



Sustainable Surface Water Management and Wastewater Treatment Plant Location: A Case Study of Urmia Lake

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ABSTRACT

The conservation of lakes is an essential issue in sustainable development. Disruption of ecological balance, destruction of biodiversity and vegetation, desertification, and storm surges are the results of lakes drying. The purpose of this paper is to introduce an integrated bi-objective sustainable water resource management model. The first objective function deals with economically optimal allocation of water to the residential, industrial, and agricultural sectors. For compliance with the requirements of sustainable development, the second objective is to maximize the amount of water allocated to the environment. For proper utilization and reuse of water resources, the location of urban wastewater treatment plants is also considered in the problem. The model is solved with data from the most important watershed in Iran, Urmia Lake. Natural and unnatural factors have dramatically reduced the amount of water intake and balance over the past two decades. The epsilon constraint is used for solving the case study model. The results show that the model can satisfy the demand of sectors, with 70 percent of the available resources. The use of this model can meet the demands of the consumer sectors, and also, it can help revitalize Urmia Lake and the ecosystem of the river in its basin.

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NOMENCLATURE

Sets and Indices		Decision Variables
I	Set of rivers ($i \in I$)	E_{it} The total amount of water allocated from the dam on river i to the environment in period t
J	Set of candidate sites for refineries ($j \in J$)	$x_{it}^{(1)}$ The total amount of water allocated from the dam on river i to the residential sector in period t
T	Set of periods ($t \in T$)	$x_{it}^{(2)}$ The total amount of water allocated from the dam on river i to the industrial sector in period t
Parameters		$x_{it}^{(3)}$ The total amount of water allocated from the dam on river i to the agricultural sector in period t
C_i	The capacity of the dam on river i	k_{it} The total amount of water allocated to the agricultural sector from the sub-network of the dam on river i in period t
I_1	The selling price of a unit of water to the residential sector	β_i Amount of wastewater collected from the residential sector of the dam on river i
I_2	The selling price of a unit of water to the industrial sector	y_{ij} A binary variable that equals one if the refinery is located at point j in the basin of river i
I_3	The selling price of a unit of water to the agricultural sector	W_{it} Amount of water at the dam on river i during period t
D_{it}^1	The demand of the residential sector from river i in period t	
D_{it}^2	The demand of the industrial sector from river i in period t	
D_{it}^3	The demand of the agricultural sector from river i in period t	
q	Cost per unit of water treatment	
h_{it}	The volume of water in river i in period t	
H_{ij}	Height of point j in the basin of river i	

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1. INTRODUCTION

Based on the principles of sustainable development, the present generation should supply its own needs from natural resources so that future generations will also be able to meet their needs from these sources adequately. According to this definition, different generations have the right to make fair use of natural resources. This contradicts man's view in the past two centuries, which was formed based on the separation of environmental, social, and economic issues. Water is an essential element for life and is the basis for sustainability on the Earth. Water resources are renewable, their overall volume is constant, while human demand is increasing. Thus, the per capita water supply for the people of the world is decreasing. Other reasons for the reduction of surface water are climate change and dam construction on rivers [1]. Dams are designed to contain surface water and use it for power generation or distribution for agricultural purposes. These facilities have disrupted the natural path of groundwater flow and dried up many rivers. Reducing surface water will not only make it difficult for major consumers to access the water but will also increase the level of surface water pollution, thereby drastically reducing the quality of water consumed (especially for residential consumers). Water resource pollution is one of the most critical threats to aquatic ecosystems and the significant challenges and crises of water resources that has made resources inaccessible due to contamination. These pollutants have adverse environmental and economic impacts.

The spatial distribution of water in Iran is very heterogeneous due to natural conditions. The time distribution of precipitation is variable in different years and even in different seasons, which has caused several problems in the past few years for different water utilization sectors, particularly the agricultural and urban drinking water supply sectors. The agricultural sector is considered to be the largest consumer of water resources in Iran, and more than 90 percent of total water consumption is attributable to this sector. The water allocation model is a method for the optimal division of water resources between stakeholders. This model determines how much water, where, and for what purpose, is allocated to each stakeholder for the maximization of their benefits [2]. It is contradictory to the principles of sustainable development to consider the increase in profit as the only target for water resource allocation models. In water allocation models, a large proportion of current resources need to be considered intact as a contribution to the ecosystem. The volume of water that is considered for the environment is equal to the amount of water that must flow into the river so that the ecosystem can meet its needs. Failure to meet this demand has irreparable consequences such as drying up

of rivers, destruction of the surrounding ecosystem, and disruption of its economic activities, such as fishing.

