	8	22972,151986	466
9	Polyline	51483,113281	10	22898,907023	466
10	Polyline	51177,109375	9	22834,548163	466
11	Polyline	42478,660156	11	20860,168335	437
12	Polyline	53811,878906	12	27742,40729	437
13	Polyline	253284,734375	13	154363,557764	3974
14	Polyline	252563,296875	14	139786,916859	1175
16	Polyline	310187,71875	16	179394,376778	3790

Figure 33: Output parameters from the Model Builder (Own elaboration)

4.3 Economical Evaluation

The output parameters obtained from the model builder are: The total length of the least cost path and the difference altitude between the demand and offer points. Subsequently, these parameters from the optimal supply routes are entered in the equations described in chapter 2.5.

Below is an example of this economic calculation between Caserones, as a demand point, and the desalination plant scheme proposed, as the offer point.

It is important to mention that the Opex is calculated considering the life of mine of each operation informed from each EIA's project. The assumed coefficient of friction (C) and energy cost (USD/MW) are 140 and 150 respectively.

1. First input parameter: Quantity of water demanded by the company: 0.518 m^3/s.
2. Second input parameter: Diameter necessary of the pipe between the supply and demand node:

$$V = \frac{4 * Q_i}{\pi * d^2} > 1.6$$

$$V = \frac{4 * 0.518}{\pi * d^2} > 1.6$$

$$d = 0.642036\ (m)$$

3. Calculation of the hydraulic slope of energy line using the parameters obtained in step 2.

$$S = \frac{(10.674 * Q_i^{1.852})}{(C^{1.852} * d^{4.871})}$$

$$S = \frac{(10.674 * 0.518^{1.852})}{(C^{1.852} * 0.642^{4.871})}$$

$$S = 0.002897$$

4. Calculation of the friction factor using the result obtained in step 3 and the distance parameter obtained from the model:

$$h_f = S * L_i$$

$$h_f = 0.002897 * 154363.6$$

$$h_f = 447.9526\ (m)$$

5. Calculation of the hydraulic pump power using the result of the step 4 and the difference altitude obtained from the model:

$$P_h = \frac{Q_i * \rho * g * (h_f + h_i)}{1{,}000{,}000}$$

$$P_h = \frac{0.518 * 1000 * 9.8 * (447.9526 + 3974)}{1{,}000{,}000}$$

$$P_h = 22.44408\ (MW)$$

6. Calculation of the operating expense.

$$OPEX = \frac{P_h * Energy\ cost * 24 * 365 * Life\ of\ Project}{1{,}000{,}000}$$

$$OPEX = \frac{22.44408 * 150 * 24 * 365 * 19}{1{,}000{,}0000}$$

$$OPEX = 560.34 \text{ MUSD}$$

7. Calculation of the capital expenditure:

$$CAPEX = L_i * C_p$$

Where

C_p: Cost of pipe: 736 (USD/m) [9]

L_i: 154363.6 (m)

$$CAPEX = 113612\ MUSD$$

5 RESULTS ANALYSIS

Of a total of 14 prospects, 6 have concentrator and leaching process, 6 have just concentrator process and 1 have just leaching process. Moreover, the operation with the highest production are El Salvador, Candelaria and Caserones.

The main source of water supply comes from groundwater while the operations with the highest water demand are El Salvador, Candelaria and Caserones.

Derived from the network optimization system produced by the Model Builder employing ArcGIS tools, empirical analysis within the existing framework reveals that out of the 6 continental water extraction nodes, a solitary point is harnessed by 3 prospects as a primary supply source for their respective mineral processing. This strategic choice appears to be influenced not solely by water rights secured, but also by the minimal geographical span separating the extraction points, indicative of a rationale aimed at mitigating operational transport expenses. This preference for proximity-based selection appears to surpass a paradigm centered on water availability and equilibrium-driven sustainable supply decisions as a system water management by basins or water balances in the different sources.

Figure 34 illustrates the water flows were demanded by every source of the system. The sources can be obtained from continental water (CW) or sea water (SW). It is possible to observe that the most utilized water source for water extraction is CW2, while the least utilized water source is CW4. This is attributed to the production and size of each prospect that extracts water from these points for their mineral processing. For instance, in the case of CW2, El Salvador, the main demand node has more intensive water consumption, simultaneously being the operation with the highest production. In contrast, Inca de Oro and San Antonio are significantly closer in distance compared to the other water sources depicted as supply nodes.

The total demanded flow in the system according to the gathered information is 4,563 m^3/s.

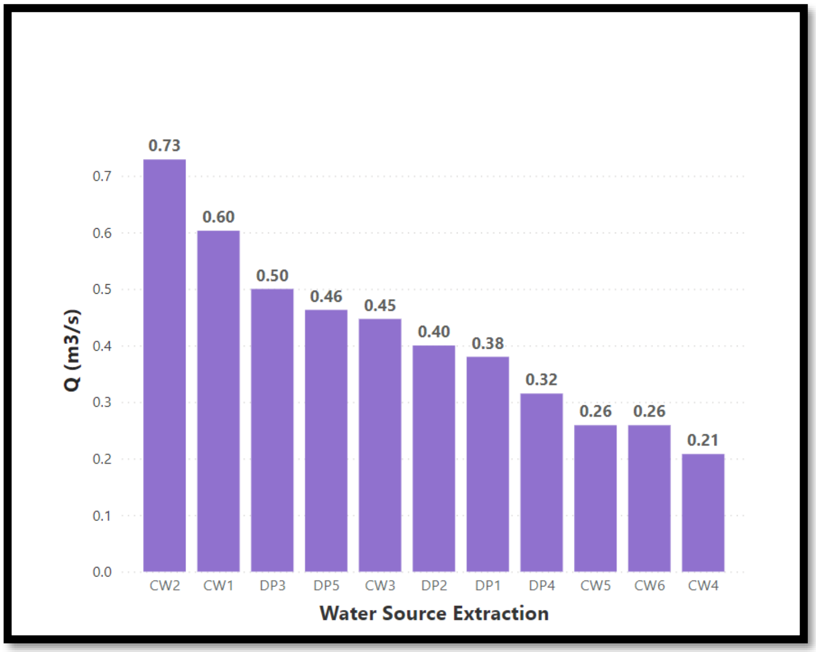


Figure 34: Water extracted by prospects from actual distribution system (Own elaboration)

Upon generating the routes, it becomes evident that there exists a compartmentalization within the water infrastructure. In other words, certain routes at specific geographic points share identical trajectories. This observation can be consistently explained by the principles of the triangular inequality theorem, wherein a subset of optimal routes effectively constitutes an optimal route. In this aspect, the interconnected water supply network holds particular significance during drought periods, characterized by water deficits at distinct extraction points, or when water quality issues and maintenance work impact segments of the network. However, to undertake a comprehensive review and analysis of the water interconnection system, a thorough assessment of the power interconnection system is requisite. Additionally, an appraisal of the strengths, opportunities, weaknesses and threats associated with the implementation of such systems within the region is imperative.

Figures 35 and 36 illustrated the hydraulic power consumption. The continental sources are abbreviated with ‘CW’ and the sea water sources are abbreviated with ‘DP’. Figures 37 and 38 illustrate the Capex and Opex pertaining to the water distribution routes connecting each demand and supply point.

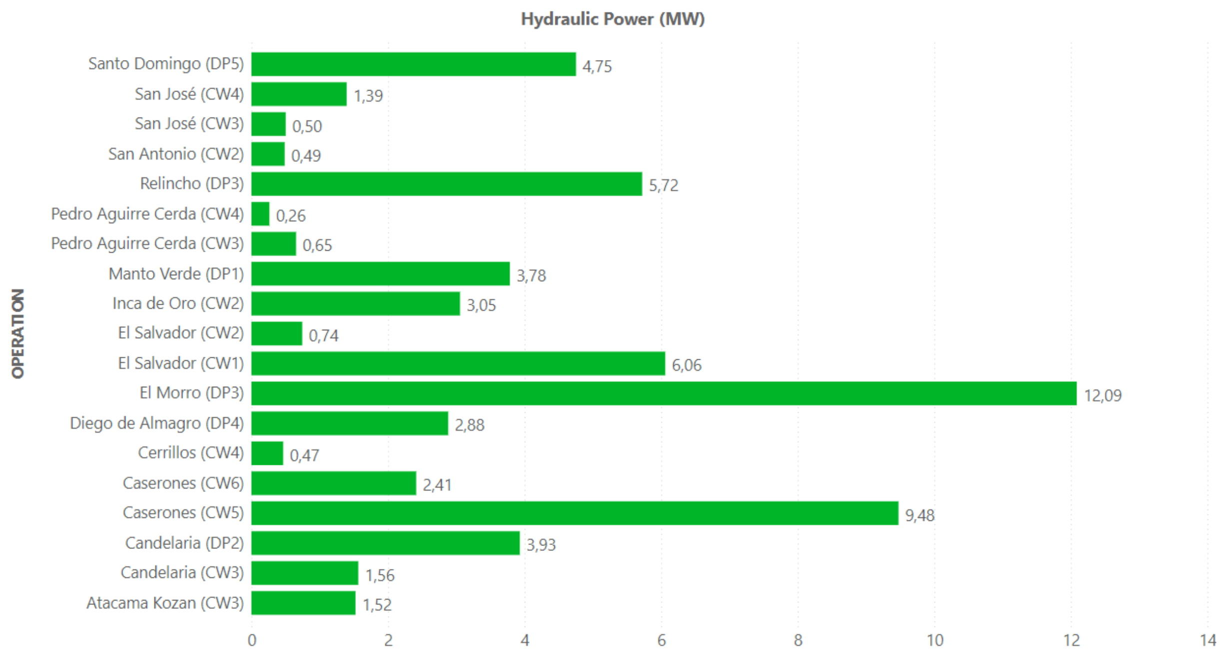


Figure 35: Hydraulic power of every route in the actual system of distribution (Own elaboration)

