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Research article

A novel mathematical model for simultaneous optimization of desalination plant location and water distribution network; A case study

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ABSTRACT

In recent decades, water scarcity has turned into a serious problem spanning many countries, now even capable of causing or inflaming ethnic and national conflicts. While our planet has very limited freshwater resources, it has huge amounts of saltwater in seas and oceans. There is a very limited number of ways that can make saltwater drinkable, the most important of them is desalination. This study aimed to provide a method for the simultaneous optimization of desalination plant location and its water distribution network based on mathematical modeling. For this purpose, the authors formulated a non-linear mathematical model with the objective of minimizing the costs of water production and transmission. A genetic algorithm was also developed for solving the proposed nonlinear model. The method was used in a case study of Sistan and Baluchestan, which is one of Iran's most water stressed provinces. The proposed genetic algorithm managed to provide an acceptable solution for this problem in 3.74 s. The best solution was found to be constructing a desalination facility with a capacity of 394,052 cubic meters per day in a single location, that is, the city of Chabahar. The water transmission lines needed for transporting water to other parts of the province and their capacities were also determined.

1. Introduction

Due to population growth and technological advancements energy consumption is outstripping supply all over the world [1]. Water is the main requirement for human communities to survive and grow. Over the last few decades, many communities have found it increasing challenging to procure reliable and healthy water supplies. Water scarcity has taken the top spot in Global Risk Report of the World Economic Forum since 2013 [2], which makes sense because many parts of the world have been struggling with frequent droughts. Indeed, water scarcity has turned into a serious problem spanning many countries and has now started to cause or inflame ethnic and national conflicts in some areas. In order to achieve global sustainability, it is crucial to ensure safe water is and will remain available to all who need it [3].

Today, four billion people face severe water shortages for at least one month each year, and more than two billion people live in regions with insufficient water supplies. An estimation of 2025 indicates that by then, half of the world's population will live in water-scarce areas, by 2030 severe water scarcity will displace as many as 700 million people, and by 2040 approximately one in every four

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children worldwide will live in extremely water stressed areas [4]. Meanwhile, global water demand is expected to increase by 55 % by 2050 [5].

The main causes of water crises are believed to be population growth, overexploitation of groundwater resources, overexpansion of agricultural and industrial activities, water pollution, climate change, and melting of natural glaciers [6].

The demand for energy in different sections of most countries is overwhelmingly increased [7]. Like other countries, Iran is facing the challenge of energy supply in various industrial, power plant, agricultural, and residential sectors, due to population growth and industrial development [8]. Iran is one of many countries in the Middle East that are experiencing unprecedented water scarcity these days. Frequent droughts combined with the overexploitation of surface and underground water resources through a vast network of hydraulic infrastructure and deep wells have put Iran in a state of perpetual water crisis signified by shrinking lakes, drying rivers and wetlands, falling groundwater levels, land subsidence, water quality degradation, soil erosion, desertification, and increasingly frequent dust storms [9].

Vast parts of Iran have a primarily dry climate and receive limited rainfall. Almost all studies conducted on Iran's water situation have described it as being critical. In a 2007 report published by the World Resources Institute (WRI), access to freshwater in Iran was rated as poor (Fig. 1). Since then and especially in recent years, Iran's water situation has become even more concerning. Fig. 2 shows the forecast of water stress in different countries in 2030.

As Fig. 2 shows, Iran is predicted to be a highly water-stressed country in 2030.

Our planet has very limited freshwater resources, which are comprehensively exploited for direct human use and industrial and agricultural purposes. However, there are huge amounts of saltwater in seas and oceans, which can be made drinkable when needed. This can be done in a limited number of ways, the most important of which is desalination. Considering how much saltwater there is in seas and oceans, water desalination facilities can be considered to have infinite water input. Thus, if utilized properly, desalination can give people the healthy, sanitary and pleasant water they need for survival, agriculture and other needs in times of drought.

Considering the scarcity of freshwater resources, which makes it important to preserve them as much as possible, industrial-scale desalination of seawater for applications where freshwater is normally used can help relieve pressure on freshwater resources and avoid the environmental damages caused by their overexploitation. Because of these reasons, many countries in dry regions have shown increasing interest in seawater desalination.

Water desalination refers to the process whereby all kinds of salts are separated from saltwater. This technology is becoming an increasingly popular way to make people access to fresh water in many countries, especially coastal countries in extremely dry regions. Given the ongoing crisis of water scarcity in Iran, this country is also expected to construct and operate desalination facilities to produce freshwater for its water needs.

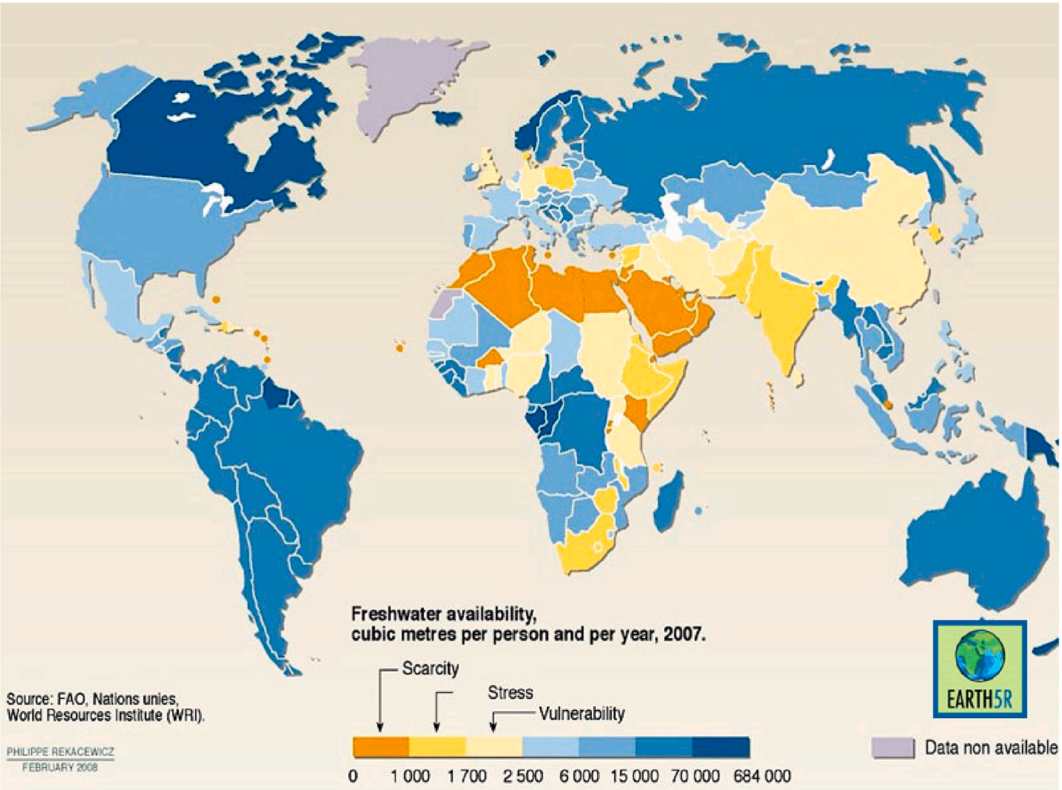

Fig. 1. Global freshwater access in 2007 [10].

