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Optimal management of multiple water resources by a heuristic optimization for a water supply in the desert cities of Western Iraq

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ABSTRACT

In the present study, two different cost-benefit functions in the related literature were compared to decide on optimum water resources for supplying the water of Rutba City, which is located in western Iraq within the administrative Anbar Province. One of the two objective functions is directly based on differences between daily incomes (water charge/m^3) and expenses (electricity price of pump stations) (maximization) while another one is based on the distances and the piezometric head differences between the water resources and the city (minimization). The objective function used by Carini et al. [2] was modified by considering the pump flow. It was solved by the heuristic optimization model, which uses the modified clonal selection algorithm (the modified Clonalg), one of the artificial immune systems under the same constraints of the required daily water demand of the city, pump discharge capacities, and limits of withdrawing water from the water resources. After running the model, it was seen that the results of the objective function as a total daily net income obtained by Eryiğit and Sulaiman [1] are better than the results of the modified function of Carini et al. [2] (2,960 and 2,950 USD/d, 2,225 and 2,212.5 USD/d for the first and second six months of the year, respectively) for Rutba City in regards to the cost-benefit relationship.

Keywords: Water supply; Water resources; Cost-benefit relationship; Heuristic optimization; Artificial immune systems

1. Introduction

Water is essential to life and growth. It is also one of the natural resources most at a risk of pollution and depletion. All nations with a dearth of water resources find themselves in challenging economic and social circumstances. The freshwater systems of rivers, lakes, and streams are some of the most delicate ecological systems and are particularly susceptible to harm from human activity and climate change. One of the most significant issues today is how to manage water resources in a way that is environmentally sustainable, especially in arid regions [3].

Water availability is a basis for the development of cities. Water supply is an urgent necessity to achieve human development goals. The role of water is growing, mostly for arid regions that do not have permanent rivers and that know low levels of rainfall, as well as the lack of suitable groundwater for drinking or irrigation [4]. With the increase in the population of cities and the increase in their water needs as a result of the development in urban

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life, the contradiction between water supply and demand has become increasingly clear [5]. Proper management of water resources includes analyzing water supply problems for drinking water distribution networks and making improvements according to the availability and distribution of these resources [6]. The problem of water scarcity appears severe in arid and semi-arid regions such as the regions of western Iraq as a result of its already harsh climate and the increase of this problem due to climate change resulting from global warming [7,8]. Therefore, decision-makers in desert cities such as Rutba City (west of Iraq) must benefit from the optimal management of all types of available water resources in a way that secures the supply of sufficient raw water to water treatment stations/plants for municipal and environmental needs [9].

In order to determine optimum water resources for a water supply (drinking and industrial water, irrigation etc.) of the cities, several optimization models, methods/techniques, and functions based on a cost-benefit relationship were introduced and used in the literature [10–24]. To contribute to the related literature, a comparison of two different objective functions depending on this relationship was performed by using a heuristic optimization in this paper as a continuation of the study of Eryiğit and Sulaiman [1]. The objective function used by Carini et al. [2] was modified by taking account of pump stations, and solved by the artificial immune systems as a heuristic optimization algorithm, and its results were compared with the previous results for making a decision on optimum water resources of Rutba City.

2. Material and method

2.1. Study area

Anbar Province, western Iraq, is characterized by the availability of sufficient water resources compared to the needs of users, but the distribution of these resources is not balanced with all the cities of the province. The Euphrates River, which supplies the province with its bulk water needs, passes through most of its main districts. However, the desert cities in the west of Anbar which are far from the Euphrates River continue to suffer from the issue of providing water resources to feed the drinking water distribution networks [25]. This issue became urgent after the population increases and the expansion of cities in recent years. The community experiences hot desert weather. The average annual depth of rainfall is 114.3 mm [26].

