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Investigation of water allocation using integrated water resource management approaches in the Zayandehroud River basin, Iran

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ABSTRACT

The Zayandehroud River is the largest river in the Gavkhouni basin, Iran. Water management in this basin is beset by poor water-allocation policies that do not adequately meet diverse demands (potable, agriculture, industry, and environmental demands). The Gavkhouni basin suffers from water scarcity and unmet water demands; especially with respect to environmental requirements. Water allocation considering appropriate priorities for all demands would be a major improvement for environmental protection in the Gavhouni basin. The application of the environmental flow in Integrated Water Resource Management offers practical options for water management in the Gavkhouni basin. Environmental flow describes the quantity, timing, and quality of water flow required to sustain freshwater, estuarine ecosystems, the human livelihoods, and well-being. A water resources management model is developed in this study for the purpose of improved water management in the Gavkhouni basin. The model involves six stages. The first stage implements a survey of resources and water use. The Environmental flow is calculated in the second stage with the hydraulic method and the Hydrologic Engineering Center- River Analysis System. The third stage applies the calculated environmental flow to the Integrated Water Resource Management approach by means of the Water Evaluation and Planning model. The fourth stage creates seven possible management scenarios in the Water Evaluation and Planning model to be applied in the period ending in the year 2041. These scenarios are ranked in the fifth stage with a multi-criteria decision-making method. The sixth stage applies the best management scenario in the study region. This study's results indicate that the annual drinking water demand under current conditions would rise from 547.6 to 760.2 Mm^3 by 2041. The annual industrial water demand is estimated to increase from 213.7 to 400.5 Mm^3, and the agricultural water demand is projected to remain constant at 1789.1 Mm^3 per yr. The annual drinking water, environmental, industrial, and agricultural unmet demands are estimated to increase from 68.1, 106.5, 73.4, and 470 to 130.1, 186.1, 141.4, and 480 Mm^3, respectively. The considered scenarios are (i) change in water supply priority, (ii) change in the population growth trend, (iii) change in return flow and water loss management utilization, (iv) change in the amount of water transferred to the Gavkhouni basin, (v) change of demand management (consumption per capita reduction), (vi) change of agricultural conditions, and (vii) change of industrial conditions. The change in water supply priority and the change in the volume of water transferred to the Gavkhouni basin scenarios are found to be of the highest priority. The best management alternative is chosen with four types of ranking (i.e., water allocation priorities) in which the ranking (i.e., drinking, Industrial, agricultural, environmental unmet water) and fourth ranking (i.e., environmental, drinking, industrial, agricultural Unmet water) are recommended as the best approach.

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1. Introduction

Rivers are one of the most important sources of freshwater. This freshwater resource and its biodiversity are subjected to many threats. Rivers have been the main source of food, water, and other services to sectors such as fisheries and agriculture. Nowadays, rivers serve multiple other functions: navigation, power generation, irrigation, industrial production, and tourism (Zehtabian et al., 2017).

Population growth, industrial development, and the expansion of agricultural land and water-resources development projects on the one hand, and reduction in the quality and quantity of water resources, and the lack of Integrated Water Resource Management (IWRM) on the other hand disregards the environmental cycles and water requirements for plants and animal species, and for aquatic ecosystems. It is necessary to plan and coordinate IWRM to avoid damages caused by insufficient streamflow in rivers. In general, IWRM involves the development and management of water, soil, and other related resources to enhance social and economic welfare in an equitable manner and to preserve ecosystems.

IWRM may occur in different ways, for example, in some cases, the quantitative and qualitative integration of water resources and water allocation for meeting diverse water demands is considered. There is no clear and basic framework for IWRM. Yet, its goal is to integrate by establishing a suitable relationship between the water resources, society, and the environment that satisfies economic, cultural, and environmental needs. Water is essential for development in arid and semi-arid countries such as Iran.

This paper applies methods for meeting the Environmental Flow (EF) requirement of the Zayandehroud River using IWRM. The industrial and drinking water uses in the Zayandehroud River basin have increased in recent years due to population growth and industrial development, which have led to reduced water allocation to the agricultural sector because the supply of drinking and industrial water has become a higher priority. This leads to rising groundwater withdrawal by farmers coping with increasing water scarcity. The over-exploitation of groundwater resources has met the agricultural water demand, but has also caused damages on the limited water resources. It is necessary to apply IWRM in the Gavkhouni basin. Numerous studies have applied IWRM the world over. Those works have employed a wide variety of models and one of the most prominent ones is the Water Evaluation and Planning (WEAP) model.

Several studies dealing with water resources management using the WEAP model have been reported. Al-Shutayri et al. (2019), for instance, examined the impacts of water supply requirements and the positive impacts of water desalination on the supply of water requirements in Jeddah, Saudi Arabia, applying a scenario-based WEAP model. The results confirmed that the WEAP model can be applied to various operating policies for water resources management in Jeddah City. Ramadan et al. (2019), applied the WEAP model to the Nile River to define future water deficit and water demand in Sharkia, Egypt. Tizro et al. (2018) evaluated the efficiency of traditional and modern irrigation systems in the Tuyserkan Plain in Hamadan province, Iran. The irrigation-efficient scenario was simulated with Modular finite-difference Flow (MODFLOW) and WEAP. Porhemmat et al., (2019) evaluated an IWRM approach through a linked WEAP-MODFLOW model in the Ravasnar-Sanjabi plain located in Kermanshah province, western Iran.

Shahraki et al. (2019) reported an IWRM-based study of agricultural water demand by evaluating several scenarios in the Hirmand basin, Iran. This study revealed that applying different policies such as increasing irrigation efficiency in agricultural water use would result in water savings and reduce water scarcity. Most IWRM studies have focused on water allocation to multiple user sectors without taking the EF into account.

The analysis of hydrological changes in rivers and their impacts on the environment has led to recognition that there is an EF requirement in rivers, which may vary along its reaches (Tharme, 2003; Zehtabian et al., 2017).

Hydraulic methods are common approaches among a wide range of methods adopted by many studies to evaluate the EF. Hydraulic methods consider the morphologic characteristics of rivers to characterize stream flow in different river reaches. The emphasis on river hydraulics means that some past applications of the hydraulic methods may have excluded knowledge about diverse aquatic species with diverse biologic requirements (Gippel et al., 1998). A study in India applied the hydraulic method and Hydrologic Engineering Center- River Analysis System (HEC-RAS) to calculate the EF requirement of the Krishna River, India (Kamur et al., 2020). The results from the hydrologic-alteration analysis showed that the required EF requirement in the Krishna River was not maintained for almost 43% of the time in the post-impact period. Farhadian et al. (2021) reported a study in Iran to evaluate the operation of the Karoon River (Iran) reservoir to meet the EF. Joseph et al. (2021) quantified the EF requirement and developed management practices in the Son River, India. Kiani (2016) simulated surface water resources and water demands (agricultural, industrial, drinking, and the environmental demand) in the Gavkhouni basin, Iran, to find possible scenarios for solving unmet water demands. This study did not consider groundwater resources.

The hydraulic method is herein applied to the Zayandehroud River because it is simple, uses readily available hydraulic data, and does not require a large amount of biological data for evaluating the EF. It is essential to investigate water scarcity and water resources management considering the EF in the Gavkhouni basin. This study analyzed the EF with the IWRM approach implementing the WEAP model. Several scenarios were defined and ranked with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), which is a common-applied method for ranking management alternatives (Liang et al., 2017; Ji et al., 2015; Wood, 2015; Zehtabian et al., 2014; Behzadian et al., 2012; Yilmaz, 2010; Jozi et al., 2012). The weighting and ranking procedures of TOPSIS was coded in Matrix Laboratory (MATLAB).

This work's novelty consists of allocating adequate water to meet the EF in the Zayandehroud River, Gavkhouni basin, applying the IWRM approach. The major part of the Gavkhouni basin is located in Isfahan Province, which is an industrial center of Iran with the largest industrial water use.

Water resources are limited in the Gavkhouni basin, and there are several social conflicts concerning the provision of adequate water. Supplying water demands in this region is challenging and the stakeholders use water to meet their needs without concern about the environment. The determination of the EF in the Gavkhouni basin is one of the main goals of the Environmental Protection Agency of Iran, which seeks to improve water quality and rehabilitate its dependent ecosystem. This would lead to the preservation of the natural environment and the biological health of the river basin, which benefit society as well. Worldwide experiences have demonstrated show that catchment revitalization leads to economic, social, and touristic prosperity (see, e.g., Mount, 1995).