Early research pertaining to optimal water allocation models dates back to the late 20th century. In the past decade, more researchers have begun to work on this topic, given an increase in the water crisis, and they have carried out more extensive research. In most of the initial research, the researchers have applied single-objective optimization methods for transboundary water. In recent research, however, multi-objective models have mainly been used for considering different aspects of natural resource management issues [2]. In this regard, multi-objective models are used for the management and allocation of water resources, which is considered as a subset of natural resource management [3]. In addition to single-objective and multi-objective models, sustainable models are used. These models seek to meet the needs of the environment as well as those of industrial and agricultural households. Many of the models and algorithms used for the allocation of water resources are based on simulation and optimization. Models proposed for the allocation of water resources can be divided into three categories: single-objective, multi-objective, and sustainable models.

Planning for surface water and underground water becomes more critical when the amount of water is lower than the total demand [4]. Most single-objective optimization models attempt to optimize water allocation in order to maximize the economic benefits. Karamuz et al. [5] presented a nonlinear model for the optimization of the use of water resources in Varamin River, which emphasizes the combined use of surface and underground water resources. The objective function of the model seeks to increase profit obtained from transportation costs and crop cultivation. Pulido-Velázquez et al. [6] proposed a nonlinear model for the economically optimal allocation of surface and underground water resources in Adra River basin. Hydrologic factors are also included in the model.

Some researchers have presented multi-objective mathematical models considering conflicting objectives and multiple stakeholders. Li et al. [7] developed a model for the management of water resources in Canada. In this study, they examined the exchange between environmental and economic objectives besides the allocation of water to different usages. Kucukmehmetoglu and Goldman [8] presented a multi-objective model for Tigris and Euphrates rivers. The basin of these rivers includes Turkey, Iraq, and Syria. For each country, a separate objective function is considered that is intended to maximize profit. Rezapur Tabari and Yazdi [9] proposed a multi-objective model that, while meeting the demands, seeks to minimize the amount of water flowing from Iran to Iraq and to maximize the transfer of water to Urmia Lake basin.

In some models, objective functions are considered for sustainable development in addition to the economic ones. Some of the most recent research that contains the aspects of sustainable development are introduced and reviewed below. Anghileri et al. [10] developed a model seeking to allocate water resources to meet the water demand of agricultural sectors and power plant facilities. The model attempts to minimize the amount of water deficit in agriculture, and it is considered as one of the constraints of the problem to meet environmental requirements. A bi-objective model has been proposed by Lalehzar et al. [11] for the needs of the agricultural sector through the use of surface water and underground water resources. One of the objective functions maximizes the net profit obtained by the agricultural sector, and the other function attempts to maximize the productivity and efficiency of the allocated water. Oxley et al. [12] presented a linear model for water resource allocation, a model consisting of 12 periods where the sustainability of resources has also been considered. The objective function of the model attempts to maximize the net profit derived from water allocation. According to the results, they have also presented two short-term (1-year) and long-term (21-year) plans for solving the problem. The long-term plan consists of several short-term plans. Zhou et al. [13] developed a sustainable model for water resource allocation. In this model, the amount of gained profit is measured with respect to water consumption. The model attempts to provide sustainable solutions by linking economic growth with the use of water resources. The case study of this research concerns the Makit County River in China.

In recent years, water pollution, along with water scarcity issues, has been a critical environmental issue [14]. The use of refined wastewater saves the other water resources, in addition to solving the environmental crises caused by the entry of sewage into the receiving environment. Given the geographical features of Iran and the increasing needs of different sectors for water, the problems caused by proper access to water resources are a major challenge in this area. Investigation of the global experience of using wastewater sources demonstrates that it is important with regard to water scarcity to use these resources as valuable sources of water, and the importance increases every day. Energy has lots of impact on planning wastewater plants [15]. Multi-criteria decision-making (MCDM) methods are frequently used in the literature for wastewater treatment location problems. The use of mathematical models is a new method for the location of wastewater treatment plants. Zhao et al. [16] used the analytic hierarchy process to locate the Guangzhou refineries. Geographic information systems are used for the location of each of the points.

According to the previous studies, there is no model for the allocation of water resources taking into account different rivers and the use of a dam for each river. A

mathematical model considering several rivers in a single drainage basin provides a more comprehensive, precise strategy for problem-solving. Dams were not assumed in most of the previous research; as a result, their potential effects have not been used for the optimization of resource allocation. Dams can help to manage integrated water resources and to cope with the seasonal water shortages. They can be useful for downstream ecosystems during periods of drought. Another essential point is concerned with the use of wastewater as a permanent source for meeting the existing demands in the agriculture sector. The use of sewage requires the location and construction of refineries.

