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# Hybrid modelling for urban water supply system management based on a bi-objective mathematical model and system dynamics: A case study in Guilan province

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**Abstract**

The increase in population, demand growth, limitation of water resources, and huge costs of water supply with the execution of new plans for water resources development have attracted more attention to the management of the existing resources and facilities exploitation. For this purpose, the present study uses optimization methods in urban water supply system programming and introduces state and flow variables to provide the urban water supply model and evaluate the factors affecting the urban water supply cycle in Guilan province using the system dynamics. Finally, a model is presented in line with the management status of the Guilan Water and Wastewater Company in Rasht branch. Evaluating the accuracy and validity of the model presented in the water supply system from different water resources shows that increasing the treatment capacity and water resources in the province can affect the treatment cost and reduce the shortage and wastewater. Regarding the parameters which have a positive effect on the amount of input water, it is required to consider appropriate systems to control the input water and manage such valuable resources. Eventually, forecasting the amount of shortage in the studied area during the next 100 years indicates a linear trend that the number of shortages increases in an upward manner in each period due to the increased population and decreased amount of precipitation.

**Keywords**: Water resource management, optimization, waste water management, water supply, system dynamics

## 1- Introduction

Water is considered a vital substance for human life and social development. The problem of water resource management has increased due to the rapid development of the economy. The shortage of water resources significantly limits social and economic development and threatens drinking water security. For this reason, the water shortage crisis is increasing due to climate change and human activities. In addition, the demand for water resources has gradually increased with the development of industrial and agricultural production, as well as the social economy (Tian et al., 2020; Salahi et al. 2023; Sohrabi et al. 2021). Furthermore, population growth, urbanization, climate change, water resources, and water distribution systems mismanagement, along with inappropriate programming increase water stress in many countries around the world. Although the optimization of water distribution systems and integrated water management techniques have been conducted in many cities, no integrated study can be found regarding urban water systems, programming, and management (Parween and Sinha, 2023; Touti and Chobar, 2020).

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Due to the increase in population, limited water resources, and other pressures on urban water systems, urban water management has become the main concern of urban policymakers during the past few years to develop efficient management solutions (Nezami et al., 2022; Asgari et al. 2022). Thus, solving network design problems has become an interesting topic in the field of wastewater management and water security because of increased population, resource shortage, environmental concerns, and the increasing need for sustainable solutions for future policy plans, especially in the areas where the demand for wastewater treatment has increased significantly due to high immigration, rapid industrialization, and tourism activities to make this topic more critical and dynamic (Demirel et al., 2022; Zandbiglari et al. 2023). Following the long-term effects of urban water services is a background for the future and a critical scientific foundation for the sustainable development of systems (Shiu et al., 2023; Eshghali et al. 2023) since the appropriate exploitation of water resources is considered an effective measure to realize the optimal allocation of water resources and can effectively decrease the regional water resource shortages, flood disasters, and other social problems, and play a key role in supporting the strategic development of water resources. Water supply for urban supply systems is a global effort and a big challenge for water resource managers in large urban areas. Water supply needs the integrated management of water quantity and quality and adaptation of the system to land use and climate change in the region (Demello et al., 2021; Hosseini et al. 2022).

The current water security models evaluate the existing security status of a system in terms of quantity, quality, and compliance indicators. Moreover, the existing studies attempt to consider this topic by using mathematical modeling approaches based on optimization perspectives, which require considerable computational efforts. In addition to mathematical optimization studies, an alternative approach based on the system dynamics method is proposed in this study to evaluate the complex dynamic and nonlinear structure of water and wastewater network design problems and water supply since the developed framework can provide an evaluation method for the water life cycle in the long term in a dynamic way to evaluate the temporal changes and the effects to deal with the challenges related to water security. The proposed System Dynamic (SD) simulation model has been designed for a populated tourist spot in Guilan province located in the north of Iran and the southwest of the Caspian Sea. Accordingly, the most significant innovation and unique contribution of this study are as follows:

- Establishing a three-phase water supply system such as the processes of water production, distribution, and purification
- Creating a quantitative relationship in the urban water supply system and evaluating the system performance based on the created relationship.
- Providing integrated programming to determine the optimal status of water supply protocols and select the most appropriate water supply strategy based on various programming periods for policymakers.
- Establishing an optimal programming cycle for a real-world water supply system by combining the bi-objective mathematical model and system dynamics modeling methods.

## 2- Literature review

In this section, previous historical studies are introduced as a review to identify research gaps. For example, Golpira and Tirkalaei (2019) evaluated the social and economic effects at different levels of environmental flow allocation in the Wei river basin in China using the systems dynamics model and VENSIM software. In this report, four methods were presented for social and economic growth and four methods for environmental water allocation. The results indicated that the developed system dynamics model has a good performance against the dynamic behavior of the system in the studied area. Nepal and Teren (2019) addressed the use of the system dynamics method in simulating the cultivation pattern of the irrigation and drainage network on the right side of the Isfahan waterfall. The results revealed that maintaining or not maintaining the limit of the total area under cultivation in the base year has the maximum amount of income compared to the cost. In addition, they used the system dynamics model in simulating the electricity production in Karun 1, Karun 3, and Karun 4 hydroelectric reservoirs with the help of VENSIM software. The design steps involved the definitions related to the required decision variables, equations, and formulas to measure the energy production of the reservoirs. The results indicated energy production in Khorasan 1 reservoir including Karun 4 and 3 reservoirs can increase by an average of 20% without considerable changes in the evaluation criteria. Song et al. (2019)

