Journal of Applied Research in Water and Wastewater 14 (2020) 102-110

Journal of
Applied Research in Water and Wastewater
Journal homepage: www.arww.razi.ac.ir

Original paper

An integrated mixed-integer linear programming (MILP) model for urban water supply chain optimization

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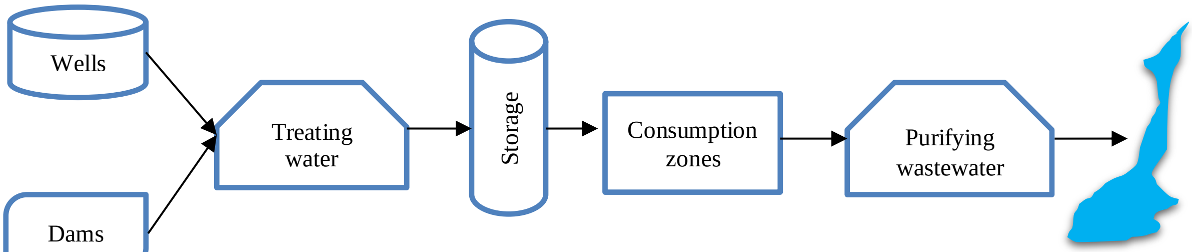
GRAPHICAL ABSTRACT



Structure of the water supply and distribution network

ARTICLE INFO

Article history:
Received 1 July 2020
Reviewed 18 September 2020
Received in revised form 19 October 2020
Accepted 20 October 2020

Keywords:
Urban water
Water resource management
Water network optimization
Integrated urban water management
Liner programing

ABSTRACT

Integrated water resources management is a systematic process for sustainable development, allocation and monitoring of water resources that is used for social, economic and environmental purposes. In this study, a multi-period mixed-integer linear programming (MILP) model for urban water supply network management is proposed. The proposed model considers all echelons of water supply chain from supply centers to wastewater treatment centers. Also, the model optimizes the decisions such as selecting the suitable water supply centers and capacity level optimization. To verify and validate the proposed model a real case study is conducted in Urmia. The model is solved by the General Algebraic Modeling System (GAMS) software and its results have been analyzed. According to the results, the optimal water supply centers, optimal water flow, optimal water inventory, and optimal capacity levels of wastewater treatment centers in different periods are determined. Also, in case of transferring the remaining additional treated water to Urmia lake, its level is increased by about 0.007 cm.

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1. Introduction

Ever-increasing advances in knowledge about the use of natural energy sources and the expansion of industries have led to the untapped use of water resources. If this trend continues to result in the misuse of water and resources, the survival of all the organisms on the planet, especially humans, will be at serious risk. According to the United Nations reports, nearly 700 million people in 43 countries suffer from water scarcity. The figure is expected to reach over 1.8 billion by 2050 in different countries facing severe water shortages (Lari and Pishvaee. 2015).

To achieve sustainable development, appropriate and optimal decisions should be made for the use of limited water resources. Hence, optimization methods play a significant role in helping authorities to allocate and manage those resources using efficient methods (Wang and Huang, 2014). Therefore, optimal mathematical decision-making methods for modeling urban water issues in the real world, help managers make decisions consistent with urban needs. Integration is the best approach to managing supply resources, and mathematical optimization techniques have also proven their ability in tackling this issue (Lan et al. 2015).

The main decisions related to the design of water systems include the multiple and different sources of supply, the dimension of the treatment plants, water transport equipment such as the size of pipes and consumption areas. These decisions are mostly settled under uncertainty conditions and are associated with population growth and access to future water supplies (Chung et al. 2009). A water supply chain includes resource management, distribution network, and consumers. Water distribution network includes treatment plants, reservoirs, consumption areas, and pipelines for water transfer. This system requires a lot of information gathering that may not be necessarily available. Problems such as measurement errors, human judgment errors, and lack of data make this information uncertain (Xu et al. 2014).

Most studies use mathematical programming techniques to optimize water resource management problems (Li et al. 2005). Wang and Huang (2013) developed an integrated approach to managing water supply sources through the combination of Interval Linear Programming, Two-stage Stochastic Programming, Chance Constrained Programming, Taguchi Orthogonal Arrays, and Composite Factorial Design. The model was a combination of methods for optimizing and designing statistical tests for allocating resources to different usages. This model has examined only the supply part of the urban water chain and has not attempted the optimal amount of allocated water at all levels. Some works reported in the literature have attempted supply resources management under uncertainty conditions. Naderi and Pishvaee (2017) presented a new mathematical model for designing a network of water supply and wastewater collection systems

