

Optimization Approach to Designing Water Supply Systems in Non-Coastal Areas Suffering from Water Scarcity

Sebastián Herrera-León^{1,2,3} · Freddy Lucay¹ ·
Andrzej Kraslawski^{3,4} · Luis A. Cisternas^{1,2} ·
Edelmira D. Gálvez⁵

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Abstract This article presents a novel optimization approach to designing water supply systems in non-coastal areas with water scarcity. In such areas, high water demand caused by population increases and economic development can only be satisfied with seawater supply. Furthermore, most of the non-coastal users are located at long distances and sometimes at altitudes very diverse from the coastline, meaning long pipelines and several pumping stations will be required to effectively supply water. The proposed optimization approach based on a mixed integer nonlinear programming model offers optimal designs of water supply systems from an economic and technical perspective. It determines the location and size of desalination plants and the design of the water transport network including pipelines of specified length and diameter and pumping stations that minimize capital and operational costs of the whole system. A case study in a hyper-arid region of Chile was used to validate the applicability of the proposed model and the results show its aptitude for determining global optimal solutions to real-scale problems.

✉ Luis A. Cisternas
luis.cisternas@uantof.cl

¹ Department of Chemical Engineering and Mineral Process, Universidad de Antofagasta, Angamos avenue 601, Antofagasta, Chile

² Center for Scientific and Technological Research in Mining, CICITEM, Antonio José de Sucre 220, Antofagasta, Chile

³ School of Business and Management, Lappeenranta University of Technology, Skinnarilankatu 34, Lappeenranta, Finland

⁴ Department of Process and Environmental Engineering, Lodz University of Technology, 116 Żeromskiego Street, Lodz, Poland

⁵ Department of Metallurgy and Mining Engineering, Universidad Católica del Norte, Angamos avenue 0610, Antofagasta, Chile

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1 Introduction

Water crisis is one of the main threats facing humanity (Chen et al. 2018). The problem is crucial in hyper-arid and arid regions of the world, where water shortage is a reality (Pereira et al. 2009). In these water-stressed regions, ensuring access to good quality water for the entire population is a rather complex task. In the search for sustainable alternatives, non-conventional water sources have been considered in water supply systems, e.g. rainwater, wastewater and seawater (Nápoles-Rivera et al. 2013). However, due to the magnitude of the ocean, seawater is considered the largest non-conventional water source on Earth capable to meet real increasing water demands around the world. In this context, seawater desalination technologies play an important role in ensuring good quality water supply in water-stressed regions. The total installed desalination capacity in 2012 was 74.8 million m³/d and is currently a growing trend mainly due to population increment, as well as industrial and agricultural activities that drive economic development in several countries (Gude 2016). The installed desalination capacity is distributed across several world regions and the most frequently used desalination technology is the reverse osmosis enjoying 63% share of the world market (Gude 2016). Desalination plants can be found in Algeria (Mohammedi et al. 2013), Spain (García-Rubio and Guardiola 2012), countries which border the Arabian Gulf (Barau and Al Hosani 2015), Israel (Tenne et al. 2013), Chile (Knops et al. 2013), Australia, USA, Singapore, China and the Kingdom of Saudi Arabia (Gude 2016), among other countries. Considering the relevance of seawater as a water source, it is clear that desalination technologies play a key role in mitigating water scarcity. Nevertheless, a clear understanding of how to integrate these types of technologies into water supply systems is required to develop optimal design.

1.1 Literature Review

Several optimization approaches have been proposed in research literature to designing water supply systems, in which seawater is considered as a water source. For instance, Kondili et al. (2010) proposed an approach based on a linear model for determining the total value of water, which the authors understand as the total revenue from water sales minus total costs of water production, in order to optimize the topology of water supply systems. Atilhan et al. (2011) introduced an approach based on a nonlinear model for determining the location, capacity, and type of technology applied in desalination plants, as well as the topology of the water supply system to meet water requirements of the users at minimum cost. Liu et al. (2011) presented an approach based on a mixed integer linear model for integrated management of water resources in insular areas, in order to minimize capital and operating costs of the whole water supply system including wastewater treatment and reclamation plants. Atilhan et al. (2012) developed an integrated approach based on a linear model for designing and operating water supply systems including wastewater treatment facilities and storage in order to maximize the economic potential of water resources that, according to the authors, is the total value of water allocated to users minus the total cost of desalinated water produced. Liu et al. (2012) proposed an approach based on mixed integer linear model in order to determine the optimal scenario that meets all water needs of an insular area at minimum cost. Al-Nory et al. (2014)

introduced an approach based on a linear model to minimize the total cost of investment and operation of a desalinated water supply system. González-Bravo et al. (2015) presented an approach based on a nonlinear model to integrate desalination plants with power plants in the optimal design of water supply systems, in order to maximize gross annual profit from water and energy sales. González-Bravo et al. (2016) developed an approach to integrate seawater desalination with power plants in an optimal design of water supply systems, with the objective to maximize gross annual profit, minimize the overall greenhouse gas emissions, and quantify jobs generated by the system. Shahabi et al. (2017) proposed an approach to integrating a mixed integer linear model, a life cycle assessment model, a cost model and a geographic information system for planning desalination water supply systems in metropolitan areas considering economic or environmental objectives depending on decision maker's preferences.