evaluated different scenarios for water resource allocation of the Choghakhor dam using the system dynamics method. The dynamic model of the VENSIM system was designed and implemented to utilize the water resources of the Choghakhor dam and meet downstream needs. In addition, the input amounts to the dam reservoir and evaporation from the dam reservoir were predicted using the Seasonal Autoregressive Integrated Moving Average (SARIMA) time series model for the next five years. The results showed that the Choghakhor dam can supply the water needs of 1600 hectares of water-consuming lands in the most optimal state. In this regard, the amount of supply for agricultural and environmental needs is 83 and 95, respectively. Tian et al. (2019) used the PSO algorithm, genetic algorithm, and ant colony optimization in studying wastewater network optimization and concluded that the particle swarm optimization (PSO) algorithm can reach the optimal solution at a smaller number and a higher speed. Zhu et al. (2020) created domestic and industrial water demand based on a bi-objective model to balance economic and environmental costs in an urban water supply system during three phases including the processes of water production, distribution, and treatment. Then, a system dynamics-based model is applied for testing the performance of the water supply system under short-term, medium-term, and long-term programming scenarios. Yu et al. (2021) studied the competition between the stakeholders of a multi-purpose ecological reservoir operation to satisfy economic, social, and ecological needs. For this purpose, a multi-objective game theory model was determined for water discharge for 10 days to satisfy the triple needs of water such as electricity production, socio-economic consumption, and environment. Dimello et al. (2021) proposed a new method for evaluating water security based on the ranking of pressure indicators that apply to a drainage basin such as water demand, regular and random pollutants, drought, and environmental changes (e.g., the share of forest vegetation) according to risk assessment in terms of pressure characteristics such as severity, occurrence, and detectability. Dang et al. (2022) formulated a multi-objective water resource allocation model to optimize efficiency and equity with sustainability (ecological river flow) as a constraint. For this purpose, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) algorithm was used to extract Pareto solutions in such a system for water resource allocation. The results showed that Pareto solutions can show the opposite relationship between efficiency and equity in water resource allocation. Demirel et al. (2022) proposed an alternative approach based on the system dynamics method to select a place for wastewater treatment facilities and network design problems. The proposed SD simulation model was designed for an area in Antalya, Turkey. This model can determine the location and time of constructing a new wastewater treatment plant and creating a public wastewater network structure for five areas downtown based on the cost issues during 2015-2040. Guilani et al. (2022) provided a sustainable selection method for the location of water treatment facilities using the best-worst method. Moreover, this model selects appropriate technologies in the treatment plant, manages water leakage in the entire transmission network using renovation, and selects different transmission technologies. Based on the obtained results, the interaction of water and energy has received special attention in this network. Shiu et al. (2023) proposed a method for dynamic life cycle assessment that considers time changes and the effects of dealing with the challenges of water treatment facilities based on the life cycle assessment principles of system dynamics models. Then, this model was applied to a water treatment plant in Kinmen Islands, Taiwan. The SD model can simulate long-term water demand in terms of growth in the domestic, agricultural, livestock, and manufacturing sectors. Zhu (2023) created an integrated framework for climate change and analyzed the effects of climate change on social-environmental aspects in many areas such as wastewater treatment, energy transmission, waste treatment, land management, and ocean management.

Based on the above-mentioned literature review, presenting an appropriate optimization model for the proper management of urban water supply resources according to the status of an area has been neglected. Thus, introducing a water supply system that includes water production, distribution, and treatment processes is recommended for establishing a quantitative relationship in the urban water supply system and describing the system performance based on this relationship. Regarding the most significant advantage of this study, it has been conducted to strengthen water resources management by considering a linear multi-objective mathematical modeling and the factors affecting water supply in a high-rainfall province like Guilan, Iran. Based on the presented modeling, total efficiency and economic benefits are obtained in domestic, industrial, and agricultural sectors. As a result, the most significant research gaps are as follows:

- A framework that tracks the optimal response to water supply protocols by changing the programming period according to an integrated method and determines the most appropriate water supply strategy and programming period for policymakers
- Establishing a three-phase water supply system that involves the processes of water production, distribution, and treatment.
- Defining a quantitative relationship in the urban water supply system to measure the performance of the system according to this relationship.
- Defining an optimal programming period for a real-world water supply system by combining the bi-objective programming and system dynamics methods.

## 3- Method

This study focuses on using mathematical modeling and system dynamics. In this regard, a bi-objective mathematical model is presented to optimize water resources. This model can focus on minimizing the cost of the whole system and minimizing the wastewater which is considered a main challenge in water resource management simultaneously. Numerous efforts have been made to manage wastewater but no satisfactory results have been obtained in the field of management. This study which focuses on Guilan province, a rainy province in northern Iran, presents a mathematical model which minimizes costs and wastewater resources and also returns water resources to the urban and rural water supply cycle. Guilan province is considered one of the few regions with abundant water in Iran. This province can be considered a model for more productivity in the field of water resources for other provinces in Iran. Figure 1 illustrates the conceptual model of the study.

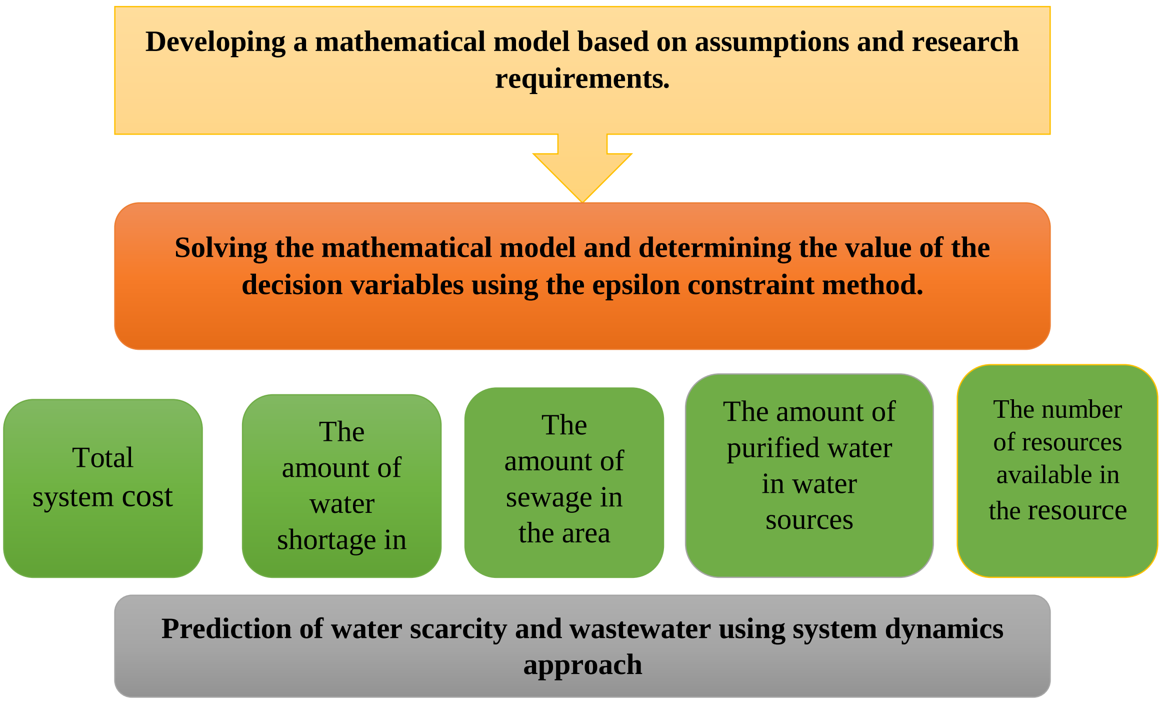


**Fig. 1.** The general structure of the study

According to figure 1, first we present a mathematical modeling based on existing assumptions to perform optimization operations. According to the nature of modeling the problem, which is among the multi-objective models, the proposed model is solved by using the epsilon constraint method in order to obtain the optimal value of the measured variables such as total system cost, the amount of water shortage in the area, the amount of sewage in the area, the amount of purified in water source and the number of available resource. Then, the measured values are provided as input to the dynamic simulation model to predict the water security situation in the long term. The reason for the simultaneous use of optimization and simulation in this study is that no matter how powerful simulation is, it is not able to determine the optimal situation as an optimization tool (Jahangiri et al., 2023; Abolghasemian and Darabi. 2018; Abolghasemian et al. 2021; Chobar et al. 2022). Therefore, to increase the effectiveness of prediction by simulation, it is necessary to first determine the optimal values by a mathematical model.

