An integer linear programming model to optimize the hub and spoke-based water desalinated transmission system
Osama Saad Al Gahtani and Mehdi Mrad

ABSTRACT
Desalinated water is becoming a significant resource in many countries. With limited water supply, several high-demand sites located far from the desalination plant and an efficient and cost-effective transmission and storage network have become critical. In many areas, desalinated water is not delivered efficiently through a pipeline and storage tank system capable of providing safe and cost-effective coverage to a wide range of demand sites. In addition, due to the limitation of transmission and storage distribution, many desalination plants are unable to achieve full production capacity. Many high-demand sites are at risk of disruption or water contamination due to single-source pipelines or desalination plants. In this study, the conceptual framework for an economically viable transmission and storage system helps decision-makers to define the requirements for the proper design of the system. The definition is introduced here to describe strategic tanks for efficient and economical supply allocation. The key aspects of setting up effective transmission and storage systems were outlined in the framework presented. To develop an efficient and cost-effective transmission and storage system, an integer linear program was constructed to solve the hub and spoke issue. A hypothetical example is presented and discussed to illustrate the advantages of the proposed model.

Key words | desalination, integer linear programming, pipeline, storage, tanks, transmission

HIGHLIGHTS
• New conceptual application to reduce the high cost of desalinated water transmission.
• New development model to optimizing the links by adding one or more tanks in the middle-way.
• Framework has developed to help the decision making to evaluate the transmission system.
• New application of the hub and spoke methodology in the water resources system.
• Risk assessment evaluation of the disruption on desalinated water services.

INTRODUCTION
Water supply is the basic need that the world is striving to achieve at the most efficient level. Due to limited freshwater resources, non-traditional water resources are growing, mainly in the arid and semi-arid countries. Looking for seawater as a source of water supply, desalination is becoming a technology used by many countries to meet increasing demand (Ghaffour et al. 2013). The advantage of desalination is the ability to ensure the supply of large quantities of water. With the advancement of technology, desalination is becoming an economical and reliable source. From historical migrations, easy access to natural sources, such as surface water and groundwater, tends to be close to large demand zones. With high demand and less rainfall, natural resources are limited and polluted. Desalination could be an excellent...
opportunity to meet demand on the shore, but the main challenge is to extend the use of desalination to meet demand far from the coast. Transmission costs could be critical and the most expensive part of the water supply system (Gonzalez-Gomez & Garcia-Rubio 2018).

In order to further develop the definition of storage, the strategic concept of the tank was introduced and discussed in this work. Strategic and operational tanks are slightly different based on their purpose. Operational tanks are usually located near or inside the demand zone for direct supply to the local pipe network. Another purpose of the operating tank is to manage the water pressure for the primary network that supplies the local systems. On the other hand, the strategic tanks are usually larger and provide more than one demand site, particularly for long transmission lines. If the source of water is near the demand site, usually there is no great need for the strategic tanks, depending on the amount and the full range of the required areas. Many researchers set a general criterion for the optimum placement of local tanks for operational tasks (Batchabani & Fuamba 2014). In practice, land disputes in many countries are one of the main obstacles (Shahabi et al. 2017). From an operational point of view, higher elevation tanks are beneficial for maintaining and providing high pressure and saving the installation of a pump station (Mays 2000). Also, if the tanks are located at lower elevations, this can save costs for more economical pipe size selection and safety regarding pipe failure, and this depends on how close the tanks are to the demand site (Walski 2000). However, these criteria conditions may also apply to strategic tanks.

Different factors affect the positioning of strategic tanks. The overall distance of the pipeline connection between desalination plants to demand sites through strategic tanks should be optimized for the proper selection of the appropriate location. The system should be compatible and flexible to meet the increase in demand, and the specification standard should be updated periodically to increase the life of the asset as stated by the Organization of Economic Cooperation and Development (OECD 2009). Also, the optimal use of resources will increase the efficiency of the system and enhance the planning of water resources to meet long-term objectives. To improve the accessibility of safe water, sustainability objectives require the allocation of costs for the promotion of the country’s economy as a whole and the protection of essential resources (Shahabi et al. 2017).