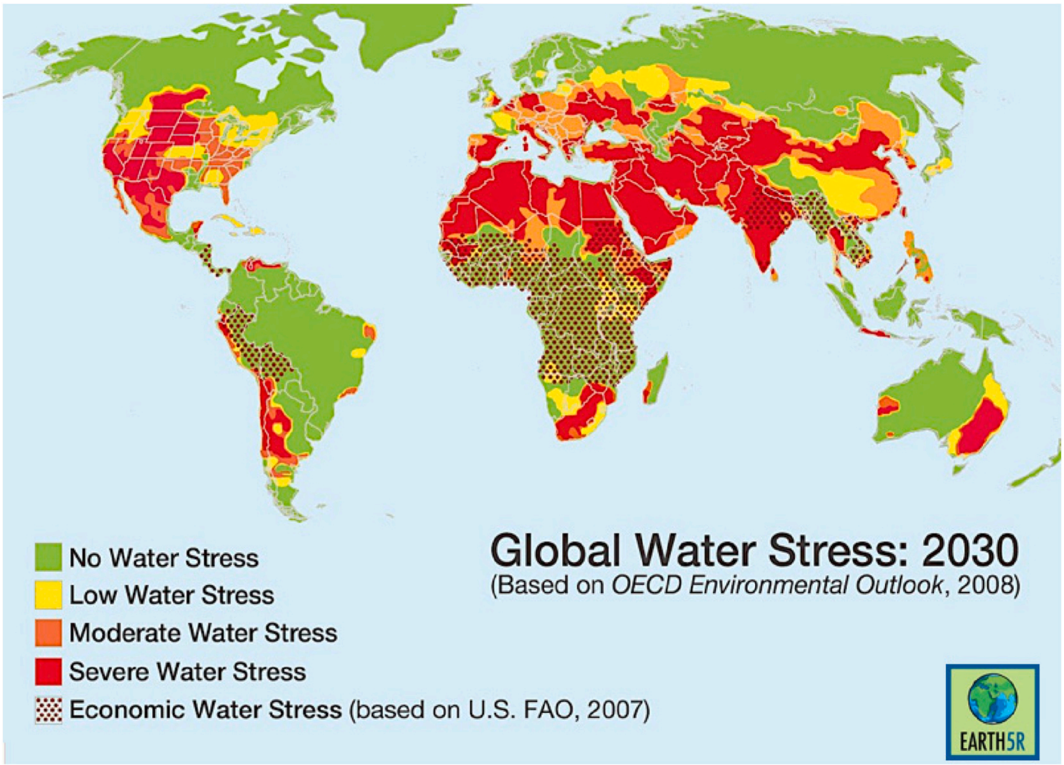

Fig. 2. Global water stress forecast for 2030 [10].

More than 45 % of the world's desalination plants are in the Middle East. Since it has been estimated that Iran's fresh water per capita has dropped below 80 % of the global average (for 2021), Iran needs to construct a series of desalination units to avoid freshwater scarcity crises. Such plants can be powered sustainably by solar, wind, geothermal and wave energy. Iran has an average solar irradiance of 15.3 kWh/m^2 per day, with more than 2800 h of sunlight per year in its central regions. This country can also potentially produce 100×10^6MW of wind power, 200 MW of geothermal power and 20 kW/m of wave power [11].

Desalination facilities are widely believed to be very costly to construct and operate. However, in a study by Crookes [12], where the system dynamics modeling approach was used to compare a large desalination plant with other common options (constructing dams, etc.) with investment and operating costs taken into account, the results showed that, contrary to expectations, such plants can reduce the water bill of all groups of consumers. Furthermore, they can ensure that even the poorest members of the society have access to healthy drinking water.

One of the key steps in the process of constructing an industrial or service facility (investment plan) is to determine the best location for that facility. This location process is crucial because the choice of where to implement a project can have many market-related, technical, and economic implications. Which location to use for constructing or expanding a plant or facility is a fundamental decision for investors with profound impacts on the strategic directions of the plant and its profitability in the long term. Thus, the failure to conduct necessary controls when choosing the location of a project can affect the long-term survival and success of the enterprise or organization. In addition to impacting the project's economic performance, appropriate location can affect the project's social, environmental, cultural and economic implications for the area around the chosen site. Choosing the wrong location for a project can have irreversible consequences, sometimes make it inevitable to carry out a highly expensive relocation and occasionally causing the project to underperform or completely fail.

One of the most reliable techniques used for location selection is mathematical modeling. Mathematical modeling is a consistent technique for describing a system with the help of mathematical language and its theorems and representations. In other words, mathematical modeling is the process of developing a mathematical representation for a given system to make it easier to analyze that system and predict its behavior.

This study aimed to find the best location and capacity for constructing desalination facilities in the Sistan and Baluchestan province of Iran such that the demands of different applicants (for drinking water) are optimally covered and the total cost including the cost of constructing the facilities and the cost of water transmission is minimized. This subject was performed by developing a mathematical model and then solving the model with a genetic algorithm. The most important innovation of this study is the simultaneous use of mathematical modeling and meta-heuristics for the combined optimization of desalination plant location and water distribution network in the format of a case study. In this process, the goal was to formulate a new mathematical model for the said problem and then develop an optimization algorithm to solve the resulting model.

In the rest of this paper, in Section 2, previous studies in the field are reviewed and categorized and the gap in the research literature is described. In Section 3, the research method is explained, the proposed mathematical model for the problem is presented, and the mechanism of a novel genetic algorithm capable of solving the problem within an acceptably short time is described. Details of the case study, the solution obtained for the case, and a complete analysis of this solution are provided in Section 4. In the end, the concluding remarks, a short description of the results, and a few suggestions for future studies are provided in Section 5.

2. Literature review

Numerous studies have been conducted on the subject of planning in the energy sector. The goal of many of these studies has been to create a scientific framework for decision-making in this field. Some of these studies have used mathematical modeling for the optimization of energy planning [13,14]. For example, Vergara-Fernandez et al. [13] developed a method based on mixed-integer linear programming (MILP) for planning of the operations of a reverse osmosis (RO) seawater desalination plant with a station of pumping in a remote arid agricultural area according to the principles of demand-side management (DSM). In this study, an on-grid photovoltaic solar power station was spotted out as the source of energy. The objective of their model was to plan the system's activities such that the daily difference between the electricity purchase costs and the revenue from selling the generated electricity is minimized. The case on which the method was tested was an agricultural area in northern Chile. In another study, Herrera-León et al. [14] proposed a method for designing partially solar-powered water desalination plants. This method, which uses mixed-integer nonlinear programming (MINLP), consists of two stages, the first attempting to minimize the entire system's cost while trying to reduce the greenhouse gas (GHG) emissions resulting from the transportation of desalinated water at the second stage with the opportunities to install photovoltaic panels taken into account. Their MINLP model considers the costs including the cost of constructing desalination plants and pumping stations, cost of construction of pipes and photovoltaic panels and also computes their GHG emissions. These researchers implemented their mathematical method in GAMS and then used the BARON solver to obtain the global optimal solution. To verify its applicability, they used the proposed method to design a desalination plant for the Atacama Desert as a case study.

As shown in Fig. 3, the existing research literature can be broadly categorized into two parts based on the objective: finding the optimal location for desalination plants and optimizing the water distribution network, both of which are reviewed below.

A) The problem of finding optimal locations for constructing desalination plants or power plants has been the subject of a number of studies. In one study, Dalabeeh [15] investigated the problem of determining the best location and capacity of wind power plants in five regions in Jordan. Gigović et al. [16] solved a similar problem for a province of Serbia by integrating Geographical Information System (GIS) with multi-criteria decision making methods (DEMATEL, ANP, and MABAC). In a study by Wu et al. [17], they proposed a decision-making framework for the optimal site of solar thermal power plants, which consists of four steps. Firstly, feasible locations are recognized considering some criteria including energy, infrastructure, land, environment and social categories. Secondly, decision criteria are weighted with the help of a fuzzy scale. Thirdly, linguistic variables (rather than fuzzy set theory or numerical values) are used to determine and incorporate experts' preferences. And finally, a group decision-making method is utilized to classify the potential locations. In the end, these researches applied their method to a case study in China to demonstrate its effectiveness. Azadeh et al. [18] proposed an integrated approach based on hierarchical data envelopment analysis (DEA) for determining the preferred geographic locations for wind power plants, which considers a wide variety of the indicators related to the subject. In order to validate their DEA model, they also used two multivariate techniques namely principal component analysis (PCA) and numerical taxonomy (NT). They tested the approach on 100 sites in 25 cities in Iran and also proved the validity of their method with the help of previous studies and real data regarding wind power in Iran. In a study by Jun et al. [19], they extracted a wide range of site selection criteria for a combined wind/solar power plant from the research literature. In their case study, these researchers chose seven locations for the