The majority of studies mentioned above have been focused on the design of topology and operation of water supply systems. However, they have not considered in detail the technical aspects of the design, such as its size, mainly the diameter of pipes and pumping stations capacity which are relevant aspects, especially knowing that only 39% of the world population lives at a distance of less than 100 km from the ocean (Ghaffour et al. 2013). Therefore, long pipelines and several pumping stations will be required to supply water, which has important economic implications. According to Balfaqih et al. (2017), a desalinated water supply system can be seen as a supply chain, where feed water is acquired, desalinated, stored, and is distributed to end users. Considering this, the main costs of a desalinated water supply system are connected with seawater extraction, desalination process, storage and desalinated water transport. However, commonly water extraction is considered part of the desalination process cost and the storage part of the water transport cost. Gude (2016) gives the estimated unit cost of desalinated water and its transportation in different countries. For instance, the estimated unit cost in Mexico City, where desalinated water is transported for 225 km and elevated 2500 m above sea level, is 2.44 US\$/m³. If the unit cost of desalination process is estimated at 1.0 US\$/m³, as was assumed by the authors, the transport of desalinated water would cost 1.44 US\$/m³, accounting for 60% of the total unit cost of the water supply system. These data are based on the study conducted by Zhou and Tol (2005), in which the authors indicated that to elevate desalinated water by 100 m vertically is about as costly as transporting it for 100 km horizontally. However, this analysis ignores the capital cost of installing pipelines, meaning more realistic estimates should be higher. Based on the information described above, costs of transporting desalinated water play a relevant role in water supply systems when the area covered by the study involves large altitude differences and long distances between desalination plants and users. In this context, several pumping stations and long pipelines could be required, which considerably increases capital and operational costs of the water supply system.

1.2 Study Objective

In this article, we propose a novel optimization approach based on a mixed integer nonlinear programming model (MINLP) for designing water supply systems in non-coastal areas suffering from water scarcity. To integrate all possible water supply alternatives, a network is introduced, which represents possible interconnections between sources, interceptors, and users. An important novelty is the determination of the optimal location and size of desalination plants, as well as water transport network design from an economic and technical

perspective. The design includes the diameter and length of pipelines and the number of pumping stations that minimize total costs.

2 Methodology

The methodology is divided into two sub-sections: problem identification and the description of the optimization model. In the first sub-section, we discuss characteristics of the issue at hand and the main aspects that have to be taken on board when designing water supply systems. In the second sub-section, the proposed optimization model is presented in detail, together with constraints and the objective function considered.

2.1 Problem Statement

The problem tackles a determined number of users in specific already identified locations, who demand different quantities of desalinated water of the same quality throughout the year. Demand for desalinated water is satisfied by installing desalination plants on the coast and a number of pumping stations depending on where users are located, i.e. on the distance and altitude difference from the coastline. Once the potential location of all elements including users, desalination plants and pumping stations are defined, logical connections between these elements are delineated. These connections are pipelines, in which water flows from desalination plants to the users. A set of available pipelines with different specific diameters were considered, which is logical taking into account that pipelines are made with standard inner diameters.

The design problem consists in determining optimal water supply system that satisfies the demand for desalinated water of several users located in an area suffering from water scarcity. The optimal system is expected to incur the lowest cost, identify the location and size of desalination plants and pumping stations, as well as the length and diameter of pipelines. To find this optimal solution, water supply system is presented as a network including nodes and arcs. Nodes represent desalination plants, pumping stations, and users, while arcs represent the pipelines. The network represents all possible water supply alternatives and is defined using a geographic information system (GIS) in SO_q desalination plants in specific locations, in certain elevations, and with maximum production capacity; N_r pumping stations in known locations and elevations; and SI_s users with known demand for desalinated water, location, and elevation. The subscripts q , r , and s represent the number of desalination plants, pumping stations, and users, respectively.

2.2 Optimization Model Description

In the mathematical representation of the network, four main sets are used: the set of desalination plants, $SO = \{so \mid so \text{ is a desalination plant}\}$, the set of pumping stations $N = \{n \mid n \text{ is a pumping station}\}$, the set of users $SI = \{si \mid si \text{ is a user}\}$, and the set of discrete pipelines diameters $D = \{d \mid d \text{ is a pipeline diameter}\}$. Potential connections between two nodes i, j are established in the set FIJ , with specified distances $(L_{i,j})$ and altitude differences $(\Delta Z_{i,j})$. By knowing potential connections between two nodes, we also know desalinated water flow inlets and outlets for each node represented by sets *input* and *output*, respectively.

In this mathematical formulation, desalinated water flows only in one direction, from the source to the user. Therefore, negative values for water flows are not considered and the network can be presented only as a tree. This consideration is relevant for avoiding the natural non-convexity of water transport network design problems, which can pose challenges to determining the global optimal solution (D’Ambrosio et al. 2015). Non-convexity in water transport network design is a difficult problem to face when, for instance, urban water systems are designed. In an urban water system, water can flow in both directions inside a pipeline, which is not easy to handle mathematically. For this reason, the mathematical community has put a lot of effort to develop sophisticated methods and tools to solve this type of problems (Bragalli et al. 2012).