The present study implements the WEAP model, which is relatively simple and user-friendly, and allows users to evaluate alternatives efficiently and analyze alternative management scenarios simultaneously. The WEAP model is appealing because of its numerous capabilities, which include simulation-optimization (Sieber et al., 2005).

This study describes the materials and methods applied in the Gavkhouni basin, which encompasses the Zayandehroud River, which consists of surveying resources and water use, identifying key parameters, EF evaluation, environmental requirement determination, and applying the EF to IWRM by modeling with the WEAP model. The novelty of this research is to consider the EF as an essential water demand by means of the IWRM approach. The study's results obtained by the application of the IWRM/WEAP approach in the Zayandehroud River are presented, followed by a discussion of the results and conclusions.

2. Materials and methods

2.1. Case study

The Zayandehroud River sub-basin lies within the Gavkhouni basin in central Iran (see Fig. 1). It is located within the coordinates 31°12′ and 33°42′ N, and 50°02′ and 53°22′ E which covers a total area of 41,491 km^2, nearly 40% of which is mountains, 59% are plains, and the remaining 1% of the basin area covers 485 km^2. The Zayandehroud River is the most important river flowing through the Gavkhouni basin, and plays a vital role in supplying drinking, industrial, and agricultural water in the central region of Iran. The rivers have a length of 405 km and an average bed slope of 0.2% (Anonymous, 2010).

2.2. Methodology

This paper's modeling approach is made up of six stages listed in Fig. 2.

2.3. Investigating resources and water uses, and identifying influential parameters

The main components of the data are water resources (groundwater and surface water), water demands (drinking, agricultural, and industrial), environmental water requirement, and management policies (the priorities of water demands and fair water allocations) (Shahin Taj, 2012). The Zayandehroud Regulating Dam's data of daily and monthly flow rates were collected from the Isfahan Water and Wastewater Company and the reports on the comprehensive water resources management scheme for Isfahan Province (Anonymous, 2010).

The Zayandehroud River is considered a surface water resource. Fig. 3 depicts the longitudinal profile of the Zayandehroud River and some of the hydrometric stations within the Gavkhouni basin. The study area extends from the Zayandehroud Dam Station (with an altitude of 1970.35 m above sea level) to the Varzaneh Station with an altitude of 1455.71 m above sea level. The length of the Zayandehroud River from the regulating dam to the Gavkhouni basin is 363.3 Km.

Climatic, topographic, and geographical conditions within the Gavkhouni basin place limitations on its surface water resources. The majority of the water sources in this area consist of groundwater. Yet, the five sub-basins do not have a piezometric monitoring system, which prevents carrying out a groundwater balance in them.

The average annual precipitation rate is 1400 mm in the western part of the Gavkhouni basin and decreases to 100 mm in the Gavkhouni wetland area. In the heights of the Zagros Mountains (the north-west) the evaporation is low, and it increases towards the east and south.

The average annual evaporation rate in the Gavkhouni basin ranges between 1700 and 3100 mm. Average annual temperature at the coldest station of the Gavkhouni basin is 1 °C and at Varzaneh station (the warmest station) is 24.1 °C (Anonymous, 2011).

Climate change has a strong impact on these rates. M-Bouvani et al. (2005) estimated climate change effects on rainfall and air temperature in the period 2010–2039. The estimated reductions in maximum and minimum rainfall by 2039 equal 224 mm/yr and 16 mm/yr, respectively. The estimated increases in maximum and minimum temperature by 2039 equals 3.2 °C, as depicted in depicted in Fig. 4, (a) (change in rainfall) and (b) (change in temperature).

Karimi (2014) studied the effects of climate change on drought in the Gavkhouni basin by simulating stream flow, soil moisture, and groundwater storage under two scenarios in the period 1974–2100. First scenario and second considered 30% and 8% decreasing in rainfall, +4.5 °C for temperature, respectively. The results revealed that by 2100 the flow would decrease, and the temperature would rise. Stream flow, soil moisture, and groundwater storage would decline under both scenarios.

In this study the effect of climate change could be appeared in decreasing the amount of water resources (e.g. surface water, groundwater) data whereas this effect in Gavkhouni basin, has been extended

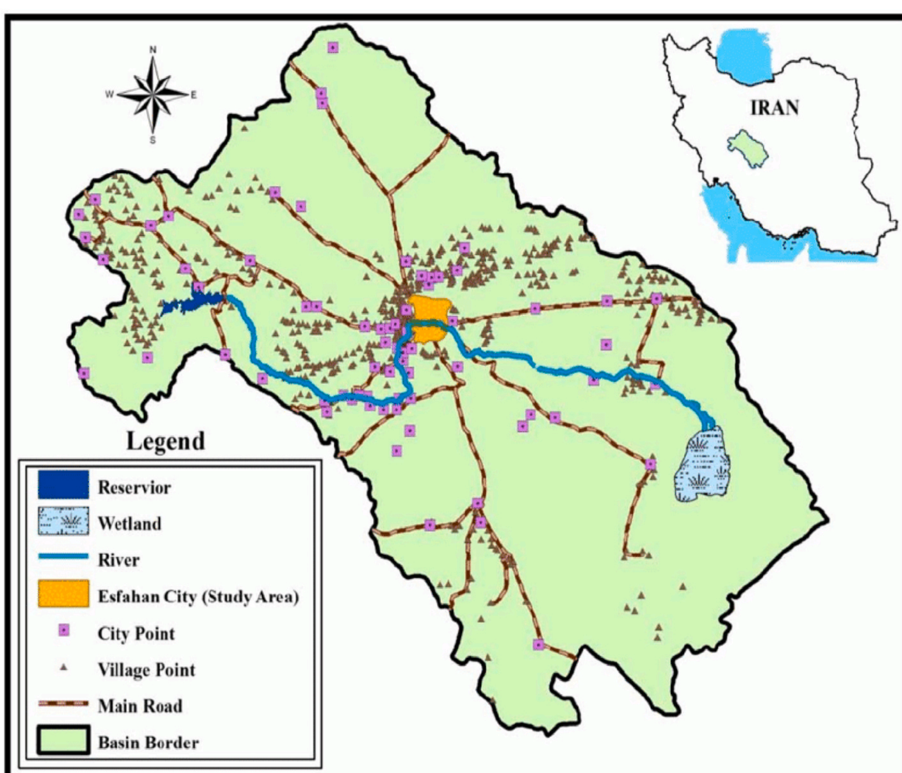

Fig. 1. Location of Zayandehroud River basin.

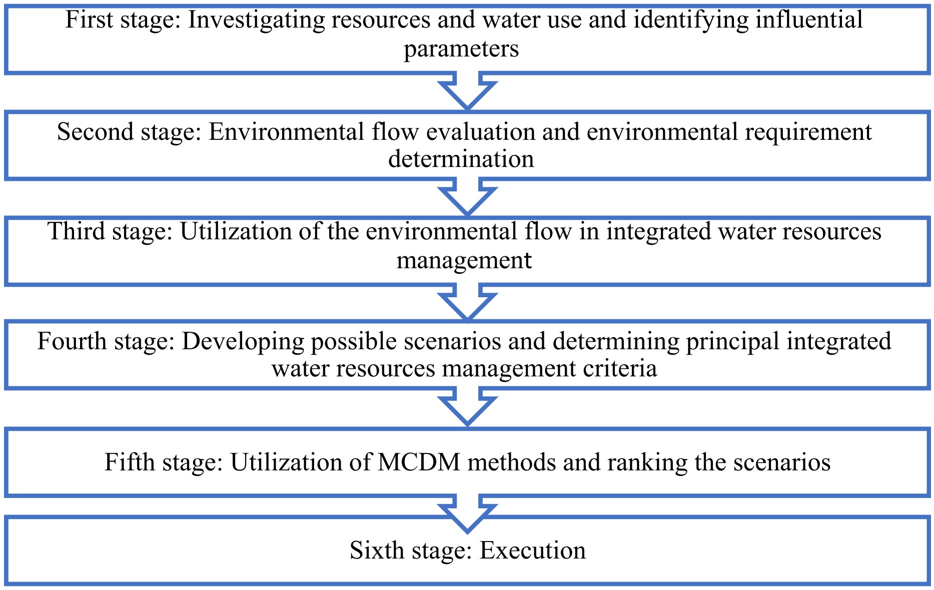

Fig. 2. Analytical toolbox for IWRM applied in the Zayandehroud river basin.