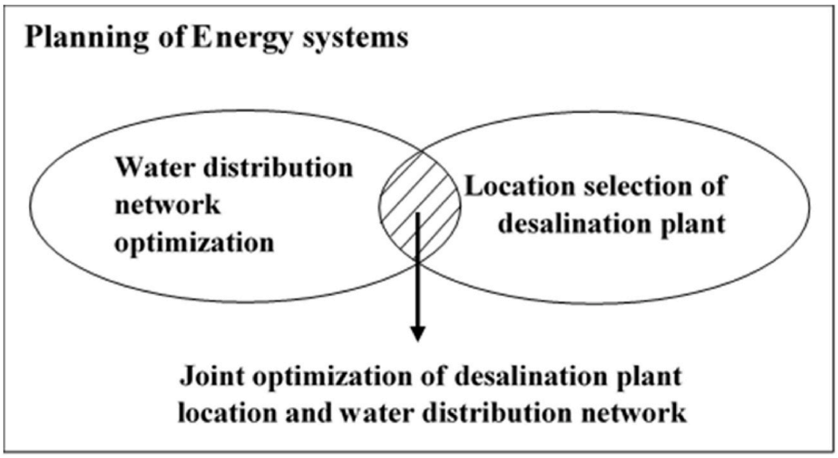

Fig. 3. Classification of the research literature.

construction of a combined wind/solar power plant, and after weighting the criteria using the order relations method, evaluated and compared these seven locations using the ELECTRE-II method. In the end, three locations were named as the best, two as the second best, and two as the worst, which were consistent with findings of similar studies. Khan and Rathi [20] used a method based on GIS to optimize the location of a large-scale photovoltaic solar power plant according to various criteria. The criteria used in this study were of two categories: 1) analysis criteria, including solar radiation availability, availability of vacant land, distance from highways, existing distribution lines, etc., and 2) exclusion criteria, including local climate variations, module soiling, topography of the site, etc. These researchers tested their method on a state in India with high solar radiation, using it to produce a number of maps showing the potential locations for constructing photovoltaic solar power plants and then analyzing the identified potential locations based on the exclusion criteria to determine the best site.

In a study carried out by Choudhary and Shankar [21], they proposed a framework based on fuzzy AHP-TOPSIS for the optimal location of thermal power plants, where social, technical, economic, environmental and political considerations (STEEP) taken into account. In this approach, possible sites are identified according to relevant considerations and fuzzy AHP is used to determine the quantitative and qualitative weights that influence the location decision. In addition to fuzzy AHP, which is used for modeling in the presence of linguistic ambiguities, vague concepts and missing information knowledge, these researchers used TOPSIS, which is a multi-criteria decision ranking method, to rate the potential sites based on their general function. They examined the efficiency of their method in a case study of thermal power plant in India, ultimately concluding that the approach provides a precise and effective decision support tool for making decision in this area. Dweiri et al. [22] developed a multi-objective decision support system for ranking the criteria for desalination plant location in the UAE with social, environmental, economic, technical and operational aspects taken into account. The results of this study showed that technical and economic criteria are the most important groups of criteria for the said purpose. In a study by Mostafaeipour et al. [23] on the location of wind-powered desalination plants in the ports and islands of southern Iran, they first identified the locations with the right potentials for this purpose, ultimately choosing 10 ports and 5 islands that suffer from water scarcity as initial candidates. They then ranked these locations based on a set of criteria including wind energy density, economic feasibility, topographic situation, frequency of natural disasters, population and distance between wind power plant and desalination facilities using the ELECTRE-III method and finally validated the results using the PROMETHEE method. Grubert et al. [24] presented a hybrid method comprised of multi-criteria decision-making and GIS for identifying suitable locations for constructing desalination infrastructure. These researchers stated that the chosen locations must have three general features: 1) Enough renewable sources to partially offset the fossil energy load, 2) water with the right properties to minimize the total energy required for desalination, and 3) a human population that is able and willing to pay the price of desalinated water. They presented a quantitative analysis method for determining the best locations for solar-powered seawater reverse osmosis (SWRO) desalination based on a set of special criteria, which involves combining spatial data on natural circumstances (solar radiation, ocean salinity, and ocean temperature) with social criteria (water crisis, water price, and population). In the end, these researchers concluded that tropical and subtropical cities that suffer from water crises are the best potential sites for constructing solar-powered SWRO facilities. Badi et al. [25] used the gray system theory to develop a method for choosing the best location of a desalination plant in Libya. These researchers used an approach based on gray numbers to demonstrate decision makers' comparative judgments and then used an extent analysis method (EAM) to choose the best location. They also assessed the method on a case study of site selection for a desalination plant in Libya.

Banat et al. [26] proposed a method for determining the most favorable geographical locations for constructing standalone desalination units, which involves using a weighted score analysis method to weight criteria and locations. In this method, the location selection is done in multiple steps, in the sense that first, the appropriate regions are determined and then the best sites in these regions are determined according to the criteria. In a study by Sepehr et al. [27], the Delphi method was used to identify the best locations for the construction of desalination plants in the coastal regions in south of Iran. Enlisting the help of 10 experts, these researchers identified eight criteria and 18 sub-criteria for this location process, produced their corresponding input layers in ArcGIS, and partitioned the area into five zones according to each sub-criterion. They then used the linear Delphi method to integrate these maps and again partitioned the final map into five zones. In this study, the most important criteria and sub-criteria were found to be environmentally sensitive regions and quality of seawater respectively. After merging the layers, these researchers specified 63 potential sites for the construction of desalination facilities in the coastal regions of the Persian Gulf and the Oman Sea in Hormozgan province. Ultimately, 27 of these sites were found to have had best environmental circumstances for constructing plants. Mahmoud et al. [28] also presented a hybrid method consisting of GIS and multi-criteria decision analysis for location and capacity determination of desalination facilities and investigated its applicability in the northwest coast of Egypt. Al-Nori et al. [29] proposed a mathematical model for optimizing a desalination supply chain, which considers a set of different options in terms of location, capacity, technology, and energy source for desalination. They also provided a decision graph representing the performance of each option compared to the quantitative and qualitative measures chosen by the decision maker. These researchers used their method in a case study in Saudi Arabia. In a study by Afify [30], the potential locations for constructing desalination plants in Egypt were determined by a combination of multi-criteria decision analysis and GIS, and after comparing the options, an action plan at the national level was presented for this purpose. Azadeh et al. [31] proposed an integrated fuzzy DEA approach for the site of wind power plants. They also provided a list of most relevant indicators for wind power plant location. They used two multivariate methods namely principal component analysis (PCA) and numerical taxonomy (NT) to validate the DEA model. They tested the proposed model on 100 sites in 25 cities in Iran while considering 20 other cities as energy consumers. Their results showed the importance of the proximity of consumers to the location of wind power plants. These researchers also showed that the fuzzification of uncertain criteria leads to a more realistic approach to the problem. In a study by Badi et al. [32], the best sites for constructing desalination plants in the northwestern coast of Libya was determined with a two-step approach: 1) minimizing the cost of water transmission and 2) examining the influence of external criteria in choosing the location, which was conducted using the combinative distance-based assessment (CODAS) method. In a case study conducted with this method, the city of Tripoli was determined as the best location. These researchers also performed a sensitivity analysis to assess the robustness of the identified locations.