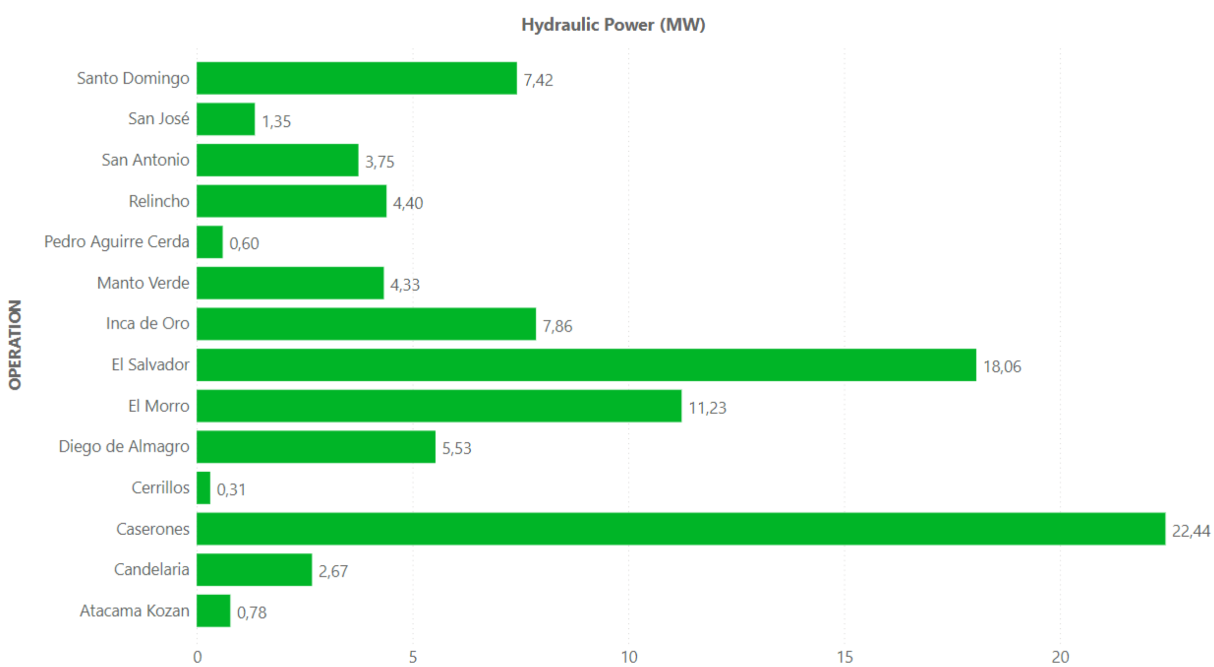


Figure 36: Hydraulic power of every route in the proposed system of distribution (Own elaboration)

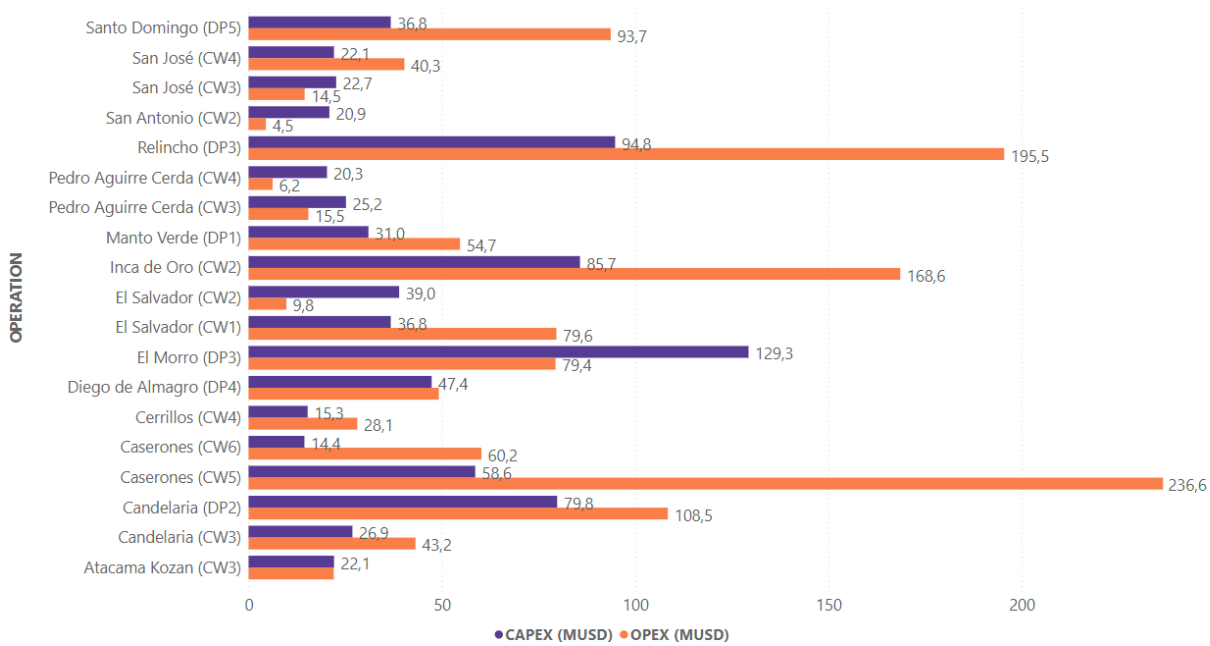


Figure 37: Capex and Opex of every prospect in the actual system (Own elaboration)

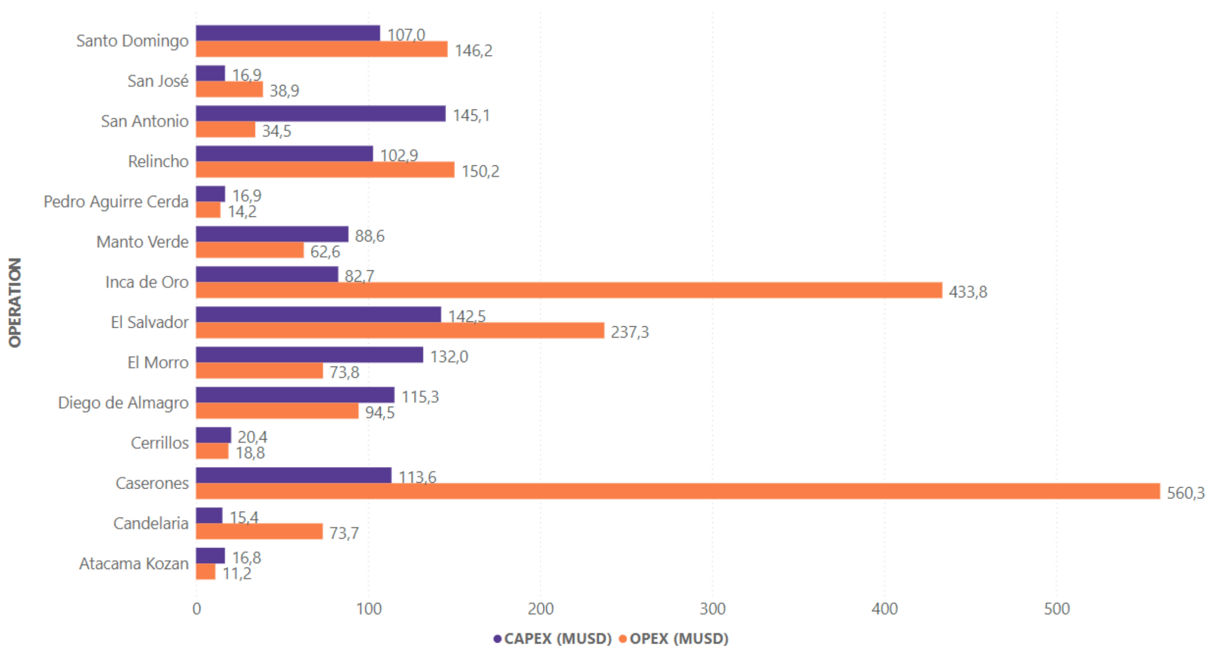


Figure 38: Capex and Opex of every prospect in the proposed system (Own elaboration)

The results of the economic evaluation are presented in Table 8 and 9:

Table 8: Results of the transport model of the actual system

Parameter	Value
Total Energy [MW]	61.76
CAPEX [USD]	$829,151,325
OPEX [USD]	$1,310,075,640
Total Investment [MUSD]	$2,139.23
CAPEX/OPEX Ratio	1.58

Table 9: Results of the transport model of the proposed system

Parameter	Value
Total Energy [MW]	90.73
CAPEX [USD]	$1,115,975,824
OPEX [USD]	$1,950,076,369
Total Investment [MUSD]	$3,066.05
CAPEX/OPEX Ratio	1.75

In the current distribution system, the operation incurring the highest energy expenditure for water supply from a desalination plant is associated with El Morro. Conversely, the operation with the highest energy consumption for water supply from a continental source is linked to Caserones.