The city of Rutba, which is located in the far west of Iraq within the boundaries of the administrative Anbar Province was studied [1,27] (Figs. 1 and 2). The city has about 50,000 inhabitants and needs 15,000 and 10,000 m^3/d of drinking water for the first six months and the second six months of the year, respectively. The water demand of the city is currently supplied through three sources with pipelines. Also, another water resource is planned as the fourth one. The first and second sources are two reaches (upstream and downstream) of the Euphrates River, as shown in Figs. 2 and 3. Pipeline 1, a cast iron pipeline with a diameter of 500 mm, is currently being constructed. There is no limit for withdrawing water from the river by pump station 1, which is 161 m above sea level (a.s.l.).

The total length of pipeline 1 is 250 km, with rising elevation to become 740 m a.s.l. at a distance of 213 km. After that, the elevation of the pipeline decreases through the city to 635 m a.s.l. Therefore, three lift stations were constructed along the pipeline. Similarly, pipeline 2 is currently being built (cast iron with a diameter of 800 mm for the first 140 km then 600 mm for 131 km to Rutba City). There is no limit for withdrawing water from the river by pump station 2, which is at 53 m a.s.l. The total length of pipeline 2 is 271 km, with a max elevation is 635 m a.s.l. at the city. Therefore, lifting stations were needed along the pipeline, and six were constructed. Pipeline 3 is currently constructed in cast iron with a diameter of 200 mm. There is a limit for withdrawing groundwater of 4,000 m^3/d from 16 pumping wells to a storage tank. Pump station 3, at elevation 595 m a.s.l., withdraws water from the storage tank to the city. The total length of pipeline 3 is 20 km, and the max elevation of the line is 635 m a.s.l. at the city, with no need for a lift station along the pipeline. Pipeline 4 is planned but not constructed yet. It may be constructed in cast iron with a diameter of 400 mm to transmit water from a dam reservoir. There is a limit for withdrawing water of 3 million m^3/y from the dam reservoir due to water scarcity. Pump station 4, at elevation 678 m a.s.l., withdraws water from the dam reservoir to the city at 635 m a.s.l. The total length of pipeline 4 is 29 km, and the maximum elevation of the line is 635 m a.s.l. at the city, with no need for a lift station along the pipeline.

These four pipelines/water resources were optimized by Eryiğit and Sulaiman [1] for a water supply of Rutba City by considering a cost-benefit relationship/analysis. They carried out this relationship according to daily incomes (water charge per m^3) and expenses (electricity price of the pump stations) of the four pipelines, and daily demand (m^3/d) of the city. In this study, this optimization problem was solved by using a different objective function and compared with the previous results. Information of electricity costs and maximum discharges (flow rates) of the pump stations were given in Table 1. A water charge tariff is 25 cents/m^3 for all the pipelines.

2.2. Objective functions

The objective function of Carini et al. [2] was used to optimize the water resources for Rutba City. This function is based on the distances and the piezometric head differences between the water resources and the city:

$$C = \sum_{j=1}^{n}\sum_{i=1}^{m}\left(K\frac{0.0012^{\frac{\alpha}{5.26}} L_{ij}^{\left(1+\frac{\alpha}{5.26}\right)}}{Y_{ij}^{\frac{\alpha}{5.26}}} Q_{ij}^{\frac{2\alpha}{5.26}} \right) \tag{1}$$

where L_{ij} is the distance between nodes i and j, and Y_{ij} is the corresponding piezometric head difference, Q_{ij} is the amount of water (L/s) transmitted from the source node i to the destination node j (Q_{ij} is a decision variable of the objective function), m is the number of water resources, n is the number of water consumers/users, K and α depend on the material of the pipeline, for the characteristics of the existing pipelines in the area of the case study, the

