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Environmentally Sound Water Resources Management in Catchment Level using DPSIR Model and Scenario Analysis

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ABSTRACT: Maharlou-Bakhtegan Catchment in the southern part of Iran is faced with water scarcity. This problem is exacerbated by environmental degradation, climate change effects, mismanagement of water resources, along with a major dependence of water demand supplies on the limited groundwater resources. In this study, a combined approach of DPSIR model along with the scenario analysis was employed to derive the optimal management strategies for the environmentally sound water resources management of Maharlou-Bakhtegan Catchment considering the conjunctive use of surface and groundwater resources. Cause-effect relationships were identified by DPSIR framework and 15 scenarios were developed based on them. For evaluating each scenario, 9 integrated water resources management indicators were introduced and evaluated by MODSIM.The results demonstrated that in scenario Scen-14, restriction for the irrigation area development, as well as other management solutions, which led to 100% supply of domestic and industrial water demands and 91% supply of agricultural water demands. Also in the last scenario the value 1.79 kg/ m^3 was received by the Agricultural water productivity indicators. Moreover, by satisfying all IWRM indicators as well as enhancing zero for negative water balance of the aquifers in Scen-14, it is clearly indicated that this scenario revealed more efficient management solutions for the environmentally sound water resources management of the catchment.

Key words: Maharlou-Bakhtegan Catchment,Water demand supply, MODSIM,Environmnet

INTRODUCTION

Different aspects of water resources management have been widely considered by lots of researchers all around the world (Venugopal *et al.*, 2009; Mahmoudi *et al.*, 2010; Nasrabadi *et al.*, 2010; Pamer *et al.*, 2011; Piccini *et al.*, 2012; Farzin *et al.*, 2012; Feng *et al.*, 2012; Guinder *et al.*, 2012; Ghaderi et al. 2012; Fazelzadeh *et al.*, 2012; Mirbagheri *et al.*, 2012). The concept of integrated water resources management (IWRM) was introduced in the realm of the International Water Resources Association some 30 years ago (Braga, 2001). IWRM is viewed as a systematic process for the sustainable development, allocation and monitoring of water resources use in the context of social, economic and environmental objectives (Un-Water and Global Water Partnership (Un-WGWP), 2005). The IWRM approach has now been accepted internationally as the way forward for efficient and sustainable development and management of the world's limited water resources and for dealing with conflicting demands. The most widely accepted definition of IWRM is: "IWRM is defined as a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Un-WGWP, 2007).

At the heart of most of these efforts, the concept of IWRM is defined as: "Equitable access to and sustainable use of water resources by all stakeholders at catchment, regional and international levels, while

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maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits" (Pollard, 2002).

The understanding of the existing policy options and actions that have been followed for management of water resources, and their theoretical background, leads to the identification of some basic and distinct paradigms of water resources management of each action (Kuhn, 1962; Gleick, 2000; Okuku and Peter, 2012; Kim *et al.*, 2012; Feizizadeh *et al.*, 2012; Strohchoen *et al.*, 2012; Tajziehchi *et al.*, 2012, Pillay and Pillay, 2013; Tisseuil *et al.*, 2013). The Driving force-Pressure-State-Impact-Response (DPSIR) approach (Walmsley, 2002; Smeets *et al.*, 1999), which is often used for the assessment of water management systems using indicators describing the existing Drivers, Pressures, State, Impacts and Responses, can be used as a new interpretation in the description of Paradigm formulation. The Drivers and Pressures and their Impact of water stress on the system were qualitatively defined in terms of a Typology, whereas the Paradigm corresponds to the dominant responses used to mitigate water stress.

DPSIR model is an extension of the Pressure-State-Response (PSR) model and was developed in the 70s by Anthony Friend (WSMP, 2002). The approach has been adopted by the European Environment Agency (EEA) and often used for the assessment of water management systems using indicators describing the existing Drivers, Pressures, State, Impacts and Responses, lends itself to a new interpretation in the description of paradigm formulation (Fig.1). This model is widely used in European countries for clarification of the environmental condition of these countries.