B) The literature also contains a number of studies on the optimization of water distribution networks. In one of these studies, Araya et al. [33] developed a method to determine the best site and size of desalination and water transmission facilities and energy recovery systems for producing desalinated water in areas with irregular topography. In this study, the said problem was formulated as a MINLP model, which was linearized into a MILP model and then solved in GAMS with the CPLEX solver. Also a case study was offered to prove the efficiency of the method to the problems of real sizes. Herrera-León et al. [34] provided an MINLP-based optimization technique to plan the water supply for non-coastal water-scarce regions. These researchers used a case study in an extremely dry area in Chile to demonstrate the efficiency of their model and its ability to generate global optimal solutions for real-sized problems. In a study by Matijasevic et al. [35] on water conservation through the optimization of processing structures, they analyzed the water network of an oil refinery and proposed a solution for minimizing the cost related to freshwater and wastewater treatment. They investigated three water-consuming processes with three pollutants and proposed three potential treatment approaches. In this study, the non-convex nonlinear programming problem was approximated to a MILP model, which was then simplified by heuristic rules and solved in MATLAB. Cassiolato et al. [36] proposed a deterministic mathematical model for the optimization of water distribution networks. They defined two problem instances for assessing the model performance, coded and solved them in GAMS, reporting that the global optimum was found for both instances. Afshar [37] used incremental solution generation - a feature of the ant colony optimization algorithm (ACO) - to improve partially constrained ACO in order to solve optimization problems with explicit constraints. This method is based on creating a tabu list for the decision points of the problem so that some of the constraints are satisfied. These researchers formulated their method for the storm water network design problem. They developed two ACO algorithms and used them to solve a benchmark problem of storm water network design. Herrera-León et al. [38] proposed a multi-objective method for the planning of integrated water supply systems for the mining industry with the objective of minimizing the systems' total operating costs and GHG emissions. These researchers chose the mining industry of Chile as a case study. Their proposed approach specifies the optimal sites and sizes of water treatment plants, pipelines, and pumping stations from a technical, economic and environmental point of view. Also considers how solar photovoltaic system can be used to reduce the systems' GHG emissions. In a study by Monsef et al. [39], they investigated the application of three multi-objective optimization algorithms namely non-dominated sorting genetic algorithm - version 2 (NSGA-II), multi-objective differential evolution (MODE), and multi-objective particle swarm optimization (MOPSO) to optimize the design of water transmission network. They examined and compared the performance of these algorithms in terms of solution accuracy and speed for four water distribution networks using a number of different experimental mathematical functions. In the end, these researchers concluded that MODE offered the best performance in terms of the defined criteria. Herrera et al. [40]

Table 1
Comparison of the present study and similar studies in the research literature.

No.	Author(S)	Year	Location	Objects		Technics					Criteria					
				Site Selection	Distribution Network Opt	Mathematical Modeling	Metaheurstics	GIS	MCDM	Communicative Methods	Economic (Costs)	Environmentally	Operational	Technical	Social	Management
1	Sepehr et al. [27]	2017	Iran (Hormozgan)	*				*		*	*	*	*	*	*	*
2	Dweiri et al. [22]	2018	UAE						*		*	*	*	*	*	
3	Geem [43]	2009	Benchmark networks		*		*				*					
4	Al-Nory et al. [29]	2014	KSA	*		*					*		*	*		
5	Badi et al. [32]	2018	Libya	*					*		*		*	*		
6	Banat et al. [26]	2007	Fictitious	*					*					*		
7	Liu et al. [42]	2011	Greece	*	*	*					*					
8	Afify [30]	2010	Egypt	*				*	*				*	*		
9	Grubert et al. [24]	2014	Global	*				*	*					*	*	
10	Mahmoud et al. [28]	2002	Egypt	*				*	*		*		*			*
11	Araya et al. [41]	2017	Chile	*	*	*					*					
12	Mostafaeipour et al. [23]	2017	Iran	*	*				*		*		*	*		
13	Herrera et al. [40]	2015	Chile	*	*	*					*					
14	Current research	2022	Iran	*	*	*	*				*		*			

proposed a MINLP model for the optimization of concurrent design of desalination plant and the network of desalinated water transmission. In this model, the site and size of plants as well as water transmission system are determined where the objective is to minimize the construction and operating costs. They also applied their method to a case study to demonstrate its efficiency.

Araya et al. [41] provided a method for determining the site and size of the desalination plant, water transmission network, and energy recovery equipment. They formulated a MINLP model for this problem, transformed it into a MILP model, and then solved it in GAMS with the CPLEX solver. In a study by Liu et al. [42], they presented a MILP-based method for integrated water resources management (IWRM) for insular regions suffering from water scarcity. Water resources include fresh seawater, wastewater and reclaimed water. This MILP model determines the location of desalination facilities, the configuration of wastewater and water treatment plants, and the water transmission infrastructure of three types of sources such that the total construction cost and the annual operating cost are minimized. Geem [43] developed a modified harmony search algorithm incorporating with the concept of particle swarm for solving the multi-state nonlinear optimization problem of water distribution network design, which falls in the category of NP-hard combinatorial problems. This algorithm showed good results when tested on four benchmark networks (namely two-loop, Hanoi, Balerma and New York City). Fakhrzad et al. [44] investigated the green vehicle routing problem with simultaneous pickup and delivery when the demand is uncertain and presented a new model. To solve such large-scale problems, a two-stage algorithm based on the modified AVNS proposed. In order to demonstrate the algorithm function, they performed computational experiments using modified versions of Solomon's benchmark instances.

A summary of similarities and differences between the present study and other studies in the relevant literature is provided in Table 1.

There is a gap in the open literature for combined optimization of desalination plant location and water distribution network in Iran. This paper aims at filling this knowledge gap by utilizing mathematical modeling and meta-heuristic algorithms.

As shown in Table 1, the most important contribution of this study is the simultaneous use of mathematical modeling and meta-

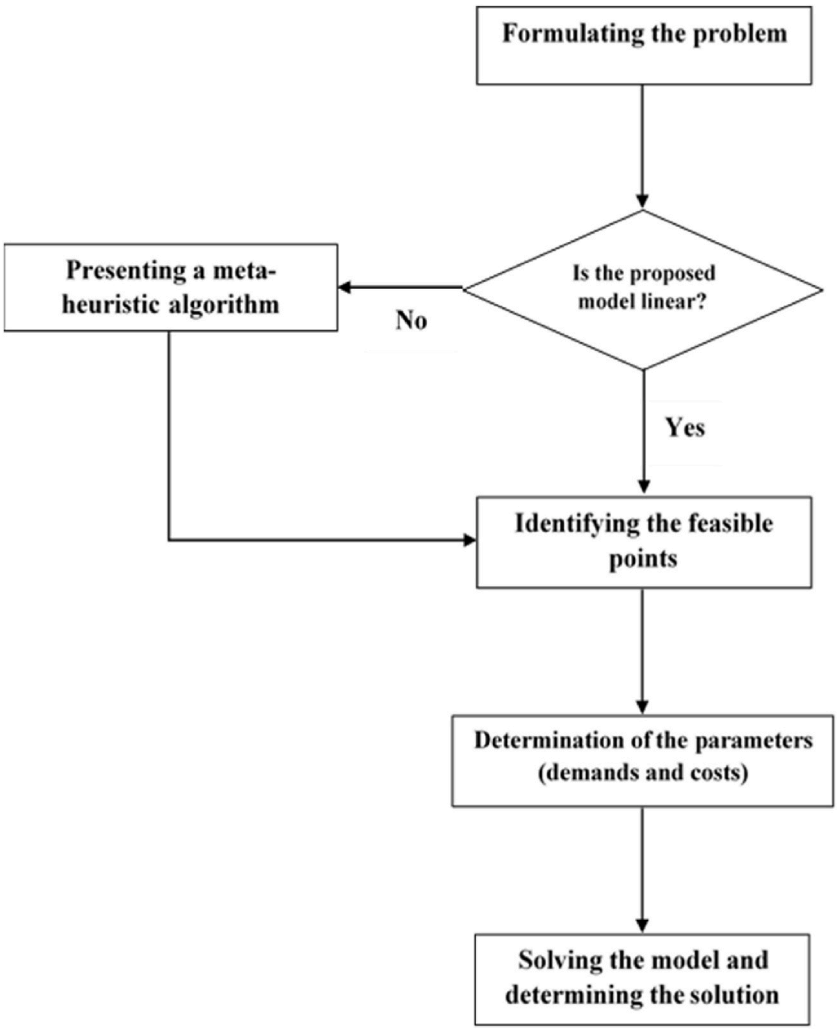

Fig. 4. Research procedure.

heuristic optimization for the combined optimization of desalination plant location and water distribution network, which is done in the format of a case study. Indeed, a limited number of studies have worked on the simultaneous optimization of desalination plant location and desalinated water distribution network, and very few of them have done so with the help of mathematical modeling. In addition, considering the massive scale of real-world problems, they are likely to require appropriate meta-heuristic solution approaches; a need that has been somewhat neglected in the literature. Thus, the study aimed to formulate a new mathematical model for the problem as well as an optimization algorithm for solving the model.

The main contributions of current research compared to previous publications are briefly as follows.

