



# Developing a sustainability assessment framework for integrated management of water resources systems using distributed zoning and system dynamics approaches

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## Abstract

The management of large-scale water resources systems requires including of different stakeholders and users from municipal, agricultural, industrial and environmental sectors. This has baffled the process of decision making for integrated water resource systems. In such systems, the interactions between various stakeholders must be carefully taken into account with the goal of aggregating interests around the sustainability concept. In this study, first, the integrated water resources systems of Big Karun Watershed, Iran, have been modeled using the system dynamics approach. The system dynamics model represents the interactions between different components of the system, including water transfer projects, dams, urban, industry, agriculture and fish farming, and environmental demands. Vensim software has been used for the system dynamics modeling. Vensim simulates the dynamics behavior of the sub-systems and overall performance of the system by comparing the current operation policies with the future management scenarios. A wide range of performance indices, such as quantitative and qualitative water stress, income, cost, and productivity, have been used here to represent different aspects of sustainability goals. Finally, the performance of the systems has been evaluated by developing a sustainability index using distributed zoning model in order to identify proper management policies for this watershed. The results indicate that downstream users demand cannot be fully met by solely considering inter-basin water transfer and agricultural development projects. The sustainable and integrated management of the whole system ties into enhancement in both infrastructure systems and the operation of the whole system. It is expected that the sustainability of the basin improves if a water market schema exists and the gained money would be used to enhance the efficiency of existing irrigation networks.

**Keywords** Integrated water resources management · Sustainability · System dynamics approach · Big Karun basin

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## 1 Introduction

Water resources are scarce in Iran. This country has been listed among countries with potential water scarcity in the future. The hydroclimatic condition and geographic location of Iran, as well as uneven spatial and temporal distribution of precipitation, resulted in water scarcity in numerous parts of the country. Population growth, urbanization, industrial development, and agricultural expansion have increased water consumption, and in turn exacerbated the situation (Madani, 2014). The combined urban and industrial sewer systems further caused degradation of water quality in this country. Thus, implementation of appropriate and sustainable water resources management, especially for the large-scale systems, is essential for this country (Akbari-Alashti et al., 2014). Existence of multiple stakeholders and users, including municipal, agricultural, industrial and environmental sectors, has baffled the process of water resource planning and allocation of adequate to meet conflicting stakeholders' demands (Bozorg-Haddad et al., 2009). In such a system, the interactions between various stakeholders must be carefully taken into consideration by aggregating interests around the sustainability goals (Loucks, 2000). In conflict objectives and multi-criteria decision-making would affect the behavior of players in a complex water resources system (Lai et al., 2008). Integrated water resources management becomes a complex task, but necessary due to multidisciplinary essence of decision making which involves socio-economic and political aspects (Sivapalan et al., 2014; Goharian et al., 2016 and 2017). Even at a sub-basin level, there might be many users with conflicting interests involved in decision making, such as local farmers, farming companies, and NGOs. In addition to the complexity associated with the decision makers' behavior, the inherent uncertainty of water consumption pattern for different purposes, drinking, hydropower, agriculture, and environmental, should be foreseen and considered. Thus, water resources management and planning are a multi-sectoral and complex matter and requires precise development and implementation of shared and acceptable plans in order to achieve a stable strategy for sustainable management (Zhou et al., 2015a, 2015b).

Considering the impact of water resources management on regional strategic planning and development, it is necessary to simulate large-scale system models to support the formation of a systematic integrated framework. System dynamics (SD) is a valuable tool to provide better understanding of nonlinear behavior of complex systems. The SD is a renowned approach for providing a theoretical concept and framework for dynamics modeling of water resource systems and explore hidden interrelationships and causal effects among system's components (Forrester, 1958). There are many studies which evaluate the effectiveness of this method in simulating water resources systems with various underlying problems. Examples of these efforts are: urban water management (Zarghami & Akbariyeh, 2012), flood and short-term and long-term irrigation effects (Winz et al., 2009), hydro-economics (Yang et al., 2009), water allocation and management (Zhang et al., 2008; Karmaouz et al., 2013), water supply and demand (Ahmad & Prashar, 2010), agronomic (Gastelum et al., 2010), climate change impact on water resources (Wang et al., 2014) (water reservoir operation (Karamouz et al., 2012), uncertainty analysis (Goharian, Burian, et al., 2018; Goharian, Zahmatkesh, et al., 2018), and urban water distribution networks (Rehan et al., 2013).

Despite system's thinking, which focuses on whole, agent-based models have been used to evaluate the role of individual and institutional behavior for adaptive management of complex water systems (Berger et al., 2007), urban water management (Gallan et al., 2009), basin management considering three off-stream human factors, one in-stream

human factors and two environmental factors (Yang et al., 2009), evaluation of the complex characteristics of residential water consumption (Chu et al., 2009), long-term operation and management of a river-reservoir system (Ricker and Labadie 2012), modeling and analyzing different levels of coordination and information exchange among decision makers in a basin (Giuliani & Castelletti, 2013), integrated water resource management through temporal and spatial analysis of water resource systems dynamics (Nikolic et al., 2013) and forecasting urban water demand (Yuan et al., 2014).

Another useful method in water resources planning process is the conflict resolution theory. This method can provide an optimal solution considering conflicts among different sectors and their utility. There are many studies which applied this method in water allocation in drinking, agricultural and industrial sectors (Mahjouri & Ardestani, 2011; Salazar et al., 2010; Shirangi et al., 2008), groundwater resources management (Kerachian et al., 2010) and water resources management in complex systems (Nouiri, 2014; Zhou et al., 2015a, 2015b).

Conflict resolution methods are not applicable for the formulation of the mentioned case study. Using these methods in this case study is time-consuming and also complicated as there are a large number of different interactions and complexities in the system. On the other hand, if the performance of all factors must be evaluated one by one and in a dynamic framework, the agent-based models are the most applicable models for system simulation. As the whole system in this case study is evaluated for each rule, SD is the most applicable method for simulation of the mentioned case study.

As mentioned before, it is necessary to fully consider the interactions within and among the large-scale systems' components. Further, using the system-of-systems approach, the interactions between systems should be assessed. The previous studies showed that SD is a suitable method for modeling of complex systems by considering quantitative, qualitative, structural, non-structural factors. In this study, considering the importance of integrated and sustainable water management, water quantity and quality allocation framework has been developed using the SD approach for the Karun River basin. Therefore, due to the complexity of system, several management scenarios are investigated and the impacts of them are evaluated on social and economic systems.

## 2 Material and methods

This section is divided into 3 subsections including development of sub-systems simulation based on SD approach, performance assessment and methodology.

### 2.1 Development of sub-systems simulation based on SD approach

The most important subsection is causal loop diagrams (CLDs) in SD approach, so CLDs for different sub-systems are illustrated in Figs. 1, 2, 3. These sub-systems are supply and demand management, hydropower generation and system performance assessment.

### 2.2 Performance assessment

The performance of large-scale system should be evaluated using a framework which considers for quantitative water stress (Eqs. 1 and 2), qualitative water stress (Eq. 3), environmental water stress (Eq. 4), income from each node agriculture and industry



Fig. 1 CLD of supply and demand management sub-system

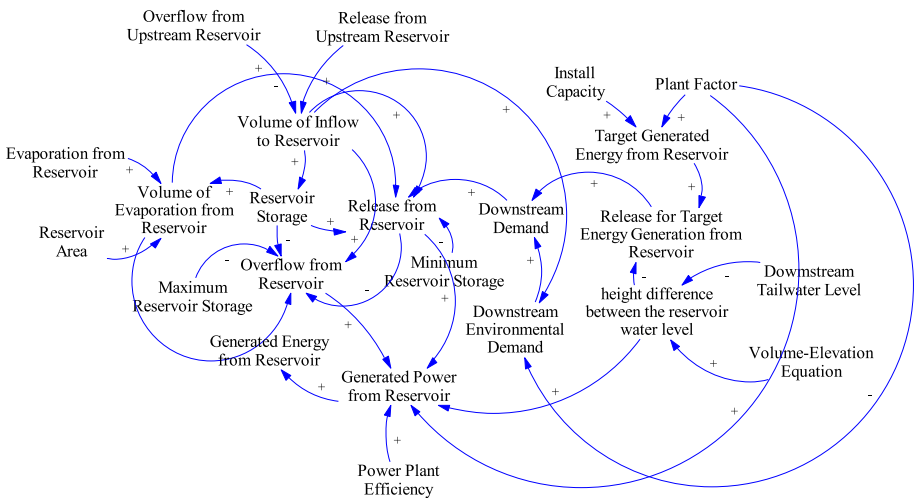
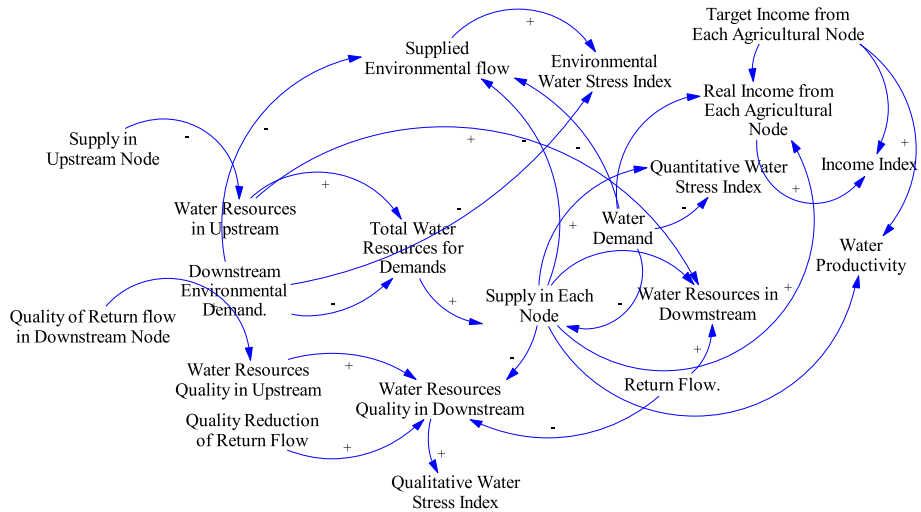


Fig. 2 CLD of hydropower generation sub-system



**Fig. 3** CLD of performance assessment sub-system

nodes (Eq. 5), water productivity in each agricultural node compared to other agricultural nodes, water productivity in each agricultural node compared to industry nodes (Eq. 6), cost of pressurized irrigation systems in the agricultural nodes (Eq. 7), and income from water transfer to central and eastern basins (Eq. 8). After calculating indexes for each system’s nodes, the performance results are classified, based on their relative performance, into excellent to poor classes. Table 1 shows range of classification of  $HWSI_{i,t}$  and  $Q'WSI_{i,t}$ .

$$HWSI_{i,t} = \frac{Sup_{i,t}}{Pop_{i,t}} \tag{1}$$

where  $HWSI_{i,t}$  is the human quantitative water stress index for  $i$ th drinking user at time  $t$  (MCM/person),  $Sup_{i,t}$  is the amount of supplied water for the drinking user of  $i$  at time  $t$  (MCM), and  $Pop_{i,t}$  is drinking user population of  $i$  at time  $t$  (person). Estimated values are assigned to the performance classes based on Falkenmark Indicator (Falkenmark, 1989). This index will be just calculated for drinking user nodes.