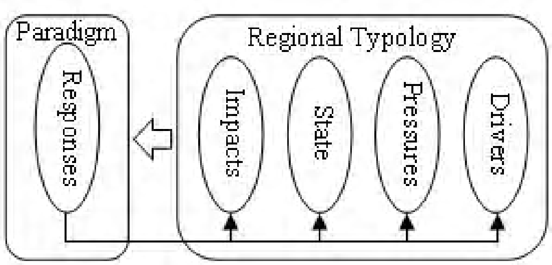

Fig. 1. Paradigm Development in the DPSIR context (WaterStrategyMan project, 2005)

Detailed information about DPSIR framework is well documented in the literature (WaterStrategyMan project, 2002; Kristensen, 2004; Samareh Hashemi, 2010; Organization for Economic Co-operation and Development (OECD), 1993).

One approach to achieve optimal water resources management is modelling water resources as a dynamic multi-period network flow problem, where all data are fixed and no level of uncertainty is considered (Sechi and Zuddas, 1998; Kuczkera, 1992).

MODSIM is a generic river basin management Decision Support System (DSS) originally conceived in 1978 at Colorado State University (Sprague and Carlson, 1982), making it the longest continuously maintained river basin management software package currently available. MODSIM includes modelling capabilities for conjunctive use of surface and ground water resources as well as simulation of stream-aquifer interactions (Labadie, 2005). Various Practical applications of MODSIM as a DSS for water resources management in catchment scale, individually or in combination with optimization and quality models, were well documented by Dai and Labadie (2001); Leu (2001); Miller *et al.* (2005) and Shourian (2008).

MATERIALS & METHODS

The aim of the present study is to put the IWRM in practice for Maharlou-Bakhtegan Catchment using DPSIR approach and scenario analysis. Fig. 2, illustrates the conceptual framework of the present research. The first step of the present study is to investigate the water resources environmental planning, management and developmental conditions from 2006 (as the water resources planning base year) until 2041 (as the development plan horizon). Maharlou-Bakhtegan Catchment which is drained mainly by the Kor River is located in the south of Iran (Fig. 3). The catchment area is 32,271 km^2 and located between longitudes 51°452 and 54°302 E, latitudes 29°352 and 31°152 N. About 16,113 km^2 of the studied catchment is a mountainous area and 16,158 km^2 of it pertains to a plain area. The main part of this catchment is located between Doroudzan Dam and Bakhtegan Lake. Total amount of surface and groundwater which flows into the catchment is about 3521.4 MCM (million cubic meters). Nevertheless, groundwater resources supply 79% of the total water needs in the catchment (Jamab, 2011).

Artificial lakes in the catchment includes: Doroodzan and Tange Boragh Dams reservoirs on the Kor River and Sivand Dam on the Sivand River. Tange-Sorkh and Tange-Hana Dams are currently under construction and are planned to be operational until 2041. Bakhtegan-Tashak Lake, Maharlou Lake and Kaaftar Lake are permanent and important natural lakes of the catchment which have been registered in the Ramsar Convention on Wetlands. In recent years, the lack of a systematic management for the water resources and inadequate allocation of water for environmental needs led to the shrinkage of Maharlou Lake. It is worth mentioning that the water balance of the aquifers has been negative in 14 sub-catchments