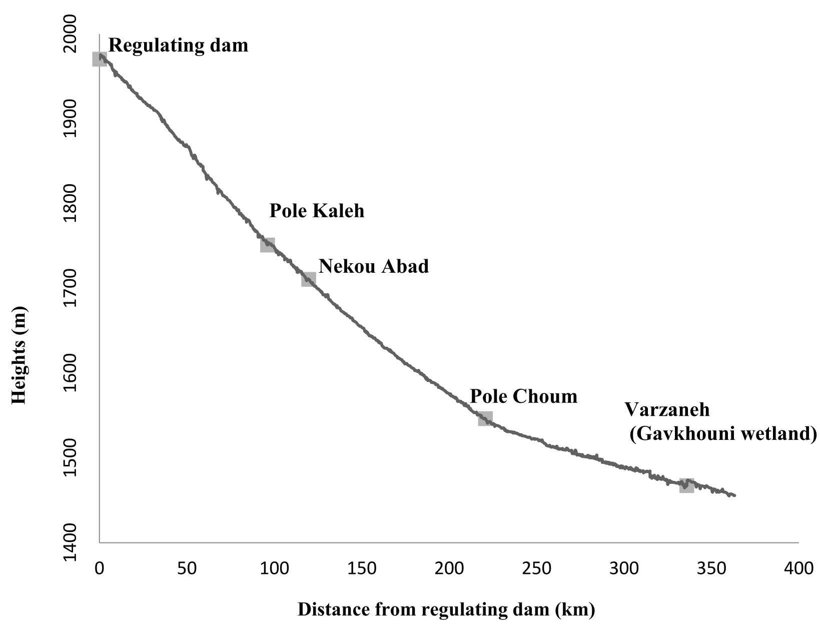

Fig. 3. The longitudinal profile of the Zayandehroud River and some of the hydrometric stations within the Gavkhouni basin.

over the years and the input data for the modelling is by consideration of climate change impacts.

The results of statistical studies have shown that the discharge from 41,503 wells, 5471 springs, and 2246 aqueducts in the Gavkhouni catchment is about 3524 Mm^3 annually (Anonymous, 2010). In 2006 groundwater withdrawal was equal to 3 Mm^3 and by the year 2011 it had declined to 2 Mm^3. This decline occurred while surface water supplies and groundwater levels were also declining (Salehian et al., 2018). Therefore, the limitation of surface water resources increases the importance of IWRM for groundwater, which increases the role of the return flow in modeling resources and water use in this region.

2.4. Environmental flow evaluation and environmental requirement determination

The hydraulic method is one is commonly used for assessing the EF (Abdi et al., 2015; Karakoyun et al., 2016; Dunbar et al., 2012). The hydraulic method is relatively simple to implement and does not require large volumes of amounts of data to assess the EF. The morphological characteristics of rivers are considered for estimating EF. Hydraulic methods simplify the assumptions of aquatic organisms' conditions and diminish the involved analysis of natural habitats of holistic methods (Gippel et al., 1998). The hydraulic method has a versatile scheme for calculating the EF. This work applies the Wetted-Perimeter method was applied (Bovee et al., 1978).

The HEC-RAS was employed to investigate the hydraulic parameters of the Zayandehroud River and estimate the required EF according to the

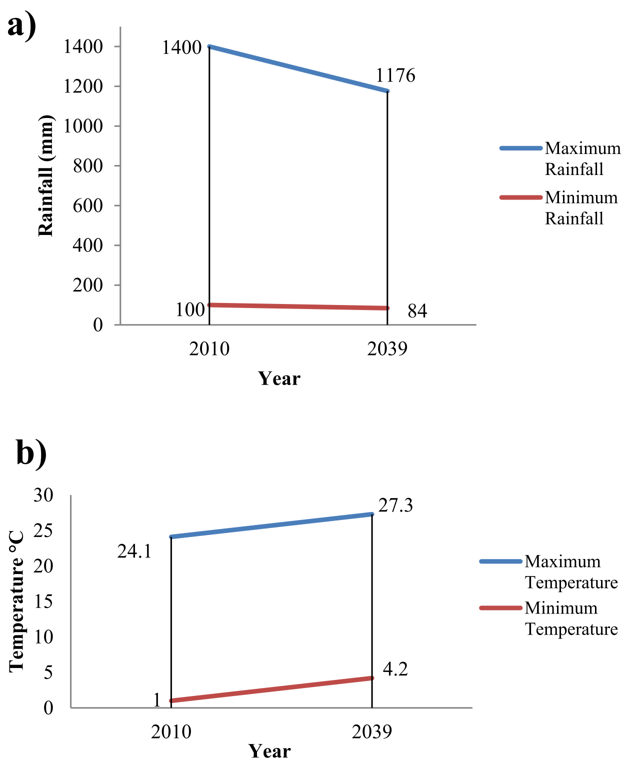

Fig. 4. (a). The impact of climate change on max and min amount of rainfall and temperature variation during the years 2010 through 2039. (b). Variation of temperature during the years 2010 through 2039.

Wetted-Perimeter method. The Varzaneh Station was selected as the most critical location of the river. Also, the mean monthly flow rate of the Zayandehroud Regulating Dam's station during 1966–2006 was employed as input data to the model, as shown in Fig. 5. Table 1 lists the modeling results, and Fig. 6 plots the flow rate versus the wetted perimeter. The point of the maximum curvature method defines the

Table 1
Results of HEC-RAS modeling at the Varzaneh station.

(Q/Q_{max})	P/P_{max}	P (m)	H (m)	A (m^2)	Q (m^3/s)
0.15	0.38	1.75	0.6	5.94	11.7
0.23	0.47	2.13	0.74	8.21	17.62
0.28	0.51	2.32	0.81	9.56	21.47
0.49	0.67	3.05	1.06	14.83	37.12
0.52	0.68	3.11	1.09	15.5	39.46
0.54	0.69	3.16	1.11	16.01	41.2
0.67	0.76	3.5	1.22	18.88	50.7
0.77	0.81	3.72	1.31	21.07	58.5
0.85	0.86	3.94	1.37	23	65.12
0.86	0.87	3.95	1.38	23.05	65.24
0.94	0.94	4.31	1.45	25.28	71.8
1	1	4.58	1.5	26.86	76.2

critical EF flow rate obtained to be 14 m^3/s. The parameters in Table 1 are: Q (Flow rate, m^3/s), A (Cross section Area, m^2), H (Water level, m), and P (Wetted-Perimeter of the cross-section, m).

2.5. Utilization of the environmental flow with integrated water resource management

The EF requirement is applied in the IWRM framework. This was accomplished by inputting water resources and their use in the WEAP model. The WEAP model consists of schematic, data, results, summary, and notes. This modeling is carried out in two stages (WEAP, 2016).

i) Graphical definition of the case study and applying the required settings and a time framework,
ii) Defining the base year and existing quantitative conditions in the intended year.

2.6. Schematic of the Gavkhouni basin

GIS (Geographic Information System) tools were used to easily set up the WEAP model. Objects (e.g., requirement nodes) were generated by GIS. The WEAP model is composed of three main components, including demand (i.e., requirements), resources, and hydrology. The red nodes represent requirements, the green nodes stand for hydrologic basins, the

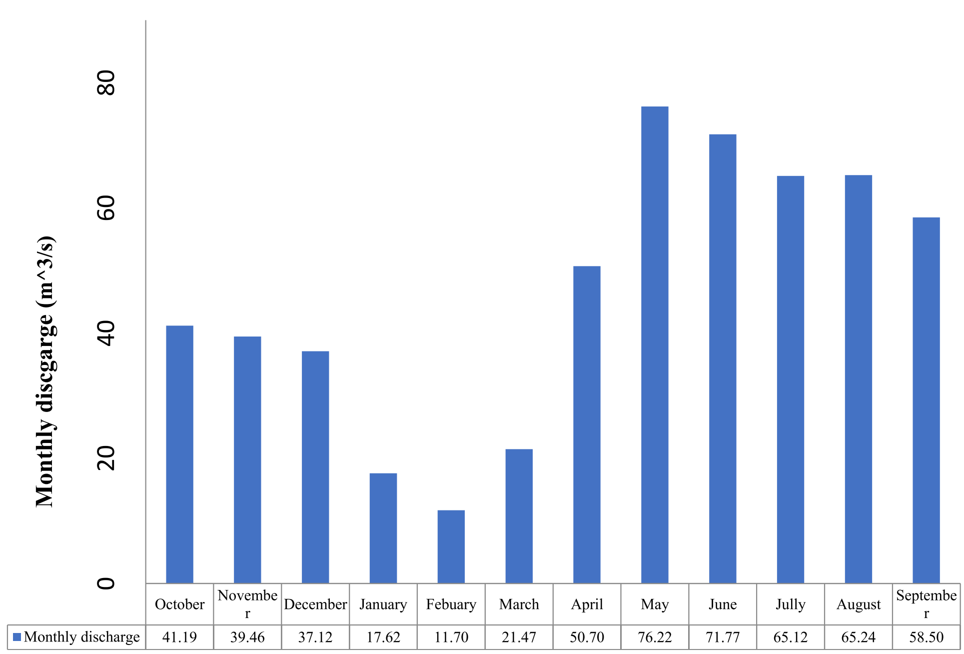

Fig. 5. Monthly discharge of the Zayandehroud Dam (1966–2006).