In the proposed distribution system, the operation with the highest energy consumption for supply from the scheme desalination plant is attributed to Caserones, while the operation with the lowest energy expenditure under this system is Cerrillos.

Although both Caserones and El Morro operations are not the largest water consumers in terms of flow demand, their significant distances from their respective extraction sources should be noted.

6 CONCLUSIONS

The economic viability of supplying desalinated water to copper mining operations in the Atacama Region depends on the participation of various sectors, both public and private, since the availability of fresh water is limited and the water requirements of the industry that process copper are increasingly major.

The Atacama Region is one of the most arid areas in the world where it mining operations depend mainly on water to carry out their tasks, being processing task the activity with the greatest demand. The scarcity of water in the Region and the proposals that the governance has raised have led medium and large mining to seek alternatives to ensure their supply, being desalinization by reverse osmosis the most viable at the present.

The construction of the plant and the energy consumption represent an important economic challenge. However, despite the high initial costs, this can be a profitable investment in the long term by having a reliable water source where the cost of supplying can be calculated considering optimal situations.

Among the most important factors to calculate this cost are the distance and the altitude difference between the operations and the plant's reservoir where the transportation cost is the highest of the total OPEX and CAPEX with values that fluctuate between US\$1.9/m^3 and US\$ 3.4/m^3 at 100 meters ASL and 4,000 meters ASL respectively.

With this uncertainty between costs, optimization tools that calculate distances and altitudes can provide more precise values, generating an optimized route network system between one point and another according to its spatial location. To considering these parameters and topography can help to mining companies optimize these associated costs.

In order to develop the economical evaluation, the water demand information can be found in various sources. However, is important to have the most reliable value because this parameter is used for getting the diameter necessary of each pipe between the supply and demand node which is the most important parameter regarded investment and operational costs. In this aspect it was decided to choose the EIA information given that the companies submitted their projects that were approved by the governance through their platform.

The proposed distribution system demonstrates a higher total energy consumption compared to the current system, with an increase of 46.91%.

The proposed system incurs a higher capital expenditure (34.59%), indicating a substantial investment required for the implementation of the new water distribution approach.

The operational costs associated with the proposed system are higher than those of the current system (48.85%). This emphasizes the importance of considering not only the initial investment but also the ongoing operational expenses in decision-making.

The total investment, encompassing both capital and operational expenditures, is notably higher for the proposed system (43.32%), suggesting a considerable financial commitment over the life of the project.

The Capex/Opex ratio for the proposed system is higher, indicating a relatively greater proportion of capital expenses compared to operational costs. This may influence financial planning and risk assessment.

The evaluation reveals that while the proposed water distribution system entails higher energy consumption and financial investment, further analysis and consideration of factors such as long-term sustainability, operational efficiency and environmental impact are crucial for making informed decisions regarding the adoption of the new system.

7 FUTURE WORK AND RECOMMENDATIONS

The current study presents an analysis of distribution water in copper mining. For getting more accurate results the model should be extend considering the water demand in gold, iron and silver mining companies in the Region.

This research uses a scheme from an already built desalination plant. The studies about environmental impacts about the plant's location was not consider. To consider the information about it, would contribute to a study for optimal sustainable locations measurements.

The results that were analysed is from a particular scenario. The analysis of water balances calculations in every extraction source could pursue sustainably aims in water management aspects.

The consideration of land use factors is essential when formulating the spatial distribution of routes, as there are state-protected wilderness areas adjacent to the operations or tailings.

It is recommended to integrate the recirculation factor for obtaining more accurate calculations and to run scenarios managing by basins with this parameter.

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9 APPENDIX

9.1 MINING GENERAL ASPECTS IN CHILE

9.1.1 Mining Sector and Economy

In Chile, mining participates in a relevant way in the national economy; it has been the most important economic sector for the country.

In terms of global copper production, the country had a participation of 16% in 1990, 25% in 2000, 35% in 2010 and 28.3% in 2018 [36] [37]. In terms of incomes, it has had a contribution of the order of 9% of GDP for the last two decades [38]. In 2018, the mining in GDP reached 9.8% [39]

The copper industry has a strong multiplying effect, contributing to the consumption of goods and services in other industries. Available research shows that for every US$100 contributed by mining to the economy, at least another US$36 in indirectly generated [38]. Considering these multiplier effects, the contribution mining activity makes to GDP could be higher than what is mentioned previously.

However, this it is not homogeneous for all Regions of the country, since the main copper deposits have been centralized in northern Chile. For example, as is shown in Figure 39, in Antofagasta Region, mining averaged 63% of the regional GDP between 2008 and 2014. For its part, Atacama had an average of 50% during the same period, while in seven other regions, mining activities accounted for over 15% of regional GDP [38].

Figures 40 and 41 show the location of the main mining operations that currently exist throughout the country of Copper and Gold respectively.

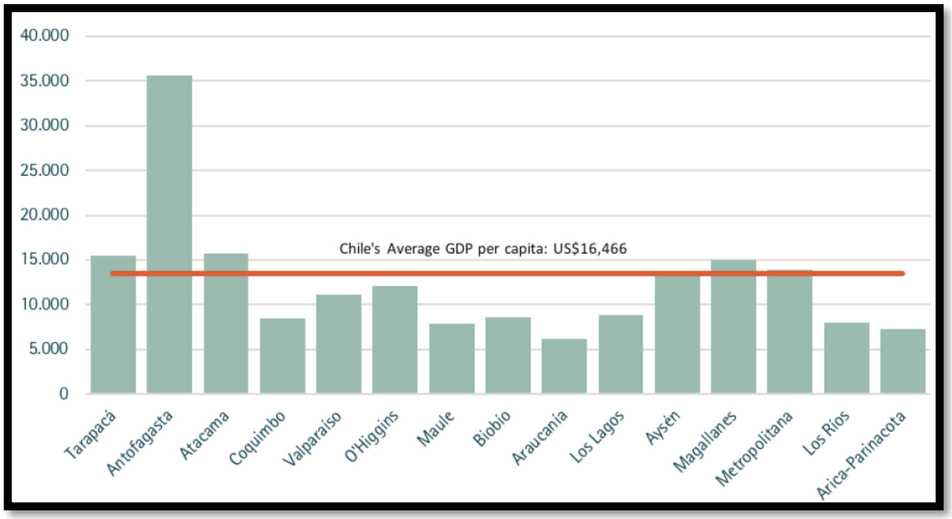

Figure 39: Percapita GDP per Region in 2015 [39]

In Chile, the main types of deposits with respect to their geological characteristics are copper porphyry, epithermal precious metal and skarn or contact metasomatic.

This ore deposits are located mainly in the north of Chile. These regions are rich in copper, gold, molybdenum, silver, iron, nitrate, boron, iodine, lithium, potassium and other resources. It reserves constitute 6.7% of the world's gold, 12.1% of the molybdenum, 13.3% of the silver, 27.7% of the copper, 53% of the rhenium, 57.9% of the lithium carbonate, 60.8% of the iodine, and 100% of the natural nitrates [40] .

Figure 40: Mining Map of Copper Operations in Chile [41]

Figure 41: Mining Map of Gold Operations in Chile [41]

9.1.2 Metals Mining Production

The quantified outputs of copper, molybdenum, gold and silver over recent years are presented in Table 10, while Figures 42 and 43 provide graphical representations of the aforementioned production data [41].

Table 10. Metal mining production in Chile 2012-2018 [41]

Metal/Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Copper (KMT Pure Content)	5433.9	5776.0	5761.1	5772.1	5552.6	5503.5	5831.6
Molybdenum (MT Pure Content)	35,089.9	38,715.4	48,770.2	52,579.3	55,647.3	62,746.1	60,705.3
Gold (Kg Pure Content)	49,936	51,309	46,031	42,501	46,333	37,911	37,066
Silver (Kg Pure Content)	1,194,521	1,173,845	1,571,788	1,504,271	1,501,436	1,318,582	1,370,237

Figure 42 and 43 shows the chronology of metal production in the country, this mean that the main minerals that have been extracted are copper and silver and that although the amount extracted by type of mineral has varied slightly over the years, there is a significant difference between the different productions.