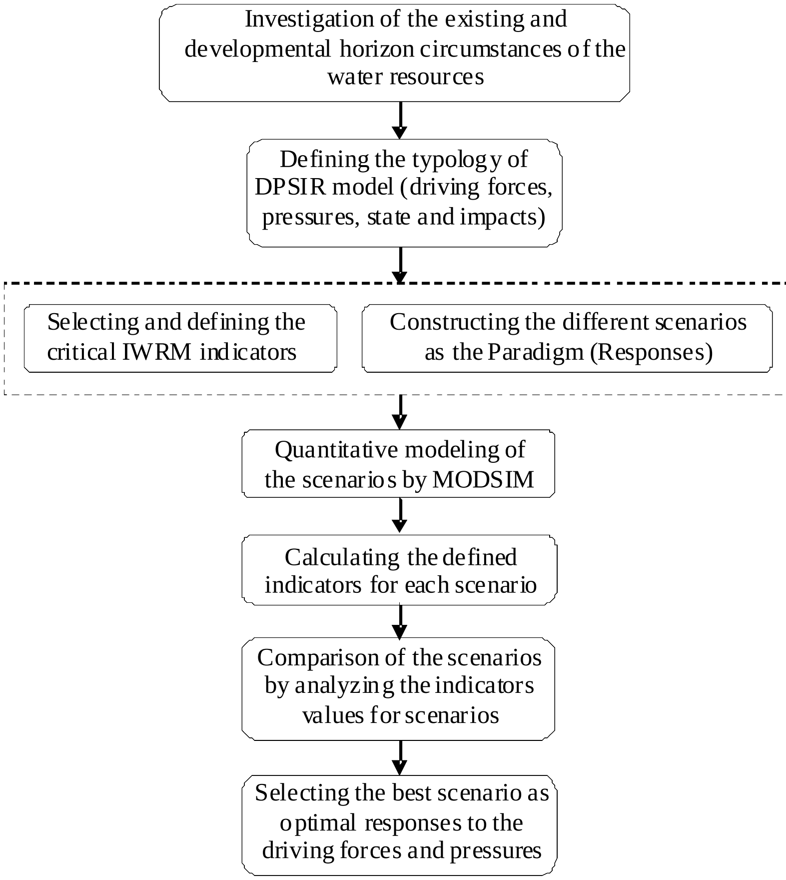

Fig. 2. Conceptual framework of the present study

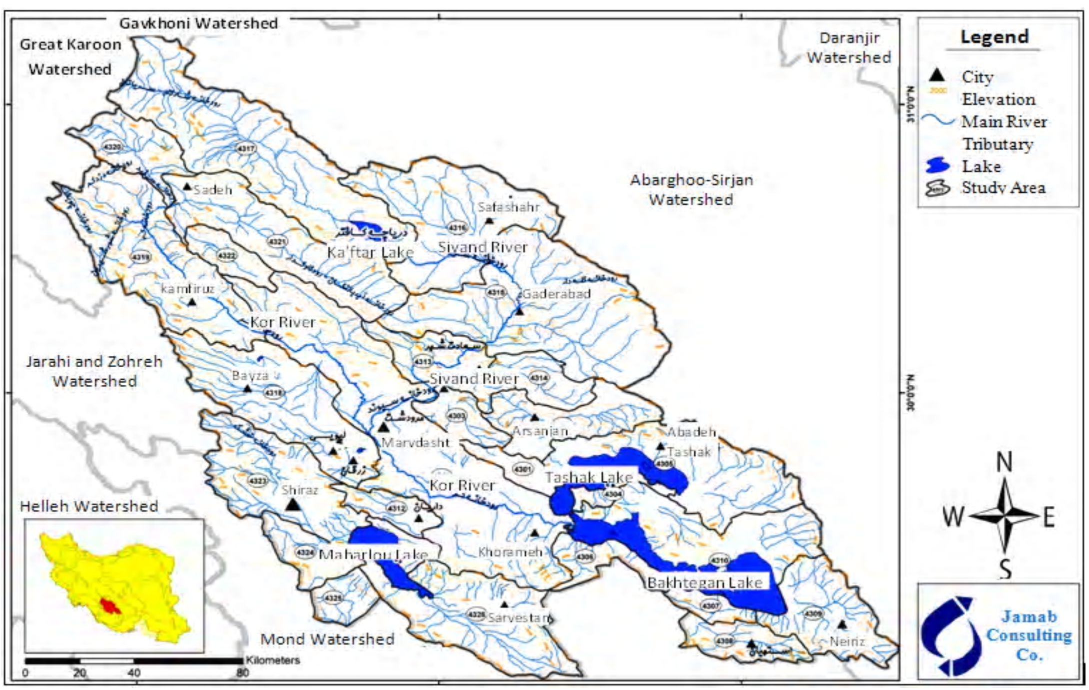

Fig. 3. Topology of Maharlou-Bakhtegan catchment (Jamab, 2011)

of the total 27 sub-catchments in Maharlou-Bakhtegan catchment area.

In short, recent droughts and consequently the reduction in natural recharge of the surface and groundwater resources have led to intensification of the overall water stress of the catchment, instability of the groundwater resources and shrinkage of the natural lakes. Secondary, the present study has tried to determine the typology elements of the DPSIR model for the studied catchment. Paradigm development of the DPSIR model for Maharlou-Bakhtegan catchment is illustrated in fig. 4.

Population growth rate in Maharlou-Bakhtegan Catchment area (0.86% per year (Jamab, 2011)) will lead to labour requisition growth and increase in domestic, industrial and agricultural water demands. Therefore, extra water withdrawal from the water resources is expected.All statistical evidence confirms that agriculture is now a key sector for water management, and still will be important for the next decades. Generally speaking, the agricultural sector consumes most of the available water in nationwide catchments. On the other hand, due to rapid population growth and consequent increasing in food demands in Iran as a developing country, agricultural development is inevitable in order to meet the food and labour requisitions in the nationwide catchments. Thus, the water managers are forced to use new and more efficient technologies for irrigation of the developing agricultural area and drainage networks. So, technological developments in the irrigation activities of the case study catchment agricultural activities is considered as one of the external driving forces due to economize and efficient water use in the agricultural sector.