**Table 1** Range of classification of  $HWSI_{i,t}$  and  $Q'WSI_{i,t}$

Class	Ranking	$HWSI_{i,t}$	$Q'WSI_{i,t}$	
			EC (mmhos/cm)	
			Domestic and industry	Agricultural
Excellent	1	$> = 9.15e-6$	$< = 312$	100–250
Good	2	$7.63e-6-9.15e-6$	312–1560	250–750
Fair	3	$6.10e-6-7.63e-6$	1560–3120	750–1500
Bad	4	$4.56e-6-6.10e-6$	3120–4680	1500–2250
Poor	5	$< = 4.56e-6$	$> 4680$	$> 2250$

$$QWSI_{i,t} = \frac{Sup_{i,t}}{Dem_{i,t}} \quad (2)$$

where  $QWSI_{i,t}$  is the quantitative water stress index in  $i$ th agricultural, industry and fish farming nodes at time  $t$ ,  $Sup_{i,t}$  is the amount of supplied water for the  $i$ th user at time  $t$  (MCM), and  $Dem_{i,t}$  is the amount of water demand for  $i$ th user at time  $t$  (MCM).

$$Q'WSI_{i,t} = \frac{S.V_{i,t}}{Inf_{i,t}} \quad (3)$$

where  $Q'WSI_{i,t}$  is the flow quality based on total dissolved solids (TDS) in  $i$ th user at time  $t$  (mgr/L),  $S.V_{i,t}$  is salt volume in  $i$ th user at time  $t$  (Ton) and  $Inf_{i,t}$  is flow in  $i$ th user at time  $t$  (MCM) (Asheghmoala, 2015). After calculating Electrical Conductivity (EC) (based on its relationship with total dissolved solids (TDS)) of flow at each of nodes, EC value is classified for agricultural and drinking, industry and fish farming users according to Wilcox and Schuler diagrams (Alizadeh, 2010). Qualitative water stress index can be calculated for all users.

$$EWSI_{i,t} = \frac{OED_{i,t}}{CED_{i,t}} \quad (4)$$

where  $EWSI_{i,t}$  is the environmental water stress index in  $i$ th user node at time  $t$ ,  $OED_{i,t}$  is amount of supplied water to meet environmental demand in  $i$ th user node at time  $t$  (MCM), and  $CED_{i,t}$  is amount of environmental demand calculated based on the Montana method in  $i$ th user node at time  $t$  (MCM)(Orth & Maughan, 1981).

$$EcWSI_{i,t} = \frac{OEB_{i,t}}{CEB_{i,t}} \quad (5)$$

where  $EcWSI_{i,t}$  is income index in  $i$ th agriculture user node at time  $t$ ,  $OEB_{i,t}$  is income from  $i$ th agriculture user at time  $t$  (currency), and  $CEB_{i,t}$  is expected income from  $i$ th agriculture user at time  $t$  (currency). This index should be calculated for agricultural users.

$$PWSI_{i,t} = \frac{OEB_{i,t}}{Sup_{i,t}} \quad (6)$$

where  $PWSI_{i,t}$  is water productivity in  $i$ th agriculture or industry nodes at time  $t$ . After calculating the productivity of each agriculture and industry users at different nodes, relative water productivity index for agriculture nodes and industry nodes is obtained and compared with the maximum water productivity of agriculture and industry nodes.

$$CWSI_{i,t} = \frac{C_{i,t}}{OEB_{i,t}} \quad (7)$$

where  $CWSI_{i,t}$  is irrigation system changing cost index for the  $i$ th agriculture node at time  $t$  and  $C_{i,t}$  is cost for structural and non-structural measures to increase efficiency of  $i$ th agriculture node at time  $t$  (currency). To calculate this index for an upgraded irrigation network, construction and maintenance costs of the new irrigation system, interest rates, and costs associated with non-structural measures, such as advertising and training, should be taken into the account. Then, present value of uniform series of annual payments is

determined, and finally, they should be compared to the annual income of the improved networks.

$$BWSI_{i,t} = \frac{B_{i,t}}{C_{i,t}} \tag{8}$$

where  $BWSI_{i,t}$  is index of income from inter-basin water transfer to  $i$ th agriculture at time  $t$  and  $B_{i,t}$  is income from inter-basin water transfer for the  $i$ th agriculture at time  $t$  (currency). It is assumed that income from water transfer is allocated only for the new irrigation systems.

### 2.3 Methodology

After describing CLDs in SD approach and performance assessment, it is necessary to explain the flowchart of study that shows different steps of work. So, this flowchart is shown in Fig. 4.

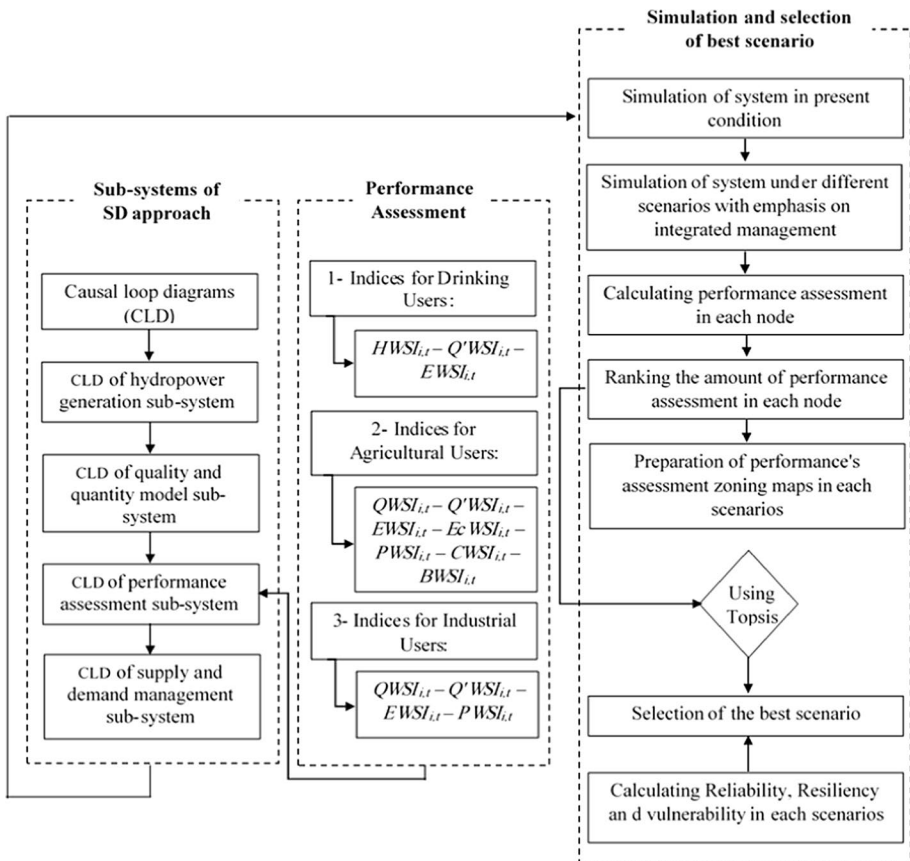


Fig. 4 Flowchart of different steps of work

### 3 The case study and data set

This section is divided into 2 different subsections: (1) introducing the case study and (2) data set of case study.

#### 3.1 Case study

Karun River basin is located in Southwestern Iran with an area of about 67,000 km<sup>2</sup>, of which 69% of this area consists of mountains and the rest are plains. Karun, as one of important rivers in Iran, plays a key role in growth and development of the southwest region. Big Karun basin, located in the middle of Zagros Mountains, consists of the Dez and Karun Rivers (Karun River is divided to two branches including Gargar and Shotayt). Average long-term yield of Karun River to Karun-4 Reservoir and average long-term inflow to Dez Reservoir (statistical period of 1957–2012) are 5,140 million cubic meters (MCM) per year and 7,537 MCM per year, respectively. The undeniable role of the Basin in Iran's economic growth resulted in deploying the water resources of the basin and extensive agricultural and industrial development.

Schematic of Big Karun basin is represented in Fig. 5, and schematic of existing dams, inter-basin water transfer plans and type of users in each branch of river in Big Karun basin is shown in Fig. 6. Dez Dam was built on Dez River, and Karun-4, Karun-3, Karun-1 (Shahid Abbaspour), Godarland (Masjed Soleiman) dams were constructed on Karun River. Furthermore, Rudbar Lorestan and Bakhtiari dams in Dez basin and Bazoft, Khersan-1, Khersan-2 and Khersan-3 dams in Karun River basin are under construction or feasibility study for the future placement. These dams are mainly operated for hydropower generation purpose. They also provide water supply to meet Khuzestan Province agricultural, municipal, and industrial demands. Characteristics of hydropower dams in Karun and Dez basins are presented in Table 2. It should be noted that under current situation, optimal operation of power plants plays an important role in supplying required electricity for the peak hours. It is expected that, in the near future, the system's value will be increased considering its unique electricity generation capacity, and future plans for the construction of new dams and power plants (Badiei, 2015).

#### 3.2 Data set

The time series of average annual inflows to the Karun-4 and Dez reservoirs and intermediate basin flow between Karun-4 and Karun-3 reservoirs, Karun-1 and Karun-3 reservoirs, Karun-1 and Godarland reservoirs, Godarland and Gotvand reservoirs, Big Shurdasht River, Dez Dam and Bande-Ghir are illustrated in Fig. 7.

The monthly water demand for different users in Dez, Karun North, and South Karun sub-basins is presented in Tables 3, 4, 5 (Iran Water and Power Resources Development Company 2010). In addition, inter-basin water transfer projects are another important component of Big Karun basin. These projects transfer a significant portion of water from Karun and Dez Rivers to meet demands of Central basin. The monthly water demand for inter-basin water transfer from Dez and Karun basins is presented in Tables 6 and 7 (Iran Water and Power Resources Development Company 2010).

In this study, SD approach is used to model the Karun River basin water resources system. The model is constructed using information related to the dams, reservoirs, inter-basin water transfer projects, nodes of water withdrawal for drinking, agriculture, industry and



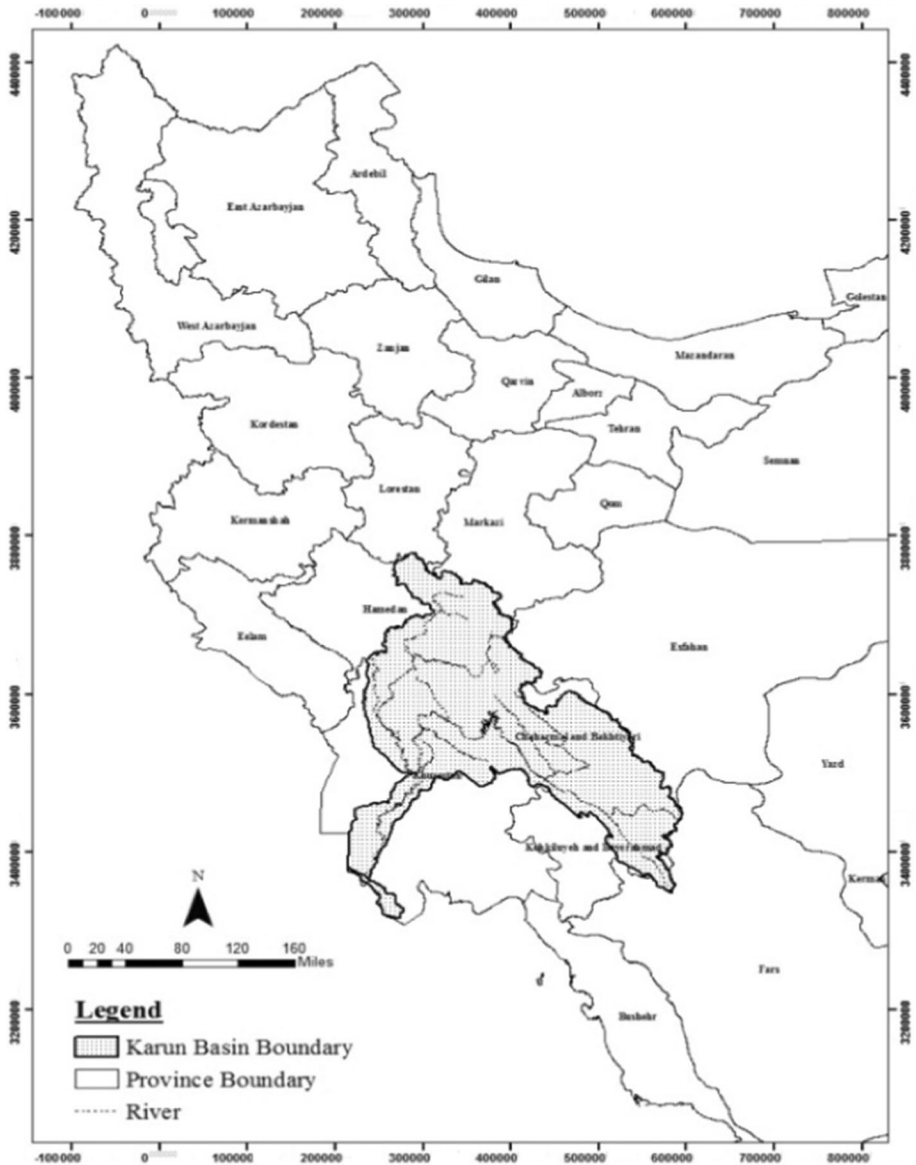


Fig. 5 Schematic of Big Karun basin

fish farming uses and the location of return flows and wastewater. Modeling of the Big Karun basin system was coded with Vensim DSS (5.9b). Then, the results of SD model are explained and discussed using a systematic performance assessment framework which reports and analyzes quantitative water stress, qualitative water stress, environmental water stress indexes, income from agriculture and industry nodes, relative water productivity of agricultural nodes, pressurized irrigation system cost, and water transfer income. To begin with, current governing conditions of system are evaluated; then, the best combination of

