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Design of desalinated water distribution networks including energy recovery devices

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Abstract

The objective of this work is to develop a methodology to determinate the location and size of desalination plants, the water distribution network, and the location and size of energy recovery devices to provide desalinated water in regions with complex topography. The novelty of the methodology is that energy recovery devices such as pumps as turbines are incorporated as an option to produce energy.

The methodology proposed uses a superstructure that represents the set of alternatives on which the optimal solution is found. A mathematical model is generated that correspond to an MINLP problem which is then transformed into an MILP problem and solved using Cplex-GAMS. A case study is presented to demonstrate the applicability of the methodology designed.

Based on a case study it is concluded that the methodology proposed can be useful for designing the whole water distribution network, including energy recovery devices, for users located in places with a complex topography.

Keywords: water distribution network, energy recovery, reverse osmosis, mathematical optimization.

1. Introduction

The Atacama Desert is the driest desert in the world and is located in the north of Chile (Antofagasta region). This desert contains metallic elements such as copper, silver, gold, molybdenum, and iron. Chile produces 35% of the world copper production, and more than half is extracted in Antofagasta. From this desert, nonmetallic minerals are also extracted such as potassium nitrate, boron, and lithium carbonate. Mining is the main activity in the region and water is an important resource for mining. However, water is a limited resource due to the overexploitation of groundwater sources. On the other hand, Antofagasta region has a large sea cost. Then, seawater has become the main source of fresh water for the region. Reverse osmosis is the technology utilized to obtain fresh water for the mining industry and urban populations. In addition, the mines are located far from the cost and, more importantly, at high altitudes. Mines elevation varies between 1,000 and 4,000 meters above the sea level.

In the region, there are several mining operations that are using desalinated water obtained through reverse osmosis. Each mining company has a desalination plant with a water distribution network (WDN) to provide water for its mining processes without any integration between companies. To obtain a more sustainable water distribution system, an integrated design that considers several mining plants, the WDN, and reverse osmosis plants could be implemented.

There have been several works about the design of reverse osmosis plants and water supply systems. El-Hawagi (1992) introduced the novel notion of synthesizing reverse osmosis networks applied for waste reduction, the synthesis was formulated as an MINLP. Considerable research about designing reverse osmosis systems and water distribution supplies has been made since then. Liu et al. (2011) consider the use of desalinated water, wastewater and reclaimed water to supply water deficient areas using a mixed integer linear programming model. The methodologies to design water supplies system usually results in Mixed Integer non-Linear Programming (MINLP) models. Liang et al. (2016) proposed a convex model to obtain the optimal design of water distribution system using Hanoi network (Fujiwara 1990) as a case study. Coelho et al. (2013) realized a review about efficiency achievement in water supply systems which includes using renewable energy sources, hydraulic simulation and optimization in water supply systems. Gonzalez-Bravo et al. (2016) presented a multiobjective optimization approach for design water distribution networks including environmental, economic, and social objectives. Herrera et al. (2015) include reverse osmosis plants and mining plants in a superstructure that contains those elements plus the WDN to design the whole system simultaneously using MINLP.

However, no work considers sites with complex topography, with changes in elevations resulting from the presence of mountains. In these cases, pumps operating as turbines can be used in water distribution systems to reduce pressure instead of using pressure reducing valves, and additionally, they can produce electricity (Tricarico et al., 2014). Nogueira et al. (2014) present models of hydropower recovery in water supply systems that could be applied in water distribution network design.

The objective of this work is to develop a procedure to identify location and size of desalination plants, the design of the water distribution system, and identify location and size of energy recovery devices that allow producing energy from the fall of water.

2. Problem statement

In this problem, we consider a complex topography and desert area; by complex, it means an area with different changes of elevation between the coast and the mine sites. The water demand of the mining plants can only be satisfied with desalinated water from reverse osmosis plants located on the shore.