The average irrigation efficiency in the catchment is about 33%. This remarkable low efficiency may be considered as one of the most important factors responsible for the increase of the water needs in the catchment. So, irrigation technological development is considered as another driving force. In this study, 18% increase in the irrigation efficiency is considered as proper response to the mentioned driving force.

Global warming phenomenon may impose negative effects on water resources. The recent study (Jamab, 2011) reveals that the climate change in the catchment will lead to 13% decrease of catchment water resources until 2041. Moreover, since the environmental sustainability is one of the most important issues of an integrated water resources management in the catchment scale, supplying environmental water needs of the rivers and lakes is

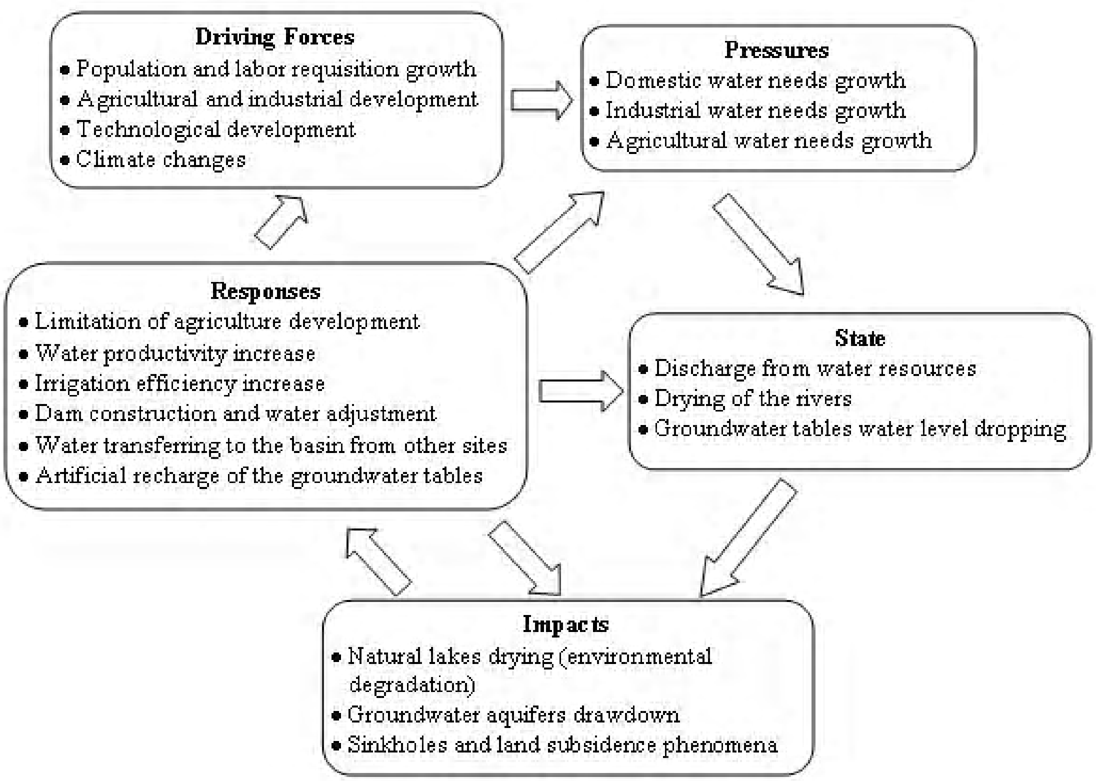

Fig. 4. Cause-effect relationships identified using DPSIR framework

considered as another driving force in the studied catchment.Therefore, in this research, priority has been given to the environmental water needs. Agricultural sector in Iran is one of the most important and powerful economic sectors of the country that is supplier of a quarter of the Gross Domestic Product (GDP), a quarter of employment, more than four-fifths of food needs, a quarter of non oil exports and about nine tenths of the industrial needs to agricultural products.