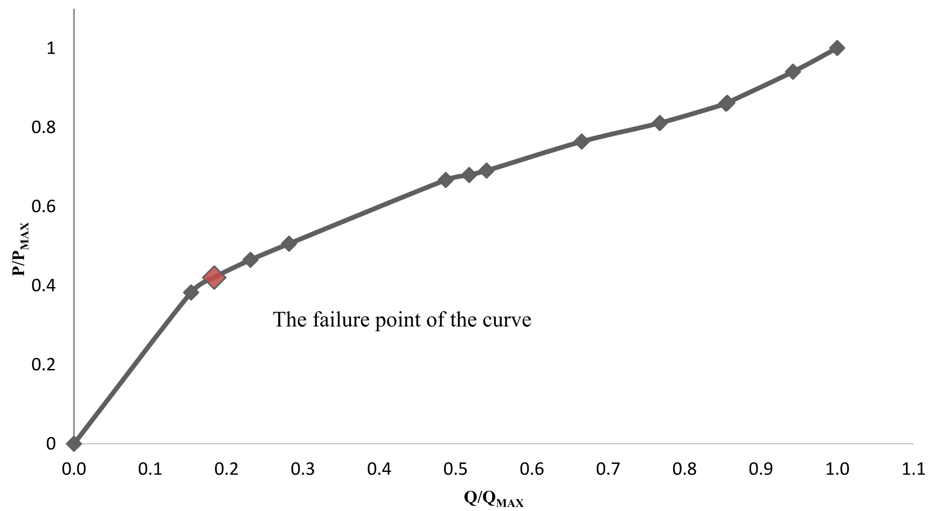

Fig. 6. Wetted Perimeter versus flow rate at the Varzaneh station.

square green nodes represent groundwater resources, and the green rhomboidal nodes stand for inter-basin water transfer resources. The red lines represent return flow and wastewater, while the green lines denote the water transfer lines from the resources to the requirements. Also, the vector files (or GIS raster) are added in the form of a layer to the model. Fig. 7 shows the schematic of the Gavkhouni basin.

2.7. *The modeling base year: 2006*

Fig. 6 shows that the Zayandehroud River's streamflow at the regulating dam location constitutes the main surface water resource in this model. Groundwater resources were added to the model according to the Iran comprehensive wastewater research scheme (2010) data. The WEAP model prioritizes water allocation using scores between 1 and 99 in a linear procedure. The supply of drinking water for urban and rural

Table 2
Water requirements in the base year (2006).

Purposes	Water demand (Mm^3)
Environment[a]	435
agriculture	1789.1
drinking	547.6
industry	213.7

[a] The Environmental demand was calculated by the hydraulic method.

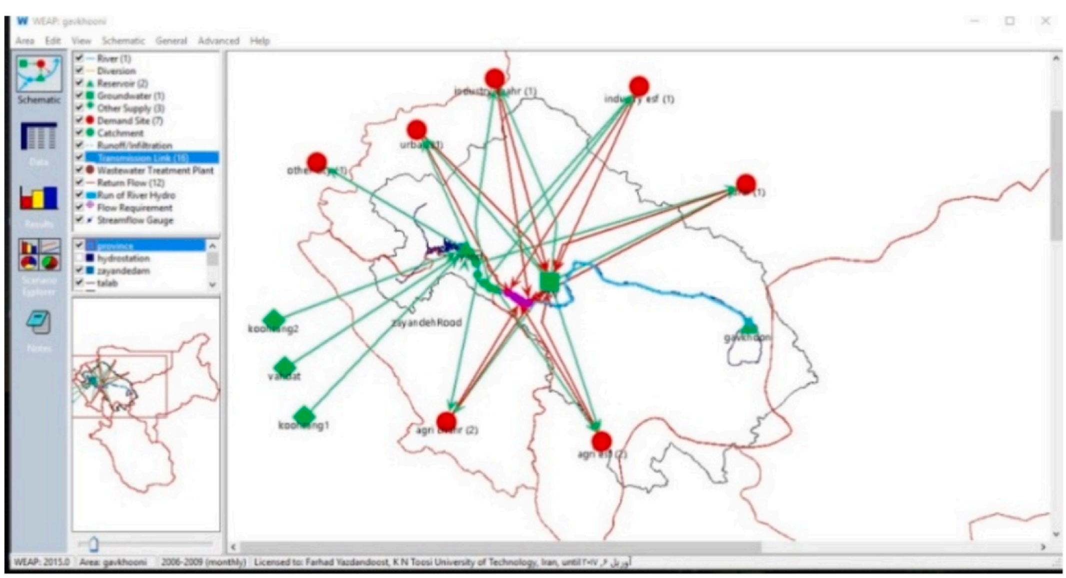

Fig. 7. The schematic of the Gavkhouni Basin in the WEAP model.
* Red nodes: Requirements
Green nodes: Hydrologic basins
The square green nodes: Groundwater resources.
The green rhombus nodes: Inter-basin water transfer resources.
The red lines: Return flow and wastewater.
The green lines: Water transfer lines from the resources to the requirements. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

areas and industrial water were assigned higher priorities than agricultural purposes. Table 2 lists the water demands in the base year (2006). The agricultural sector accounts for a large portion of the demands. Transfer of water from resources to the points of use was prioritized, and each demand was supplied first by the surface water resources and then by the groundwater resources. Table 3 lists the water-transferring projects between the Gavkhouni basin and other basins.

The year 2006 was selected as the base year for the Gavkhouni basin because it had the best available data for the Zayandehroud River than any other year. The outputs of other modeling studies in the Gavkhouni basin were used for model calibration (Kiani, 2016). Table 4 lists the modeling results in the base year. It was attempted to evaluate current modeling results with other modeling studies (Kiani, 2016). The observed differences between them originate from differences between the input data and assumptions made in different studies.

Kiani (2016) reported two types of scenarios (changing the amount of water transferred to the Gavkhouni basin, and changes in agricultural conditions). In comparison, the novelty of this work is the diverse types of scenarios that encompass multiple decisions and solutions in the Gavkhouni basin.

2.8. *Developing possible scenarios and determining principal integrated water resource management criteria*

The scenarios that were introduced based on the factors impacting water resources management in this case study are defined as follows.

1. Change of water supply priority
2. Change in the population growth trend
3. Change in return flow and water loss management
4. Changing in the amount of water transferred to the Gavkhouni basin
5. Change of demand management (consumption per capita reduction)
6. Change in agricultural conditions
7. Change in industrial conditions

The WEAP model's outputs are used based on the criteria and scenarios created in this work. This study applied water demand, unmet demand, and supply requirements based on the scenarios.

2.9. *Multi-criteria decision making applications and ranking of scenarios*

Multi-Criteria Decision making (MCDM) applications are applied to select the best alternative for management problems involving multiple criteria and alternatives. The WEAP modeling can compare a small number of scenarios, but it does not rank them.

MCDM applications are employed to rank alternative management scenarios. This wok applies an adapted entropy method to weigh the management scenarios, and the TOPSIS method was employed to rank the scenarios. TOPSIS assigns higher ranks to the management alternatives that have higher similarity to the ideal solution (Zehtabian et al., 2014). The weighting and ranking procedure of TOPSIS was coded in MATLAB.

Table 3
Water transfer projects between Gavkhouni basin and other basins.

No	Project name	Beginning catchment	Ending catchment	Project Status	The volume of transferred Water (Mm^3)
1	Dam and first Kouhrang Tunnel	Karoun	Gavkhouni	Utilization	311.7
2	Dam and second Kouhrang Tunnel-Marbaran Tunnel	Karoun	Gavkhouni	Utilization	288.7
3	Dam and Cheshmeh Langan Tunnel	Dez	Gavkhouni	Utilization	178.1

Table 4
Water demands, unmet demand in the Gavkhouni basin (2006).