A superstructure that includes these reverse osmosis plants, the WDN, the energy recovery devices, and mining plants is considered to find the optimal solution. Some nodes of the WDN are located on the top of mountains, then in that way, some pipelines have to ascend and then descend by a mountain (Figure 1). We evaluate the possibility of using pumps running as turbines below the mountain to convert energy from a waterfall into mechanic energy that can be used as electrical power in the WDN.

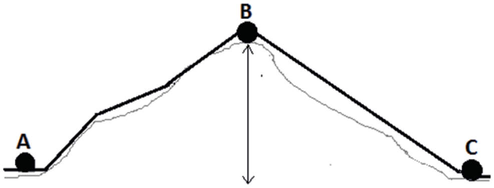

Figure 1: Mountain scheme, point A represents a node with pumps, point B represents a node that is only a junction between pipes, and in point C there is a pump running as a turbine as an energy recovery device.

The objective is to find locations and size of reverse osmosis plants and pumping stations, pumping stations and pipes diameter; operational conditions of pumping stations and WDN considering using pumps as turbines, which allow finding the optimal design.

3. Mathematical formulation

Four sets represent the superstructure: the set of RO plants *SO*= {*so* | *so* is a RO plant}, the set of pumping stations *N*={*n* | *n* is a node}, the set of mining plants *SI*={*si* | *si* is a mining plant}, and the set of pipe diameters *D* = {*d* | *d* is a pipe diameter}. In a node, there can be a traditional pumping station, a junction between two pipes without pumps or pumps running as turbines. The distance between two points and elevation of each point are designated based on topographical data using Google Earth.

The water flow is in one direction, from the source to the users, which allows finding the global optimum. This assumption is important to avoid the non-convexity of water transport network problems. Only feasible connections between nodes are considered in the network.

Part of the model are equations of continuity for RO plants, nodes, and mining plants; these equations are presented below, Eqs (1)-(3),

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

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

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

Where $Q_{i,j}$ is the volumetric flow pumped from i to j, the constrains associated with the maximum production capacity of RO plants and desalinated water demands of the mining plants are also included in the model.

For the selection of the pipe diameter from points i to j, a disjunction is used which is expressed using the convex hull method. The friction factor is assumed to be a function of the pipe diameter and the roughness. The Reynolds number is considered big enough to not represent a contribution to the friction factor (Swamee and Jain, 1976).

The objective function minimizes the total annualized cost of desalination plants, pipes, pumping stations, and pumps running as turbines required to supply the mining plants. It also includes the energy generated if there are pumps running as turbines. The cost of producing desalinated water was extracted from the database cost raised by Wiltholz (2008); the function used includes the UPC, which is the unit cost of producing desalinated water. The cost of transporting the water is represented by a function proposed by Swamee (2001), this function includes the annualized cost of pipelines and operational cost of pumping stations. The function includes the pumping head $H_{n,j}$, which is calculated with the Darcy-Weisbach equation, which is:

$$H_{n,j} = H_0 + \Delta z_{n,j} + \frac{8 f L_{n,j} {Q_{n,j}}^2}{\pi^2 g {D_{n,j}}^5} \tag{4}$$

Where $\Delta z_{n,j}$ is the elevation difference from n to j, H_0 is the terminal head and $L_{n,j}$ is the length of the pipe from n to j.

The pumping head for pumps running as turbines was also calculated with Darcy Weisbach equation extracted from Swamee and Sharma (2008), the price of this type of device was estimated based on the water flow and pumping head. The civil work and maintenance work of these devices was estimated using values from Fontana et al. (2008). The energy produced by energy recovery devices is a function of the head drop (Fontana et al. 2008).

There are two nonlinear functions in the objective function, one is the UPC and the other is the term Q^3, which appear when the Darcy-Weisbach equation is multiplied for the water flow. The model is a MINLP problem. In order to obtain the global optimum in short time, these two functions were linearized using piecewise methodologies (Lin et al. 2013). Piecewise methodologies allowed to obtain a model that correspond to a MILP problem.