The agricultural development which requires more water withdrawal from the limited water resources has been proposed as one of the external driving forces (Jamab, 2011). Considering the defined Typology of the DPSIR model in the previous step, selected critical

Table 1. Proposed IWRM indicators of the DPSIR framework

No.	Indicator description	Unit	Position in DPSIR	Calculating method	Interpretation
1	Domestic water supply	%	Pressure	Allocated volume per demand volume	These indicators provide a measure of domestic, industrial and agricultural sectors water demand supply, respectively. Supply of 100% domestic and industrial water needs and supply of more than 90% agricultural water needs are assumed to be acceptable.
2	Industrial water supply				
3	Agricultural water supply				
4	Relative Water Stress	-	Pressure, State	Sum of domestic, industrial and agricultural water supply to total water storage volume of the surface and groundwater resources.	This indicator provides a measure of the water demand pressures which are imposed by the catchment water consumers. 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.
5	Groundwater resources sustainability	-	State	Ratio of total discharges from the groundwater resources to their total recharge	> 1: critical 0.8< <1: very unsustainable 0.4< <0.8: unsustainable <0.4: sustainable Value of this indicator implies more environmentally sound paradigm.
6	Environmental water demand supply	%	Impact	Ratio of allocated water to total environmental water need	Supply percentages greater than 80% signifies the more environmentally sound paradigm.
7	Groundwater resources attenuation period	year	Impact	Ratio of Total storage volume of the groundwater resources to their annual withdrawal	Longer the attenuation time period of the groundwater resources implies the more environmentally sound paradigm. In this paper attenuation periods longer than 9 years is assumed to be optimal.
8	groundwater renewability potential	-	State	Ratio of static volume of the groundwater resources to their natural recharge volume	< 10: high potential 10< <30: intermediate potential 30< < 50: low potential > 50: no potential Value of this indicator implies more environmentally sound paradigm.
9	Agricultural water productivity	Kg/m^3	Response	Total agricultural crop yield as weight of crop products per unit volume of the agricultural water	Ideal value for this index has been determined 2 kg/m3 for 35-year outlook (until horizon 2041) in the country agricultural development programs. In this paper values greater than 1 is assumed to be optimal.

Table 2. Proposed scenarios and their assumptions

Scenario Name	Definition and Assumptions
Scen-0	As a base scenario in year 2006, it is assumed that the water resources; water needs and consumptions as well as water allocation priorities are included in the existing condition.
Scen-1	Different water needs and consumptions according to horizon 2041; Water resources condition and discharge from the groundwater resources are considered in existing condition of 2006 year; Assuming that the structural facilities are not operational.
Scen-2	Assumptions of the Scen-1 along with under construction facilities operation.
Scen-3	Assumptions of the Scen-2 plus water demands management strategies.
Scen-4	Assumptions of the Scen-2 along with structural facilities operation.
Scen-5	Assumptions of the Scen-4 plus water demand management strategies.
Scen-6	Assumptions of the Scen-5 plus aquifers water balance enhancing program.
Scen-7	Assumptions of the Scen-4 accompanied by construction of the structural facilities having water allocation plans (i.e. Tange-Sorkh Dam and putting in operation of the previously defined water transferring facilities).
Scen-8	Assumptions of the Scen-7 together with implementation of the water demands management strategies.
Scen-9	Assumptions of the Scen-8 besides the aquifers water balance enhancing program.
Scen-10	Assumptions of the Scen-9 plus considering the climate change negative effects.
Scen-11	Assumptions of the Scen-3 along with the construction of the Tange-Sorkh Dam.
Scen-12	Assumptions of the Scen-3 along with the construction of the Tange-Hana Dam.
Scen-13	Assumptions of the Scen-3 plus water transferring facilities operation.
Scen-14	As balance scenario. Assumptions of the Scen-6 along with the reduction in agricultural water needs equal to Scen-0 (existing condition in year 2006) and elevating the environmental water allocation priority.

IWRM indicators are presented in Table 1. As previously mentioned, each indicator will be quantified by modelling results of the scenarios. The forth indicator named relative water stress or relative water demand (RWD) provides a measure of the different water demand pressures relative to the local and upstream water supplies. Areas experiencing water stress and water scarcity can be identified by relative water demand ratios exceeding 0.2 and 0.4, respectively. A threshold of 0.4 signifies severity of water stressed conditions (Vörösmarty *et al*., 2000). The agriculture in the case study catchment is a key sector regarding its water consumption level as well as food and labour supply. So, the prospects for the future of the catchment are clear. Agriculture will have to respond to changing patterns of demand for food and combat food insecurity and poverty along with the marginalized communities. In so doing, agriculture will have to compete for scarce water with other users and reduce pressure on the water environment. Agriculture policies and investments will therefore need to become much more strategic. They will have to unlock the potential of agricultural water management practices to raise productivity, spread equitable access to water, and conserve the natural productivity of the water resource base.