### 3-1- Urban water supply system

Water resources programming and management in the urban water supply system can be regarded as a multi-objective optimization problem due to various objectives, constraints, and highly diverse variables. For this purpose, figure 2 shows the general structure of the urban water supply system in the Rasht.

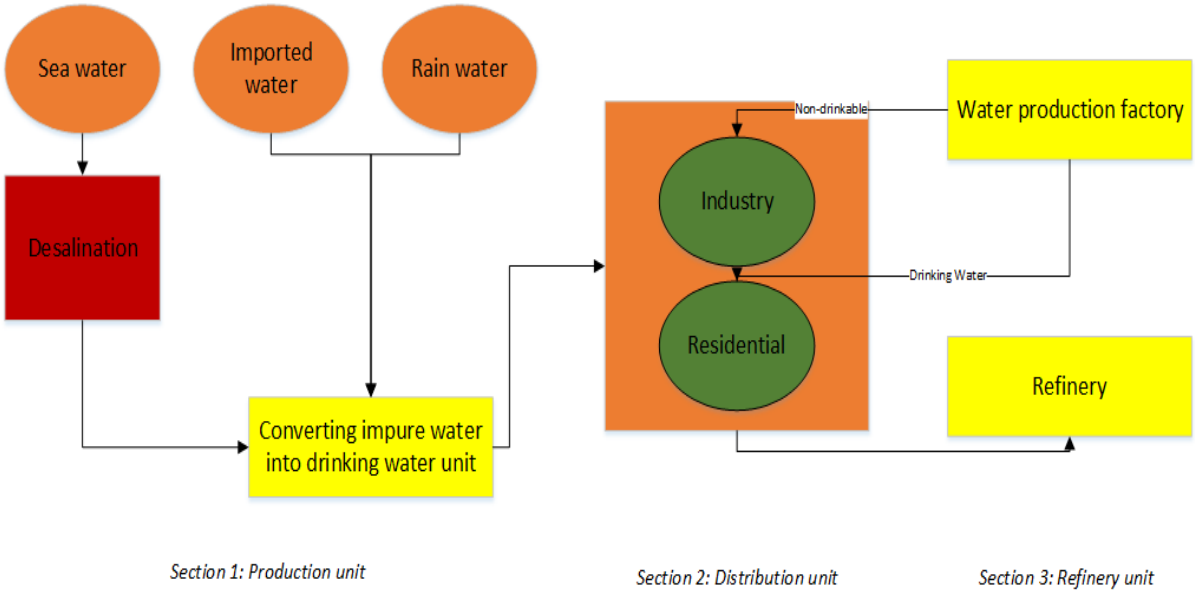


**Fig. 2.** The general model of the urban water supply system in the Rasht

As shown in figure 2, three main sectors play a role in the intended urban water supply system in the Rasht. The first sector known as the production part includes different water resources such as seawater, rainwater, imported water from neighboring countries, underground water reservoirs, and other types. In addition to these water resources, the desalination unit operates in the production sector along with different water resources to turn the water of the Caspian Sea into drinking water. Further, the treatment unit works there to convert the water from reservoirs, rain, imported water, and wastewater into drinking water. The second sector is the distribution network or the water consumption sector which is consumed by two major groups of subscribers of water resources such as industrial and residential subscribers. Finally, the water used in the distribution sector is collected and transferred to the recovery (reproduction) and treatment sectors so that a part of this water is returned to the consumption cycle (industrial and residential consumption) if possible. In this sector, there are water treatment plants and drinking water production plants. Part of the water entering the water treatment plants is poured into the sea without any special treatment. The other part is transferred to the water production plants after treatment to provide the water required by the industrial and residential sectors. An inclusive urban water supply system for all types of residential and industrial consumptions has a relatively complicated mechanism that needs a comprehensive and optimal management plan to achieve its critical goals. Since there is an optimization problem in the urban water system programming and management, a modeling optimization problem should be established in the standard structure to solve this problem. The next section presents the mathematical model related to the optimal management and programming of the urban water system.

## 3-2- Mathematical model

This section explains the research assumptions, parameters, variables, objective functions, and their constraints to introduce the mathematical modeling.

### 3-2-1- Assumptions

The most significant assumptions of this study are as follows:

1- The parameters are determined definitively
2- The model is multi-periodical
3- Every area includes the city and its subordinate villages.
4- Water resources are considered constructed.
5- The construction of treatment systems is considered a variable.
6- In addition to the construction cost, the treatment systems have a management fee per kilometer of water resources.
7- Water supply resources have fees.
8- Energy consumption and its cost are regarded for water resources and treatment systems.
9- Wastewater and shortage are considered in the present model.

### 3-2-2- Notations

Table 1 presents all the indices, parameters, and variables considered in the mathematical model.

**Table 1.** Mathematical model notation

| **Indices** | |
|---|---|
| **Description** | **Notation** |
| Number of areas | I |
| Number of treatment systems | J |
| Number of water supply resources | K |
| Time | T |
| **Parameters** | |
| Description | Symbol |
| The amount of water consumption in area $i$ in time $t$ | $\mathrm{DEM}_{it}$ |
| Cost of water treatment system construction j in area $i$ | $\mathrm{FCJ}_{ij}$ |
| Cost of water supply resource $k$ in area $i$ | $\mathrm{FCK}_{ik}$ |
| Cost of settling the water treatment system $j$ | $\mathrm{VCJ}_{j}$ |
| The number of water resources entering the area $i$ in time $t$ | $\mathrm{EW}_{it}$ |
| The capacity of water treatment system $j$ in area $i$ | $\mathrm{CAPJ}_{ij}$ |
| Water resource capacity $k$ in area $i$ | $\mathrm{CAPK}_{ik}$ |

**Table 1.** Continued

| Description | Notation |
|---|---|
| The amount of energy consumption for water treatment in the water treatment system $j$ | $\mathrm{ENC_j}$ |
| Cost of energy consumption per unit for water treatment in the water treatment system $j$ | $\mathrm{UENC_j}$ |
| The amount of energy consumption in the water supply resource $k$ | $\mathrm{ENCK_k}$ |
| Cost of energy consumption per unit for the water supply resource $k$ | $\mathrm{UENCK_k}$ |
| Cost of water transmission from water supply resource k to water treatment system $j$ in area $i$ | $\mathrm{TC_{kji}}$ |
| **Variables** | |
| It is a binary variable. Its value is 1 water treatment system $j$ is constructed in area $i$; otherwise, it is zero. | $\mathrm{X_{ij}}$ |
| It is a continuous variable. The amount of water transmission from water supply resource $k$ to water treatment system $j$ in area $i$ | $\mathrm{U_{kji}}$ |
| It is a continuous variable. The number of water resources available in water supply resource $k$ in area $i$ | $\mathrm{Y_{ik}}$ |
| It is a continuous variable. The amount of treated water in the water treatment system $j$ in time $t$ | $\mathrm{Z_{jt}}$ |
| It is a continuous variable. The amount of wastewater in area $i$ in time $t$ | $\mathrm{WW_{it}}$ |
| It is a continuous variable. The amount of water shortage in area $i$ in time $t$ | $\mathrm{LW_{it}}$ |