Depending on the challenges faced by the various water utilities and the nature of the topography, it is difficult to find a defined solution for the transmission systems that satisfy both current and future uses. These challenges include exhausted and contaminated water resources, the efficiency of energy use, especially when reaching or bypassing high mountains, and the limitation of financial and enhanced water services (Nafi et al. 2015). The domestic supply of all potential sites and the variety of water sources for each location of demand must, therefore, be recognized. In addition, the high cost of the transmission system generates an adaptive revenue policy based on the utility challenge of collection. Finally, the various water uses of urban and industrial sectors should be managed by an efficient water system.

In the literature, there are a number of different optimization models for the transmission and storage systems of desalination plants (Al-Nory et al. 2014; Saif & Almansoori 2014; Shahabi et al. 2017). In these models, the location of the desalination plant is supported on the basis of land availability, energy consumption, and environmental impact. However, all of these works are assumed to have ‘operational’ storage tanks located near either desalination plants or demand sites. In addition, the link between supply and demand is directed from one site to another and sometimes merges from one line to the other (Al-Nory & Graves 2015). In this work, a new concept of configuring the connection between the supply and demand sites is introduced using a hub and spoke model which has been widely used in other fields such as air transport (Okkal & Ozger 2013), urban transport (Hosapujari & Verma 2013), and telecommunications (Detienne et al. 2017). The hub and spoke model is introduced in the desalinated water transmission system in order to ensure water supply to different cities in case of failure of water desalination stations or water transmission links. A common technique used to optimize the hub and spoke models is integer linear programming (ILP) (Correia et al. 2011; Gelareh & Nickel 2011). Thus, a novel ILP model is designed in order to reduce the total distance of the transmission links in the considered hub and spoke system of desalinated water transmission.
CRITERIAL DIMENSIONS OF TRANSMISSION AND STORAGE SYSTEMS

Transmission and storage are a major cost component in the water supply system. Defining the framework for designing an efficient transmission and storage system is required to help the service providers to build an efficient system. Five criteria for the transmission and storage of desalinated water systems are presented and defined in this section. The system should be flexible, economical, and satisfy the rapid increase in demand. Also, the system should be reliable for operating under different disruptive conditions and sustain the water resources for long-term performance and protect the ecosystem. To serve the strategic goals, transmission and storage should be flexible in design to meet the regulation and policy requirements. The system should, finally, attract investors for long-term income and sustainable financial results.

System efficiency

The main purpose of the strategic tanks is to securely supply water to large demand cities of urban and industrial use. More income businesses are expected in large cities than in medium and small cities. For some countries, desalinated water is the main source for urban use, and the strategic tanks should be distributed efficiently to serve and satisfy the current and future demand in all cities with the minimum cost possible. Transmission costs are high, and strategic tanks should be effectively distributed to serve potential demand sites. As a result, extra attention is needed to locate the strategic tanks for the maximum benefit and economic level of transmission.

One of the methods that can be used for optimizing the location of the strategic tank is the hub and spoke method. The optimum position of the strategic tanks’ ‘hubs’ is necessary for supplying water to the demand sites in the transmission and storage system. Pressure control, reduction of the total length of the pipes, and estimation of the size of the tanks are the primary variables for controlling the capital cost of the system. The change in topography and the dispersal of cities make challenging tasks for the security of supply. In this study, an integer linear program that respects the concept of hub and spoke models is presented in the ‘hub and spoke method’ section.