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using two-stage stochastic programming method taking into account both the typical business and the risk of uncertainty. Due to the complexity of the mathematical model, they used Bezdek fuzzy clustering method and the Benders decomposition method for obtaining an optimal solution. The paper examined three levels of the water supply chain under conditions of uncertainty and various scenarios that reduced system costs. It is necessary for managers to use optimal and comprehensive solutions instead of providing cross-sectional ones for different parts. The need to develop sources and facilities to support service providers is essential to determine optimal use of water and assure availability of sources. Insufficient attention to urban water management leads to more costs and water shortage (Fattahi and Fayyaz. 2009). They proposed a multi-objective linear programming model which considers three main criteria: drinking water quality, sustainability of resources, and socioeconomic effects for assessing the satisfaction of people using the analytic hierarchy process. For validation, the proposed model was implemented in Hamadan city as a case study. Principles of integrated urban water management and urban water cycle sensitivity due to frequent occurrence of disasters such as floods and droughts, the reduction of water quality and its shortage due to the expansion of urbanization, and frequent reconstruction and upgrading water infrastructures are of great importance (Bach et al. 2014). For example, Qin and Xu (2011) proposed the two-stage planning model for urban water supply resources management on four levels: Sources, treatment plants, reservoirs, and consumption areas under uncertainty conditions. Acceptability-Index-based Two-step Interval Programming model is developed from the old two-stage interval planning, which is a combination of the reversal of the levels of constraints in an optimal framework. This pattern also minimizes overall system costs and specifies the volume allocated at each level. The article attempts a real-world urban water chain, but has reduced consumption areas and overall costs under uncertain demand. Lari and Pishvaee (2015) presented a two-stage multi-period mixed-integer non-linear programming model for optimizing allocation and location in the municipal water supply chain that covers steps from sources to consumption areas.

Investigating the literature illustrates some gaps including lack of supply centers and water treatment centers in modeling water distribution network. Also, fixed capacities are considered for different facilities of the network. Table S4 (supplementary file) categorizes the related literature in detail. Also, comparison of the proposed model with related models are illustrated.

In this paper, a Mixed Integrated Linear Programming (MILP) model is designed to manage an integrated urban water supply chain in six levels: (1) supply sources, (2) treatment plants, (3) reservoirs, (4) consumer areas, (5) wastewater treatment plants, (6) Urmia lake. Urmia urban water network has been considered as a case study. We have tried to use realistic assumptions in the presentation of the mathematical model, so the proposed pattern has the maximum overlap with the water network under investigation. Results will provide useful information for urban water planning managers to make optimal decisions and optimize the costs of the system.

The main contributions that differentiate this paper from the available works in the literature include: (1) Developing a comprehensive MILP model that includes all water supply chain layers from dams to wastewater treatment under multi-period condition, (2) Considering wastewater treatment centers and optimizing their capacities over the planning horizon, (3) Determining the best supply centers (dam or well) in different periods, and (4) Applying the model in a real case in Urmia.

The remainder of this article is as follows: the next section illustrates the formulation of the problem as an MILP model. Section 3 presents a case study and analyzes the results. Finally, section 4 presents research guidelines for future studies.

2. Problem description

2.1. Problem definition

An integrated mixed-integer linear programming model for optimal urban water management is presented in this section. The main issue is the integrated assessment of the urban water network supply chain so that the optimal volume to enter and leave the system can be obtained. Also, the proposed model minimizes the operating and fixed costs of the system as much as possible. In this way, the amount of water loss in the system is minimized and new facilities are created, if need be.

According to Fig. 1, the urban water network has been studied in six levels. The water enters the treatment plants from a supply source that may include one, two, or the entire dam, river, wells, and fountains. Treatment plants include drainage pools, filters, air-conditioning devices, and disinfection. After performing these operations, the treated volume is introduced into the reservoirs for storage. Finally, this amount is injected into the water distribution network, which includes pipelines, tubes, main tubes, and injector sections. Hereafter, the produced wastewater is collected by the consumption zones which is the output of the network. Wastewater is divided into three categories of household, industrial, and surface sewages, which are sent to sewage refinery through transfer lines. Wastewater treatment is carried out in three stages: primary purification, secondary settle, and third-party refining. Afterward, the refined wastewater overflows through the transmission lines to Urmia lake, which is experiencing a rising drought from the beginning of 1991. Most of the mathematical models proposed so far have included only some part of this chain, e.g. distribution system or resource management. However, in addition to optimizing the system from source to consumption area, the proposed model optimizes wastewater treatment and capcity levels of wastetreatment centers.

2.2. Mathematical formulation of the problem

In the following, the indices, parameters, and variables used in mathematical modeling of the urban water network supply chain problem are described (see Nomenclature section).

2.2.1. Objective function

The objective function is as follows:

$$
\begin{aligned}
\min \mathbf{Z} = & \sum_r \sum_t \sum_p XW_{rtp} C1_{rp} + \sum_r \sum_p CRS_{rp} Y_{rp} \\
& + K\left[\sum_c \sum_p CWS_{cp} X_{cp}\right] + \sum_r \sum_t \sum_p XW_{rtp} C2_{rtp} \\
& + K\left[\sum_c \sum_s \sum_p XC_{csp} C3_{csp}\right] + \sum_t \sum_s \sum_p YW_{tsp} C4_{tsp} \\
& + \sum_s \sum_z \sum_p XE_{szp} C5_{szp} + \sum_z \sum_f \sum_p CT2_{zfp} XF_{zfp} \\
& + \sum_f \sum_p XD_{fp} CD_{fp} + \sum_r \sum_t \sum_p LCXW_{rtp} \beta_t \\
& + \sum_c \sum_s \sum_p XC_{csp} \alpha_{cs} LC + \sum_t \sum_s \sum_p LCYW_{tsp} \lambda_{ts} \\
& + \sum_s \sum_z \sum_p XE_{szp} \mu_{sz} LC + \sum_t \sum_s \sum_p YW_{tsp} CT1_{tp} \\
& + \sum_s \sum_z \sum_p XE_{szp} CM_{sp} + \sum_s \sum_p IV3_{sp} CS_{sp} \\
& + \sum_z \sum_f \sum_p XF_{zfp} CW_{fp} + \sum_m \sum_f CE_{mf} HF_{mf} W_{mf}
\end{aligned} \tag{1}
$$