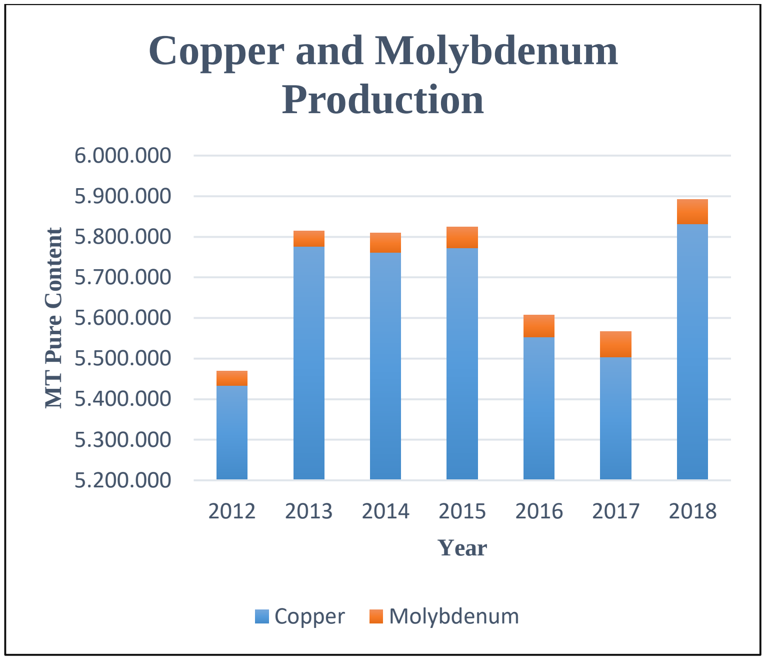

Figure 42: Copper and molybdenum production in Chile 2012 – 2018 [41]

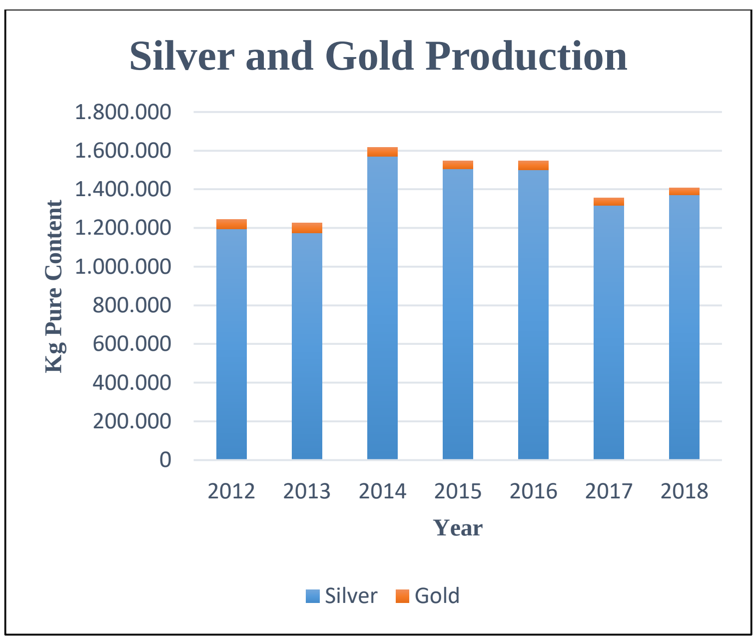

Figure 43: Silver and gold production in Chile 2012 – 2018 [41]

With regard to potential scenarios of global copper demand it is expected, at short term, that all the countries, excepting China, would increase the demand with an average ratio of 2.1% per year.

However, in the immediate years to 2021, is expected a slowdown in economic growth of 4.1% in 2022 and 3.2% in 2023 [42].

At long term copper demand projections are very positive. Refined copper consumption by 2050 could reach 38 million tons annual with an annual increase of more than 450 KTMF as is shown in Figure 44 [43].

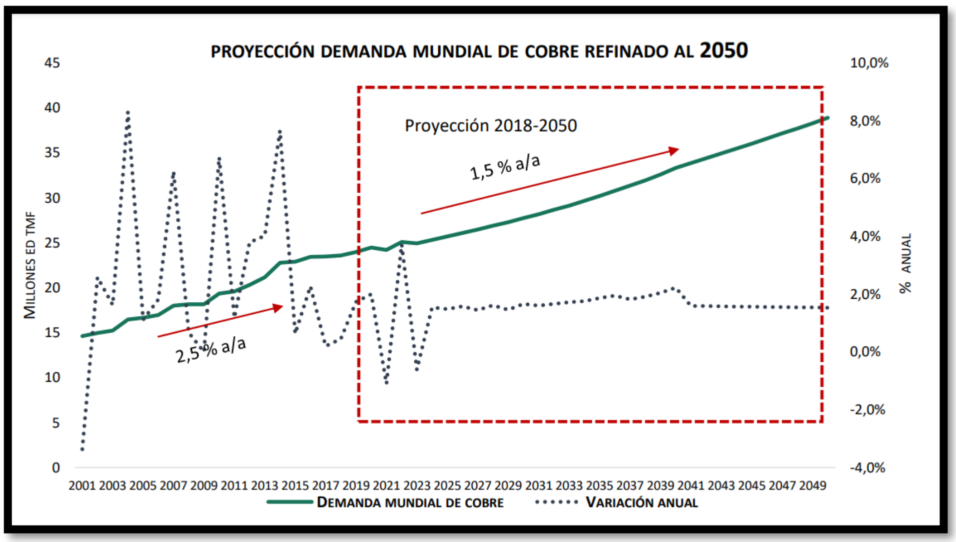

Figure 44: World demand for copper and its annual variation [44]

9.1.3 Ore Grade and Projection

Ore grade in minerals is the amount of valuable metal in it. In copper case, it is reported as a percentage, in the case of precious metal ores as gold and silver, its analysis is reported in g/TM or troy ounce/TC.

One of the major challenges that Chilean mining faces is the lowering of the grades in its deposits. In 1992, 21% of the world copper production was made from minerals with better grades than Chilean minerals. In 2010, it was 35% and in 2020 raised to 43% [36] . This means the requirement of greater energy and water resources per ton of copper produced.

A competitiveness indicator of Chilean copper industry is the average copper grades which companies work them for the mineral processing. Table 11 shows a trend towards copper processing with lower grades.

Table 11. Average copper mining grades in Chile, by process type [7]

Process Type/Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Concentrator Plant	0.97	0.92	0.87	0.85	0.89	0.90	0.87	0.81	0.80	0.78
Heap Leach	0.68	0.67	0.65	0.66	0.66	0.67	0.64	0.60	0.61	0.51
ROM or Dump Leach	0.43	0.43	0.43	0.49	0.41	0.43	0.40	0.39	0.35	0.34
Average	0.76	0.75	0.70	0.72	0.71	0.72	0.69	0.65	0.65	0.61

The mean copper grade has been decreased and in total there is not many high grade deposits in the world, but the ability to profitably extract metals from low grades ores improves over time. This massive decrease in copper ore grades was not driven by depletion of higher grade deposits with resulting higher copper prices. It was instead a direct result of innovation which converted massive supplies of previously worthless "waste" rock into valuable ore. This technological leap was not a fortuitous one-off event. Improvements in extractive technologies are ongoing and continue to render ever lower grades of ore economically viable. This being the case, when demand continues to increase it would expect average grades to decrease, regardless of whether high grade resources are depleted or not [44].

In addition, there are similar points regarded to ore grade's trends processed in recent years that has a significance in process production for getting the same quantity of pure copper [7]. In Figure 45, the brown line shows the ore grade's average which the industries work for sulphides and oxidized minerals. The orange line shows the ore grades for concentration process, the yellow one for heap lixiviation process and the green one for dump lixiviation.

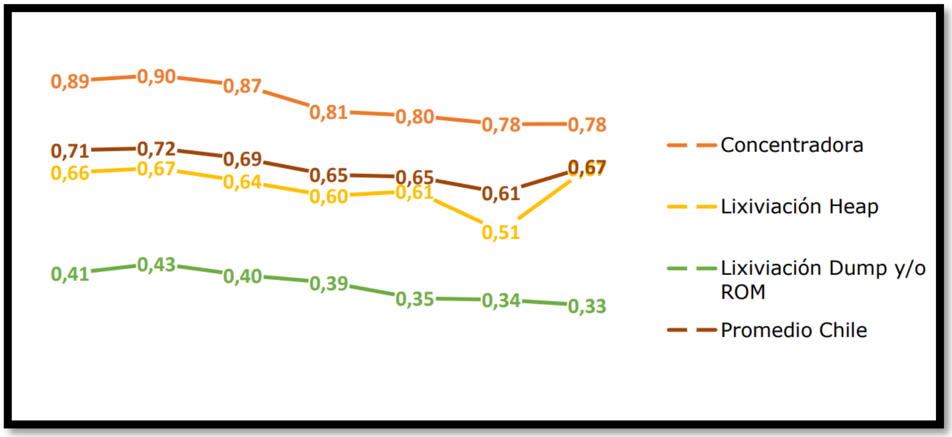

Figure 45: Average grades of oxide and sulphide minerals in Chile 2013 - 2019 (%) [7]

9.1.4 Copper Ore Processing

The minerals of interest that are extracted from the mine are separated from the waste through processing methods that depend on technical, economic, social and environmental variables. Within technical variables is the mineralogy for obtaining valuable minerals [7].

For copper sulphide minerals such as Chalcopyrite ($CuFeS_2$), Chalcocite (Cu_2S), Covellite (CuS), Bornite (Cu_5FeS_4), Enargite (Cu_3AsS_4), are characterized by having a low solubility in water and acid solutions, therefore, its processing is based on the concentration by flotation that consists in the injection of chemical reagents that give hydrophobic properties to the particles [7].

For copper oxidized minerals such as Atacamite ($Cu_2Cl(OH)_3$), Chrysocolla ($(Cu, Al)_4H_4(OH)_8Si_4O_{10}\cdot nH_2O$), Tenorite ($CuO$), or Cuprite ($Cu_2O$), are characterized by having a high solubility in water and in weakly acidic solutions, therefore, its processing is based on leaching that consists in the dissolution of copper present in different mineralogical forms [7].

In Chile, 80% of copper processing corresponds to copper sulphides, therefore, a significant amount of water is necessary for its production [7].