### 3-2-3- Objective functions

The first objective function of the raised problem in equation 1 is to minimize the cost of water supply including the energy cost, amount of energy consumption, and cost of constructing a treatment system, cost of managing water resources, the cost of managing the treatment system, and the cost of transmitting water resources. In addition, the second objective of the problem in equation 2 is to minimize wastewater and water shortage for the entire system where wastewater is measured based on the amount of demand and consumption, and the shortage is determined based on the input.

$$min\, z1 = \sum_i^I \sum_j^J FCJ_{ij} \,.\, X_{ij} + \sum_i^I \sum_k^K FCK_{ik} \,.\, Y_{ik} + \sum_j^J \sum_t^T VCJ_j \,.\, Z_{jt} + \sum_j^J \sum_t^T ENC_j \,.\, UENC_j . Z_{jt} + \sum_i^I \sum_k^K ENCK_k \,.\, UENCK_k . Y_{ik} + \sum_i^I \sum_j^J \sum_k^K TC_{kji} \,.\, U_{kji} \tag{1}$$

$$min\, z2 = \sum_i^I \sum_t^T WW_{it} + LW_{it} \tag{2}$$

### 3-2-4- Constraints

$$\sum_{i=1}^I X_{ij} = 1 \tag{3}$$

$$U_{kji} \leq X_{ij} \tag{4}$$

$$\sum_{i=1}^{I} U_{kji} = 1 \tag{5}$$

$$Y_{ik} \le CAPK_{ik} \tag{6}$$

$$Z_{jt} \le CAPJ_{ij} \tag{7}$$

$$Z_{jt} \le M.X_{ij} \tag{8}$$

$$WW_{it} = EW_{it} - DEM_{it} \tag{9}$$

$$LW_{it} = DEM_{it} - \sum_{k=1}^{K} Y_{ik} \tag{10}$$

$$\sum_{j=1}^{J} Z_{jt} \le \sum_{k=1}^{K} Y_{ik} \tag{11}$$

$$X_{ij} \in \{0,1\} \tag{12}$$

$$U_{kji} \in \{0,1\} \tag{13}$$

$$Y_{ik} \ge 0 \tag{14}$$

$$Z_{jt} \ge 0 \tag{15}$$

$$\mathrm{WW_{it}} \ge 0 \tag{16}$$

$$\mathrm{LW_{it}} \ge 0 \tag{17}$$

Based on equation 3, every treatment center can be constructed merely in one area. Equation 4 shows that the transmission of resources from treatment centers is according to the construction of the treatment center. According to equation 5, water transmission from water resources to treatment centers is only significant in one area. In addition, equation 6 reveals the capacity limitation of water resources. Equation 7 shows the limitation of the treatment center's capacity. Equation 8 indicates that if there is a treatment plant, it can include water resources. Furthermore, equation 9 addresses the calculation of wastewater in the system and equation 10 considers the calculation of shortage in the system. Equation 11 indicates that water resources in treatment centers cannot be more than the water resources in water resource systems. Equation 12-17 presents the type of variables in the problem, which is a binary integer and continuous (positive).

## 4- Solution method: Epsilon constraint

The solution method in this study includes the exact method which involves the epsilon constraint algorithm. This section explains this algorithm and the problem is solved using the epsilon constraint method. In this regard, the first objective is considered the main objective, and the second objective is constrained to the upper limit of epsilon and applied to the constraints of the problem. Based on the epsilon method, the constraint of the multi-objective model becomes a single-objective model 18. In this method, one objective function is selected and other objective functions are converted into constraints by considering the amounts determined by the decision-maker or modeler. In addition, the problem becomes a single objective linear programming model and is solved by the linear programming method. The epsilon constraint method is one of the exact methods for obtaining the optimal Pareto solution which was presented for the first time by Aljadan. Compared to other multi-objective optimization methods, the main advantage of this method is its application in non-convex solution spaces since the methods such as the weighted combination of objectives lose their efficiency in non-convex spaces. The computational time of an algorithm is one of the significant features of any algorithm for evaluation. The use of the meta-heuristic algorithm leads to a sharp reduction in the computational time since one of the major weaknesses of the algorithms based on exact search, including the epsilon method, is the high constraint of their computational time. A framework presented by Pirouz and Khoram (2016) is one of the modified versions of the epsilon constraint method. Abolghasmian et al. (2020) and Abolghasmian et al. (2022) have recently recommended the use of this version due to its two major advantages. The less search space for finding non-dominant points is one of the advantages of this method. Another advantage of this method is its less execution time than the original method. Based on this method, first, the single-objective optimization problem is solved for each objective and then the length of the step is determined. Then, a set of appropriate points is generated. Finally, the single-objective optimization is solved and the Pareto frontier is estimated.

$$min\, f_1(x) \tag{18}$$

$$f_i(x) \leq e_i$$

$$x \in X$$

The first objective in equation 18 is considered the main objective and the second to $n-th$ objectives are limited to the maximum value $e_i$. In the epsilon constraint method, different solutions are obtained which may not be effective by changing the values of $e_i$. The problem can be solved by modifying the above-mentioned model which is known as the modified epsilon constraint method. In this method, the previous equation is rewritten as equation 19.

$$\min f_1(x) - \sum_{i=1}^{2} \phi_i s_i \tag{19}$$
$$fi(x) + s_i = e_i$$
$$x \in X$$
$$s_i \geq 0$$

Where $s_i$ represents the auxiliary non-negative variables and $\phi_i$ shows a parameter for the normalization of objectives.

## 5- Development of system dynamics model

The simulation using the system dynamics approach in this study involves the following steps:

**Step 1: Development of the simulation model**

All of the key effective variables are specified in the cause-effect loop diagram and then converted into a flow diagram by VENSIM software to analyze the effective factors. Then, an integrated SD model is simulated based on the relationships between the variables.

**Step 2: Definition of cause and effect relationship**

The cause and effect diagram is always considered to indicate the dynamic interactions between the system elements where the positive and negative effects of the elements on each other are shown with (+) and (-) signs, respectively.

**Step 3: Drawing the flow diagram**

The flow diagram has a quantitative nature and depends on the definition of some variables for problem-solving.

The variables used in the system dynamics in this study involve the variables of the mathematical model whose values can be achieved by solving the mathematical model and are entered as parameters in VENSIM software. Table 2 presents the cause and effect variables required in the system dynamics model.