- Developing a novel mathematical model to solve the problem of simultaneous optimization of desalination facilities locating and water distribution network.
- Presenting an efficient novel genetic algorithm to solve the issue in question.
- Using real data in the case study to help the policymakers in future decisions.

The research results are a valuable reference for optimization of desalination plant location and its water distribution network.

3. Methodology

The general procedure of conducting this study in its different stages is illustrated in Fig. 4. The first step of this study was to formulate a mathematical model for the problem. After model formulation, a meta-heuristic solution algorithm was developed for solving the model and finally the proposed method was applied to a case study.

3.1. Mathematical modeling

This study aimed to provide a mathematical model to ascertain the location and capacity of desalination facilities in the study area such that the demands of different applicants (for drinking water) are optimally covered with the minimum total cost, including the cost of constructing the facilities and the cost of water transmission/distribution. For this purpose, a non-linear mathematical model pursuing the said objective was formulated.

Descriptions of problem parameters and model variables are provided in Tables 2 and 3, respectively. Six general categories of parameters and six general categories of decision variables were used in the mathematical model.

The proposed model is as follows:

$$\text{Min}\sum_j S_j.\delta_j.H_j + \sum_j \sum_{j' \neq j} g_{jj'}.\gamma_{jj'}.V_{jj'} + \sum_j P_j \tag{1}$$

s.t.

$$\delta_j.H_j + \sum_{j' \neq j} V_{j'j} \geq \sum_{j' \neq j} V_{jj'} + D_j, \forall j \tag{2}$$

$$\delta_j = 0, \forall j \notin \omega \tag{3}$$

$$1 - x_j \leq M\left(\sum_{j' \neq j} \gamma_{jj'}\right), \forall j \tag{4}$$

$$M.\, y_j \geq \sum_{j' \neq j} \gamma_{jj'}, \forall j \tag{5}$$

$$x_j + y_j = 1, \forall j \tag{6}$$

$$P_j \geq P.y_j, \forall j \tag{7}$$

Table 2
Model parameters.

Parameter	Definition
S_j	Unit cost of production at location j
$g_{jj'}$	Unit cost of transferring desalinated water from location j to location j'
D_j	Water demand at location j
P_j	Cost of constructing a water pumping facility
ω	Set of cities where desalination facilities can be built
M	A large positive number

Table 3
Decision variables.

Variable	Definition
δ_j	$= 1$ if a desalination plant is built at location j; $= 0$ otherwise
$\gamma_{jj'}$	$= 1$ if water is transferred from location j to location j'; $= 0$ otherwise
H_j	Required capacity to produce desalinated water at location j
$V_{jj'}$	Required capacity to transfer desalinated water from location j to location j'
x_j	$= 0$ if at least one outbound transmission line is built at location j; $= 1$ otherwise
y_j	$= 1$ if at least one outbound transmission line is built at location j; $= 0$ otherwise

$$P_j \leq (1 - x_j)P, \forall j \tag{8}$$

$$x_j \in \{0, 1\} \tag{9}$$

$$y_j \in \{0, 1\} \tag{10}$$

$$\delta_j \in \{0, 1\} \tag{11}$$

$$\gamma_{jj'} \in \{0, 1\} \tag{12}$$

$$V_{jj'} \geq 0 \tag{13}$$

$$H_j \geq 0 \tag{14}$$

Equation (1) represents the objective function of the problem, including the cost of constructing the desalination plant, the cost of water transmission, and the cost of pumping facilities. Equation (2) guarantees that the sum of desalinated water and inbound freshwater at each location is not lower than the sum of water demand and outbound water in that location. Equation (3) ensures that desalination plants will be built only in cities where this possibility exists. Equations (4)–(6) are the definitions of binary variables x_j and y_j ($x_j = 0$ and $y_j = 1$ if there at least one outbound transmission line is built at location j and $x_j = 1$ and $y_j = 0$ if no such transmission line exists). Equations (7) and (8) are the definitions of the cost of constructing pumping facilities. The cost of constructing pumping facilities will be P if at least one outbound transmission line is built at location j and will be zero otherwise. Equations (9)–(14) define the type of decision variables used in the model.

3.2. Proposed genetic algorithm

Considering the non-linearity of the presented mathematical model, this section provides an efficient novel genetic algorithm for solving the problem within an acceptably short time. The algorithm procedure is shown in Fig. 5. Initial constraints, crossover operator and forming the next generation is novel and specific to this paper.

3.2.1. Solution representation

The solutions of the model are represented by the chromosome structure shown in Fig. 6. Each chromosome consists of $(n(\omega) + j * (j - 1))$ genes, where the first $n(\omega)$ genes represent the capacity to produce fresh water in the cities of set ω and the remaining genes represent the capacity to transfer water from location i to location j. The sequence of genes in a chromosome is schematically shown in Fig. 6.

3.2.2. Initial population generation

The initial population is generated at random. It should be explained that at all stages of the algorithm, chromosome selection is done with three main conditions.

1 for $\in \omega$: if $Cap\,j = 0$, then: for j': $Vol\,jj' = 0$.
2 for $\in \omega$: if $Cap\,j \neq 0$, then: sum $(Vol\,jj') + D_j \leq Cap\,j$.
3 for $\notin \omega$: sum $(Vol\,jj') + D_j \leq$ sum$(Vol\,j'j)$.

3.2.3. Parent selection strategy

The parents are selected by the roulette wheel method. For this purpose, after applying a coefficient representing selection pressure, a defined fitness function is calculated for each chromosome and the chromosomes are ranked in the order of their fitness value. Then, each chromosome is assigned a probability (a fraction of the cumulative probability of all chromosomes) and finally two dissimilar chromosomes are randomly selected as parents according to these probabilities.

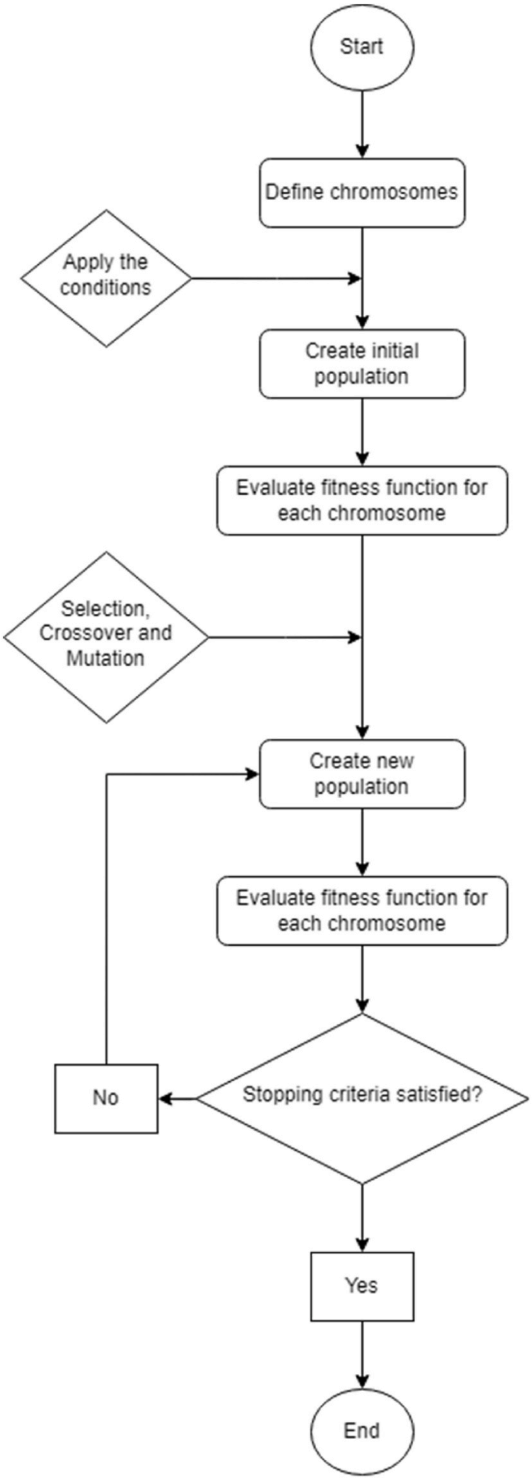

Fig. 5. The genetic algorithm procedure.

