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Integrated Planning of Water Resources Based on Sustainability Indices, a Case Study: Hamoon- Jazmorian Basin

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Abstract

Nowadays, the water supply and water demand management are the main issues in water resources planning. It is more important in a river basin with a complex system facing with droughts, climate changes, inter-basin water transfer and operational and under study dams. In this paper, for water resources planning in a river basin and reducing the difference between water resources and water demands, the river basin conditions are assessed under different scenarios. In order to simulate the water resources and demands in the future, the MODSIM is used for river basin modeling. To calibrate the developed model, historical values of groundwater table fluctuations in different plains and flow changes in different hydrometric stations, are compared with the results of MODSIM. Then some indices based on three criteria including water and environmental resources sustainability, economic sustainability and social equality are defined to evaluate the scenarios. The indices are quantified and explained in current and future conditions. The results show the higher performance of Scenario 4 including the execution of under study projects along with demand management and aquifer restoration.

Keywords: River basin planning, MODSIM, Sustainable indices, Integrated water resources

Introduction

Water scarcity and decreasing water quality has forced many countries to review and revise their insight on water resources management. Recently, the viewpoint of water resources management based on increasing water supply for water demands, has changed to comprehensive consideration based on water demand.

Before 1990s, management decisions on different aspects of water resources (such as water quality, groundwater, water supply and health, irrigation, hydropower, etc.) usually had been made separately and independently in different disciplines. Whereas advanced water management attends antithetical profits through coordinated and multidisciplinary ways including social, economic and environmental considerations. This approach is called integrated water resource management (IWRM) which is towards the concept of the sustainable development.

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One of the challenges for integrated water resources management and sustainable development is to cover the imbalance in economic, social and environment factors. IWRM is not an aim by itself but it is a means to achieve a premier goal that indeed is sustainable development. Sustainable development is possible by recognition of regional potentials whether with agricultural, industrial, or tourist etc. flourishing.

There are several socio- economic and natural factors in integrated approach (cohesion) that are known as three columns of sustainability:

1. Economic efficiency of water consumption
2. Social equality: people' right to access to water with appropriate quantity and quality.
3. Environmental and ecological sustainability (UN-GWP, 2007)

The concept of IWRM at the basin area was established about 40 years ago by the global association of water resource in scientific meetings (Braga, 2001). But, nowadays IWRM is a worldwide and known criteria and index (Swatuk , 2005). According to the report that the global water partnership (GWP), UNDP, UNEP and the Japan Water Forum have presented in the fourth world conference on water in 2006, many countries have planned to achieve this goal since 2002. Also in 2006, the UN secretary asked all of countries to provide the progress report of development of IWRM and water efficiency in 2008 considering the suggestions of the UN water and wastewater council (UN-GWP, 2007).

Although researchers have paid particular attention to application of water resources planning models, sustainable development indices is often missing in assessment of river basin conditions. Dai and Labadie (2001) used MODSIM model for stimulation of river basin network with regard to water quality constraints. In this study, they linked MODSIM and Qual2E to simulate the quality of irrigation return flow with the aim of maintaining quality thresholds in the river and agreement between consumers regarding their water rights priorities. Cai et al. (2002) used a long-term modeling framework which uses quantified sustainability criteria in a long-term optimization model of a basin, ensuring risk minimization in water supply, environmental conservation, equity in water allocation, and economic efficiency in water infrastructure development. Lanini et al. (2004) developed an integrated model of a watershed to be used as a tool to make debates and consultations between stakeholders to enhance the participatory process. They used knowledge and expertise of geological, hydro-geological and hydrological features of the catchment basin to develop a conceptual model of the socio- hydro-system of a case study. Davis (2007) explained the principles of integrated water resources management and introduced participation of shareholders in the implementation of integrated management process as a way to support social goals.

Baloch and Tanek (2008) described major environmental resource management issues in the light of Balochistan Conservation Strategy (BCS) and recommended Integrated Watershed Management (IWM) as an integrated holistic approach towards problem identification and management. The legal, institutional and participatory components for implementation of an IWM plan in Balochistan are also considered. Savenije and Zaag (2008) reviewed water security as well as water conflict and then concluded with an analysis of the role of the IAHS International Commission on Water Resources Systems (ICWRS) in promoting IWRM.