2.2.1 Constraints

For each node, flow conservation constraints based on the continuity equation ensure that desalinated water flows produced or introduced into a node are equal to desalinated water flows consumed or extracted at the same node. Flow conservation in the desalination plants, pumping stations and users is described in Eqs. (1), (2) and (3), respectively. The variable $Q_{i,j}$ refers to water flow pumped from node i to j ; and the nodes i and j are elements of the set $SI \cup SO \cup N$. For a better understanding of variables, see the nomenclature section.

$$Q_{so}^* = \sum_{n \in output} Q_{so,n} \quad \forall so \in SO \tag{1}$$

$$\sum_{i \in input} Q_{i,n} = \sum_{j \in output} Q_{n,j} \quad \forall n \in N \tag{2}$$

$$Q_{si}^* = \sum_{n \in input} Q_{n,si} \quad \forall si \in SI \tag{3}$$

Constraints associated with the maximum production capacity of desalination plants (C_{so}^{max}), and desalinated water requirements set by users (R_{si}), are described in Eqs. (4) and (5) respectively. To adjust the size of the problem, it is recommended to consider C_{so}^{max} as the sum of the R_{si} of all users, i.e. $C_{so}^{max} = \sum_{si \in SI} R_{si}$.

$$Q_{so}^* \leq C_{so}^{max} \quad \forall so \in SO \tag{4}$$

$$Q_{si}^* \geq R_{si} \quad \forall si \in SI \tag{5}$$

For the selection of pipeline diameter between nodes i and j and its inner area, a disjunction constraint based on the binary variable $y'_{i,j,d}$ is used, which is expressed in Eq. (6).

$$\forall_{d \in D} \begin{bmatrix} y'_{i,j,d} \\ D_{i,j} = D_d \\ A_{i,j} = A_d \end{bmatrix} \quad \forall (i,j) \in FIJ \tag{6}$$

Binary variable $y'_{i,j,d}$ allows selecting one of the available diameters. Therefore, there will always be a type of diameter selected, which means there will always be a connection between all nodes i and j . The model must be able to evaluate the existence of a pipeline between two nodes to evaluate different topologies. To ensure this existence, a new binary variable is included, $y_{i,j}$. If the binary variable $y_{i,j}$ is zero, there is no pipeline diameter (and pipeline area) between nodes i and j . This dependency is expressed using Eqs. (7), (8) and (9).

$$\sum_{d \in D} y'_{i,j,d} = y_{i,j} \quad \forall (i,j) \in FIJ \tag{7}$$

$$D_{i,j} = \sum_{d \in D} D_d \cdot y'_{i,j,d} \quad \forall (i,j) \in FIJ \tag{8}$$

$$A_{i,j} = \sum_{d \in D} A_d \cdot y'_{i,j,d} \quad \forall (i,j) \in FIJ \tag{9}$$

A relevant criterion in the design of a water supply network is the maximum velocity (v^{max}) of water flowing into pipelines. This parameter must not exceed a specific value to avoid a number of potential operating problems, for instance, the flow-assisted corrosion problem. Because velocity is a parameter and not an explicit variable, maximum velocity is expressed as a bounded function of the water flow by using the relationship between velocity and pipeline area, as described in Eq. (10).

$$Q_{i,j} \leq v^{max} \cdot A_{i,j} \quad \forall (i,j) \in FIJ \tag{10}$$

The fundamental mathematical model for a pipeline is the energy equation, which is expressed in Eq. (11). This equation results in $H_{i,j}$ that is the pressure value known as hydraulic head, expressed in terms of column of water, necessary to transport the water flow from node i to node j . The $\Delta Z_{i,j}$ is the altitude difference between node i and node j , H_j is the pressure in the terminal node j , and $h_{i,j}$ is the pressure loss in the pipeline due to friction.

$$H_{i,j} = \Delta Z_{i,j} + H_j + h_{i,j} \quad \forall (i,j) \in FIJ \tag{11}$$

To explicitly describe pressure loss in the pipeline caused by friction ($h_{i,j}$) we use the so-called Darcy-Weisbach equation (Swamee and Sharma 2008), expressed in Eq. (12). In this equation, g is the gravitational constant and f is the friction factor dependent on pipeline type considered constant for each diameter available in this formulation.

$$h_{i,j} = \frac{8 \cdot f \cdot L_{i,j} \cdot Q_{i,j}^2}{\pi^2 \cdot g \cdot D_{i,j}^5} \quad \forall (i,j) \in FIJ \tag{12}$$

From a mathematical viewpoint, Eq. (12) creates problems when the chosen diameter is zero because this function is discontinuous at the origin. When discontinuous functions are

present in the mathematical model, global optimization algorithms (e.g. branch-and-bound types) are not able to handle them and global solutions cannot be reached. To avoid the problem, zero diameter is avoided in the set of available diameters and a new continuous variable ($DY_{n,j}$), dependent on the binary variable $y_{i,j}$, is added as shown in Eq. (13). The new continuous variable $DY_{n,j}$ replaces the discrete variable $D_{i,j}$ in Eq. (12). Then, if binary variable $y_{n,j}$ is zero (no pipeline), it is logical that the new continuous variable is also zero.

$$DY_{i,j} \cdot D_{i,j}^5 = y_{i,j} \quad \forall (i,j) \in FIJ \tag{13}$$

2.2.2 Objective Function

The objective function seeks to minimize the total cost (TC) of the water supply system, which satisfies demand for desalinated water represented by several users. The TC includes the capital cost of pipelines ($TC_{i,j}$), and the capital and operational costs of the desalination plants (TC_{so}) and pumping stations (TC_n). The objective function is noted in Eq. (14).

$$TC = \sum_{so \in SO} TC_{so} + \sum_{i,j \in FIJ} TC_{i,j} + \sum_{n \in N} TC_n \tag{14}$$