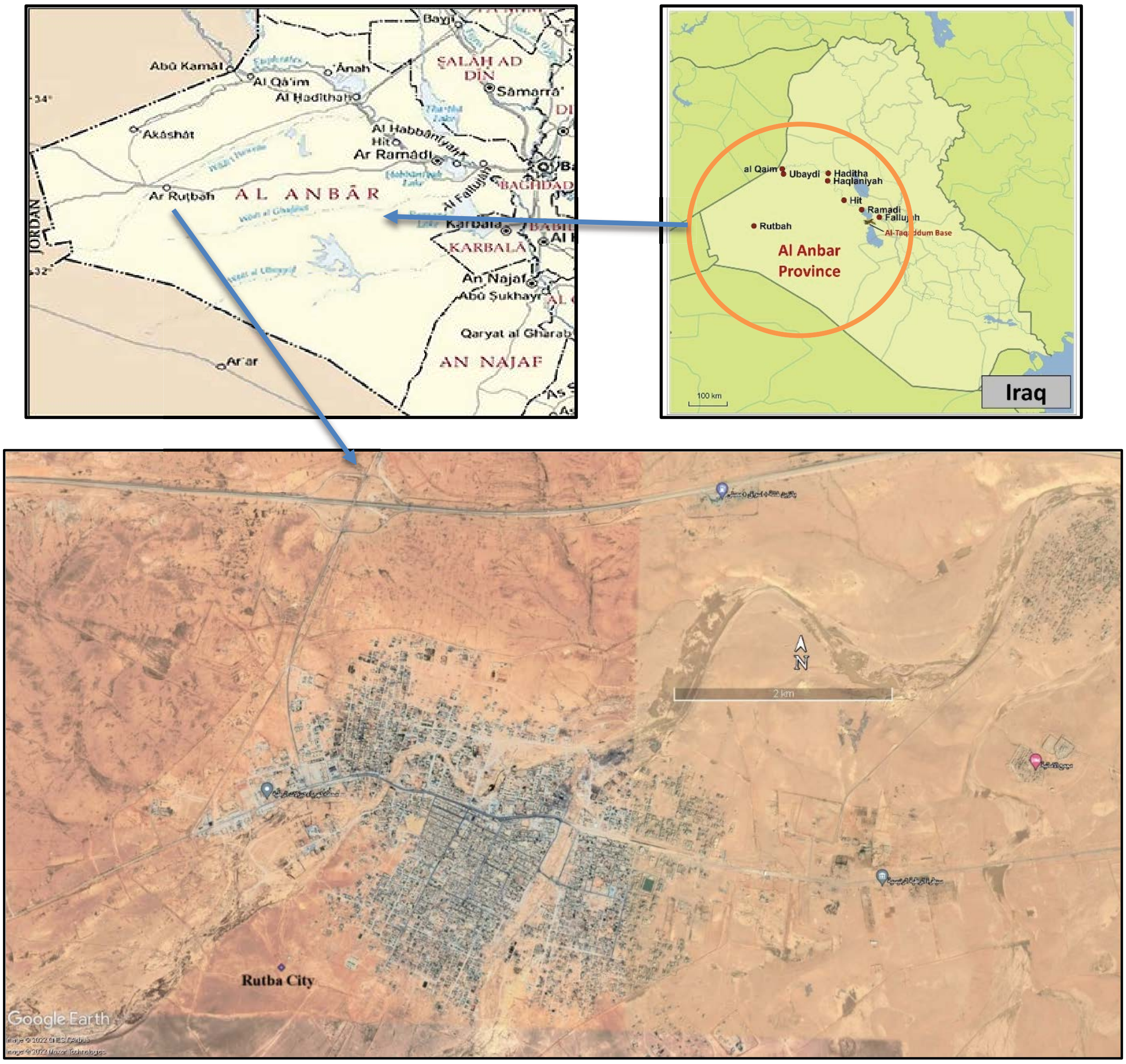

Fig. 1. Study area (Rutba City, Anbar Province).

value α ~ 1 is assumed [28], while the parameter K can be left in parametric form because it does not influence the minimum cost configuration.