Shourian et al. (2008) presented a MODSIM generalized river basin network flow model, with the capability of simulating various characteristics and features of water resources in a river basin, and Particle Swarm Optimization (PSO) algorithm. In the developed PSO-MODSIM model, the size of planned dams and water transfer systems, as design variables, and the relative priorities for meeting reservoir target storages, as operational variables, are varied and evolved using PSO algorithm. Ahmadi et al. (2012) developed a new model to connect three groups of decision makers in pollution control, agricultural agency and water authority considering economic, environmental and social aspects. A Genetic Algorithm based optimization model incorporates the uncertainty of water quality data while maximizing agricultural production upstream, mitigating the unemployment impacts of land use changes and providing reliability of water supply downstream of the watershed.

The main novelty of this paper is to quantify the future condition of the river basin utilizing a combination index based on the certain criteria. The criteria are calculated based on the results of a water planning model of a river basin during a planning horizon. Some scenarios are defined for evaluating different internal and external causes. Therefore, this paper proposed an algorithm to assess future condition of a river basin and decide about water development projects. Therefore, different elements of this paper are including development of a water resources planning model, model calibration, defining some operation scenarios, defining of some sustainable development criteria, defining a combination index and ranking the scenarios based on the sustainable development index.

Materials and Methods

In order to investigate basin area conditions in terms of supply of water demands including domestic, industry, agriculture and environmental sectors, the current (year 2007) and future (35 year later) conditions of the basin are simulated. The water resources allocation is modeled in MODSIM environment. The developed scenarios are evaluated by economic, environmental and social criteria. Then a combination index based on the criteria utilizing analytic hierarchy process (AHP) method is developed and quantified for different sceneries. Finally the best management scenario is selected.

The water resources planning model

MODSIM, a generalized river basin network model, developed by Labadie (1970) has been used to simulate operations of river systems. Links and nodes in MODSIM represent physical, hydrologic features of a river basin system, and artificial and conceptual elements for modeling water allocation systems. An example of a network modeled in MODSIM is shown in Figure 1. Although MODSIM is a simulation model, an optimization approach provides a tool for assuring allocation of flows in a river basin considering water rights and other priority rankings $t = 1,...,T$ as follows (Labadie, 2007):

$$Min \sum_{k \in A} c_k q_k \tag{1}$$

$$s.t.$$

$$\sum_{k \in O_i} q_k - \sum_{j \in I_i} q_j = b_{it}(q) \quad \forall i \in N \tag{2}$$

$$l_{kt}(q) \le q_k \le u_{kt}(q) \qquad \forall k \in A \tag{3}$$

where N is the set of nodes, A is the set of arcs or links in the network, O_i is the set of links originating at node i (i.e., outflow links); I_i is the set of all links terminating node i (i.e., inflow links); q_k is the integer valued flow rate in link k, c_k are the costs, weighting factors, or priorities per unit of flow rate in link k; b_{it} is the (positive) gain or (negative) loss at node i at time t, and $l_{kt}, u_{kt}(q)$ are specified lower and upper bounds, respectively, on flow in link k at time t. The priority order of the water demands to be met is considered as domestic, industry, agriculture and environment during current condition in developed model. The priority order is changed to domestic, environment, industry and agriculture for assessing future conditions.