**Table 2.** System dynamics model variables

| Dynamics model parameters | |
|---|---|
| *Description* | *Symbol* |
| The number of water resources available in water supply source $k$ in area $i$ | $Y_{ik}$ |
| The amount of treated water in the water treatment system $j$ in the time $t$ | $Z_{jt}$ |
| The amount of wastewater in area $i$ in time $t$ | $WW_{it}$ |
| The amount of water shortage in area $i$ in time $t$ | $LW_{it}$ |
| **Dynamic model variables** | |
| The total cost of the water resources system | F1 |
| The total amount of shortage and wastewater in the system | F2 |

## 5-1-Results

### 5-1-1- Results of numerical solution for the model

This section presents the results of solving the model and its validation by solving the model in different dimensions (small, medium, and large). For this purpose, Table 3 presents the dimensions of the problem.

**Table 3.** Dimensions of the problem and predetermined parameters

| Problem dimensions | Problem | Area i | Treatment system j | Water supply resources | Time t |
|---|---|---|---|---|---|
| Small | 1 | 15 | 12 | 20 | 10 |
| | 2 | 16 | 12 | 20 | 10 |
| | 3 | 17 | 12 | 20 | 10 |
| | 4 | 18 | 12 | 20 | 10 |
| | 5 | 19 | 12 | 20 | 10 |
| | 6 | 20 | 12 | 20 | 10 |
| | 7 | 21 | 12 | 20 | 10 |
| Medium | 8 | 22 | 14 | 25 | 12 |
| | 9 | 23 | 14 | 25 | 12 |
| | 10 | 24 | 14 | 25 | 12 |
| | 11 | 25 | 14 | 25 | 12 |
| | 12 | 26 | 14 | 25 | 12 |
| | 13 | 27 | 14 | 25 | 12 |
| Large | 14 | 28 | 16 | 30 | 15 |
| | 15 | 29 | 16 | 30 | 15 |
| | 16 | 30 | 16 | 30 | 15 |
| | 17 | 31 | 16 | 30 | 15 |
| | 18 | 32 | 16 | 30 | 15 |
| | 19 | 33 | 16 | 30 | 15 |
| | 20 | 34 | 16 | 30 | 15 |

As observed, the dimensions of the problem are changed in each example above. An increase in dimensions affects the value of objective functions and calculation time on the condition that the modeling is conducted correctly. For this purpose, Table 4 shows the results of the objective function values and the calculated time.

**Table 4.** Results of the mathematical model solution

| Problem dimensions | Problem | Supply cost $(Z_1)$ | Wastewater and shortage $(Z_2)$ | Calculation time |
|---|---|---|---|---|
| Small | 1 | 142744 | 3309361 | 18 |
| | 2 | 144184 | 3324486 | 36 |
| | 3 | 145869 | 3337927 | 48 |
| | 4 | 147512 | 3352119 | 64 |
| | 5 | 148587 | 3366940 | 76 |
| | 6 | 149944 | 3383915 | 89 |
| | 7 | 151091 | 3396378 | 107 |
| Medium | 8 | 153059 | 3414299 | 120 |
| | 9 | 154107 | 3424478 | 139 |
| | 10 | 155121 | 3442370 | 149 |
| | 11 | 156516 | 3459297 | 167 |
| | 12 | 158157 | 3471627 | 177 |
| | 13 | 160079 | 3486565 | 189 |
| Large | 14 | 161459 | 3497552 | 204 |
| | 15 | 162997 | 3514357 | 223 |
| | 16 | 164203 | 3524721 | 236 |
| | 17 | 165461 | 3540257 | 251 |
| | 18 | 166838 | 3558616 | 268 |
| | 19 | 168390 | 3578511 | 281 |
| | 20 | 170349 | 3590094 | 295 |

Table 4 presents the results of 20 examples including the cost of water supply and the amount of wastewater. To check the accuracy of the model, the results obtained from the diagrams of these amounts are presented. For example, as shown in figure 2, the cost of the entire system increases with the increased dimensions of the problem, indicating the model's accuracy and validity. Figure 3 shows the amounts of wastewater and shortage are presented. As a result, an increase in dimensions leads to the natural increase of wastewater and shortage in the urban water supply system. Finally, the calculation time increases by increasing problem dimensions which is another proof of the model validity (figure 4).