Resilience

The resilience definition in the water system is a quantitative way to measure the ability of the water system to recover from disruptive events (Shin et al. 2018). In strategic tanks, the size of the tank can play an important role in securing the urban and industrial supply, especially in emergency events (Bhatia et al. 2018). The tank size should be large enough to carry the amount of water for immediate release ‘carryover storage’ and for future use ‘optimal hedging’ (Draper & Lund 2004; Shiau 2011). This describes the way in which the system can recover from the risk exposures in the short and long term. The history of water use is required for predicted future drought events (Tarawneh et al. 2017). At all levels, the size of the tank should be able to cover the emergency for a defined number of days of shortages and has the capacity for system recovery.

Full understanding of the variability of water demand during the day will help to prevent the functional interruption of water supply. Strategic tanks and pipelines should be configured to satisfy everyday demand in order to ensure the continuity of supply. From the real-time flow data during the day, the maximum daily rate can be estimated seasonally all year long. The tank capacity should be designed on the basis of the difference in volume between the incoming and outgoing tanks. Locating the tanks in the middle of the route will help to reduce the effect of any shortcoming in pumping stations. This has a direct effect on the number of hours in which the transmission line operates. However, most diesel, gas, or electrical pumps usually operate with limited time (less than 16 hours) (Trifunovic 2002). There is a need for storage tanks and an alternative route of the flow path to address any disruption in pumping stations. Owing to the fact that strategic tanks can serve many demand sites, the tank size accounting for an emergency can be reduced, and different calculations should consider that.

In addition to the tank size, several criteria need to be considered in designing the tanks. The tank placement should be in a high place to allow the water supply to cover a wider range along with the city network. An
adequate amount of pressure in the system would reduce the risk of electricity deficiency. To prevent endangered tank failure of the local flood risk, special arrangements are required to redirect the flood path from the city side (Figure 1). If there is to be more than one tank in the same location, they should be spatially separated enough to prevent the danger of over-collapse. The system of transmission and storage should be evaluated hydraulically and tested under various possible disruptive events. In addition, different paths of flow will help to overcome any disruptive scenarios. Finally, the provision of ready alternative sources is an essential aspect in the event of an emergency.

The disruptive events in the water system could take the form of different types and measurements; dynamics where the events are time-dependent, or static where the events occur independently of time (Shin et al. 2018). Earthquakes and plant shutdowns are examples of dynamic resilience. As well, resilience can be measured in either probabilistic or deterministic methods. Resilience measurements are important for designing the system, and can provide the decision-makers knowledge of the reliability of the water system to operate under various conditions.

Finance sustainability

In the presence of severe lack of water resources, transmission and storage are becoming major unavoidable costs. For widespread transmission lines and storage tanks, the operating costs are an obstacle to the future expansion of the system. Registered private or public corporations are assigned to run transmission lines and storage tanks in some countries. However, the cost along the water supply chain must be governed by trade agreements. Sustainability of financing for the allocation of costs must be established over a defined period and for emergency events. Water rights and regulatory systems need to be well defined for the monetary advantage associated with water resources allocation and use. The financial plan should be included in the main goals of the national water strategy or the declared government policies. To do that, a good cost-benefit analysis system is needed to establish prioritizing the various investment programs. According to the OECD (2009), the typical cost reduction in a water system could be in operation, as well as the capital cost. A good financial plan of the transmission line should be well designed to meet the current need and the expansion necessary for future demand.

Another important factor is to design the transmission lines based on the financial sustainability goal. The revenue stability from industrial cities can give priority to such a project. Additional transmission lines or storage tanks might need to be added to ensure the stability of financial income. Another issue is that certain projects can have a big impact on the country's economy or be enforced for political reasons. Religious or tourist events or hosting big events are examples of such projects. For this, it might be necessary to elaborate on the transmission lines or storage capacity to shield the global impact and build trust among outside investors. To balance these objectives with the requirement of an increase in demand, if a gap in funding occurs, different approaches and activities should plan to investigate the reduction of expenses. In many countries and for indirect economic impact, the major projects of transmission and storage are subsidized. However, global experiences show that shifting these funds from granting to long-term and low interest rates would improve the efficiency of financial expenses (OECD 2009). In addition, the efficiency and effectiveness of the various operating programs and strategic initiatives will strengthen revenue stability, in particular with regard to the adaptation of the asset management procedure.