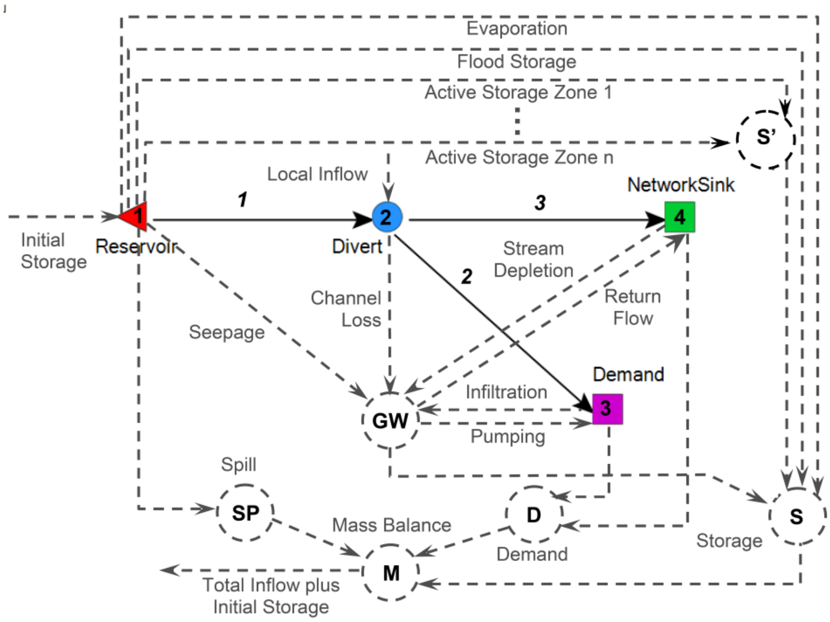

Figure 1. Illustration of MODSIM network structure with artificial nodes and links

Application of Analytical Hierarchy Process (AHP)

The AHP was developed by Saaty (1980 and 1990) and has been widely used in both fields of theory and practice. This method is based on pair-wise comparison of the importance of different criteria and sub-criteria. The consistency of comparisons could be verified.

The difference between the dominant eigenvalue, λ_{max}, and k (dimension of pair-wise comparison matrix) is defined by as the Inconsistency Index, II Saaty (1980 and 1990):

$$II = \frac{\lambda_{\max} - k}{k - 1} \quad (4)$$

The Inconsistency Ratio, IR is then defined as:

$$IR = II / CRI \quad (5)$$

Where, CRI is the Inconsistency Index of the random matrix obtained by calculating II for randomly filled n by n matrix. If $IR < 10\%$, then the consistency criterion is satisfied otherwise the decision maker should be asked to revisit the pair-wise comparisons. This procedure continues until all pair-wise comparisons satisfy the consistency criterion. The eigenvector of pair-wise comparison matrix is then used for estimating the relative weight (importance or priority) of different alternatives. For more information about AHP, the readers are referred to Saaty (1980 and 1990).

Sustainability indices

In order to evaluate the basin sustainability of water resources in a river basin, certain criteria are selected containing environment, economic and social criteria considering IWRM approach. Table 1 presents the criteria, their characteristics and their calculation method. After applying the water resources planning model in a case study, the best scenarios is selected through quantifying the sustainable development criteria.

Table 1. Selected indices for evaluating different scenarios

Name of index	Unit	Index calculating	Index commentary
Domestic,, industrial and agricultural supply	%	Ratio of allocated water to water demand	Supply of 100% domestic and industrial water needs and supply of more than 90% agricultural water demand are assumed to be acceptable.
Environmental water rights supply	%	Ratio of allocated water to water demand	The amounts are appropriate more than 90 percent
Relative water stress	-	Ratio of water allocation to renewable water resources in the basin area	Water stress and water scarcity conditions will be experienced for values exceeding 0.2 and 0.4, respectively. A threshold of 0.4 signifies severity of water stressed conditions.
Dependence on groundwater	%	Ratio of water withdrawal from the aquifer to total surface and groundwater consumption in the basin area	Less than 26 percent: Low dependence Between 25 to 50 percent: Average dependence More than 50 percent: High dependence
Groundwater development	%	Ratio of water withdrawal from the aquifer to the renewable groundwater resources	Less than 25 percent: potential Between 25 to 40 percent: Conditional potential More than 40 percent: No potential
Aquifer sustainability	-	Ratio of water withdrawal from the aquifer to the aquifer recharges	More than 1: Critical Between 0.8 to 1: Very Unsustainable Between 0.6 to 0.8: Sustainable Between 0.4 to 0.6: Low sustainable Less than 0.4: Sustainable
Groundwater resources attenuation period	-	Ratio of static volume of the aquifer to the aquifer annual withdrawal of aquifer	Less than 10: High potential Between 10 to 30: Average potential Between 30 to 50: Weak potential More than 50: No recovery
Irrigation efficiency	%	Ratio of water consumption to water supplied	-
Conflicts	-	The number of conflicts between stakeholders/ water users in the basin	-
Agricultural water productivity	Kg/m3	Ratio of agricultural productions to water consumption	2 Kg/m3is considered for suitable future horizons

The case study

Hamoon- Jazmorian basin is located in the south- eastern part of Iran. The area of basin is approximately 69390 square kilometers covered parts of Sistan and Baluchistan and East and Kerman provinces. Hamoon- Jazmorian basin consists of approximately 48 percent mountain areas and 52 percent plains, foothills and salt marsh. In the basin all of rivers and streams flow toward Hamoon- Jazmorian Lake. Hamoon- Jazmorian is not considered as registered wetlands; however it is formed as a lake or a temporary water zone because of flood drainage in some wet years. Halil and Bampour rivers are main drainage systems. The location of Hamoon- Jazmorian basin area is presented in Figure 2.