As seen in objective function (1), the costs attempted in our formulation include: purchase cost, transfer costs through pipelines between resources - treatment plants, resources - reservoirs, treatment plants - reservoirs, reservoirs - consuming zones, consuming zones - wastewater treatment plants, and the transmission of wastewater refined to Urmia lake, water leakage in resource transfer channels - water refinery, resources-reservoirs, water refinery-reservoirs, reservoirs - consumption areas, purification in refinery, operating and water storage in reservoirs, sewage treatment in wastewater treatment plants, and the cost of developing wastewater treatment plant capacity. It should be noticed that the cost of water purchase is the cost to be paid to the water organization for water supply. Furthermore, operational costs in reservoirs and wastewater treatment plants include total electricity consumption, staff and maintenance costs. After solving the model, the optimal flow rate between the sources - treatment plants, resources - reservoirs, treatment plants - reservoirs, storage tanks - consumption areas, consumption areas - wastewater treatment plants, wastewater treatment plants - Urmia lake will be achieved. Furthermore, the optimal amount in the reservoirs to be stored are obtained.

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2.2.2. Constraints

The constraints of the proposed model are presented in the following.

$$\sum_{s}(1-\mu_{sz})\,XE_{szp}\;BB_{sz}=DD_{zp}\qquad \forall\, z,p \tag{2}$$

Constraint (2) states that the amount of water sent from reservoirs to consumer areas, plus the volumes lost in the mentioned route, should meet the demand of each zone.

$$XD_{fp}=\xi\sum_{z}FF_{zf}\,XF_{zfp}\qquad \forall\, f,p \tag{3}$$

Constraint (3) shows that only a percentage of refined wastewater flows into Urmia lake.

$$\sum_{f}XF_{zfp}=\ \omega\sum_{s}BB_{sz}\,XE_{szp}\qquad \forall\, z,p \tag{4}$$

Constraint (4) indicates that in each period, a percentage of consumed water by consumers is always converted to sewage which is not treated in wastewater treatment plants. That is, due to lack of collection systems, only some part of the urban wastewater enters the wastewater treatment plants.

$$RR_{rt}\,XW_{rtp}\le(\,RR_{rt}\,E)Y_{rp}\qquad \forall\ r,t,p \tag{5}$$

$$CC_{cs}\,XC_{csp}\ \le(CC_{cs}\,E\,)X_{cp}\qquad \forall\, c,s,p \tag{6}$$

$$SS_{ts}\,YW_{tsp}\le(SS_{ts}\,E)\qquad \forall\, t,s,p \tag{7}$$

$$BB_{sz}\,XE_{szp}\le(BB_{sz}\,E)\qquad \forall\, s,z,p \tag{8}$$

$$FF_{zf}\,XF_{zfp}\le(FF_{zf}\,E\ )\qquad \forall\, z,f,p \tag{9}$$

Constraints (5)-(9) are the logical constraints of the problem. Therefore, these constraints indicate respectively that to transfer the volume from the sources to the refinery, the well into the reservoirs, the water treatment plant to the reservoirs, reservoirs to the consumption zones, and, at the end, the consumption zones to the wastewater treatment plant should be channeled communication (pipelines). Using these constraints, optimal communication paths for transmission are identified.

$$\begin{aligned}IV3_{sp}=IV_{s.p-1}&+\sum_{t}(1-\lambda_{ts})YW_{tsp}\,SS_{ts}\\&+\sum_{c}(1-\alpha_{CS})\,XC_{csp}\\&-\sum_{z}(1-\alpha_{CS})\,XC_{csp}\qquad \forall\, s,p\end{aligned} \tag{10}$$

Eq. 10 shows that the inventory at the end of any period in a reservoir is equal to the amount of previous period, plus the volume transferred from the refinery, taking into account the amount lost in the transfer route, the amount moved from wells to reservoirs after the loss in the path, minus the amount transferred from the reservoir to the the consumption areas.

$$\begin{aligned}IV3_{s.1}=IV03_{s}\ +\sum_{t}(1-\lambda_{ts})YW_{tsp}\,SS_{ts}+\sum_{c}(1-\alpha_{CS})\,XC_{csp}\\-\sum_{z}(1-\alpha_{CS})\,XC_{csp}\qquad \forall\, s,p\end{aligned} \tag{11}$$

Equation (11) is the same as constraint (10), with the difference of the first period.

$$\sum_{r}(1\text{-}\beta_{t})XW_{rtp}\;\;RR_{rt}\text{=}\sum_{s}YW_{tsp}SS_{ts}\qquad \forall\ \ t,p \tag{12}$$

Eq. 12 indicates the balance in the refineries. The maximum remaining storage time in the refinery is related to the filtering stage. So, it is virtually impossible to consider the inventory at the beginning and end of the period. Similarly, the water loss at the same stage is related to the washing of filters, which is about 3 to 5 percent. As a result, the water supplied from the resource to the refinery is transferred to reservoirs after refining operations and a small amount of leakage into it.

$$IV1_{rp}=IV_{r.p-1}+PR_{rp}-TB_{rp}-\sum_{t}XW_{\,rtp}RR_{rt}\qquad \forall\, r,p \tag{13}$$