Governance

Building effective transmission and storage systems will have an impact on the overall layout of the institutional setup of the water sector. The participation of a range of...
stakeholders for the cost and use of the resources will help the decision-makers to achieve social benefits and expand the benefit throughout the country. Some countries follow the single-buyer model and delegate the transmission to a single operator to reduce the cost and make it easy to exchange the experience from different parts of the country (Shahid et al. 2019). This gives the flexibility to serve different states based on the demand requirement under various circumstances and availability of sources. For example, the government can transfer the water from different sources to serve any new development businesses to benefit the whole country without affecting the current state operation. The single-buyer model will also increase the efficiency of shareholders among service providers on the supply side and prevent the monopoly of the overall supply chain. The decision-maker can allocate the water between different demand sites for the water and treated wastewater for various political reasons. However, the implementation of the single-buyer model needs a careful strategy because the model does not have a quick response to big changes in the market (Lovei 2000).

With the technology advancement, the specification standard for safety and risks should be adapted for transmission and storage expansion or to increase the system capability performance in an emergency event. For such a decision, regulation should be flexible and efficient for such standards to be rapidly implemented. A range of institutions, public agencies, and stakeholders need to be involved in such decisions that may delay the system adaptation. A proper political process for various cases and incidents is needed to ensure that such decisions are effective in order to achieve the right objectives. Allocation of clear responsibility among the stakeholders and risk assessment cycle may develop the right procedures and fast decisions.

The other issue is whether the private sector should be involved or not. Different studies based on different countries’ experiences have been done in this field (Gonzalez-Gomez & Garcia-Rubio 2018). Some studies show that the cost of the project would be higher with private management (Barbosa & Brusca 2015; Chong et al. 2015). On the other side, good regulatory arrangements could reduce the marginal increase in cost (Martinez-Espineira et al. 2009). Garcia-Valinas et al. (2013) argue that the more sustainable way is when water projects can be run publically with strict regulations. For either way, the government should create a clear dispute process and measures to ensure long-term service sustainability and to deal with future challenges.

Environmental

The environmental impact is a global concern regarding the threat of degradation of natural resources. With a well-developed transmission system, the strategy for switching between different sources should be flexible and sufficient to achieve a sustainable environmental objective. Local environmental regulations may require priority to be given to the use of groundwater and surface water for irrigation to achieve food security. On the other hand, some policies require industrial use, by incorporating recycled water in the process, to restrict their use of desalination water. In 2016, treated wastewater was reused at a rate of 100% in Kampala, the capital of Uganda (IWA & OFID 2018).

Usually, more than one agency would be involved in regulating and setting the standards about water quality. Water quality could impact structural materials and require the improvement of the design and the standard in transmission lines and storage tanks, and that could increase the cost. In addition to the cost, robust coordination with production and distribution entities under the agreement will minimize public health concerns and the use of the public. Life cycle environmental impact assessment would be a useful tool to evaluate the cost impacts to the environment (Shahabi et al. 2017). Good coordination and public involvement with a strong monitoring system are important for public safety and cost reduction.

Issues of energy reduction, wastewater treatment, and rainwater collection and harvesting and environmental evaluation of desalinated water are addressed in several studies (Chen & Wang 2009; Morales-Pinzona et al. 2012; Shahabi et al. 2017). Specifically, the reduction of the energy used in operation of the pump station is the essential objective in designing the transmission. An excellent hydraulic pipeline design system can reduce energy losses due to pipe friction. Furthermore, existing strategic tanks in the middle of the transmission lines would play a key role in controlling the pressure and reducing the risk
dependence of the pump station. The optimal locations of the strategic tanks and pump station for saving energy need professional hydraulic calculation. However, the topography of the natural landscape would play a significant transformation in the use and saving of energy.