Figure 46 shows the raw water unit use per ton of ore processed where the equation considered to obtain these unit coefficients for concentration and hydrometallurgy process is the following:

Equation 10

$$unit\ coefficient = \frac{(amount\ of\ continental\ water\ demand)}{(ton\ of\ ore\ processed)}\frac{(m^3)}{(ton)} \quad \ldots (10)$$

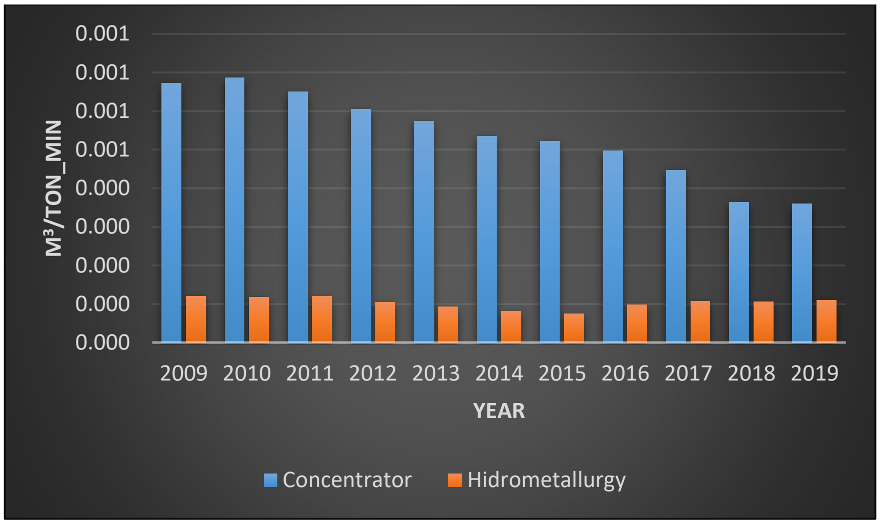

Figure 46:Unit Fresh Water Use per Ton of Ore Processed [7]

The unit consumption in the concentrator plant is greater than in the hydrometallurgical process. This is due, as will be seen later, to the amount of water required for the milling, flotation and thickening processes from concentration treatment, which is greater than that used in the crushing, leaching, solvent extraction and electrowinning processes from hydrometallurgical treatment.

9.2 WATER GENERAL ASPECTS IN CHILE

9.2.1 State of Water Resources

The bodies of water can be found as follows:

- **Surface Water:** Main water resources the country has, including salty water. For storage, the country has more than 60 accumulation reservoirs, mostly destined for irrigation, hydroelectricity and drinking water [45].

- **Underground Water:** Correspond to unconsolidated quaternary sediments of alluvial, fluvial, fluvial – glacial origin, among others. For human consumption, in urban areas it reaches 40% of the total volume consumed and for rural areas, 76% [45].
- **Surface – Underground Water Interaction:** This is due to the characteristics geomorphological and geological that the country presents. In rivers you can see places where surface waters recharge aquifers and in others where waters underground come out on slopes [45].
- **Glaciers:** They constitute one of the main sources of fresh water on the planet. Chile has the 76% of the glacier surface of the South American continent [45].
- **Lakes and Lagoons:** Important reserve in the country. They are mainly located in the southern zone and represent an area of 1.5% of the national territory [45].

Chile compared internationally is considered privileged in what correspond to the availability of water resources. It has 1,251 rivers, which are in the 101 main basins existing in the country. In addition, there are 12,784 bodies of water as lakes and lagoons of all kinds of shapes and sizes plus 24,114 glaciers. In general, the water resources present on them contain good quality water and are important flow regulators in basins [46].

The average precipitation at country level is 1,525 mm/year and a high mean annual freshwater availability per capita of about 53,953 m^3. This is the total average runoff, that is, the volume of water from the precipitations that run down the surface and underground channels. This value is much higher than the world average of 6,600 m^3/person/year and much higher than the value of 2,000 m^3/person/year, internationally considered as the threshold for sustainable development (World Bank, 2010) [47] [10]. However, the availability is unequal throughout the national territory with values as low as 52 m^3 per capita per year in the north (Antofagasta Region, 22°S) and as high as 2,993,535 m^3 in Aysén (45°S) (Atlas del Agua, 2016). Table 12 shows the difference of average precipitation and runoff between the northern zones and southern zones.

Figure 47 displays central and northern Chile with isohyets representing mean annual precipitation, the locations of aquifers and their sustainable volumes calculated by the catchment water balance as reported by the Chilean National Water Department (DGA).

Table 12. Water resources in Chile's regions [10]

	Region	Population Density	Hydrographic Basins	Average Precipitation	Runoff	Per capita runoff
North Macro zone	Arica y Parinacota	7.6 persons/km^2	39	87 mm/year	36.9 m^3/s	510 m^3/person/year
	Tarapacá					
	Antofagasta					
	Atacama					
	Coquimbo					
Centre Macro zone	Valparaíso	141.5 persons/km^2	16	943 mm/year	1,116 m^3/s	3,169 m^3/person/year
	Metropolitana					
	O'higgins					
	Maule					
South Macro zone	Biobío	32 persons/km^2	26	2,420 mm/year	7,834 m^3/s	56,799 m^3/person/year
	La Araucanía					
	Los Ríos					
	Los Lagos					
Austral Macro zone	Aysén	1.1 persons/km^2	20	2,963 mm/year	20,258 m^3/s	2,340,227 m^3/person/year
	Magallanes y Antártida Chilena					

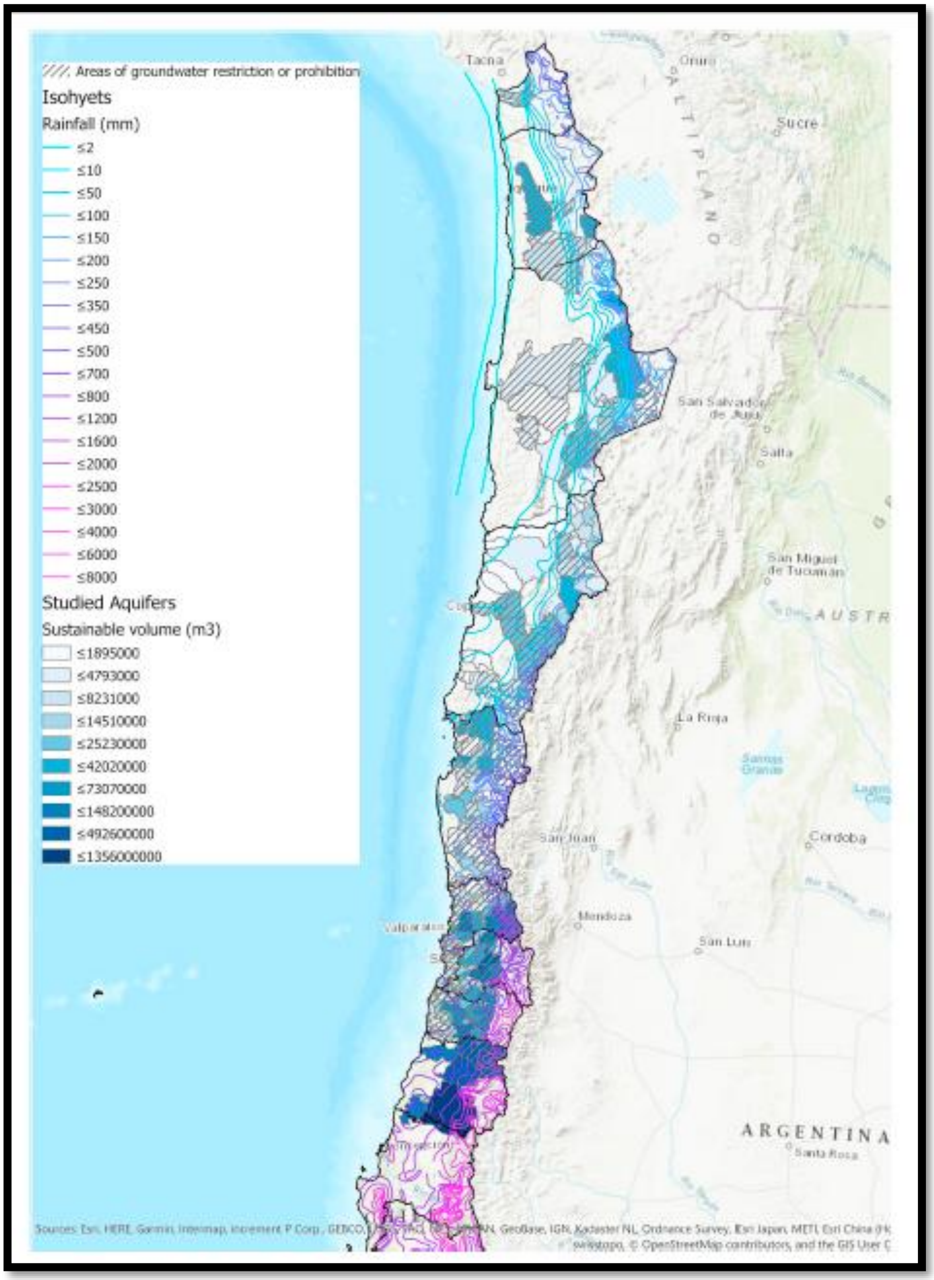

Figure 47: Mean annual rainfall and aquifer storage in central and northern Chile [5]

9.2.2 Droughts, Availability and Uses of Water Resources

Despite this great availability of water, climate change has generated drought, one of the worst meteorological phenomena that can affect the planet. During the last years in the northern, central, south-central and southern areas of Chile have faced severe water scarcity due to the decrease of rainfall, flow rates and a considerable increase in the isotherm zero, affecting the availability of surface water as soil moisture and subsequently groundwater recharged. This situation has caused a rainfall deficit of up to 100% in cities from Coquimbo and Valparaiso Regions [11].