The structure of this paper is organized as follows. In the next section, the problem description and mathematical model are presented. In Section 3, the case study is introduced and analyzed using the proposed model. The results of the model are described in Section 4, followed by the conclusion in Section 5. Figure. 1 presents the research methodology.

2. PROBLEM DESCRIPTION AND MATHEMATICAL MODEL

The proposed model is a mixed-integer programming (MIP) model. As far as water resource management is concerned, the solution space is continuous, but since water treatment plants are located in discrete space (selection of a number of candidate sites by defining integer decision variables), the proposed model is a MIP. The purpose of exploitation of water

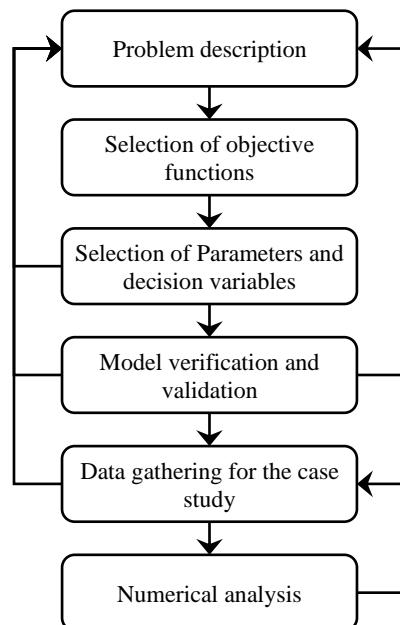


Figure 1. Research methodology

resources is to determine the amount of harvest and the distributions of the time and place of exploitation of each resource for reduction of the number of deficiencies and the negative effects of poor distribution of river flow, water storage, and more favorable water demand management. For an illustration of the proposed model, a network is considered that consists of several types of nodes; a number of nodes represent dams on rivers, and another number of nodes include candidate sites for construction of refineries (where rivers cross). Each of the dams will have one to three demand node(s) according to the conditions and purpose of its construction. These demand nodes represent the residential, industrial, and agricultural sectors. For modeling the refinery location problem, candidate sites are considered on the sub-network of each dam for the construction of refineries. The amount of wastewater allocated to a treatment plant is equal to the specified coefficient of the total water delivered to the household.

On the paths of rivers, there are water storage facilities (dams). The purpose of creating storage facilities is to deal with shortages throughout the year. When the river enters the dam, the water is packed up behind the wall and is divided between consumers during the year. The reserved water is used for meeting the demands of each of the residential, industrial, and agricultural sectors and the environment. The rivers flow all the way to a point and form a lake. The main assumptions that are made during the modeling are as follows.

- The problem is assumed to be dynamic or multi-period. Each of the months of the year constitutes one of the planning periods.
- The amount of river water in each period is given and fixed.
- A certain percentage of the water allocated to the residential sector can be directed to the refinery.
- The refined urban wastewater is used in the agricultural sector.

The mathematical model of the problem is as follows.

$$\begin{aligned} \text{Max } Z_1 = & \sum_{i \in I} \sum_{t \in T} \left(I_1 x_{it}^{(1)} + I_2 x_{it}^{(2)} + I_3 x_{it}^{(3)} \right) + \\ & \sum_{i \in I} \sum_{j \in J} \frac{y_{ij} \beta_i H_{ij}}{\max(H_{ij})} \left(I_3 - \frac{q H_{ij}}{\min(H_{ij})} \right) \end{aligned} \quad (1)$$

$$\text{Max } Z_2 = \sum_{i \in I} \sum_{t \in T} E_{it} \quad (2)$$

$$\beta_i = b \sum_{t \in T} x_{it}^{(1)} \quad \forall i \quad (3)$$

$$k_{it} = x_{it}^{(3)} + b x_{it}^{(1)} \quad \forall i, t \quad (4)$$

$$D_{it}^1 - x_{it}^{(1)} \geq 0 \quad \forall i, t \quad (5)$$

$$D_{it}^2 - x_{it}^{(2)} \geq 0 \quad \forall i, t \quad (6)$$

$$D_{it}^3 - x_{it}^{(3)} \geq 0 \quad \forall i, t \quad (7)$$

$$W_{it} = \vartheta C_i \quad \forall i \quad (8)$$

$$W_{it} = W_{i(t-1)} - x_{i(t-1)}^{(1)} - x_{i(t-1)}^{(2)} - x_{i(t-1)}^{(3)} - E_{i(t-1)} + h_{it} \quad \forall i, t \in \{2, 3, \dots, 12\} \quad (9)$$

$$(x_{it}^{(1)} + x_{it}^{(2)} + x_{it}^{(3)} + E_{it}) \leq W_{it} \quad \forall i, t \quad (10)$$