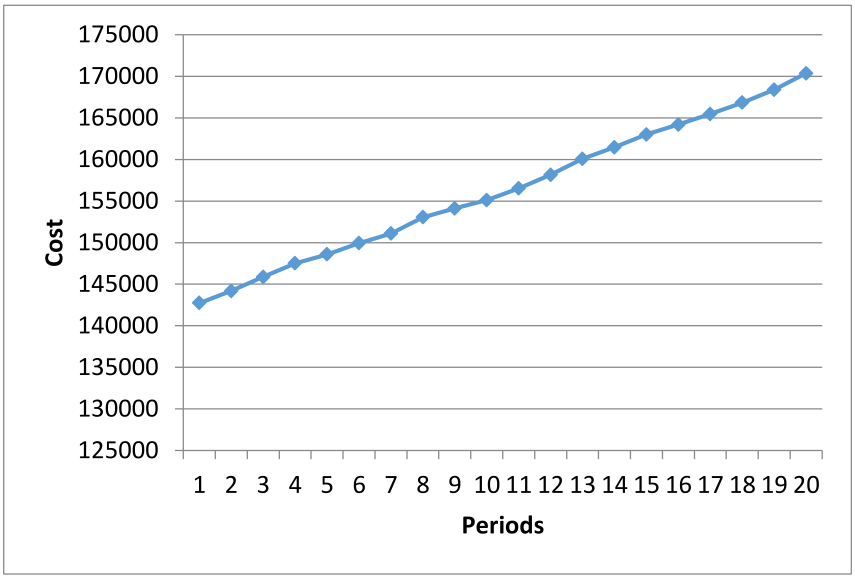


**Fig. 2.** The amounts resulting from the cost in different dimensions

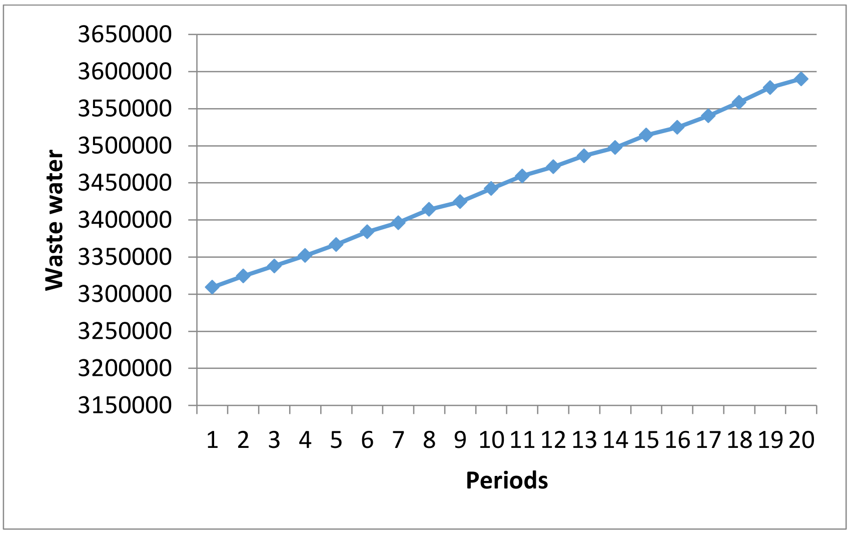


**Fig. 3.** The amounts of wastewater in different dimensions

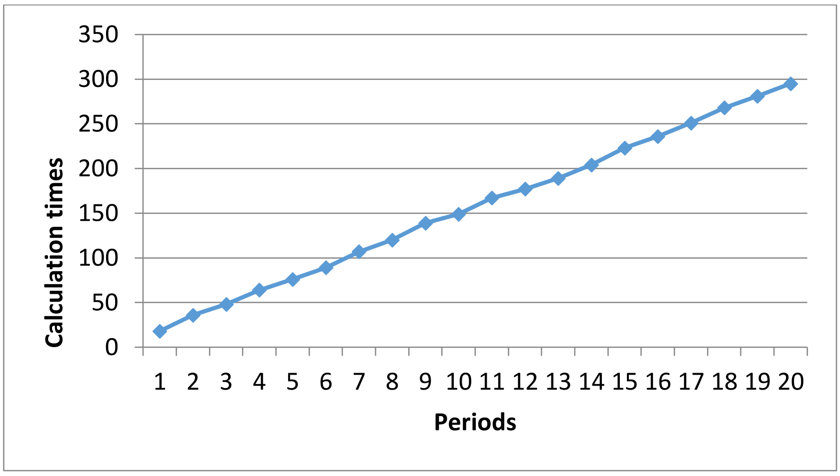


**Fig. 4.** The amounts obtained from the calculation time in different dimensions

## 5-2- Case study

Urban water and wastewater companies were established with the approval of the Islamic Council in Iran on January 1, 1991. These companies aim to create and operate urban water facilities and collect, transfer, and treat wastewater within the legal limits of the cities in each province. The relevant tasks were already fulfilled by the regional water companies in part of the province and by municipalities in smaller cities. After the establishment of the urban water and Wastewater Company in Iran, these functions were transferred to the new company. The same tasks in the rural sector were assigned to the newly established rural water and wastewater companies on December 13, 1995. Before that, such services had been conducted in Jihad, construction, and health centers in the villages. By merging the urban and rural water and wastewater companies in March 2019, all the service functions in the cities and villages regarding the supply and distribution of sanitary and drinking water, as well as the collection, transmission, and treatment of wastewater have been entrusted to the integrated water and wastewater companies. In general, water and wastewater companies have a non-governmental nature, as well as financial and legal independency, and are governed based on commercial law.

### 5-2-1- Practical results

Since the epsilon limit method has been introduced for solving the mathematical problem, the value of the objective functions is calculated for different epsilon values and presented in Table 5. This model is solved by using GAMS software version 24.1.2 and the CPLEX tool in personal computer with Intel core i3 2.20 GHZ and 4 GB RAM. Table 5 presents different values for epsilon and the objective functions are solved with such values. The values of the objective function show no significant change by increasing epsilon to a certain level. However, an increase in the value of epsilon shows a considerable slope in the values of the objective functions from some point, e.g. the first objective function. Such changes have indicated different slopes in the objective functions. Based on the obtained results, the feasible region and the improving vector of the objective functions were created for testing different values of epsilon. Accordingly, the significant changes of epsilon at the 50-900 interval were determined as the improving vector. Determining this interval indicates that the solution to the problem is outside the feasible region if the epsilon is considered less than 50 and more than 900. Thus, the epsilon value for searching the local optimum for the first objective function is on point 500 since the optimal solution occurs for the first objective function. The optimal situation for the second objective function occurs at epsilon 150 and the optimal solution range is at 150-500 epsilon. Table 5 provides the results of solving the model with a step length equal to 50 for epsilon.

**Table 5.** The results of solving the model using the epsilon constraint method

| Epsilon | Cost (thousand Rial) | The amount of wastewater and shortage (cubic liters) | Final execution time (minutes) |
|---|---|---|---|
| 50 | 512 | 0.71 | 57 |
| 100 | 563 | 0.74 | 55 |
| 150 | 382 | 0.70 | 62 |
| 200 | 450 | 0.75 | 57 |
| 250 | 430 | 0.78 | 68 |
| 300 | 413 | 0.75 | 75 |
| 350 | 398 | 0.75 | 58 |
| 400 | 365 | 0.75 | 94 |
| 450 | 348 | 0.74 | 86 |
| 500 | 307 | 0.75 | 58 |
| 550 | 480 | 0.71 | 62 |
| 600 | 512 | 0.76 | 48 |
| 650 | 563 | 0.76 | 72 |
| 700 | 450 | 0.82 | 98 |

**Table 5.** Continued

| Epsilon | Cost (thousand Rial) | The amount of wastewater and shortage (cubic liters) | Final execution time (minutes) |
|---|---|---|---|
| 750 | 460 | 0.73 | 78 |
| 800 | 413 | 0.83 | 81 |
| 850 | 510 | 0.75 | 82 |
| 900 | 398 | 0.86 | 70 |
| Optimum | 307 | 0.70 | 48 |

## 5-2-2- Sensitivity analysis

This section provides the sensitivity analysis of the significant parameters of the problem and compares the effectiveness of each parameter on the values of the objective functions for the cost of water supply and the amount of wastewater and shortage. Tables 6 and 7 present the result of this sensitivity analysis.

**Table 6.** Comparison of parameters affecting the urban water supply cost

| Water supply cost | Demand | Construct ion cost | Resource cost | Treatment cost | Input water | Capacity | Energy consump tion cost | Energy consump tion value | Transmis sion cost |
|---|---|---|---|---|---|---|---|---|---|
| 10% | 0.008638 | 0.009408 | 0.011804 | 0.008477 | -0.01212 | -0.01212 | 0.011153 | 0.011258 | 0.008862 |
| 20% | 0.019802 | 0.018301 | 0.023576 | 0.019319 | -0.02285 | -0.024 | 0.020425 | 0.021503 | 0.018325 |
| 30% | 0.027447 | 0.031133 | 0.03255 | 0.032405 | -0.03531 | -0.03794 | 0.032352 | 0.0283 | 0.02519 |
| 40% | 0.035404 | 0.041377 | 0.038717 | 0.042669 | -0.0501 | -0.05381 | 0.040323 | 0.037539 | 0.032173 |
| 50% | 0.044155 | 0.050631 | 0.046318 | 0.048831 | -0.06137 | -0.06633 | 0.051125 | 0.04726 | 0.039032 |

As shown in table 6, the parameters of Input water and capacity have the most negative effect on changing water supply cost percentage. Thus, it worsens the solution in water management. While other parameters have a positive effect and improve the solution. The effectiveness of the capacity and input water is 6.6% and 6.1%, respectively. In other words, increasing the capacity can reduce the cost by 7% while the amount of input water is 6.1%, leading to a reduction and improvement in the solution. The capacity and the amount of input water are the only decreasing parameters and the others have an increasing effect.