Purposes	Current modeling results (Mm^3)		Other modeling results (Mm^3)	
	Water demand	Unmet demand	Water demand	Unmet demand
Drinking water	599.1	68.1	742	82
Industry	235	73.4	318	110
Agriculture	1789.1	470	1185	473
Environment	435	106.5	231	118

2.10. *Model application*

The required data were input, the base model was created, and the possible scenarios based on the circumstances of the society were identified. The model was then applied. Public participation was included to improve the chances of IWRM success. The opinions and viewpoints of those residents in impacted communities are essential in the successful management of water resources, and to gather information and sharing experiences. In this manner changes in policy and decision-making can be implemented more easily and rapidly.

3. Results

3.1. *Scenario 1: change water supply priority*

It was initially assumed in the base model that drinking and industrial water demands were of priority higher than agricultural and environmental demands in central Iran. This placed environmental demand as the lowest priority (i.e., 99). It should be noted that this scenario changed the four main demands, and different sub-scenarios were defined. Table 5 shows the results of different sub-scenarios for this scenario.

3.1.1. *Sub-scenario 1*

Drinking, industrial, agricultural, and environmental requirements are the first to fourth priorities, respectively.

3.1.2. *Sub-scenario 2*

Drinking, environmental, industrial, and agricultural requirements are the first to fourth priorities, respectively.

3.1.3. *Sub-scenario 3*

Industrial, environmental, drinking, and agricultural requirements are the first to fourth priorities, respectively.

Table 5
The results of different sub-scenarios for scenario 1.

Purposes	Base Model (Mm^3)	First Condition (Mm^3)	Second Condition (Mm^3)	Third Condition (Mm^3)	Fourth Condition (Mm^3)
Environment	186.1	121.7	97.4	75.2	8.8
Drinking water	130.1	97.8	97.8	229.4	176.2
Industry	141.4	201.1	216.4	130.4	216.4
Agriculture	480	481	483.4	483.4	483.4

3.1.4. Sub-scenario 4

Environmental, drinking, industrial, and agricultural requirements are the first to fourth priorities, respectively.

It is seen in Table 5 that making the environmental demand as the highest priority would reduce the unmet environmental demand but this would not be applicable in actuality. The second sub-scenario seems to be a better choice as it reduces both environmental and drinking unmet water demands. Fig. 8 shows the graphical differences of each demand for the sub-scenarios.

3.2. Scenario 2: change in the population growth rate

Scenario 2 predicts the drinking water demand of both urban and rural areas based on the population growth rate. Table 6 represents water demands and unmet water demands for two population changes according to the comprehensive drinking water consumption and unmet demand and wastewater of urban and rural areas (Comprehensive water scheme research for the Gavkhouni basin, 2006) and the second on the population projection by the Iran Statistical Research Institute, 2009, with the focus on Iran's population until 2026.

The population census in Iran is done every 10 years and the prediction of population growth until 2026 was shown in a report of the Comprehensive Water Scheme for the Gavkhouni "Population forecast of the country and provinces of urban and rural by 2026 (Statistical Research Institute, 2009)" By calculating population rate (r) for given years, the population in the year 2041 is determined. The population projections are made with the following equations:

$$Pn = P(1 + r)^n \quad \text{Eq (1)}$$

In which P_n, n, and r denote the population in 2041, the number of years, and the population annual growth rate, respectively; where:

$$r = \left(\sqrt[n]{\frac{Pn}{P0}} - 1\right) * 100 \quad \text{Eq (2)}$$

In which P0, denotes the population in the year (here 2026).

Two population projections were used for the scenarios. The first one was selected from the population census (the base model, Comprehensive water scheme research for the Gavkhouni basin, 2006), and the second one was calculated with equations for population growth (Iran Statistical Research Institute, 2009).

Table 7 presents the results of water demands for diverse purposes corresponding to two population projections.

3.3. Scenario 3: change in the return flow and water loss management

Various factors such as irrigation efficiency, common irrigation methods, distribution methods, topographic conditions, soil texture, the water quality of surface water, and seepage of groundwater sources cause inefficiency in water usage which some amounts of water will return to the water resources system, this is known as return flow.

The WEAP model labels return flow and water loss as "Reuse" and "Loss," respectively. The base model adds the return flow and water loss. This scenario involves two sub-scenarios that were investigated. The first one included only the use of return flow, which was performed in all sectors.

Due to the drastic changes in the cited parameters at the basin scale, the accurate determination of returned flow requires extensive field studies and measurements, which are costly and time-consuming. This work considered the return flow and loss as percentages of the water use in the model.

Treatment plants were not modeled, and the return flow according to reports in this region was assumed to increase by 10% (Comprehensive water scheme research for the Gavkhouni basin, 2006). Reusing water would be as water saving, which requires the establishment of more treatment plants in the catchment. Water treatment plants drastically increase the amount of returned flow due to the treatment of a large amount of wastewater or reused water in this region, and a large fraction of the agricultural and unmet environmental demand would be eliminated. This study only examines the percentage of return flow and loss for diverse demands, and their quality characteristics are not considered.

Table 8 lists the best use of return flow, which is associated with the second sub-scenario aimed to reduce the loss, manage lost water, and increase the reuse of water by boosting the efficiency of the water

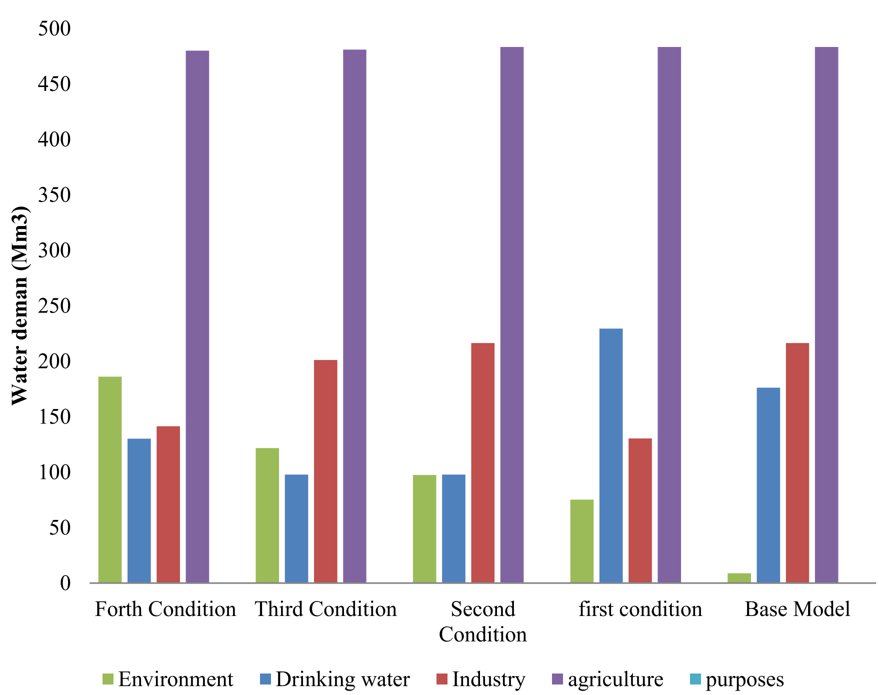

Fig. 8. Graphical representation of the sub-scenarios (first to fourth conditions).

Table 6
Water demands and unmet water demands for two population growth rates.

Purposes	Base model		Population in 2041 according to population rate	Population growth		Population in 2041 according to census
	Water demand (Mm^3)	Unmet water (Mm^3)		Water demand (Mm^3)	Unmet water (Mm^3)	
Urban drinking water	515.5	105.9	5,727,241	449	87.8	4,819,815
Rural drinking water	43.7	5.5	520,125	37.7	4.3	464,173

Table 7
Results of water demands for diverse purposes according to the population growth rate.

Purposes	Base model		Population growth	
	Water demand (Mm^3)	Unmet water (Mm^3)	Water demand (Mm^3)	Unmet water (Mm^3)
Environment	435	186.1	435	142.6
Drinking	760.2	130.1	688	94
Industry	400.5	141.4	400.5	88.2
Agriculture	1789.1	480	1789.1	476

Table 8
Best use of return flow.

Purposes	Base model		Return flow usage	
	Supply requirement (Mm^3)	Unmet water (Mm^3)	Supply requirement (Mm^3)	Unmet water (Mm^3)
Environment	483.3	186.1	457.9	66.4
Drinking	622.3	130.1	342.1	24.4
Industry	437	141.4	218.5	58.8
Agriculture	610	480	203.3	156.5

distribution network. Table 9 lists the predicted variations in unmet water demands and water supply requirements in 2041. The use of water treatment plants unmet demands would be drastically reduced by more repairs and maintenance in the irrigation and water distribution networks.