Eq. 13 indicates inventory at the end of the period in the source of water supply. Then, the amount is equal to the remaining water from the previous period, plus the volume from the rainfall in the present period, minus the amount evaporated.

$$IV1_{r.1}=IV01_{r}\ +PR_{rp}-TB_{rp}-\sum_{t}XW_{\,rtp}RR_{rt}\qquad \forall\ \ r,p \tag{14}$$

Eq. 14 is the same as the Eq. 13, with the difference of the first period.

$$IV3_{sp}\ge\varepsilon_{sp}\sum_{z}DD_{zp}\,BB_{sz}\qquad \forall\, s,p \tag{15}$$

Constraint (15) is associated with the safety stock of water. It states that the volume of water in reservoirs should meet the demand in each period.

$$IV3_{sp}\le CA_{sp}\qquad \forall\, s,p \tag{16}$$

Constraint (16) satisfies the capacity constraint of reservoirs.

$$\sum_{r}(1-\beta_{rt})XW_{rtp}\;\;RR_{rt}\le TC_{tp}\qquad \forall\, t,p \tag{17}$$

Constraint (17) satisfies purification capacity of water treatment plants.

$$IV1_{rp}\le CP_{rp}\qquad \forall\, r,p \tag{18}$$

Constraint (18) satisfies capacity of water resources.

$$\sum_{t}XW_{rtp}\le MA_{rp}\,Y_{rp}\qquad \forall\, r,p \tag{19}$$

Constraint (19) indicates that if a dam or river is selected for urban drinking water, its total capacity cannot be used. That is, the volume of water transferred from the resource to the water treatment plant should always be less than the maximum permissible amount.

$$\sum_{s}XC_{csp}\ \le\ MC_{cp}\,X_{cp}\qquad \forall\, c,p \tag{20}$$

Constraint (20) indicates that if a well is selected as the source of water supply, the water moved to reservoirs should be less than the maximum allowable water output from that well.

$$\sum_{z}XF_{zfp}\ge CF_{fp}+\sum_{m}CE_{mf}\,W_{mf}\qquad \forall\, f,p \tag{21}$$

Constraint (21) is associated with the development of wastewater treatment plant capacity and the creation of new phases. In this way, the total amount of wastewater collected from the consumer's area should always be less than the capacity of the existing wastewater treatment center and the new phases that are required to be created.

$$Y_{rp}\ ,X_{cp}\ ,W_{mf}\epsilon\{0,1\} \tag{22}$$

$$XW_{rtp}\ ,XC_{csp}\ ,YW_{tsp}\ ,XE_{\ szp},XD_{fp}\ ,\ XF_{zfp}\ ,\ IV1_{\ rp}\ ,IV3_{sp}\ \ \ge0 \tag{23}$$

Constraints (22) and (23) are the binary and non-negativity restrictions of variables.

3. Results and discussion

The studied case is related to Urmia urban water network. Urmia city is located at the center of the West Azerbaijan Province in the northwest of Iran. Urmia's population is 856914 people. Urmia urban water network is studied for one year with a focus on different consumptions in the city which includes a number of branching 171645 and the number of units 295296. Urmia urban water network supply chain consists of six levels. It has a main water supply source called Shahar-Chay Dam and also 38 wells drilled along the river bed. It has two refineries. It also has 17 reservoirs in different parts of the city that transfer water to the consumption areas and they are divided into ten main areas. Urmia has a wastewater treatment plant, which has a total of five phases, but two phases have been constructed and arranged in orbit. The Urmia's Shahr-Chay dam feeds three sectors: agriculture, household, and industrial. The amount of water dedicated to the household sector is sent through pipelines to refineries. At this stage, due to the use of steel and concrete canals, the leakage of is assumed to be negligible. After performing the purification operations, the purified water is sent to the reservoirs in the city. Moreover, several reservoirs in the city are fed through wells using transmission pipelines. Then, the water in the reservoirs is injected through the pipelines to various parts of the city, where a high rate of leakage occurs. Finally, the collected sewage is transported there through pipelines and then, after the

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sewage treatment operation, the refined volume is transferred to Urmia lake.