The scarcity of fresh water in arid areas is an economic, environmental, and social problem (Tundisi, 2008; Gleik, 2000). This has allowed to authorities to focusing on reducing the impact to avoiding the detriment of economic and social activities in the country [11].

Until 2020, there are 134 decreed zones with water scarcity. Some statistics are shown in Table 13, according to data since 2008, reported by the DGA, where Valparaíso, Santiago and Coquimbo have the major concentration of scarcity zones [48].

Table 13. Water scarcity zones by regions in Chile since 2008 to 2020 [49]

Regions	**Area (km^2)**	**Water Scarcity Zones**
Arica y Parinacota	16,873	
Tarapacá	42,226	
Antofagasta	126,049	
Atacama	75,176	8
Coquimbo	40,580	26
Valparaíso	16,396	51
Santiago	15,403	28
O'higgins	16,387	3
Maule	30,296	14
Ñuble	13,178	
Biobío	23,890	2
La Araucanía	31,842	
Los Ríos	18,430	
Los Lagos	48,584	1
Aysén	108,494	1
Magallanes y Antártica Chilena	132,297	

About water balances and its projections made based on the economic and infrastructure growth planned to build, there is a deficit between supply and demand from Arica y Parinacota to Santiago Region, which will increase substantially towards a horizon of 15 more years [18] [10] . This can be appreciating in Table 14, Figure 48 and 49.

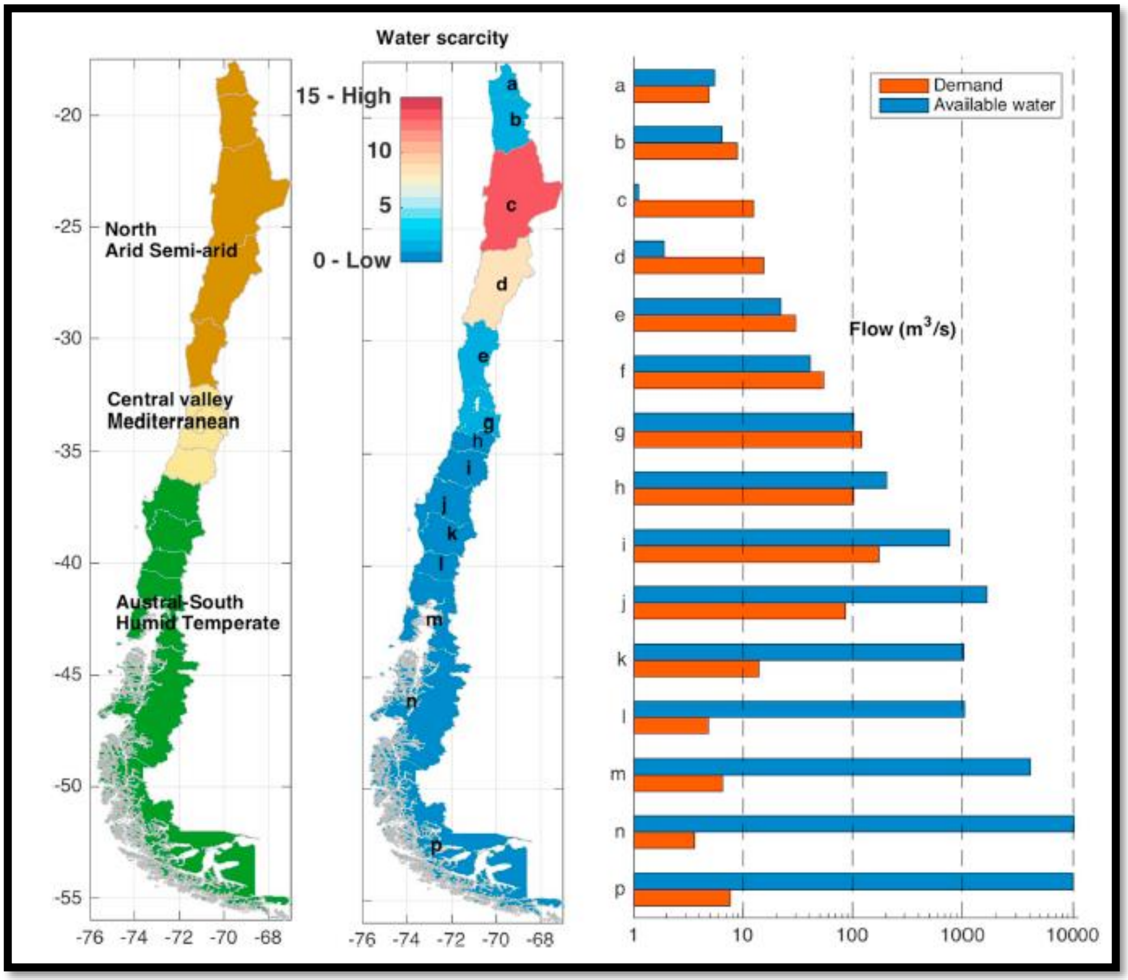

Figure 48: A map of climate zones, the water balance of supply and demand and water scarcity indexes for each region [18]

Table 14. Current and projected future regional water balance in 15 years (m^3/s) [10]

Region	**Current Demand**	**Current Supply**	**Current Balance**	**Future Demand**	**Future Supply**	**Future Balance**
Tarapacá	16.7	11.9	-7.4	26.3	11.9	-17.0

Antofagasta	23.0	0.90	-22.0	34.8	0.90	-33.8
Atacama	16.7	1.9	-14.8	22.4	1.9	-20.5
Coquimbo	35.0	22.2	-12.8	41.8	21.1	-20.7
Valparaíso	55.5	40.7	-27.4	64.2	36.6	-38.7
Santiago	116.3	103.0	-35.6	124.9	92.7	-51.4
O'higgins	113.5	205.0	38.7	119.1	184.5	18.7
Maule	177.1	767.0	442.5	184.5	690.3	383.6
Biobío	148.0	1,638.0	1,249.1	246.0	1,474.2	1,033.3
Araucanía	25.5	1,041.0	767.3	38.3	936.9	675.4
Los Lagos y Los Ríos	12.0	5,155.0	3,905.8	17.9	4,639.5	3,508.1
Aysén	24.9	10,134.0	8,284.6	27.0	10,134.0	8,282.9
Magallanes	8.4	10,124.0	8,394.6	15.7	10,124.0	8,387.2
Total Country	772.6	29,244.6	22,962.7	962.8	28,348.5	22,107.1

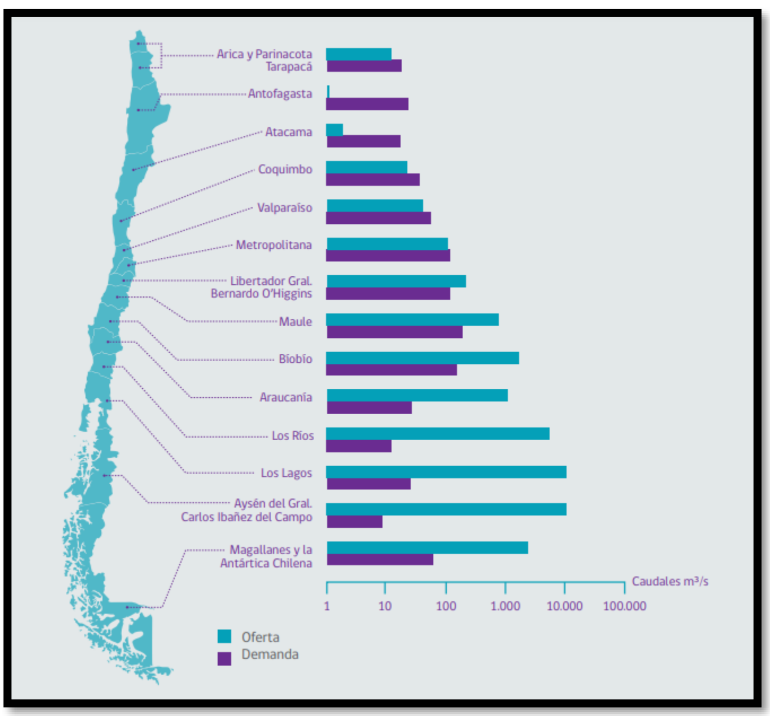

Figure 49: Water availability and extraction by Regions [10]

As can be seen, current and future water balances are negative from Tarapacá to Santiago. The difference is significant between the northern Regions and those of the centre and south. While in the South the availability of water is abundant, having a maximum balance variation of 51.7% corresponding to the O'higgins Region, in the North, there may be a variation of up to 129.7% availability corresponding to the Tarapacá Region. This situation produces greater scarcity over time.

Figure 50 shows the existing water gap of 25 basins out of a total of 101, where the reference supply and water consumption parameters are analysed and compared. Heterogeneous situations can be seen, without a tendency or majority behaviour towards one condition or another [46].

However, information can be extracted from the 3 main basins found in the Atacama Region: Río Copiapó, Río Salado and Río Huasco.