HUB AND SPOKE METHOD

Hub and spoke is a form of transport topology optimization method used to manage capacity in several supply chain fields (Aziz et al. 2018). Contrary to the point-to-point transportation systems, the hub and spoke requires that the path be broken between two points while using one or more hubs where customers or freights are grouped and dispatched to their final destinations. Supply and demand management may be critical for the desalination supply chain. On the one hand, many desalination plants do not meet their operating capacity and, on the other hand, many demand sites are unable to present the required quantity due to poor distribution of the transmission and storage part. In the event of an emergency, a sudden drop in supply would disturb the operating utilities. For current design practice, the only response is to install large-scale tanks to supply the demand sites to reduce system redundancy. Failure in transmission lines due to pipe burst or short supply at pumping stations poses a high risk of disruption. However, the additional cost of producing the different routes, either to reach the demand sites or to depart from the plant site, needs to be optimized to reach the optimal system setup. The benefit of the hub and spoke method is that alternative water flow is provided for the integration of supply sites, the transfer of water on demand, and reduction in the cost of the entire pipeline length and tank scheme.

Model development and components

For model development, a different component needs to be defined. The locations of desalination plants usually do not have much flexibility since they need to be set next to the intake source, and they are determined based on land availability under the restriction of urban plan development. In the current model, the set of plant locations is fixed, and it can be variable for future expansion under different options if available. The demand sites are usually immovable and definitely can be expanded. The strategic tank components are variable, and mathematical models can identify the optimal locations in order to reduce the total length of transmission links, under the conceptual framework of hub and spoke models.

Sources (desalination plants), hubs (strategic tanks), and demand sites constitute the conceptual nodes, which are the defining element of the supply chain network. For each node, there is an alteration to track the flow of water arriving and departing. The size of the tanks and the plant capacity can be estimated based on the total demand for all sites and the number of hubs and plants used. To state the decision problem, the location of the source nodes and demand sites needs to be defined based on current or future use, and the iterative change in the number of hubs is evaluated based on the resulting total length of the transmission lines. Finally, that decision needs to be carefully assessed on the basis of the framework’s priority criteria. For example, some additional links may need to be added to improve process efficiency or minimize risk or to reduce reliance on other natural sources.

Assumptions

In order to design a resilient water transmission network, we suggest building strategic tanks that may supply cities for a predefined duration even though problems occur in one or more water desalination facilities or transmission links. For that aim, we assume the following:
1. Each tank should be supplied by at least two desalination facilities.
2. All the tanks should be grouped in a ring in order to ensure that each tank may supply all the other tanks and may be supplied by all the other tanks.
3. The number of tanks to build is predefined.

METHODOLOGY

An integer linear program is proposed in order to minimize the total distance of the water transmission links. All the components of the network are summarized in an undirected graph $G(V, E)$, where $V$ is the set of nodes, and $E$ is...
the set of edges. The set of nodes \( V \) includes three subsets 
\( (V = S \cup H \cup T) \), where:

- \( S \): is the set of source nodes representing the actual desalination centers
- \( H \): is the set of nodes representing the potential locations of the tanks (hubs)
- \( T \): is the set of destination nodes representing the cities to which the water should be supplied

The set of edges \( E \) includes three subsets 
\( (E = E_1 \cup E_2 \cup E_3) \), where:

- \( E_1 \): is the set of edges linking each source to all possible location of hubs
- \( E_2 \): is the set of edges linking the hubs to each other
- \( E_3 \): is the set of edges linking each potential location of the hub to all the destinations

- \( D \): number of tanks to build
- \( d_{ij} \): distance of link \((i,j) \) \( \forall (i, j) \in E \)

### Decision variables

\[
x_{ij} = \begin{cases} 
1 & \text{if the link } (i, j) \text{ is selected} \\
0 & \text{otherwise} 
\end{cases} \quad \forall (i, j) \in E
\]

\[
y_i = \begin{cases} 
1 & \text{if the tank location } i \text{ is selected} \\
0 & \text{otherwise} 
\end{cases} \quad \forall i \in H
\]