3.1. Data collection

The raw data of this study are based on the urban water network of Urmia city. It includes costs such as the cost of creating a dam and save the water for sale with added value, labor, etc., which is constant for all months of the year. The transferring cost between the dam and the refinery is equal to the total cost of maintenance and repair of the transmission lines, the depreciation of the transmission facilities and equipment, and the share of the absorbed service cost calculated per cubic meter of water. Transferring costs from wells to reservoirs is the same. Delivery fee from the refineries to reservoirs is also equal to the total electricity consumption, staff salaries, maintenance, and pumping it from the water there to reservoirs calculated per cubic meter of water. Given that about 80 to 90 percent of the water needs of each region are provided from reservoirs in the same area, the distribution fee in the consumption zones is also mentioned. On the other hand, the most ideal way to extract urban drinking water is to use the surface rather than underground resources. Besides, in the proposed model for accessing water from each resource, the cost of choosing a source is as same as the cost of accessing it, which is calculated for two wells and dam sources according to the dependent parameters in a separate way. Here, the factors affecting the operating cost of purifying, are depreciation of facilities and the cost of consumables. Thereupon, it is calculated for each of the refineries according to their capacity. Urmia wastewater treatment plant has a very large land in which five wastewater treatment modules are intended. But at present, the two modules are in orbit and the other modules have not yet been established and have not been used. Therefore, the cost of developing Urmia urban wastewater purification capacity is the cost of establishing and in the orbit of these three modules. Also, the operational cost of wastewater treatment in the two modules depends on parameters such as electricity and consumables, staff salaries, maintenance, repair, and other costs, which are calculated for each cubic meter of municipal wastewater. The parameter of the cost of wastewater transfer from the consumption zones to wastewater treatment plants is the total of the wastewater collection system from the consumption zones plus transferring it. There are two costs for different cisterns in the city: (1) Operational cost of the reservoir, which includes electricity consumption, consumables, depreciation, and others. (2) The cost of repair and maintenance of the reservoir depends on the parameters such as the life of the reservoir and how they are made, repairs, the salaries of employees, and the capacity of the cisterns. Safe-keeping in daily use is 50% in urban areas and 100% in cities with a population of 100,000 or less. In all reservoirs, we always have a percentage to keep inventory safe, since those reservoirs are filled with water every day with a constant input of water. But its output is different, and at night, it is reduced, so safety reserve is related to days. For example, we describe the way of aggregating 4 parameters as follows: Table S1 (supplementary file) shows the amount of demand for consumption areas in terms of cubic meters per month. So, the data in the table are empirically determined by the question of the experts and classification of consumption areas in terms of the numbers of branches given to the regions. Table S2 (supplementary file) shows the maximum capacity of water storage in reservoirs of different urban areas in a day. Table S3 (supplementary file) shows the transferring sewage fee from consumption areas to the wastewater treatment plant. Considering that the losses volume in each route or section is equal to the amount that must reach the user, it also generates income for Water and Wastewater Company, but now it is a lost opportunity. Therefore, the leakage cost is exactly equivalent to the cost of water for the Water and Wastewater Company that sells to consumers.

3.2. Solution method

To evaluate the performance and efficiency of the proposed model, it is implemented in Urmia urban water network. The proposed mathematical model is solved by GAMS 23.5 software using Cplex solver. To investigate the accuracy of the model, the achieved results were investigated by the experts of the West Azerbaijan Province Water & Wastewater Co. They expressed that the results are consistent with the current decisions in the company. Also, to develop the proposed model the relevant papers in the literature are carefully evaluated and their main features (such as constraints: demand, inventory balance, and capacity) are considered in the model. The proposed model could improve the total cost of the Urmia urban water system. The obtained results determine the optimal flow in the supply and distribution network. According to the results, the module 1 of the Urmia wastewater treatment plant cannot refine wastewater from the intake, so there is a need to activate the modules 2 and 3. Fig. 2 shows that in the spring, water from the Shahar Chay dam is transferred to the first and second refinery.

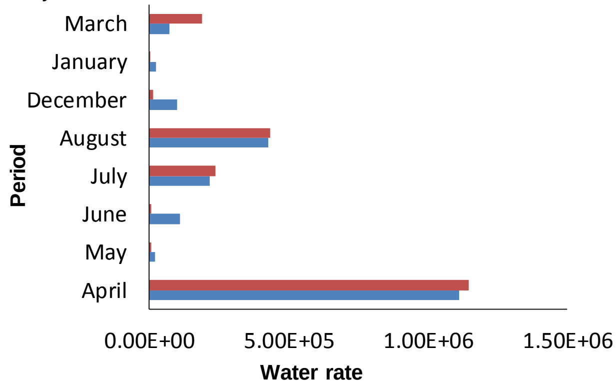

Fig. 2. Water harvesting from Shahar Chay dam in different months of the year (m^3).

According to the experts of Urmia Water and Wastewater Company, the amount entering the treatment center is in line with reality. But the volume entering the treatment plant 2 is lower than the present value. Therefore, the treatment plants will just purify the water during the months mentioned. Then, the optimal water rate is transferred to the reservoirs 3, 11, 1 and 4. Fig. 3 shows that reservoirs 3, 1, 11, and 4 should be supplied just through a treatment plant. Furthermore, in April, considering the first period of the proposed model, we have the highest water flow through each of the 38 wells to the reservoirs. In August, due to the peak condition of air temperature and increase of demand, has the second-highest water rate.

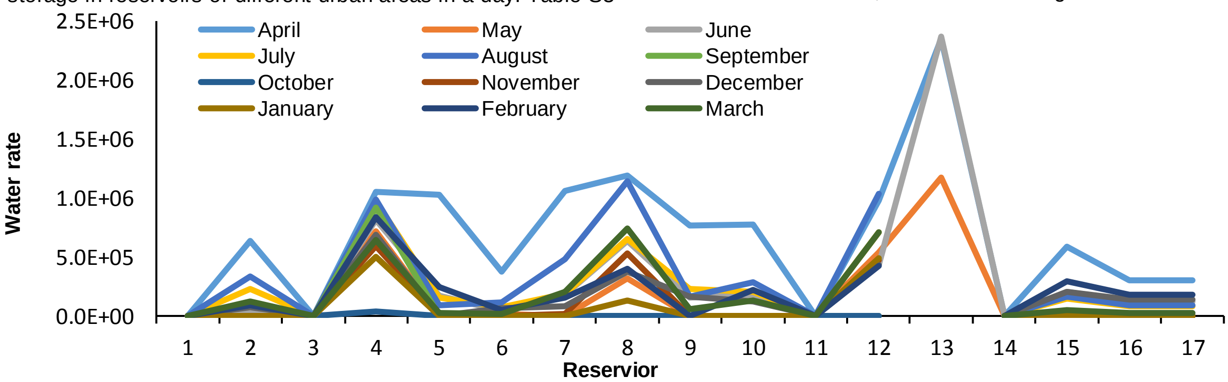

Fig. 3. The optimal amount of water flow from the wells to reservoirs (m^3).