$$W_{it} \leq C_i \quad \forall i, t \quad (11)$$

$$E_{it} \geq \rho h_{it} \quad \forall i, t \quad (12)$$

$$\sum_{i \in I} \sum_{j \in J} y_{ij} = n \quad (13)$$

$$\sum_{j \in J} y_{ij} = 1 \quad \forall i, t \quad (14)$$

$$x_{it}^{(1)} - f D_{it}^1 \geq 0 \quad \forall i, t \quad (15)$$

$$x_{it}^{(1)}, x_{it}^{(2)}, x_{it}^{(3)}, E_{it} \geq 0 \quad \forall i, t \quad (16)$$

$$y_{ij} \in \{0, 1\} \quad (17)$$

As the first objective function, Equation (1) seeks to allocate water resources to the agricultural, industrial, and residential sectors and to select locations from among the candidate sites for construction of refineries so that the total profit is maximized. The greater the height of the point selected for construction of a treatment plant, the wider the covered agricultural land; on the other hand, the greater the altitude, the higher the cost per liter of refined water. Given the purpose of maximizing profit, the expression $\frac{H_{ij}}{\max(H_{ij})}$ takes a greater value as a coefficient with a greater H_{ij} value. In the other part, however, $\frac{H_{ij}}{\min(H_{ij})}$ causes the greatest amount to be obtained when the nominator takes the lowest value. The objective function seeks to provide a balance between profitability and cost increase. Equation (2) as the second objective function represents the environmental component in the mathematical model and attempts to increase the amount of water allocated to the environment. It somehow guarantees the sustainability of the future environmental water resource system. Constraint (3) concerns the amount of water that comes from the refinery and is consumed in the agricultural sector. Constraint (4) specifies the total amount of water delivered to the agricultural sector. This amount is obtained through the summation of the amount of water allocated to the agricultural sector from the main source (the dam) and the amount of treated wastewater. Constraints (5), (6), and (7) ensure that the amounts of water allocated to the residential, industrial, and agricultural sectors, respectively, are less than or equal to the demands of

these sectors. This limitation is essential for saving water and preventing water loss. The relationship expressed in Constraint (8) determines the amount of water at each dam during the first period. Constraint (9) calculates the amount of water available at each dam for periods 2 to 12. The total amount of water remaining from the previous period and the amount of water entering the dam in this period make up the total available volume of water. This amount of water should be allocated to the three sectors. The remainder will be transferred to the next period. Constraint (10) controls the volume of water allocated from the dam so that the total amount of water allocated in each period to the consumer sectors and environment does not exceed the amount of water stored at the dam. Constraint (11) indicates that the volume of water at the dam should not be higher than the total capacity of the dam. Constraint (12) refers to the amount of water flowing into the river. This constraint has been presented for the environment section of the model. This section provides the minimum water right of the river. The minimum water right is considered so that the water can flow to the end of its course, and the organisms and those who feed on the ecosystem of the river will continue to supply needed water. Constraint (13) specifies the number of refineries that are set up to clean up urban wastewater. Constraint (14) ensures that only one treatment plant is located in the subnet of each dam. Constraint (15) ensures that f percent of the demand for the residential sector is first secured in any case. This equation is intended to include the higher priority of the residential sector in the model. Constraints (16) and (17) indicate the domains of the decision variables.

In the second part of the first objective function, two decision variables are multiplied. The term consists of the product of a continuous variable and a binary variable. A new binary variable u_{ij} along with three new constraints (18 to 20) are added to the model. These equations state that if y_{ij} is zero, u_{ij} is equal to zero, but if y_{ij} is 1, u_{ij} is smaller than β_i in Equation (19) and higher than or equal to the same value in Equation (20), which means that it is equal to β_i . The product of variables β_i and y_{ij} in the second part of the first objective function is replaced.

$$u_{ij} \leq M y_{ij} \quad (18)$$

$$u_{ij} \leq \beta_i \quad (19)$$

$$u_{ij} \geq \beta_i - (1 - y_{ij})M \quad (20)$$

Unlike a single-objective optimization problem, it is impossible to obtain a solution that can satisfy all the objectives of multi-objective models. A set of optimal Pareto (efficient) solutions is, therefore, obtained instead of an optimal solution. Epsilon constraint, introduced by Haimes [17], is one of the most widely used methods for

solving multi-objective problems. The main idea of the method is that one of the objectives is chosen as the primary objective function, and the other ones are moved to the constraints. The right-hand-side values of the constraints corresponding to the objective functions are changed from upper bound toward lower bound (in the minimization problems), and the problem is solved repeatedly until all possible Pareto solutions are generated [18]. The steps of the epsilon constraint method for a problem with two objectives are briefly described below.