3.4. Scenario 4: changing the amount of water transferred to the Gavkhouni basin

It may be possible to transfer water from high rainfall and low population areas to low-rainfall and high population areas by several methods using water transfer structures such as canals, pipes, aqueducts. This section, evaluates the use of inter-basin transferred water projects for supplying Gavkhouni water demands, while the disadvantages of transferring water from the origin basin could not be overshadowed.

The evaluation is focused on the operation of the Kouhrang 3, Behesht-Abad, and Khadangestan tunnels, all of which transfer water from the Karoun basin to the Gavkhouni basin to reduce the amount of unmet water demand. The Behesht-Abad tunnel was designed to satisfy the industrial and agricultural water needs, while the Kouhrang 3 tunnel controls water deficiencies for drinking, agricultural, and industrial purposes, and the Khadangestan tunnel was originally planned to accomplish some objectives in the agricultural sector. Table 10 lists changes in the amount of unmet demand by allocating more water transferred by 2041. Waster is transferred directly to the Zayandehroud river.

Table 9
Water loss management.

Purposes	Base model		Loss Water Management	
	Supply requirement (Mm^3)	Unmet water (Mm^3)	Supply requirement (Mm^3)	Unmet water (Mm^3)
Environment	483.3	186.1	435	38.1
Drinking	622.3	130.1	28.6	19
Industry	437	141.4	133.5	32
Agriculture	610	480	18.4	138.9

The results show that allocating water to the river the environmental deficit would be reduced appropriately. The results presented in Table 11 show that drinking and industrial unmet water needs would be eliminated, the environmental unmet demand would be alleviated only marginally, and the environmental water deficiency could be reduced further.

The advantage of using inter-basin transferred water projects for supplying Gavkhouni water demands is evaluated next, while the disadvantages of transferring water from the origin basin are taken into account.

Inter-basin water transfer projects are intended to solve the problem of water shortage or full utilization of water resources (Zhuang, 2016). Yet, they may have adverse unintended impacts.

3.5. Scenario 5: demand management (lowering per-capita water consumption in various fields)

This scenario involves three cases.

3.5.1. Case I

Based on the data in the base year, consumption of drinking water in urban and rural areas has been much lower than water being consumed in the industrial and agricultural sectors. This area includes 21 cities; therefore, it would be expected that the levels of education and social commitment exhibited by the residents would be much higher by 2041. Accordingly, it is anticipated that the per-capita drinking water consumption in urban areas will decline to the global average. In this case, the per-capita water use in urban areas would decrease by one-half. Table 12 presents the results of the demand management scenario for Case I.

3.5.2. Case II

Based on the governmental policies for future developments, a 20% reduction in the industrial demand by 2041 has been targeted (this reduction can be realized by virtue of either drinking water uses in the

Table 10
Changes in the amount of unmet water demand by allocating transferred water by 2041.

Type	Purposes	Unmet water (Mm^3)
Base model	Environment	130.1
	Drinking	141.4
	Industry	480
	Agriculture	186.1
Transferred water to the Zayandehroud River	Environment	103.5
	Drinking	131.8
	Industry	469
	Agriculture	49

Table 11
Variations of unmet water demands by applying extra water to the use points by 2041.

Type	Purposes	Unmet water demand (Mm^3)
Base model	Environment	130.1
	Drinking	141.4
	Industry	480
	Agriculture	1,86.1
Transferred water to each demand use point	Environment	112.6
	Drinking	0
	Industry	0
	Agriculture	215.8

Table 12
Water demand management case 1 results by 2041.

Purposes	Base model		Water demand Management (1)	
	Water demand (Mm^3)	Unmet water (Mm^3)	Water demand (Mm^3)	Unmet water (Mm^3)
Environment	435	186.1	435	153.9
Drinking	760.2	130.1	502.1	63
Industry	400.5	141.4	400.5	132.1
Agriculture	1789.1	480	1789.1	476

industry or water uses at industrial workshops). Table 13 presents the results of the demand management scenario.

3.5.3. Case III

This case surveys the consideration of the two previous cases simultaneously to see the combined effect of managing demands for not only drinking water in urban areas but also industrial use. Table 14 presents the results of the demand management scenario in Case III.

3.6. Scenario 6: change in agricultural conditions

The supply of drinking and industrial water has higher priorities than the supply of agricultural water requirements due to the arid and semi-arid climates of the majority of the Gavkhouni basin.

Because of the economic conditions in Iran and the fact that the farmers do not face favorable economic conditions their living expenses will increase over time. This may increase the need for water in agriculture and increase the request of farmers for cultivating crops with a high rate of water consumption such as rice, which would increase the agricultural water demand.

Increasing or reducing under-cultivated areas were considered in two different sub-scenarios of scenario 6 based on the existing information and the effectiveness of the cultivation areas in water management.

Table 15 shows that under cultivation area remaining unchanged means nearly 73% of agricultural water demand would be supplied. Increasing cultivation area reduced agricultural water supply to 60% while decreasing cultivation area substantially raised agricultural water supply to 82% in 2041. The increased and reduced under-cultivation areas impacted the other requirements and unmet demands. Table 16 provides the variations of unmet water demand for other uses regarding changes in agricultural demand.

Table 13
Water demand management case 2 results by 2041.

Purposes	Base model		Water demand Management (2)	
	Water demand (Mm^3)	Unmet water (Mm^3)	Water demand (Mm^3)	Unmet water (Mm^3)
Environment	435	186.1	435	166
Drinking	760.2	130.1	760.2	113.9
Industry	400.5	141.4	32.6	106.7
Agriculture	1789.1	480	1789.1	479

Table 14
Water demand management case 3 results by 2041.

Purposes	Base model		Water demand management (3)	
	Water demand (Mm^3)	Unmet water (Mm^3)	Water demand (Mm^3)	Unmet water (Mm^3)
Environment	435	186.1	435	127.7
Drinking	760.2	130.1	502.1	52.7
Industry	400.5	141.4	320.6	120.3
Agriculture	1789.1	480	1789.1	469

Table 15
Change in land under cultivation and Agricultural demand by 2041.

Change in cultivation of land	Area of cultivation (m^2)	Water demand (Mm^3)	Unmet water (Mm^3)	Supply requirement (Mm^3)
Farmland area in the base model	297,786	1789.1	480	610
Decreasing farmland area	99,262	597.2	135.9	203.6
Increasing farmland area	893,358	5397.5	2153	2683.8

3.7. Scenario 7: change in industrial conditions

Isfahan Province enjoys a much higher development rate than the other provinces due to its industrial policies and geographical conditions. Table 17 lists the increased number of industrial machines and unmet demands. Table 18 provides the variations of unmet demands of other needs due to the change in industrial conditions.

The results indicate that applying a higher number of industries in the area considerably changed the environmental unmet demand and may drastically destroy the environment. Fig. 9 shows the unmet water demands for drinking and environmental purposes with respect to all the scenarios.

The unmet water demand for drinking and environmental purposes in all scenarios was compared.

3.8. Weighting and ranking scenarios

The scenario results do not identify a clear superior management alternative due to a large number of options. MCDM methods can be effective for weighting and ranking scenarios. Coding in MATLAB environment was used, as presented in Appendix 1. This study evaluates scenarios ranking criteria for drinking, industrial, agricultural, and environmental unmet demand, considering four weighing schemes for the cited scenarios. This is shown in Table 19.

Figs. 10–13 display the ranking results for the scenarios built by the WEAP with the MCDM method – the entropy method for weighting, and TOPSIS for ranking.

It is seen in Figs. 10–13 that water loss management and returning flow enhancement ranked first and second in all the scenarios, respectively. Drinking water scarcity was the most significant decision-making index, as shown in Fig. 10. Reducing water consumption per capita (or demand management) is of importance. Drinking water consumption per capita in Iran is twice larger than the global rate, which means that public awareness enhancement and proper consumption (savings) may help reduce water consumption in the scenario of demand management through culturalization. Encouraging proper civic action, raising public awareness, adequate education in schools and the community, and suitable water saving can help reduce per capita water use.

Saving water by proper consumption in industrial workshops can

Table 16
Variations of unmet water demand for other water uses regarding changes in the agricultural demand by 2041.

Purposes	Base model		Decreasing farmland		Increasing farmland	
	Water demand (Mm^3)	Unmet water (Mm^3)	Water demand (Mm^3)	Unmet water (Mm^3)	Water demand (Mm^3)	Unmet water (Mm^3)
Environment	435	186.1	435	171.4	435	462.2
Drinking	760.2	130.1	515.5	135.7	515.5	157.5
Industry	400.5	141.4	366.7	152	366.7	156.3
Agriculture	1789.1	480	597.2	135.9	5367.5	2153

Table 17
Increasing the number of industrial machines and unmet water demands by 2041.