The cost of producing desalinated water is highly variable and depends on several factors (Al-Nory et al. 2014). In the formulation of the objective function for this article, desalination plants operating mode is based on the reverse osmosis process (RO plants). However, the use of other desalination processes, such as, e.g., multi-stage flash distillation process is easily adaptable. We used data from the cost database developed by Wittholz et al. (2008) that comprises data from 112 RO plants from different sources including surveys, reports, and manuscripts. Based on cost data collected, the authors estimated the variation of unit production cost to produce desalinated water depending on the size of the RO plant. Unit production cost includes annualized capital cost and the annual operating cost for any RO project. Hence, we may assume that it represents the global economy of an RO project. If the unit production cost is multiplied by the production capacity of the plant, then the total cost of a desalination system is obtained. The TC_{so} , based on the cost database of Wittholz et al. (2008), is expressed as Eq. (15). The proposed equation represents the economies of scale that prevail in RO plants, i.e. a RO plant of smaller capacity has a higher unit production cost than a larger plant. Parameters A, B and C were adjusted for maximum desalinated water production by each RO plant at the rate 1.5 m³/s. Value parameters are A = 0.00105, B = -0.00602 and C = 0.0255. However, parameters A, B and C must be adjusted depending on data used to solve the problem. Based on these data, unit production cost of RO plants ranges between 0.4 and 1.0 \$/m³ according to the production capacity.

$$TC_{so} = A \cdot Q_{so}^{*3} + B \cdot Q_{so}^{*2} + C \cdot Q_{so}^* \quad \forall so \in SO \tag{15}$$

The costs of pipelines ($TC_{i,j}$) and the pumping station (TC_n) represent the cost of water transport network. The $TC_{i,j}$ is a function of the material, length and diameter of a selected pipeline. In this formulation, $TC_{i,j}$ is annualized by dividing the cost by the annuity present worth factor corresponding to the discount rate (dr) (Cisternas et al. 2014) expressed in the Eq.

(16). Pipeline cost parameters, k_p and m_p , depend on the pipeline material that are handled by suppliers. Therefore, to identify a standard value of pipeline cost parameters is not an easy task and usually there is not much data available. In this article, adjustment parameters k_p and m_p are obtained from data sets of Samra and Abood (2014), which are shown in the nomenclature section.

$$TC_{i,j} = \frac{k_p \cdot L_{i,j} \cdot D_{i,j}^{m_p}}{\left(\frac{(1 + dr)^{inv} - 1}{dr \cdot (1 + dr)^{inv}} \right)} \quad \forall (i, j) \in FIJ \tag{16}$$

The total cost of a pumping station is shown in Eq. (17). As described by Swamee and Sharma (2008), the capital cost of installing pumping stations is proportional to the power required to transport water. Similarly, operational costs are proportional to the cost of electricity. In Eq. (17), parameters k_n and m_n represent pump cost coefficients related to the capital cost of pumping stations, which were obtained from data sets of Samra and Abood (2014). On the side of operational costs, T represents the number of hours in a year, F_A days worked in a year, F_D hours worked per day, and E_c the cost per unit of energy. Adjustment values of these parameters are shown in the nomenclature section.

$$TC_n = \frac{k_n}{\left(\frac{(1 + dr)^{inv} - 1}{dr \cdot (1 + dr)^{inv}} \right)} \cdot (P_n)^{m_n} + T \cdot F_D \cdot F_A \cdot E_c \cdot P_n \quad \forall n \in N \tag{17}$$

Power (P_n) is the function of water flow discharged by the pumps and the hydraulic head, which is expressed in Eq. (18). Parameter ρ represents mass density of fluid, η is the combined efficiency of the pump and prime mover, and g gravitational acceleration.

$$P_n = \frac{\rho \cdot g}{\eta} \cdot \sum_{j \in output} Q_{n,j} \cdot H_{n,j} \quad \forall n \in N \tag{18}$$

In Fig. 1, costs of the pipelines and pumping stations calculated based on proposed mathematical formulation are contrasted with data presented by Zhou and Tol (2005). It shows pumping stations cost separately and in conjunction with the cost of pipelines. In most cases, our cost of pipelines with the pumping stations is higher than the cost presented by Zhou and Tol (2005) because they ignore capital cost related to the installation of pipelines in their analysis. The cost of pipelines depends on the material, length, diameter, and investment years. This conceptual analysis covered 25 years of investment with a discount rate of 0%. Other factors that could increase the cost of pipelines include the type of soil and the need to build tunnels to install pipelines due to complex topographies in some areas. In these cases, some parameters shown in the nomenclature section need to be adjusted to local realities. However, these factors will not be considered in this study.

In summary, the water supply system is represented as a MINLP model, described by Eqs. (1)–(13) and Eq. (14) as the objective function that includes Eqs. (15)–(18). The MINLP model was applied to the case study in a hyper-arid region of northern Chile to validate its applicability and evaluate its convergence time.