Gains in water productivity are possible by providing more reliable irrigation supplies. However, an increase in water productivity may or may not lead to greater economic or social benefits (FAO, 2012). In this research, 14 management scenarios (namely Scen-1 to Scen-14) are defined as the Paradigm of the DPSIR model for Maharlou-Bakhtegan Catchment. Definition of the scenarios and their assumptions are presented in Table 2. These scenarios are developed to put into account the integrity issues (i.e. economic, social and environmental considerations) for the sustainable water resources management of the catchment. Moreover, the individual and combined effects of the structural and non-structural management efforts will be examined by 2041 as responses to the driving forces, pressures and impacts in the catchment.

Major assumptions and conditions which were used for construction of the scenarios includes: (1)

the artificial recharge facilities for the critical aquifers with the capacity of approximately 24.5 MCM per year; (2) conventional, typical and ideal domestic water consumption patterns. According to the previous study (Jamab, 2011), water needs for these water consumption patterns have been calculated by 299, 287 and 274 litres per capita per day, respectively; (3) four water transferring facilities from the neighbour catchments to the studied catchment with total flow rate of 120 MCM per year; (4) water demand management strategies as an increase of the irrigation efficiencies and the domestic water consumption pattern improvement up to its ideal value (i.e. 274 litres per capita per day); (5) the aquifers water balance enhancing program; (6) negative effects of climate change on water resources due to reduction of the whole catchment water resources by 13% in contrast with existing condition in base year of 2006.

In this study, MODSIM version 8.1 was utilized for modelling of the management scenarios in order to quantify the DPSIR approach indicators. The time period for modelling of the scenarios is considered 36 years from 2006 until 2041. 40 years historical data (from 1967 to 2006) were collected from Regional Water Authority of Fars Province and Jamab (2001) technical reports and used for calibration of the model. The available data for modelling includes: (1) water flow rate time series from the hydrometric stations; (2) monthly time series of the historical water needs (domestic, industrial and agricultural); (3) monthly time series of the water needs (domestic, industrial and agricultural); (4) monthly wastewater discharge flow rates from the various water consumers to the surface and groundwater resources; (5) characteristics of the dams including: maximum, minimum and initial volumes as well as target storages, Area/Capacity/Elevation/ Hydraulic capacity and monthly net evaporation rate from the dams reservoir; (6) monthly environmental water needs of rivers and natural lakes. Allocated water to the demand sites as well as in-stream water flow rates based on modelling results were compared with observed data. Since the agriculture is the greatest water consumer in the catchment, if the model results were significantly different from the observed data, agricultural water needs time series and returning wastewater coefficients would be recalibrated and the model would be executed for several times until the modelling results were consistent with the observed data. Modelled topology of the catchment in MODSIM is shown in Fig. 5.

RESULTS & DISCUSSION

Results of the proposed approach for sustainable water resources management of the Maharlou-Bakhtegan Catchment is presented in Table 3. Also, Negative water balance diagram for the aquifers within all scenarios is shown in fig.6.

The acceptable values for the indicators are presented in Table 3 in bold. According to Table 3, despite the coverage of the optimal values for the domestic and industrial demand sites in the sixth, ninth and fourteenth scenarios, optimal value for agricultural water supply was achieved only in the last scenario (Scen-14). This reveals the fact that while the agricultural sector consumes most of the available water, none of the proposed management strategies can individually meet the defined minimum agricultural water demands unless the agricultural development would be limited.