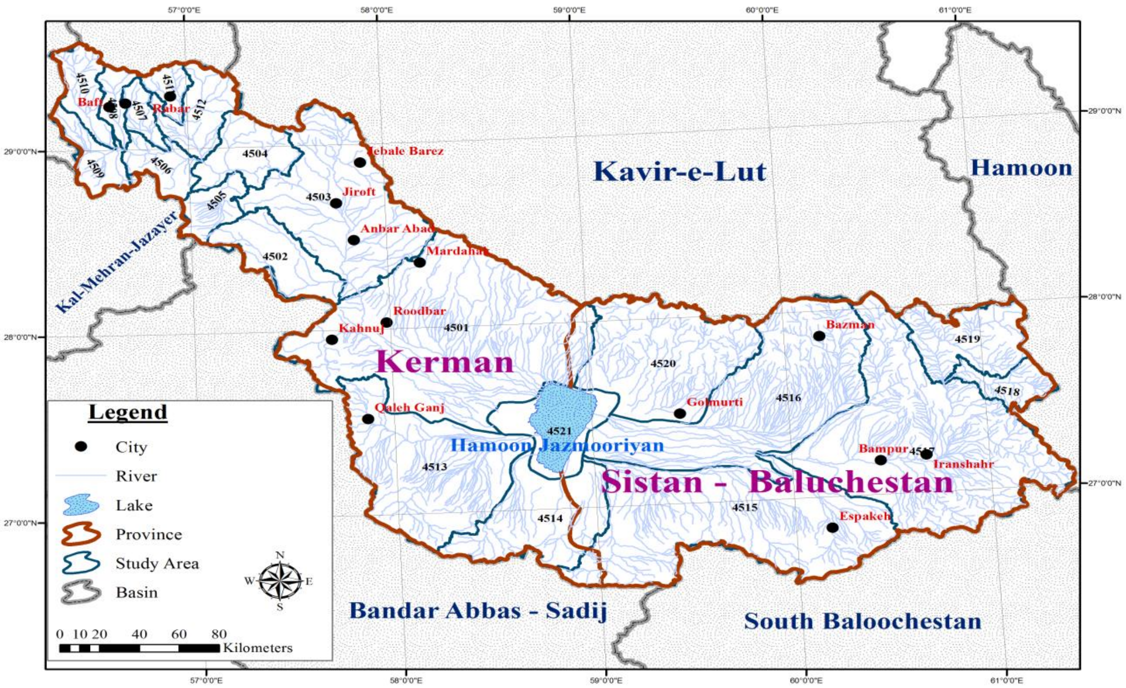

Figure 2. The location of Hamoon- Jazmorian basin area

Agriculture sector in this basin area is the greatest water consumer in comparison with domestic and industrial sectors. In the current situation, despite the low irrigation efficiency, a large number of basin area is allocated to agriculture. In addition increasing groundwater withdrawal is considered as a serious threat for water resources. Figure 3 shows water demands of Hamoon- Jazmorian basin area of different sectors in the current and future conditions. If water demand management is performed with irrigation efficiency improvement, the future water demands will be reduced.