In Urmia, there is a link between all reservoirs of the city and the consumption zones, and there is no efficient plan for water harvesting from the reservoirs. The optimal output of the model has solved this problem throgh increasing the capacity of wastewater treatment palnt (activating modules 2 and 3). Fig. 4 illustrates the amount of water rate from reservoirs to consumer zones.

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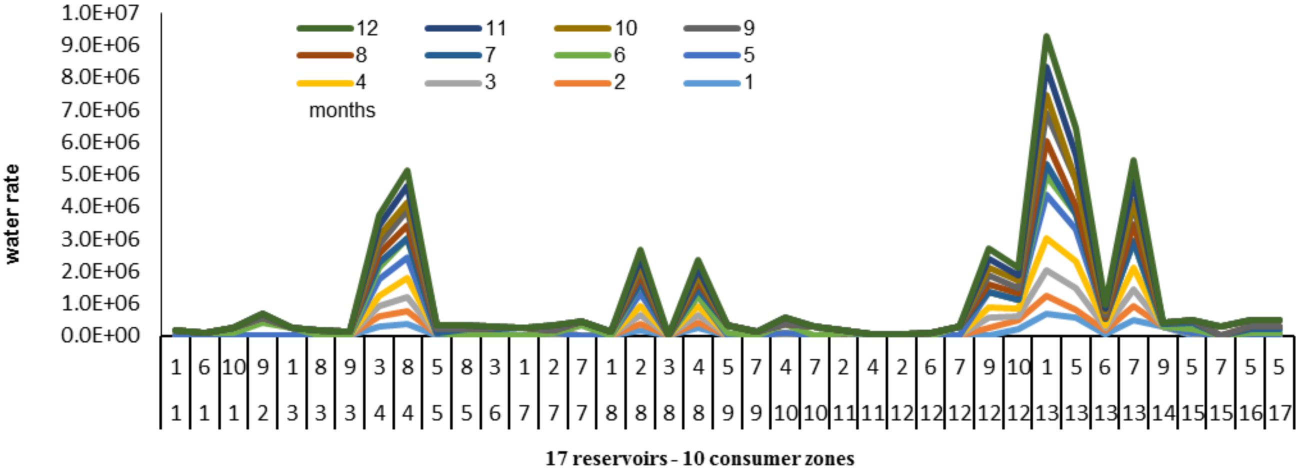

Fig. 4. Amount of water transfer from reservoirs to consumer zones in all of 12 months (m^3).

Fig. 5 shows the optimal amount of refined wastewater transferred to Urmia lake. By this way, about 20458153 cubic meters water will be entered to the lake, annually. This help to prevent the drynees of the lake.

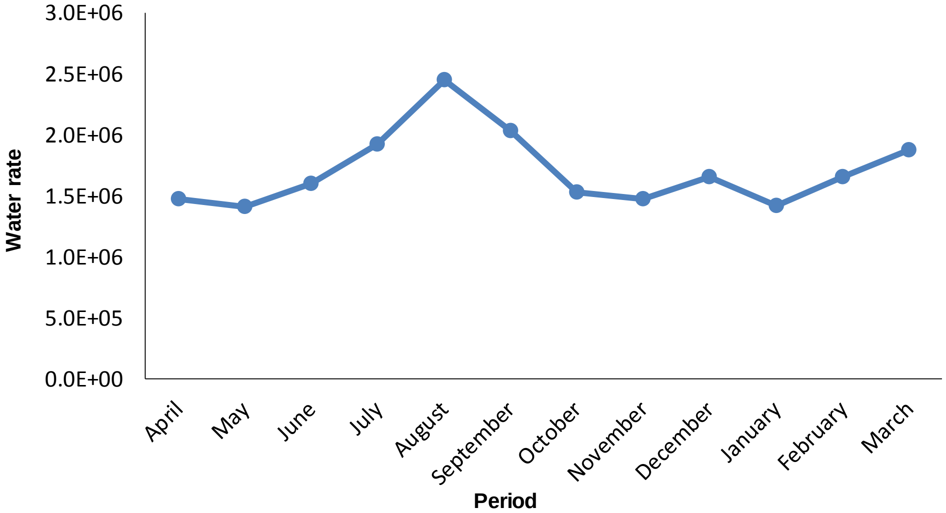

Fig. 5. The rate of the overflow of refined wastewater into Urmia lake during one year (m^3).

Fig. 6 shows the status of remaining water at the Shahar Chay dam after satisfying demands.
The obtained amounts help the to allocate the optimal amount to urban drinking water, agricultural and industrial uses. Finally, because the amount of leakage in the urban water distribution network of Urmia is very high, Figure 7 shows the sensitivity analysis of the leakage parameter in the interval [-20%, -15%, -10%, -5%, 0%, 5%, 10%, 15%, 20%].