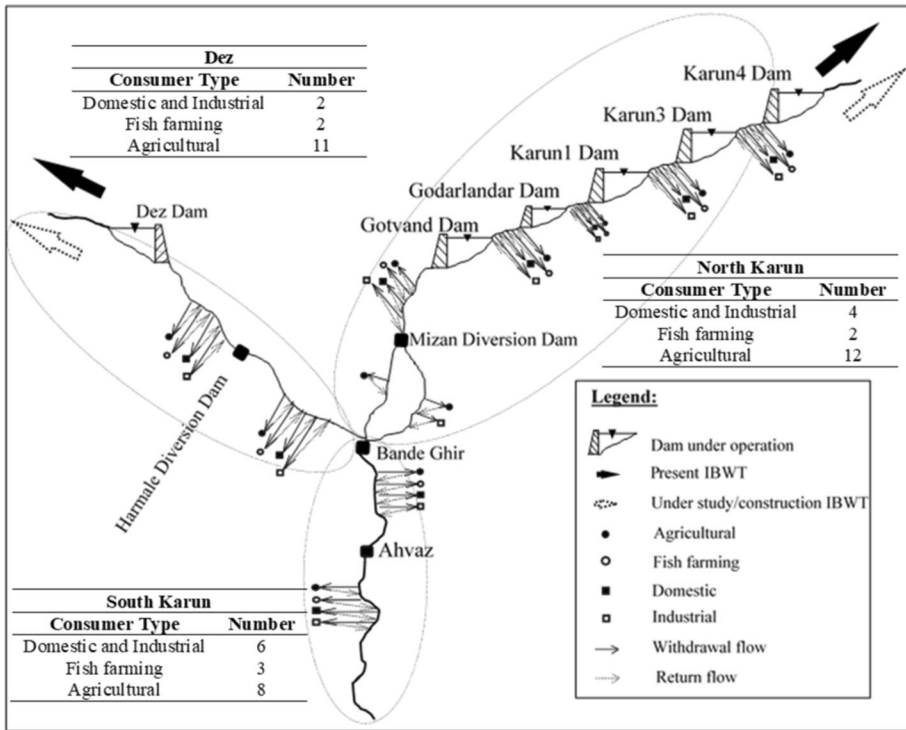


Fig. 6 Schematic of existing dams, inter-basin water transfer plans and type of users in each branch of river in Big Karun basin

decision variables are selected by considering different decision variables (different inputs) and determination of indexes' values for each set of decision variables (Table 8).

### 4 Results and discussion

In this study, Big Karun basin system has been simulated using SD approach. Modeling of the Big Karun basin system was coded with Vensim DSS (5.9b). This system involves 7 dams, 12 drinking and industrial users, 7 fish farming, 34 agricultural users, 5 existing inter-basin water transfer projects, and 7 under study/construction inter-basin water transfer projects. The Big Karun basin system operation has been simulated for the period of 1957–2013. This period is simulated as the status quo scenario. In addition to the current condition scenario, other scenarios are formed in which different under study/construction inter-basin water transfer projects, under study/construction agricultural expansion projects, and efficiency improvement in modern irrigation systems are tested. Different scenario modes are presented in Table 9.

The results of the simulation model under different scenarios are analyzed for the drinking, industry, agriculture, and fish farming user nodes. These results are then fed into the performance assessment framework to estimate different indexes, including quantitative water stress, qualitative water stress, environmental water stress, income from each

**Table 2** General and technical characteristics of operating dams in Big Karun basin

Parameters	Unit	Karun-4	Karun-3	Karun-1	Godarland	Gotvand	Dez
Area of upstream basin	Km <sup>2</sup>	12 '813	24 '260	26 '838	27 '632	32 '425	17 '430
Average annual discharge	m <sup>3</sup> /s	190	332.8	392.5	412	466	256.6
Crest length	m	1 '032	850	542	382	246	354
Type of dam	-	2 arch concrete	2arch concrete	2arch concrete	Clay core rockfill	Clay core rockfill	2arch concrete
Bed elevation of dam	m	840	665	365	240	75	164
Normal elevation	m	1 '025	845	532	372	230	352
Minimum operation level	m	996	800	500	363	185	310
Minimum reservoir storage	10 <sup>6</sup> m <sup>3</sup> /s	1 '266	1 '141	1 '095	181	117	1 '126
Reservoir storage	10 <sup>6</sup> m <sup>3</sup> /s	748.7	1 '689	1 '318	46	3 '050	2 '048
Installation Capacity	MW	1 '000	2 '000	2 '000	2 '000	1 '500	520
Powerhouse efficiency	%	92	92.4	90	92	93	89
Number of units	-	4	8	8	8	4	8
Design elevation	m	162	167	154	138	130	165
Design discharge	m <sup>3</sup> /s	171	172	191	1 '600	1 '265	357

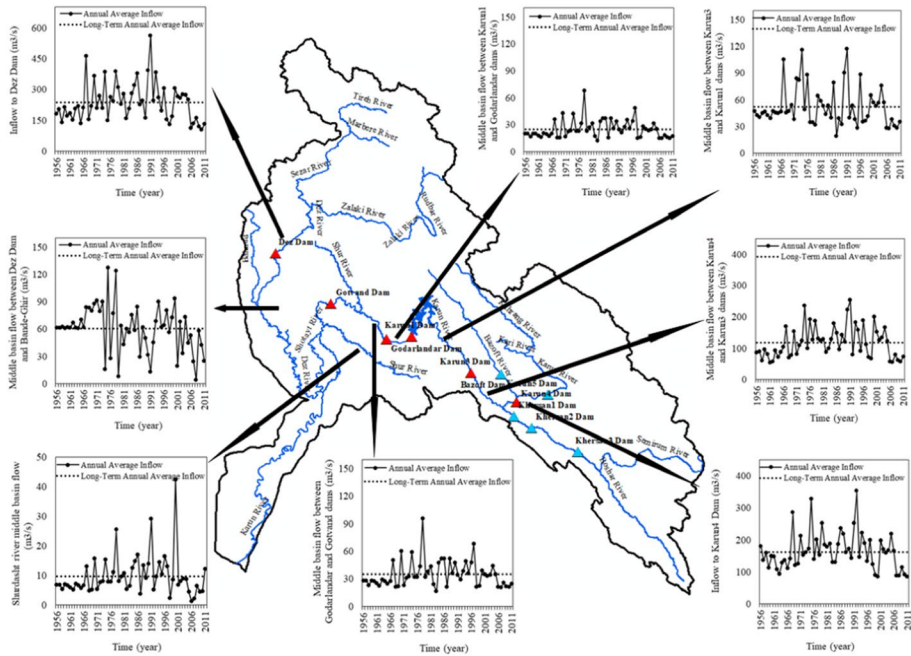


Fig. 7 Average annual inflow at the entrance to the dams and basins

agriculture and industry nodes, relative water productivity of agricultural nodes, relative water productivity of agricultural and industry nodes, cost of pressurized irrigation systems in irrigation network nodes, and income from inter-basin water transfer. Clearly, the pressurized cost index and income from water transfer cannot be calculated for the status quo scenario. These two indexes are designed to analyze the future potential and under study/construction inter-basin water transfer and implementation of modern irrigation systems projects.

Among numerous users and stakeholders in North Karun, Dez and South Karun River basins, results of performance indexes are shown for the outlet node (Darkhojn to Persian Gulf water rights) of Big Karun River (Figs. 8,9,10,11,12 and 13).

#### 4.1 QWSI analysis results

Figure 8 indicates that, under the status quo scenario and based on historical water rights of Darkhojn to Persian Gulf, agricultural demand was not fully provided most of the time. The amount of shortage is higher at the end of the operation period, which overlaps with the drought period. According to Fig. 8-S1-b, water stress index of Scenario 1 is ranked excellent only for 22 years and the ranking for the rest of period varies between good and fair. Under the full inter-basin transfer condition, water supply is ranked fair and for 1 year the ranking is bad. For Scenario 2, agricultural water rights of Darkhojn to Persian Gulf are met completely just for 2 years. Results indicate that implementation of under study/construction agricultural development projects will have minimal effect on water stress index compared to the full transfer inter-basin water transfer projects. Accordingly, based

**Table 3** Monthly water demand for different users in Dez River basin ( $\text{m}^3/\text{s}$ )

Basin	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Domestic and industry	Dezful	2.5	2.5	2.5	3.4	3.4	3.4	3.5	3.5	3.5	3.4	2.5	2.5	3.0
	Dez Sugar Can Industry	6.4	6.4	6.4	6.4	6.4	6.4	3.4	3.4	3.4	6.4	6.4	6.4	5.7
Agriculture water right	Dez Dam to Harmale	0.5	3.1	6.4	9.7	3.9	1.7	7.9	11.8	11.8	7.3	4.4	0.1	5.7
	Harmale to Bande-Ghir	1.0	6.9	14.1	21.6	8.6	3.8	17.6	26.2	26.1	16.3	9.7	0.1	12.7
Irrigation networks	West Dez-without Ret flow	2.2	17.0	35.0	53.5	19.8	4.5	21.9	37.5	41.5	28.7	22.7	0.5	23.8
	West Dez-with Ret flow	1.3	10.0	20.6	31.4	11.7	2.7	12.9	22.0	24.3	16.8	13.3	0.3	14.0
	East Dez and Sabili	2.2	17.5	36.1	55.1	20.5	4.7	22.6	38.6	42.8	29.6	23.4	0.5	24.5
	Ajirub	0.2	0.5	1.2	1.7	0.8	0.6	1.6	1.7	1.7	5.4	5.3	3.6	1.9
Fish farming	Miyanab Sugar Can	0.0	0.0	17.6	10.6	7.6	4.5	4.5	17.2	7.6	4.7	0.0	0.0	6.2
	Haftapeh Sugar Can	0.0	0.0	32.6	19.6	14.0	8.4	8.4	31.9	14.0	8.7	0.0	0.0	11.5
Fish farming	Shavur1	1.9	3.2	6.6	8.3	5.1	1.9	4.7	6.9	5.2	3.3	3.0	0.9	4.3
	Khomeini-West Sugar Can	0.0	0.0	8.9	5.4	3.8	2.3	2.3	8.7	3.8	2.4	0.0	0.0	3.2
	Dehkoda Sugar Can	0.0	0.0	33.0	19.8	14.2	8.5	8.5	32.3	14.2	8.8	0.0	0.0	11.6
	Andimeshk Fish	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
	Dez Small Fish Project	0.0	0.4	0.8	0.8	0.8	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.4