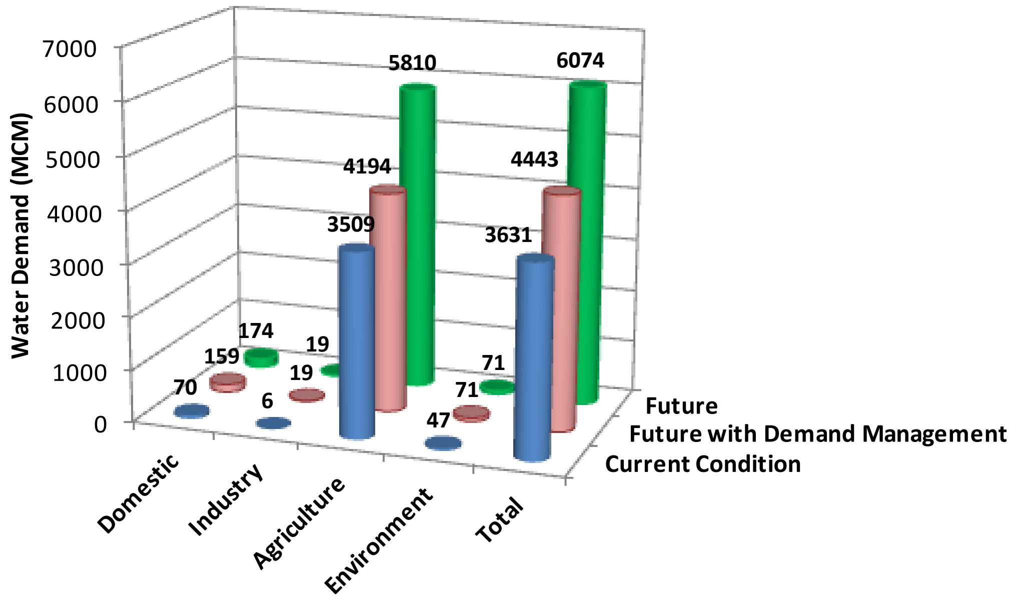

Figure 3. Water demands of different sectors of Hamoon- Jazmorian basin area in current and future conditions

Results of applying the proposed methodology

Results of water resources planning model in a river basin

Figure 4 shows Hamoon- Jazmorian basin modeled in MODSIM environment. In this Figure, nodes present water demands of domestic, industrial, agricultural and environmental sectors of the study area. The links are provided between the water demand nodes and surface and groundwater resources. One of the novelties of this paper is modeling of groundwater resources in MODSIM environment. In the model, aquifers are considered as reservoirs. In each aquifer, the water table fluctuations are reported based on the aquifer storage.

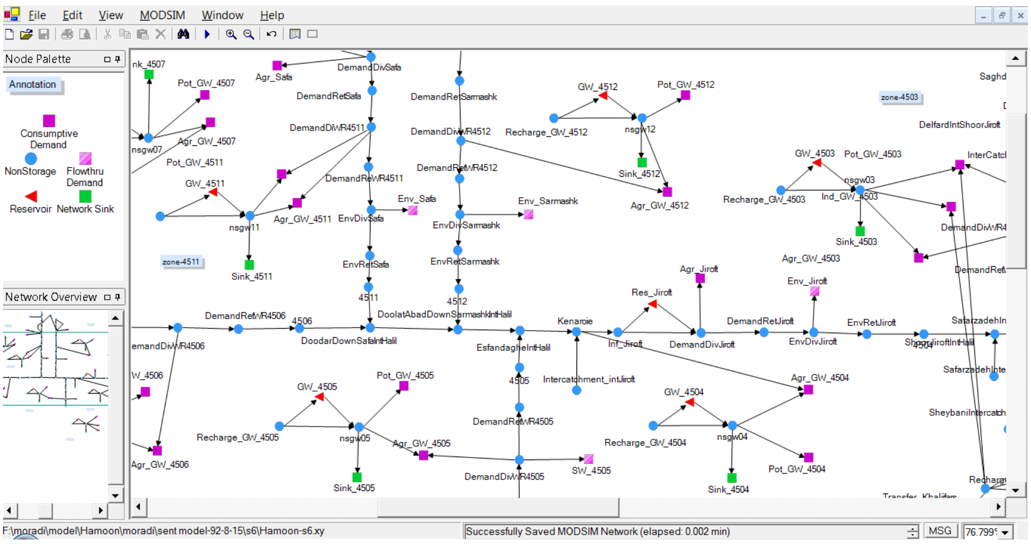

Figure 4. Modeling of Hamoon- Jazmorian basin area in MODSIM software

In order to calibrate the water resources planning model, the results of the developed model including changes in groundwater table in the aquifers and inflow at hydrometric stations are compared with historical values. Figure 5 presents inflow at Safarzedeh station on Halil River simulated in MODSIM in comparison with the historical values.