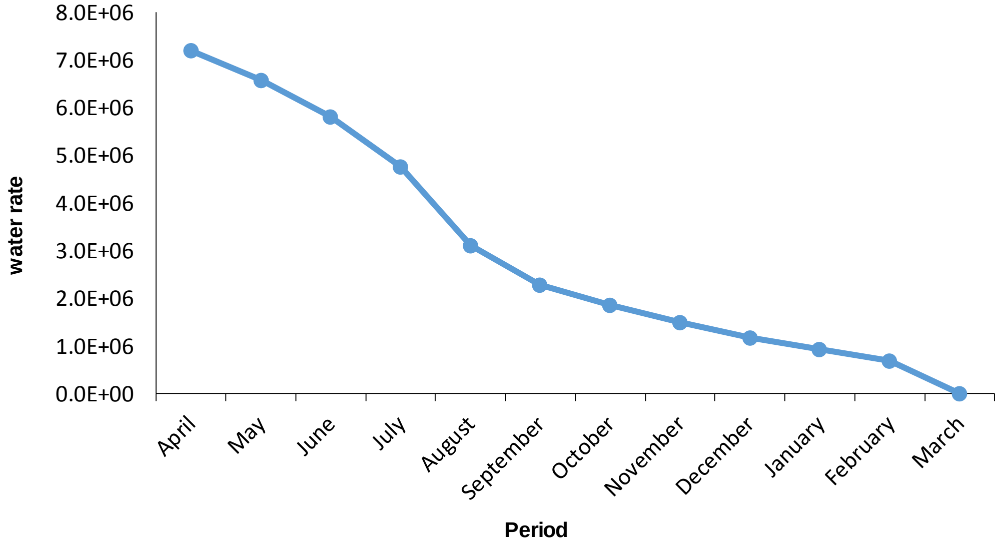

Fig. 6. General water status at the end of each month in Shahar chay dam (m^3).

It also shows that the relation of water leakage in the network with the system costs is almost linear, and with its increase, the cost also increases. Therefore, city officials must pay special attention to this issue and take appropriate measures to reduce leakage in the network, such as the use of new transmission pipes instead of using worn-out pipes.municipality.

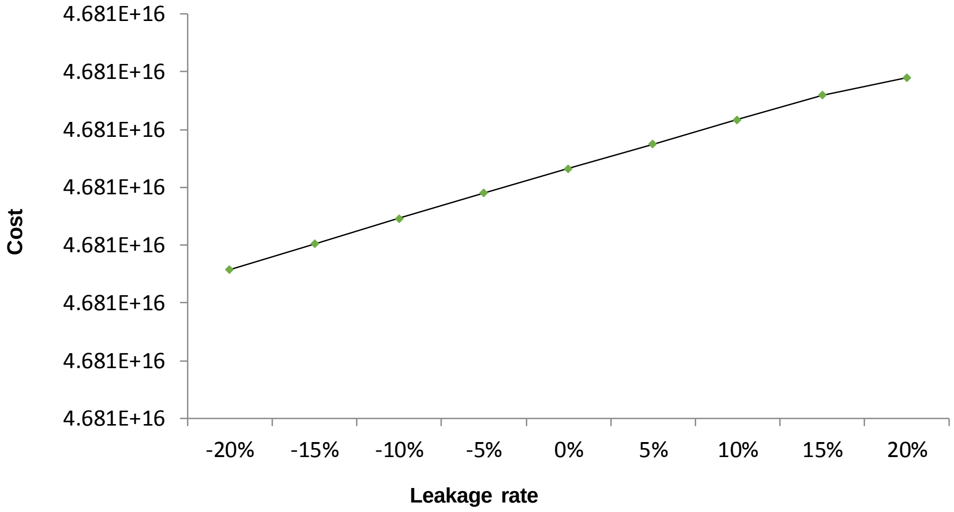

Fig. 7. Sensitivity analysis on the water leakage rate.

4. Conclusions

In this paper, an integrated MILP model for urban water supply chain management for 12 periods is proposed. Then, it is implemented in Urmia city. In addition, to cover all levels of the network, this article has considered the management of urban water consumption and has added two levels. Therefore, in this study, the urban water supply chain has been integrated from supply to consume centers. Actual data was obtained from the West Azerbaijan Province Water and Wastewater Company. The output of the model can determine the optimal flow among all levels of the considered system, and also the optimal status of the water supply facilities is determined. Using the data related to the company's financial statements and comparing it with the cost function of the resulting model, it has been able to reduce the operating and fixed costs of the urban water system of Urmia by about 1%. On the other hand, determination of optimal amounts of water allocation at the levels of the supply chain will help municipal managers in Urmia to make optimal and appropriate decisions in the system. This results to avoid large amounts of waste in the network and prevent additional allocation costs.

For future research, the model could be studied under uncertainty of parameters or could be solved by metaheuristic algorithms for large cases.

Acknowledgement

The authors appreciate the West Azerbaijan Province Water & Wastewater Co. For their financial support. Also, The authors would like to thank the respected editor in chief and anonymous referees to their helpful comments which improved the content of the paper substantially.