But, it was modified since the pipelines have pump stations as follows:

$$C = \sum_{j=1}^{n}\sum_{i=1}^{m}\left(K\frac{0.0012^{\frac{\alpha}{5.26}}L_{ij}^{\left(1+\frac{\alpha}{5.26}\right)}}{Y_{ij}^{\frac{-\alpha}{5.26}}}Q_{ij}^{\frac{2\alpha}{5.26}}\right) \tag{2}$$

This modification means that a higher piezometric head is more cost.

Note that n was assigned 1 because Rutba City was only considered as the water consumer.

Eryiğit and Sulaiman [1] introduced two sub-objective functions which were simultaneously used to maximize total daily net income (difference between total daily income and expense). The objective function of total daily income ($\mathrm{OF}_{\mathrm{income}}$) was defined as follows:

$$\mathrm{OF}_{\mathrm{income}} = \mathrm{WT}\sum_{i=1}^{n}Q_i \tag{3}$$

where WT is the water tariff for all the pipelines (25 cents/m^3), Q_i is the daily discharge of pump station i (m^3/d), and n is the total number of the pump stations. The objective function of total daily expense ($\mathrm{OF}_{\mathrm{expense}}$) was defined as follows:

$$\mathrm{OF}_{\mathrm{expense}} = \sum_{i=1}^{n}\left(\frac{Q_i}{Q\max_i}\mathrm{TEC}_i\right) \tag{4}$$

where $Q\max_i$ is the maximum daily discharge of pump station i (m^3/d), and TEC_i is the total daily electricity cost of

Fig. 2. Locations of the four pipelines and water resources.

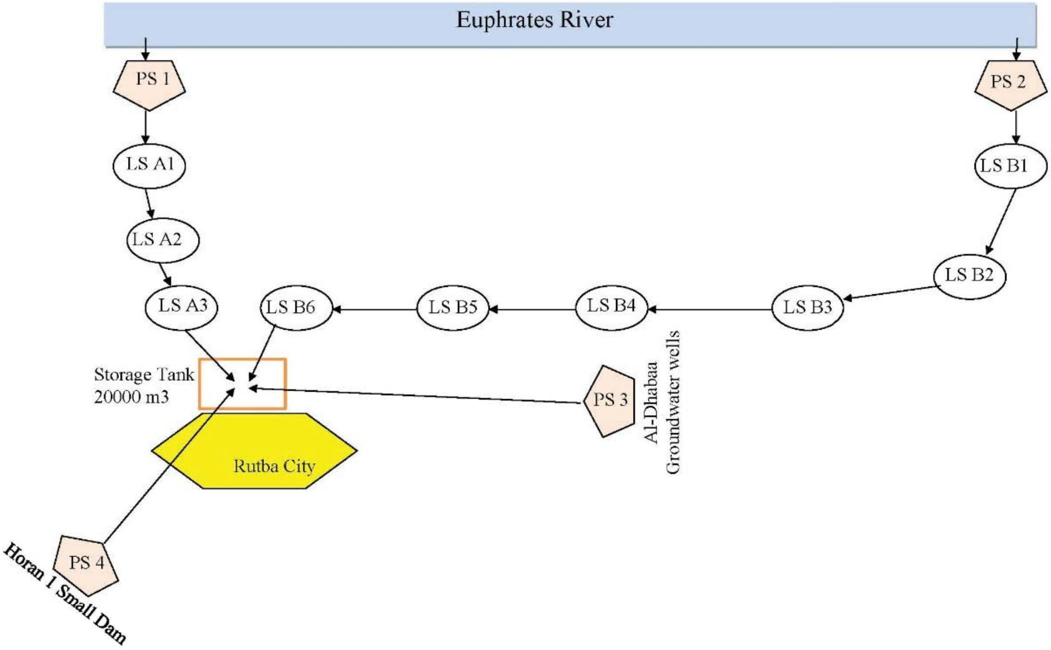

Fig. 3. Layout of the pump and lift stations (PS: pump station, LS: lift station).