**Table 4** Monthly water demand for different users in the North Karun River basin (m<sup>3</sup>/s)

Basin	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Domestic and industry	Gotvand	0.4	0.4	0.4	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.4	0.4	0.5
	Shushtar	1.4	1.4	1.4	1.9	1.9	1.9	2.0	2.0	2.0	2.0	1.4	1.4	1.7
	North Karun Sugar Cane Industry	6.4	6.4	6.4	6.4	6.4	6.4	3.4	3.4	3.4	6.4	6.4	6.4	5.7
Agriculture water right	Haftkel and Rambormoz	0.4	0.4	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.4	0.4	0.4
	Gargar	0.8	3.4	6.7	9.9	5.4	11.3	13.3	15.3	12.5	7.0	3.3	0.6	7.5
	Gotvand to Bande-Mizan	0.0	0.2	0.4	0.5	0.2	0.0	0.3	0.5	0.5	0.3	0.2	0.0	0.3
Irrigation networks	Shotayt	0.8	3.3	6.6	9.7	5.3	11.0	13.0	14.9	12.2	6.9	3.2	0.6	7.3
	Shahid	0.82	1.12	2.11	3.56	4.87	5.8	3.58	2.14	1.57	0.91	0.97	0.82	2.38
	Dimche 2	0.7	3.5	7.1	10.0	3.2	0.3	1.0	1.8	2.1	1.9	3.9	0.2	3.0
	Dimche 1	0.7	3.7	7.3	10.3	3.3	0.4	1.1	1.8	2.2	1.9	4.0	0.2	3.1
	Gotvand and Aghili	0.6	3.3	6.6	9.3	3.0	0.3	1.0	1.6	2.0	1.7	3.6	0.2	2.8
Fish farming	Dimche 1-West Sugar Can	0.0	0.0	63.7	38.3	27.3	16.4	16.4	62.3	27.3	17.0	0.0	0.0	22.5
	Daryun	0.3	1.6	3.2	4.4	1.6	1.8	1.8	2.5	2.3	1.5	1.1	0.2	1.9
	MiyabShushtar	1.6	9.0	19.0	30.2	17.6	21.0	13.5	23.6	21.4	16.4	7.9	1.4	15.3
Fish farming	Khomeini-East Sugar Can	0.0	0.0	26.8	16.1	11.5	6.9	6.9	26.2	11.5	7.1	0.0	0.0	9.5
	Gargar and Zahriyeh	0.4	1.9	3.7	5.3	3.0	3.3	3.1	3.1	2.4	1.3	1.6	0.2	2.4
	North Karun Small Fish Project	0.4	0.6	0.8	0.8	0.8	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.6
	Gargar Fish	0.0	1.6	3.3	3.3	3.3	1.4	1.4	1.4	1.4	1.4	1.4	0.7	1.7

**Table 5** Monthly water demand for different users in South Karun River basin (m<sup>3</sup>/s)

Basin	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	
Domestic and industry	Molasani and Vais	0.9	0.9	0.9	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.0	0.9	1.1	
	Ramin Powerhouse	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	
	Ahvaz	16.4	16.4	16.0	18.2	18.1	18.4	19.3	19.3	19.3	19.3	19.3	16.7	16.5	17.9
	Mahshahr and Bandare-Ennam	0.7	0.7	0.6	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7
Agriculture water right	South Karun Sugar Cane Industry	19.3	19.3	19.1	19.3	19.3	19.3	10.3	10.3	10.3	10.3	19.3	19.3	17.0	
	Abadan and Khorramshahr	4.0	4.0	3.8	6.2	6.5	6.3	6.6	6.6	6.6	6.6	4.1	4.0	5.5	
	Ahvaz-Darkhoin	8.7	19.0	34.0	45.7	58.8	75.9	78.2	71.7	52.7	27.4	17.4	8.7	41.9	
	Bande-Ghir to Ahvaz	2.4	8.2	14.7	17.5	4.1	5.6	12.4	14.4	10.0	5.9	4.9	1.2	8.5	
Irrigation networks	Darkhoin-Khalij fars	0.6	1.4	2.5	3.3	4.3	5.5	5.7	5.2	3.8	2.0	1.3	0.6	3.0	
	North-East Ahvaz	2.3	8.4	17.0	20.8	10.3	10.2	14.5	14.3	9.4	7.0	5.4	1.2	10.1	
	Jafir	7.5	18.0	32.5	40.7	27.9	24.0	32.5	33.1	21.8	11.3	9.2	5.6	22.1	
	Amirkabir-Kuchakhan Sugar Can	0.0	0.0	67.8	40.7	29.1	17.5	17.5	66.3	29.1	18.0	0.0	0.0	23.9	
Fish farming	Farabi-Farsi Sugar Can	0.0	0.0	103.0	61.8	44.2	26.5	26.5	100.7	44.2	27.4	0.0	0.0	36.3	
	Abadan-Khorramshahr Network	4.9	10.7	21.0	33.8	39.6	58.8	52.7	48.7	40.2	20.4	13.6	4.9	29.4	
	Ahvaz-Khorramshahr Small Fish Project	0.0	2.4	4.9	4.9	4.9	2.1	2.1	2.1	2.1	2.1	2.1	2.0	2.6	
	Abadan Fish	0.0	6.8	14.8	14.8	14.8	5.4	5.4	5.4	5.4	5.4	5.0	2.5	7.2	
	Bahmanshir Fish	0.0	7.0	13.0	13.0	13.0	6.5	6.5	6.5	6.5	6.5	6.5	3.2	7.4	

**Table 6** Monthly water demand for existing or under study/construction inter-basin water transfer in Dez River basin (m<sup>3</sup>/s)

Basin	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Present	Dez to Qomrud	4.9	6.1	8.6	13.1	11.6	5.5	3.1	2.6	2.0	2.4	3.9	5.1	5.7
	Cheshmeh Langan Tunnel	1.5	3.3	6.0	11.8	11.2	5.7	2.3	0.9	0.4	0.3	0.6	1.2	3.8
	Khadangestan Tunnel	0.7	0.9	2.6	8.2	9.0	4.5	2.0	0.9	0.5	0.5	0.7	1.1	2.6
Under study/ construction	Gukan Tunnel and Dam	2.4	4.9	9.1	19.9	19.6	9.9	4.0	1.5	0.6	0.5	1.0	2.2	6.3
	Kamalsaleh Dam	2.0	2.0	2.2	1.9	2.0	2.0	2.1	2.3	2.1	2.0	2.2	2.0	2.1



**Table 7** Monthly water demand for existing or under study/construction inter-basin water transfer in Karun River basin ( $\text{m}^3/\text{s}$ )

Basin	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Present	Kuhrang-1	4.5	5.1	7.9	16.5	19.9	18.9	15.6	11.0	6.8	5.3	5.3	5.1	10.2
	Kuhrang-2	4.8	6.0	9.4	18.4	25.3	21.0	14.2	7.2	4.1	3.2	4.4	4.8	10.2
	Kuhrang-3	4.4	5.0	9.0	16.4	19.3	12.2	7.5	5.0	3.5	3.1	4.4	4.7	7.9
Under study/ construction	Beheshtabad	24.3	31.3	56.3	87.7	84.0	39.9	20.9	14.6	10.8	10.4	17.0	23.5	35.1
	Sulakan	6.6	8.1	12.8	14.9	12.3	7.8	4.9	3.4	3.0	3.1	4.6	6.9	7.9
	Shahrid Dam	0.7	0.9	1.7	2.9	3.9	4.6	2.9	1.7	1.2	0.7	0.8	0.7	1.9
	Bideh Dam	7.4	7.4	7.6	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.4	7.4	7.4

**Table 8** Evaluated modes in each simulated scenarios of Big Karun basin

No. of scenario	Mode or modes to be considered
1	Present condition
2	Considering full transfer of under study/operation IBWT
3	Considering agricultural development projects under study/construction
4	Considering full transfer of under study/construction IBWT and agricultural development projects study/construction
5	Considering hedging transfer of study/construction IBWT
6	Considering hedging transfer of study/construction IBWT and agricultural development plans study/construction
7	Considering hedging transfer of study/construction IBWT and various practices to improve the efficiency of modern irrigation networks
8	Considering hedging transfer of study/construction IBWT and various practices to improve the efficiency of modern irrigation networks and agricultural development projects study/construction

**Table 9** Range of classification of different index in Karun basin

Class	Ranking	$HWSI_{i,t}$	$QWSI_{i,t}$	$Q'WSI_{i,t}$		$EWSI_{i,t}$	$EcWSI_{i,t}$	$PWSI_{i,t}$
				EC (mmhos/cm)				
				Domestic and industry	Agricultural			
Excellent	1	$> = 9.15e-6$	1	$< = 312$	100–250	1	1	1
Good	2	$7.63e-6-9.15e-6$	0.9–1	312–1560	250–750	0.9–1	0.9–1	0.8–1
Fair	3	$6.10e-6-7.63e-6$	0.75–0.9	1560–3120	750–1500	0.8–0.9	0.7–0.9	0.6–0.8
Bad	4	$4.56e-6-6.10e-6$	0.55–0.75	3120–4680	1500–2250	0.7–0.8	0.5–0.7	0.4–0.6
Poor	5	$< = 4.56e-6$	$< 0.55$	$> 4680$	$> 2250$	$< 0.7$	$< 0.5$	$< 0.4$

on Fig. 8-S4, Big Karun basin does not have enough capacity for implementation of new development projects in the framework of water transfer and agricultural development projects. It is important to consider that operation of these projects, regardless of basin management aspects such as efficiency improvement, selling water to destination basin, causes severe shortage in meeting of Big Karun River end users' demand. Although water supply for this node can be increased by implementing hedging rules for under study/construction inter-basin water transfer, water stress index is ranked fair in 46 years. In Scenario 5, condition is better compared to operation of under study/construction agricultural development projects (Scenario 3). If the inter-basin water transfer project (considering hedging rules) and agricultural development project (Scenario 6) are operated simultaneously, water stress index would be ranked worse (Fig. 8-S6). In Scenario 6, supplied demand will rank bad for less time steps (3 years) compared to the full transfer and agricultural development projects. As shown in Fig. 8-S7, implementing management alternatives to improve efficiency

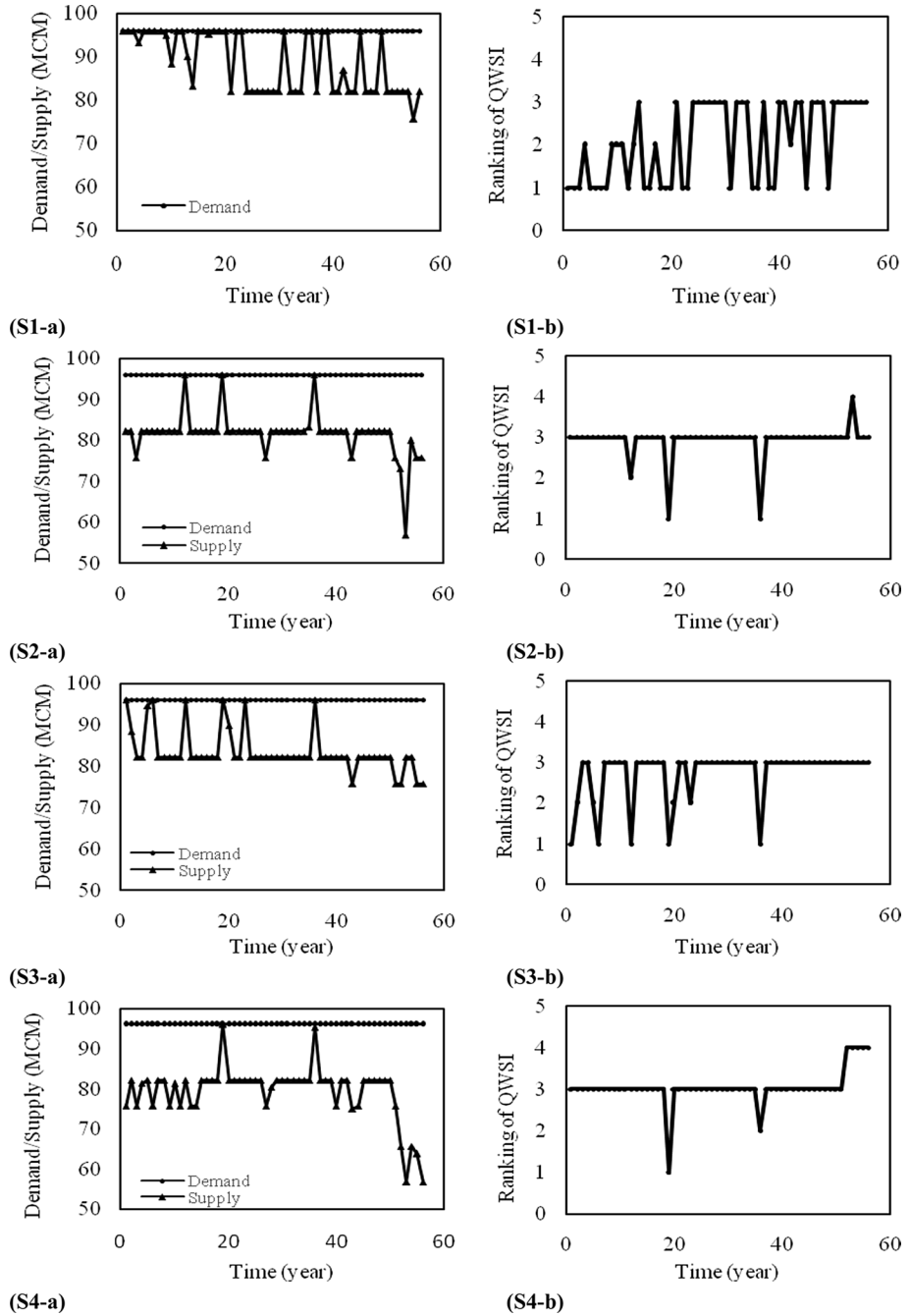


Fig. 8 a QWSI and b ranking of QWSI in Darkhojn to Persian Gulf agricultural node in Scenarios 1 to 8