**Table 7.** Comparison of the parameters affecting the wastewater and shortage

| Water supply cost | Demand | Construc tion cost | Resource cost | Treatme nt cost | Input water | Capacity | Energy consumpti on cost | Energy consump tion value | Transmissi on cost |
|---|---|---|---|---|---|---|---|---|---|
| 10% | 0.004954 | 0.003617 | 0.003372 | 0.00512 | -0.00359 | -0.00323 | 0.003726 | 0.003234 | 0.005885 |
| 20% | 0.009562 | 0.006929 | 0.008745 | 0.010833 | -0.00904 | -0.00762 | 0.008989 | 0.007001 | 0.008943 |
| 30% | 0.014761 | 0.010269 | 0.013466 | 0.015987 | -0.01303 | -0.01349 | 0.013736 | 0.01253 | 0.011872 |
| 40% | 0.019297 | 0.015422 | 0.017261 | 0.020491 | -0.01802 | -0.0184 | 0.01676 | 0.016575 | 0.015553 |
| 50% | 0.024502 | 0.018362 | 0.02031 | 0.02548 | -0.02342 | -0.02295 | 0.021526 | 0.019683 | 0.019704 |

As shown in table 7, the amount of input water and capacity reduces the amount of shortage and wastewater while the treatment cost and demand have the maximum effect on the shortage with 2.5 and 2.4%, respectively. It should be noted that the amount of input water reduces the shortage by 2.5% and the capacity reduces the shortage by 2.2%.

### 5-3- System dynamics

This section evaluates the performance of the urban water supply system dynamics model in the long term in the VENSIM software version 7.3.5. Predetermined parameters are required for running the model whose values are determined using the mathematical model. Thus, table 8 indicates the value of the mathematical model variables used in the system dynamics model.

**Table 8.** Determined parameters of the system dynamics model based on the mathematical model

| Parameter | Water supply resource | | |
|---|---|---|---|
| | 20 | 20 | 30 |
| $Y_{ik}$ | 1555 | 1742 | 1853 |
| $Z_{jt}$ | Treatment system | | |
| | 12 | 14 | 16 |
| | 1222 | 1456 | 1525 |
| $WW_{it}$ | Time | | |
| | 10 | 12 | 15 |
| | 333 | 286 | 328 |
| $LW_{it}$ | Time | | |
| | 10 | 12 | 15 |
| | 1200 | 1500 | 1600 |

A cause and effect diagram is created according to figure 5 by considering the values obtained in table 8 and based on solving the mathematical model in the system dynamics model.

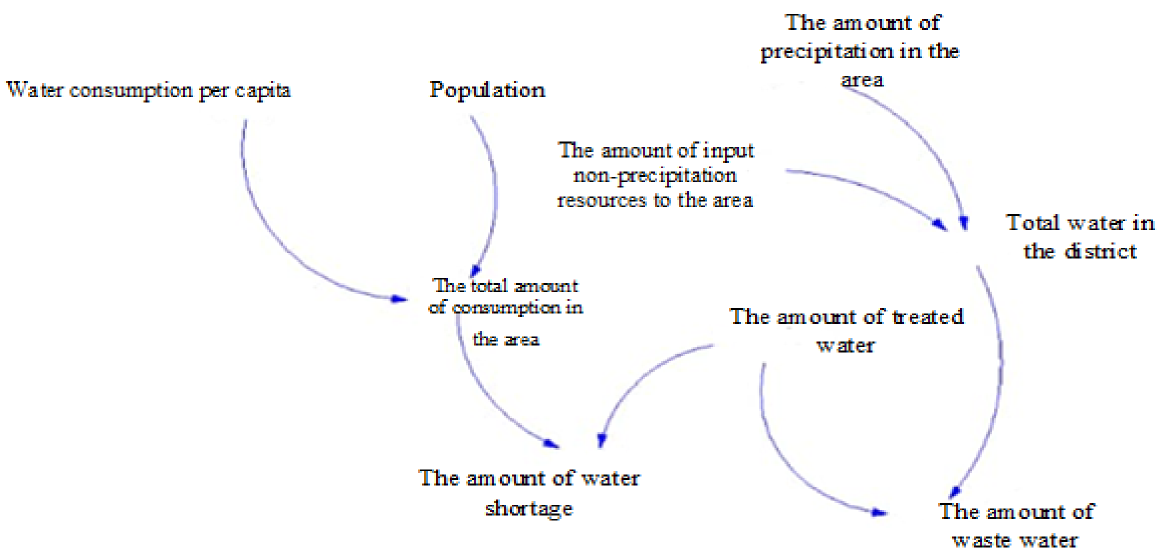


**Fig. 5.** Cause and effect diagram of the present study

Figure 6 shows that the consumption rate per capita is multiplied by the population in the area and then the consumption value is obtained. The amount of input water along with the amount of precipitation constitutes the total amount of water in the area. Finally, the amount of shortage is determined based on the amount of treated water and the amount of waste. To clarify the results, the flow storage diagram is presented based on figure 6.

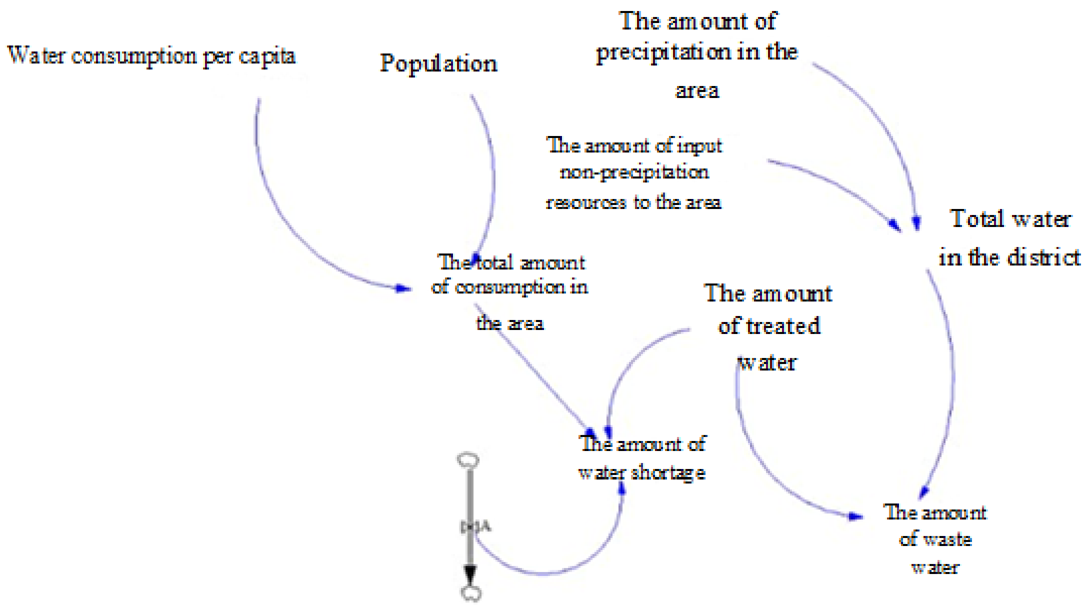


**Fig.6.** Current flow storage diagram of the present study

As displayed in figure 7, the cause-effect relationships are presented in the form of a quantitative diagram which is used for forecasting the level of shortage. Figure 7 shows the final results of the shortage for the next 100 years in Guilan province.