4. Case Study

An area of Antofagasta region was used as a case study. This area features significant changes in the elevation because the Coast Mountain Range crosses this area. This case study contains four mining plants that need to be supplied by three potential RO plants. Since there are mountains in the area, pumps running as turbines are considered in some pumping stations. Distances and elevation points were determined using Google Earth. Figure 2 is an image of the superstructure with all the elements proposed.

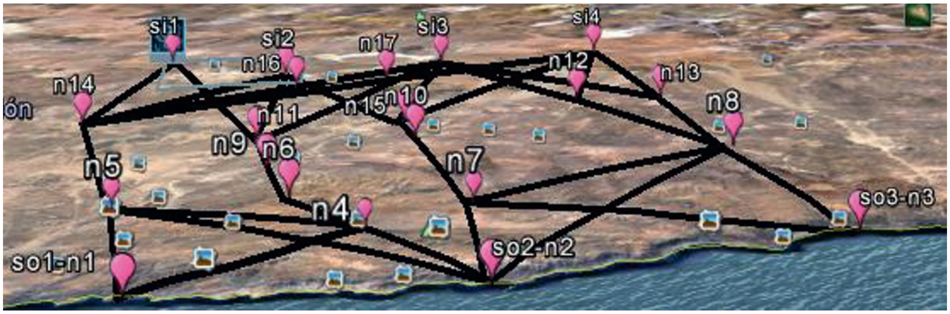

Figure 2: Superstructure with the location of potential reverse osmosis plants, potential nodes, and mining plants of the case study in Antofagasta region (from north to south).

RO plants are located on the coast, so their elevation is zero. There is a zone between n_5 and n_8 where there is a mountain range, about 40 km of extension. In this zone, the use of pumps running as turbine was considered. In the nodes located at the sides, there are conventional pumps because the elevation is ascendant so no energy recovery was considered. In the pipeline that goes from RO plant so_1 elevation varies from 0 to 1.8 km above sea level and in the another extreme, from RO plant so_3 elevation is also ascendant from 0 to 3 km meters about sea level at n_{13}. Mining plants are located at elevations between 3.1 and 3.6 km meters about sea level, being si_3 the highest. Connections between nodes that are infeasible were not considered as an option.

The requirement of desalinated water of the water distribution network is 1 m^3/s, for each mining plant are si_1 0.2, si_2 0.3, si_3 0.2, and si_4 0.3 m^3/s.

The model was solved as an MILP problem using Cplex solver in GAMS environment. This solver allows finding the global optimum in a short time, which is a desirable attribute for complex models. A ranking of three solutions was evaluated to compare them operationally and economically where solution 1 is the global solution (Table 1). The three first solutions consider using pumps running as turbines. For solution 4, the option of using energy recovery devices was removed, and therefore this is the optimal solution without energy recovery devices.

Based on the results of table 1, the first three solutions of the ranking considered so_2 as the RO plant and the use of energy recovery devices, this seems logical since so_2 is an RO plant located in the middle. The cost of not crossing the mountains and going around is reflected in the total cost shown in solution n°4.

Table 1: Ranking of solutions for the case study.

Solution	RO plants	n° pumping stations	n° pumping stations as turbines	Energy generated by pumps as turbines MW-h/year	Total cost (million USD/year)
1	so_2	6	2	71,108	86.83
2	so_2	6	1	55,684	87.11
3	so_2	6	2	74,050	87.49
4	so_1	5	0	0	91.19

5. Conclusions

A methodology for the simultaneous design of the water supply system, find locations and size of reverse osmosis plant and energy recovery devices in a place with a complex topography was addressed. A case study was used to validated the model. The results indicate that is feasible the use of energy recovery devices to produce energy in the WDN in order to obtain an integrated and sustainable system. Linearization of some functions allowed to find the global optimum in a short period of time which is a desired attribute for complex models. In the future, more elements are going to be added to the model like using reservoirs to storage water, different sources of water, and different water qualities in order to obtain a more realistic model.

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