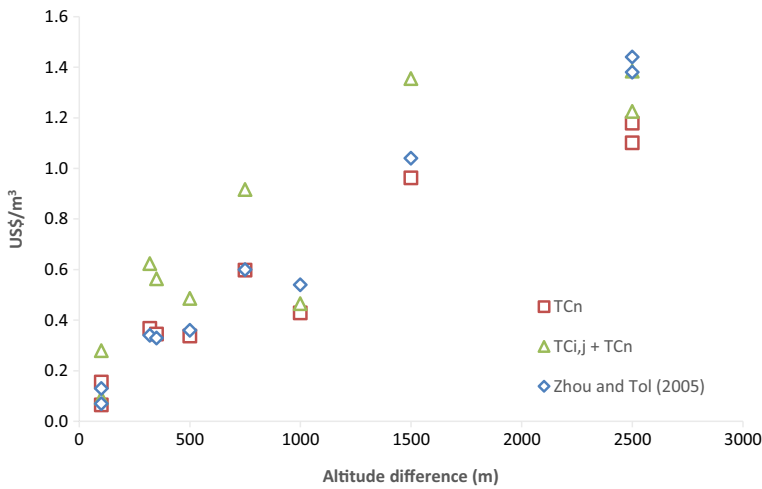


Fig. 1 Desalinated water transport costs

3 Case Study

The case study was carried out in northern Chile, specifically in the Antofagasta region, which according to its geography is a hyper-arid region (Pereira et al. 2009). It is located in the Atacama Desert, where annual rainfalls are one amongst the lowest in the world reaching approximately 1.7 mm (Clarke 2006). However, the concentration of minerals in soils of this region is quite high (Cisternas and Gálvez 2014), which is why explorations, extractions, and mining production have always existed in this area. In fact, it is remarkable to mention that only in the Antofagasta region, more than forty mining activities are in operation, and many others are at the stage of feasibility studies. In this context, intensive hydrographic basin consumption over time by mining operations, rather loose regulations, and climate change have produced a significant water scarcity. In order to safeguard the ecosystems of the region, practically all the existing areas with sub-aquifers have been declared to be under official protection. Globally mining industry is a relatively small consumer of water, but in regions where mining does occur, it may often be the major local consumer (Northey et al. 2016). In this context, any new mining plant or expansion of an existing mining installation in the Antofagasta region must consider using seawater as an option to satisfy its water requirements (Cisternas and Gálvez 2017). To achieve adequate water quality for mineral processing, there must be a desalination plant in the water supply system.

Today, some mining companies established in the region, such as BHP Billiton and CODELCO-Chile, have begun to consider installing their own desalinated water supply systems. BHP Billiton Company is working on building a system for the production and transport of 3.2 m³/s of desalinated water for its mining operation Escondida. The investment project is worth ca. 3500 million \$US. Four pumping stations and two pipes 1.0 m in diameter are planned for transporting desalinated water from the desalination plant to the mining operation located 180 km away and 3100 m above the sea level. Meanwhile, CODELCO-Chile is examining the possibility to install a desalination plant to supply its mining operation, Radomiro Tomic. The desalination plant will produce desalinated water at 1.6 m³/s, which will be transported by a pipe of 1.2 m in diameter for 160 km. Five pumping stations will be needed

to transport desalinated water from the coast to the mining operation located 3000 m above the sea level. The total investment cost of the project is estimated to be 1500 million US\$.

As noted before, the current strategy of mining companies consists in building an independent water supply system to satisfy their specific water requirements. However, shared infrastructure is observed as a potential opportunity (Dixon 2013). Moreover, from an economic perspective, a shared water supply system could be the only possibility for medium-scale mining companies and other users in the region, mainly due to high investment required for these types of projects. In the previous study, we were the first to propose a methodology to design a shared water supply system in this context (Herrera et al. 2015). However, the methodology consisted of two stages and only local solutions to the problem were achieved.

The case study considers six potential medium-scale mining plants as users, six RO plants, and twenty-five pumping stations in the northern part of Antofagasta region, which were defined using the GIS software Google Earth Pro version 7.1.5. The main characteristics of the system are geographic locations and elevations of nodes, the maximum capacity of each RO plant, desalinated water requirement of each mining operation, and distances between each potential connection, shown in Tables 1 and 2. An illustrative scheme of the case study is shown in Fig. 2. The pressure (H_j) in each terminal node was considered equal to zero and the value considered for v^{max} was 2.5 m/s (Nayyar 2000). In this case study we propose five pipe diameters: 0.7, 0.8, 0.9, 1.0, and 1.1 m.

3.1 Results

The globally optimal solution was obtained using the Branch-And-Reduce Optimization Navigator (BARON) in GAMS environment. The optimal cost was 71.33 million US\$ per year, and it was calculated in 15723 s. Considering an investment period of 25 years and a discount rate of 0%, the total investment was 1783 million US\$. The optimal solution consists of one RO plant that produces 1.1 m³/s of desalinated water that satisfies water requirements of all mining operations considered in the case study. Furthermore, six pumping stations were chosen to transport the desalinated water produced.

Based on Fig. 3, desalinated water is produced in SO₄ and transported to the mining operation SI₄ through pumping stations N₁₆ and N₁₇, then transported to mining operations SI₅

Table 1 Main characteristics of the water supply system of the case study

	Geographic location		C ^{max} [m ³ /s]	Desalinated water requirements [m ³ /s]	Altitude [m.a.s.l]
	Latitude	Longitude			
SO ₁	21°45'42.01"S	70° 9'26.91"O	1.5	–	0
SO ₂	21°57'49.68"S	70°10'28.14"O	1.5	–	0
SO ₃	22°13'9.10"S	70°13'38.79"O	1.5	–	0
SO ₄	22°33'2.47"S	70°15'51.63"O	1.5	–	0
SO ₅	22°43'3.25"S	70°16'47.80"O	1.5	–	0
SO ₆	22°51'42.82"S	70°17'43.46"O	1.5	–	0
SI ₁	21°32'0.12"S	68°20'20.96"O	–	0.10	3736
SI ₂	21°58'53.08"S	68°41'55.48"O	–	0.15	3342
SI ₃	22°24'4.28"S	68°54'51.15"O	–	0.20	2335
SI ₄	22°36'47.85"S	69°40'24.15"O	–	0.15	1461
SI ₅	22°48'28.22"S	69°23'14.38"O	–	0.10	1703
SI ₆	23° 1'38.78"S	69° 3'35.53"O	–	0.30	2424

Table 2 Elevations, locations and distances between elements of the water supply system