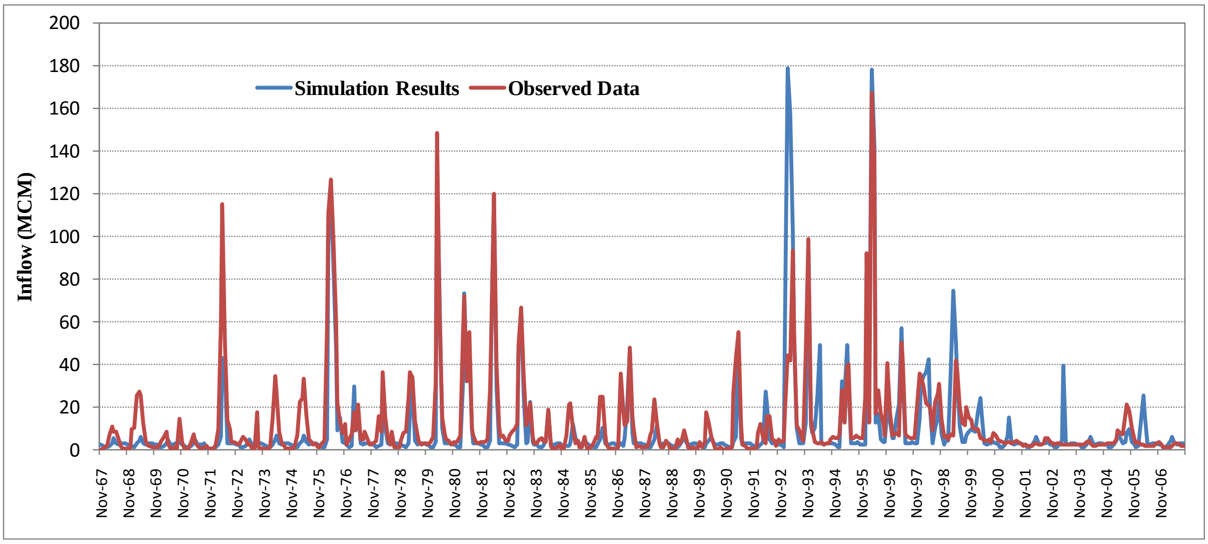

Figure 5. The calibration results of the water resources model in Safarzadeh station on Halil River

In order to show a projection of the basin area conditions in the future, different scenarios are defined based on changes of agricultural, domestic and industrial water demands. The other issues such as irrigation efficiency improvement, operation of water development projects and applying aquifer restoration policies are considered. Therefore, four scenarios influenced of internal and external factors of the river basin are defined and presented in Table 2.

Table 2. Summary of water resources planning scenarios of Hamoon- Jazmorian basin area

Name of scenario	Scenario definition	Agriculture		Domestic water demand	Industrial water demand
		Water demand	Irrigation Efficiency		
Scenario 0	As a base scenario, the river basin conditions are modeled in year 2007.	Existing agricultural water demands	Present	Existing domestic water demand	Existing industrial water demand
Scenario 1	Higher water demands in 35 years later; no water resources development project is operated. The conditions of water resources and discharge from the groundwater resources are considered in existing condition.	Computing agricultural water demand in the future of planning (In terms of adding executive and studies projects)	Present	Future domestic water demand	Future industrial water demand
Scenario 2	Scenario 1 + water resources development projects are operated	Computing agricultural water demand in the future of planning (In terms of adding executive and studies projects)	Present	Future domestic water demand	Future industrial water demand
Scenario 3	Scenario 2 + Demand management	Computing agricultural water demand in the future of planning (In terms of adding executive and studies projects) considering irrigation efficiency improvement	Development	Future domestic water demand	Future industrial water demand
Scenario 4	Scenario 3 + Aquifers restoration	The agricultural water demand from the aquifer or groundwater withdrawal should be reduced until the aquifer deficits become zero	Development	Future domestic water demand	Future industrial water demand

The developed MODSIM model is revised accordingly for each scenario and then is run to obtain the water supply of different water demands. Table 3 shows the calculated indices for different scenarios based on the modeling results.