Given that $\mathbf{X} = \{x_1, x_2, \dots\}$ is the decision variable vector of the problem, $f_j(\mathbf{X}), j = 1, 2$ is the j th objective function, and $g_i(\mathbf{X}), i = 1, 2, \dots, m$ is the i th constraint of the problem, the algorithm begins by optimizing the main objective function. If $f_1(\mathbf{X})$ is assumed as the main objective function, P_1 is solved as the first model.

$$P_1: \text{Max } f_1(\mathbf{X})$$

$$\text{s.t.: } g_i(\mathbf{X}) \leq 0 \forall i$$

Suppose that $\mathbf{X}_1 = \{x_{11}, x_{21}, \dots\}$ is the solution to the problem. For obtaining the first efficient point, model P_2 should be solved considering the second objective function and adding the constraint associated with the first objective function. The structure of P_2 is as follows.

$$P_2: \text{Max } f_2(\mathbf{X})$$

$$\text{s.t.: } g_i(\mathbf{X}) \leq 0 \forall i, f_1(\mathbf{X}) \geq f_1(\mathbf{X}_1)$$

Since the optimal value of the first objective function is $f_1(\mathbf{X}_1)$, the mathematical model obtains the best value of the second objective function provided that the optimal value of the first objective function is maintained. If the optimal solution to problem P_2 is \mathbf{X}_2 It will be the first efficient solution to the problem. The algorithm attempts to obtain the second efficient solution by improving the second objective function. For this purpose, model P_3 is solved.

$$P_3: \text{Max } f_1(\mathbf{X})$$

$$\text{s.t.: } g_i(\mathbf{X}) \leq 0 \forall i, f_2(\mathbf{X}) \geq f_2(\mathbf{X}_2) + \Delta$$

In this mathematical model, Δ is a positive number. In the above model, the improvement of the second objective function worsens the first objective function due to the conflict between the objectives. If \mathbf{X}_3 is assumed to be the optimal solution for P_3 , the fourth mathematical programming is solved for obtaining the second most efficient solution to the problem.

$$P_4: \text{Max } f_2(\mathbf{X})$$

$$\text{s.t.: } g_i(\mathbf{X}) \leq 0 \forall i, f_1(\mathbf{X}) \geq f_1(\mathbf{X}_3)$$

The sequential solution of the models for the first and second objective functions continues as long as there is a possibility of further improvement of the second objective function, in which case the model with an odd number corresponding to these conditions will be infeasible. According to the above reasoning, all solutions obtained in models with even numbers will be efficient solutions to the problem. Since the solution space of the problem under investigation is continuous, it is not possible to obtain all the efficient points of the

problem. The value of parameter Δ determines the number of solutions obtained from the algorithm; the smaller the value of the parameter, the larger the number of obtained efficient solutions.

In the following section, the case study of the Urmia Lake basin is described as a practical, challenging example from Iran, and the relevant mathematical model is solved for illustration of how the epsilon constraint algorithm is used for solving the proposed mathematical model.

3. CASE STUDY

The watershed of Urmia Lake, located in the northwest of Iran with an area of 51876 km², is one of the largest hypersaline lakes in the world [20]. The basin is located between the provinces of West Azerbaijan, East Azerbaijan, and Kurdistan (Figure 2). The geologically remarkable location of the basin, the high evaporation rate, and the accumulation of solutes in the lake have turned it into an extremely salty lake. The lake was designated as a Ramsar site in 1974 (an international wetland) and was declared a protected area by UNESCO in 1976. Although the lake has experienced severe fluctuations during the past century, the trend rate has been increasing over the past two decades. The downtrend of the lake began after its high water balance in 1995, and the lake has fallen by more than 8 meters over twenty years. Based on recorded figures, the average level of the lake has dropped by 40 centimeters annually during the past twenty years. Due to the low depth of the lake, the above decrease in water balance has caused a considerable percentage of the lake area to dry, and evaporation and lack of access to adequate water resources have led to a loss of 30 billion cubic meters of its water volume.

Since Urmia Lake is located in a closed drainage basin, its water resources include direct rainfall and runoff from streams and rivers, and evapotranspiration is a factor affecting the output of the lake. Therefore, the continuous decrease in the lake water volume due to evaporation and inadequate water resources to

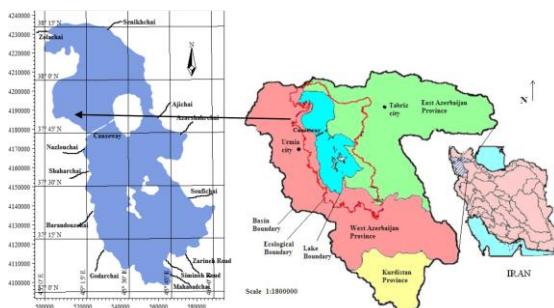


Figure 2. The geographic location of Urmia Lake, northwest of Iran [19]

compensate for that and maintain water balance are considered as the leading causes of drought. Based on the research, three main factors effective on the drought in Urmia Lake include:

- Excessive percolation of the renewable resources in the basin;
- Unbalanced development of the agricultural sector in the basin;
- Climate change and persistence of droughts.