Geographic location		[m.a.s.l.]		Distances between two nodes [kilometer]													
	Latitude	Longitude	Elevation	N ₂	N ₃	N ₄	N ₅	N ₇	N ₈	N ₉	N ₁₀	N ₁₂	N ₁₃	N ₁₄			
SO ₁ -N ₁	21°45'42.02"S	70°9'26.92"E	0	3	—	—	—	—	—	—	—	—	—	—			
N ₂	21°45'30.27"S	70°7'46.79"E	815	—	31.5	—	—	—	22.9	—	—	—	—	—			
N ₃	21°43'18.65"S	69°49'39.66"E	1609	—	—	76.4	—	—	—	70.9	—	—	—	—			
N ₄	21°37'51.61"S	69°5'48.02"E	2406	—	—	—	12.3	—	—	—	39.8	—	—	—			
N ₅	21°36'58.09"S	68°58'46.27"E	3198	—	—	—	—	—	—	—	—	28.8	—	—			
SO ₂ -N ₆	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	1.97	—	—	—	—	37.9	—			
N ₇	21°57'50.25"S	70°9'26.57"E	888	—	—	—	—	—	3.61	—	—	—	—	106			
N ₈	21°57'52.25"S	70°7'23.75"E	1653	—	—	—	—	—	—	95.5	—	—	—	—			
N ₉	21°58'36.67"S	69°11'57.19"E	2213	—	—	113	46	—	—	—	20.6	—	—	—			
N ₁₀	21°58'43.80"S	69°0'0.63"E	3007	—	—	—	—	—	—	—	—	25.3	—	—			
SO ₃ -N ₁₁	22°13'9.04"S	70°13'39.07"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₁₂	22°13'18.18"S	70°12'35.10"E	798	—	—	—	—	—	29.9	—	—	—	—	—			
N ₁₃	22°15'22.21"S	69°58'1.33"E	1645	—	—	—	—	—	—	85.1	—	—	—	81			
N ₁₄	22°21'50.11"S	69°11'24.25"E	2126	—	—	—	—	—	—	—	46.9	—	—	—			
N ₁₅	22°24'4.28"S	68°54'51.15"E	2335	—	—	—	—	—	—	—	—	—	—	—			
SO ₄ -N ₁₆	22°33'2.60"S	70°15'51.42"E	0	—	—	—	—	—	—	—	—	—	42.9	—			
N ₁₇	22°33'14.89"S	70°13'56.87"E	866	—	—	—	—	—	—	—	—	—	—	56.9			
N ₁₈	22°36'47.85"S	69°40'24.15"E	1461	—	—	—	—	—	—	—	—	—	—	—			
SO ₅ -N ₁₉	22°43'3.25"S	70°16'47.80"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₂₀	22°43'22.52"S	70°14'32.32"E	813	—	—	—	—	—	—	—	—	—	—	—			
N ₂₁	22°45'39.04"S	69°58'41.41"E	1368	—	—	—	—	—	—	—	—	—	—	—			
N ₂₂	22°48'28.22"S	69°23'14.38"E	1703	—	—	—	—	—	—	—	—	—	—	—			
SO ₆ -N ₂₃	22°51'42.85"S	70°17'43.87"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₂₄	22°52'10.16"S	70°14'26.95"E	799	—	—	—	—	—	—	—	—	—	—	—			
N ₂₅	22°54'31.80"S	69°57'10.62"E	1600	—	—	—	—	—	—	—	—	—	—	—			
	Latitude	Longitude	Elevation	N ₁₅ -S ₃	N ₁₇	N ₁₈ -S ₄	N ₂₀	N ₂₁	N ₂₂ -S ₅	N ₂₄	N ₂₅	S ₁	S ₂	S ₆			
SO ₁ -N ₁	21°45'42.02"S	70°9'26.92"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₂	21°45'30.27"S	70°7'46.79"E	815	—	—	106	—	—	—	—	—	—	—	—			
N ₃	21°43'18.65"S	69°49'39.66"E	1609	—	—	—	—	—	—	—	—	—	—	—			
N ₄	21°37'51.61"S	69°5'48.02"E	2406	—	—	—	—	—	—	—	—	—	—	—			
N ₅	21°36'58.09"S	68°58'46.27"E	3198	—	—	—	—	—	—	—	—	—	—	—			
SO ₂ -N ₆	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₇	21°57'50.25"S	70°9'26.57"E	888	—	—	—	—	—	—	—	—	—	—	—			
N ₈	21°57'52.25"S	70°7'23.75"E	1653	—	—	—	—	—	—	—	—	—	—	—			
N ₉	21°58'36.67"S	69°11'57.19"E	2213	—	—	—	—	—	—	—	—	—	—	—			
N ₁₀	21°58'43.80"S	69°0'0.63"E	3007	—	—	—	—	—	—	—	—	—	—	—			
N ₁₁	22°13'9.04"S	70°13'39.07"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₁₂	22°13'18.18"S	70°12'35.10"E	798	—	—	—	—	—	—	—	—	—	—	—			
N ₁₃	22°15'22.21"S	69°58'1.33"E	1645	—	—	—	—	—	—	—	—	—	—	—			
N ₁₄	22°21'50.11"S	69°11'24.25"E	2126	—	—	—	—	—	—	—	—	—	—	—			
N ₁₅	22°24'4.28"S	68°54'51.15"E	2335	—	—	—	—	—	—	—	—	—	—	—			
N ₁₆	22°33'2.60"S	70°15'51.42"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₁₇	22°33'14.89"S	70°13'56.87"E	866	—	—	—	—	—	—	—	—	—	—	—			
N ₁₈	22°36'47.85"S	69°40'24.15"E	1461	—	—	—	—	—	—	—	—	—	—	—			
N ₁₉	22°43'3.25"S	70°16'47.80"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₂₀	22°43'22.52"S	70°14'32.32"E	813	—	—	—	—	—	—	—	—	—	—	—			
N ₂₁	22°45'39.04"S	69°58'41.41"E	1368	—	—	—	—	—	—	—	—	—	—	—			
N ₂₂	22°48'28.22"S	69°23'14.38"E	1703	—	—	—	—	—	—	—	—	—	—	—			
N ₂₃	22°51'42.85"S	70°17'43.87"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₂₄	22°52'10.16"S	70°14'26.95"E	799	—	—	—	—	—	—	—	—	—	—	—			
N ₂₅	22°54'31.80"S	69°57'10.62"E	1600	—	—	—	—	—	—	—	—	—	—	—			
N ₂₆	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₂₇	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₂₈	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₂₉	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₃₀	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₃₁	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₃₂	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₃₃	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₃₄	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₃₅	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₃₆	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₃₇	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₃₈	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₃₉	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₄₀	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₄₁	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₄₂	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₄₃	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₄₄	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₄₅	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₄₆	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₄₇	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₄₈	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₄₉	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₅₀	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₅₁	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₅₂	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₅₃	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₅₄	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₅₅	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₅₆	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₅₇	21°57'49.65"S	70°10'28.28"E	0	—	—	—	—	—	—	—	—	—	—	—			
N ₅₈	21°57'49.65"S	70°10'28.28"E	0	—	—	—											