Basin	Water demand (Mm^3)	Supply requirement (Mm^3)	Unmet water (Mm^3)	Water demand (Mm^3)	Supply requirement (Mm^3)	Unmet water (Mm^3)
Gavkhouni	400.5	437	141.4	641.1	699.4	270

Table 18
Unmet water of other purposes due to a change in the industrial conditions.

Purposes	Base model		Change in Industry
	Water demand (Mm^3)	Unmet water (Mm^3)	Unmet water (Mm^3)
Environment	435	186.1	328.9
Drinking	760.2	130.1	172.2
Agriculture	1789.1	480	481

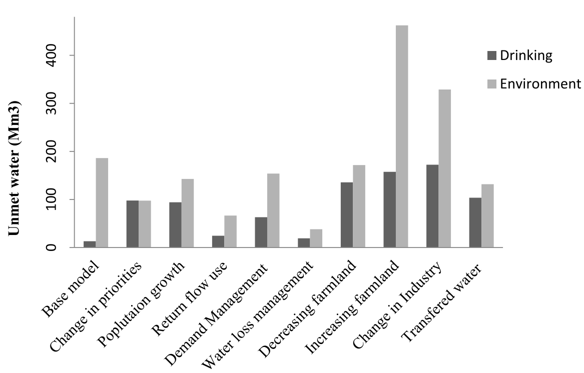

Fig. 9. Unmet water demand for drinking and environmental purposes corresponding to all the scenarios.

Table 19
Four situations to weigh the cited scenarios.

First scheme	Second scheme	Third scheme	Fourth scheme
Drinking Unmet water	Drinking Unmet water	Industrial Unmet water	Environmental Unmet water
Industrial Unmet water	Environmental Unmet water	Environmental Unmet water	Drinking Unmet water
Agricultural Unmet water	Industrial Unmet water	Drinking Unmet water	Industrial Unmet water
Environmental Unmet water	Agricultural Unmet water	Agricultural Unmet water	Agricultural Unmet water

reduce the per capita water use. The population growth trend change can also reduce drinking water demand by 2041. Adding more transferred water to the Gavkhouni basin by diverse hydraulic structures, changes in priority of requirements, and under-cultivated area reduction were placed in the subsequent ranks.

The second weighting scheme switched the environmental demand from the fourth priority to the second one as shown in Fig. 11. Similar to the first weighting water loss management, returning flow enhancement, and demand management were ranked first to third, respectively. The enhancement of water transfer to the catchment, population growth modification, and changes in priority of requirements was placed in the next ranks. The under-cultivation area enhancement, industrial changes, and the maintenance of the current situations in the area (control model) were found to be inappropriate scenarios according to this weighting.

As shown in Fig. 12 the third weighting scheme is unrealistic as industrial unmet water demand was considered to be more important than drinking water and environmental purposes. Demand management, population growth rate modification, and addition of water transferred to the basin were found to be much more effective to cope with water scarcity. It would be found that change in priority requirements (decreasing priority of industrial water demand), under cultivation area increase, and the growth of industrial workshops would significantly worsen the water-supply problem.

The fourth weighting scheme considers unmet environmental demand to be the most important, as shown in Fig. 13. Water transferred in addition to the catchment was found to be of the highest importance. Demand management and water consumption reduction in other applications, changes in priority of requirements, and under cultivation area reduction stand in the next ranks to reduce the environmental unmet water demand. It is obvious under cultivation growth and industrial workshops addition in the area would worsen the environmental demand.

Considering the objectives of the study and the importance of environmental unmet water the first and fourth weighing schemes were found to be of the highest importance, which is reported in Tables 20 and 21.

4. Discussion

This study evaluated the water management problems in the Gavkhouni basin by developing an analytical evaluation package of the EFs with an IWRM approach for optimal water resource allocation, prevention of improper water resource consumption, and preservation of resources for the future using multicriteria decision making.

The EF was calculated with the hydraulic method. The EF for the Zayandehroud River was calculated to be 14 m^3/s equivalents to 441.5 Mm^3/yr. This amount would revitalize the Gavkhouni basin. The WEAP model was used for managing resources and water use from present until 2041. Drinking, environmental, industrial, and agricultural water demands were prioritized to diminish the environmental unmet water demand.

Results indicate that the annual drinking water requirement would be 760.2 Mm^3 by the year 2041. The annual industrial and agricultural water requirements are estimated to be 400.5 $Mm^3$and 1789.1 Mm^3, respectively. The annual unmet drinking water demand, environmental unmet demand, industrial, and agricultural unmet water demands are

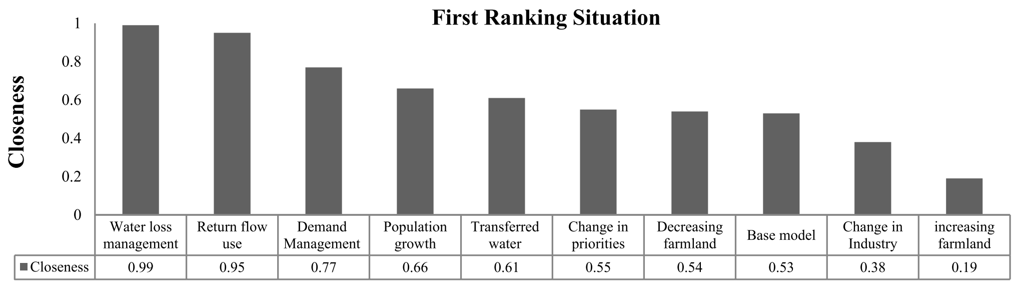

Fig. 10. Ranking results of the MCDM method for the first ranking scheme (the entropy method for weighting and TOPSIS for ranking were used).

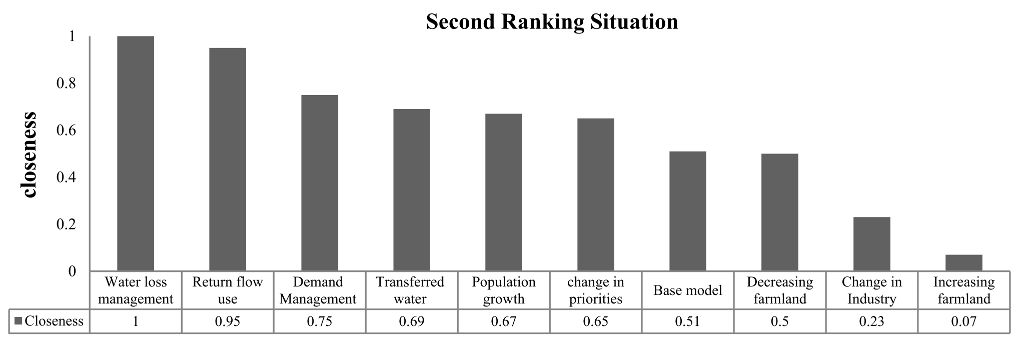

Fig. 11. Ranking results of the MCDM method for the 2nd weighing scheme (the entropy method for weighting and TOPSIS were used for ranking).

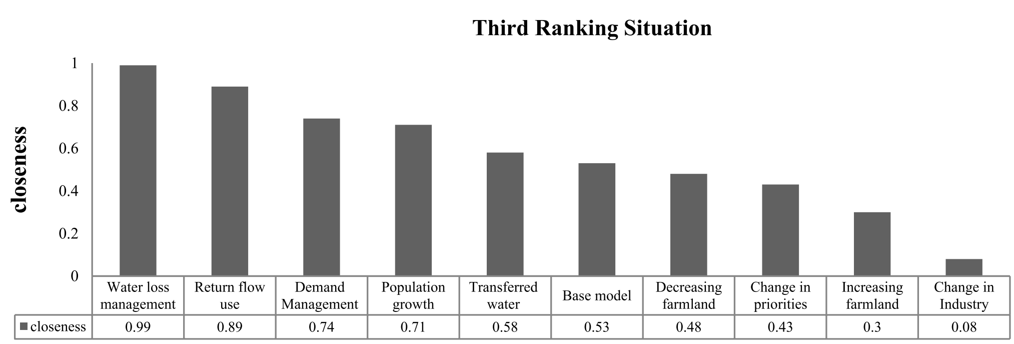

Fig. 12. Ranking results of the MCDM method for the 3rd weighing scheme (the entropy method for weighting and TOPSIS for ranking).