Officially 25 small and large rivers have been identified and named that enter Urmia Lake, out of which nine rivers, including (1) Mahabad, (2) Gadar, (3) Shahr-Chay, (4) Nazlou, (5) Zola, (6) Barandoz, (7) Zarrineroud, (8) Simineroud, and (9) Sarouk have the highest amount of inlet water and are considered in the model. The selected rivers contain more than 78 percent of the water entering Urmia Lake. The selection has been based on criteria such as monthly average, permanence, and availability of a dam on the river. These rivers have the highest monthly averages in the drainage basin of the lake. Another reason for this choice is the significant difference between the maximum and minimum volumes of water in different months in these rivers, which is why water resources management is necessary for them. Figure 3 shows the average monthly discharge of the rivers considered in the model. In this chart, the bars corresponding to each river show the average drainage of a 12-months period (based on the solar calendar and left to right). The dams constructed on the courses of the selected rivers are also included in the model. Information on the capacity of the dams is given in Table 1.

According to expert opinions, a number of candidate sites have been considered in each of the cities for the construction of refineries. The height of these candidate sites is given in Table 2. These points have been selected on the basis of environmental conditions and being situated upstream for agricultural lands.

The monthly demands of urban, industrial, and agriculture sectors are given in Table 3.

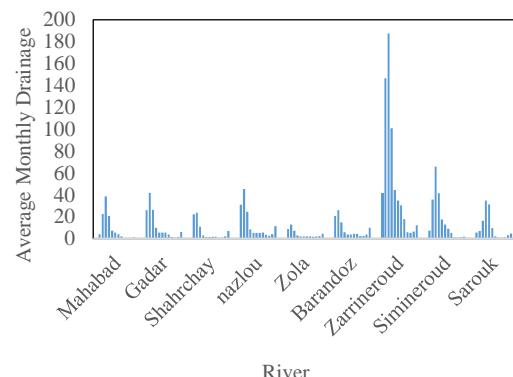


Figure 3. Average monthly discharge of the rivers

TABLE 1. Dams capacity

Dam	Capacity (million cubic meters)
Mahabad	197
Hasanlou (Gadar)	94
Shahr-chay	199
Nazlo	273
Barandoz	147.5
Zola	132.5
Simineroud	269
Zarrineroud	605
Sarouk	110

TABLE 2. Height of the candidate sites

River	Site 1	Site 2	Site 3
Mahabad	37	126	130
Sharchay	91	102	53
Nazlou	148	119	130
Barandoz	67	120	154
Simineroud	24	53	87
Zarrineroud	54	47	80
Zola	113	84	167

TABLE 3. Monthly demands of urban (in thousand cubic meters), industrial and agriculture sectors

Dam	Urban sector	Industrial sector	Agriculture sector
Hassanlou	0	0	16800
Mahabad	1280	702	17500
Sharchay	6333	507	17500
Nazlou	3166	990	60340
Zola	501	330	22722
Barandoz	2500	675	12981
Simineroud	450	1305	36400
Zarrineroud	8500	342	71400
Qaranaz	0	0	12180

4. RESULTS AND DISCUSSION

In this section, the proposed mathematical model is solved using the epsilon constraint algorithm in light of the information given on Urmia Lake basin. The purpose of the model is to determine how surface water entering Urmia Lake is allocated to the three consumption sectors (residential, agricultural, and industrial) as well as how

five sites are selected among the candidate sites for construction of a water treatment plant. It is not possible to construct a refinery in the basin of Hasanlou and Qaranaz dams because the wastewater is delivered to the refinery from urban sewage, and these two dams have agricultural applications only, and their sub-network does not include the residential sector. The values of the other parameters are presented in Table 4.

The model is implemented in GAMS 30.1.0, and the CPLEX solver solves the sample problem on a computer with a 3.2 GHz Core i7 processor and 8 GB of RAM. Figure 4 shows the Pareto frontier of the solutions obtained through the epsilon constraint method. The first objective function is selected as the main one, and the second objective function is re-calculated in each iteration according to the change in the value of the main objective function. The first objective function of the model seeks to increase the profit gained from the allocation, and the second objective function is intended to increase the amount of water allocated to the environment; therefore, an increase in the value of each objective function reduces that of the other. This behavior can be understood well using the Pareto front. According to the obtained figure, it can be seen that the functions are linearly related in the lower part. This part of the Pareto frontier concerns the case where the residential, industrial, and agricultural sectors are adequately supplied. At the first breakpoint from the right, the amount of available water fails to meet the demand of the residential, industrial, and agricultural sectors simultaneously, and the sector with the least profit (namely, the industrial sector) is eliminated, and the available water is allocated to the other sectors. The line leading to the second breakpoint of the model is decreasing the amount of water allocated to the agricultural sector. At the end of the line, the second breakpoint, the agricultural share of the water supply at the dam reaches zero, and no more water is released to meet the demand of this sector.