Results show that the environmental water needs are only satisfied in the sixth and the fourteenth scenarios. In this regard, the last scenario has received the highest score among all scenarios because of the environmental water allocation priority. Relative water stress of the whole catchment has been improved by the acceptable level (less than 0.4) in the Scen-14. This desirable result is mainly supported in this scenario by neglecting the agricultural development program. For the other scenarios, this indicator received values higher than acceptable level. It can be clearly understood that there is a considerable decrease in water demand supplies as well as groundwater resources' sustainability and renewability potential through implementation of the Scen-10.The agricultural water productivity indicators for the Scen-6, Scen-8, Scen-9 and Scen-14 are 1.01, 1.02, 1.21 and 1.79 kg/m^3, respectively, which are significantly close to the ideal crop yield value of 2 kg/m^3. These optimal values are mainly due to higher irrigation efficiency; water demands management strategies as well as aquifers water balance enhancement. The major improvement in this indicator occurred in the Scen-14. By giving a higher priority to the environmental sectors in Scen-14, available water for the environmental sectors was increased by 10% and 31% in comparison with Scen-0 and Scen-1, respectively. By applying aquifers water balance enhancing programs via the scenarios Scen-6, Scen-9, Scen-10 and Scen-14, negative water balance of the aquifers was drastically decreased near to zero. It can be undoubtedly expressed that by imposing the limitation on the agricultural area development beside the other management solutions via Scen-14, the negative water balance of the aquifers will reach to zero.

Table 3. Results of the proposed approach for integrated water resources management of the Maharlou-Bakhtegan catchment

Indicator Name	Unit	Scen-0	Scen-1	Scen-2	Scen-3	Scen-4	Scen-5	Scen-6	Scen-7	Scen-8	Scen-9	Scen-10	Scen-11	Scen-12	Scen-13	Scen-14
Domestic water supply	%	**100**	87	87	95	95	96	**100**	88	95	**100**	91	98	98	95	**100**
Industrial water supply	%	**100**	83	83	92	89	91	**100**	87	92	**100**	92	93	93	92	**100**
Agricultural water supply	%	**92**	62	62	78	64	81	88	83	85	89	58	83	85	85	**91**
Relative Water Stress	-	0.51	0.69	0.69	0.57	0.57	0.53	0.55	0.67	0.54	0.46	0.79	0.55	0.57	0.59	**0.38**
Groundwater resources sustainability	-	1.02	1.46	1.25	1.02	1.2	1.1	0.48	1.2	1.15	**0.45**	1.65	1.02	1.02	1.02	**0.25**
Environmental water supply	%	77	65	65	73	68	73	**80**	68	72	**81**	63	76	73	76	**85**
Groundwater resources attenuation period	Year	5.6	6.1	6.1	6.2	5.9	6.5	**10**	6	6.2	**10.1**	5	6.2	6.2	6.2	**10.7**
groundwater renewability potential	-	**1.27**	**1.31**	**1.43**	**1.40**	**1.48**	**1.33**	**0.80**	**1.45**	**1.40**	**0.81**	**0.70**	**1.40**	**1.40**	**1.40**	**0.81**
Agricultural water productivity	Kg/m^3	0.61	0.94	0.94	0.93	0.62	0.94	**1.01**	0.90	**1.02**	**1.21**	0.80	0.97	0.96	0.96	**1.79**