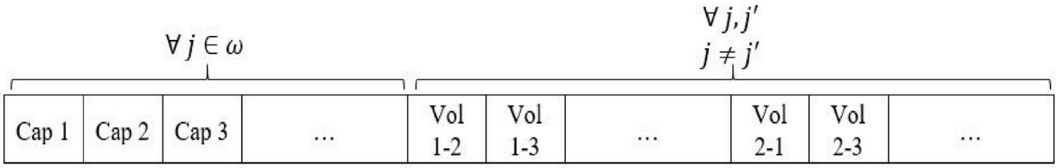

Fig. 6. Representation of chromosomes.

3.2.4. *Offspring selection strategy*

Offspring are selected by the crossover operator described in Section 3.2.5.1.

3.2.5. *Genetic operators*

3.2.5.1. Crossover operator. A special type of single-point crossover operator is used to produce offspring. This operation starts with the generation of a random number n from the interval [1, L] where L is the chromosome length. The first offspring is then produced by copying the first n genes of the first parent and placing the rest of the genes in the same order as they are in the second parent. For the second offspring, the same operation is performed with the roles of the parents reversed.

3.2.5.2. Mutation operator. This operator generates mutated chromosomes by swapping two randomly selected genes of a parent chromosome with each other.

3.2.6. *Forming the next generation*

In order to continue the algorithm to the next generation, first 30 % of the elites of the previous generation, 5 % of the population of mutated chromosomes and 25 % of the offspring produced by the crossover operator are transferred to the next generation. Then, unchosen chromosomes of the previous generation and offspring produced by the crossover operator are taken into account, and as much as 40 % the population's size are chosen by chance and transferred to the next generation.

3.2.7. *Stopping rule*

Two stopping conditions are considered for the algorithm. Once any of these conditions are met, the algorithm will stop and report

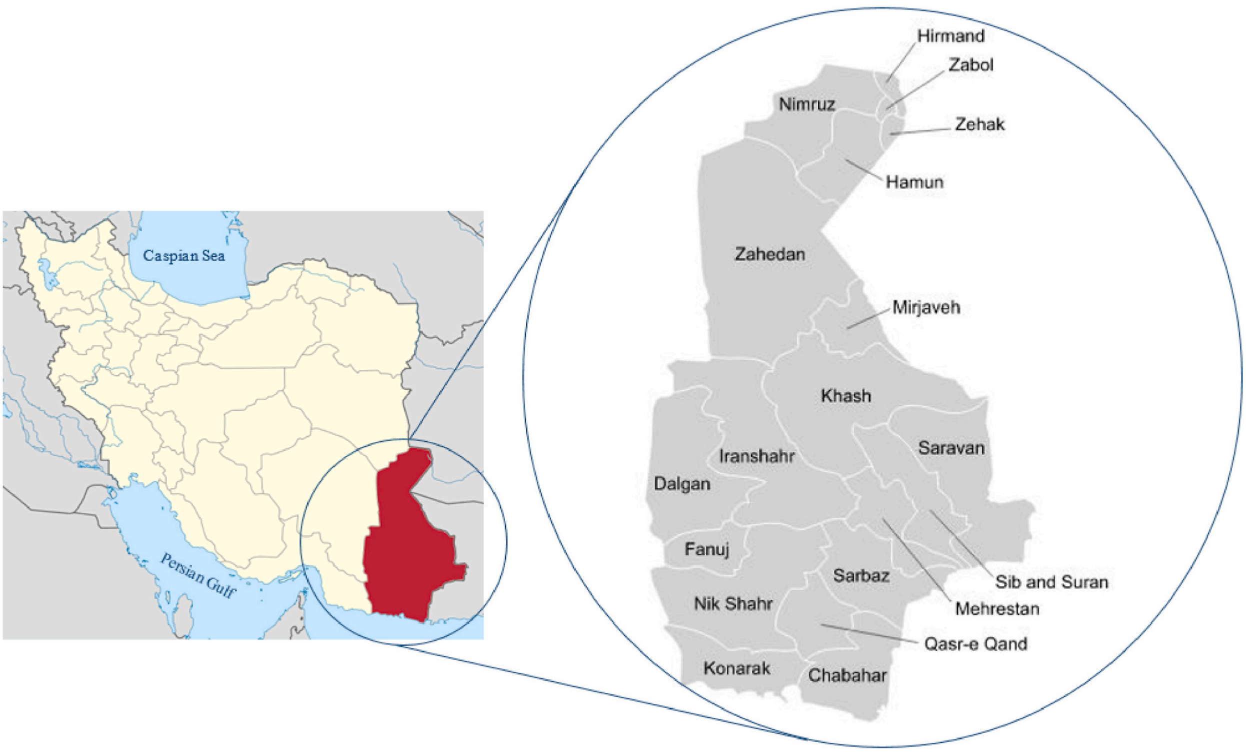

Fig. 7. Geographical location of Sistan and Baluchestan province.

the best found solution. These two conditions are.

1 The algorithm producing 500 generations of chromosomes;
2 The best value obtained from the fitness function remaining constant for 200 consecutive generations.

4. Analysis

4.1. Case study

One of the provinces of Iran (Sistan and Baluchestan) was selected as a case study.

Sistan and Baluchestan is a province in the southeast of Iran with the city of Zahedan as its provincial capital. With an area of about 180,726 square kilometers, Sistan and Baluchestan is Iran's second largest province. It has a population of 2,775,014 according to the latest official census (2016) [45]. This province has a mostly hot and dry climate with very low precipitation, which falls in the desert/arid class. Some parts of this province have very limited access to drinking water. However, it has a 300-km water border with the Sea of Oman. Sistan plain receives less than 65 mm of rain per year, which is far lower than the 5000 mm evaporation it experiences. Overall, these conditions explain the severe physical dryness of the area and why it experiences devastating water scarcity whenever there is a decline in the discharge of Hirmand River. The 120-day winds that blow from late spring to the end of summer tend to aggravate the dryness of this environment. Baluchistan's climate is characterized by high average temperatures and low temperature fluctuations. Because of Balochistan's low precipitation and lack of mountain snow sources, most of the river flows in this area are temporary and seasonal, which is why limited groundwater sources are the only source of drinking water for many its parts. Zahedan is the coldest and Iranshahr is the warmest county in the province.

In the 2016 official census, Sistan and Baluchestan province consisted of 19 counties. The map of the counties of Sistan and Baluchestan province is displayed in Fig. 7.

The model presented in Section 3-1 was used to optimize the location of the desalination plant and the water distribution network for the case study.

4.2. Assumptions

In general, each problem is solved based on a series of assumptions. The assumption made in this study, are as follows.

1) Desalination facilities can be built on the coast
2) The cost of fresh water production in each county is proportional to its population.
3) The daily water demand of each county is equal to its population multiplied by the average water consumption per capita, which according to the CCW Institute, is 142 L per day [46].

The population of the counties of Sistan and Baluchestan province and their water demand according to the 2016 census are provided in Table 4 and Fig. 8. In the 2016 census, the most populous counties of the province were Zahedan, Chabahar and Iranshahr in that order.

Table 4
Population of the counties of Sistan and Baluchestan province in the 2016 census and their water demand [45].