For the Copiapó River Basin there is strong pressure on water resources. It denotes a maximum urgency for the organization of supply and demand. In these cases, the low availability of water is a limiting factor for economic development [46].

For the Salado River Basin, there is strong pressure on the water resource, requiring ordering of supply and demand, to assign priorities for use, pay attention to aquatic ecosystems and improve water efficiency [46].

For the Huasco River Basin, it indicates that the availability of water is becoming a limiting factor for development [46].

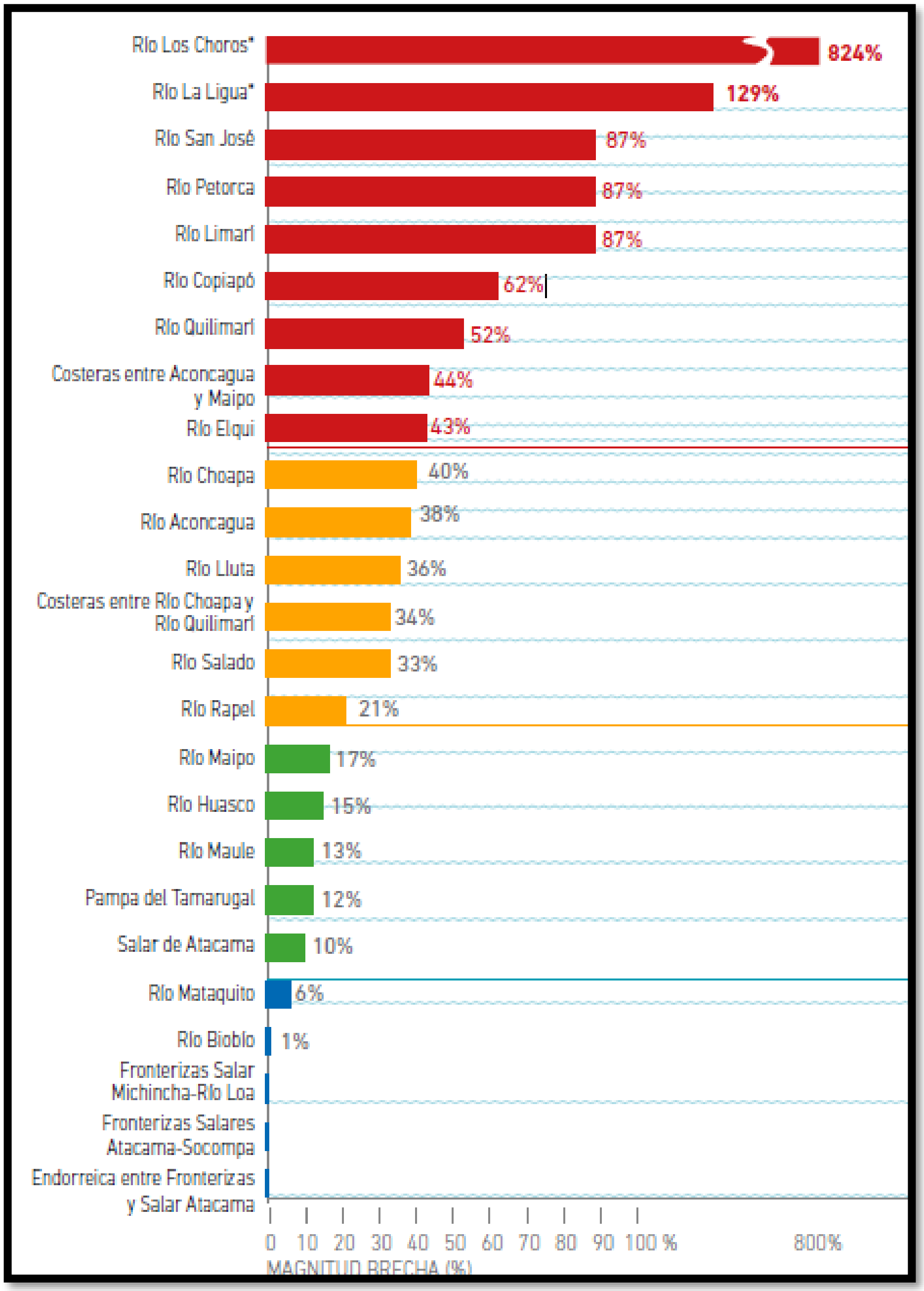

Figure 50: Water gap in 25 basins analyzed [47]

At the same time, in Chile large volumes of water are used in water-scarce regions where mining takes place, alongside agriculture and small communities. At global scale, mining is a relatively small water consumer but habitually at local scale is a major water consumer (*Northey et al., 2016*).

One of the main economic activities that takes place in the north is mining, concentrating 78% of the national total of companies dedicated to the extraction of copper, gold, silver and other minerals. This activity requires water to carry out its processes, with an estimated demand of 29.38 m^3/s. The agricultural sector is the one that most uses the water resources for irrigation of crops and watering hole for animals with a demand of 51.45 m3/s [49]. Figure 51 displays the consumption by sector at national level, where the highest corresponds to agriculture sector representing an 82% and the smallest correspond to mining sector representing a 3% of the total consumptive uses.

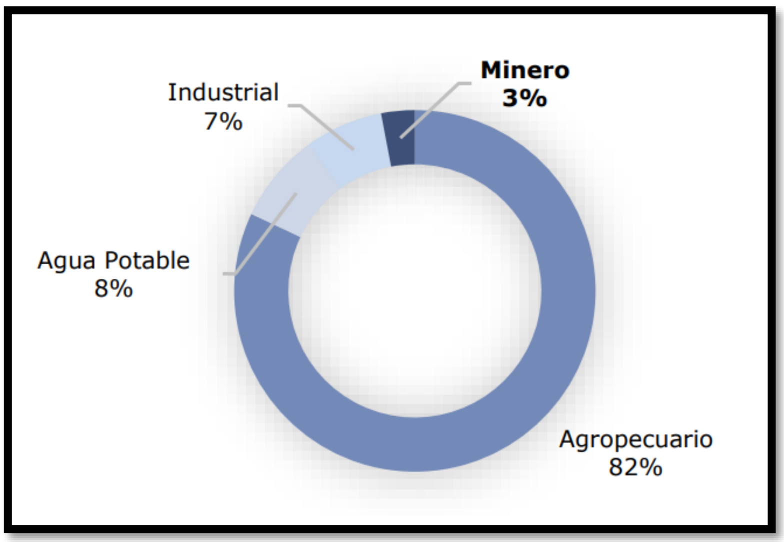

Figure 51: Distribution of consumptive uses of water in Chile [10]

9.3 Examples of seawater use in mining with saline water

Plant	Country	Metal	State	Technology
El Boleo Project	Mexico	Copper, Cobalt, Zinc, Manganese	Project	Leaching
Mount Keith	Australia	Nickel	Operating	Flotation
Sierra Gorda	Chile	Copper, Molybdenum	Operating	Flotation, Leaching

Black Angel	Greenland	Lead, Zinc	Closed	Flotation
Batu Hijau	Indonesia	Copper, Gold	Operating	Flotation
Beverley Uranium Mine	Australia	Uranium	Operating	Leaching in situ
Minera Michilla	Chile	Copper	Closed	Leaching
Antucoya Project	Chile	Copper	Project	Leaching
Minera Las Luces	Chile	Copper	Operating	Flotation
Minera Algorta Norte S.A.	Chile	Iodine	Operating	Leaching

9.4 THE PATH COST TOOL

The Path Cost tool produces an output raster that records the least cost path or paths from the selected locations to the closest source cell defined within the accumulative cost surface, in terms of cost distance [50]. One or more of the weighted cost tools (Cost Distance, Cost Back Link, or Cost Allocation) are generally required to run prior to running Cost Path to create the input cost distance and back link rasters. These are mandatory input rasters to Cost Path.

Cost Distance tool calculates the least accumulative cost distance for each cell from or to the least-cost source over a cost surface [51].

Cost Back Link tool defines the neighbour that is the next cell on the least accumulative cost path to the least-cost-source [52].

Cost Allocation tool calculates, for each cell, its least-cost source based on the least accumulative cost over a cost surface [53].

Thus, the inputs necessary to get the output cost path raster are:

1. Raster or feature destination data: A raster or feature dataset that identifies those cells from which the least-cost path is determined to the least costly source [50].

2. Cost distance raster: The name of a cost distance raster to be used to determine the least-cost path from the destination locations to a source. It stores, for each cell, the minimum accumulative cost distance over a cost surface from each cell to a set of source cells. It is usually created with the Cost Distance, Cost Allocation or Cost Back Link tools [50].
3. Cost backlink raster: The name of a cost back link raster used to determine the path to return to a source via the least-cost path [50].

9.5 GENERALS ASPECTS OF TRANSPORT MODEL

Unbalanced Transportation Problem: A transportation problem is said to be unbalanced when the total demand is not equal to the total supply. In this situation, there will be need to create a dummy and this depends on the excess or shortage between the demand and the supply. That is there will be need to create dummy demand if supply is greater that demand or dummy supply if the demand is greater than supply with zero cost of transportation [26].

Balanced Transportation Problem: A transportation problem is said to be balanced when the total demand is equal to the total supply. That is

Equation 11

$$\sum_{i=1}^{m} a_i = \sum_{j=1}^{n} b_j \qquad \ldots (11)$$

Where *"m"* are the sources of the homogeneous product, *"n"* the destinations where the homogeneous product goes, *"a_i"* are the units of product available in the sources of origin (*m*) and *"b_i"* are the units of product that requires the destinations points (*n*) [26].