Table 3. Indices quantitative results for evaluating different scenarios

Index	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Domestic water demand supply (%)	99 High	98 High	99 High	99 High	99 High
Industrial water demand supply (%)	100 High	99 High	99 High	99 High	99 High
Agricultural water demand supply (%)	98 High	63 Average	66 Average	89 Average	93 High
Environmental water rights supply (%)	92 High	92 High	90 High	90 High	90 High
Relative water stress	0.92 Extreme water stress	0.97 Extreme water stress	1.00 Extreme water stress	0.97 Extreme water stress	0.85 Extreme water stress
Dependence on groundwater (%)	86 High	87 High	84 High	84 High	80 High
Groundwater development (%)	112 No development	119 No development	118 No development	115 No development	98 No development
Aquifer sustainability	1.12 Critical	1.19 Critical	1.18 Critical	1.15 Critical	0.98 Extremely Unsustainable
Groundwater resources attenuation period	14 Average	13 Average	13 Average	13 Average	14 Average
Irrigation efficiency	41 Average	41 Average	41 Average	57 Average	57 Average
Aquifers deficit (MCM)	-339 High	-525 High	-515 High	-459 High	0 No deficit

The results of water supply of domestic, industrial, agricultural and environmental sectors for different sectors are presented in Figure 6. The results show domestic and industrial water demands in all scenarios is almost fully supplied. According to increasing the irrigation efficiency in demand management scenarios (Scenarios 3 and 4), the percentage of agricultural water demand supply is significantly improved. The water supply improvement has been growing better in scenario 4, because in this scenario the agricultural water demands are decreased until the aquifer deficit become zero. In this scenario, the conditions become more balanced and deficiencies have been close to the permitted range assuming that agricultural cultivated area will be reduced as the largest consumer of groundwater resources.

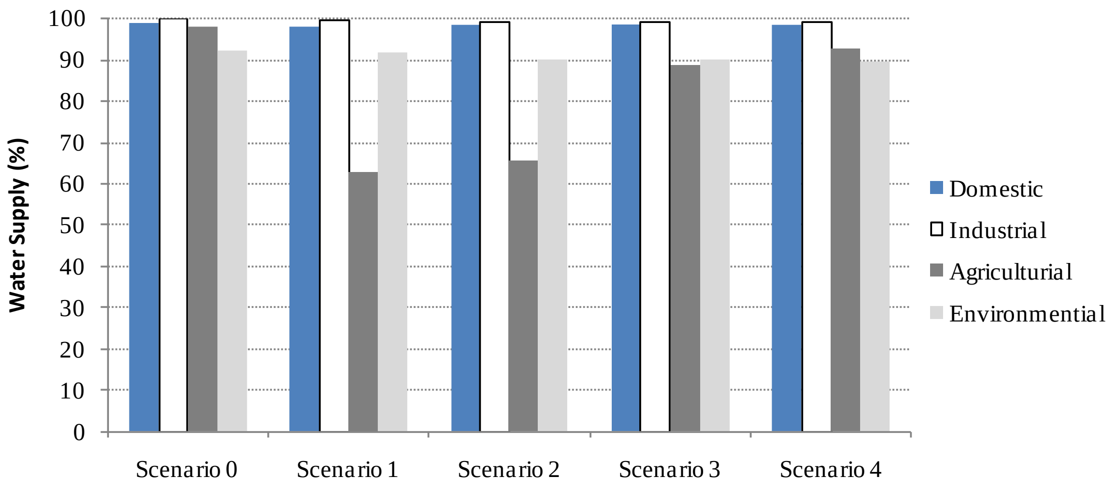

Figure 6. The amount of water demand supply (percent) of Hamoon- Jazmorian in different scenarios

As presented in Table 3, the aquifer deficit has the maximum value in scenario 1 as 525 MCM. It is because of this scenario is as usual by increasing water demands and there is not any policy about water development project and water demand. The aquifer deficits in other scenarios are declined by operating water development projects, improvement irrigation efficiency, and limiting the cultivated area, in scenarios 2, 3 and 4, respectively.

Evaluation the scenarios

Considering socio-economic criteria in IWRM approach, the criteria of sustainability of water resources and environment in the river basin, economic sustainability and social equity are defined to evaluate the river basin conditions. In quantifying the criteria, the calculated indices obtained based on the MODSIM results are utilized. In order to ranking the scenarios based on a unique and combination index, the analytical hierarchy process (AHP) is used.

AHP is one the most comprehensive system developed for decision making with multiple criteria, hierarchically. The process is based on pair-wise comparison of the importance of different criteria and sub-criteria. Therefore, during some discussion meetings, three levels of goals, criteria and indices shows in Table 4 are defined. Then pair-wise comparison of the importance of different criteria and sub-criteria is carried out by experts. The weights for three levels are computed and presented in the first to third colorful rows in Table 4.