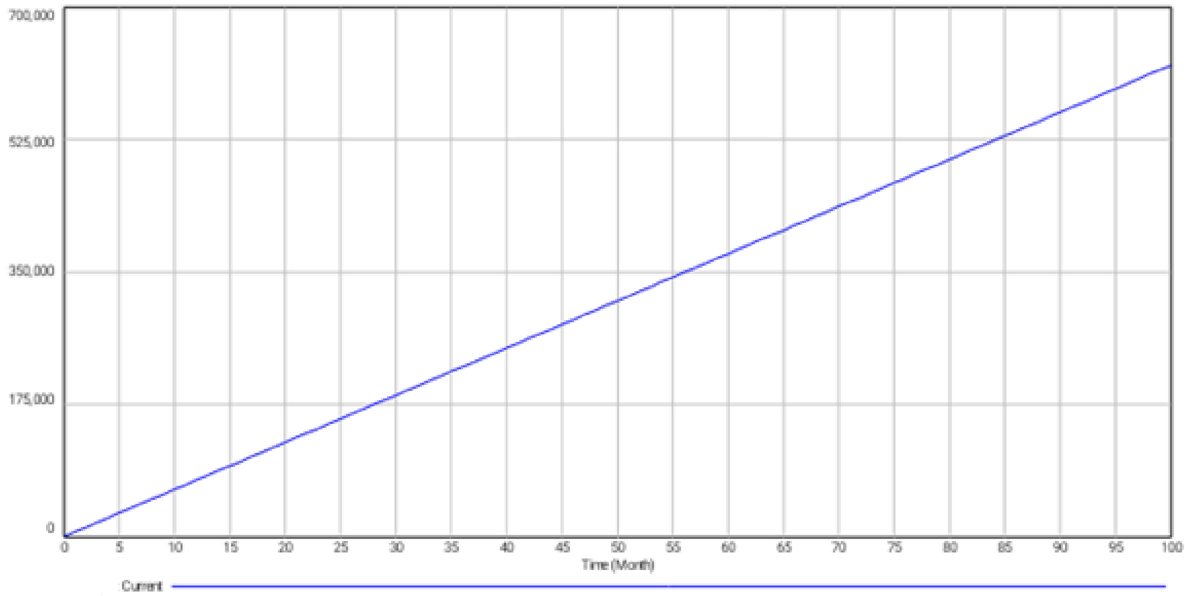


**Fig. 7.** Forecasting the amount of shortage

Figure 7 shows that the amount of shortage in the studied area will follow a linear trend during the next 100 years. In each period, the number of shortages increases based on the increase in the population and the decrease in the amount of precipitation in the area. However, this increase fails to follow the exponential distribution and the amount of shortage can be expected in the studied area according to the increase in the population and the amount of precipitation.

## 6- Conclusion

The present study aimed to optimize and plan the urban water supply system using bi-objective optimization and system dynamics method and the case study was the Water and Wastewater Organization in Guilan province. For this purpose, library studies were conducted and research gaps were extracted based on the conducted studies. The proposed method in this study was to provide a hybrid model of mathematical modeling, meta-heuristic algorithms, and system dynamics approach. The decision variables including the number of water resources in the reservoir, the amount of treated water in the water treatment system, the amount of wastewater in the area, and the amount of water shortage in the area along with the amount s of the objective functions were obtained using the mathematical model and meta-heuristic algorithm. Then, the amounts were entered into the system dynamics approach as input amounts and the shortage in future periods was predicted, indicating a linear trend up to more than 520 thousand units. In addition, the sensitivity analysis is the reverse effect of the capacity and the amount of input water and the direct effect of transmission cost, energy consumption, energy consumption cost, treatment cost, resource cost, construction cost, and demand. Among the parameters with a direct effect on energy consumption cost, the construction cost and treatment cost have the maximum effect on the supply cost while treatment cost and demand have the maximum effect on the shortage and wastewater in the system. In many past studies, only one aspect of mathematical modeling or simulation has been addressed. Such as the study of Guilani et al. (2022) and Zhu et al. (2023), who only investigated climate change and water resource management through mathematical modeling. Also, in the studies of Demirel et al. (2022) and Shiu et al. (2023), climate cycle changes have been investigated using system dynamics. But in this research, to increase the accurate prediction of water resources management in order to increase the security of this valuable resource in human life, both mathematical modeling and simulation have been used simultaneously to increase the accuracy of prediction in the long term. Based on the findings, the most significant suggestions for managers as a roadmap for the future are as follows: (I) Increasing the treatment capacity and water resources in Guilan province can affect the treatment cost and reduce the shortage and wastewater. Thus, an increase in investment to enhance the treatment capacity and water resources is one of the approaches regarding the prevention of shortage and control of wastewater considering the abundant water resources in Guilan province. Although the investment can be expensive in the short term, it prevents increasing costs and emerging water shortages in the long term. (II) Regarding the parameters which have a positive effect such as the amount of input non-precipitation water entering Guilan province from other provinces, appropriate control should be performed through different methods to increase the water resources in the province. In this regard, maintaining the input water can have more advantages than rainwater. If the right systems are used and managed well to control the input water, an increase can be expected in water resources and result in a reduction in costs and wastewater in Guilan province. (III) Energy consumption control is one of the factors which strongly affects the cost. The use of devices with less energy consumption can be useful in the treatment and maintenance of water sources. (IV)The construction cost is regarded as an essential factor of cost. Using the existing resources appropriately and constructing new facilities can have a significant effect in terms of cost. (V) Demand is considered a significant factor in creating a shortage in the present model. The effect of demand on the cost is not as much as other parameters while it can affect the shortage and wastewater. In this regard, acculturalization regarding consumption and optimized consumption by using construction tools and valves can improve demand. Furthermore, presenting and analyzing the present model in the low-water provinces of Iran such as Yazd and Kerman, using more decision variables and parameters in the mathematical model, applying multiple meta-heuristic algorithms and comparing their performance, considering the uncertainty in some parameters such as the demand for wastewater, and using the system dynamics tool to predict the situation in the long term are considered as the most critical suggestions for the development of the present study in future studies. Also, the network fatigue factor should be applied in the modeling and a resilient modeling should be presented to deal with this feature.

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