The critical point about the practical case is that it can be stated given the behavior of the two objective

TABLE 4. Parameters values used in the mathematical model

Parameter	Value
I_1	3000 (Rial)
I_2	400 (Rial)
I_3	800 (Rial)
q	1000 (Rial)
b	50%
ρ	10%
ϑ	30%
f	50%

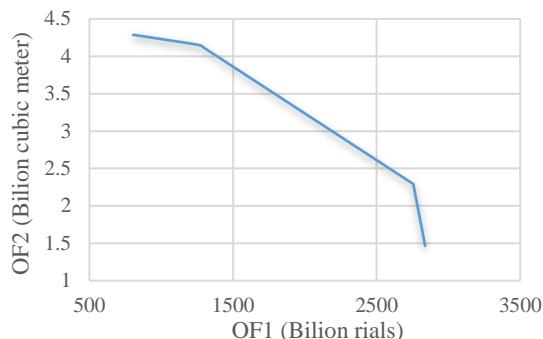


Figure 4. The Pareto frontier of the case study

functions in the solution space of the problem that it is not necessary to solve the model using conventional methods, such as the epsilon constraint method to obtain the Pareto frontier and the way in which the objective functions interact with each other. Instead, the Pareto frontier can be achieved by obtaining the values of the two functions at several points (in this case, 5 points). The first point is the maximum value of the first objective function, for which the value of the second objective function also needs to be calculated. The next point, as discussed above, represents the case where the amount of water allocated from the dam to the industrial sector has been eliminated. For obtaining this point, the above value is set to zero, and the objective function values are calculated according to these conditions. The next breakpoint indicates the case where no water is supplied to the agricultural and industrial sectors. At this point, the amount of water allocated to the agricultural and industrial sectors is zero. In order for the next and final point on the diagram to be obtained, a minimal amount of water should be supplied to the residential sector as input to the mathematical model in addition to the allocation of no water to the above sectors. Here, this is assumed to be equal to half the demand. When all the demand is met, the first objective function is maximized, but as the amount of allocated water is reduced, profit decreases, and the allocation of water to the environment increases on the other hand. The breakpoints appear where supply to one sector is completely stopped.

Given the inherent uncertainty of the problem, the solutions of the model should be investigated in different conditions. The water levels of the rivers in the basin have changed in recent years, which is why this parameter has been selected for sensitivity analysis. According to Figure 5, which shows the sensitivity analysis made on the amount of surface water in the lake, a 30% reduction of surface water resources will not make it challenging to meet the full range of existing demand. Through the comparison of the 100% and 40% curves of water resources, it can be found that water allocation to the industrial sector has been entirely discontinued by a reduction of resource consumption by 60%. As the

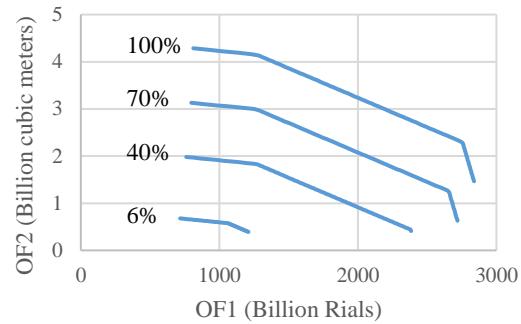


Figure 5. Sensitivity analysis of the volume of the river

diagram shows, water supply to the agricultural sector is not eliminated on any of these curves, and the breakpoint turns into a minimal arc in the final diagram. The curvature and survival of the agricultural sector are due to the establishment of refineries in which a part of the agricultural water comes from them. In other words, the allocation of resources from dams to agriculture is completely stopped, but wastewater treatment plants respond to some of the demands of the sector through refinement. It should be noted that it is possible only in areas where water is allocated to the residential sector to respond to agricultural demand through refineries. According to a sensitivity analysis of the problem, if surface water resources in Urmia lake fall by 94%, they will still be capable of meeting the demand of the residential sector.

5. CONCLUSION

In this paper, the allocation problem of surface water to residential, agricultural, and industrial sectors and the location of water treatment plants were discussed. In the first and second sections, the generalities and definitions and the necessity of integrated water resources management were described. The relevant classification and research were then addressed.