Table 2 (continued)

	Geographic location		[m.a.s.l.]	Distances between two nodes [kilometer]									
N ₇	21°57'50.25"S	70° 9'26.57"O	888	-	-	-	-	-	-	-	-	-	
N ₈	21°57'52.25"S	70° 7'23.75"O	1653	-	-	-	-	-	-	-	-	-	
N ₉	21°58'36.67"S	69°11'57.19"O	2213	-	-	-	-	-	-	-	-	-	
N ₁₀	21°58'43.80"S	69° 0'0.63"O	3007	-	55.4	-	-	-	-	84.3	-	-	
SO ₃ -N ₁₁	22°13'9.04"S	70°13'39.07"O	0	-	-	-	-	-	-	-	-	31.1	
N ₁₂	22°13'18.18"S	70°12'35.10"O	798	-	-	70.2	-	-	-	-	-	-	
N ₁₃	22°15'22.21"S	69°58'1.33"O	1645	-	-	-	-	-	-	-	-	-	
N ₁₄	22°21'50.11"S	69°11'24.25"O	2126	-	28.7	-	-	-	-	-	-	-	
N ₁₅	22°24'4.28"S	68°54'51.15"O	2335	-	-	-	-	-	-	-	-	51.6	
SO ₄ -N ₁₆	22°33'2.60"S	70°15'51.42"O	0	-	3.41	-	-	19.2	-	-	-	-	
N ₁₇	22°33'14.89"S	70°13'56.87"O	866	-	-	57.9	-	-	-	34.8	-	-	
N ₁₈	22°36'47.85"S	69°40'24.15"O	1461	-	-	-	-	-	36.4	-	-	-	
SO ₅ -N ₁₉	22°43'3.25"S	70°16'47.80"O	0	-	18.8	-	-	-	-	-	17.3	-	
N ₂₀	22°43'22.52"S	70°14'32.32"O	813	-	-	59.7	-	-	-	27.5	-	36.2	
N ₂₁	22°45'39.04"S	69°58'41.41"O	1368	-	-	-	-	-	60.9	-	-	-	
N ₂₂	22°48'28.22"S	69°23'14.38"O	1703	-	66.3	-	-	-	-	-	-	-	
SO ₆ -N ₂₃	22°51'42.85"S	70°17'43.87"O	0	-	-	-	-	16.3	-	-	-	-	
N ₂₄	22°52'10.16"S	70°14'26.95"O	799	-	-	-	-	-	-	29.5	-	29.9	
N ₂₅	22°54'31.80"S	69°57'10.62"O	1600	-	-	-	-	-	59.1	-	-	-	
				-	-	-	-	-	-	-	-	-	92.6

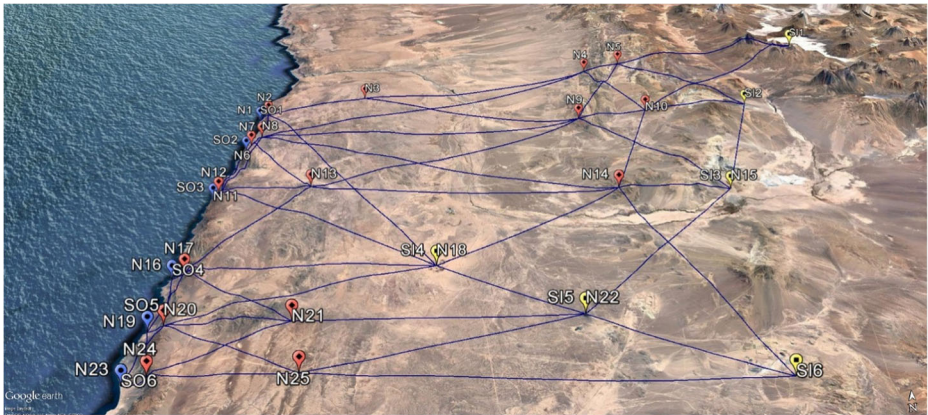


Fig. 2 Illustrative scheme of the case study

and SI₆ through pumping stations N₁₈ and N₂₂. From SI₄, water is also transported to SI₁ and SI₂ through pumping stations N₁₈, N₁₄ and N₁₀. The maximum pipe diameter (1.1 m) was chosen to connect desalination plant SO₄ and the mining plant SI₄, where maximum quantity of water is transported at 1.1 m³/s. In node SI₄, water is divided into two streams to satisfy the requirements of the remaining mining operations. Therefore, diameters chosen by the model are between 0.7 and 0.8 m after this node depending on water flow transported. The optimization model consistently selects a smaller pipe diameter for smaller flows of desalinated water.