pipeline *i*, including pump station and lift stations (USD/d). The difference between $\text{OF}_{\text{income}}$ and $\text{OF}_{\text{expense}}$ (total daily net income) was maximized. Total daily net income (OF_{net}) was calculated as follows:

$$\text{OF}_{\text{net}} = \text{OF}_{\text{income}} - \text{OF}_{\text{expense}} \tag{5}$$

The modified objective function [Eq. (2)] was minimized by the heuristic optimization model using the modified Clonalg [29], a class of the artificial immune systems under the constraints of the required daily water demand of the city (15,000 m^3/d for the first six months and 10,000 m^3/d for the second six months of the year), pump discharge capacities (maximum discharges of the pump stations)

Table 1
Geographical coordinates, electricity costs and maximum discharges (flow rates) of the pump stations

Station	Latitude (DD)	Longitude (DD)	Unit cost of electricity (USD/d)	Max. discharge (m^3/d)
PS 1	34.359527	41.125197	85	4,600
PS 2	33.525093	42.941172	125	9,000
PS 3	32.956198	40.516547	425	4,000
PS 4	32.873354	40.034560	75	8,000
LS A1	34.271112	40.991696	125	–
LS A2	33.970431	40.384494	150	–
LS A3	33.671147	39.984403	100	–
LS B1	33.301308	42.622152	125	–
LS B2	33.302498	42.284902	125	–
LS B3	33.191327	41.708680	125	–
LS B4	33.046509	41.124411	165	–
LS B5	33.053816	40.590964	150	–
LS B6	33.064543	40.395617	150	–

and limits of withdrawing water from the water resources. After that, total daily net incomes of the optimum water resources (optimum daily water quantity transmitted by each pump station) was calculated to compare with the previous results.

Eq. (2) was integrated into the algorithm coded in Matlab programming language, and the model was run ten times by using a PC with Intel Core I5-8300H CPU 2.3 GHz with a maximum iteration number (1,000) for the comparison. Same parameter values of the algorithm were applied in this study.

3. Results and discussion

After the objective function [Eq. (2)] was minimized by the modified Clonalg, the obtained results were compared with the results of Eryiğit and Sulaiman [1] (Tables 2 and 3). The best result of total net income was 539,850 USD for the first 6 months (Pipeline 1: 3,000 m^3/d, Pipeline 2: ~0 m^3/d, Pipeline 3: 4,000 m^3/d, Pipeline 4: 8,000 m^3/d). For the second six months, the best result of total net income was 402,675.6 USD (Pipeline 1: ~0 m^3/d, Pipeline 2: ~0 m^3/d, Pipeline 3: 2,000 m^3/d, Pipeline 4: 8,000 m^3/d). As can be seen in the tables, 1,830 and 2,275 dollars of total net income more (10 and 12.5 dollars of total daily net income more) were obtained by Eryiğit and Sulaiman [1] than the Eq. (2) (the present study) for the first and second six months, respectively.

The optimization model minimized the objective function according to the distances and the differences of the piezometric head between the water resources and the city (The lengths and piezometric head differences of the pipelines/pump stations 1-2-3-4 to the city are 250, 271, 20, 29 km and 579, 582, 40, 43 m, respectively). For both periods, the model selected the maximum discharges of the pipelines/pump stations which have the minimum distance and the minimum piezometric head to the city to satisfy the required daily water demands (15,000 and 10,000 m^3/d). Because higher piezometric head and longer distance are more cost in the Eq. (2). For this reason, the pipelines 4-3-1 and the pipelines 4-3 were selected by the model to supply the water demands for the first and second six months of the year, respectively. On the other hand, the model preferred in the order of the pipelines 4-1-3 and the pipelines 4-1 in the study of Eryiğit and Sulaiman [1] because of the incomes and expenses. Although the length of pipeline 4 is longer (29 km) than pipeline 3 (20 km), the model prioritized pipeline 4 with the maximum discharge capacity (8,000 m^3/d for both periods) since there is also the gravity flow between pump station 4 (678 m) and the city (635 m).