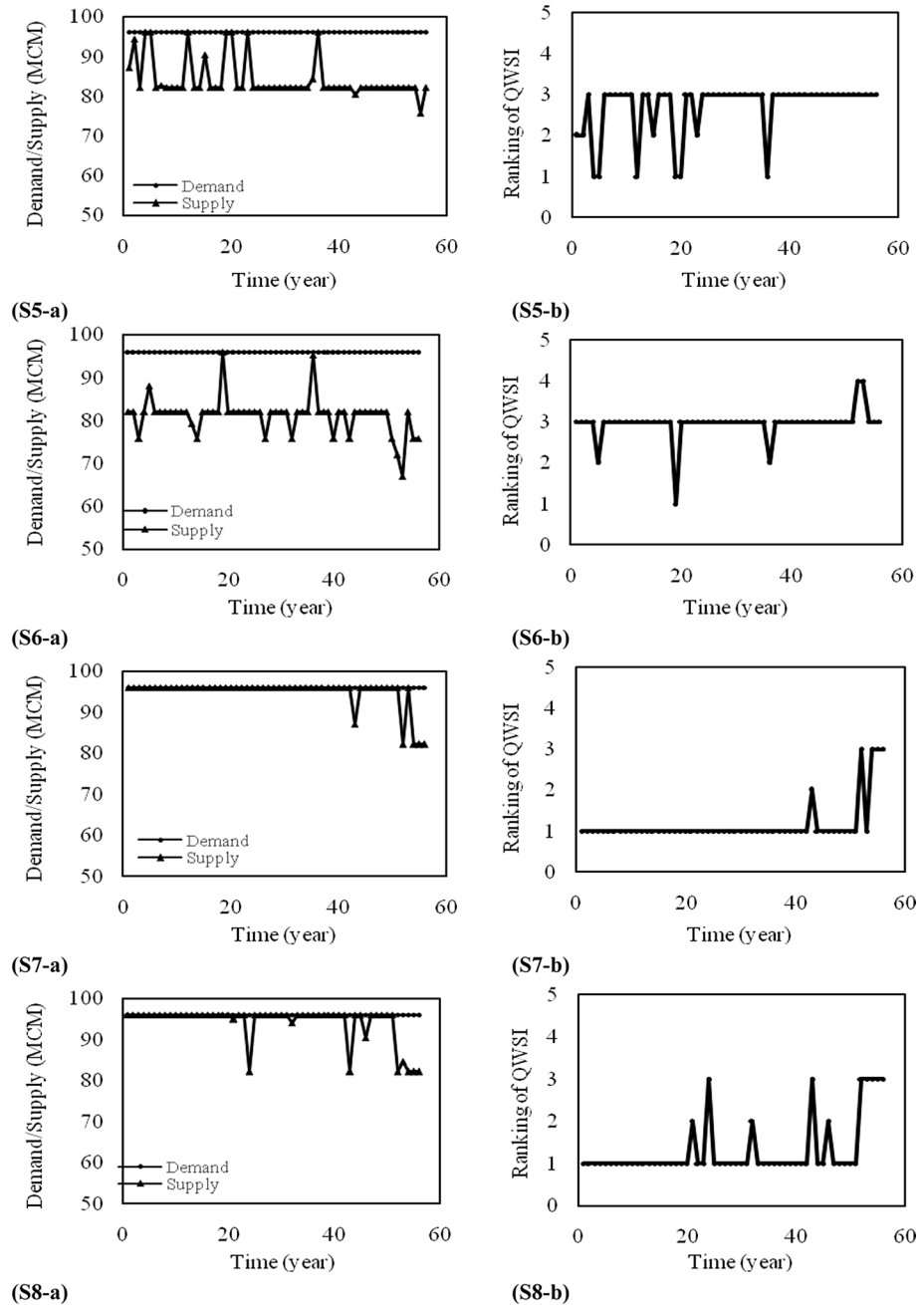


Fig. 8 (continued)

of upstream agricultural nodes causes not only transfer of hedging inter-basin water transfer but also getting in rank first (excellent) for meeting demand in water right nodes of Darkhojn to Persian Gulf. In Scenario 7, the reliability of demand meeting for this node is

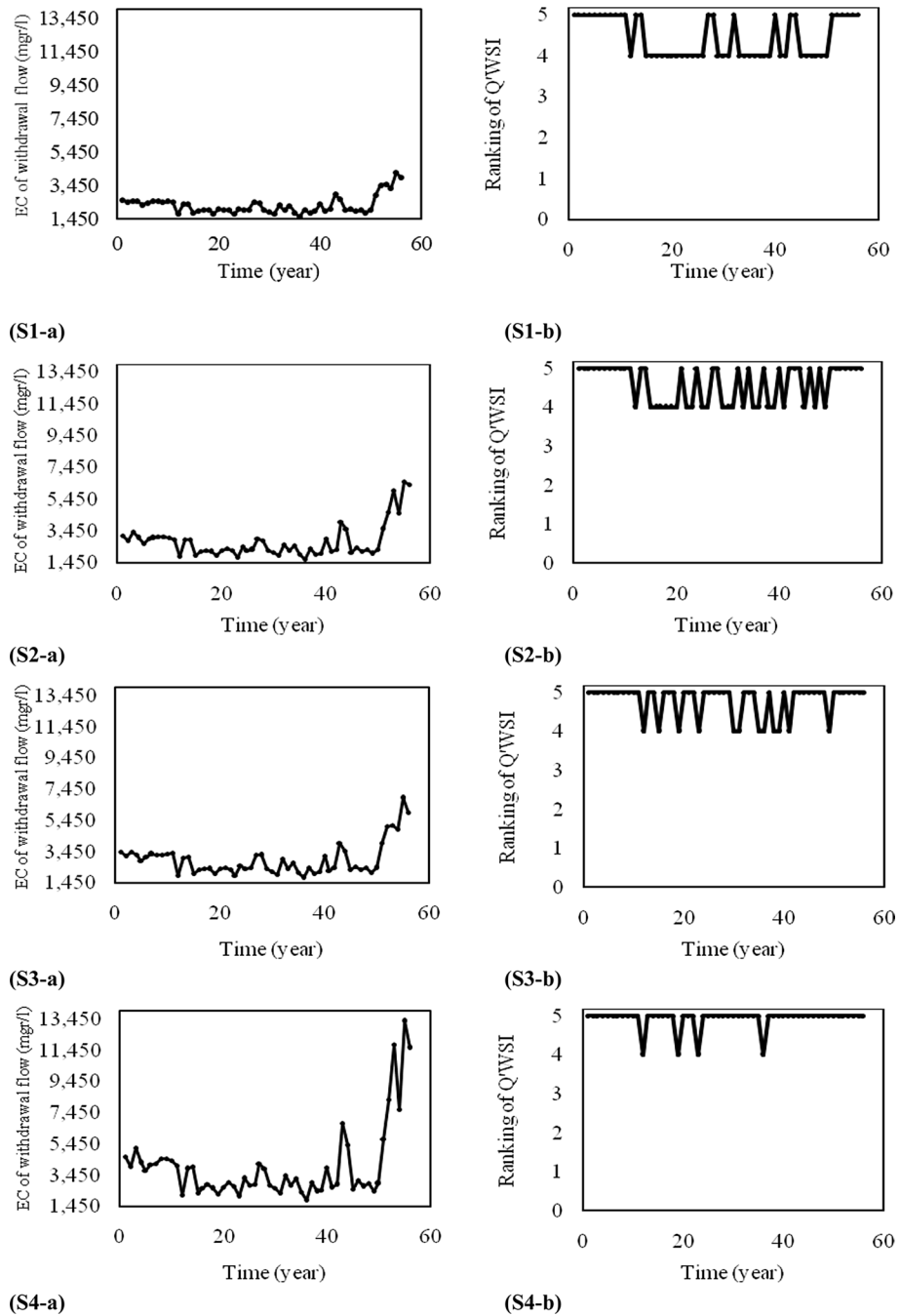
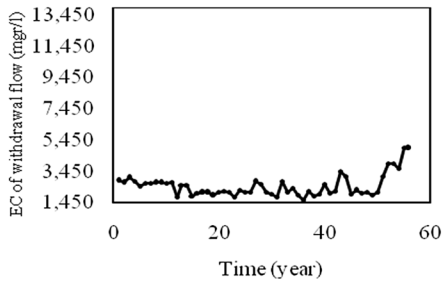
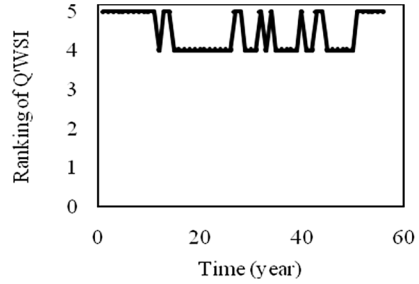


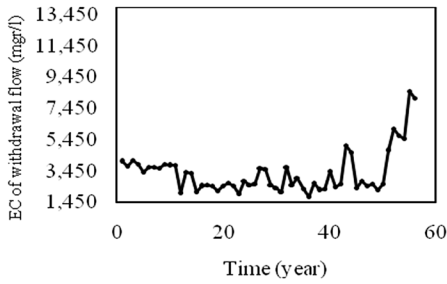
Fig. 9 a Q'WSI and b ranking of Q'WSI in Darkhojn to Persian Gulf agricultural node in Scenarios 1 to 8



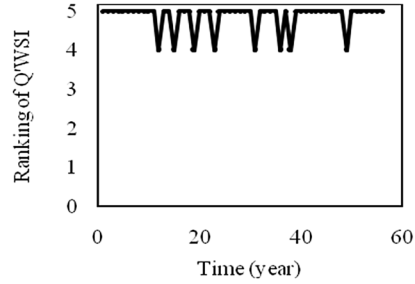
(S5-a)



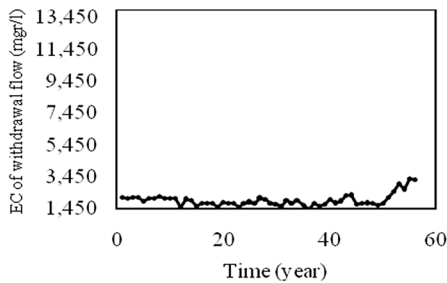
(S5-b)



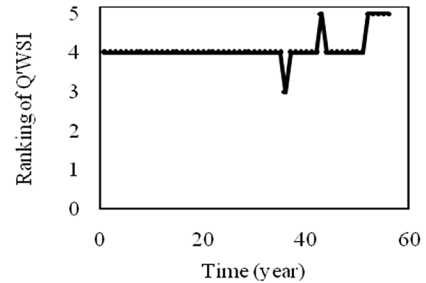
(S6-a)



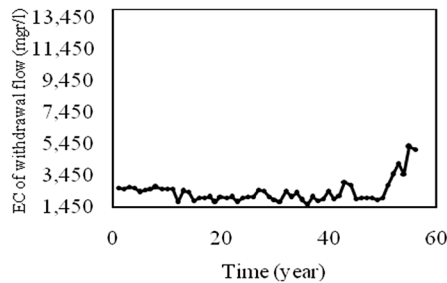
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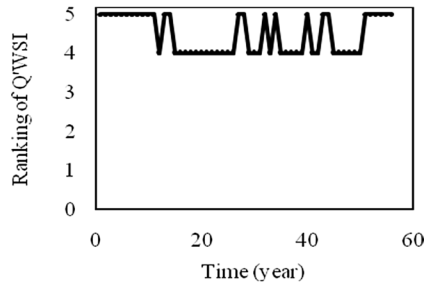
(S7-a)



(S7-b)



(S8-a)



(S8-b)

Fig. 9 (continued)

acceptable even with inter-basin water transfer operation. In this situation, system has this capacity to meet this node demand quantitatively even if agricultural upstream development projects are operated (Scenario 8).