In order to compare the water supply system determined as the optimal solution for the case study, we analyzed current strategy used by mining companies, which is to install independent water supply systems. The total cost of the project was calculated considering an independent desalinated water supply system for each mining operation considered in the case study. Cost calculated for optimal solution obtained using GAMS/BARON is 83.25 million US\$ annually, taking 76.85 s to calculate it. The same investment period and discount rate of the case study were used and the total investment was 2081.25 million US\$, equivalent to 16.7% more than the previously obtained globally optimal solution.

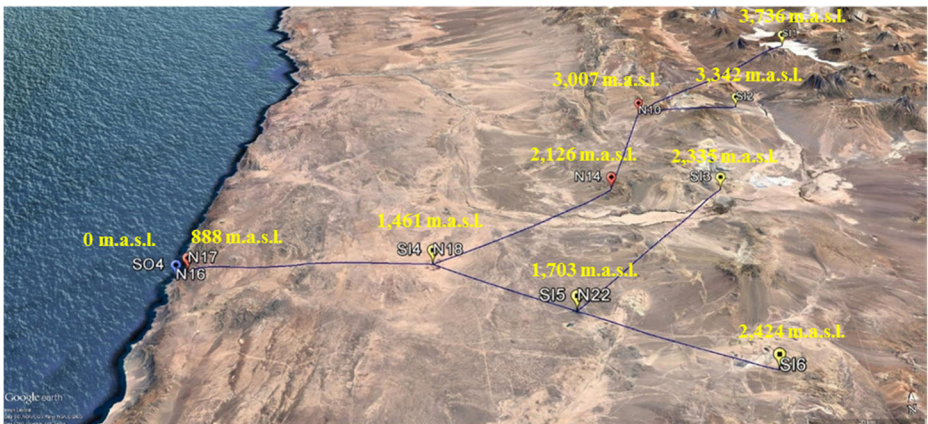


Fig. 3 Globally optimal solution of the case study

Table 3 Case studies used in sensitivity analysis and their results

Case studies			Results			
Number of potential RO plants	Number of potential pumping stations	Number of mining plants	Number of RO plants selected	Number of pumping stations selected	Total cost [million US\$]	Convergence time [s]
2	6	2	1	3	483	0.84
3	10	3	1	4	803	2.54
4	14	4	1	4	1098	18.69
5	20	5	1	5	1265	203.91
6	25	6	1	6	1783	15723

Finally, a sensitivity analysis was carried out to evaluate the convergence time of the proposed MINLP model considering five realistic case studies. The main characteristics of the case studies and their results are shown in Table 3. As expected, the convergence time increases with the scale of the problem. The global optimal solution to each problem suggests that the most economical system always entails installing only one RO plant to satisfy water requirements of all users, which encourages the development of an integrated water supply system.

4 Concluding Remarks

A novel optimization approach was proposed to design water supply systems in non-coastal areas suffering from water scarcity. The optimization approach based on a MINLP model is capable of determining global solutions for real-scale problems from an economic and technical perspective. To evaluate the applicability of the proposed model, a case study in northern Chile was presented. Based on the results obtained, the MINLP model is a useful tool that can be applied to other non-coastal areas suffering from water scarcity where seawater can be viewed as a potential solution.

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Nomenclature

$A_{i,j}$	discrete variable of pipe area (m)
A_d	parameter of pipe area (m)
C_{so}^{max}	maximum capacity of RO plant so (m^3/s)
D_d	parameter of pipe diameter (m)
$D_{i,j}$	discrete variable of pipe diameter (m)
dr	discount rate (y^{-1})

$DY_{n,j}$	continuous variable extra (m^{-5})
E_c	electric cost (US\$/kWh) = 0.12
f	friction factor (dimensionless) = 0.02
F_A	rate of days worked in a year (dimensionless) = 1
F_D	rate of hours worked in a day (dimensionless) = 1
g	constant of gravitational acceleration (m/s^2) = 9.8
$H_{i,j}$	hydraulic head from node i to j (m)
H_j	the pressure required in the terminal node j (m)
inv	investment years (y)
k_n	capital cost parameter of pumping stations (US\$/ kW^{m_n}) = 2.25
k_p	cost parameter of the pipes installation (US\$/ m^{m_p}) = 1.5
$L_{i,j}$	length of pipe from node i to j (m)
m_n	capital cost parameter of pumping stations (dimensionless) = 1
m_p	cost parameter of the pipes installation (dimensionless) = 1
P_n	power of the electric motor (kW)
$Q_{i,j}$	desalinated water flow pumped from node i to j (m^3/s)
Q_{si}^*	desalinated water flow delivered to node si (m^3/s)
Q_{so}^*	desalinated water flow produced for node so (m^3/s)
R_{si}	desalinated water flow required for node si (m^3/s)
T	quantity of hours in a year (h/y) = 8760
TC	total cost of the system (million US\$/y)
$TC_{i,j}$	capital costs annualized of the pipes (million US\$/y)
TC_n	capital and operational costs of the pumping stations (million US\$/y)
v^{max}	maximum linear velocity into pipes (m/s)

$y'_{i,j,d}$	binary variable to select diameter d to the pipe from node i to j (dimensionless)
$y_{i,j}$	binary variable to select the existence of the pipe from node i to j (dimensionless)
$\Delta Z_{i,j}$	altitude difference between node i and j (m)
η	efficiency of the electric motor (dimensionless) = 0.9
ρ	water density (kg/m^3) = 1000

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