Appendix.
Supplementary data
Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.watres.2008.11.014

Nomenclature

r	Index of dams and rivers as sources of water supply (r = 1,…., R)
c	Index of wells as water supply sources (c = 1,….., C)
t	Index of water treatment plants (t =1,…,T)
s	Index of water reservoirs (s =1,…., S)
z	Index of water consumption areas (z =1,…., Z)
f	Index of wastewater treatment plants (f =1,…, F)
m	Index of new phases of wastewater treatment plant (m = 1,….., M)
p	Index of time period (p =1,…P)

Parameters

β_t	Water loss in wastewater treatment plant t (in percent)
α_{cs}	The amount of water leakage in the transfer paths from well c to reservoir s (in percent)
λ_{ts}	The amount of water leakage in the transfer paths from the treatment plant t to the reservoir s (in percent)
μ_{sz}	The amount of water leakage in the transfer paths from the reservoir s to the consumption zones z (in percent)
$C1_{rp}$	Cost of purchasing per unit of water from resource r in period p $(m^3/Rial)$
$C2_{rtp}$	Transfer cost of per unit of water from resource r to treatment plant t in period p $(m^3/Rial)$
$C3_{csp}$	Transfer cost of per unit of water from well c to reservoir s in period p $(m^3/Rial)$
$C4_{tsp}$	Transfer cost of per unit of water from treatment plant t to reservoir s in period p $(m^3/Rial)$
$C5_{szp}$	Transfer cost of per unit of water from reservoir s to consumer zone z in period p $(m^3/Rial)$
CRS_{rp}	Resource r selection cost as a source of water supply in period p $(Rial)$
CWS_{cp}	Well c selection cost as a source of water supply in period p $(Rial)$
$CT1_{tp}$	The operational cost of treatment of per unit of water at treatment t in period p $(m^3/Rial)$
$CT2_{zfp}$	Transfer cost of per unit of water from consumer zone z to wastewater treatment plant f in period p $(m^3/Rial)$
CW_{fp}	The operational cost of treatment of per unit of wastewater at wastewater treatment t in period p $(m^3/Rial)$
CD_{fp}	Transfer cost of per unit of purified wastewater from wastewater treatment plant f to Urmia's lake in period p$(Rial)$
CM_{sp}	The operational cost of per unit of water in reservoir s in period p $(Rial)$
CS_{sp}	The maintenance cost of per unit of the remaining water in reservoir s in period p

Please cite this article as: S. Hanife Dokht Ghayour, M. Soleimapour, R. An integrated mixed-integer linear programming (MILP) model for urban water supply chain optimization, Journal of Applied Research in Water and Wastewater, 7 (2), 2020, 102-110.

	(Rial)
CL_{szp}	Leakage cost of water in the path of transfer from the reservoir s to the consumer zone z in period p (Rial)
HF_{mf}	The cost of developing new phases m in wastewater treatment plant f
$IV01_r$	Inventory of water in resource r at the beginning of planning horizon (m^3)
$V02_t$	Inventory of water at treatment plant t at the beginning of the planning horizon (m^3)
$IV03_s$	Inventory of water at reservoir s at the beginning of the planning horizon (m^3)
PR_{rp}	The amount of water obtained from rainwater for resource r in period p (m^3)
TB_{rp}	The amount of evaporated water from source r in period p (m^3)
DD_{zp}	The amount of demand for consumer zone z in period p (m^3)
RR_{rt}	If there is a route between resource r and treatment plant t 1; otherwise 0
CC_{cs}	If there is a route between well c and reservoir s 1; otherwise 0
SS_{ts}	If there is a route between treatment plant t and reservoir s 1; otherwise 0
BB_{sz}	If there is a route between reservoir s and consumer zone z 1; otherwise 0
FF_{zf}	If there is a route between consumer zone z and wastewater treatment plant t 1; otherwise 0
CA_{sp}	The capacity of water storage at reservoir s in period p(m^3)
TC_{tp}	Water purification capacity at water treatment plant t in period p (m^3)
CP_{rp}	The capacity of dam and water resource r for storage in period p (m^3)
MA_{rp}	The maximum amount of water extraction from the dam and river r in period p (m^3)
MC_{cp}	The maximum amount of water extraction from well c in period p (m^3)
CF_{fp}	The primary capacity of the wastewater treatment plant f in period p (m^3)
CE_{mf}	The capacity of new developed phases m in wastewater treatment plant f (m^3)
ε_{sp}	The percentage which to hold water safety stock is in the reservoir s by managers in period p
LC	The fixed cost of water loss (Rial)
ω	Percentage of water converted from consumer to wastewater
K	Choice of the wells cost factor
ξ	Percentage of purified wastewater flow that overflow into the lake from wastewater
Variables	
XW_{rtp}	The amount of water transferred from resource r to treatment plant t in period p (m^3)
XC_{csp}	The amount of water transferred from well c to reservoir s in period p (m^3)
YW_{tsp}	The amount of water transferred from treatment plant t to reservoir s in period p (m^3)
XE_{szp}	The amount of water transferred from reservoir s to consumer zone z in period p (m^3)
XF_{zfp}	The amount of water transferred from consumer zone z to wastewater treatment plant f in period p (m^3)
XD_{fp}	The amount of purified wastewater transferred from wastewater treatment plant f to Uremia's lake in period p (m^3)
$IV1_{rp}$	Water inventory of resource r at the end of period p (m^3)
$IV2_{tp}$	Water inventory of water treatment plant t at the end of period p (m^3)
$IV3_{sp}$	Water inventory of water reservoir s at the end of period p (m^3)
W_{mf}	If the new phase m is used in the wastewater treatment plant f 1; otherwise 0
Y_{rp}	If source r is selected as water supply resource in period p 1; otherwise 0
X_{cp}	If well c is selected as water supply resource in period p 1; otherwise 0

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