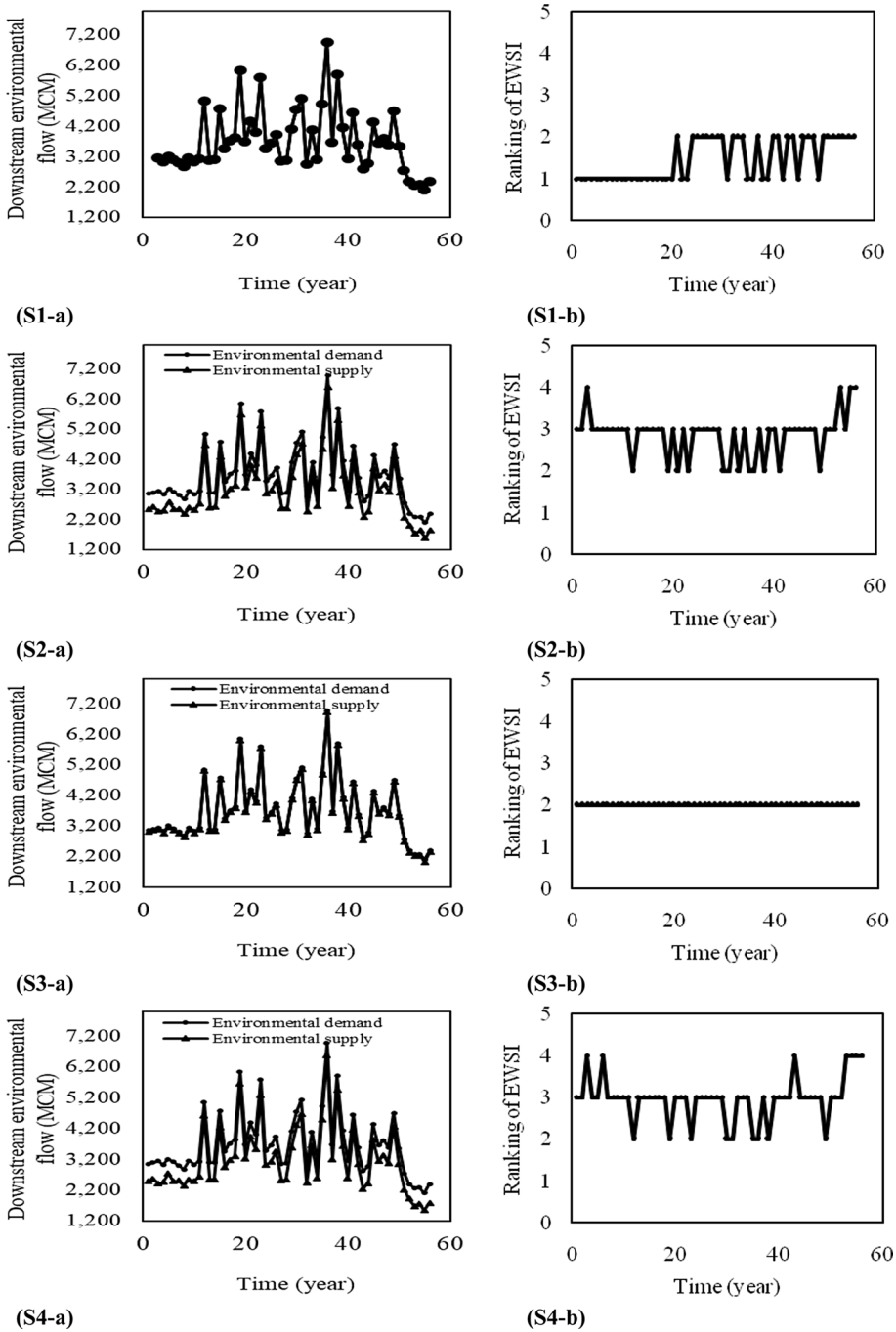
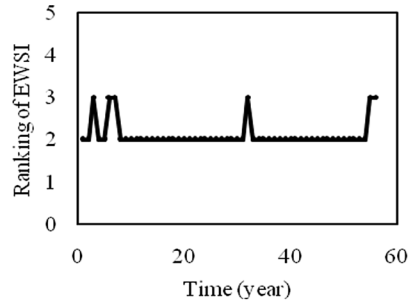
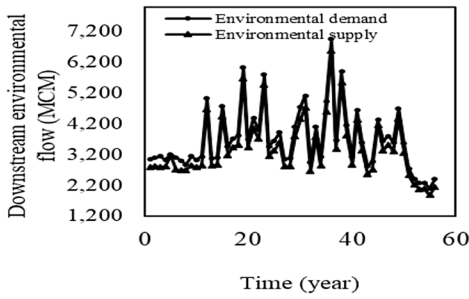
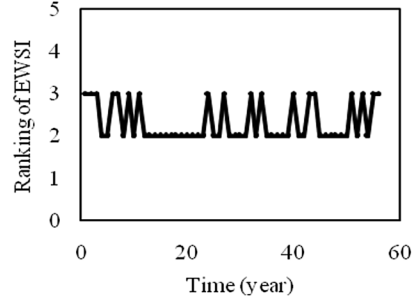
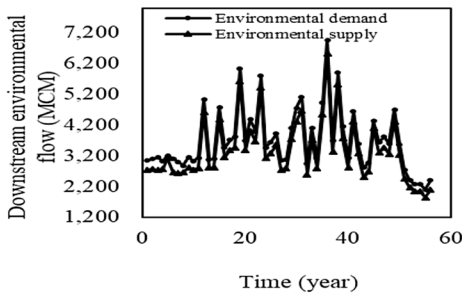


Fig. 10 a EWSI and b ranking of EWSI in Darkhojn to Persian Gulf agricultural node in Scenarios 1 to 8



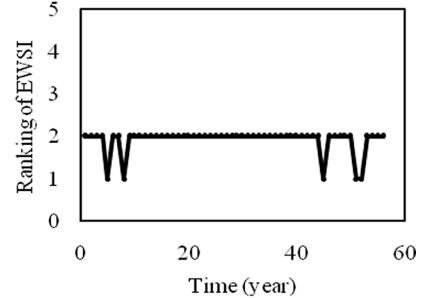
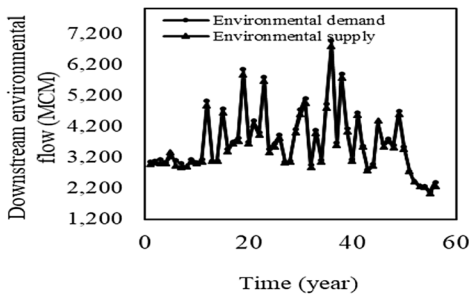
(S5-a)

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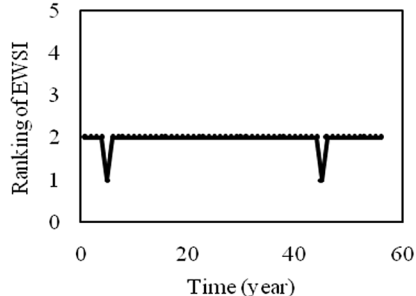
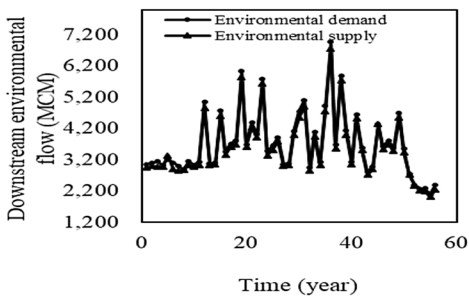
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(S7-a)

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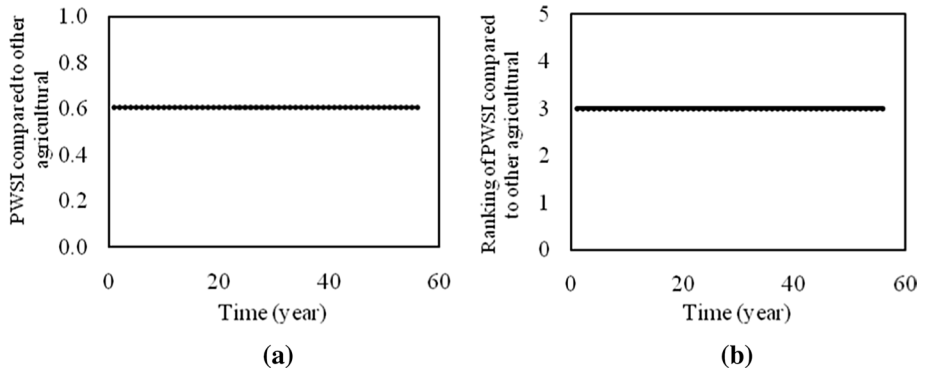


(S8-a)

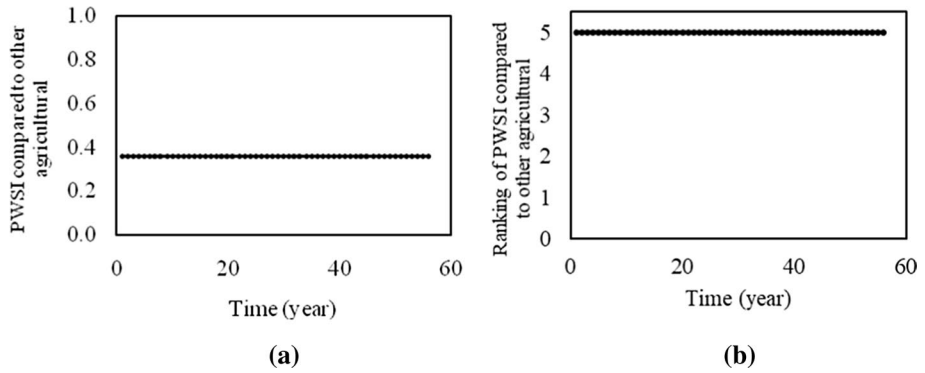
(S8-b)

Fig. 10 (continued)

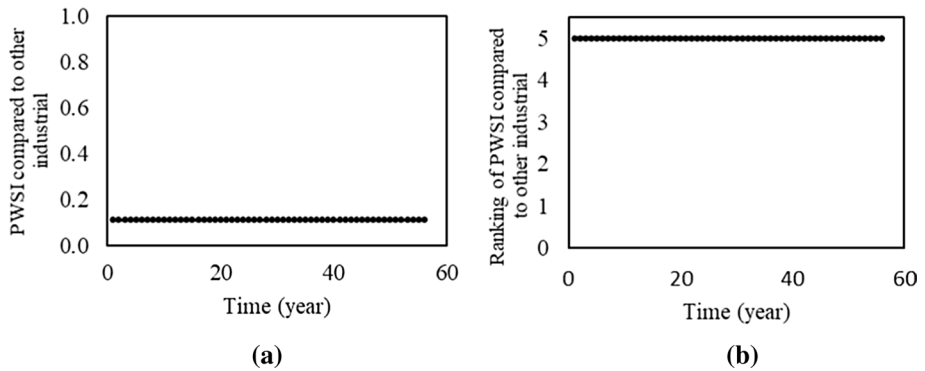




**Fig. 11** **a** PWSI compared to other agricultural and **b** ranking of PWSI compared to other agricultural in Darkhoin to Persian Gulf agricultural node in Scenarios 1 to 6