The numbers of a_i and b_i are positive integers and the cost *"C_{ij}"* of transporting one unit of product from the source *"m"* to the destination *"n"* is given for each *i* and *j* [26].

The objective is to develop an integral transportation schedule that meet all demands from current inventory at the minimum total shipping cost.

The above equation is guaranteed by creating either a fictitious destination with a demand equal to the surplus, if total demand is less than the total supply, or a dummy source with a supply equal to the shortage if total demand exceeds total supply [26].

If X_{ij} represent the number of units to be shipped from sources *i* to *j*, mathematical model for the problem is

Equation 12

$$\min Z = \sum_{i}^{m}\sum_{j}^{n} C_{ij}X_{ij} \qquad \text{... (12)}$$

Subject to

$$\sum_{j}^{n} X_{ij} \le a_i \qquad , for\ all\ i$$

$$\sum_{i}^{m} X_{ij} \ge b_j \qquad , for\ all\ j$$

With all X_{ij} nonnegative and integer [26].

9.6 Other Relevant Information of the Prospects

9.6.1 Caserones

- It belongs to Lumina Copper Company which integrates the Japanese Firms Pan Pacific Copper Co. Ltd. (77,37%) y Mitsui & Co., Ltd. (22,63%). Pan Pacific Copper Co., Ltd. Is conformed of the companies JX Holding, Inc. (51,50%) y Mitsui Mining & Smelting Co., Ltd (25,87%).
- Its production began in 2013.
- It has an annual production of 150,000 tons of pure copper.
- Mineral extraction is done using open pit method.
- It is located 170 km from the coast and 4,300 m.a.s.l.

9.6.2 Candelaria

- It belongs to Freeport McMoRan Copper & Gold.
- Its production began in 1993.
- It has an annual production of 175.000 tons of pure copper.
- It has 1 open pit mine and 2 underground mines.
- It is located 75 km from the coast and 650 m.a.s.l.

9.6.3 Pedro Aguirre Cerda (Ojos del Salado)

- It belongs to Lundin Mining and Sumitomo.
- Its production began in 1929 (Planta Punta del Cobre).
- It has 2 underground mines.
- It has an annual production of 30,000 tons of copper concentrate.
- It is located 70 km from the coast and 600 m.a.s.l.

9.6.4 El Salvador

- It belongs to CODELCO.
- Its production began in 1959.
- It has an annual production of 48.000 tons of pure copper.
- It has 1 underground mine.
- It is located 120 km from the coast and 3,000 m.a.s.l.

9.7 MODEL BUILDER DIAGRAM FOR DEVELOPING ROUTES

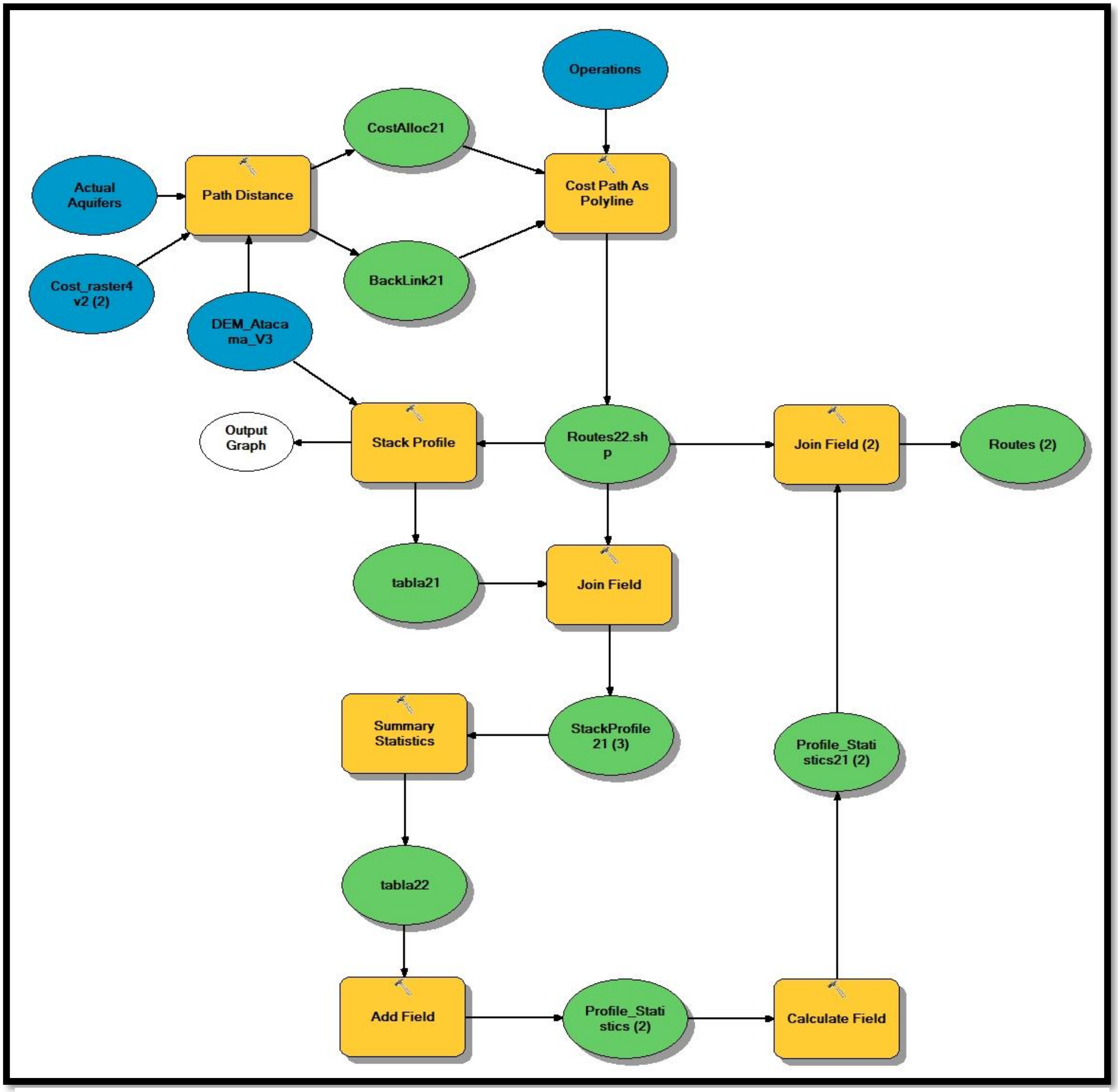

Figure 52: Model builder diagram for developing routes (Own elaboration)

UNIVERSIDAD DE CONCEPCIÓN - FACULTAD DE INGENIERÍA
Departamento de Ingeniería Metalúrgica
Hoja Resumen Memoria de Título

Título: Tools for planning regional water supplies in mining regions: Viability of mining through a centralized desalination plant scheme in Chile's Region III

Nombre Memorista: NATALIA CONSTANZA OBREGÓN ROJAS

Modalidad	**Investigación**
Concepto	MUY BUENO
Calificación	6.6
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Prof. René Gómez P.

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Comisión (Nombre y Firma)

Prof. Andrés Ramírez M.

Resumen

La actividad minera cuprífera en Chile en los últimos años muestra una tendencia hacia el cambio de matriz de producción, aumentando la extracción de minerales de sulfuros por sobre la extracción de minerales de óxidos. El procesamiento de sulfuros para la producción de concentrados de cobre se realiza mediante flotación, el cual tiene demandas de agua más intensivas, utilizando cantidades significativamente mayores que en el proceso de lixiviación.
Paralelamente las sequías que predominan en el sector norte de Chile, provocadas mayoritariamente por el cambio climático y la sobre explotación de cuencas, han originado la necesidad de abarcar un estudio interdisciplinario con la participación de distintas partes involucradas para lograr una gestión eficiente del agua en las regiones.

Una de estas es la región de Atacama, segunda más afectada del país, con balances negativos de oferta y demanda de agua, actuales y proyectadas, para el sector minero, agrícola y comunitario. Una de las soluciones que la gobernanza ha planteado es la construcción de plantas desalinizadoras de mar con el fin de reducir riesgos de suministro. Sin embargo, estos suministros se caracterizan por tener altos costos operacionales debido a la distancia y diferencia de altura que hay entre el reservorio de agua desalada y las operaciones.

Estos antecedentes motivan esta investigación a evaluar y comparar 2 sistemas de redes de suministro hacia operaciones con planta de tratamiento de cobre en la región de Atacama, siendo el primero la representación actual de demanda con suministro de agua continental y desalada, y el segundo un sistema propuesto de solo agua desalada como suministro a través de un esquema de planta desalinizadora. Los parámetros para realizar esta evaluación se obtienen mediante un modelo desarrollado en el programa ArcGIS que integra herramientas de cálculo optimizado de costes de rutas y distancias, según la ubicación espacial de los puntos de ofertas y demanda.

El modelo arrojó un OPEX y un CAPEX para el sistema actual de 1.310,076 MUSD y 829,151 MUSD respectivamente. En contraste, para el sistema propuesto, con solo la planta desalinizadora como distribuidora de agua, el OPEX Y el CAPEX alcanzaron valores de 1.950,076 MUSD y 1.115,976 MUSD respectivamente.