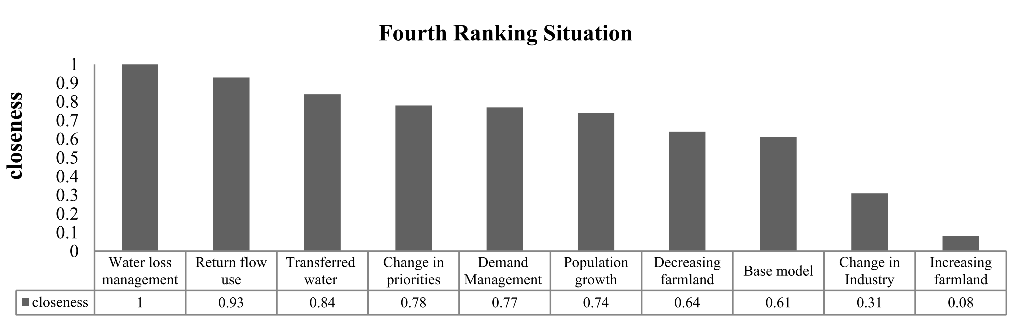

Fig. 13. Ranking results of the MCDM method for the 4th weighing scheme (the entropy method was used for weighting and TOPSIS for ranking).

Table 20
Results of ranking scenarios for the first weighing scheme.

Rank	Scenario	Unmet water (Mm^3)			
		Drinking	Industry	Agriculture	Environment
1	Water loss management	19	32	138.9	38.1
2	Return flow use	24.4	58.8	156.5	66.4
3	Demand Management	52.7	102.3	469	127.7
4	Population growth	94	88.2	476	142.6
5	Transferred water	103.5	131.8	470	49
6	Change in priorities	98.8	216.4	483.4	97.4
7	Decreasing farmland	135.7	152	135.9	171.4
8	Base model	130.1	141.4	480	186.1
9	Change in Industry	172.3	270	481	328.9
10	Increasing farmland	157.5	156.3	2153	462.2

Table 21
Results of ranking scenarios for the 4th weighing scheme.

Rank	Scenario	Unmet water (Mm^3)			
		Drinking	Industry	Agriculture	Environment
1	Water loss management	19	32	138.9	38.1
2	Return flow use	24.4	58.8	156.5	66.4
3	Transferred water	103.5	131.8	470	127.7
4	Demand Management	52.7	102.3	469	97.4
5	Change in priorities	97.8	216.4	483.4	142.6
6	Population growth	94	88.2	476	171.4
7	Decreasing farmland	135.7	152	135.9	186.1
8	Base model	130.1	141.4	480	328.9
9	Change in Industry	172.3	270	481	328.9
10	Increasing farmland	157.5	156.3	2153	462.2

estimated to be 130.1, 186.1, 141.4, and 480 Mm^3, respectively. The results reveal that the Gavkhouni basin is currently suffering from water scarcity in all sectors. Diverse scenarios are applied for predicting the reduction of unmet environmental water demand by 2041.

The First scenario focused on the priority of minimizing the environmental unmet demand. By 2041 the environmental, industrial, agricultural, and drinking unmet demand is projected to be 97.4, 216.4, 483.4, and 97.8 Mm^3, respectively. In the Gavkhouni basin, the environmental requirement has not been taken into account, a large portion of the environmental demand will be met by placing environmental demand as the second priority.

The second scenario changed the population growth and approximately evaluated the required water demands and predicted unmet demand on the year 2041.

The third scenario focused on the amount of water lost the water distribution and irrigation networks. Water may be diverted from these networks by inhabitants near the water inlets and less water is available downstream. It is necessary to plan for annual maintenance of the water distribution system network to minimize leakage to reduce the supply requirements (Al-Shutayri et al., 2019).

Using new technology in irrigation methods, land leveling, and energy-saving projects in irrigation and agriculture sectors would reduce leakage and save energy properly (Ramadan et al., 2019). A surface water drainage system like pipe, tunnels, or aqueducts would be advantageous to reduce water scarcity in the Gavkhouni basin.

Moreover, wastewater treatments plants can release large amounts of treated wastewater and return flow which can be utilized in the agricultural, industrial, and environmental sectors. This option was not evaluated in this study because of a lack of reliable data and political constraints existed in this basin. A study in the Nile basin indicated that the increased number of water treatment plants keeps water quality within regulatory requirements (Ramadan et al., 2019).

The fourth scenario was about changes in the amount of inter-basin water transferred to the Gavkhouni basin. Water transferred to the Gavkhouni basin reduces Environmental problems. Kiani (2016) revealed that inter-basin transferred water can eliminate unmet water demands in the agricultural and environmental sectors. Results of the current study revealed that inter-basin transferred water from other regions increases conflicts and challenges among neighboring provinces and it is not a socially appropriate method in all cases.

The fifth scenario showed that although unmet drinking water demand can recover from water management and water consumption per capita reduction; this has no significant impact on eliminating the environmental unmet demand by the year 2041. Proper management decreases the annual Environmental unmet demand by 58 Mm^3.

Al-Shutayri et al. (2019) in Jeddah (Saudi Arabia) reported that it is necessary to apply a water management plan to conserve water in households. Ramadan et al. (2019) in the Nile basin study involved the public and private sectors in managing water consumption. Shahraki et al. (2019) revealed recent policies providing water supply for one million people and managing drinking water shortage by reducing domestic water use and reducing per capita water use have a positive effect on the increase of water flow.

Under the six scenarios if the agricultural demand remains in third priority excessive withdrawal of groundwater will occur. This will increase the annual environmental unmet water demand to 462.2 Mm^3. By decreasing the cultivated area the unmet annual environmental water demand would be 171.4 Mm^3 by 2041.

Since different studies in Iran also emphasised that water consumption in agriculture sector is at the highest level (Shahraki et al., 2019), so increasing irrigation efficiency in the agricultural sector; could be considered as a solution to reduce the total water demand. A Nile basin study showed that using new technology in irrigation methods, land leveling, and energy-saving projects in irrigation and agriculture sectors have multiple benefits (Ramadan et al., 2019).

The reduction of the area under cultivation has a key role on unmet agricultural water use. Other studies in Jeddah, Saudi Arabia, explain this similarly and that work recommends a strong institutional framework between water planners and decision-makers to better implementation of water conservation and reuse of treated wastewater for agriculture (Al-Shutayri et al., 2019).

The seventh scenario introduces a large number of industries and the annual environmental unmet demand reaches 328.9 Mm^3, which may be harmful to the environment.

Scenarios ranking was done with MCDM for choosing appropriate management alternative in the study basin. Some specific hydrologic conditions of arid and semi-arid regions (e.g., rare and dispersed rainfall) limit access to surface resources, excessive population growth, increasing water demand, competition, extensive contamination of surface water and groundwater resources, and above all these challenges, climate change, drought, and human activities may reduce the scarce water resources in the Gavkhouni basin and impose severe hardship on society in the absence of an IWRM approach.

5. Conclusions

In this study IWRM in the Gavkhouni basin were evaluated with 7 scenarios to create a mind map for minimizing the environmental and total unmet water demand in the Gavkhouni basin in the year 2041. This contributes to making sustainable water management, preserving the natural environment, and biological values of the study basin. The following conclusions make a bridge for meeting the environmental unmet demands.

- Management of water losses can increase irrigation efficiency aand decrease waste from water distribution networks. The agricultural sector is recommended to adopt innovative methods of irrigation such as sprinkler irrigation and drip irrigation and repair the old irrigation system.
- Demand management can be performed by underestimated actions in this basin such as modifying water consumption, culturalization, changing water consumption patterns, and public participation.
- Wastewater treatment plants would have a significant impact on reducing the unmet water demand. This study assumes that returning flow would be a portion of the water use. To improve accuracy, it is recommended to model wastewater treatment plants in the area.
- Inter-basin water transfer projects to the Gavkhouni basin play an effective role in meeting the environmental water demand. However, such constructions would lead to public dissatisfaction in the origin basins and also, bring water deficiency in the origin basin, which complies with inter-basin water transfer rules and act as a hinder.
- Decision-makers must incorporate environmental water requirements as a particular component in their decisions and consider the EF with available methods. It is recommended to use methods requiring much more input data and is more accurate. For instance, additionally, the habitat simulation method requires hydrological and hydraulic factors, biological parameters, and habitat conditions of the dominant species.
- It is highly recommended to study climate change effects which require more significant investments for field measurements and experiments to result in more reliable and accurate data.
- This study revealed a toolbox for including EF in IWRM approaches. For adding more detailed inquires, it is highly recommended stakeholders consider economic, political, social perspectives.

CRediT authorship contribution statement

Elnaz Zehtabian: Writing – original draft. **Reyhaneh Masoudi:** Writing – original draft. **Farhad Yazdandoost:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.136339.

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