**Fig. 12** **a** PWSI compared to other agricultural and **b** ranking of PWSI compared to other agricultural in Darkhoin to Persian Gulf agricultural node in Scenarios 7 and 8



**Fig. 13** **a** PWSI compared to industrial and **b** ranking of PWSI compared to industrial in Darkhoin to Persian Gulf agricultural node in Scenarios 1 to 8

## 4.2 Q'WSI analysis results

Figure 9-S1 shows that the quality of withdrawal flow in Darkhoin to Persian Gulf water rights had poor quality and is always ranked fourth (bad) or fifth (poor) according to Wilcoxon diagrams. It is obvious that such a poor-quality will result in lower crop yield and increase of social dissatisfaction. The quality of withdrawal flow from Big Karun River Darkhoin to Persian Gulf water rights agricultural node will be decreased dramatically, if under study/construction inter-basin water transfer project is considered, which decreases crop yield and economic development (Scenario 2). On the other hand, rising trend of EC values is an important issue at the end of the operational period. Based on Fig. 9-S2-b, qualitative water stress index is ranked poor in 25 time-steps which emphasize on EC value greater than 2,250 micromho/cm. This condition is exacerbated under Scenario 3, which is under study/construction agricultural development projects scenario. As mentioned before, Big Karun basin does not offer adequate capacity of new inter-basin water transfer and agricultural development projects. In fact, development will not be possible neither based on quantitative analysis, nor by qualitative investigations (Fig. 9-S4). In Scenario 4, EC value of withdrawal flow is in a range of 1,843–13,300 micromho/cm, which is not proper for the crop production. Even hedging of inter-basin water transfer projects demands does not show dramatic impact on basin's quality improvement at the end nodes. This trend will be worsening by adding agricultural development projects. As shown in Fig. 9-S7, implementing structural and non-structural practices in order to improve irrigation efficiency at the irrigation networks nodes causes drop in ranking of the withdrawal flow for this node. In Scenario 7, frequency of poor ranking is reduced compared to the previous modes. The rank fifth has been observed only at the end of the operation period. In this scenario, EC value of withdrawal flow for the Darkhoin to Persian Gulf water rights node is ranging between 1,339 and 3,316 micromho/cm and the frequency of bad ranking is more than other rank. It should be noted that Scenario 7 part of pressurizing cost has been paid by water transfer profit. So, both Karun and Central basins have profited from water allocation revenue. Also, operation of agricultural development projects increases the system's vulnerability (Scenario 8).

## 4.3 EWSI analysis results

Figure 10-S1 shows that in 22 years during the operational period, environmental water stress index is ranked second (good), which indicates that water required for environmental needs has been used alternatively used to meet drinking, industry, and fish farming demands of upstream users. Rank 2 represents the situation when at least 90% of environmental demand is supplied (based on Montana method). Figure 10-S2 shows that the downstream environmental demand has never been fully met and the environmental stress index is ranked third (Fair) 41 times under full transfer of inter-basin water transfer. In Scenario 2, the system is also ranked fourth (bad) in 4 years when 80% of environmental demand has been met. The second rank (good) also belongs to the agricultural development scenario (Scenario 3). If both full transfer of inter-basin water transfer and agricultural development (Scenario 4) are implemented at the same time, water provided for downstream environmental requirement would be decreased to meet demands of upstream users; consequently, incidents of ranking 4 (bad) will be increased under this scenario. Hedging of inter-basin water transfer projects results in improvement of environmental stress index

and improve its ranking from third (fair) to second (good). In Scenario 6, adding agricultural development causes increase in frequency of its ranking (fair). Hedging of inter-basin water transfer projects and improved irrigation system efficiency (Scenario 7) results in better ranking, ranked second (good) and first (excellent) for environmental stress index.

#### 4.4 PWSI analysis results

Figures 11 and 12 show the water productivity index of Darkhoin to Persian Gulf water rights agricultural node, which is compared to the value of other agricultural nodes. Figures 11, 12 introduce current irrigation system (Scenarios 1–6) and improved irrigation system (Scenarios 7 and 8), respectively. Results indicate that the water productivity index value is estimated 0.6 and it is ranked as third, while there is no improvement in efficiency of upstream agricultural nodes. This index value and rank are 0.4 and 5, respectively, for efficiency improvement mode due to the increase in income under efficiency improvement modes in modern irrigation network. Improvement in modern irrigation network causes the increase in income. While the income from old water rights is fixed, water productivity index for these nodes will be ranked lower compared to the other agricultural nodes.

Based on Tables 2, 3 and 4, the agricultural users (demand nodes) are split into two sectors, namely “historical water rights nodes” and “modern irrigation network”. The modern agricultural network is able to adjust the amounts of water to plants at needed intervals. Among the study nodes, the outlet of the system, which is part of the historical water rights nodes, is called Darkhoin to Persian Gulf agricultural node. Ahvaz to Darkhoin agricultural node is another example of nodes with historical water right.

In Fig. 13, water productivity of Darkhoin to Persian Gulf agricultural node is compared to the water productivity of industry nodes. Results indicate that water productivity of agricultural nodes is less than industry nodes. In fact, it shows less income for agricultural nodes compared to the industry nodes for a unit of water use.

It should be noticed that since, in Iran, the income from consuming of one cubic meter of water in the agricultural sector is approximately 30 cents, it is assumed that 5 cents of each cubic meter transferred water will be allocated to the receiving basin. This procedure allocates evenly the water between the Karun basin as source basin and central basin as the destination basin. After calculating total income, receiving money for each irrigation network has been estimated based on their shares from total consumption of agricultural nodes.

#### 4.5 Performance criteria analysis results

In addition to mentioned indexes, system performance criteria, including reliability, resilience and vulnerability, have been calculated and evaluated for North Karun, Dez and South Karun basins. Results are presented in Tables 10, 11 and 12 (Bozorg-Haddad, 2014).

The results in Table 9 indicate that drinking, industry, and fish farming users are affected by none of the evaluated scenarios in North Karun. The same results are observed for Dez and South Karun. It can be due to the priorities in water demand. Because higher priority is given in order to the supply of drinking, industry, fish farming, environmental and agricultural demands. So, agricultural nodes are affected by different scenarios more than other nodes.

The presented results in Table 10 show that performance criteria of agricultural nodes are approximately constant among different scenarios in North Karun. So, different

**Table 10** Values of performance criteria in drinking, industry and fish farming nodes

scenario	North Karun				Dez				South Karun			
	Reliability		Resiliency		Vulnerability		Reliability		Resiliency		Vulnerability	
	Reliability	Resiliency	Vulnerability	Resiliency	Reliability	Resiliency	Vulnerability	Reliability	Resiliency	Vulnerability	Resiliency	
1	100.0	100.0	0.0	84.37	96.4	84.37	7.36	100.0	100.0	0.0	100.0	100.0
2	99.7	100.0	0.08	84.37	96.4	84.37	8.11	100.0	100.0	0.30	99.6	0.30
3	100.0	100.0	0.0	84.37	96.4	84.37	7.36	100.0	100.0	0.0	100.0	0.0
5	99.7	100.0	0.08	84.37	96.0	84.37	8.11	100.0	100.0	1.29	99.6	1.29
6	100.0	100.0	0.0	84.37	96.4	84.37	7.01	100.0	100.0	0.0	100.0	0.0
7	100.0	100.0	0.0	100.0	96.4	84.37	7.36	100.0	100.0	0.0	100.0	0.0
8	100.0	100.0	0.0	100.0	98.2	100.0	5.07	100.0	100.0	0.0	100.0	0.0
					98.2	100.0	5.07	100.0	100.0	0.0	100.0	0.0

**Table 11** Values of performance criteria in agricultural nodes

scenario	North Karun			Dez			South Karun		
	Reliability	Resiliency	Vulnerability	Reliability	Resiliency	Vulnerability	Reliability	Resiliency	Vulnerability
1	93.2	93.13	0.67	94.5	75.53	25.04	70.9	60.67	36.33
2	93.0	92.99	1.99	94.0	71.0	26.79	57.4	50.15	59.15
3	93.2	93.13	0.67	94.2	71.36	28.69	60.7	49.76	52.28
4	93.0	92.99	1.99	93.6	70.0	44.90	51.3**	49.4**	72.66**
5	93.0	92.99	1.03	94.5	73.16	25.74	62.0	53.64	46.90
6	93.0	92.99	1.03	93.9	70.32	28.93	55.6	51.07	59.77
7	93.2	93.13	0.75	98.5	85.42	11.86	88.8*	70.51*	19.65*
8	93.2	93.13	0.75	98.2	89.58	16.41	82.7	71.4	33.69

\*The best mode

\*\*The worst mode

**Table 12** Results of TOPSIS decision-making method for selecting the best scenario in Big Karun basin

Consumption Type	The best scenario	The worst scenario	Consumption Type	The best scenario	The worst scenario
Gotvand	-	-	Ajrub	7	4
Gotvand and Aghili	7-8	4	Dez Dam to Harmale	1	8
Dimche 2	7-8	4	Dez Small Fish Project	7	4
Dimche 1	7-8	4	Shavuri	7	4
North Karun Sugar Cane Industry	1-3	7-8	Miyab Sugar Can	7	4
Dimche 1-West Sugar Can	7-8	4	Haftapeh Sugar Can	7	4
Dimche 2 Sugar Can	7-8	4	Khomeini-West Sugar Can	7	4
North Karun Small Fish Project	7-8	4	Dehkoda Sugar Can	7	4
Haftkel and Ramhormoz	7-8	4	West Shoebiye	7	4
Gotvand to Bande-Mizan	1-3	7-8	Dez Sugar Can Industry	1	8
Shushtar	7-8	4	Harmale to Bande-Ghir	1	8
Gargar and Zahriyeh	7-8	4	Bande-Ghir to Ahvaz	1	8
Gargar	1-3	7-8	Molasani and Vais	7	4
Gargar Fish	7-8	1	North-East Ahvaz	7-8	4
Daryun	7-8	4	Ramin Powerhouse	7	4
Shotayt	1-3	7-8	Ahvaz	7	4
MiyabShushtar	7-8	4	Jafr	7	4
Khomeini-East Sugar Can	7-8	4	Farabi-Farsi-Khazai Sugar Can	7	4
East Shoebiye	7-8	4	Amirkabir-Kuchakhan Sugar Can	7	4
Shahid	1-3	7-8	South Karun Sugar Cane Industry	1	4
Dezful	-	-	Mahshahr and Bandare-Emam	7	4
West Dez-with Ret flow	7-8	4	Ahvaz-Darkhoi	1	4
West Dez-without Ret flow	7-8	4	Ahvaz-Khorramshahr Small Fish Project	7	4
East Dez and Sabili	7-8	4	Darkhoi-Khalij fars	1	4
Andimeshk Fish	7-8	4	Big Karun basin	7	4

scenarios have approximately similar quantity outcomes in agricultural nodes. The results also indicate that although the impact of different scenarios on Dez basin is more compared to North Karun basin, the most variation and impacts can be seen in South Karun basin. This basin faces the most negative and positive impacts from Scenarios 4 and 7, respectively.

#### 4.6 Performance indexes zoning maps results

In order to provide a better picture of Big Karun basin, under different management options, zoning maps are formed for each scenario. Among the scenario maps, three maps are selected to be shown for Scenarios 1, 4 and 7.

In Fig. 14, the zoning map of water stress index is shown for different user nodes of Karun basin. It can be seen that in North Karun basin only Gargar water right agricultural node is faced water shortage. The system cannot also meet the whole required demand in Dez basin before the convolution with the middle basin flow. But water shortages are not severe in North Karun and Dez basins. After forming Big Karun River by joining Gargar, Shotayt and Dez Rivers, there is sufficient water resources for meeting users' demand at the mouth of the South Karun basin (Bande-Ghir). But shortage is observed in Jafir agricultural node (modern irrigation network) to downstream and severe shortage is observed in Ahvaz to Darkhojn agricultural node. Figure 14-b shows the aggregation of shortages in future development projects (Scenario 4). Based on Fig. 14-c, the reliability of meeting demand is acceptable for the Karun basin under integrated management scenario and by considering water is transferred to central basin. Figure 15-a shows that the water quality of Karun River is in average range in tributaries of Gargar and Shotayt Rivers and end sections of Dez River. It is obvious that the river has poor water quality in South Karun. Operation of all the future development projects would result in lower water quality. In Scenario 4, the withdrawal flow from all nodes, from Bande-Ghir to downstream, is ranked in poor class.