In order to rank the scenarios, the weights of different index and the score to each index fir different scenarios are used. The scores to the indices are assigned based on results of MODSIM model. The indices which are not possible to quantify their effects in simulation model including conflicts index, experts' judgments are utilized based on the knowledge of the changes in the scenarios. Weighted score of each index is computed by multiplying the partial score in the related index weight. The total weight of each scenario is obtained from adding the weighted score of all criteria. Whatever of obtained score in each scenario is more, the basin area condition is more stable in the related scenario. It should be noticed that increasing water development projects and water demand policies leads to decrease water losses and improve water efficiency. The weighted scores of water resources and environmental sustainability, economic sustainability and social equity criteria in different scenarios are presented in Table 4.

Table 4. The results of ranking different scenarios

Name of scenario										
	The goal	Sustainability of water resources and environment in the river basin						Economic Sustainability	Social Equity	The total weight of scenario
	Criteria	Supply and demand balance			Development of water resources		Environmental vulnerability			
	Indices	Water stress relative	Percent of water demands supply	Sustainable aquifer	Groundwater development	Irrigation efficiency	Environmental water rights supply	Water productivity in agricultural production	Conflicts	
	The goal weighting coefficients	0.641						0.238	0.121	1.000
	The criteria weighting coefficients	0.392			0.163		0.086	0.238	0.121	1.000
	The indices weighting coefficients	0.173	0.122	0.097	0.109	0.054	0.086	0.238	0.121	1.000
Scenario 0	Partial score	1	9	1	1	1	9	1	5	3.148
	Weighted score	0.173	1.099	0.097	0.109	0.054	0.772	0.238	0.606	
Scenario 1	Partial score	1	1	1	1	1	9	1	4	2.050
	Weighted score	0.173	0.122	0.097	0.109	0.054	0.772	0.238	0.485	
Scenario 2	Partial score	1	3	1	1	1	9	1	4	2.294
	Weighted score	0.173	0.366	0.097	0.109	0.054	0.772	0.238	0.485	
Scenario 3	Partial score	1	9	1	1	3	9	3	4	3.611
	Weighted score	0.173	1.099	0.097	0.109	0.163	0.772	0.713	0.485	
Scenario 4	Partial score	1	9	3	1	3	9	5	4	4.280
	Weighted score	0.173	1.099	0.291	0.109	0.163	0.772	1.188	0.485	

The results show that Scenario 4 has the most weighted score according to the amounts of partial and weighted scores. In this scenario considered as the best one, all water development projects are under execution in the basin area and demand management strategies are applied to reduce water demand and balance the aquifers.

Conclusion

Considering the basin area as a practical unit for water resource planning and management is very important from IWRM aspect. Interconnected and integrated water resources management is a systematic process which leads to sustainable development, more efficient water allocation and monitor water resources in terms of social, economic and environmental goals. Water resource planning and management in different sectors including agricultural, domestic, industrial and environmental separately leads to contradiction and create an unsustainable system in the basin area.

Contrasting development plans with limited water resources and environmental problems are observed in Hamoon- Jazmorian basin area. The basin area has highly dependent on groundwater resources, whereas water withdrawal from most of the aquifer is over the renewable water. Excessive emphasizing on agricultural water allocation, lack of attention to the environmental water rights about surface water and groundwater depletion have caused lots of damages to many ecosystems in the region such as Hamoon- Jazmorian wetland.

There is no possibility to increase water harvesting at the basin because the most dam plans have been completed and also recently the aquifers withdrawal has been constrained. Therefore, the supply management strategy will not have enough efficiency because almost all of the available water resources in the basin area have been allocated and now it is operated. On the other hand demand management is urgently needed to reform consumption pattern particularly in the agricultural sector. Meanwhile, the results of this paper shows that the irrigation efficiency and agricultural water productivity is low in this region.

Therefore, legal and economic instruments and more suitable technology should be used to control and prevent over-extraction from wells in the region. Paying more attention to water user organizations and water councils, using the cooperation of all shareholders in coordinating decisions, utilizing economic instruments such as water markets and also using the modern irrigation can be as a practical tool for achieving efficient management in the basin area.

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