The purpose of this study was to provide a mathematical model for the revival of Urmia Lake in such a way that some key features and conditions of the basin could be expressed in the model. The mathematical model had two objective functions, which examined the economic and environmental aspects of the problem simultaneously. The first objective function emphasized the supply of water to residential, agricultural, and industrial uses, and the second objective was to meet the environmental demands and sustainability of water resources. The main difference between the proposed model and those in the other studies is the location decision regarding the wastewater treatment plants. In order to apply the proposed model in a real-world situation, the case of Urmia lake was introduced by

addressing the current status of the lake, and rivers and dams data in the lake basin. Given the inherent uncertainty of the problem, three scenarios of water crisis were defined, and the conditions of the water resources and their associated uses in each of the scenarios were investigated.

Solving the model for the different scenarios concludes that by reducing water resources by 30 percent, the needs of the major consumer sector can still be met. If the volume of water resources is reduced by more than 30 percent, the water allocated to the industrial sector and then to agriculture will gradually decrease. The agricultural sector is a major consumer of water resources. By reducing the amount of water needed by the agricultural sector, it can dramatically increase the environmental contribution of water resources. One way to reduce water consumption in agriculture and hence to accelerate the revival and sustainability of Urmia lake is to produce less water-intensive crops. Determining the optimal cropping policy in a geographical area is one of the most common agricultural issues. The purpose of this problem is to determine the best cropping pattern considering the water resources limitation and the type of crop soil. By integrating the cropping problem with the water resources management, it can improve agricultural productivity on the one hand, and reduce water consumption in this high-consumption sector, on the other.

Based on the issues discussed in the literature on the subject and throughout the study, suggestions are made in this section for the development and completion of the research as well as for other research areas that have not been addressed.

- The use of underground resources in the model and the way in which they can be used can make up a useful topic. The use of underground water can contribute to the integrated management of water resources in Urmia Lake basin.
- The use of robust methods in the mathematical model can bring its conditions closer to real-world conditions.
- In future research, it can be investigated whether it is justifiable to establish the new dams based on how the existing dams were considered in this research, and treatment plants were located. It should be noted that there are several dams under construction in the basin of the lake.
- The discussion on the transfer of water from Aras River to Urmia Lake and the method and amount of transfer can be examined in the model. This plan is one of the alternatives of the Iranian government to revive Urmia Lake.
- The amount of water to be transferred from the rivers available on the border between Iran and Iraq, where

water transfer tunnels are under construction, can be examined. Upon entrance of this item into the mathematical model, the Iraqi share of the water and its particular conditions should be considered.

- Artificial recharge of groundwater aquifers is also added to the model as a method for the provision of sustainability in water resources.

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Persian Abstract

چکیده

خشک شدن دریاچه‌ها می‌تواند منجر به برهم خوردن تعادل اکولوژیک، نابودی نوع زیستی و پوشش گیاهی و جنگلی، گسترش بیابان و طوفان ریزگردها شود. در این مقاله یک مدل دوهدفه یکپارچه برای مدیریت پایدار منابع آب ارائه می‌شود. تابع هدف اول، تخصیص اقتصادی منابع آب به بخش‌های خانگی، صنعتی و کشاورزی را بهینه می‌نماید. برای در نظر گرفتن نیازمندی‌های توسعه پایدار، تابع هدف دوم درصد است میزان آب تخصیص داده شده به محیط زیست را بیشینه سازد. برای دستیابی به مدل یکپارچه مدیریت منابع آب، مکان‌یابی تصفیه‌خانه‌های پساب نیز در مدل در نظر گرفته می‌شود. برای حل مدل ریاضی از داده‌های دریاچه ارومیه به عنوان بزرگترین دریاچه ایران استفاده می‌شود. طی دو دهه اخیر، عوامل طبیعی و غیرطبیعی باعث افت شدید سطح آب این دریاچه و بروز مشکلات زیست‌محیطی فراوانی در منطقه شده است. در نهایت از روش محدودیت اپسیلون برای حل مدل و به دست آوردن راه حل‌های مؤثر و همچنین مشخص نمودن نحوه تعامل توابع هدف، استفاده می‌شود. نتایج به دست آمده نشان می‌دهد که مدل با ۷۰ درصد منابع موجود، توانایی برآورده ساختن تقاضای بخش‌های مختلف را دارد. استفاده از این مدل جهت تخصیص آب می‌تواند به نحو مطلوب تقاضای مورد نیاز بخش‌های مختلف را تأمین کرده و به احیای دریاچه ارومیه و اکوسیستم رودخانه‌ها نیز کمک نماید.