### ILP

\[
\text{Min } Z = \sum_{(i, j) \in E} d_{ij} x_{ij} \tag{1}
\]

\[
\sum_{(i, j) \in E_1} x_{ij} = 1 \quad \forall i \in S \tag{2}
\]

\[
|S| y_i \geq \sum_{(i, j) \in E_1} x_{ij} \quad \forall j \in H \tag{3}
\]

\[
y_j \leq \sum_{(i, j) \in E_1} x_{ij} \quad \forall j \in H \tag{4}
\]

\[
y_i \leq \sum_{(i, j) \in E_2} x_{ij} \quad \forall i \in H \tag{5}
\]

\[
y_i \leq \sum_{(j, i) \in E_2} x_{ij} \quad \forall i \in H \tag{6}
\]

\[
x_{ij} \leq y_i \quad \forall (i, j) \in E_2 \tag{7}
\]

\[
x_{ij} \leq y_j \quad \forall (i, j) \in E_2 \tag{8}
\]

\[
y_i \leq \sum_{(i, j) \in E_2} x_{ij} \quad \forall i \in H \tag{9}
\]

\[
|T| y_i \geq \sum_{(i, j) \in E_3} x_{ij} \quad \forall i \in H \tag{10}
\]

\[
\sum_{(i, j) \in E_3} x_{ij} = 1 \quad \forall j \in T \tag{11}
\]

\[
\sum_{i \in H} y_i = D \tag{12}
\]

\[
x_{ij} \in \{0, 1\} \quad \forall (i, j) \in E \tag{13}
\]

\[
y_i \in \{0, 1\} \quad \forall i \in H \tag{14}
\]

The objective function (1) aims to minimize the total length of the transmission lines. Constraints (2) state that each desalination plant should supply at least one strategic tank. Constraints (3) require that the tank should not be linked to any desalination plant if it is not selected in the final solution. Constraints (4) imply that if a hub is selected, then it must receive water from one desalination plant, at least. Constraints (5) and (6) ensure that each of the chosen hubs is connected to another hub in order to ensure that at least another hub can be supplied. Constraints (7) and (8) forbid non-selected hubs to have any link with selected hubs. Once it is selected, the hub should supply at least one city. This last meaning is expressed by constraint (9). Constraint (10) means that each selected hub should visit one city at least, and constraint (11) requires that each city should be visited by one hub. Constraint (12) sets the predefined number of hubs to build. Finally, constraints (13) and (14) require all the decision variables to be binary.

The ILP (1)–(14) is valid only for the case of two hubs. If a single hub should be selected, then constraints (5) and (6) should be removed. In addition, the assumption (2) is not respected. Thus, in order to group all the selected hubs in a single ring, we should add the following constraint:

\[
x_{ij} + x_{ji} \leq 1 \quad \forall (i, j) \in E_2 \tag{15}
\]

Note that constraint (15) will satisfy the ring assumption only in the case of three, four, or five hubs. If the number of
predefined hubs is larger or equal to six, then other sub-tour elimination constraint should be used in order to link all the hubs in a single ring.

**Hypothetical example**

A hypothetical example has been applied to discuss the concept presented in this research. The coverage area is assumed flat, and is 500 km long and 500 km wide. At the coast side, six supply nodes (desalination plants) are distributed evenly at 100 km apart. At the demand sites, there are six demand sites (cities) located 500 km away from the coastal line and distributed at equal distances. This hypothetical example is generated similarly to the case of desalinated water distribution network between the eastern and the central region of the Kingdom of Saudi Arabia. The potential locations of the hubs are distributed on the area horizontally and vertically with a distance of 50 km between every two consecutive locations on the same horizontal or vertical lines, as shown in Figure 2. Thus, the total number of nodes in the graph is 111 nodes. Each desalination node is assumed to have a possible direct link to any potential node and each hub can be linked to any other hub. In addition, each potential hub is supposed to be linked to each city. The total number of arcs in the graph is 10,890 arcs.