Required daily water demands of the city for both periods (15,000 and 10,000 m^3/d for the population of 50,000) were completely supplied by the pipelines by complying with all the constraints (maximum capacities of the pump discharges and limits of withdrawing water from the water resources). The model solved the objective function [Eq. (2)] with the approximate results to the previous study at a similar time (mean run time is 3 mins while mean run time of Eq. (5) is 3.1 mins) in the same conditions (PC, iteration number, parameters of the algorithm). This indicates that the optimization model works consistently for different objective functions of the same optimization problem. Therefore, it can be said that the difference between the results of both objective functions is due to their approaches on the cost-benefit relationship (not because of the model).

4. Conclusion

Within this study, two different cost-benefit functions were compared under the same constraints to decide on optimum water resources to supply the water of Rutba City. Thus, the optimization model was also able to be tested by using different objective functions to solve the same problem. Furthermore, the objective function used by Carini et al. [2] was modified to be applicable for the pumped pipelines.

According to the results, the objective function of Eryiğit and Sulaiman [1] was better than the modified function of Carini et al. [2] for the city in terms of total net income. However, the results and mean run times were close each

Table 2
Comparison of results of both objective functions for the first six months

Run No.	Total net income for first 6 months (USD)		Total daily net income (USD/d)		Total daily income (USD/d)		Total daily expense (USD/d)		Pipeline 1 (m^3/d)		Pipeline 2 (m^3/d)		Pipeline 3 (m^3/d)		Pipeline 4 (m^3/d)		Run time (s)	
	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study
1	541,680	539,849.8	2,960	2,950	3,750	3,750	790	800	4,600	2,999.80	0	0.20	2,400	4,000	8,000	8,000	233.9	183.1
2	541,671.4	539,850	2,959.95	2,950	3,750	3,750	790.05	800	4,600	2,999.98	48.19	0.02	2,351.81	4,000	8,000	8,000	235.1	184.2
3	541,643	539,849.6	2,959.8	2,950	3,750	3,750	790.2	800	4,600	2,999.65	207.98	0.35	2,192.02	4,000	8,000	8,000	234.6	183.0
4	541,674.3	539,849.7	2,959.97	2,950	3,750	3,750	790.03	800	4,600	2,999.81	32.27	0.20	2,367.73	4,000	8,000	8,000	231.7	183.2
5	541,669.5	539,849.7	2,959.94	2,950	3,750	3,750	790.06	800	4,600	2,999.73	59.16	0.27	2,340.84	4,000	8,000	8,000	218.6	183.3
6	541,663.4	539,849.9	2,959.91	2,950	3,750	3,750	790.09	800	4,600	2,999.94	93.16	0.06	2,306.84	4,000	8,000	8,000	172.6	182.7
7	541,680	539,848.8	2,960	2,949.99	3,750	3,750	790	800.01	4,600	2,999.08	0	0.92	2,400	4,000	8,000	8,000	170.2	183.1
8	541,680	539,850	2,960	2,950	3,750	3,750	790	800	4,600	2,999.97	0	0.03	2,400	4,000	8,000	8,000	174.4	184.2
9	541,680	539,849.6	2,960	2,950	3,750	3,750	790	800	4,600	2,999.65	0	0.35	2,400	4,000	8,000	8,000	179.1	182.9
10	541,658.1	539,848.1	2,959.88	2,949.99	3,750	3,750	790.12	800.01	4,600	2,998.54	123.04	1.47	2,276.96	4,000	8,000	8,000	171.3	183.3
Mean	541,670	539,849.5	2,959.95	2,950	3,750	3,750	790.05	800	4,600	2,999.62	56.38	0.39	2,343.62	4,000	8,000	8,000	202.1	183.3
Std.	12.2	0.6	0.07	0.00	0	0	0.07	0	0	0.46	68.44	0.46	68.44	0	0	0	30.6	0.5
Min.	541,643	539,848.1	2,959.8	2,949.99	3,750	3,750	790	800.00	4,600	2,998.54	0	0.02	2,192.02	4,000	8,000	8,000	170.2	182.7
Max.	541,680	539,850	2,960	2,950	3,750	3,750	790.2	800.01	4,600	2,999.98	207.98	1.47	2,400	4,000	8,000	8,000	235.1	184.2

Water demand of the city is 15,000 m^3/d for the first six months.