County	Population in 2016	Water demand (Liter/day)
Iranshahr	254,314	36,112,588
Dalgan	67,857	9,635,694
Sarbaz	186,165	26,435,430
Konarak	98,212	13,946,104
Chabahar	283,204	40,214,968
Qasr-e Qand	61,076	8,672,792
Nik Shahr	141,894	20,148,948
Fanuj	49,161	6,980,862
Khash	173,821	24,682,582
Zabol	165,666	23,524,572
Nimruz	48,471	6,882,882
Hamun	41,017	5,824,414
Hirmand	63,979	9,085,018
Zehak	74,896	10,635,232
Zahedan	672,589	95,507,638
Mirjaveh	45,357	6,440,694
Saravan	191,661	27,215,862
Sib & Suran	85,095	12,083,490
Mehrestan	70,579	10,022,218

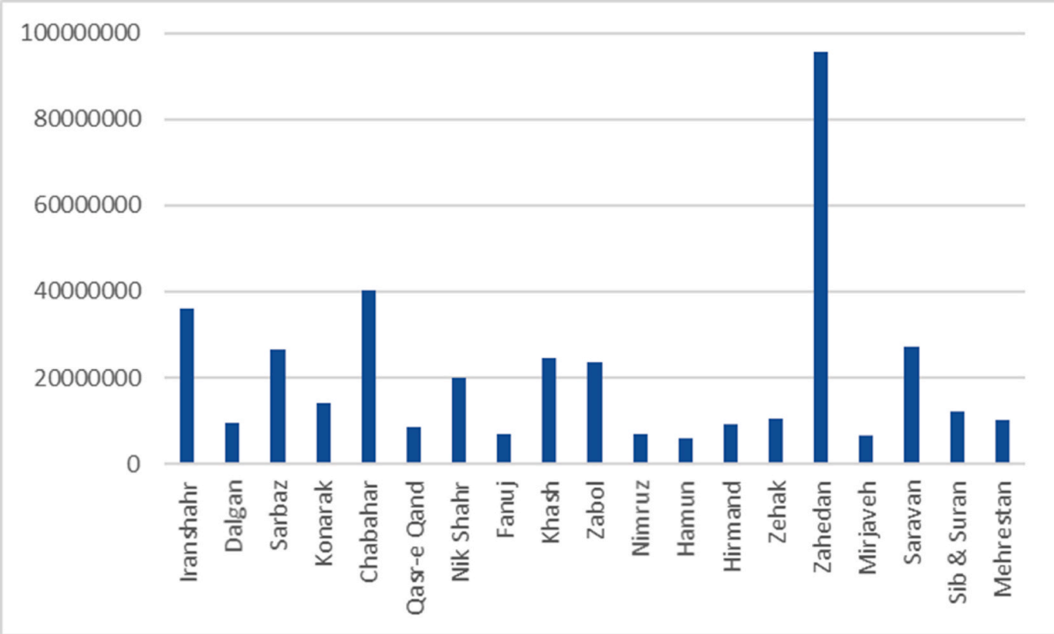

Fig. 8. Water demand of the counties of Sistan and Baluchestan province [45,46].

Table 5
Distance between the counties of Sistan and Baluchestan province (in kilometers).[47]

County	Iranshahr	Dalgan	Sarbaz	Konarak	Chabahar	Qasr-e Qand	Nik Shahr	Fanuj	Khash	Zabol	Nimruz	Hamun	Hirmand	Zehak	Zahedan	Mirjaveh	Saravan	Sib & Suran	Mehrestan
Iranshahr																			
Dalgan	280																		
Sarbaz	120	188																	
Konarak	285	109	285																
Chabahar	309	75	251	54															
Qasr-e Qand	232	181	185	185	206														
Nik Shahr	168	200	270	121	143	64													
Fanuj	162	290	264	212	233	156	92												
Khash	149	425	253	458	479	402	338	332											
Zabol	554	830	658	863	884	807	743	737	407										
Nimruz	566	842	671	875	896	819	755	749	420	14									
Hamun	535	811	639	843	864	787	724	717	388	21	33								
Hirmand	586	863	691	895	916	839	775	769	440	33	47	51							
Zehak	560	836	664	868	890	813	749	743	413	26	40	27	38						
Zahedan	328	604	432	636	657	580	517	510	181	212	224	192	243	220					
Mirjaveh	263	539	367	572	593	516	452	446	114	301	313	282	333	310	84				
Saravan	226	386	199	485	449	383	416	410	156	543	555	524	575	552	334	272			
Sib & Suran	183	344	156	443	407	340	374	367	145	531	543	512	563	540	322	260	43		
Mehrestan	124	285	97	384	348	281	315	308	153	540	552	521	571	548	330	268	101	59	

Fig. 9. Water distribution network for the studied case.

4) The cost of transferring desalinated water from location *j* to location *j'* and vice versa is equal to the distance between the two locations.

The distance between the counties of Sistan and Baluchestan province is given in Table 5.

5) The cost of pumping water to downstream from a county was considered to be 10 % of the fixed cost of fresh water production in that county.

4.3. Problem solution

To solve the problem with the proposed genetic algorithm, the algorithm was coded in Python 3.9.7 and executed on a laptop with an Intel® Core™ i7@2.40GHz processor and 8.0 GBytes of 2400 MHz DDR3 RAM, producing the following results.

The complete results of the genetic algorithm are provided in Tables 1 and 2 of Appendix 1.

According to these results, only Site 5 is proposed for constructing a desalination plant, when site 4 and site 5 are the potential locations.

These results also show the need for constructing transmission lines from Site 5 to Site 4, from Site 5 to Site 6, from Site 6 to Site 7, from Site 6 to Site 3, from Site 7 to Site 8, from Site 8 to Site 2, from Site 2 to Site 1, from Site 3 to Site 19, from Site 19 to Site 18, from Site 18 to Site 17, from Site 17 to Site 9, from Site 9 to Site 16, from Site 16 to Site 15, from Site 15 to Site 12, from Site 12 to Site 11, from Site 12 to Site 14, from Site 14 to Site 10, and from Site 10 to Site 13 with the capacities given below.

Therefore, it is recommended to construct the desalination facilities with a capacity of 394,052 cubic meters per day in the city of Chabahar. In addition to Chabahar, pumping facilities need to also be constructed in Qasr-e Qand, Nikshahr, Fanuj, Dalgan, Sarbaz, Mehrestan, Sib & Suran, Saravan, Khash, Mirjaveh, Zahedan, Hamun, Zehak and Zabol. The proposed water distribution network for Sistan and Baluchestan is shown in Fig. 9. This is a feasible solution as it satisfies all the problem constraints and assumptions.

Fig. 9 shows the water distribution network that once the desalination facilities are constructed will transport the water from Chabahar to Konarak and Qasr-e Qand, from Qasr-e Qand to Sarbaz and Nikshahr, from Nikshahr to Fanuj, from Fanuj to Dalgan, from Dalgan to Iranshahr, from Sarbaz to Mehrestan, from Mehrestan to Sib & Suran, from Sib & Suran to Saravan, from Saravan to Khash, from Khash to Mirjaveh, from Mirjaveh to Zahedan, from Zahedan to Hamun, from Hamun to Nimruz and Zehak, from Zehak to Zabol, and from Zabol to Hirmand. Also, pumping facilities must be constructed in 14 counties midst the distribution network.

5. Conclusion

This study presented a method for the simultaneous design of the location of a desalination plant and its water distribution network based on mathematical modeling. For this method, the authors formulated a new non-linear mathematical model that minimizes the costs of water production and transportation, including the cost of constructing desalination facilities, the cost of water transmission between cities, and the cost of constructing pumping facilities. An efficient genetic algorithm was also developed for solving the model within an acceptably short time. The method was used in a case study of Sistan and Baluchestan, which is one of Iran's most water stressed areas. When solving the model for Sistan and Baluchestan with the proposed solution algorithm, this algorithm generated an acceptable solution in 3.74 s. The best solution was found to be constructing a desalination facility with a capacity of 394,052 cubic meters per day in the city of Chabahar. This amount of water can certainly alleviate the water scarcity problems of Sistan and Baluchestan, helping it avoid constant water crises. The obtained solution also involves constructing a water distribution network across Sistan and Baluchestan as shown in Fig. 9. This solution can be expected to help decision-makers in macro planning and policymaking and the residents of the case study which is considered one of the most arid areas in the world.

The authors recommend taking the following approaches in future studies.

- Forecasting water demand for long-term planning periods
- Incorporating uncertainty in the problem's model.
- Using some other algorithms to compare their capability of solving the problem.

Data availability statement

The data associated with the study are available at [https://old.sci.org.ir/english/Population-and-Housing-Censuses], reference number [45].

The code associated with the study will be made available on request from the corresponding author from the date of publication.

CRediT authorship contribution statement

Mohammad Hossein Sattarkhan: Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Ali Mostafaeipour:** Validation, Supervision, Project administration. **Ahmad Sadegheih:** Validation, Supervision.