Consequently, the number of decision variables in the model is 10,989 binary variables. The ILP model is coded in C++ and solved with one of the best commercial solvers CPLEX. The model is solved under four different scenarios. In the first scenario, we considered only one hub, while in the second, third and fourth scenarios, we have considered two, three, and four hubs, respectively. Figure 3 shows the results for the four different scenarios, and Table 1 shows the total length for every scenario. Results show that the optimal scenario cost is when there are two tanks. The total saving in total length was only 42 km, but the cost of installing tanks may add to accounting for the total save in cost. It may be worth mentioning here that if considering the point-to-point link connection, each desalination plant with a single line to the demand node with the six tanks located at each demand site, the total length will be 3,000 km, which is about 558 km shorter than the hub to spoke setup. If the number of source nodes is less than the
number of demand nodes, the point-to-point solution will increase the overall distance. Nevertheless, the drops in desalination production due to the variability in supply-demand add up the cost of four tanks to the point-to-point needed to build six tanks next to each city. Moreover, the high risk of disruption would be in the case of the point-to-point option, the limitation of system expansion for small future demand sites, and the inability to maintain the optimal use of other resources.

Tables 1 and 2 give demand and supply information about the desalination plants and the major cities. There is a variable production amount of water along with the desalination plants, and the larger production lies on the second source point (S2). The most challenging city (D3), representing five million residents with the highest income and two industrial cities can have an economic impact. It is essential to consider the variance of the water resource, which demonstrates that the two industrial cities depend solely on the desalination sources.

Figure 2 represents a flat area to simplify the problem in which the 2D problem is described. Considering the topography of the area may have a high impact on the cost because of extra lengths and pumping stations. In this case, a more advanced model is needed to consider the hydraulic model and to manage the pipe pressure. However, the 2D model is enough to give a rough calculation for presenting the concept of this research. In addition, seasonal variations in the demand for water are critical for addressing peak demand and corresponding peak pressure.

In the context of the two-hub option, a single link must be established for each supply and demand site in which the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Total length analysis at different number of hubs</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. hubs</td>
<td>Total length (kM)</td>
</tr>
<tr>
<td>1</td>
<td>3,600.21</td>
</tr>
<tr>
<td>2</td>
<td>3,557.66</td>
</tr>
<tr>
<td>3</td>
<td>3,567.56</td>
</tr>
<tr>
<td>4</td>
<td>3,581.73</td>
</tr>
</tbody>
</table>

Figure 3 | Model outcomes for different numbers of strategic tanks.
The system is put at risk since the entire plant capacity depends on one connection. At demand sites, once the flow leaves the tanks, there is a single link to connect each demand site to the nearest hub, which places high demand cities at risk, especially if no additional sources are present. Table 2 shows that the highest production is the second plant which produces one million cubic meters per day. Table 3 shows that the highest demand city is S3 where the desalination represents two-thirds of the city’s demand. If resilience is considered, it may recommend more than two links for the big plant and highest demand city. Figure 4 shows a suggested system setup with more resilience for water disruption. Another factor that may be considered is the loss of revenue due to the consequences of water disruption in industrial cities, and the economic impact may contribute to significant investment in some of the factories.

**CONCLUSIONS**

A new configuration setup for the transmission and storage system of desalinated water is proposed using a hub and spoke method. The proposed model is introduced in order to ensure the sustainability of the water demanding cities in the case of failure of transmission links or even damage to the desalination facilities. The main objective is to identify the strategic tanks’ locations that minimize the transmission links in the desalinated water network. For that aim a novel ILP is introduced. The efficient distribution of storage tanks is discussed here and evaluated under different perspective viewpoints. In addition to the minimization of the total distance of the water network, future works may consider other considerations, such as the number of pumps required in the network, and the cost of each tank based on its location. The quantitative model should have the potential to change the current configuration of the transmission and storage system in the context of the conceptual framework.
DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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