Table 3
Comparison of results of both objective functions for the second six months

Run No.	Total net income for second six months (USD)		Total daily net income (USD/d)		Total daily income (USD/d)		Total daily expense (USD/d)		Pipeline 1 (m^3/d)		Pipeline 2 (m^3/d)		Pipeline 3 (m^3/d)		Pipeline 4 (m^3/d)		Run time (s)	
	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study	Eryiğit and Sulaiman [1]	Present study
1	404,950	402,675.1	2,225	2,212.5	2,500	2,500	275	287.5	2,000	0.007	0	0.017	0	1,999.98	8,000	8,000	169.7	180.1
2	404,950	402,675.1	2,225	2,212.5	2,500	2,500	275	287.5	2,000	0.022	0	0.006	0	1,999.97	8,000	8,000	170.1	180.2
3	404,810.6	402,675.6	2,224.23	2,212.5	2,500	2,500	275.77	287.5	1,878.44	0.002	6.11	0.033	115.45	1,999.99	8,000	8,000	171.6	180.9
4	404,950	402,675.4	2,225	2,212.5	2,500	2,500	275	287.5	2,000	0.008	0	0.096	0	1,999.91	8,000	8,000	170.0	180.4
5	404,933.9	402,675	2,224.91	2,212.5	2,500	2,500	275.09	287.5	1,987.79	0.001	12.21	0.072	0	1,999.93	8,000	8,000	169.5	180.4
6	404,947.5	402,675.1	2,224.99	2,212.5	2,500	2,500	275.01	287.5	1,997.84	0.061	0	0.259	2.16	1,999.68	8,000	8,000	172.2	180.9
7	404,939.7	402,675	2,224.94	2,212.5	2,500	2,500	275.06	287.5	1,991.43	0.006	3.09	0.061	5.49	1,999.93	8,000	8,000	169.3	180.3
8	404,950	402,675.1	2,225	2,212.5	2,500	2,500	275	287.5	2,000	0.022	0	0.086	0	1,999.89	8,000	8,000	169.1	180.6
9	404,950	402,675.2	2,225	2,212.5	2,500	2,500	275	287.5	2,000	0.007	0	0.003	0	2,000	8,000	8,000	171.9	180.6
10	404,950	402,675	2,225	2,212.5	2,500	2,500	275	287.5	2,000	0.012	0	0	0	1,999.99	8,000	8,000	169.5	181.2
Mean	404,933.2	402,675.2	2,224.9	2,212.5	2,500	2,500	275.1	287.5	1,985.5	0.015	2.14	0.063	12.31	1,999.93	8,000	8,000	170.3	180.6
Std.	43.4	0.2	0.24	0	0	0	0.24	0	37.88	0.018	4.09	0.077	36.28	0.09	0	0	1.2	0.4
Min.	404,810.6	402,675	2,224.23	2,212.5	2,500	2,500	275	287.5	1,878.44	0.001	0	0	0	1,999.68	8,000	8,000	169.1	180.1
Max.	404,950	402,675.6	2,225	2,212.5	2,500	2,500	275.77	287.5	2,000	0.061	12.21	0.259	115.45	2,000	8,000	8,000	172.2	181.2

Water demand of the city is 10,000 m^3/d for the second six months.

other. This demonstrates that the stability of the optimization model is high even using different objective functions. Moreover, the results of the modified function make sense and accord with its approach which minimizes the cost depending on the distances and the piezometric head differences between the water resources and the city. In future studies, this modified function can be used by the model to solve more complicated pumped pipe networks.

Conflict of interest statement

The authors declare that there is no conflict of interest.

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