Declaration of competing interest

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

Appendix A. Results obtained by solving the model for the studied case with the proposed genetic algorithm

Table 1
Location and capacity of desalination facilities

i	δ_i	H_i (m^3)	i	δ_i	H_i (m^3)
1	0	0	11	0	0
2	0	0	12	0	0
3	0	0	13	0	0
4	0	0	14	0	0
5	1	394,052	15	0	0
6	0	0	16	0	0
7	0	0	17	0	0
8	0	0	18	0	0
9	0	0	19	0	0
10	0	0			

Table 2
Water distribution lines and capacity

jj'	$\gamma_{jj'}$	$V_{jj'}$ (m^3)	jj'	$\gamma_{jj'}$	$V_{jj'}$ (m^3)	jj'	$\gamma_{jj'}$	$V_{jj'}$ (m^3)
1,2	0	0	7,8	1	52,729	13,14	0	0
1,3	0	0	7,9	0	0	13,15	0	0
1,4	0	0	7,10	0	0	13,16	0	0
1,5	0	0	7,11	0	0	13,17	0	0
1,6	0	0	7,12	0	0	13,18	0	0
1,7	0	0	7,13	0	0	13,19	0	0
1,8	0	0	7,14	0	0	14,1	0	0
1,9	0	0	7,15	0	0	14,2	0	0
1,10	0	0	7,16	0	0	14,3	0	0
1,11	0	0	7,17	0	0	14,4	0	0
1,12	0	0	7,18	0	0	14,5	0	0
1,13	0	0	7,19	0	0	14,6	0	0
1,14	0	0	8,1	0	0	14,7	0	0
1,15	0	0	8,2	1	45,748	14,8	0	0
1,16	0	0	8,3	0	0	14,9	0	0
1,17	0	0	8,4	0	0	14,10	1	**32,610**
1,18	0	0	8,5	0	0	14,11	0	0
1,19	0	0	8,6	0	0	14,12	0	0
2,1	1	36,113	8,7	0	0	14,13	0	0
2,3	0	0	8,9	0	0	14,15	0	0
2,4	0	0	8,10	0	0	14,16	0	0
2,5	0	0	8,11	0	0	14,17	0	0
2,6	0	0	8,12	0	0	14,18	0	0
2,7	0	0	8,13	0	0	14,19	0	0
2,8	0	0	8,14	0	0	15,1	0	0
2,9	0	0	8,15	0	0	15,2	0	0
2,10	0	0	8,16	0	0	15,3	0	0
2,11	0	0	8,17	0	0	15,4	0	0
2,12	0	0	8,18	0	0	15,5	0	0
2,13	0	0	8,19	0	0	15,6	0	0
2,14	0	0	9,1	0	0	15,7	0	0
2,15	0	0	9,2	0	0	15,8	0	0
2,16	0	0	9,3	0	0	15,9	0	0
2,17	0	0	9,4	0	0	15,10	0	0
2,18	0	0	9,5	0	0	15,11	0	0
2,19	0	0	9,6	0	0	15,12	1	**55,952**
3,1	0	0	9,7	0	0	15,13	0	0
3,2	0	0	9,8	0	0	15,14	0	0
3,4	0	0	9,10	0	0	15,16	0	0
3,5	0	0	9,11	0	0	15,17	0	0
3,6	0	0	9,12	0	0	15,18	0	0
3,7	0	0	9,13	0	0	15,19	0	0

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Table 2 (*continued*)

jj'	$\gamma_{jj'}$	$V_{jj'}$ (m^3)	jj'	$\gamma_{jj'}$	$V_{jj'}$ (m^3)	jj'	$\gamma_{jj'}$	$V_{jj'}$ (m^3)
3,8	0	0	9,14	0	0	16,1	0	0
3,9	0	0	9,15	0	0	16,2	0	0
3,10	0	0	9,16	1	157,900	16,3	0	0
3,11	0	0	9,17	0	0	16,4	0	0
3,12	0	0	9,18	0	0	16,5	0	0
3,13	0	0	9,19	0	0	16,6	0	0
3,14	0	0	10,1	0	0	16,7	0	0
3,15	0	0	10,2	0	0	16,8	0	0
3,16	0	0	10,3	0	0	16,9	0	0
3,17	0	0	10,4	0	0	16,10	0	0
3,18	0	0	10,5	0	0	16,11	0	0
3,19	1	231,905	10,6	0	0	16,12	0	0
4,1	0	0	10,7	0	0	16,13	0	0
4,2	0	0	10,8	0	0	16,14	0	0
4,3	0	0	10,9	0	0	16,15	1	**151,460**
4,5	0	0	10,11	0	0	16,17	0	0
4,6	0	0	10,12	0	0	16,18	0	0
4,7	0	0	10,13	1	9,085	16,19	0	0
4,8	0	0	10,14	0	0	17,1	0	0
4,9	0	0	10,15	0	0	17,2	0	0
4,10	0	0	10,16	0	0	17,3	0	0
4,11	0	0	10,17	0	0	17,4	0	0
4,12	0	0	10,18	0	0	17,5	0	0
4,13	0	0	10,19	0	0	17,6	0	0
4,14	0	0	11,1	0	0	17,7	0	0
4,15	0	0	11,2	0	0	17,8	0	0
4,16	0	0	11,3	0	0	17,9	1	**182,583**
4,17	0	0	11,4	0	0	17,10	0	0
4,18	0	0	11,5	0	0	17,11	0	0
4,19	0	0	11,6	0	0	17,12	0	0
5,1	0	0	11,7	0	0	17,13	0	0
5,2	0	0	11,8	0	0	17,14	0	0
5,3	0	0	11,9	0	0	17,15	0	0
5,4	1	13,946	11,10	0	0	17,16	0	0
5,6	1	339,891	11,12	0	0	17,18	0	0
5,7	0	0	11,13	0	0	17,19	0	0
5,8	0	0	11,14	0	0	18,1	0	0
5,9	0	0	11,15	0	0	18,2	0	0
5,10	0	0	11,16	0	0	18,3	0	0
5,11	0	0	11,17	0	0	18,4	0	0
5,12	0	0	11,18	0	0	18,5	0	0
5,13	0	0	11,19	0	0	18,6	0	0
5,14	0	0	12,1	0	0	18,7	0	0
5,15	0	0	12,2	0	0	18,8	0	0
5,16	0	0	12,3	0	0	18,9	0	0
5,17	0	0	12,4	0	0	18,10	0	0
5,18	0	0	12,5	0	0	18,11	0	0
5,19	0	0	12,6	0	0	18,12	0	0
6,1	0	0	12,7	0	0	18,13	0	0
6,2	0	0	12,8	0	0	18,14	0	0
6,3	1	258,340	12,9	0	0	18,15	0	0
6,4	0	0	12,10	0	0	18,16	0	0
6,5	0	0	12,11	1	6,883	18,17	1	**209,799**
6,7	1	72,878	12,13	0	0	18,19	0	0
6,8	0	0	12,14	1	43,245	19,1	0	0
6,9	0	0	12,15	0	0	19,2	0	0
6,10	0	0	12,16	0	0	19,3	0	0
6,11	0	0	12,17	0	0	19,4	0	0
6,12	0	0	12,18	0	0	19,5	0	0
6,13	0	0	12,19	0	0	19,6	0	0
6,14	0	0	13,1	0	0	19,7	0	0
6,15	0	0	13,2	0	0	19,8	0	0
6,16	0	0	13,3	0	0	19,9	0	0
6,17	0	0	13,4	0	0	19,10	0	0
6,18	0	0	13,5	0	0	19,11	0	0
6,19	0	0	13,6	0	0	19,12	0	0
7,1	0	0	13,7	0	0	19,13	0	0
7,2	0	0	13,8	0	0	19,14	0	0
7,3	0	0	13,9	0	0	19,15	0	0

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Table 2 (*continued*)

jj'	$\gamma_{jj'}$	$V_{jj'}$ (m^3)	jj'	$\gamma_{jj'}$	$V_{jj'}$ (m^3)	jj'	$\gamma_{jj'}$	$V_{jj'}$ (m^3)
7,4	0	0	13,10	0	0	19,16	0	0
7,5	0	0	13,11	0	0	19,17	0	0
7,6	0	0	13,12	0	0	19,18	1	**221,882**

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