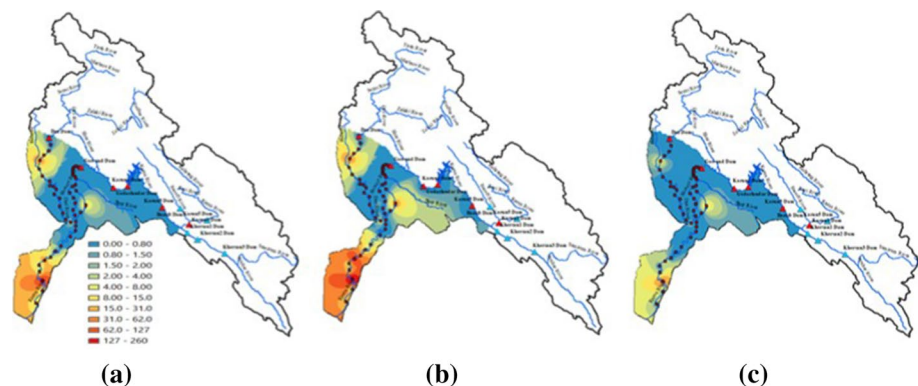
As mentioned before, in Scenario 7 Big Karun basin can be considered as a system where integrated water management plan is implemented. In order to establish a water allocation balance between numerous stakeholders, part of efficiency improvement costs is paid by income from water transfer. Zoning map of income distribution gained from hedging under study/construction inter-basin water transfer projects demand is illustrated in Fig. 16 for different modern irrigation network nodes. Results indicate that 23%, 28%, and 37% of efficiency improvement cost for the irrigation network nodes in North Karun, Dez and South Karun basins, respectively, are paid from income gained by inter-basin water transfer.

In Fig. 17, zoning of cost distribution for the changes irrigation system is illustrated for modern irrigation networks in Big Karun basin. The comparison of required costs for irrigation systems and incomes from changing irrigation is shown in this Fig. 18, which indicates an increase and reduction in costs for starting nodes of Dez River and end nodes of Big Karun, respectively.

Finally, Fig. 16, which is a picture of zoning environmental water stress in different nodes of Big Karun basin, shows 20% of shortage in environmental demands in North and South Karun is expected, if the development continues based on current management policies.

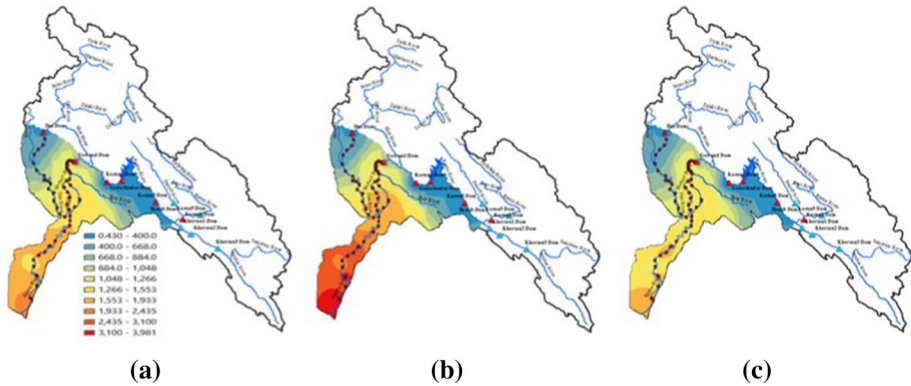
#### 4.7 TOPSIS analysis results

Table 11 presents the results of the TOPSIS decision-making technique for selection of the best scenario in Big Karun basin. We assumed an equal weight for all indexes. Table 10 shows that for all modern agricultural nodes (irrigation network), Scenarios 7 and 8 are selected as the superior scenarios. The reason can be found in the income increase from each network in terms of efficiency improvement. On the other hand, the results of TOPSIS method show the same results for the Scenarios 7 and 8 in North Karun basin, while in Scenario 8 the agricultural development projects have been added to the system, located in Dez and South Karun. It should be noted that results of Scenarios 1 to 6 are similar, and Scenario 4 has been selected as the worst option among modern irrigation network of North Karun. The same situation is observed for Dez River basin nodes. At the nodes, which are located before the nodes of first agricultural development project, Scenarios 7 and 8 have been selected as the best options. But Scenario 7 will be the best option in Ajirub irrigation network to downstream and by adding Balarud and Shavur irrigation network projects. In Dez basin, the difference between rankings of different scenarios is negligible; this reflects the low impact of inter-basin water transfer and agricultural development projects in North Karun and Dez basins. Scenarios 7 and 8 have equal ranks in South Karun's North-East Ahvaz irrigation network, which is not affected by agricultural development projects. In downstream of North-East Ahvaz irrigation network, the situation is different because of adding South-East and South-West Ahvaz irrigation networks. It should be noted that in none of these nodes, system can meet the additional demand of inter-basin water transfer and agricultural development projects. Scenarios 1 and 3 are the best scenarios in terms of water right users in North Karun River. As mentioned before, no agricultural development project has been predicted for North Karun basin; so, Scenarios 1 and 3 show the same results. The relative productivity index to agricultural nodes indicate that scenarios with efficiency improvement plans are not appropriate in water right agricultural nodes (Figs. 9, 10). Income from modern irrigation networks is increased during system simulation and efficiency improvement, while the income from old water rights is fixed. So, lower values have allocated to water productivity in old water right compared to water productivity of other agricultural node index. The same situation is observed for the industry users because the water productivity index in each node is decreased compared



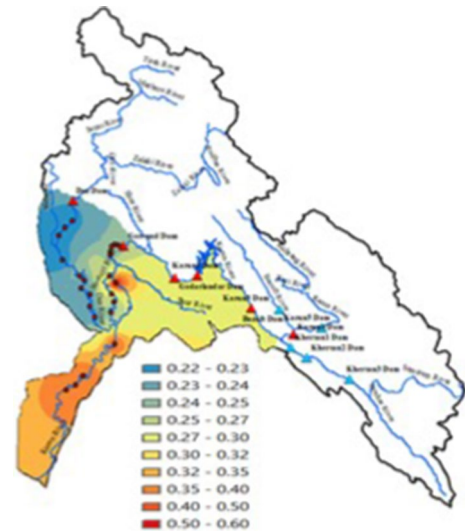
**Fig. 14** Zoning shortage of different user nodes in Big Karun basin in **a** Scenario 1, **b** Scenario 4, and **c** Scenario 7





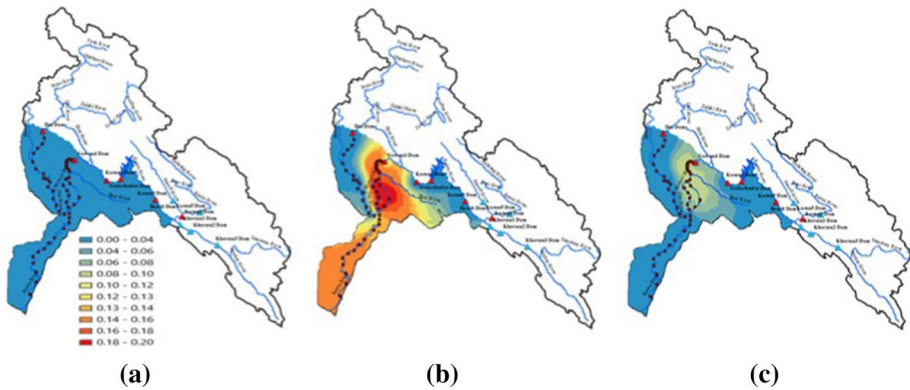
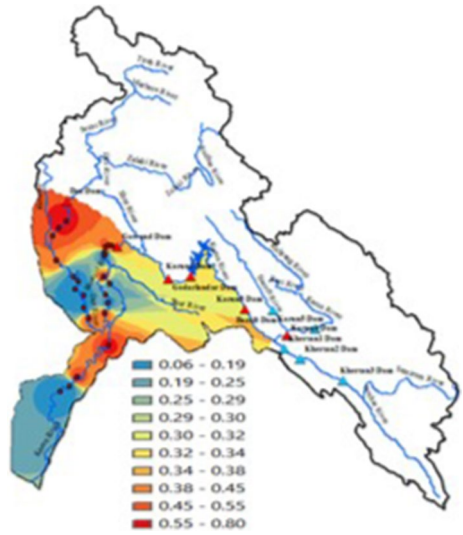
**Fig. 15** Zoning the flow quality of different user nodes in Big Karun basin in **a** Scenario 1, **b** Scenario 4, and **c** Scenario 7

**Fig. 16** Zoning of income distribution from hedging inter-basin water transfer in modern irrigation networks in Big Karun basin for Scenario 7



to agricultural nodes (in efficiency improvements and increase water productivity in modern agricultural nodes situations); so, for the industry nodes under efficiency improvement mode are selected as the worst-case scenario because of higher values of this index compared to other indexes. In water right agricultural nodes of South Karun basin, Scenario 4 is the worst option unlike water right agricultural nodes of North and Dez basins, in which Scenario 7 or 8 is the worst option (because of water productivity index). Because in water right agricultural nodes of South Karun, the quantitative water stress, qualitative water stress, environmental water stress indexes improve significantly that the impact of the water productivity index reduction will be negligible.

**Fig. 17** Zoning of changing irrigation system cost distribution in modern irrigation networks in Big Karun basin for Scenario 7



**Fig. 18** Zoning of environmental demand stress in different user nodes in Big Karun basin in **a** Scenario 1, **b** Scenario 4, and **c** Scenario 7

### 5 Concluding remarks

In the present study, the concept of integrated and sustainable management has been evaluated for a large-scale system. In this regard, Big Karun basin was considered and evaluated based on the SD approach. The SD model includes 6 dams, 5 inter-basin water transfer, 7 under study/construction inter-basin water transfer, 12 drinking and industry users, 7 fish farming users and 34 agriculture users. The environmental demand is also determined for each river based on Montana method. The SD model is able to simulate not only the flow quantity but also water quality at different nodes. The results are analyzed based on a multi-criteria performance assessment framework, including quantitative water stress index, qualitative water stress index, environmental water stress, income from each agriculture and industry nodes, water productivity in each agriculture node compared to other agriculture nodes, water productivity in each agriculture node compared to industry

nodes, cost of irrigation systems pressurizing in agriculture nodes (irrigation network) and income from water transfer to destination basins. Existing policies are simulated as status quo scenario, and future management alternatives formed seven more scenarios. To better understand the performance of different scenarios, each performance index was classified in the range of excellent (1) to poor (5) condition. In addition to the mentioned indexes, behavior of each scenario is analyzed based on statistical performance criteria, reliability, resiliency and vulnerability, and the best scenario was selected using TOPSIS method. The results indicate that in a large-scale system with many involved stakeholders and users, it is necessary to consider various internal and external factors such as the quality of water resources, downstream environmental demand, income and costs of changing irrigation systems in order to struck balance among different stakeholders in a basin and other basins. It is also suggested that these metrics should be join statistically using the joint-probability functions to address the simultaneous existence of these metrics into water system performance index (Goharian, Burian, et al., 2018; Goharian, Zahmatkesh, et al., 2018). According to the results, although the impact of future development projects operation is negligible on upstream stakeholders and users, sustainability of system especially in downstream requires implementation of integrated and sustainable management actions in all sectors. If current policies continue, system cannot meet the future demand of developing projects. Even full capacity inter-basin water transfer will result in reduction hydropower generation and reliability of water supply in the basin. The results also indicated that there will be a water allocation balance among source basin stakeholders and stakeholders at the source and destination basins through selling a portion of upstream inflow to destination basins, institution water tariffs and paying part of changing irrigation systems costs in destination basin.

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**Data availability** All of the required data have been presented in our article.

**Declaration**

**Conflict of interests** There are no conflicts of interest.

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