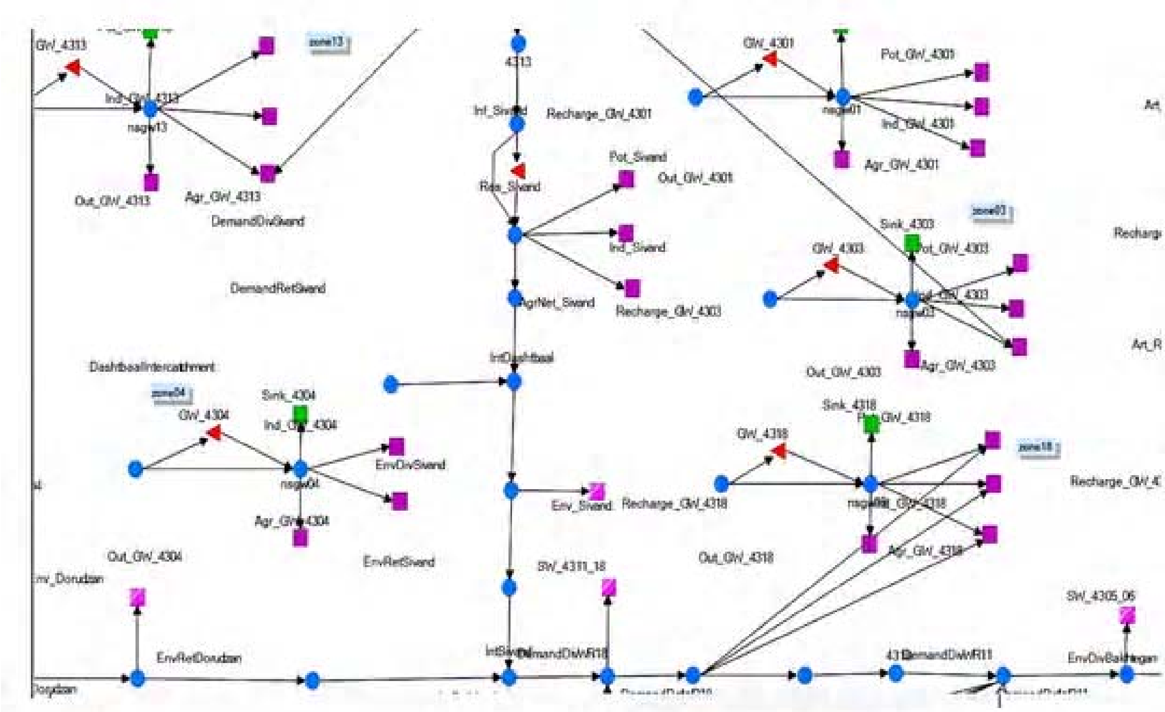

Fig. 5. Typology of the Maharlou-Bakhtegan Catchment modelled in MODSIM

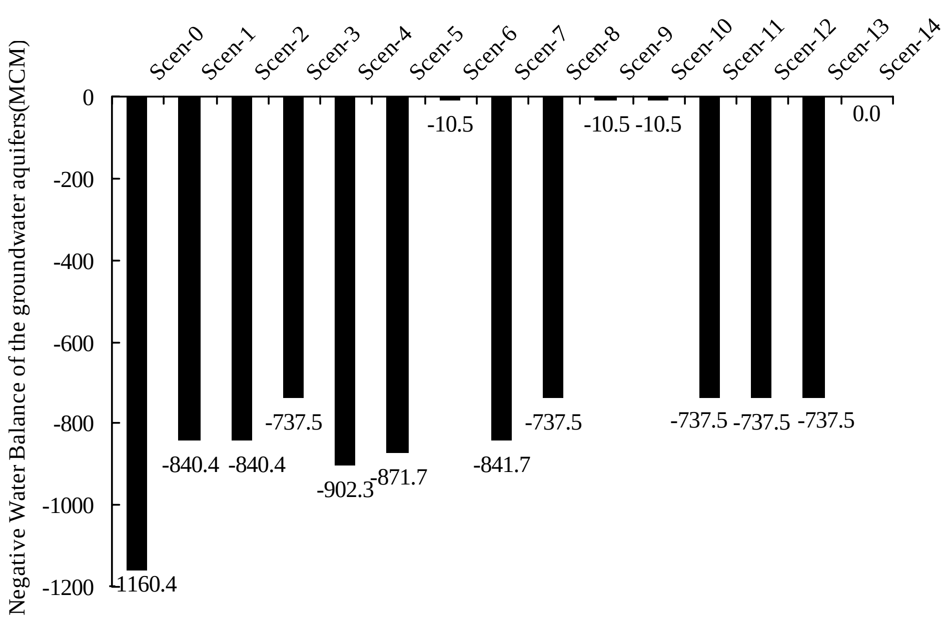

Fig. 6. Groundwater aquifers negative water balance in different scenarios

CONCLUSION

The results imply that the application of the water resources management strategies through scenarios Scen-3 to Scen-14 will lead to more water supplies for the domestic, industrial and agricultural water demand sites. By constructing the irrigation and drainage networks and water transfer facilities from neighbor catchments in Scen-2, it can be seen that only a minor growth occurs in the water need supplies as well as in other sustainability and water productivity indicators. Despite the significant positive effects of applying the aquifers water balance programs along with the water demands management strategies on all indicators via scenarios Scen-6 and Scen-9, none of the mentioned scenarios leads to all indicators to reach to their desirable values except for scenario Scen-14 in which the irrigation area development is limited. Results for Scen-10 shows that the positive effects of all the management solutions are considerably neutralized by negative effects of the climate changes. It can be concluded from the Table 3 that the individual effects of the proposed dams and water transfer facilities operation in the catchment via scenarios Scen-11 to Scen-13 have approximately the same effects on improvement of the indicators, especially on water demand supplies and relative water stress of the whole catchment area. In short, it can be derived from the results that none of the management solutions in the scenarios, individually or in combination, has major effects on the improvement of the indicators up to their desirable levels. However, by applying the agricultural area development limitation besides the other proposed management solutions, all of the indicators will reach to their desirable values.

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